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Influence of the biomechanical variables of the gait cycle in running economy

Influencia de variables biomecánicas del ciclo de paso en la economía de carrera

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Abstract

The aim of this study was to investigate the relationships between biomechanical variables and running economy (RE). Eleven recreational (RR) and 14 well-trained runners (WT) completed 4 min stages on a treadmill at different speeds. During the test, biomechanical variables such as ground contact time (tc), swing time (tsw), stride length, frequency and angle and the length of the different subphases of ground contact were calculated using an optical measurement system. VO2 was measured in order to calculate RE. The WT runners were more economical than the RR at all speeds and presented lower tc, higher tsw, longer strides, lower stride frequencies and higher stride angles ($P<0.05$). Similarly, the WT runners experienced a later propulsion subphase than the RR runners ($P<0.05$). RE was positively related to tc, stride frequency and 10-km race pace, whereas it was negatively related to tsw, stride length, stride angle and the propulsive subphase. Our results suggest that running patterns characterized by longer stride lengths and higher stride angles, lower stride frequencies and tc, higher tsw and later propulsion suphases may enable an efficient energy use per stride.

Key words: ground contact; stride angle; swing time; stride length; stride frequency.

Resumen

El objetivo de este estudio fue el investigar las relaciones entre diferentes variables biomecánicas y la economía de carrera (RE). Once atletas populares (RR) y 14 atletas altamente entrenados (WT) completaron estadios de 4 min en tapiz rodante a diferentes velocidades. Durante el test, el tiempo de contacto (tc) y de vuelo (tsw), la longitud, frecuencia y ángulo de zancada y la duración de las diferentes sub-fases del tiempo de contacto se calcularon usando un sistema óptico. Se midió el VO2 para calcular la RE. Los atletas WT fueron más económicos que los RR y presentaron menores tc, mayores tsw, zancadas más largas, frecuencias más bajas y ángulos mayores ($P<0.05$). Además, los atletas WT experimentaron la sub-fase propulsiva más tarde que los RR ($P<0.05$). La RE estuvo positivamente relacionada con el tc, la frecuencia de zancada y el ritmo de 10 km, mientras que estuvo negativamente relacionada con el tsw, longitud y ángulo de zancada y la sub-fase propulsiva. Estos resultados sugieren que una biomecánica caracterizada por zancadas más largas, ángulos de zancada y tsw mayores, menores frecuencias y tc, y sub-fases propulsivas más tardías pueden favorecer un uso energético más eficiente.

Palabras clave: tiempo de contacto; ángulo de zancada; tiempo de vuelo; longitud de zancada; frecuencia de zancada.

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Introduction

Sustained running performance is reliant on a complex interaction of factors that lead to efficient muscular work and should result in fast and effective running gait (Joyner, 1991). Historically, physiological factors such as cardiac output, oxygen delivery to working muscles and maximal oxygen uptake (VO_{2max}) have been thoroughly researched as predictors of exercise performance (Nummela, Keränen & Mikkelsson, 2007). These predictors reveal certain aspects to elite- and world-class performance and are able to distinctively identify discrepancies between untrained and well-trained groups. However, the ability to unravel the difference between these well-trained homogenous groups is more challenging (Levine, 2008).

Since the 1970s running economy (RE) has been investigated, although it is often still referred to as "being relatively ignored in the scientific literature" (Foster & Lucia, 2007). When working with well-trained homogenous groups and East African runners, RE has been found to most appropriately discriminate between their performances (Lucia et al., 2006; Pate, Macera, Bailey, Bartoli & Powell, 1992). Consequently, RE is considered, together with VO_{2max} and the lactate threshold, as an important factor related to distance running success (Conley & Krahenbuhl, 1980; Di Prampero, Atchou, Brückner & Moia, 1986).

RE is commonly defined as the steady-state oxygen uptake (VO_2) required at a given submaximal speed (Cavanagh & Williams, 1982; Karp, 2010; Nummela et al., 2007) or as the energy requirement per distance (Di Pampero et al., 1986; Helgerud, Engen, Wisloff & Hoff, 2001). It can also be expressed as the percentage of the maximal oxygen uptake utilized ($\%VO_{2max}$) (Conley & Krahenbuhl, 1980) or as mechanical efficiency, which is the ratio between work output and oxygen cost (Åstrand, Rodahl, Dahl & Strommer, 1986).

Several studies have reported inter-individual variations in RE (Conley & Krahenbuhl, 1980), which reflects its importance in running performance (Helgerud, Støren & Hoff, 2010). Physiological factors (Mayhew, 1997), muscle fiber distribution (Bosco et al., 1987), age (Krahenbuhl & Pangrazi, 1983), sex (Bransford & Howley, 1987) and anthropometric factors (Bergh, Sjödin, Forsberg & Svedenhag, 1991) have also been proposed to explain the inter-individual variability in RE.

