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The biomechanics of running and running styles: a synthesis

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ABSTRACT

Running movements are parametrised using a wide variety of devices. Misleading interpretations can be avoided if the interdependencies and redundancies between biomechanical parameters are taken into account. In this synthetic review, commonly measured running parameters are discussed in relation to each other, culminating in a concise, yet comprehensive description of the full spectrum of running styles. Since the goal of running movements is to transport the body centre of mass (BCoM), and the BCoM trajectory can be derived from spatiotemporal parameters, we anticipate that different running styles are reflected in those spatiotemporal parameters. To this end, this review focuses on spatiotemporal parameters and their relationships with speed, ground reaction force and whole-body kinematics. Based on this evaluation, we submit that the full spectrum of running styles can be described by only two parameters, namely the step frequency and the duty factor (the ratio of stance time and stride time) as assessed at a given speed. These key parameters led to the conceptualisation of a so-called Dual-axis framework. This framework allows categorisation of distinctive running styles (coined 'Stick', 'Bounce', 'Push', 'Hop', and 'Sit') and provides a practical overview to guide future measurement and interpretation of running biomechanics.

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Biomechanics; kinematics; running; wearable technology; qualitative analysis

Introduction

Runners, coaches, clinicians, and scientists use wearable technology, optical systems and force transducers to quantify running. Typically, measurements are performed to either optimise running economy (Kyrolainen et al., 2001; Moore, 2016; Tawa & Louw, 2018; Van Hooren et al., 2019) or reduce injury risk (Brindle et al., 2019; Ceyssens et al., 2019; Goss & Gross, 2012). However, without considering the interdependencies and redundancies between parameters, false claims and misleading interpretations are readily made. The analysis of isolated parameters may explain in part why the conclusions regarding different kinematic and kinetic parameters and running economy are often contradictory (Van Hooren et al., 2020), and why the literature on the relationship between running technique and injury risk suffers from considerable inconsistencies (Brindle et al., 2019; Ceyssens et al., 2019; Mousavi et al., 2019). Furthermore, feedback from commercial applications is predominately based on isolated parameters.

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Unfortunately, the analysis, presentation and interpretation of isolated biomechanical parameters are also common in science, in spite of the recognition of several researchers that running styles cannot be described based on a single parameter (Black et al., 2018; Folland et al., 2017; Williams & Cavanagh, 1985). The effectiveness of feedback or studies based on isolated parameters should therefore be reconsidered.

In this review, we define a running style as a visually distinguishable movement pattern of a runner. It is likely that such a running style can be characterised by a set of parameters. Yet, the key parameters required to characterise the full spectrum of running styles remain to be determined. Identification of the minimal set of parameters and reaching consensus on their interpretation would help to clarify the existing literature on running biomechanics and facilitate future studies and feedback applications to design targeted interventions to improve running performance or reduce injury risk.

Therefore, this synthetic review aims to identify the (minimal) set of parameters that lead to a concise, yet, comprehensive description of the full spectrum of running styles. To this end, the interdependency between the parameters and their relationship with speed will be studied. Since the goal of locomotion is to transport the BCoM, we expect that fundamental differences between running styles will be apparent in the BCoM trajectory. In running, most of the body's movements occur in the sagittal plane. This is reflected by the relatively high force amplitudes in the vertical and the horizontal direction compared to the medio-lateral direction (Hamner & Delp, 2013; Nordin et al., 2017). Likewise, energy expenditure in running is predominately determined by movements in the sagittal plane. Arellano and Kram (2014) have estimated that runners use 80% of the net metabolic cost for bodyweight support and forward propulsion, 7% for leg swing, and only 2% for sideward balance control, leaving 11% of the variance unexplained. Therefore, we believe it is safe to assume that differences in running styles will be apparent in the sagittal plane trajectory of the BCoM. Reasonably accurate predictions of the BCoM trajectory in walking, hopping and running have been made using the spring-mass model (Blickhan, 1989; Coleman et al., 2012; Farley & Gonzalez, 1996). According to this model, which is in essence a mass on a weightless pogo Stick (the spring leg), the runner's mass, leg length and velocity determine the bouncing trajectory of the BCoM (Arampatzis et al., 1999; Blickhan, 1989; Brughelli & Cronin, 2008a). The spring-mass model and its assumptions are therefore discussed in detail later in this review to explain biomechanical interdependencies as well as the relevance of specific spatiotemporal parameters.

The approximately sinusoidal BCoM trajectory in the sagittal plane is characterised by the frequency of movement, vertical displacement during the stance and flight phase, and the landing/take-off asymmetry (Figure 1). These characteristics can be predicted from commonly used spatiotemporal parameters, including step frequency (SF), step length (SL), stance time (t_{stance}), flight time (t_{stance}), and vertical displacement (VD_{step}). The characteristics of the BCoM and the associated spatiotemporal parameters will be discussed systematically in this review to identify the key parameters to describe a running style. The BCoM movements result from forces exerted on the ground, which in turn result from joint moments in limbs and trunk (Figure 2). Consequently, spatiotemporal parameters, limb and trunk kinetics and ground reaction forces are interrelated mechanically. To provide a full overview, we subsequently discuss the relationship between limb and trunk kinematics and the spatiotemporal parameters. Ultimately, these discussions will culminate in a Dual-axis framework, which characterises different running styles based on the identified key parameters.

