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The concurrent effects of strike pattern and ground-contact time on running economy

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ABSTRACT

Objectives: Running economy is a key determinant of endurance performance, and understanding the biomechanical factors that affect it is of great theoretical and applied interest. This study aimed to analyse how the ground-contact time and strike pattern used by competitive runners concurrently affect running economy.

Design: Cross-sectional.

Methods: Fourteen sub-elite male competitive distance runners completed a 6-min submaximal running trial at 14 km h^{-1} on an outdoor track using their habitual strike pattern ($n = 7$ rearfoot strikers: average age, 25.3 years old (SD = 2.4); average weight, 64.7 kg (SD = 5.6); average height, 175.3 cm (SD = 5.2); $n = 7$ midfoot strikers: average age, 25.0 years old (SD = 2.8); average weight, 69.6 kg (SD = 4.0); average height, 180.1 cm (SD = 5.1). During the run, the oxygen uptake and ground-contact time were measured.

Results: Midfoot strikers showed a significantly shorter ($p = 0.015$) mean contact time (0.228 s (SD = 0.009)) compared with rearfoot strikers (0.242 s (SD = 0.010)). Conversely, there was no significant difference ($p > 0.05$) between the groups with respect to mean oxygen uptake (midfoot strikers: 48.4 ml min^{-1} kg^{-1} (SD = 5.3); rearfoot strikers: 49.8 ml min^{-1} kg^{-1} (SD = 6.4)). Linear modelling analysis showed that the effect of contact time on running economy was very similar in the two groups, with a 1 ms longer contact time involving an approximately 0.51 ml min^{-1} kg^{-1} lower oxygen uptake. In contrast, when controlling for contact time, midfoot striking involved an approximately 8.7 ml min^{-1} kg^{-1} lower oxygen uptake compared with rearfoot striking.

Conclusions: When adjusting the foot–ground contact biomechanics of a runner with the aim of maximising running economy, a trade-off between a midfoot strike and a long contact time must be pursued.

1. Introduction

Running economy (RE), which is defined as the oxygen consumption (VO_2) at a fixed submaximal running speed, is a key component of performance in distance events. Indeed, RE is related to a runner's final time in long-distance races in athletes with similar VO_2 maxima,[1,2] and RE improvements over time have a positive influence on individual performance.[3,4] The acknowledged importance of RE as a determinant of performance has stimulated the search of factors that may affect RE. Among the various factors examined for possible relationships with RE, a great deal of attention has been given to mechanical descriptors of the running gait, following the assumption that optimal movement patterns and force applications can result in less total work and thus less physiological strain.[5]

In such a research context, the foot–ground contact time (t_c) has frequently been analysed in relation to RE. It has been demonstrated in the field of comparative biology that $1/t_c$ is directly proportional to the metabolic cost of running.[8,9] Some studies carried out on competitive athletes have supported this finding, providing evidence that a longer t_c is associated with a lower oxygen consumption and thus a better RE.[6,7] However, somewhat surprisingly, other authors have failed to show a significant correlation between t_c and RE in competitive runners,[10,11] or have even found an opposite relationship, with shorter t_c values associated with a better RE.[12]

In human running, the muscles, tendons and ligaments of the lower limb and the foot store elastic energy during the loading phase of the gait and return that energy during the pushing phase, allowing the runner to reduce the work done by the muscles and save metabolic energy.[13] Therefore, the RE of a runner is favourably influenced by effective exploitation of this elastic energy. For biomechanical reasons, the effectiveness of such a mechanism is strongly affected by the runner's strike pattern, with

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Table 1
Mean (SD) anthropometric, training and performance characteristics of the runners.

	Midfoot runners (n = 7)	Rearfoot runners (n = 7)
Age (years)	25.3 (2.4)	25.0 (2.8)
Body mass (kg)	64.7 (5.6)	69.6 (4.0)
Height (cm)	175.3 (5.2)	180.1 (5.1)
Endurance running experience (years)	7.6 (1.9)	6.0 (2.2)
Seasonal personal best 5000 m time (s)	969 (44)	1003 (37)
Training volume (km week^{-1})	102.9 (18.0)	100.7 (18.8)

a more forefooted strike allowing the runner to store and return a higher amount of elastic energy.[14] However, the hypothesised effect of strike pattern on RE has not found confirmation in the literature because no difference in RE has been found between the conditions of forefoot and rearfoot running.[14,15] The intermediate condition of midfoot striking, however, has not yet been considered in studies assessing the relationship between strike pattern and RE.

A possible drawback to understanding how t_c and strike pattern affect RE may be that the effects of such factors tend to mutually cancel each other out. Indeed, while forefoot or midfoot striking should allow a runner to have a lower VO_2 than rearfoot striking (thanks to the more effective elastic energy storage/reuse), those strike patterns involve shorter t_c values[16,17] that, according to the aforementioned proportionality between metabolic cost and $1/t_c$ demonstrated for hopping and running mammals,[9] might be disadvantageous for RE. In contrast, prolonging the t_c as long as possible could eventually represent the right way to minimise the metabolic cost, but such a strategy would presumably require a runner to use an otherwise unfavourable rearfoot strike pattern. Thus, to better understand how t_c and strike pattern influence RE, it seemed necessary to evaluate such factors simultaneously.

