SPORTS BIOMECHANICS
https://doi.org/10.1080/14763141.2022.2094825

Examination of running pattern consistency across speeds

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ABSTRACT

Duty factor (DF) and step frequency (SF) are key running pattern determinants. However, running patterns may change with speed if DF and SF changes are inconsistent across speeds. We examined whether the relative positioning of runners was consistent: 1) across five running speeds (10–18 km/h) for four temporal variables [DF, SF, and their subcomponents: contact (t_c) and flight (t_c) time]; and 2) across these four temporal variables at these five speeds. Three-dimensional whole-body kinematics were acquired from 52 runners, and deviations from the median for each variable (normalised to minimum-maximum values) were extracted. Across speeds for all variables, correlations on the relative positioning of individuals were *high* to *very high* for 2–4 km/h speed differences, and *moderate* to *high* for 6–8 km/h differences. Across variables for all speeds, correlations were *low* between DF-SF, *very high* between DF-t_c, and *low* to *high* between DF-t_c, SF-t_c, and SF-t_c. Hence, the consistency in running patterns decreased as speed differences increased, suggesting that running patterns be assessed using a range of speeds. Consistency in running patterns at a given speed was low between DF and SF, corroborating suggestions that using both variables can encapsulate the full running pattern spectrum.

ARTICLE HISTORY
Received 23 November 2021
Accepted 22 June 2022

KEYWORDS
Gait analysis; motion analysis; biomechanics; temporal variables; Relative positioning

Introduction

The spring–mass model represents running as a 'bouncing' gait modelled using a mass connected to a massless spring (Blickhan, 1989). In this model, the supporting leg behaves like a spring during stance and each stance is separated by a flight time (t_f), i.e., a period where the limbs are not in contact with the ground. The presence of this flight phase distinguishes running from walking (Novacheck, 1998).

Each runner adopts a unique and natural running pattern that is challenging to describe using a single variable (Folland et al., 2017). As early as 1985, the running pattern was viewed as a global system with several interconnected variables (Subotnick,

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1985). More recently, the synthetic review of van Oeveren et al. (2021) proposed that the full spectrum of running patterns could be described combining two temporal variables: step frequency (SF) and duty factor (DF), where DF reflects the relative contribution of the ground contact time (t_c) to the running stride (Folland et al., 2017; Minetti, 1998). According to van Oeveren et al. (2021), knowing DF and SF allows to categorise running patterns in one of five distinct categories, namely 'stick', 'bounce', 'push', 'hop', and 'sit', but keeping in mind that running patterns operate along a continuum. Individuals spontaneously and subconsciously adopt their own running pattern, a choice shown to be self-optimised and central in the development of an economical and safe running gait (Cavanagh & Williams, 1982; Moore et al., 2016; Moore, 2016; Williams & Cavanagh, 1987). The understanding of the individual running patterns might be important for improving performance, optimising training, and preventing running-related injuries.

The importance of DF and SF in determining running patterns (van Oeveren et al., 2021) corroborates previous findings. On the one hand, DF has been used to categorise runners with distinct running patterns (Lussiana et al., 2019; Patoz et al., 2020). Runners with a low DF exhibit a more symmetrical stance phase (similar brake and push times), anterior (midfoot and forefoot) strike pattern, and extended lower limb during t_c than runners with a high DF. In contrast, runners with a high DF exhibit greater lower limb flexion during t_c, a more rearfoot strike pattern, and lesser work against gravity to generate forward propulsion (Lussiana et al., 2019; Patoz et al., 2020). Despite these biomechanical differences, the running economy of runners within these two DF groups are similar (Lussiana et al., 2019), suggesting two energetically equivalent strategies at endurance running speeds. On the other hand, SF can reveal individual muscle recruitment patterns of runners and strategies to increase running speed (Dorn et al., 2012) or achieve top-end running speeds (Salo et al., 2011). Even in subgroups of individuals with similar sprint velocities, a range of SF and step length combinations are present (Hunter et al., 2004).

Running speed affects DF and SF, with an increase in running speed decreasing DF (Lussiana et al., 2019; Minetti, 1998; van Oeveren et al., 2021) and increasing SF (Dorn et al., 2012; Ogueta-Alday et al., 2014; van Oeveren et al., 2021). These changes are likely related to changes in their subcomponent variables t_c and t_f. Indeed, t_c decreases with an increase in running speed, whereas t_c increases (da Rosa et al., 2019; Lussiana et al., 2019; Ogueta-Alday et al., 2014; van Oeveren et al., 2021). Given the speed-dependency of these variables, van Oeveren et al. (2021) suggested using an absolute speed to define running patterns as stick, bounce, push, hop, and sit.

Worth noting is the large interindividual variations in temporal variables (DF, t_c, t_f, and SF) reported at absolute running speeds (Lussiana et al., 2019; Ogueta-Alday et al., 2014) and the large interindividual variations in the individual strategies adopted to adapt to changes in running speeds (Forrester & Townend, 2015; Hébert-Losier et al., 2015; Salo et al., 2011). For instance, a curve-clustering approach on the footstrike angle of runners across speeds revealed three subgroups: those that maintained a rearfoot strike pattern, those that maintained a forefoot or midfoot strike pattern, and those that transitioned from a rearfoot to a less rearfoot strike pattern with increasing speed (Forrester & Townend, 2015). Therefore, the running pattern of an individual could also change with speed if the relationship between or changes in the underlying temporal variables are inconsistent across running speeds. Such understanding would then allow us assessing if the evaluation of running patterns could be generalised across speeds and studies.

Hence, our first aim was to assess if running patterns are consistent across running speeds by examining the consistency in four temporal variables (DF, SF, t_c, and t_f). For instance, we investigated whether a runner with a high DF (with respect to the group median) at a slow running speed also exhibits a high DF at a faster running speed. We hypothesised that consistency would be greater when differences in running speeds were smaller, as previously observed for footstrike angle (Forrester & Townend, 2015).

