

RESEARCH ARTICLE

The implications of time on the ground on running economy: less is not always better

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ABSTRACT

A lower duty factor (DF) reflects a greater relative contribution of leg swing versus ground contact time during the running step. Increasing time on the ground has been reported in the scientific literature to both increase and decrease the energy cost (EC) of running, with DF reported to be highly variable in runners. As increasing running speed aligns running kinematics more closely with spring–mass model behaviours and re-use of elastic energy, we compared the centre of mass (COM) displacement and EC between runners with a low (DF_{low}) and high (DF_{high}) duty factor at typical endurance running speeds. Forty well-trained runners were divided in two groups based on their mean DF measured across a range of speeds. EC was measured from 4 min treadmill runs at 10, 12 and 14 km h⁻¹ using indirect calorimetry. Temporal characteristics and COM displacement data of the running step were recorded from 30 s treadmill runs at 10, 12, 14, 16 and 18 km h⁻¹. Across speeds, DF_{low} exhibited more symmetrical patterns between braking and propulsion phases in terms of time and vertical COM displacement than DF_{high}. DF_{high} limited global vertical COM displacements in favour of horizontal progression during ground contact. Despite these running kinematics differences, no significant difference in EC was observed between groups. Therefore, both DF strategies seem energetically efficient at endurance running speeds.

KEY WORDS: Running form, Biomechanics, Energy cost, Self-optimization

INTRODUCTION

The spring–mass model has been used for decades to study the biomechanical characteristics of locomotion (Blickhan, 1989). This model assumes that the body acts as a spring in which the centre of mass (COM) passively bounces on a massless muscle–tendon unit spring, with no energy lost due to the viscosity of structures (Blickhan, 1989). This simplistic model considers the storage and release of elastic energy as an integral component of animal locomotion. This storage and return of energy has been identified as one of the main factors influencing the energetic cost (EC) of running (Moore, 2016). Dalleau et al., 1998 reported an inverse relationship between the cost of running and leg stiffness (as leg

stiffness increases, cost of running decreases), and proposed that the re-use of elastic energy is an appropriate model to further understand the inter-individual differences in the cost of running. On this basis, the most economical running strategy would be to decrease the duration of the ground contact phase (t_c) due to its inverse relationship with vertical stiffness (Morin et al., 2007). However, vertical stiffness cannot increase indefinitely and is limited to preserve the integrity of the anatomical structures during ground contact (Gollhofer et al., 1984). In addition, the nature of the relationship reported to exist between EC and t_c in runners is inconsistent in the scientific literature, with a longer t_c also reported as being more economical than a shorter t_c by Kram and Taylor (1990). These authors claimed that a long t_c allows force to be generated over a longer period, reducing EC. Moreover, for a given step frequency, a decrease in t_c would lengthen the duration of the aerial phase (t_a) and promote vertical displacement of the COM (Δz), which is known to increase EC (Folland et al., 2017). The relationship between EC and movement pattern is complex.

Running forms should be viewed as a ‘global system’ where relationships exist between biomechanical parameters, as highlighted by the relationship governing t_c and footstrike pattern (Di Michele and Merni, 2014). Instead of decreasing t_c to minimize EC, one effective strategy could be to increase t_c to limit Δz and t_a . Such a biomechanical strategy to optimize EC has been proposed recently under the name ‘terrestrial running form’ (Lussiana et al., 2017a), which resembles the grounded locomotive pattern used by some animal species (e.g. quail: Andrada et al., 2013) or the Groucho running style (McMahon et al., 1987). Although Groucho running has been associated with an increased EC by McMahon et al. (1987), individuals were asked to artificially modify their running biomechanics by accentuating leg flexion. Generalizing these results to people who naturally adopt such a running form is not appropriate given that self-selected patterns are often the most economical ones at an individual level as highlighted in a recent review (Moore, 2016). In addition, running biomechanics depend on the environment in which individuals run (Lussiana and Gindre, 2016). For instance, an increase in running speed typically reduces t_c and increases t_a (Brughelli et al., 2011), while the braking (t_c^-) and propulsion (t_c^+) times become more symmetrical ($t_c^- \approx t_c^+$) (Cavagna, 2006, 2010) and align more closely with the spring–mass model as running speed increases. The storage and release of elastic energy could be enhanced at higher running speeds, with a short t_c and high t_a becoming more efficient (Cavagna et al., 2008a). Indeed, high forces applied on a short t_c and an increase of the temporal symmetry of the running step might facilitate isometric muscle contractions, causing the tendons to act as simple springs and favouring elastic energy storage and return (Cavagna, 2006). However, at slower running speeds, the assumptions of quasi-symmetrical ground contact and aerial times underlying the spring–mass model might not apply as readily.

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List of symbols and abbreviations

COM	centre of mass
DF	duty factor
DF _{high}	group runners with high duty factor
DF _{low}	group runners with low duty factor
EC	energy cost of running
RER	respiratory exchange ratio
t_a	duration of the aerial phase
t_a^+	duration of the upward displacements of the centre of mass during the aerial phase
t_a^-	duration of the downward displacements of the centre of mass during the aerial phase
t_a^+/t_a	t_a^+ expressed as a percentage of $t_a^+ + t_a^-$
t_c	duration of the contact phase
t_c^+	duration of the upward displacement of the centre of mass during the contact phase
t_c^-	duration of the downward displacement of the centre of mass during the contact phase
t_c^+/t_c	t_c^+ expressed as a percentage of $t_c^+ + t_c^-$
t_s	duration of the leg swing phase
\dot{V}_{O_2}	oxygen consumption
\dot{V}_{CO_2}	carbon dioxide production
Δy_c	forward displacement of the centre of mass during the contact phase
Δz	global vertical displacement of the centre of mass
Δz_a	vertical displacement of the centre of mass during the aerial phase
Δz_a^+	upward displacement of the centre of mass during the aerial phase
$ \Delta z_a^- $	absolute downward displacement of the centre of mass during the aerial phase
Δz_c	vertical displacement of the centre of mass during the contact phase
Δz_c^+	upward displacement of the centre of mass during the contact phase
$ \Delta z_c^- $	absolute downward displacement of the centre of mass during the contact phase
$\Delta z_a^+/\Delta z_a$	Δz_a^+ expressed as a percentage of $\Delta z_a^+ + \Delta z_a^- $
$\Delta z_c^+/\Delta z_c$	Δz_c^+ expressed as a percentage of $\Delta z_c^+ + \Delta z_c^- $