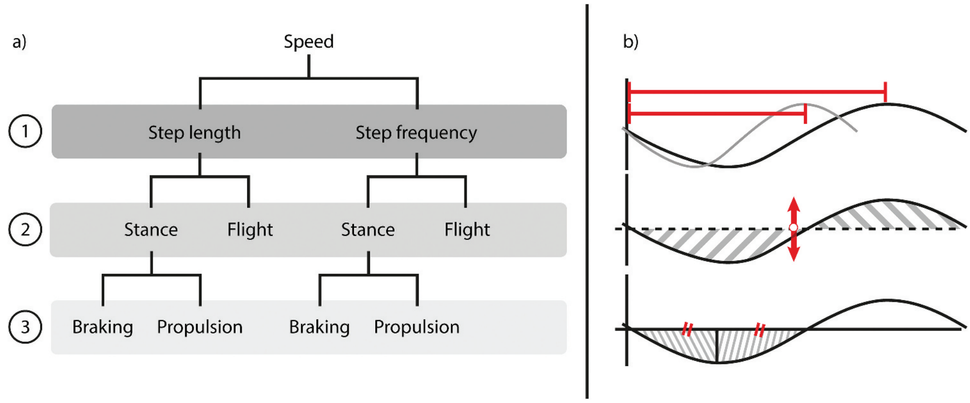

Figure 1. A) Hierarchical breakdown of the three levels and their subphases in relation to running speed. In panel b), a visualisation of each level. On the first level, the balance between step frequency and step length to determine movement speed. On the second level, the subdivision of a step into stance and flight phase, which further specifies the timing, horizontal distance and vertical displacement per phase. On the third level, the ratio between braking and propulsion phase. The ratios between the subphases at each level, together characterise the sinusoidal body centre of mass trajectory (BCoM). This review is structured accordingly.

Step frequency and step length

Between running styles, SF varies. SF can be readily observed and measured, and research has shown that runners can voluntarily modify SF at a given speed (Moore, 2016). SF modification relates to the kinematics and kinetics of the runner. Therefore, many scientists and practitioners measure SF to assess running style. Running speed is the product of SF and SL, implying that if running speed is held constant, SL and SF are inversely related (Figure 3, Appendix Equation 1). To undercut suggestions that either SF or SL can be changed independently at a given speed, it might be clearer to consider the relation between SF and SL as a ratio (SL/SF) that varies with speed. SF is simply a conversion of step time and can be calculated with SF = $60/(t_{stance} + t_{flight})$ (Appendix, Equation 2, 3). In words, SF is affected directly by changes in t_{stance} and t_{flight}. Since any change in GRF orientation or amplitude is likely to affect t_{stance} or t_{flight}, it can be expected that most, if not all, parameters directly or indirectly affect the SL/SF ratio.

Runners are commonly advised to run at 180 steps per minute (e.g., Daniels, 2013). This advice supposes that SF should be consistent across running speeds and individuals. Other common assumptions are that better runners run with higher SF's and that running with higher SF's reduces injury risk (Daniels, 2013; Lieberman et al., 2015). However, evidence to support these assumptions is equivocal. The assumption that SF is constant across running speeds seems to be invalid given that numerous studies have shown that both SL and SF have a positive curvilinear relationship with speed (Bailey et al., 2017; Mercer & Dolgan, 2008; Le Meur et al., 2013; Nummela et al., 2007; Ogueta-Alday et al., 2014; Padulo et al., 2012; Sinning & Forsyth, 1970; Van Oeveren et al., 2019;