Our second aim was to assess the consistency across the four temporal variables at an absolute running speed. Given that DF and SF are proposed to be two independent key running pattern determinants (van Oeveren et al., 2021), the association between these two variables should be low. Hence, we hypothesised that consistency would be low between DF and SF. On the other hand, we anticipated greater consistency between DF and its subcomponent variables (t_c and t_f) as well as between SF and t_c and t_f.

Material and methods

Participants

Fifty-two runners, 32 men (age: 32 ± 9 yr, mass: 66 ± 11 kg, height: 175 ± 7 cm, running distance: 53 ± 21 km/week, running experience: 8 ± 8 yr, and best half-marathon time: 92 ± 10 min) and 20 women (age: 32 ± 9 yr, mass: 52 ± 6 kg, height: 162 ± 4 cm, running distance: 50 ± 22 km/week, running experience: 7 ± 4 yr, and best half-marathon time: 102 ± 12 min) 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 or ≤2 h for 21.1 km. The ethical committee of the

National Sports Institute of Malaysia approved the study protocol prior to participant recruitment (ISNRP: 26/2015, which adhered to the latest version of the Declaration of Helsinki of the World Medical Association.

Experimental procedure

Each participant completed one experimental laboratory session. After providing written informed consent, participants ran 16 min (4 min at 9 km/h, 10 km/h, 12 km/h, and 14 km/h in that order) on a treadmill (h/p/cosmos mercury®, h/p/cosmos sports & medical gmbh, Nussdorf-Traunstein, Germany) as a warm-up ensuring stabilisation of shoe stiffness properties (Divert et al., 2005) and promoting treadmill familiarisation (Arnold et al., 2019; Lindorfer et al., 2020). Then, retro-reflective markers were positioned on individuals (described in *Data Collection* section) to assess running kinematics. For each participant, a 1-s static calibration trial was recorded, which was followed by 5 × 30-s runs at 10, 12, 14, 16, and 18 km/h (with 1-min recovery periods between each runs) to collect three-dimensional (3D) kinematic data in the last 10-s segment of these runs

(30 ± 2 running steps), resulting in at least 20 steps being analysed (Riazati et al., 2019). All participants were familiar with running on a treadmill as part of their usual training programs and wore their habitual running shoes during testing (shoe mass: 226 ± 37 g, stack height: 25 ± 3 mm, and heel-to-toe drop: 7 ± 3 mm).

Data collection

3D kinematic data were collected at 200 Hz using seven infrared Oqus cameras (five Oqus 300+, one Oqus 310+, and one Oqus 311+) and Qualisys Track Manager software version 2.1.1 build 2902 together with the Project Automation Framework Running package version 4.4 (Qualisys AB, Göteborg, Sweden). Thirty-five retro-reflective markers of 12 mm in diameter were used for static calibration and running trials, and were affixed to the skin and shoes of individuals over anatomical landmarks using double-sided tape following standard guidelines from the Project Automation Framework Running package (Tranberg et al., 2011) as already reported elsewhere (Lussiana et al., 2019). 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). More explicitly, the 3D 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.

Temporal variables

Running events were derived from the trajectories of the 3D marker data using similar procedures to those previously reported (Lussiana et al., 2019; 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. All events were verified to ensure correct identification and were manually adjusted when required.

t_c was defined as the time from footstrike to toe-off of the same foot while t_f was defined as the time from toe-off of one foot to footstrike of the contralateral foot. SF was calculated as $\mathrm{SF} = 1/(t_c + t_f)$, and DF as $\mathrm{DF} = t_c\mathrm{SF}/2$. For all temporal variables, the values extracted from the 10-s data collection for each participant were averaged. To express the temporal variables as relative, each variable was normalised using the min-max scaler approach, i.e., $(x - x_{\mathrm{min}})/(x_{\mathrm{max}} - x_{\mathrm{min}})$ where x represents the value for a given participant and $x_{\mathrm{min/max}}$ the minimum/maximum among all participants at a given speed. The normalised variables were used in subsequent statistical analyses.

Statistical analysis

Descriptive statistics are presented using mean ± standard deviation. The consistency in running patterns across running speeds was evaluated by examining the relative positioning of runners for each temporal variable and tested speed. The relative positioning was obtained by calculating the deviations from the median of the temporal values. These datasets were normally distributed based on Kolmogorov–Smirnov tests ($P \geq 0.34$). Pearson's correlation coefficients (r) on the relative values together with corresponding 95% CI [lower, upper] and P-values were extracted to explore the consistency between each pair of running speeds for each of the four temporal variables. The same statistical approach was used to explore the consistency between each pair of temporal variables for each of the five running speeds. Correlations were considered *very high*, *high*, *moderate*, *low*, and *negligible* when absolute r values were between 0.90 - 1.00, 0.70–0.89, 0.50–0.69, 0.30–0.49, and 0.00–0.29, respectively (Hinkle et al., 2002). Statistical analyses were performed using Jamovi (version 1.6, https://www.jamovi.org) with a level of significance set at $P \leq 0.05$ for all analyses.

Results

As speed increased from 10 to 18 km/h, DF and t_c decreased by 8.5 ± 2.8% and 87 ± 20 ms, while t_f and SF increased by 42 ± 20 ms and 0.42 ± 0.16 Hz, respectively (Table 1 and Figure 1). The relative DF, SF, t_c, and t_f values for all participants and each running speed are depicted in Figure 2.

Consistency across running speeds for each temporal variable

Correlations for each one of the four relative temporal variables were *high* to *very high* for each pair of running speeds when changes were 2–4 km/h ($P < 0.001$, Table 2), except for the correlation between 10 and 14 km/h for t_c being *moderate*. Correlations were *moderate* to *high* for each pair of running speeds when changes were 6–8 km/h for the four relative temporal variables ($P < 0.001$; Table 2).

The relative DF values for all participants and each running speed are depicted in Figure 3. According to the correlations reported in Table 2, similar figures and corresponding interpretations would result using the three other variables (t_c, t_f, and SF).