Considering the behaviour of running mechanics during both t_c and the swing phase (t_s) provides a better understanding of the global running form compared with when these temporal parameters are taken into account separately. The duty factor (DF) is the ratio of one to the other, with a greater DF reflecting a greater relative contribution of t_c and a lesser relative contribution of t_s (and therefore t_a) to the running step (Minetti, 1998). DF has been reported to be highly variable amongst runners, with values ranging from 0.257 to 0.403 at similar running speeds (Folland et al., 2017). However, DF has not been studied intensively and no relationship between DF and economy has yet been described. Thus, the objective of this study was to investigate the kinematic and energetic values between runners with a high (DF_{high}) and low (DF_{low}) DF at typical endurance running speeds, including measures of COM displacement, temporal symmetry of the running step and EC. As the DF_{high} runners exhibit long t_c and short t_s (and t_a), we hypothesized a larger forward COM displacement during ground contact times and a smaller vertical COM displacement during aerial times compared with the DF_{low} group for a given speed. In addition, having a low DF (short t_c) should promote an elastic behaviour; therefore, we hypothesized greater symmetry within contact and aerial phases compared with the DF_{high} group. Moreover, a similar EC at endurance running speeds has been observed in runners exhibiting different running forms (Lussiana

et al., 2017a). Therefore, despite these differences in running kinematics, we anticipated similar EC values at typical endurance speeds (i.e. 10, 12 and 14 km h⁻¹) between groups.

MATERIALS AND METHODS**Participants**

Fifty-four trained runners, 33 males (mean±s.d.: age 31±8 years, height 175±6 cm, mass 66±9 kg and weekly running distance 53±15 km) and 21 females (age 32±7 years, height 162±3 cm, mass 52±4 kg and weekly running distance 50±14 km) voluntarily participated in this study. For study inclusion, participants were required to be in good self-reported general health with no current or recent (<3 months) musculoskeletal injuries and to meet a certain level of running performance. More specifically, in the last year, runners were required to have competed in a road race with finishing times of ≤50 min for 10 km, ≤1 h 50 min for 21.1 km or ≤3 h 50 min for 42.2 km. Participants who were, or could be, pregnant were not eligible. The ethical committee of the National Sports Institute of Malaysia approved the study protocol prior to participant recruitment (ISNRP: 26/2015), which was conducted in accordance with international ethical standards (Harriss et al., 2017) and adhered to the Declaration of Helsinki of the World Medical Association.

Experimental procedure

Each participant completed one experimental session in the biomechanics laboratory of the National Sports Institute of Malaysia. Running bouts were always performed in the morning (start of exercise between 07:00 h and 09:00 h), to avoid circadian variance in performance, and under similar environmental conditions (28°C and 74% relative humidity). Participants reported to the laboratory after 10–12 h overnight fast. All participants were advised to avoid strenuous exercise the day before the test. After providing written informed consent, participants ran three laps on a 400 m athletic track at a constant self-selected speed (12.7±1.3 km h⁻¹), which was followed by 2 min at 9 km h⁻¹ on a treadmill (h/p/cosmos mercury®, h/p/cosmos sports & medical gmbh, Nussdorf-Traunstein, Germany) as a warm-up. Participants then completed three 4 min runs at 10, 12 and 14 km h⁻¹ (with 2 min recovery periods between each run) on the treadmill, during which time EC was assessed. Retro-reflective markers were subsequently positioned on individuals (described below) to assess running biomechanics. Each participant then completed five 30 s runs at 10, 12, 14, 16 and 18 km h⁻¹ (with 1 min recovery periods between each run) on the same treadmill, during which time 3D kinematic data were collected. EC and biomechanics were assessed separately, given constraints (e.g. presence of testing equipment that can occlude markers) in measuring the two sets of data simultaneously and to allow assessment of biomechanics at running speeds over steady-state thresholds (16 and 18 km h⁻¹). All participants were familiar with running on a treadmill as part of their usual training programmes and wore their habitual running shoes during testing.

Runners were classified in two groups (DF_{high} and DF_{low}) based on their mean DF recorded from the five 30 s runs at 10, 12, 14, 16 and 18 km h⁻¹. Based on standard sample size calculations, a total of 18 participants per DF group was needed for the purpose of this study (Zar, 1999). Hence, to highlight the presence of different biomechanical running strategies, the statistical analysis focused on the 20 runners with the highest DF and the 20 runners with the lowest DF. Therefore, 14 participants with mid-range DF were excluded from the analysis. These participants were similar in terms

of baseline characteristics to the remainder of the group (age, height, mass and running distance, $P>0.05$). The baseline characteristics of the DF_{high} and DF_{low} groups are given in Table 1 and were similar between groups. As would be anticipated, two-way (DF group \times speed) repeated-measures analysis of variance (RM ANOVA) indicated differences in DF between groups at all speeds examined (mean values 0.330 ± 0.018 for DF_{low} and 0.385 ± 0.028 for DF_{high}, $P<0.001$, Fig. 1). The DF values in our population are in line with those previously reported in the literature at similar running speeds and agree with the proposition that running locomotion DF values should be under 0.500 (Folland et al., 2017; Minetti, 1998). Running speed also affected DF (main effect, $P<0.001$), with the change in DF with speed being group specific (interaction effect, $P=0.003$). An increase in speed was associated with a greater decline in DF in the DF_{high} than in the DF_{low} group (Fig. 1).