RE is also influenced by biomechanical variables, largely attributed to ground contact characteristics (Chapman, Laymon, Wilhite, McKenzie, Tanner & Stager, 2011; Kyröläinen, Belli & Komi, 2001). Shorter ground contact times are correlated with a higher VO_2 (Kram & Taylor, 1990), whereas small vertical oscillations (Gregor & Kirkendall, 1978), longer strides (Tartaruga et al., 2012), smaller changes in speed during ground contact (Kaneko, Ito, Fuchimoto, Shishikura & Toyooka, 1985) and lower peak ground reaction forces (Anderson, 1996) have been related to economical runners.

Increasing relative running speeds have been found to influence an athlete's RE (Daniels & Daniels, 1992). For example, elite middle-distance runners have efficient RE at speeds above or at marathon pace, and less efficient RE below marathon pace when compared to long-distance runners (Daniels & Daniels, 1992). It appears that runners with different training specializations have multiple factors influencing their RE and may be a possible reason for inconsistent findings (Di Prampero et al., 1986).

At present, the response of RE at different exercise intensities is not well understood. Fast running speeds may be a result of higher vertical ground reaction forces whilst minimizing the ground contact time of the foot (Weyand, Sternlight, Bellizzi & Wright, 2000). However, a shorter ground contact time has been shown to correlate with a higher mass-specific metabolic cost of running (Kram & Taylor, 1990). Therefore, it may be inferred that runners must find a way to increase their speed for the distance being raced with longer contact times to minimize the metabolic cost of running.

To date, the influence of biomechanical variables on metabolic cost of running between runners of different athletic ability at different speeds remains unclear. Thus, the purpose of this study was to investigate the influence of biomechanical variables, such as ground contact time, swing time, stride length and frequency, stride angle and the distribution of the different subphases during the ground contact on RE in recreational and well-trained runners.

Methods

Participants. Eleven recreational (mean ± SD: age 38.5 ± 4.0 years, height 176.9 ± 6.9 cm,) and 14 well-trained male long distance runners (mean ± SD: age 27.9 ± 6.4 years, height 176.7 ± 5.3 cm) took part in this study. Before participation, all athletes underwent a medical examination to ensure that they were free of cardiovascular, musculoskeletal and metabolic disease. The Ethics Committee for research on Human subjects of the University of the Basque Country (CEISH/GIEB) approved this study, which was performed in accordance with the principles of the Declaration of Helsinki (October 2008, Seoul). All athletes were informed about all the tests and possible risks involved and provided a written informed consent before testing.

Performance was rated according to the runners' recent 10-km personal best time. Inclusion criteria in the well-trained group was current participation in national or international level competitions and a 10-km race time <33.5 min. The recreational group trained a minimum of three days a week of running sessions and a 10-km race time >35 min. None of the recreational runners had an athletics license from any athletics federation.

Twenty-four hours prior to testing, athletes were encouraged to abstain from a hard training session and competition in order to be well rested for the tests. They were also requested to maintain their pre-competition diets throughout the test procedures. All athletes had previous experience with treadmill running, including a thorough familiarization session with the treadmill used for the study.

Anthropometry. Height (cm) and body mass (kg) were determined by the use of a precision stadiometer and balance (Seca, Bonn, Germany) and body mass index (BMI) was then determined. All measurements were taken with the participants wearing only running shorts. Eight skinfold sites (biceps, triceps, subscapular, supraspinale, abdominal, suprailiac, mid-thigh, and medial calf) were measured in duplicate with skinfold calipers (Holtain, Crymych, UK) by the same researcher to the nearest millimeter and the skinfold sum was calculated. Body fat percentage (%BF) was calculated for each athlete as previously described (Yuhasz, 1974).

Treadmill speed test. All participants completed a maximal incremental running test at 1% slope on a treadmill (ERGelek EG2, Vitoria-Gasteiz, Spain), which started at 9 km·h^{-1} without previous warm up. The speed was increased by 1.5 km·h^{-1} every 4 min until volitional exhaustion, with a minute of recovery between each stage (Yoshida, 1984; Maldonado, Mujika & Padilla, 2002; Maldonado-Martín, Mujika & Padilla, 2004). The treadmill was calibrated using a measuring wheel (ERGelek, Vitoria-Gasteiz, Spain) with a measurement error <0.5 m per 100 m interval. All testing sessions were performed under similar environmental conditions (20-24 ºC, 45-55% relative humidity).