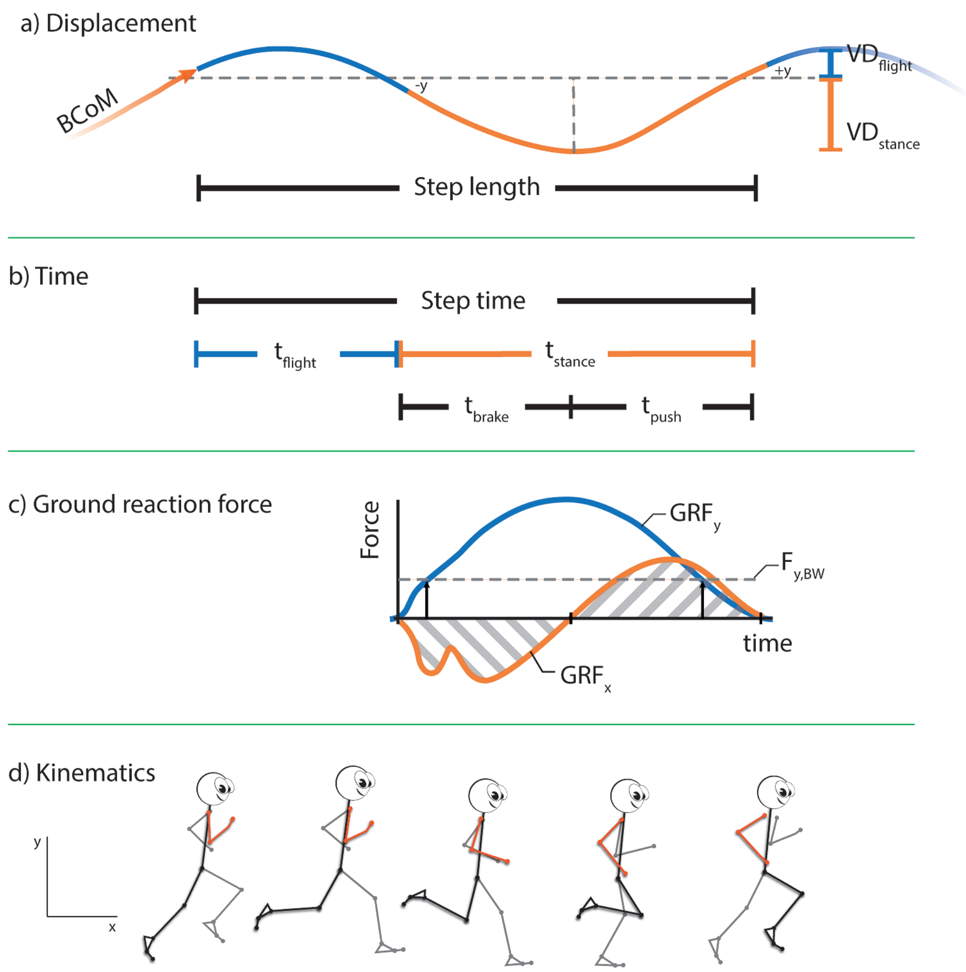

Figure 2. Overview of the parameters discussed in this review. The BCoM trajectory in place (panel a) or time (panel b) results from the ground reaction force (GRF, panel c) following from joint moments in limbs and trunk (panel d). Consequently, the spatiotemporal parameters, limb and trunk kinetics and ground reaction forces are interrelated mechanically. The landing/take-off asymmetry can be assessed by dividing the stance phase in a braking phase and a propulsion phase using the sign change of the horizontal GRF (GRF_x). Typically, for speeds below 20 km/h, $t_{brake}<t_{prop}$ and take-off height>touch-down height as depicted with -y and +y. Based the vertical GRF (GRF_y) the effective stance time can be determined. As visualised in panel c, the effective stance time is defined by the time where the GRF_y exceeds the GRF_y required to support the body weight ($F_{y,BW}$).

Weyand et al., 2000). SL increases more rapidly at speeds below ~20 km/h and SF increases more rapidly at speeds above ~20 km/h (Figure 3.a). The flattening of the SL curve at a certain speed may suggest that SL limits a further increase in speed. For speeds up to 25 km/h, the ankle plantar flexors, soleus and gastrocnemius contribute greatly to vertical forces and thus the increase in SL (Dorn et al., 2012). At speeds above 25 km/h, the strategy shifts to bringing the swing leg quickly forward using the hip musculature, iliopsoas, gluteus maximus and hamstrings to increase SF further (Dorn et al., 2012). An early shift towards high SF at relatively low speeds may indicate an inability of the runner

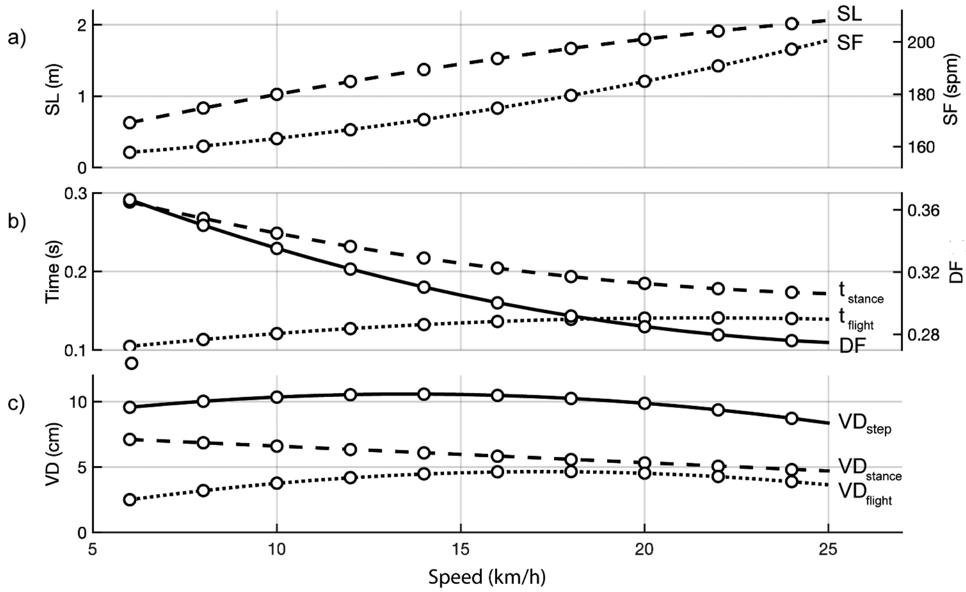

Figure 3. Parameter changes across running speeds. Panel a): step length (–, SL, in metres) and step frequency (:, SF, in steps per minute). Panel b): Duty Factor (—, DF), stance time (–, t_{stance}), flight time (t_{flight}) in seconds. Panel c): Measured vertical displacement (—, VD_{step}) divided in calculated vertical displacement during stance phase (–, VD_{stance}) in cm (see Appendix, Equation 19) resulting in vertical displacement during flight phase (:, $VD_{flight} = VD_{step}—VD_{stance}$). The relations presented are based on data (captured with a Garmin Forerunner 620) derived from 470 training sessions of an experienced endurance runner (5 km in 16:20) (Van Oeveren et al., 2019).

to generate power with (or via) the calf muscles and the runner would then be more reliant on hip musculature. Hence, the shift in SL/SF ratio across running speeds may reveal individual limitations and strengths. Note that such differences may only be revealed when the individuals in question are challenged to run at high speeds.