Physiological parameters

Gas exchange was measured using TrueOne 2400 (ParvoMedics, Sandy, UT, USA) during the three 4 min running bouts. Prior to the runs, the gas analyser was calibrated using ambient air (O_2 : 20.93% and CO_2 : 0.03%) and a gas mixture of known concentration (O_2 : 16.00%, CO_2 : 4.001%). Volume calibration was performed at different flow rates with a 3 l calibration syringe (5530 series, Hans Rudolph, Shawnee, KS, USA). Oxygen consumption ($\dot{V}O_2$), carbon dioxide production ($\dot{V}CO_2$) and respiratory exchange ratio (RER) values were averaged over the last minute of each 4 min running bout. Steady state was confirmed through visual inspection of the $\dot{V}O_2$ and $\dot{V}CO_2$ curves. RER had to remain below unity during the trials for data to be included in the analysis, otherwise the corresponding data were excluded as they were deemed to not represent a submaximal effort. No trials were excluded on this basis. EC was expressed as the number of kilocalories required per distance covered per body mass ($kcal\ kg^{-1}\ km^{-1}$). The caloric equivalent of the $\dot{V}O_2$ ($kcal\ l^{-1}$) was determined based on the average RER recorded over the last minute (Astrand and Rodahl, 1986; Fletcher et al., 2009). A higher EC cost indicates a less economical running form.

Biomechanical parameters

During the 30 s runs on the treadmill, whole-body 3D kinematic data were collected at 200 Hz using seven infrared Oqus cameras (five Oqus 300+, one Oqus 310+ and one Oqus 311+), Qualisys Track Manager software (version 2.11, build 2902) and the Project Automation Framework Running package (version 4.4) from Qualisys AB (Gothenburg, Sweden). Thirty-five retro-reflective markers of 12 mm diameter were affixed to the skin and shoes of

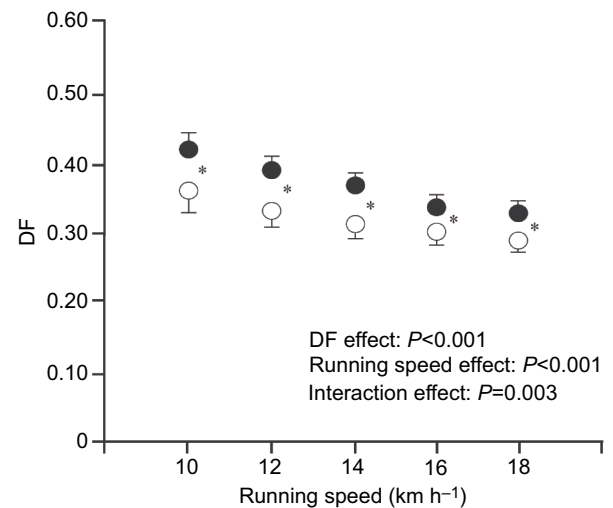


Fig. 1. Duty factor (DF) of the two running groups at each running speed.

The white circles represent the running group with a low mean duty factor (DF_{low}). The black circles represent the running group with a high mean duty factor (DF_{high}). Values are means \pm s.d., $n=20$ per group. *Significant difference ($P<0.05$) between DF groups as determined by Holm–Šidák *post hoc* tests.

individuals over anatomical landmarks using 3M™ double-sided tape, Hypafix® adhesive non-woven fabric and Mastisol® liquid adhesive following standard guidelines from the Project Automation Framework Running package (Tranberg et al., 2011). The 3D marker data were exported in .c3d format and processed in Visual3D Professional software version 5.02.25 (C-Motion Inc., Germantown, MD, USA). The marker data were interpolated using a third-order polynomial least-square fit algorithm, allowing a maximum of 20 frames for gap filling, and subsequently low-pass filtered at 20 Hz using a fourth-order Butterworth filter. From the marker set, a full-body biomechanical model with six degrees of freedom and 15 rigid segments was constructed. Segments included the head, upper arms, lower arms, hands, thorax, pelvis, thighs, shanks and feet. In Visual3D, segments were treated as geometric objects. Segments were assigned inertial properties and COM locations based on their shape (Hanavan, 1964) and attributed relative mass based on standard regression equations (Dempster, 1955). Whole-body COM location was calculated from the parameters of all 15 segments.

Running events were derived from the kinematic data using similar procedures to those previously reported in the literature (Lussiana et al., 2017b; Maiwald et al., 2009). More explicitly, a mid-foot landmark was generated midway between the heel and toe markers. Footstrike was defined as the instance when the mid-foot landmark reached a local minimal vertical velocity prior to it reaching a peak vertical velocity reflecting the start of swing. Toe-off was defined as the instance when the toe marker attained a peak vertical acceleration before reaching a 7 cm vertical position. t_s and t_c were defined as the time from toe-off to touch-down and from touch-down to toe-off of the same foot, respectively, and t_a as the time from toe-off to touch-down of the opposite foot. Mid-stance and mid-flight events were calculated to divide t_c and t_a , respectively. Mid-stance was defined as the instance when COM reached its lowest vertical position during t_c . Mid-flight was defined as the instance when the COM reached its highest vertical position during t_a . All events were verified to ensure correct identification and manually adjusted when required. Values for t_c , t_a and t_s were

Table 1. Participant characteristics for the low (DF_{low}) and high (DF_{high}) duty factor running groups