Therefore, the aim of this study was to analyse the concurrent effect of t_c and strike pattern on RE in competitive runners. We hypothesised the following: (i) within groups of runners using a similar strike pattern, runners with longer t_c values would show lower VO_2 values, and (ii) when controlling for the effect of t_c, runners with a more rearfooted strike pattern would show higher VO_2 values.

2. Methods

Fourteen sub-elite male distance runners were recruited from local track and field clubs. To have an almost equal number of runners for each strike pattern, the athletes contacted for participation were first asked to indicate their habitual strike pattern (forefoot, midfoot, or rearfoot) when running at or around a speed of 14 km h^{-1} (i.e., the speed used in this study). All of the involved runners indicated that they were midfoot or rearfoot strikers, confirming that forefoot striking is very uncommon at relatively low running speeds.[17,18] Therefore, we decided to focus the analysis only on the midfoot and rearfoot strike patterns. The actual strike pattern of each participant was checked during the data collection session (see below for details). The declared pattern was confirmed for thirteen out of fourteen runners, while one self-declared midfoot striker was classified as a rearfoot striker. The final sample included seven rearfoot and seven midfoot strikers. Their anthropometric, training and performance characteristics are reported in Table 1. All of the participants, after having been informed about the study's purpose and procedures, signed a written informed consent to participate. The research was carried out according to the ethical guidelines of the declaration of Helsinki and was approved by the University of Bologna Bioethics Committee.

All of the measurements were performed on a 400-m outdoor athletic track. The runners first participated in a preliminary session during which they were familiarised with the testing protocol and apparatus. During that session, recommendations were given for the data collection session, including avoiding strenuous training for at least three days prior to the test, not drinking caffeinated or alcoholic beverages for approximately 24 h, and wearing the shoes that they habitually used for slow-pace training (avoiding the use of lightweight or minimal shoes).

The RE and t_c were measured during the same single session, which was performed during an off-season period for all the athletes. The measurements were performed in the early or mid-afternoon, corresponding to the habitual training time for most of the participants. The weather conditions were good with no rain or wind, and the ambient temperature ranged from 18 °C to 21 °C. After a 10-min warm-up consisting of light jogging followed by five submaximal sprints of about 70 m, the runners were equipped with a portable gas analyser (K4b2, Cosmed, Rome, Italy).[19] The device consisted of a face mask connected to a central unit of about 0.5 kg fixed to a chest harness worn by the runner that was calibrated prior to use according to the manufacturer's guidelines. Then, a 6-min running trial at a speed of 14 km h^{-1} was performed in the first lane of the athletic track for a total distance of 1400 m. The 14 km h^{-1} speed was selected because it was generally a slow pace for all of the participants, thus allowing them to run under fully aerobic conditions. Acoustic signals with reference cones placed every 50 m were used to facilitate the runners maintaining the set speed. An operator verified the actual speed with a stopwatch, noticing only trivial differences (<2 s for each 400-m lap) with respect to the prescribed speed. The RE was computed based on the average VO_2 in the last minute of the 6-min run.

A photoelectric cell system (Optojump, Microgate, Bolzano, Italy)[20] consisting of 100 × 4 × 3 cm bars, each functioning as a transmitting or receiving unit, was used to measure t_c with an apparatus set-up similar to the apparatus used in a previous study.[21] The Optojump system was set in the first lane of the track with the bars placed in two parallel series of ten, each individually made up of transmitting or receiving units. The runners passed through this 10-m segment three times during the 6-min run. Overall, a total of 12–15 strikes (3 × 4 to 5) were acquired. The median of all (left and right) of the available strikes for a runner was taken as the t_c of that runner. During the run, the athletes were filmed at 300 frames s^{-1} with a camera (Exilim ex-f1, Casio, Tokyo, Japan) placed perpendicular to the running direction. The video recordings were analysed to determine the strike pattern of each runner. Strikes in which (i) the foot first contacted the ground with the heel or the rear one-third of the sole and (ii) the sole from heel to ball contacted the ground at the same time were classified as rearfoot and midfoot, respectively.[18] Nearly ten strikes obtained from different passages were examined for each runner. In all of the cases, the pattern was almost the same in all of the examined strikes, allowing us to classify that runner unambiguously as either a forefoot or midfoot striker.

Statistical analyses were carried out using the software R.[22] Assumptions of normality and homoscedasticity were verified for each variable using the Shapiro–Wilk and Levene's tests, respectively. Subsequently, differences between midfoot and rearfoot strikers with respect to their anthropometric/performance characteristics, t_c, and RE were compared using Student's t test for independent samples. Next, a simple linear regression analysis of RE as a function of t_c was performed for the whole sample of runners. Finally, after checking the homogeneity of the slopes of RE on t_c regressions across the strike pattern groups, linear models were used to analyse the effect of both single predictors (t_c and strike pattern) on RE when controlling for the effect of the other. The coefficient of determination (R^2) was used to evaluate the models' fit and the proportion of the total RE variance explained by the