During the test, respiratory variables were continuously measured using a gas analyzer system (Ergocard, Medisoft, Sorinnes, Belgium) calibrated before each session. Volume calibration was performed at different flow rates with a 3 L calibration syringe (Medisoft, Sorinnes, Belgium) allowing an error ≤ 2%, and gas calibration was performed automatically by the system using both ambient and reference gases (CO_2 4.10%; O_2 15.92%) (Linde Gas, Germany). $\dot{V}O_2$ data collected during the last 30 s of each workload under the lactate threshold was averaged and designated as the steady-state value for data analysis. RE was defined as steady-state $\dot{V}O_2$ per distance covered ($ml \cdot kg^{-1} \cdot km^{-1}$) and $\dot{V}O_2$ was also normalized per $kg^{0.75}$ to reduce the influence of body mass (Helgerud et al., 2010). Heart rate (HR) was recorded continuously by a heart rate monitor (Polar RS800, Kempele, Finland).

Runners were considered to have attained their $\dot{V}O_{2max}$ when two of the following criteria were fulfilled: 1) a *plateau* in $\dot{V}O_2$; 2) HR within 5 beats·min^{-1} of theoretical maximal HR (220-age) 3); Respiratory exchange ratio (RER) > 1.15

Peak treadmill speed (PTS; in $km \cdot h^{-1}$) was calculated as follows taking every second into account:

$$\text{PTS= Completed full intensity } (km \cdot h^{-1}) + [(\text{seconds at final speed} \cdot 240\ s^{-1}) \cdot 1.5\ km \cdot h^{-1}]$$

Determination of lactate threshold. Immediately after each exercise stage, capillary blood samples from the earlobe were obtained and lactate concentrations were determined with the use of a portable lactate analyzer (Lactate Pro, Arkray, KDK Corporation, Kyoto, Japan.). This system has been previously validated (Tanner, Fuller & Ross, 2010). The lactate threshold was determined for each participant from the blood lactate concentrations and speed data obtained during the treadmill speed test. A third order polynomial regression equation was calculated with the plasma lactate concentrations versus speed. The lactate threshold was identified as the point on the polynomial regression curve that yielded the maximal distance to the straight line formed by the two end data points (Cheng, Kuipers, Snyder, Keizer, Jeukendrup & Hesselink, 1992).

Biomechanics

Stride angle, ground contact time, swing time and stride length and frequency were measured for every step during the treadmill speed test using an optical measurement system (Optojump-next, Microgate, Bolzano, Italy). The values of minutes 2 and 3 of each workload where averaged and used for data analysis. This system is developed to measure with 1 kHz precision all flying and ground contact times while running. Optojump-next system consists of two bars (size 100 cm × 3 cm × 4 cm), one containing the reception and control unit, the other embedding the transmission electronics. Each of these contains 32 light emitting diodes (LEDs), positioned 0.3 cm from ground level at 3.125 cm intervals. The LEDs on the transmitting bar communicate continuously (1 kHz) with those on the receiving bar.

Ground contact time was defined as the time from when the foot contacts the ground to when the foot toes off the ground and was determined by the disruption of the infrared gates of the Optojump-next system. Using the same principle, swing time was defined as the time from toe off to initial ground contact of consecutive footfalls of the same foot. Stride length and stride frequency were defined as the length the treadmill belt moves from toe off to initial ground contact in successive steps and as the number of ground contact events per minute, respectively. The Optojump-next system has been shown to determine accurately these variables before (Debaere, Jonkers & Delecluse, 2013).

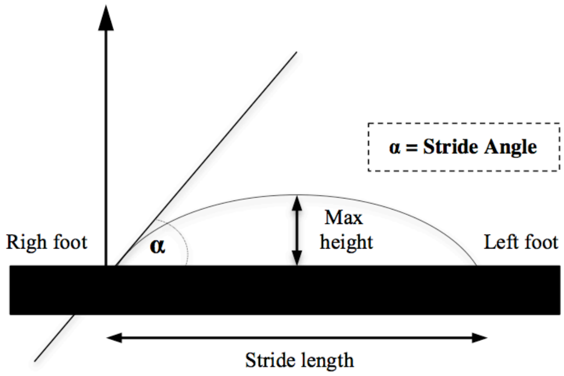

Figure 1. Schematic representation of the stride angle measured by the Optojump-next system.

Stride angle was defined as the angle of the parabola tangent derived from the theoretical arc traced by a foot during a stride and the ground (Figure 1). The theoretical parabola for the stride angle determination was calculated by the Optojump-next system through the stride length and the maximal height of the foot during a stride.

Lastly, the percentage of the ground contact time at which the different subphases of stance phase occurs (initial contact, midstance and propulsion) was also measured for every step during the treadmill speed test automatically by the Optojump-next system. During the stance phase of the gait cycle, the initial contact subphase corresponds to the time from initial *ground contact* to *foot flat*; midstance subphase from *foot flat* to initial *take off* and propulsive subphase from initial *take off* to *toe off*. The coefficient of variation of the variables measured with the Optojump-next ranged from 1.0 to 7.6 % (author`s unpublished data).