	DF _{low}	DF _{high}	<i>P</i>
Sex	12M, 8F	12M, 8F	NA
Age (years)	29.6 \pm 9.0	32.4 \pm 7.7	0.300
Mass (kg)	56.3 \pm 10.4	62.2 \pm 8.4	0.057
Height (cm)	166.6 \pm 8.1	171.6 \pm 8.3	0.061
Running distance (km week ⁻¹)	52.9 \pm 22.4	48.6 \pm 20.2	0.712
10 km running time (min:s)	42:33 \pm 03:36	44:38 \pm 03:30	0.747
Shoe mass (g)	213 \pm 35	232 \pm 34	0.104
Shoe heel height (mm)	24.2 \pm 3.1	25.6 \pm 2.9	0.102
Shoe heel-to-toe drop (mm)	7.0 \pm 3.1	8.0 \pm 3.2	0.246

Data are means \pm s.d. M, male; F, female.

calculated based on touch-down and toe-off events, and DF was calculated as follows (Minetti, 1998):

$$DF = t_c \cdot (t_s + t_c)^{-1}. \quad (1)$$

The maximum vertical displacement of the COM during a step (Δz) was calculated as the difference of the COM height between mid-flight and mid-stance events. The vertical and forward displacement of the COM during the contact phase were calculated between touch-down and toe-off events and are represented as Δz_c and Δy_c , respectively, with Δz_a representing the vertical displacement of the COM during the aerial phase calculated between toe-off and touch-down events. All values are expressed as a percentage of COM height in static upright stance. The subcomponent of Δz_c , i.e. absolute downward ($|\Delta z_c^-|$) and upward (Δz_c^+) displacement of the COM during the contact phase and their respective durations (t_c^- and t_c^+) were calculated between touch-down and mid-stance events and between mid-stance and toe-off events, respectively. Upward (Δz_a^+) and absolute downward ($|\Delta z_a^-|$) displacement of the COM during the aerial phase and their respective durations (t_a^+ and t_a^-) were calculated between toe-off and mid-flight events and between mid-flight and touch-down events, respectively. Finally, the total vertical displacement of the COM during a contact or an aerial phase was expressed as follows:

$$\Delta z_i = \Delta z_i^+ + |\Delta z_i^-| \quad (2)$$

where $i=c$ or a . The ratios $\Delta z_c^+/\Delta z_c$ and t_c^+/t_c as well as $\Delta z_a^+/z_a$ and t_a^+/t_a were also calculated to explore upward and downward movement symmetries (Cavagna, 2010). Step symmetry has previously been calculated by Cavagna (2006) using effective contact and aerial times based on vertical ground reaction forces being below and above body weight, respectively, as opposed to the temporal kinematic procedures used in the present study. The difference in computational methods should not affect our results and interpretations as relative and absolute reliability of effective (accelerometer) and visual (video camera) measurements of contact and aerial times have been reported as good (Gindre et al., 2016).

Statistics

As all data were normally distributed on the basis of the Kolmogorov–Smirnov test, parametric statistical methods were employed for data analysis. Descriptive statistics of data are presented as mean \pm s.d. values. Two-way (DF groups \times speed) RM ANOVA employing Holm–Šidák procedures for pair-wise *post hoc* comparisons were used to investigate whether the EC and the biomechanical parameters differed between DF_{low} and DF_{high} groups, while accounting for the effect of running speed. Statistical significance was set at $P<0.05$. Statistics were performed using SigmaStat 12 for Windows (Systat Software Inc., San Jose, CA, USA).

RESULTS

EC

There was no main effect of DF on EC across speed ($P=0.556$, Fig. 2), but a main effect of speed on EC was observed ($P=0.022$). However, the effect of speed on EC depended on DF group ($P=0.025$, Fig. 2). EC decreased in the DF_{low} group with an increase in speed ($-2.3\pm 2.6\%$ from 10 to 14 km h⁻¹, $P=0.008$), but EC did not significantly change in the DF_{high} group across speed ($1.5\pm 3.8\%$ from 10 to 14 km h⁻¹, $P=0.781$).

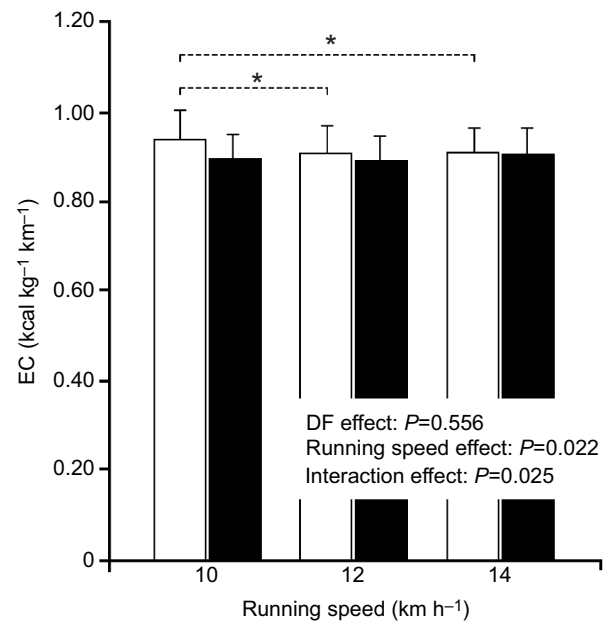


Fig. 2. Energy cost (EC) of the two running groups at each running speed. The white bars represent the DF_{low} running group. The black bars represent the DF_{high} running group. Values are mean \pm s.d., $n=20$ per group. *Significant difference ($P<0.05$) between running speeds as determined by Holm–Šidák *post hoc* tests.

COM displacement

There was a significant main effect of DF and speed on Δz and Δy_c (Fig. 3), and an interaction effect on Δz . The DF_{low} group exhibited greater Δz ($P=0.047$) and lower Δy_c ($P<0.001$) than the DF_{high} group at all speeds, whereas increasing speed decreased Δz and increased Δy_c in both groups ($P<0.001$). The interaction effect indicated a greater decrease in Δz in the DF_{low} group than in the DF_{high} group with speed.