Consistency across temporal variables for each running speed

Correlations were *low* between relative DF and SF at all tested speeds ($P \leq 0.02$; Table 3). Correlations were *very high* between relative DF and t_f at all tested speeds ($P < 0.001$); and *high* between relative DF and t_c at 10 and 12 km/h ($P < 0.001$), but *moderate* at 14, 16, and 18 km/h ($P < 0.001$; Table 3).

Table 1. Duty factor, contact time, flight time, and step frequency at five running speeds.

Running speed (km/h)	Duty factor (%)	Contact time (ms)	Flight time (ms)	Step frequency (Hz)
10	38.6 ± 3.4	274 ± 24	81 ± 27	2.83 ± 0.16
12	35.1 ± 2.8	242 ± 19	103 ± 23	2.91 ± 0.18
14	33.2 ± 1.5	220 ± 18	112 ± 21	3.02 ± 0.19
16	31.2 ± 2.4	201 ± 17	121 ± 20	3.12 ± 0.21
18	30.1 ± 2.3	186 ± 15	124 ± 20	3.24 ± 0.24

Values are means ± standard deviations.

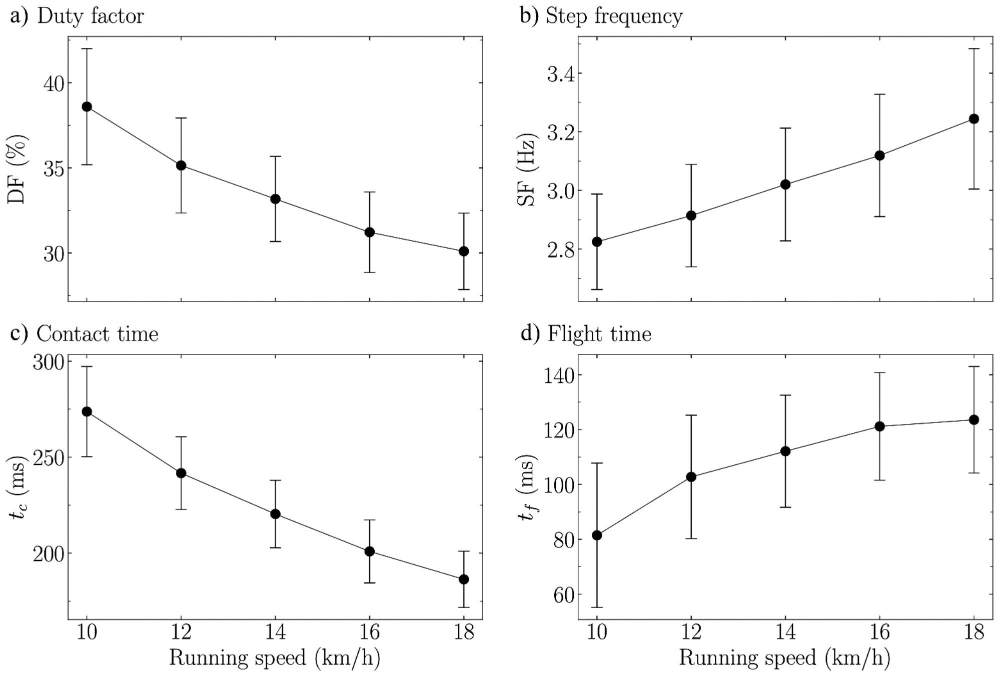


Figure 1. a) Duty factor (DF), b) step frequency (SF), c) contact time (t_c), and d) flight time (t_f) at five running speeds. Circles and error bars represent means and standard deviations, respectively.

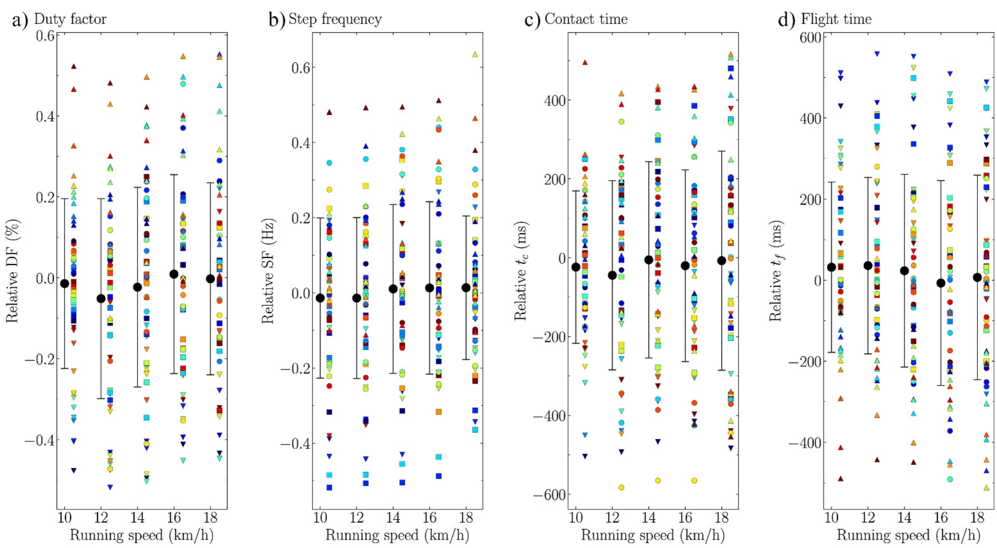


Figure 2. Relative (deviations from the median) a) duty factor (DF), b) step frequency (SF), c) contact time (t_c), and d) flight time (t_f) values at five running speeds for all participants. Circles and error bars represent means and standard deviations, respectively. The combination of a colour and symbol represents a given participant and allows to observe the interindividual differences across both running speeds and temporal variables.

Table 2. Pearson's correlation coefficients (*r*) and corresponding 95% confidence intervals [lower, upper] and *P*-values for the relationships of the relative values for pair of running speeds among five different speeds (10, 12, 14, 16, and 18 km/h) and for four temporal variables (duty factor, contact time, flight time, and step frequency).