Statistics. All values are expressed as mean ± standard deviation (SD) and statistical analyses of data were performed using the Statistical Package for the Social Sciences 15.0 software package (StatSoft, Tulsa, OK, USA). Data were screened for normality of distribution and homogeneity of variances using a Shapiro-Wilk normality test and a Levene's test respectively. An independent Student t-test was used to determine differences between the groups at the set running speeds. In cases where variables were not normally distributed, a Mann-Whitney U-test was utilized. Pearson and Spearman correlations assessed relationships between variables.

The magnitude of differences or *effect size* (ES) were calculated for significant differences according to Cohen (1998) and interpreted as small (>0.2 and <0.6), moderate (≥0.6 and <1.2), large (≥1.2 and <2) and very large (≥2 and <4) according to the scale proposed by Hopkins, Marshall, Batterham and Hanin (2009). Significance for all analyses was set at $P<0.05$.

Results

Descriptive characteristics and maximal treadmill test results of both recreational and well-trained runners are listed in Table 1. The well-trained runners were younger and faster according to their best 10-km time than the recreational runners ($P<0.001$, very large ES). The well-trained runners were lighter, and presented lower BMI values, sum of skinfolds and %BF than the recreational runners ($P<0.05$; moderate and large ES).

Further, the well-trained runners achieved a higher PTS ($P<0.001$, very large ES) and a higher VO_{2max} than the recreational runners ($P<0.05$, moderate ES). There were no significant differences in other any maximum physiological variables, such as HR_{max} or RER_{max} between the two groups (Table 1).

Table 1. Subject characteristics and maximal test results of the recreational and well-trained runners.

	Recreational (n =11)	Well-trained (n =14)	Effect sizes
Age (years)	38.5 ± 4.0	27.9 ± 6.4***	1.98
PTS ($km \cdot h^{-1}$)	17.8 ± 1.7	21.7 ± 1.1***	2.72
10-km race time (min)	38.9 ± 3.2	31.7 ± 1.4***	2.96
Height (cm)	176.8 ± 6.9	176.7 ± 5.3	0.01
Mass (kg)	69.6 ± 7.4	64.7 ± 3.9*	0.82
BMI	22.2 ± 1.8	20.8 ± 1.4*	0.86
∑ 8 skinfold (mm)	70.7 ± 23.3	46.6 ± 12.0**	1.30
∑ 6 skinfold (mm)	60.3 ± 19.5	39.2 ± 10.7**	1.34
%BF	12.0 ± 2.5	9.5 ± 0.9**	1.33
VO_{2peak} ($ml \cdot kg^{-1} \cdot min^{-1}$)	63.9 ± 7.1	69.5 ± 3.4*	1.00
HR_{max} ($beats \cdot min^{-1}$)	183.4 ± 6.9	187.1 ± 5.8	0.58
RER_{max}	1.19 ± 0.08	1.21 ± 0.06	0.28

n, number of participants; PTS, peak treadmill speed; BMI, body mass index, ∑ 8 skinfolds, biceps, triceps, subscapular, supraspinale, abdominal, suprailiac, mid-thigh, and medial calf; ∑ 6 skinfolds, triceps, subscapular, abdominal, suprailiac, mid-thigh, and medial calf; %BF, percentage of body fat; VO_{2peak}, maximum oxygen uptake rate; HR_{max}, maximum heart rate; RER_{max}, maximum respiratory exchange ratio. Values are means ± SD. Significantly different when compared to recreational runners: $^{*}P<0.05$; $^{**}P<0.01$; $^{***}P<0.001$

The well-trained runners were significantly more economical than their recreational counterparts according VO_2 (relative to body mass and relative to body mass$^{0.75}$) and the oxygen cost of running per distance ($ml \cdot kg^{-1} \cdot km^{-1}$) at 9 $km \cdot h^{-1}$, 10.5 $km \cdot h^{-1}$, 12 $km \cdot h^{-1}$ ($P<0.05$; moderate ES), 13.5 $km \cdot h^{-1}$ ($P<0.01$, large ES) and 15 $km \cdot h^{-1}$ ($P<0.05$, moderate ES) (Figure 2).