All the Δz subcomponents investigated were affected by the increase in speed (Table 2), with Δz_a^+ being greater in the DF_{low} than in the DF_{high} group (DF main effect, $P=0.008$; Table 2). Interaction effects between DF groups and speed were observed for Δz_c^+ , Δz_a^+ and $|\Delta z_a^-|$ (all $P<0.001$). The increase in speed was associated with a greater decrease in Δz_c^+ ($P=0.003$) in the DF_{low} than in the DF_{high} group.

Temporal characteristics

There was a significant main effect of DF on all temporal parameters except for t_a^- (Table 3). The two subcomponents of the contact phase were longer for the DF_{high} than for the DF_{low} group, with a more pronounced difference for t_c^+ ($P<0.001$) than for t_c^- ($P=0.004$). The opposite was observed for t_a , with greater values for the DF_{low} group and a more pronounced difference between groups for t_a^+ ($P<0.001$) than for t_a^- . Running speed affected all temporal parameters, with a decrease of t_c , t_c^- and t_c^+ , and an increase of t_a , t_a^+ and t_a^- from 10 to 18 km h⁻¹ (main effect of speed, $P<0.001$). Interaction effects were observed for most parameters, indicating a more pronounced decrease of t_c and t_c^+ , and an increase of t_a and t_a^+ with the increase of speed in the DF_{high} group (all $P\leq 0.010$). t_a^- remained similar across speed for the DF_{high} group but decreased for the DF_{low} group ($P<0.001$).

Step symmetry

The DF_{low} group exhibited more symmetrical upward to downward motion in terms of t_c^+/t_c , t_a^+/t_a and $\Delta z_a^+/\Delta z_a$ than the DF_{high} group

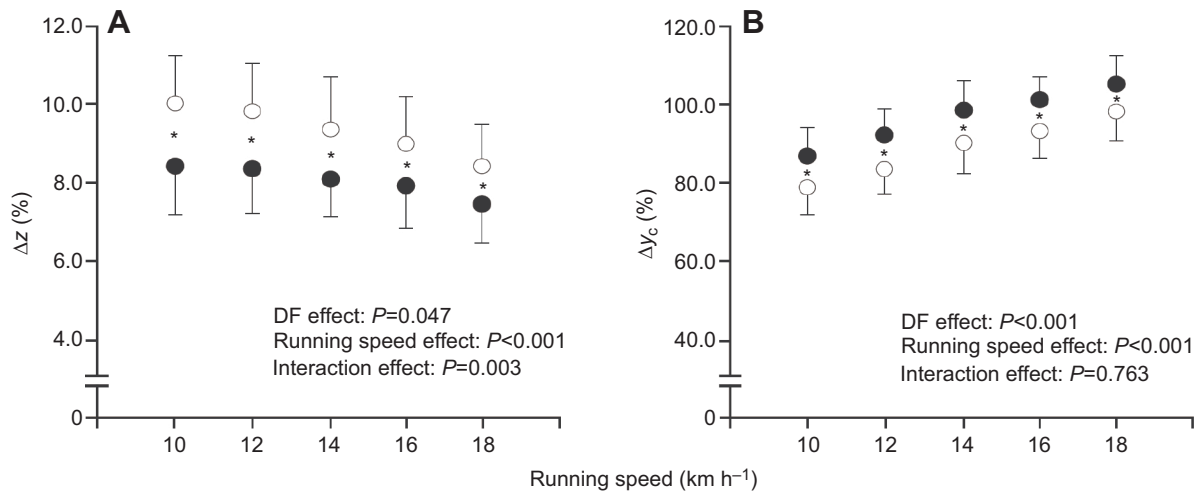


Fig. 3. Displacement of the centre of mass (COM) as function of running speed for the two running groups. (A) Vertical displacement of the COM during the entire running step (Δz). (B) Horizontal displacement of the COM during the contact phase (Δy_c). The white circles represent the DF_{low} running group. The black circles represent the DF_{high} running group. Values (means \pm s.d.) are expressed as a percentage of COM height in static upright stance, $n=20$ per group. *Significant difference ($P<0.05$) between DF groups as determined by Holm–Šidák *post hoc* tests.

(DF main effect, $P\leq 0.009$; Table 4). Running speed affected all four symmetry-related parameters (speed main effect, $P<0.001$), with all measures becoming more symmetrical with an increase in running speed. The change in symmetry values with speed was more pronounced in DF_{high} for t_a^+/t_a and in DF_{low} for $\Delta z_c^+/\Delta z_c$ (interaction effects, $P<0.001$ and $P=0.003$, respectively).

DISCUSSION

In this study, in accordance with our hypotheses, the DF_{high} group demonstrated larger forward displacement of the COM during ground contact (Δy_c), smaller vertical displacement of the COM during the aerial phase (Δz_a^+) and less temporal symmetry in terms of contact and aerial phases (t_c^+/t_c and t_a^+/t_a) than the DF_{low} group. Despite these observations, EC did not appear to be significantly different between these two groups at typical endurance running speeds. The different strategies used to minimize EC between DF groups can be distinguished by simple temporal step measurements.