Once corrected for speed, individual differences in the SL/SF ratio still exist. Individual characteristics such as leg length, body mass and age have been shown to partly explain individual differences in SF's (Van Oeveren et al., 2019). Evidence for SF differences related to performance levels is mixed. Remarkably high SF's have been found in highly trained runners (193 spm, 17.5 km/h) compared to well trained (181 spm, 17.9 km/h) and untrained runners (178 spm, 16.7 km/h) (Slawinski & Billat, 2004). However, Preece et al. (2019) did not find significant differences in SF's between high performance and recreational runners after having corrected SF for leg length (11.9–20.2 km/h). Also, in training data of 256 runners, performance and years of experience did not contribute significantly to the prediction of SF, in contrast to (estimated) leg length, body mass and age (Van Oeveren et al., 2019). Several studies reported even lower SF's in faster runners (8–20 km/h) (Da Rosa et al., 2019) and lower SF's in elite marathon runners (161–165 spm, 14–18 km/h) compared to amateur runners (170–177 spm) (Padulo et al., 2012). Together these results suggest that more experienced and faster runners are just as likely, if not more so, to run with lower SF's instead of higher SF's.

The relationship between SF and injury incidence is indirect. Several authors have found an association between SF and potential injury-related kinetic variables such as impact forces, high tibial accelerations or high joint forces (e.g., Heiderscheit et al., 2011; Hobara et al., 2012; Lenhart et al., 2014; Lieberman et al., 2015; Willson et al., 2015). However, only one study found a direct relationship between SF and injury risk (Luedke et al., 2016). While in a recent large-scale study, injury history, experience and performance were not associated with SF at given speeds (Van Oeveren et al., 2019).

Several studies have shown that both high and low imposed SF's increase the (aerobic) energy cost estimated with gas exchange equipment and heart rate monitors (Cavanagh & Williams, 1982; Farley & Gonzalez, 1996; I. Hunter et al., 2017; I. Hunter & Smith, 2007; Mercer & Dolgan, 2008; De Ruiter et al., 2019, 2013; Snyder & Farley, 2011; Van Oeveren et al., 2017). Most runners seem to self-optimise the SL/SF ratio (I. Hunter et al., 2017), except for novice runners (De Ruiter et al., 2013; Van Oeveren et al., 2017) and some experienced runners (De Ruiter et al., 2020). Based on the current literature, it is safe to assume that runners with sufficient running experience mostly have adopted a running style with low energy consumption through a process of self-optimisation (Cavanagh & Williams, 1982; I. Hunter & Smith, 2007; Moore et al., 2012; Van Oeveren et al., 2019). The higher energy consumption with imposed high SF can be explained by the higher costs to move the limbs (e.g., internal work) (Cavagna & Kaneko, 1977), whereas low SF may increase the work done to move the BCoM (e.g., external work). Cavagna et al. (1991) suggested that SF at a given speed is chosen as a compromise between minimising average power over the step (high SF) and the average power over the positive work phase (propulsion-average power) (large SL). On this account, the average power would be limited by the oxygen uptake or aerobic power, while the propulsion-average power would be limited by the anaerobic capacity. In practice, part of the work done to move the limbs can be (re)used to move the BCoM (Willems et al., 1995). Therefore, the demarcation between internal and external work is complex to establish with high precision. The possibility to transfer the energy of previously initiated limb movements (kinetic and potential energy) between subsequent phases implies that high or low SL/SF ratios may not necessarily indicate inefficiency. Since both high and low SF's resulted in an increased aerobic energy consumption, the limits may not only be determined by the aerobic and anaerobic power production, but the efficiency at a certain SL/SF ratio may also depend on the individuals' ability to store and reuse the energy that is not directly used to propel the BCoM. Individual preferences may thus depend on the reuse of work done to move the limbs and the efficiency with which the runner can generate propulsive bursts during the short t_{stance}.

Theoretically the SL/SF ratio reflects the proportion of the work done to move the limbs relative to the work done to accelerate the BCoM directly and provides crucial information about the BCoM trajectory. To interpret the SL/SF ratio, running speed should be taken into account. Moreover, the shift in SL/SF ratio with speed may reveal individual limitations and strengths. Even though experienced runners are likely to have energetically optimised their SL/SF ratio, differences in running styles between experienced runners still exist. The SL/SF ratio has limitations when it comes to describing the running style. Imagine two runners of similar stature running at the same speed with the same SF. Both can have distinctive running styles in that one may be running with a short t_{stance} + long t_{flight}, and the other may be running with a long t_{stance} + short t_{flight}. We can conclude that the SL/SF ratio by itself is insufficient to fully describe a running style, and additional parameters are thus required. The possible variations in the ratios between t_{stance} and t_{flight} may explain the mixed and scarce evidence for a direct relationship between SF and injury incidence, performance and experience.

Stance phase and flight phase

Once the SL/SF ratio has been defined, a logical next step in characterising the sinusoidal BCoM trajectory is to determine the vertical position around which the BCoM oscillates (Figures 1 and 2). This can be accomplished by subdividing one step into a stance and a flight phase. These phases split the step horizontally, along the time axis, into t_{stance} and t_{flight} and vertically, along a distance axis, into VD_{stance} and VD_{flight}. The ratio between the stance and flight phase allows estimating vertical stiffness (Appendix, Equation 16–23).