Running speed pair (km/h)	Statistics	Duty factor	Contact time	Flight time	Step frequency
10 - 12	*r*	0.86 [0.76, 0.92]	0.83 [0.73, 0.90]	0.89 [0.81, 0.93]	0.98 [0.96, 0.99]
	P	**<0.001**	**<0.001**	**<0.001**	**<0.001**
10 - 14	*r*	0.72 [0.56, 0.83]	0.69 [0.51, 0.81]	0.78 [0.64, 0.87]	0.93 [0.88, 0.96]
	P	**<0.001**	**<0.001**	**<0.001**	**<0.001**
10 - 16	*r*	0.64 [0.45, 0.78]	0.63 [0.44, 0.77]	0.73 [0.56, 0.83]	0.86 [0.77, 0.92]
	P	**<0.001**	**<0.001**	**<0.001**	**<0.001**
10 - 18	*r*	0.58 [0.37, 0.74]	0.54 [0.32, 0.71]	0.66 [0.47, 0.79]	0.77 [0.63, 0.86]
	P	**<0.001**	**<0.001**	**<0.001**	**<0.001**
12 - 14	*r*	0.91 [0.84, 0.95]	0.90 [0.83, 0.94]	0.93 [0.88, 0.96]	0.97 [0.94, 0.98]
	P	**<0.001**	**<0.001**	**<0.001**	**<0.001**
12 - 16	*r*	0.79 [0.66, 0.88]	0.83 [0.72, 0.90]	0.83 [0.73, 0.90]	0.92 [0.87, 0.96]
	P	**<0.001**	**<0.001**	**<0.001**	**<0.001**
12 - 18	*r*	0.68 [0.51, 0.81]	0.71 [0.54, 0.82]	0.73 [0.57, 0.84]	0.83 [0.71, 0.90]
	P	**<0.001**	**<0.001**	**<0.001**	**<0.001**
14 - 16	*r*	0.86 [0.77, 0.92]	0.90 [0.83, 0.94]	0.90 [0.83, 0.94]	0.97 [0.95, 0.98]
	P	**<0.001**	**<0.001**	**<0.001**	**<0.001**
14 - 18	*r*	0.73 [0.57, 0.83]	0.82 [0.70, 0.89]	0.77 [0.63, 0.86]	0.88 [0.80, 0.93]
	P	**<0.001**	**<0.001**	**<0.001**	**<0.001**
16 - 18	*r*	0.86 [0.77, 0.92]	0.91 [0.85, 0.95]	0.90 [0.83, 0.94]	0.93 [0.88, 0.96]
	P	**<0.001**	**<0.001**	**<0.001**	**<0.001**

Statistically significant correlations ($P \le 0.05$) are in bold font. Correlations were considered *very high*, *high*, *moderate*, *low*, and *negligible* when absolute *r* values were between 0.90–1.00, 0.70–0.89, 0.50–0.69, 0.30–0.49, and 0.00–0.29, respectively (Hinkle et al., 2002). Cells were coloured according to the intensity of the correlations, i.e., the larger the correlation, the darker the shaded area.

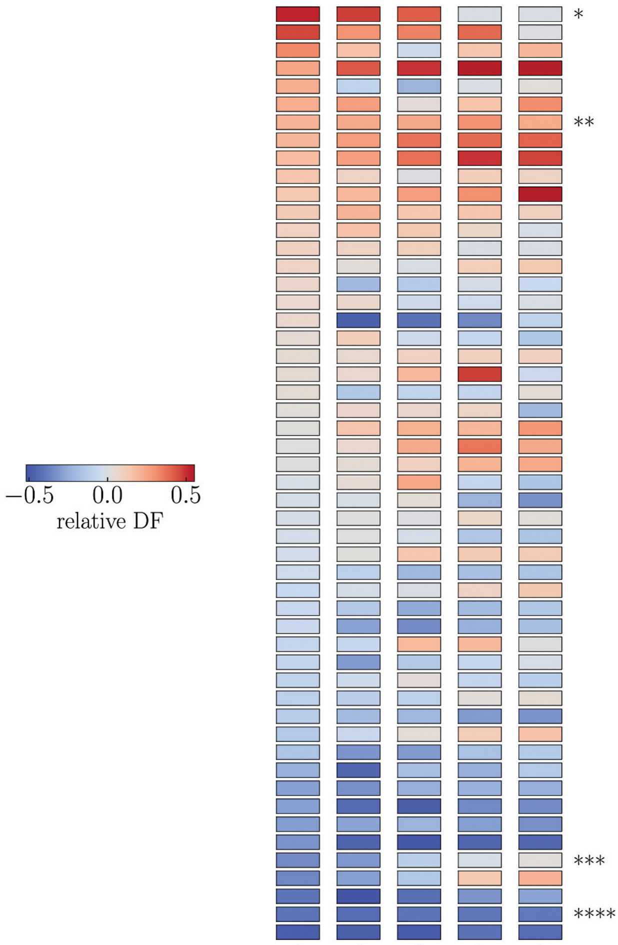
Correlations between relative SF and t_f were *moderate* at all speeds (P < 0.001), except for being *high* at 18 km/h (P < 0.001). Correlations were *low* between relative SF and t_c at 10, 12, and 14 km/h ($P \le 0.03$), and *moderate* at 16 and 18 km/h (P < 0.001; Table 3).

Correlations between relative t_c and t_f were *moderate* at 10 km/h ($P < 0.001$), *low* at 12, 14, and 16 km/h ($P \le 0.04$). Correlations were *negligible* at 18 km/h ($P = 0.21$; Table 3)

The relative temporal variables are depicted in Figure 4 for all participants running at 10 km/h. According to the correlations reported in Table 3, similar figures and corresponding interpretations would result using the four other running speeds (12, 14, 16, and 18 km/h).