EC of the DF_{low} and DF_{high} groups was not significantly different between 10 and 14 km h⁻¹. This finding is in contrast with a previous study showing that habitual rearfoot strikers (shorter t_a and

longer t_c) compared with habitual mid-foot strikers (longer t_a and shorter t_c) had lower EC at 11 and 13 km h⁻¹, but not at 15 km h⁻¹ (Ogueta-Alday et al., 2014). However, in the present study, a speed effect was observed for the DF_{low} group. Although running biomechanics became more symmetrical in both DF running groups as speed increased, the DF_{low} group exhibited a greater step symmetry than the DF_{high} group, in spite of larger changes in temporal parameters in the DF_{high} group. The ratio t_c^+/t_c decreased with increasing speed, becoming closer to 0.5 above 14 km h⁻¹. This decrease could be due to less stretching and shortening of the muscle and greater stretching and shortening of the tendon occurring as muscle force increases with speed. This alteration would lead to greater elastic energy storage and return, and therefore lower EC at high speeds for the DF_{low} group. Thus, in higher running speed conditions, the speculated increase in the re-use of energy could be a more desirable EC reduction strategy (Lai et al., 2014), reflecting kangaroo species where elastic structures return more energy at higher than at lower speeds (Dawson and Taylor, 1973). In contrast, a decrease of EC could be speculated for the DF_{high} group when decreasing speed to values below 10 km h⁻¹

Table 2. Vertical displacement of the centre of mass (COM) during the running step for the DF_{low} and DF_{high} running groups at the different running speeds

Running speed (km h ⁻¹)	DF group	$ \Delta z_c^- $ (%)	Δz_c^+ (%)	Δz_a^+ (%)	$ \Delta z_a^- $ (%)
10	DF _{low}	6.4 \pm 1.0	9.3 \pm 1.1	0.6 \pm 0.6	3.5 \pm 0.8
	DF _{high}	5.7 \pm 0.9	8.3 \pm 1.1	0.0 \pm 0.2*	2.5 \pm 0.7
12	DF _{low}	6.1 \pm 1.0	8.5 \pm 1.0	1.2 \pm 0.6	3.7 \pm 0.8
	DF _{high}	5.4 \pm 0.9	8.1 \pm 0.9	0.2 \pm 0.1*	2.8 \pm 0.7
14	DF _{low}	5.7 \pm 0.9	7.7 \pm 1.1	1.6 \pm 0.6	3.6 \pm 0.7
	DF _{high}	5.2 \pm 0.9	7.6 \pm 0.8	0.4 \pm 0.3*	2.8 \pm 0.6
16	DF _{low}	5.5 \pm 0.9	6.8 \pm 0.8	2.1 \pm 0.7	3.4 \pm 0.5
	DF _{high}	5.0 \pm 0.8	6.9 \pm 0.9	0.9 \pm 0.5*	2.8 \pm 0.8
18	DF _{low}	5.2 \pm 0.8	6.1 \pm 0.7	2.2 \pm 0.7	3.1 \pm 0.5
	DF _{high}	4.7 \pm 0.7	6.2 \pm 0.7	1.2 \pm 0.6*	2.7 \pm 0.9
DF effect		0.225	0.303	0.008	0.095
Running speed effect		<0.001	<0.001	<0.001	<0.001
Interaction effect		0.600	<0.001	<0.001	<0.001

Data are means \pm s.d. Absolute downward ($|\Delta z_c^-|$) and upward (Δz_c^+) displacement during the contact phase, and upward (Δz_a^+) and absolute downward ($|\Delta z_a^-|$) displacement during the aerial phase are presented. Values are expressed as a percentage of COM height in static upright stance. Significant differences ($P<0.05$) identified by the two-way RM ANOVA are indicated in bold. *Significant difference between DF groups as determined by Holm–Šidák *post hoc* tests.

Table 3. Temporal parameters of the running steps for the DF_{low} and DF_{high} running groups at the different running speeds

Running speed (km h ⁻¹)	DF group	t_c (s)	t_c^- (s)	t_c^+ (s)	t_a (s)	t_a^+ (s)	t_a^- (s)
10	DF _{low}	0.252±0.016	0.097±0.009	0.155±0.013	0.101±0.023	0.024±0.019	0.077±0.008
	DF _{high}	0.289±0.025*	0.107±0.013*	0.181±0.014*	0.069±0.023*	0.003±0.022*	0.066±0.009
12	DF _{low}	0.223±0.014	0.092±0.008	0.131±0.010	0.120±0.016	0.041±0.012	0.079±0.008
	DF _{high}	0.255±0.020*	0.098±0.010*	0.157±0.012*	0.080±0.020*	0.010±0.017*	0.070±0.009
14	DF _{low}	0.205±0.013	0.087±0.008	0.118±0.008	0.126±0.016	0.048±0.012	0.078±0.008
	DF _{high}	0.234±0.019*	0.094±0.009*	0.140±0.012*	0.090±0.018*	0.021±0.018*	0.069±0.009
16	DF _{low}	0.187±0.012	0.084±0.008	0.102±0.009	0.134±0.015	0.058±0.011	0.076±0.006
	DF _{high}	0.210±0.015*	0.089±0.007*	0.121±0.010*	0.105±0.013*	0.036±0.010*	0.069±0.010
18	DF _{low}	0.175±0.010	0.080±0.008	0.094±0.008	0.133±0.017	0.060±0.013	0.073±0.007
	DF _{high}	0.194±0.014*	0.085±0.008*	0.109±0.009*	0.111±0.017*	0.045±0.014*	0.069±0.011
DF effect		<0.001	0.004	<0.001	<0.001	<0.001	0.179
Running speed effect		<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Interaction effect		0.004	0.074	0.010	<0.001	0.001	<0.001

Data are means±s.d. Duration of the contact phase (t_c), duration of downward (t_c^-) and upward (t_c^+) displacement of the COM during the contact phase, duration of the aerial phase (t_a) and duration of upward (t_a^+) and downward (t_a^-) displacement of the COM during the aerial phase are presented. Significant differences ($P<0.05$) identified by two-way RM ANOVA are indicated in bold. *Significant difference between DF groups as determined by Holm–Šidák *post hoc* tests.

because it would be preferable to limit vertical displacement of the COM and to promote its forward progression. Indeed, the percentage contribution from elastic energy to positive work during running has been shown to decrease when speed is reduced (Lai et al., 2014). Therefore, relying on the re-use of elastic energy to reduce the EC of running might not be the most favourable strategy. It has recently been shown that the vertical COM displacement (during t_c or the whole step) explains a large part of the inter-individual difference in EC (27.7% for the amplitude of the pelvis vertical displacement during ground contact) at speeds between 10 and 12 km h⁻¹ (Folland et al., 2017), indicating how this particular metric could be important at slower running speeds. Nevertheless, these findings should be re-examined given that no significant main effect of DF was observed across typical endurance speeds, with no evidence how DF, kinematic parameters and EC values interplay at slower and faster running speeds.