Stance time

The time component t_{stance} is in itself relevant since a runner can only produce forces to propel the BCoM during the stance phase. For running speeds between 8 and 20 km/h, t_{stance} has a strong negative curvilinear relation with speed with values typically ranging between 0.34 and 0.18 seconds (Carrard et al., 2018; Chapman et al., 2012; Clark & Weyand, 2014; Concejero et al., 2013; Dorn et al., 2012; Forrester & Townend, 2015; García-Pinillos et al., 2018; Hoyt et al., 2000; Nummela et al., 2007; Pavei et al., 2017; Roche-Seruendo et al., 2018; Da Rosa et al., 2019; De Ruiter et al., 2016; Weyand et al., 2000) (Figure 3). Due to the reduction in t_{stance} with increasing speed, the GRF curves are compressed along the time axis, with increased force amplitudes to attain a sufficient impulse to maintain speed ($I = \int(F\Delta t)$ (Clark & Weyand, 2014; Dorn et al., 2012; Hamner & Delp, 2013; Nummela et al., 2007; Weyand et al., 2000). Weyand et al. (2010) concluded that running speed is limited by the ability to generate the forces required to attain the running speed during a short t_{stance}, not by the maximum force that the runner can exert on the ground. If a runner's force production is limited, as Weyand et al. (2000), (2010) suggested, then t_{stance} should be regarded mainly as a consequence of running speed where the horizontal velocity of the BCoM above the ground limits t_{stance}. Especially in attaining sprinting speeds (~25 km/h), the ability to generate forces during short stance times seems to be the limiting factor.

Nummela et al. (2007) stated that the ability of fast force production is essential for both running economy and attaining high maximal speeds, and that t_{stance} is the only factor directly related to both running economy and maximal running speed. In conformation of this claim, it was found that experienced sprinters have shorter t_{stance} than less experienced runners while running at the same speeds (Chapman et al., 2012; Clark & Weyand, 2014; Cunninghan et al., 2013). However, within an 8–20 km/h speed range t_{stance} did not yield significant differences between runners of different performance levels (Gómez-Molina et al., 2017; Preece et al., 2018; Da Rosa et al., 2019). Interestingly, these studies found significant differences in t_{flight} and effective t_{stance}. The term 'effective' in this context refers to the part under the GRF curve where the vertical GRF exceeds the force required to support the body weight (Figure 2). Overall, it seems that t_{stance} is relatively constant across performance levels up to speeds of 20 km/h, while individual differences in t_{stance} may be observed at higher speeds, possibly due to the inability of lesser runners to generate high braking and propulsive forces within a short time.

Consistent with the findings of Nummela et al. (2007), also other studies showed that shorter t_{stance} corresponded to a better running economy in mixed groups of runners (Folland et al., 2017; Tam et al., 2018). One study even found a high correlation between t_{stance} and running economy in a group of elite female runners, but in this study the effects of speed were ignored, which obscures the interpretation of this result (Mooses et al., 2018). In contrast, within a group of elite runners, no differences in t_{stance} were found despite differences in running economy (Santos-Concejero et al., 2017). Within a group of habitual runners running at 14 km/h, longer t_{stance} was even associated with a better running economy (Di Michele & Merni, 2014). These mixed results with regard to the relation between t_{stance} and running economy may reflect individual differences in muscular properties.

There are only a limited number of studies in which t_{stance} is corrected for body size. Yet, the relation of leg length with the time component t_{stance} is not difficult to understand. At a given (horizontal) speed, t_{stance} can be derived from the horizontal distance covered by the BCoM during the stance phase ($t_{stance} = d_{stance} \cdot v_x$, Appendix, Equation 6). Imagine a long-legged runner with the same hip angle at touch-down and take-off as a short-legged runner. At the same speed, the horizontal distance covered by the BCoM distance during the stance phase of the long-legged runner will be larger and t_{stance} will be longer than in the short-legged runner (Whitcome et al., 2017). Since this relationship between leg length and t_{stance} is linear, t_{stance} can be expressed as a ratio of leg length (L_0/t_{stance}). Alternatively, Chapman et al. (Chapman et al., 2012) normalised t_{stance} to standing height instead of using leg length. Preece et al. (2018) used the conventions provided by Hof (1996), which entail dividing t_{stance} by $\sqrt{(L_0/g)}$ (Appendix, Equation 10). Both methods allow interindividual comparisons with regard to running style, but the method of Hof (1996) might be more correct from a mechanical point of view. Note that, for a given speed and after correction for leg length, the residual interindividual variation in t_{stance} is relatively small and possibly hard to quantify or modify voluntarily.

Flight time

Some runners seem to hardly touch the ground, while others appear to have difficulty to become airborne. Indeed, marked differences exist in the time component t_{flight} between runners. For example, high-performance runners distinguish themselves from recreational runners by having longer t_{flight} at given speeds (García-Pinillos et al., 2019; Padulo et al., 2012; Preece et al., 2018; Da Rosa et al., 2019). Chapman et al. (Chapman et al., 2012) found shorter t_{flight} in female than male runners. The same was found by Barnes et al. (2014), who also found a strong correlation between t_{flight} and running economy in female runners, but not in male runners. Age may play a role as well, given that older runners have shorter t_{flight} than younger runners at given speeds (Cavagna et al., 2008; Pantoja et al., 2016). Overall, there seems to be consensus that differences between runners (performance, gender and age) are reflected in t_{flight}.