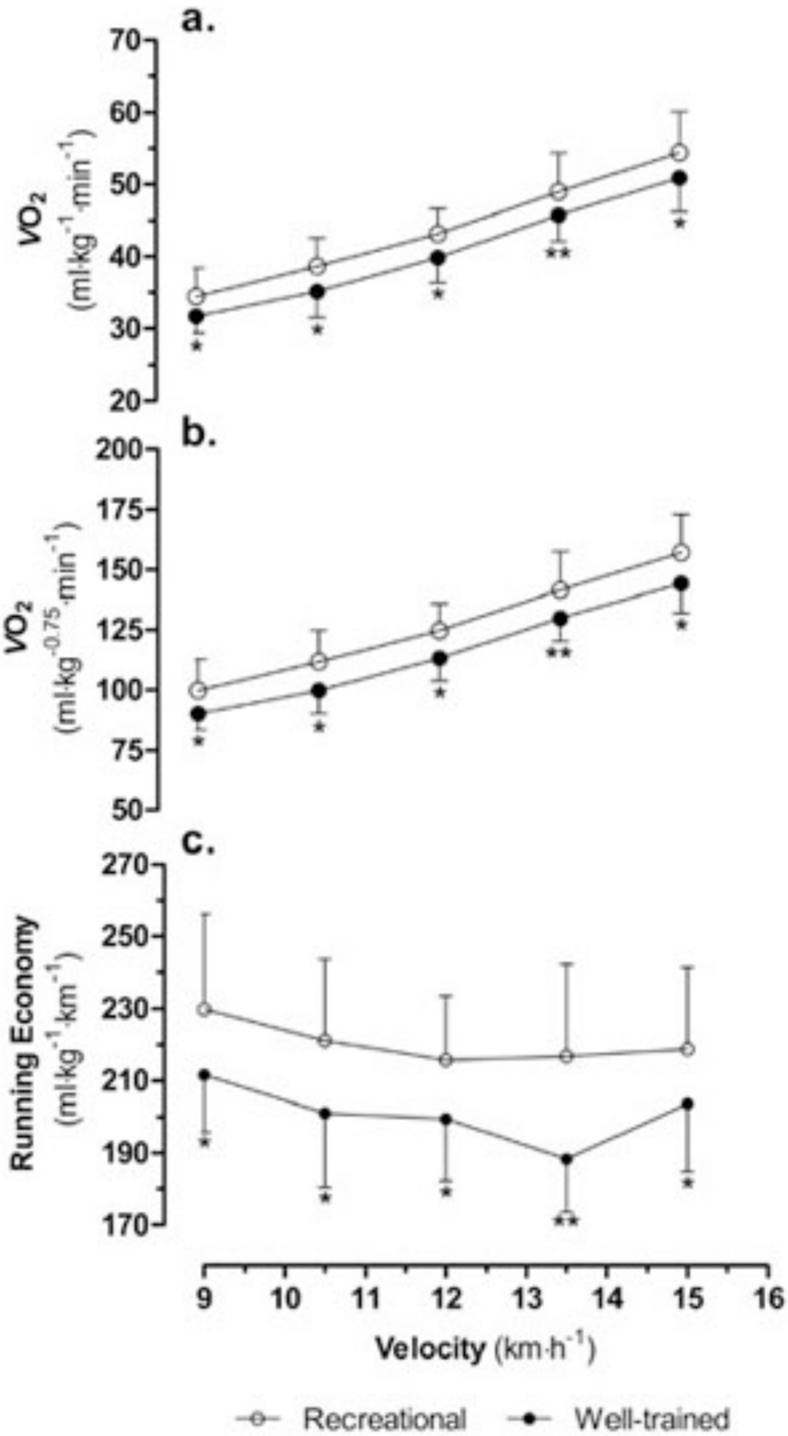

Figure 2. Oxygen uptake (VO_2) relative to body mass and to body mass$^{0.75}$ and running economy values measured in the recreational and the well-trained runners at different speeds. Significantly different when compared to recreational runners: $^{*}P<0.05$; $^{**}P<0.01$

Biomechanically, the recreational runners presented higher t_c at 12 km·h^{-1}, 13.5 km·h^{-1} ($P<0.05$, moderate ES) and 15 km·h^{-1} ($P<0.01$, large ES) and lower t_{sw} at 10.5 km·h^{-1} ($P<0.05$, moderate ES), 12 km·h^{-1}, 13.5 km·h^{-1} and 15 km·h^{-1} ($P<0.01$, large ES) than the well-trained runners. Similarly, the recreational group experienced earlier propulsion subphase than the well-trained group during ground contact at 10.5 km·h^{-1}, 12 km·h^{-1} and 13.5 km·h^{-1} ($P<0.05$, moderate ES) (Figure 3).