At speeds between 10 and 14 km h⁻¹, the DF_{low} group ran with similar EC values to those of the DF_{high} group with a smaller proportion of time spent on the ground to the detriment of larger vertical oscillation of the COM during the aerial phase. From an elastic energy storage perspective, the stretching of muscle–tendon units needs a certain amount of force to be efficient. At endurance running speeds, the force needed to stretch the muscle–tendon units

could be generated via the potential energy from the Δz , and counterbalance the negative effect of a higher vertical displacement during t_a on EC. In addition, with a shorter duration of t_c , leg stiffness increases as a result of the existence of an inverse relationship between these two quantities (Morin et al., 2007). Therefore, runners belonging to the DF_{low} group seem to rely on the re-use of elastic energy to a greater extent to reduce EC. In contrast, the DF_{high} group appear to minimize EC by reducing vertical displacement, favouring forward displacement (Δy_c) of the COM, and demonstrating an asymmetry in the temporal step parameters to the detriment of a longer t_c . An increase of t_c with particular lengthening of t_c^+ enhances Δy_c such that the COM is directed more horizontally than vertically. In addition, as supported by Kram and Taylor (1990), a longer t_c allows force to be generated over a longer period, reducing EC. Moreover, the change of these parameters together with the reduction of t_a limits the vertical oscillation, especially during the aerial phase, to benefit the horizontal progression. However, as for short t_c , a large proportion of the positive work is better explained using the stretch–shortening cycle model and recovery of stored elastic energy (Cavagna, 2009, 2010; Roberts, 2016). There are various biomechanical models used to understand human and mammalian locomotion, all of which have strengths and limitations. In the current paper, the stretch–shortening paradigm was the working model employed.

Table 4. Symmetrical parameters of the running steps for the DF_{low} and DF_{high} running groups at the different running speeds

Running speed (km h ⁻¹)	DF group	t_c^+/t_c (% of t_c)	$\Delta z_c^+/\Delta z_c$ (% of $ \Delta z_c^- + \Delta z_c^+$)	t_a^+/t_a (% of t_a)	$\Delta z_a^+/\Delta z_a$ (% of $\Delta z_a^+ + \Delta z_a^- $)
10	DF _{low}	61.5±2.4	59.2±2.4	23.8±8.9	14.6±9.1
	DF _{high}	62.6±1.9	59.3±1.8	5.2±3.4*	0.0±0.9*
12	DF _{low}	58.7±2.2	58.2±2.8	34.2±5.9	24.5±8.9
	DF _{high}	61.6±2.0*	60.0±2.3	12.5±7.2*	6.7±4.4*
14	DF _{low}	57.6±2.1	57.5±2.7	38.1±4.8	30.8±7.9
	DF _{high}	59.8±1.8*	59.4±2.6	23.3±7.9*	12.5±7.3*
16	DF _{low}	54.5±2.8	55.3±2.8	43.3±3.6	38.2±6.7
	DF _{high}	57.6±2.2*	58.0±3.7*	34.3±7.1*	24.3±10.2*
18	DF _{low}	53.7±2.9	53.9±3.0	45.1±4.5	41.5±7.0
	DF _{high}	56.2±2.2*	56.9±3.9*	40.5±6.8	30.8±9.5*
DF effect		0.009	0.113	<0.001	<0.001
Running speed effect		<0.001	<0.001	<0.001	<0.001
Interaction effect		0.539	0.003	<0.001	0.104

Data are means±s.d. Duration (t_c^+/t_c) and magnitude ($\Delta z_c^+/\Delta z_c$) of the upward displacement of the COM during the contact phase, and duration (t_a^+/t_a) and magnitude ($\Delta z_a^+/\Delta z_a$) of the upward displacement of the COM during the aerial phase are presented. $\Delta z_c^+/\Delta z_c$ and $\Delta z_a^+/\Delta z_a$ are expressed as a percentage of the sum of the absolute value of the downward ($|\Delta z_c^-|$ or $|\Delta z_a^-|$) and upward (Δz_c^+ or Δz_a^+) displacement of the COM during contact (t_c) and aerial (t_a) phases, respectively. t_c^+/t_c and t_a^+/t_a are expressed as a percentage of t_c and t_a , respectively. Significant differences ($P<0.05$) identified by two-way RM ANOVA are indicated in bold. *Significant difference between DF groups as determined by Holm–Šidák *post hoc* tests.