The manner in which t_{flight} increases with running speed is described by a positive curvilinear relationship (Figure 3) (Carrard et al., 2018; Concejero et al., 2013; García-Pinillos et al., 2018; Roche-Seruendo et al., 2018). Typically, t_{flight} ranges between ~100 to 150 ms. Within 7 to 20 km/h, t_{flight} is shorter than t_{stance}. At high speeds, t_{flight} seems to reach a maximum (Dorn et al., 2012; Mann et al., 2015; Nummela et al., 2007; Pavei et al., 2017; Roche-Seruendo et al., 2018; Da Rosa et al., 2019; Weyand et al., 2000). In consequence, since t_{stance} decreases as a function of speed, t_{flight} exceeds t_{stance} at 'sprint' speeds around ~25 km/h (Nemtsev et al., 2015; Weyand et al., 2000).

Once the runner is off the ground, the body behaves like a ballistic object. Accordingly, due to the gravitational force, the BCoM describes a parabolic trajectory (Blazevich, 2017). Therefore, common laws of ballistic motion can be applied to estimate the vertical and horizontal displacement (VD_{flight} and SL) during the flight phase when t_{flight} is known (Appendix, Equation 11–15). Given a constant gravitational acceleration and assuming a constant force due to air resistance, the distance covered during the flight phase (d_{flight}) depends on the take-off angle (θ_{off}), the velocity at take-off, and the BCoM height at take-off relative to the height at touch-down (Blazevich, 2017; Ishimura & Sakurai, 2016; J. Hunter et al., 2004). Practically, this implies that surface inclination and air resistance would influence t_{flight} at least to some degree (Padulo et al., 2012).

For a given speed, t_{flight} depends predominantly on the take-off angle. Optimisation of the take-off angle would result in a maximal flight distance. Take-off angle might be even more informative than t_{flight} as it both provides information on horizontal and vertical displacement. Take-off angles have been calculated for sprint running (Cunha et al., 2002; Ishimura & Sakurai, 2016) and the long jump (Bridgett & Linthorne, 2006). Unfortunately, studies focusing on take-off (or touch-down) angles during constant speed running are scarce. As far as we know, only one study calculated a 'stride angle' and found a strong correlation between this stride angle and running economy (Santos-Concejero et al., 2017). It should be noted that since the angle was calculated as the arctangent from step length and height (gt_{swing} 2/8, Appendix, Equation 14), it seems more appropriate to label it as 'step angle'. Also, Garmin ® sports watches provide a metric that reflects a push-off angle called vertical ratio (Garmin Ltd. or Subsidiaries, 2019). The vertical ratio is calculated by the ratio of VD_{step} and SL (Appendix, Equation 15). Theoretically, take-off angles, leg angles at toe-off or push-angles could provide insight in both the vertical and horizontal displacement, but, as said, empirical studies measuring take-off and touch-down angles are rare.

The interindividual differences in t_{flight} and its associations with performance, RE, gender and age indicate that t_{flight} reveals essential information about running styles. A longer t_{flight} gives the runner time to move the legs forward, which reduces energy consumption required for leg movements (internal work), especially at high constant running speeds. In order to bring about a flight phase, the runner needs to generate a force that at least exceeds the force required to support body weight. The flight phase therefore reflects the runner's ability to generate power during the relatively short t_{stance}. However, without insight into the forward displacement, a runner might as well be jumping in place. When SL and t_{flight} are analysed together, it becomes more likely that different running styles can be distinguished.

Vertical displacement

The BCoM of a runner oscillates within a range of approximately 6 to 10 cm (Da Rosa et al., 2019; Gullstrand et al., 2009; Halvorsen, 2012). Imagine a runner who is running with 170 steps per minute. After one hour this runner might have displaced his or her BCoM vertically by 1020 m. It is sometimes suggested that vertical displacement over a step (VD_{step}) should be minimised to avoid unnecessary work against gravity (Saunders et al., 2004). Indeed, running with exaggerated VD_{step} resulted in increased energy cost (Tseh et al., 2008). However, a runner can reuse part of the potential and kinetic energy gained during the flight phase in the subsequent landing (Cavagna et al., 1977). To this end, energy is absorbed during the braking phase and returned during the propulsion phase, which requires a certain VD_{stance}. Furthermore, the vertical displacement during the flight phase (VD_{flight}) reduces the (internal) work needed to bring the leg forward. When SF increases, VD_{step} typically decreases (Gullstrand et al., 2009; Slawinski & Billat, 2004). The resultant VD_{step} is therefore not straightforward to interpret, and a runner cannot simply minimise VD_{step} as is sometimes suggested (Adams et al., 2018).

It is well known that the BCoM does not oscillate symmetrically around an equilibrium point. Further subdivision of VD_{step} into vertical displacement during stance (VD_{stance}) and flight phases (VD_{flight}) is therefore necessary (Cavagna, 2006, 2009; Da Rosa et al., 2019). Over a range of speeds, approximately 2/3rd of the VD_{step} occurs during t_{stance} and 1/3rd during t_{flight} (Da Rosa et al., 2019). The VD_{stance}/VD_{flight} ratio is relatively stable, but not constant over speeds. At low running speeds (~7-12 km/h), t_{flight} increases more than t_{stance} (Carrard et al., 2018; Concejero et al., 2013; Gómez-Molina et al., 2017) and VD_{flight} accordingly increases more than VD_{stance} (Cavagna, 2006, 2009; Cavagna et al., 2008; Da Rosa et al., 2019; Slawinski & Billat, 2004). VD_{step} decreases thereafter between ~12 and 22 km/h, due to the rapid increase of SF relative to the SL (Gullstrand et al., 2009; Slawinski & Billat, 2004). As a result, VD_{stance} and VD_{flight} combined reach a maximum VD_{step} between 10 and 15 km/h (Chapman et al., 2012; Nummela et al., 2007; Da Rosa et al., 2019) (Figure 3). Correspondingly, the vertical GRF has an inverted U-shaped relationship with running speed (Schache et al., 2014; Weyand et al., 2000). Also, the energy cost has an inverted U-shaped relationship with running speed, where the most economical running speed was found at around 13 km/h (Black et al., 2018; Carrard et al., 2018). It is conceivable that there is a direct association between VD_{step} and running economy that stems from the balance between internal and external work. In that case, VD_{step} could, for example, be used to determine the optimal marathon tempo and therefore a better understanding of VD_{step} may result in some practical applications. In any case, it is clear that conclusions regarding VD_{step} depend on the speed range measured, which explains some of the discrepancies in literature on this topic. Furthermore, it is important for the interpretation of VD_{step} to realise that substantial individual differences in the VD_{step}–speed relationship can be expected since the speed at which VD_{step} reaches its maximum depends on both the VD_{flight} and VD_{step}.