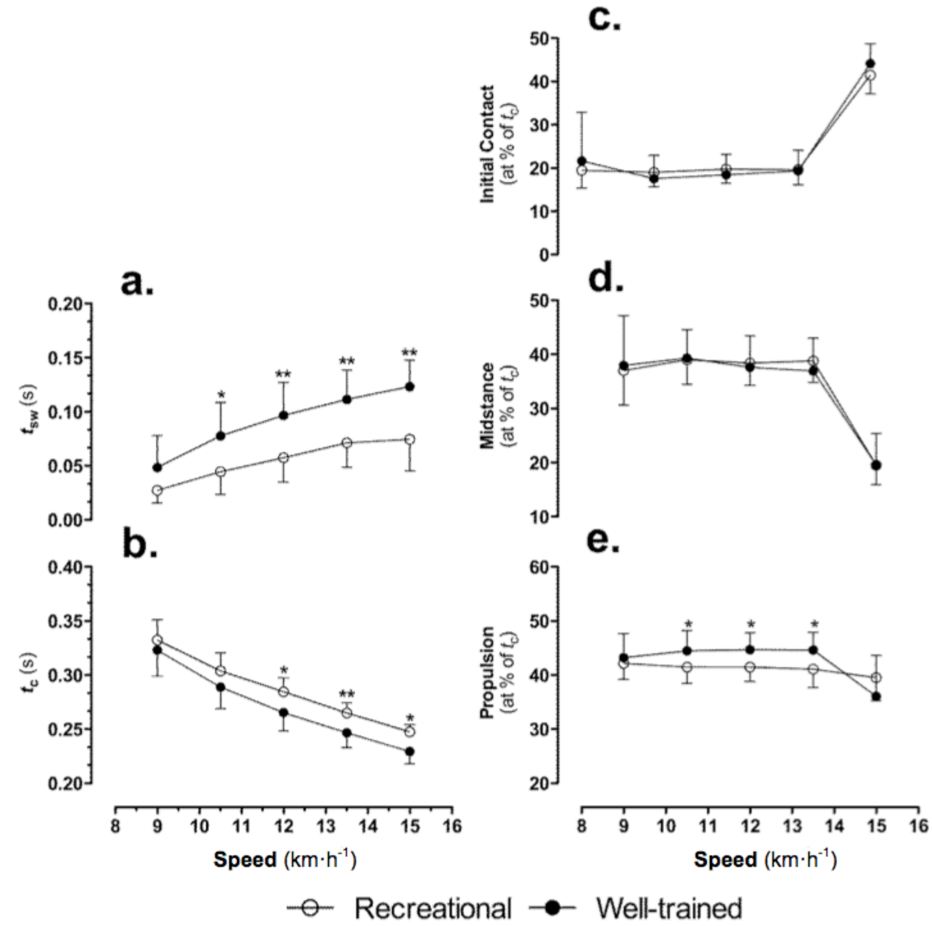

Figure 3. Ground contact time (t_c), swing time (t_{sw}) and the percentage of the ground contact time (% of t_c) at which the different subphases of stance phase (initial contact, midstance and propulsion). Significantly different when compared to recreational runners: $^{*}P$<0.05; $^{**}P$<0.01

Additionally, the recreational runners exhibited shorter stride lengths at 12 km·h^{-1}, 13.5 km·h^{-1} (*P*<0.05, moderate ES) and 15 km·h^{-1} (*P*<0.01, large ES), lower stride frequencies at 12 km·h^{-1}, 13.5 km·h^{-1} (*P*<0.05, moderate ES) and 15 km·h^{-1} (*P*<0.01, large ES) and lower stride angles at 10.5 km·h^{-1} (*P*<0.05), 12 km·h^{-1}, 13.5 km·h^{-1} and 15 km·h^{-1} (*P*<0.01, large ES) than the well-trained runners (Figure 4).