Discussion and implications

In agreement with our first hypothesis, smaller differences between two running speeds were associated with greater consistency in running patterns, i.e., greater consistency in the four temporal variables examined (DF, SF, t_c, and t_f). Correlations of the relative values were *high* to *very high* for 2–4 km/h speed differences, whereas *moderate* to *high* for 6–8 km/h differences. In agreement with our second hypothesis, the consistency between DF and SF variables was low at each tested speed, and greater between DF



running speed (km/h)	10	12	14	16	18
median of normalized DF	0.48	0.52	0.50	0.45	0.45
median DF (%)	38.8	35.7	33.4	31.1	30.1
minimum DF (%)	31.1	29.9	28.3	26.8	25.9
maximum DF (%)	47.3	41.2	38.4	36.4	35.4

Figure 3. Relative (deviations from the median) duty factor (DF) values for all participants and five running speeds. Runners were relatively positioned according to their relative DF values at 10 km/h. The star symbols depict four participants with distinct behaviours. * participant with a DF much higher than the median at 10 km/h, but a decreasing DF with increasing speed resulting in a DF closer to the median at 18 km/h. ** participant with a DF higher than the median at all tested speeds. *** participant with a DF lower than the median at 10 km/h, but an increasing DF with increasing speed resulting in a DF closer to the median at 18 km/h. **** participant with a DF much lower than the median at all tested speeds.

and both its subcomponents as well as between SF and both its subcomponents than between DF and SF variables. Across speeds, correlations were *low* between relative DF and SF, *very high* between relative DF and t_f, and *low* to *high* between relative DF and t_c, SF and t_f, and SF and t_f. From a practical perspective, the lower consistency in running patterns observed as speed differences increased suggests that running patterns should be

Table 3. Pearson's correlation coefficients (r) and corresponding 95% confidence intervals [lower, upper] and P-values for the relationships of the relative values for pair of temporal variables among duty factor (DF), contact time (t_c), flight time (t_f), and step frequency (SF), and for five running speeds.

Variable pair	Statistics	10 km/h	12 km/h	14 km/h	16 km/h	18 km/h
DF – SF	r	0.38 [0.11, 0.59]	0.38 [0.13, 0.60]	0.34 [0.07, 0.56]	0.32 [0.05, 0.55]	0.41 [0.16, 0.62]
	P	**0.006**	**0.005**	**0.01**	**0.02**	**0.002**
DF – t_f	r	-0.98 [-0.99, -0.97]	-0.96 [-0.98, -0.93]	-0.94 [-0.96, -0.89]	-0.91 [-0.95, -0.85]	-0.91 [-0.95, -0.85]
	P	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
DF – t_c	r	0.77 [0.63, 0.86]	0.71 [0.54, 0.82]	0.67 [0.48, 0.80]	0.65 [0.46, 0.79]	0.57 [0.35, 0.73]
	P	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
SF – t_f	r	-0.53 [-0.70, -0.30]	-0.62 [-0.76, -0.41]	-0.64 [-0.78, -0.44]	-0.67 [-0.80, -0.49]	-0.74 [-0.85, -0.59]
	P	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**<0.001**
SF – t_c	r	-0.30 [-0.53, -0.03]	-0.38 [-0.59, -0.12]	-0.47 [-0.66, -0.23]	-0.50 [-0.68, -0.27]	-0.51 [-0.69, -0.28]
	P	**0.03**	**0.006**	**<0.001**	**<0.001**	**<0.001**
$t_c – t_f$	r	-0.65 [-0.79, -0.46]	-0.49 [-0.67, -0.25]	-0.37 [-0.58, -0.11]	-0.29 [-0.52, -0.02]	-0.18 [-0.43, 0.10]
	P	**<0.001**	**<0.001**	**0.007**	**0.04**	0.21

Statistically significant correlations ($P \leq 0.05$) are in bold font. Correlations were considered *very high*, *high*, *moderate*, *low*, and *negligible* when absolute r values were between 0.90–1.00, 0.70–0.89, 0.50–0.69, 0.30–0.49, and 0.00–0.29, respectively (Hinkle et al., 2002). Cells were coloured according to the intensity of the correlations, i.e., the closer to one the correlation, the darker the red shaded area and the closer to minus one the correlation, the darker the blue shaded area.

assessed at a range of speeds or at a specific speed. In other words, the generalisation of running patterns across speeds may not be valid. Noteworthy is the considerable inter-individual differences observed in terms of the evolution of the relative variables with changes in speed, with some runners demonstrating similar running patterns across speeds and others changing running patterns. The low consistency between DF and SF at a given running speed corroborates previous findings that SF does not necessarily encapsulate the same running pattern information than DF. As proposed by van Oeveren et al. (2021), the full spectrum of running patterns can be described using both DF and SF. Individuals spontaneously and subconsciously adopt their own running pattern. This spontaneous choice was shown to be self-optimised, which is a central element in the development of an economical and safe running gait (Cavanagh & Williams, 1982; Moore et al., 2016; Moore, 2016; Williams & Cavanagh, 1987). Hence, being able to analyse the full spectrum of running patterns may be important to interpret measurements, to design and test specific coaching interventions, and to conduct research to answer questions regarding performance, running economy, and injury risk.

The stronger correlations of the relative temporal variables (DF, SF, t_c, and t_f) for 2–4 km/h than 6–8 km/h speed differences (Table 2) indicate greater consistency in variables when changes in running speeds are smaller. In other words, the running pattern is less consistent when measured over a larger speed range (Figures 2 and 3). This result supports that the running pattern should be defined at a given speed (van Oeveren et al., 2021). Moreover, large interindividual variations in the consistency in running patterns across running speeds were observed (Figure 3). For instance, there were runners with a DF higher than the median at 10 km/h, but a decreasing DF with increasing speed resulting in a DF closer to the median at 18 km/h; runners with a DF higher than the median at all tested speeds; runners with a DF lower than the median at 10 km/h, but an increasing DF with increasing speed resulting in a DF closer to the median at 18 km/h; and runners with a DF much lower than the median at all tested