VD_{step} in walking and running is the result of several interacting mechanisms, which are explained by the spring-mass model and elaborations thereof. To what extent the mechanisms play a role in the resultant VD_{step} strongly depends on running speed (see Figure 4) and running style (Lee & Farley, 1998). VD_{flight} is relatively straightforward to understand since it results from the take-off angle and take-off velocity as discussed previously for t_{flight}. VD_{flight} results from the force generated during the stance phase and therefore relates to VD_{stance}. There are two mechanisms that explain VD_{stance} changes with speed. The inverted pendulum principle (Figure 4.a) predicts that the BCoM reaches a maximum height at midstance. This geometrical increase of VD_{stance} plays an essential role in walking (Lee & Farley, 1998), but in running the BCoM reaches its lowest point halfway the stance phase and its highest point during the flight phase, which can be explained by adding spring properties to the model (Figure 4.b) (Blickhan, 1989). The combination of the inverted pendulum model and the vertical spring model is called the spring-loaded inverted pendulum (or SLIP) model. The two mechanisms as combined in the SLIP model have opposite effects on VD_{stance}. Other mechanisms play a role as well. For example, in one model it was shown that the translation of the CoP under the foot reduces VD_{step} when leg stiffness is not adjusted accordingly (Bullimore & Burn, 2006). Additional effects in VD_{step} can be expected from the BCoM landing-take-off height difference (Cavagna, 2006), partly effected by the effect of leg retraction, that is, the backward rotation of the swing leg before initial contact (e.g., Karssen et al., 2011, 2015; Seyfarth et al., 2003). Leg retraction is likely to affect the BCoM height at initial contact (Figure 4.c), the duration of t_{stance} and the (related) leg stiffness.

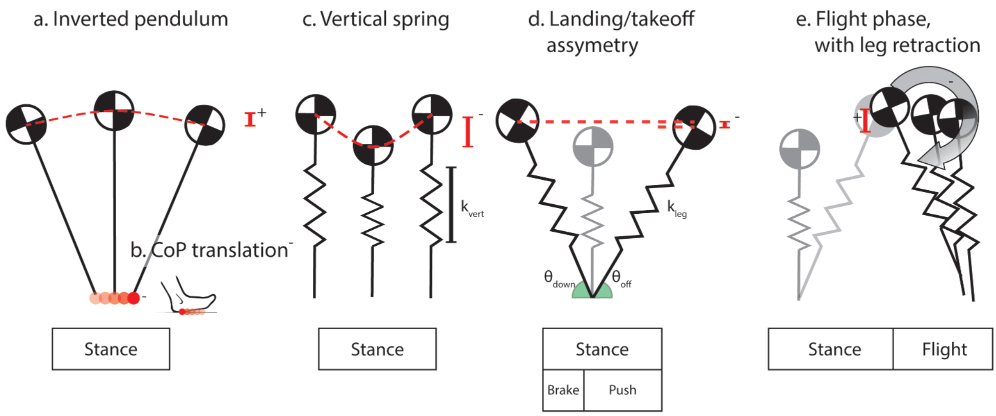

Figure 4. The effects of various spring-mass model mechanisms on the vertical displacement during the stance phase (VD_{stance}). The contribution of the mechanisms (a-e) to the resultant VD_{stance} (vertical red bars) is speed dependent and varies between individuals. a) The inverted pendulum model predicts that the BCoM will elevate during the stance phase. This elevation is relatively large with longer stance times (t_{stance}) as common at lower speeds. b) Typically, with longer t_{stance} the CoP translates from heel to toe (red dots). Such CoP translation affects the leg compliance and has been found to contribute to a reduction of VD_{stance}. c) The vertical spring stiffness (K_{vert}) predicts that the leg-spring is loaded during stance phase and the BCoM is lowered during stance. d) The spring-loaded inverted pendulum model (SLIP model) consisting of a combination of a and b. Changes in the leg angle due to speed are taken into account, which allows the calculation of leg stiffness (K_{leg}). The spring-leg is commonly defined by a straight line between the centre of pressure (CoP) and the BCoM. Alternatively, bony landmarks (for example, the ankle joint to trochanter major) have been used to define the spring-leg. Due to differences in, amongst others, the touch-down angle (θ_{down}) and take-off angle (θ_{off}), the landing take/off does not occur symmetrically, resulting in a lower BCoM at the end of the stance phase. e) The flight phase increases VD_{flight}. While leg retraction in the final flight phase increases the height of BCOM at landing.