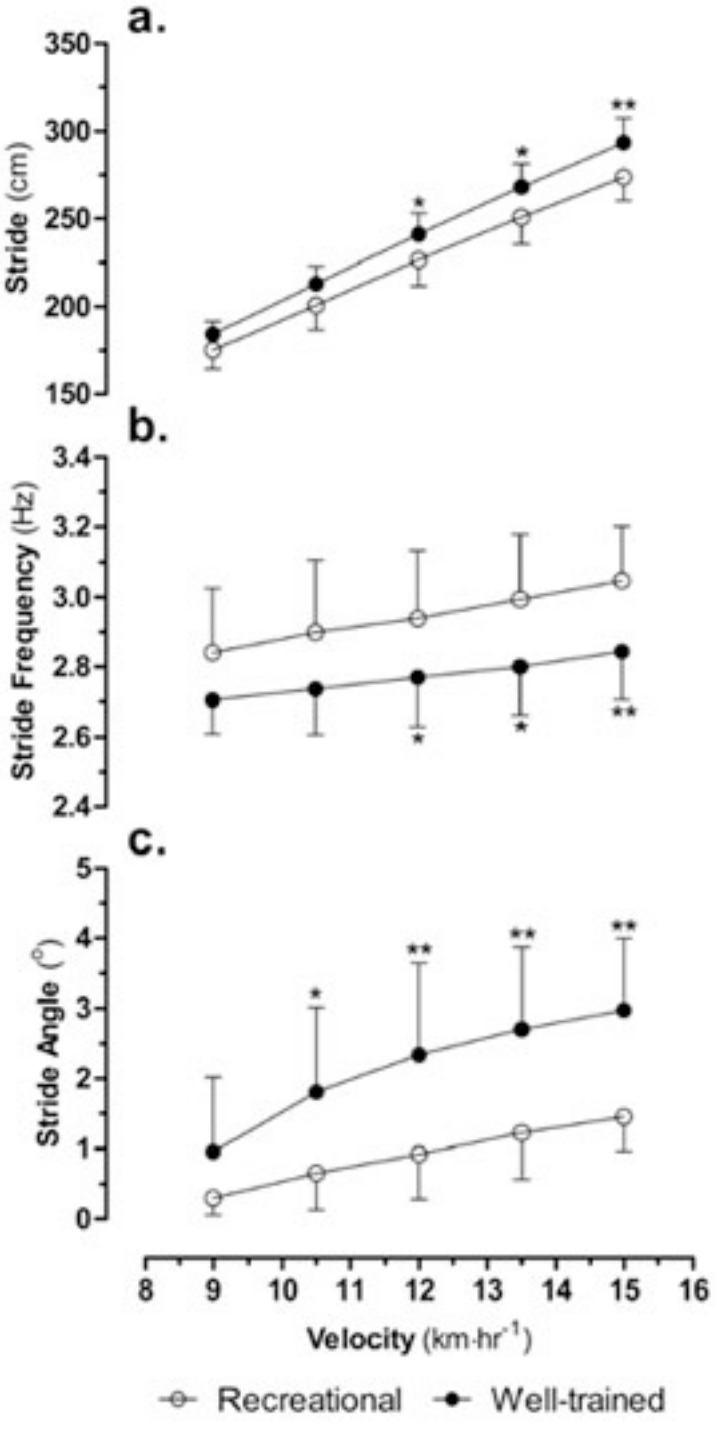

Figure 4. Stride length, stride frequency and stride angle values measured in the recreational and the well-trained runners at different speeds. Significantly different when compared to recreational runners: $^{*}P<0.05$; $^{**}P<0.01$

RE was positively correlated with t_c at 12 km·h^{-1} and 13.5 km·h^{-1} ($P<0.05$) and with the stride frequency at 9 km·h^{-1}, 10.5 km·h^{-1}, 12 km·h^{-1}, 13.5 km·h^{-1} and 15 km·h^{-1} ($P<0.01$). On the other hand, RE correlated negatively with t_{sw} at 10.5 km·h^{-1} ($P<0.05$), 12 km·h^{-1} ($P<0.01$), 13.5 km·h^{-1} ($P<0.001$) and 15 km·h^{-1} ($P<0.05$) and with the stride length at 9 km·h^{-1}, 10.5 km·h^{-1}, 12 km·h^{-1} ($P<0.01$) and 13.5 km·h^{-1} ($P<0.001$). Similarly, RE was also negatively correlated with the stride angle at 10.5 km·h^{-1} ($P<0.05$), 12 km·h^{-1}, 13.5 km·h^{-1} ($P<0.01$) and 15 km·h^{-1} ($P<0.05$), and with the propulsive subphase at 10.5 km·h^{-1} ($P<0.05$).

Table 2. Interrelationships between biomechanical variables as well as running performance according 10-km race time and running economy at different speeds.

	Running economy at (km·h^{-1})				
Biomechanical variables	9	10.5	12	13.5	15
Contact time	-0.08	0.15	**0.45***	**0.45***	0.36
Swing time	-0.35	**-0.46***	**-0.61****	**-0.65*****	**-0.43***
Stride length	**-0.61****	**-0.52****	**-0.56****	**-0.65*****	-0.39
Stride frequency	**0.63****	**0.56****	**0.56****	**0.65****	0.37
Stride angle	-0.34	**-0.44***	**-0.60****	**-0.62****	**-0.42***
Contact subphase	0.02	0.13	0.25	0.10	0.00
Midstance subphase	0.08	0.19	-0.07	0.13	0.11
Propulsive subphase	-0.21	**-0.40***	-0.22	-0.26	-0.13
10-km race time	**0.57****	**0.63****	**0.66*****	**0.79*****	**0.57****

Significant correlations: $^{*}P<0.05$; $^{**}P<0.01$; $^{***}P<0.001$

Finally, running performance according to the best 10-km race time was positively correlated with RE at 9 km·h^{-1}, 10.5 km·h^{-1} ($P<0.01$), 12 km·h^{-1}, 13.5 km·h^{-1} ($P<0.001$) and 15 km·h^{-1} ($P<0.01$), whereas neither the contact subphase nor the midstance subphase showed any significant correlation with RE (Table 2).

Discussion

The first finding of this study was that there were significant biomechanical differences that discriminated between the recreational and well-trained runners at various submaximal speeds, in addition to all traditional maximal variables (such as VO_{2max} and PTS) and RE.

The well-trained runners were more economical than the recreational runners at all submaximal running speeds in this study (Figure 2). This is in agreement with previous studies, which have reported better RE in elite runners compared to good runners at a set speed (Nummela et al., 2007). Further, Helgerud et al. (2010) described that RE is proportional to body mass allometrically scaled. When VO_2 was normalized to body mass$^{0.75}$ in our study the differences were accentuated between both groups. This finding suggests that other factors may contribute to differences in RE and not only anthropometrical variables (Saunders, Pyne, Telford & Hawley, 2004).