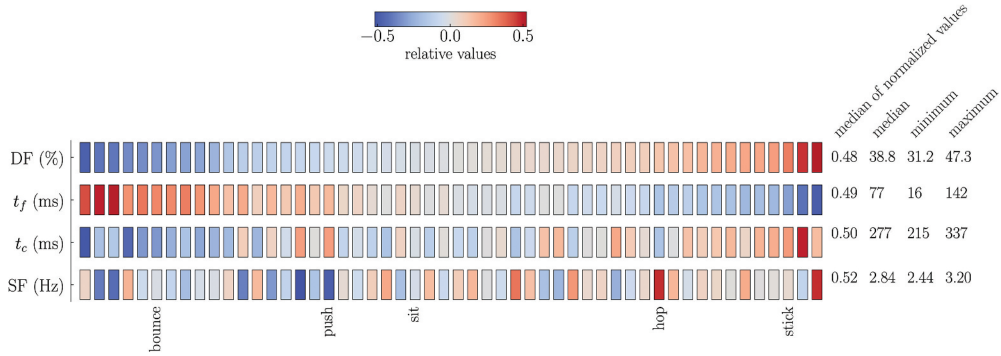


Figure 4. Relative (deviations from the median) duty factor (DF), contact time (t_c), flight time (t_f), and step frequency (SF) values for all participants at 10 km/h. Runners were relatively positioned according to their relative DF values at 10 km/h. The relative t_f values are almost the exact opposite to the relative DF values (Pearson correlation coefficient: −0.98). One participant representing each of the five running pattern categories proposed by van Oeveren et al. (2021) based on the combination of DF and SF is identified, namely bounce (low DF and median SF), push (low SF and median DF), sit (median DF and SF), hop (high SF and median DF), and stick (high DF and median SF).

speeds. This agrees with previous observations that individuals adapt to running speeds differently (Forrester & Townend, 2015; Hébert-Losier et al., 2015; Salo et al., 2011), which might be linked to differences in anthropometric characteristics, age, and running training (van Oeveren et al., 2019). Performing a more detailed analysis that incorporates clustering approaches might reveal subgroups that respond similarly to changes in running speeds. As absolute running speeds were used rather than relative speeds (based on the level of participants), it would not be possible to identify whether sudden changes in DF and/or SF take place at given relative intensities. Overall, coaches should evaluate the running pattern of their athletes using a range of speeds or at a specific speed.

As indicates the *low* correlations between relative DF and SF values at all tested speeds (Table 3), the consistency between these two variables was low. Similarly, Figure 4 depicts how runners with a low/high DF can present with either a low/high SF. These results again reflect previous ones wherein SF does not necessarily encapsulate the same running pattern information than DF, and that combining DF and SF information should allow to describe the full running pattern spectrum (van Oeveren et al., 2021). As depicted in Figure 4, each of the five categories proposed by van Oeveren et al. (2021) were represented herein. Specifically, there were stick (high DF and median SF), bounce (low DF and median SF), hop (high SF and median DF), push (low SF and median DF), and sit (median DF and SF) runners. Moreover, there were runners in between these categories, which also confirms that running patterns operate along a spectrum (Figure 4) (van Oeveren et al., 2021).

Given that the risk of injury was shown greater in runners with a lower DF, especially in softer shoes (Malisoux et al., 2022), quantifying DF might be informative for lower-limb injury prevention. The present study found *very high* correlations between relative DF and t_f values at all tested speed (Table 3 and Figure 4), suggesting that the relative t_f is equivalent to the relative DF. In other words, individual variations in t_f are equivalent to variations in DF. The interrelatedness of DF and t_f and their importance in running are further highlighted by their established correlations to ground reaction force metrics. Indeed, DF and t_f are related to the average vertical ground reaction force during t_f (Beck et al., 2020) and effective vertical impulse during t_f (Dorn et al., 2012), respectively. Both the average vertical ground reaction force during t_f and effective vertical impulse during t_f are proportional to the peak vertical ground reaction force, as supports the sine wave model of the vertical ground reaction force (Morin et al., 2005) and experimental data (Bonnaerens et al., 2021). The present study reported lower association between relative t_c and DF values (correlations were *moderate* to *high*; Table 3 and Figure 4) than relative t_c to DF values. This result is primarily driven by the midrange DF runners (Figure 4). Altogether, these observations indicate that runners with a relatively long t_f (or short t_c) are runners with a relatively low DF within a group of runners, i.e., DF is mainly controlled by t_f and less by t_c. Overall, the kinematic differences previously observed between high and low DF runners (Lussiana et al., 2019; Patoz et al., 2020) should generalise well to runners with short and long t_f, but might not generalise as well to runners with long and short t_c. Among these three variables (DF, t_c, and t_f), one might be easier to evaluate subjectively, which would be ideal for track and field running coaches, athletes, and practitioners seeking to describe running patterns along a spectrum. Indeed, running coaches could then subjectively evaluate their runners and identify the low DF runners using either DF, t_f, or t_c Nevertheless, further studies comparing subjective and objective evaluations of runners using DF, t_f, and t_c would be needed to assess if one of these variables is easier to subjectively evaluate than the others.

The *moderate* to *high* correlations between relative SF and t_f values and *low* to *moderate* correlations between relative SF and t_c values (Table 3 and Figure 4) follow the same trend than those between relative DF and t_f or t_c, i.e., correlations were larger with t_f than with t_c. Hence, t_f also determines more of the variation of SF than t_c.