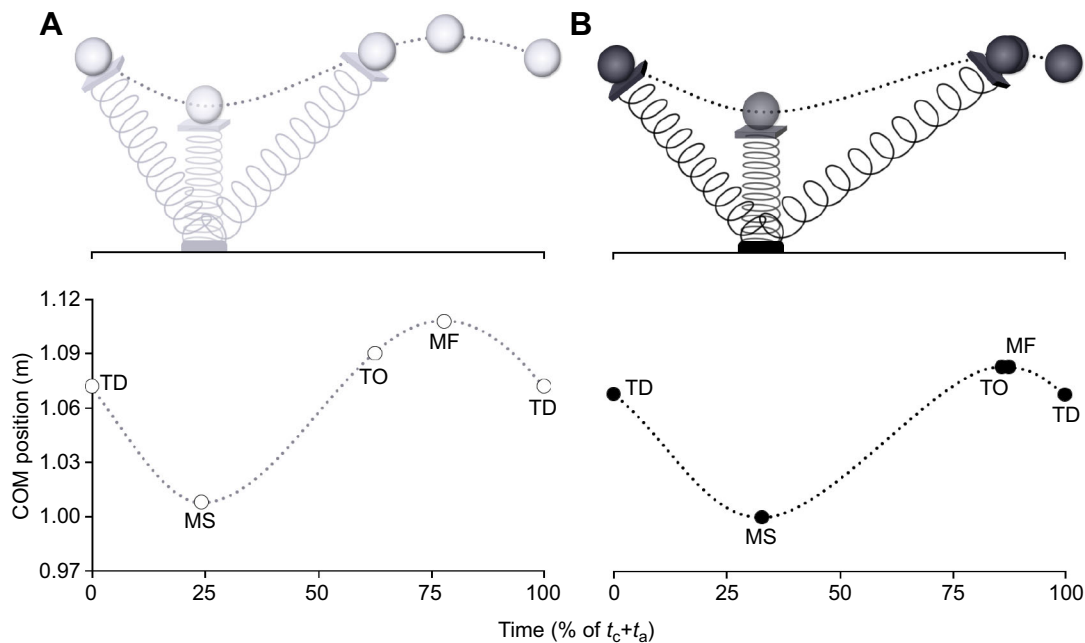


Fig. 4. Representation of COM displacement while running at 14 km h⁻¹. (A) A runner from the DF_{low} group. (B) A runner from the DF_{high} group. The vertical displacement of the COM during the running step includes a contact phase (t_c) and an aerial phase (t_a). TD, touch-down; MS, mid-stance; TO, toe-off; MF, mid-flight.

The existence of asymmetries between the braking and propulsion phases in runners – more precisely, the proportionally longer ground contact time than aerial time (DF_{high} group) – mirrors previous observations of a relatively longer t_c^+ than t_c^- , with lower apparent elastic behaviour in elderly (73.6±5.5 years) than in younger (20.8±1.6 years) runners (Cavagna et al., 2008b). Our findings extend these previous results and indicate that inter-individual differences in the optimization of the spring–mass model during running are not due to age alone, but reflect spontaneous movement patterns. Here, we provide biomechanical evidence to support the proposal that minimizing vertical displacement and work against gravity can be a cost-efficient strategy, despite a lower compliance to the spring–mass model (Fig. 4). Thus, we propose that EC can be minimized through different mechanisms: (1) optimization of the spring–mass model, leading to the re-use of elastic energy (DF_{low}), and (2) limiting vertical displacement of the COM to promote forward progression (DF_{high}). These different minimization strategies can be distinguished by simple temporal step measurements. Some runners further rely more on one mechanism than the other, which is also reflected by some runners having a similar EC despite exhibiting more than twice the vertical displacement of other runners (Folland et al., 2017).

A particular running condition (i.e. speed or distance) can influence the preferred running biomechanics; hence, it is difficult to prove the existence of a single ideal running form. Thus, we encourage running coaches to consider the characteristics of running form at an individual level, as well as the specific race demands in training prescription and preparation. The distinction of running forms can be performed easily as it only requires the measurement of temporal step characteristics. For now, the effect of an acute and chronic change in DF on the EC of runners remains to be tested, although it has been shown that acute changes in self-selected running forms (e.g. a decrease in stride length and vertical oscillation) tend to increase EC (Dallam et al., 2005; Moore, 2016).

Several limitations to this study exist. To start with, there are relatively few studies on DF, making it difficult to know what DF values are typical or how these values are likely to change with confounding variables, such as footwear or running surface. In our study, participants wore their own shoes. To date, the empirical evidence regarding the effect of footwear on EC is conflicting, with some studies indicating an effect (e.g. Hoogkamer et al., 2018) and others indicating no effect (e.g. Cochrum et al., 2017) of footwear on EC when matched for mass. Another limitation is that segment inertial properties in our study were not based on each individual's actual segmental properties. However, the use of standard regression equations is a widespread non-invasive technique that does not require use of expensive magnetic resonance imaging and exposure of individuals to radiation. Finally, the working model is that the re-use of elastic energy reflects spring–mass model mechanics. The impulsive collision model proposed by Ruina et al. (2005) exemplifies how a locomotive pattern can appear elastic without any storage and return of elastic energy, cautioning against reliance on biomechanics alone to infer energy storage and release. That said, Ruina et al.'s (2005) model is very simple and is not suited to understanding how DF affects the cost of running as the model employs an instantaneous impulsive collision (a DF of zero). No calculation on the use of elastic energy was performed in this study given that it would not be representative of the true elastic energy stored in the lower limb in the case of the DF_{high} group. Indeed, the formula used to compute elastic energy is correct only within the limits of the spring–mass model, a model which we assume is no longer optimized for the DF_{high} group because of the lack of symmetry within the running step.

In summary, runners with a low DF favour short contact times and have a more symmetrical running step. This may be due to less stretching and shortening of the muscle and greater stretching and shortening of the tendon, which would lead to greater re-use of elastic energy and lower EC. Runners with a high DF favour long contact times and reduce work against gravity to promote forward

progression to lower EC. Overall, the two running forms (i.e. high and low DF), which can be distinguished by a simple measurement of running step temporal parameters, were here associated with similar EC, suggesting that both strategies can be used efficiently at typical endurance running speeds. These results can impact how running technique and optimal running forms are perceived in diverse environments.

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Competing interests

The authors declare no competing or financial interests.

Author contributions

Conceptualization: T.L., C.G.; Methodology: T.L., L.M., K.H.-L.; Software: K.H.-L.; Validation: K.H.-L.; Formal analysis: T.L., K.H.-L.; Investigation: T.L., K.H.-L.; Resources: T.L.; Data curation: T.L., K.H.-L.; Writing - original draft: T.L.; Writing - review & editing: A.P., C.G., L.M., K.H.-L.; Supervision: L.M., K.H.-L.; Project administration: L.M.; Funding acquisition: T.L., L.M., K.H.-L.

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