Accordingly, we found that biomechanical variables were significantly different at speeds above 9 km·h^{-1} (Figures 3 & 4). In this regard, this study confirms that well-trained runners present particular running patterns characterized by longer stride lengths, lower stride frequencies, lower t_c and higher t_{sw} that enable effective and efficient energy use per stride. These findings are in agreement with previous studies investigating male and female runners and trained and untrained runners (Anderson, 1996; Cavanagh & Williams, 1982; Chapman et al., 2011; Kaneko et al., 1985, Tartaruga et al., 2012). Previous researchers have found that self-selected stride lengths demand less oxygen at a given speed compared to other predetermined stride lengths (Hogberg, 1952). Further, well-trained runners acquire an optimal stride length and stride frequency over time based on perceived exertion (Saunders et al., 2004) and may also be physiologically adapted to some stride lengths and frequencies at particular speeds (Anderson, 1996). Duggan and Bhat (2005) suggested that these biomechanical differences may be a result of an increased flexibility and eccentric muscle strength in the well-trained groups.

Greater flexibility and eccentric muscle strength may be revealed by stride angle. Stride angle comprises of stride length and the maximum height the foot reaches during swing phase. Both features are biomechanically driven by the extent of hip, knee and ankle flexion-extension. The well-trained runners in this study exhibited significantly greater stride angles than the recreational runners (Figure 4). This difference in stride angle is exemplary of the ability for well-trained runners to efficiently maximize t_{sw} with greater hip, knee and ankle flexion and minimize t_c with effective energy transfer during the propulsion subphase as found in the well-trained runners in this study.

These phenomena may be depicted in well-trained athletes as the ability of the foot to reach the glutes. Many coaches and keen athletic observers have note this as a flick or buttkick. However, this has not been well described, as the analysis of swing phase biomechanics during running is often overlooked in importance when compared to ground contact. This flick or buttkick during swing phase appears to be associated with the ability for the athlete to efficiently transfer energy generated from minimal ground contact to ground contact and drive the body forward (Novacheck, 1998).

In this study both t_{sw} and stride angle were strongly associated with RE at the set speeds (Table 2). Kram and Taylor (1990) alluded that the work done against the environment may be less important than the ability for the muscles and tendons to lift and accelerate the body and limbs. As it has been documented, a majority of muscles are active during the swing phase, most particularly in the acceleration of the limbs and preparation for ground contact (Chumanov, Heiderscheit & Thelen, 2011). Thus, it appears that the swing phase and stride angle may be an effective discriminator of efficient gait patterns and should be analysed further in its contribution to the economy of motion.

Variables related to the ground contact phase of the gait cycle have been reported to be the major determinants of metabolic demand (Anderson, 1996; Kyröläinen et al., 2001, Saunders et al., 2004). For example, propulsion subphase during the ground contact was experienced significantly later in the well-trained runners than in the recreational runners at certain speeds (Figure 3). The propulsion subphase is where force is applied from the lower limbs to the ground to obtain forward horizontal displacement during running. Novacheck (1998) describes that the percentage of the gait cycle at which *toe off* occurs depends not only on the speed, but also on the athletic ability of the runner (Novacheck, 1998). Therefore, these differences between groups appear to be an indicator of the superior athletic ability of the well-trained runners when compared to the recreational runners. In this regard, the significant correlation found in this study between RE and the percentage at which the propulsive subphase occurs, may imply that differences in the propulsive subphase kinetics can influence the energy cost of running. However, the lack of ground contact forces analysis in this study impedes to speculate for a possible explanation for this correlation.

Lastly, an efficient RE was also associated with faster 10-km race time (Table 2). This finding is evidence that running performance according to 10-km race time is associated with an efficient RE. Subsequently, faster race times may be, at least in part, a result of better RE that may be facilitated by the various biomechanical changes previously discussed, such as, lower t_c, increased t_{sw}, longer stride lengths, lower stride frequencies and higher stride angles. Further research simultaneously investigating the musculotendinous involvement, in-depth biomechanical analysis and complex multivariate statistics are required, in order to elucidate the physiological and biomechanical changes that occur to achieve optimal RE and improved performance.

Conclusion

Part of the differences observed between RE in recreational and well-trained athletes were found to be a result of differing athletic ability and biomechanical features. Our results suggest that particular running patterns characterized by longer stride lengths, lower stride frequencies, greater stride angles, lower t_c, higher t_{sw} and later propulsion suphases during the ground contact enable an effective and efficient energy use per stride. Therefore, changes in the biomechanical running technique can influence the energy cost of running and lead to improve performance.

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