Bear in mind that the running trials were performed on a treadmill, hence generalisation to overground running is not guaranteed (Bailey et al., 2017). Nevertheless, as temporal variables between treadmill and overground running are largely comparable (Van Hooren et al., 2020), our results may still apply to overground running. In addition, absolute running speeds were used, which enables generalisability with findings from other studies using absolute speeds. However, future studies might seek to examine the consistency in running patterns based on DF and SF variables across relative speeds [i.e., percent of maximal aerobic speed or maximal oxygen uptake, or percent of maximal lactate steady state to avoid influencing motor unit recruitment strategy (Burnley & Jones, 2018; Fletcher et al., 2009)] to establish whether sudden changes in DF and/or SF could take place at given relative intensities. Moreover, the eligibility criteria about the level of running performance was independent of the sex of the runners, implying that women were of a higher relative standard than men. Furthermore, no sex distinction was considered in the present study. Although a relatively large sample size was employed ($n = 52$), which would have allowed us to separate out men ($n = 32$) and women ($n = 20$), we preferred to not do such separation to increase the statistical power as well as to keep the method as simple as possible to have an easy-to-read manuscript. Besides, even though correlations are known to be affected by the range of the sample (a large range could lead to very high correlations), the present study reported only a 13 ± 12% larger range for men than women when considering the four temporal variables at all tested speeds. The larger range reported for men than women could not be explained by the difference in relative performance standard between men and women. Indeed, even though women reported a 10% slower best half-marathon racing time than men, their range of best racing time was 20% larger than men, which is opposed to the 10% smaller range obtained for the temporal variables compared to men. Nevertheless, future work should focus on the impact of sex when examining the running pattern consistency across running speeds.

Conclusion

This study revealed that the consistency in running patterns decreased as speed differences increased. Therefore, running patterns should be assessed using a range of speeds or at a specific speed. Moreover, there were large interindividual differences across the relative temporal variables examined (DF, SF, t_c, and t_f), highlighting individualised strategies to adapt in running speed changes. In accordance with a previously proposed running pattern model, relative DF and SF were weakly related, indicating that both variables encapsulate different information on running patterns.

Acknowledgments

The authors thank Mr. Chris Tee Chow Li for assistance during the data collection process. The authors also thank the participants for their time and participation.

Authors' contribution

TL carried out the lab work and collected data; AP and BB performed the data analysis, carried out the statistical analysis, and wrote the original draft of the manuscript; AP, TL, BB, CG, DM, and KH-L critically revised the manuscript; TL, CG, DM, and KH-L conceived of the study, designed the study, and coordinated the study. All authors gave final approval for publication and agreed to be held accountable for the work performed therein.

Data availability statement

The datasets supporting this article are available on request to the corresponding author.

Disclosure statement

The authors declare no conflicts of interest.

Funding

This study was financially supported by the University of Bourgogne Franche-Comté (France) and the National Sports Institute of Malaysia.

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References

Arnold, B. J. W., Weeks, B. K., & Horan, S. A. (2019). An examination of treadmill running familiarisation in barefoot and shod conditions in healthy men. *Journal of Sports Science*, *37*(1), 5–12. https://doi.org/10.1080/02640414.2018.1479533

Bailey, J. P., Mata, T., & Mercer, J. D. (2017). Is the relationship between stride length, frequency, and velocity influenced by running on a treadmill or overground? *International Journal of Exercise Science*, *10*(7), 1067–1075.

Beck, O. N., Gosyne, J., Franz, J. R., & Sawicki, G. S. (2020). Cyclically producing the same average muscle-tendon force with a smaller duty increases metabolic rate. *Proceedings of the Royal Society B: Biological Sciences*, *287*(1933), 20200431. https://doi.org/10.1098/rspb.2020.0431

Blickhan, R. (1989). The spring-mass model for running and hopping. *Journal of Biomechanics*, *22*(11), 1217–1227. https://doi.org/10.1016/0021-9290(89)90224-8

Bonnaerens, S., Fiers, P., Galle, S., Derie, R., Aerts, P., Frederick, E., Kaneko, Y., Kaneko, Y., Derave, W., De Clercq, D., Segers, V. (2021). Relationship between duty factor and external forces in slow recreational runners. *BMJ Open Sport & Exercise Medicine*, *7*(1), e000996. https://doi.org/10.1136/bmjsem-2020-000996

Burnley, M., & Jones, A. M. (2018). Power–duration relationship: Physiology, fatigue, and the limits of human performance. *European Journal of Sport Science*, *18*(1), 1–12. https://doi.org/10.1080/17461391.2016.1249524

Cavanagh, P. R., & Williams, K. R. (1982). The effect of stride length variation on oxygen uptake during distance running. *Medicine and Science in Sports and Exercise*. *14*(1), 30–35. https://doi.org/10.1249/00005768-198201000-00006

da Rosa, R. G., Oliveira, H. B., Gomeñuka, N. A., Masiero, M. P. B., da Silva, E. S., Zanardi, A. P. J., & Peyré-Tartaruga, L. A. (2019). Landing-Takeoff asymmetries applied to running mechanics: A new perspective for performance. *Frontiers in Physiology*, *10*(415). https://doi.org/10.3389/fphys.2019.00415

Divert, C., Baur, H., Mornieux, G., Mayer, F., & Belli, A. (2005). Stiffness adaptations in shod running. *Journal of Applied Biomechanics*, *21*(4), 311–321. https://doi.org/10.1123/jab.21.4.311

Dorn, T. W., Schache, A. G., & Pandy, M. G. (2012). Muscular strategy shift in human running: Dependence of running speed on hip and ankle muscle performance. *The Journal of Experimental Biology*, *215*(11), 1944–1956. https://doi.org/10.1242/jeb.064527

Fletcher, J. R., Esau, S. P., & MacIntosh, B. R. (2009). Economy of running: Beyond the measurement of oxygen uptake. *Journal of Applied Physiology*, *107*(6), 1918–1922. https://doi.org/10.1152/japplphysiol.00307.2009

Folland, J. P., Allen, S. J., Black, M. I., Handsaker, J. C., & Forrester, S. E. (2017). Running technique is an important component of running economy and performance. *Medicine & Science in Sports & Exercise*, *49*(7), 1412–1423. https://doi.org/10.1249/MSS.0000000000001245

Forrester, S. E., & Townend, J. (2015). The effect of running velocity on footstrike angle–a curve-clustering approach. *Gait & Posture*, *41*(1), 26–32. https://doi.org/10.1016/j.gaitpost.2014.08.004

Hébert-Losier, K., Mourot, L., & Holmberg, H. C. (2015). Elite and amateur orienteers' running biomechanics on three surfaces at three speeds. *Medicine & Science in Sports & Exercise*, *47*(2), 381–389. https://doi.org/10.1249/mss.0000000000000413

Hinkle, D. E., Wiersma, W., & Jurs, S. G. (2002). *Applied statistics for the behavioral sciences*. Houghton Mifflin.

Hunter, J. P., Marshall, R. N., & McNair, P. J. (2004). Interaction of step length and step rate during sprint running. *Medicine and Science in Sports and Exercise*, *36*(2), 261–271. https://doi.org/10.1249/01.Mss.0000113664.15777.53

Lindorfer, J., Kröll, J., & Schwameder, H. (2020). Familiarisation of novice and experienced treadmill users during a running session: Group specific evidence, time and individual patterns. *Human Movement Science*, *69*, 102530. https://doi.org/10.1016/j.humov.2019.102530

Lussiana, T., Patoz, A., Gindre, C., Mourot, L., & Hébert-Losier, K. (2019). The implications of time on the ground on running economy: Less is not always better. *The Journal of Experimental Biology*, *222*(6), jeb192047. https://doi.org/10.1242/jeb.192047

Maiwald, C., Sterzing, T., Mayer, T. A., & Milani, T. L. (2009). Detecting foot-to-ground contact from kinematic data in running. *Footwear Science*, *1*(2), 111–118. https://doi.org/10.1080/19424280903133938

Malisoux, L., Gette, P., Delattre, N., Urhausen, A., & Theisen, D. (2022). Spatiotemporal and ground-reaction force characteristics as risk factors for running-related injury: A secondary analysis of a randomized trial including 800+ recreational runners. *The American Journal of Sports Medicine*, *50*(2), 537–544. https://doi.org/10.1177/03635465211063909

Minetti, A. E. (1998). A model equation for the prediction of mechanical internal work of terrestrial locomotion. *Journal of Biomechanics*, *31*(5), 463–468. https://doi.org/10.1016/S0021-9290(98)00038-4

Moore, I. S. (2016). Is there an economical tunning technique? a review of modifiable biomechanical factors affecting running economy. *Sports Medicine*, *46*(6), 793–807. https://doi.org/10.1007/s40279-016-0474-4

Moore, I. S., Jones, A. M., & Dixon, S. J. (2016). Reduced oxygen cost of running is related to alignment of the resultant GRF and leg axis vector: A pilot study. *Scandinavian Journal of Medicine & Science in Sports*, *26*(7), 809–815. https://doi.org/10.1111/sms.12514

Morin, J.-B., Dalleau, G., Kyröläinen, H., Jeannin, T., & Belli, A. (2005). A simple method for measuring stiffness during running. *Journal of Applied Biomechanics*, *21*(2), 167–180. https://doi.org/10.1123/jab.21.2.167

Novacheck, T. F. (1998). The biomechanics of running. *Gait & Posture*, *7*(1), 77–95. https://doi.org/10.1016/S0966-6362(97)00038-6

Ogueta-Alday, A. N. A., Rodriguez-Marroyo, J. A., & Garcia-Lopez, J. (2014). Rearfoot striking runners are more economical than midfoot strikers. *Medicine & Science in Sports & Exercise*, *46*(3), 580–585. https://doi.org/10.1249/MSS.0000000000000139

Patoz, A., Lussiana, T., Thouvenot, A., Mourot, L., & Gindre, C. (2020). Duty factor reflects lower limb kinematics of running. *Applied Sciences*, *10*(24), 8818. https://doi.org/10.3390/app10248818

Riazati, S., Caplan, N., & Hayes, P. R. (2019). The number of strides required for treadmill running gait analysis is unaffected by either speed or run duration. *Journal of Biomechanics*, *97*, 109366. https://doi.org/10.1016/j.jbiomech.2019.109366

Salo, A. I. T., Bezodis, I. N., Batterham, A. M., & Kerwin, D. G. (2011). Elite sprinting: Are athletes individually step-frequency or step-length reliant? *Medicine & Science in Sports & Exercise*, *43*(6), 1055–1062. https://doi.org/10.1249/MSS.0b013e318201f6f8

Subotnick, S. I. (1985). The biomechanics of running. Implications for the prevention of foot injuries. *Sports Medicine*, *2*(2), 144–153. https://doi.org/10.2165/00007256-198502020-00006

Tranberg, R., Saari, T., Zügner, R., & Kärrholm, J. (2011). Simultaneous measurements of knee motion using an optical tracking system and radiostereometric analysis (RSA). *Acta Orthopaedica*, *82*(2), 171–176. https://doi.org/10.3109/17453674.2011.570675

Van Hooren, B., Fuller, J. T., Buckley, J. D., Miller, J. R., Sewell, K., Rao, G., Barton, C., Barton, C., Bishop, C., Willy, R. W. (2020). Is motorized treadmill running biomechanically comparable to overground running? A systematic review and meta-analysis of cross-over studies. *Sports Medicine*, *50*(4), 785–813. https://doi.org/10.1007/s40279-019-01237-z

van Oeveren, B. T., de Ruiter, C. J., Hoozemans, M. J. M., Beek, P. J., & van Dieën, J. H. (2019). Inter-Individual differences in stride frequencies during running obtained from wearable data. *Journal of Sports Sciences*, *37*(17), 1996–2006. https://doi.org/10.1080/02640414.2019.1614137 van Oeveren, B. T., de Ruiter, C. J., Beek, P. J., & van Dieën, J. H. (2021). The biomechanics of running and running styles: A synthesis. *Sports Biomechanics*, 1–39. https://doi.org/10.1080/14763141.2021.1873411

Williams, K. R., & Cavanagh, P. R. (1987). Relationship between distance running mechanics, running economy, and performance. *Journal of Applied Physiology*, *63*(3), 1236–1245. https://doi.org/10.1152/jappl.1987.63.3.1236