Lumping the effects of the inverted pendulum, the spring loading and the flight phase on vertical displacement together in a single parameter (VD_{step}) renders its interpretation, let alone its manipulation (Adams et al., 2018; Eriksson et al., 2011; J. Hunter et al., 2004), rather complicated. Since vertical displacement in running is partly explained by the spring properties of the leg, further insight into stiffness is required to further clarify the interpretation of vertical displacement.

Vertical stiffness

The spring properties of the muscle tendon complex are believed to play a crucial role in the efficiency of running compared to walking. Therefore, the mechanics of the stance leg are modelled as a spring. In general terms, a linear spring with a constant stiffness (k) will produce a force (F) proportional to the displacement (y) from its equilibrium length, which is known as Hooke's law ($-F = y.\ k$, Appendix, Equation17).

It should be realised that in practice, it is difficult to distinguish cause and effect of the variables in the linear spring model, especially when geometrical effects are taken into account. To explain this further, a long t_{stance} will geometrically result in a large excursion of the inverted pendulum (Figure 4.a). In addition, a long t_{stance} will, most likely, correspond to a lower GRF when impulse is maintained. For a long t_{stance} the lower GRF and increased (upward) excursion of the inverted pendulum would result in a low VD_{stance} if we assume that the stiffness (k) is kept constant. The expected lower vertical component of the GRF would thereby result in a reduced VD_{flight}. A long t_{stance} in combination with a short t_{flight} will therefore result in a low vertical displacement. There seems to be consensus that better runners run with a relatively short t_{stance} and long t_{flight} (García-Pinillos et al., 2019; Preece et al., 2018; Da Rosa et al., 2019). To generate sufficient force for a flight phase it is necessary to 'compress' the leg spring. Therefore, it is possible to observe more VD_{stance} in better runners. If leg stiffness would be increased a lower VD_{stance} would be necessary to generate the same force. However, a higher leg stiffness during running would also shorten t_{stance}, thereby resulting in opposing effects on VD_{stance} due to less excursion of the inverted pendulum and a lower GRF. Overall, if we take speed into account it seems that VD_{step} in better runners is more likely to be high compared to less proficient runners. Any generic suggestions to minimise VD_{step} are therefore dubious, in spite of the common assumption that VD_{step} should be minimised.

In accordance with the general linear spring formula two conventions provide the basis for commonly used spring-mass models to calculate stiffness: vertical stiffness (K_{vert}) and leg stiffness (K_{leg}) (Brughelli and Cronin, 2008b). Vertical stiffness is defined as the ratio of maximal force to $VD_{stance,}$ ($K_{vert} = F_{max}/VD_{stance}$, Appendix, Equation 21) (Farley & Gonzalez, 1996; Morin et al., 2005; Brughelli & Cronin, 2008a, 2008b). Leg stiffness is defined as the ratio of the maximal force to the maximum leg compression during the stance phase ($K_{leg} = F_{max}/\Delta L$, Appendix, Equation 18, 22, 23) (Farley & Gonzalez, 1996). K_{vert} changes substantially with running speed since the leg angle of attack (Figure 4.d, θ_{down}) is speed dependent. To overcome this problem, K_{leg} corrects for the speed dependency by taking changes in effective leg length ΔL into account. Where leg length is commonly defined as the distance between the centre of pressure and the BCoM (see Figure 4 caption for further details). To estimate ΔL the horizontal distance between BCoM and the point of initial contact are used $d_{BCoM\text{-}ic} = v_x.t_{stance}/2$, Appendix, Equation 8). Notice that this correction takes the inverted pendulum principle into account. With this correction K_{leg} is relatively stable across speeds (Arampatzis et al., 1999; García-Pinillos et al., 2019; Morin et al., 2007). The difference between K_{vert} and K_{leg} underscores the difference between stiffness when hopping in place and stiffness during forward motion. For the estimation of the effective leg length in the K_{leg} models there are additional issues to consider as noticed under the paragraph Vertical displacement. The leg is placed under a steeper (closer to 90°) angle with the surface at initial contact relative to take-off (Cunha et al., 2002; Maykranz & Seyfarth, 2014) and the knee bends at initial contact (Lin et al., 2014). The effective leg length is further affected by the excursion of the CoP under the foot (Bullimore & Burn, 2006; Morin et al., 2007). Also, the CoP excursion and the effective leg length may change when runners tend to land more on the fore-foot at higher speeds (Breine et al., 2014; Clark et al., 2014; Lai et al., 2020). Lastly, pendulum effects of the segmented swing-leg on stiffness should be considered (Clark et al., 2017; Kugler & Janshen, 2010; Maykranz & Seyfarth, 2014; Rashty et al., 2014). Together, this would result in a complex model to estimate leg stiffness. As far as we know, these issues have not been incorporated into a single model to be tested across a range of speeds in various running styles. Nevertheless, faster runners seem to have higher vertical stiffness (Barnes et al., 2014; García-Pinillos et al., 2019; Da Rosa et al., 2019). In line with these results, experienced sprinters had less knee flexion during the stance phase and a shorter t_{stance} compared to middle- and long-distance runners at speeds from 11 to 21 km/h (Cunninghan et al., 2013).

The calculations for stiffness strongly depend on the ratio between t_{stance} and t_{flight}. In addition, body mass, gravitational acceleration, leg length and running speed are taken into account (Morin et al., 2005). Likewise, Duty factor (DF) is calculated as the ratio of t_{stance} over stride time (DF = $t_{stance}/(2 \cdot t_{stance}/(2 \cdot (t_{stance}+t_{flight}))$, Appendix, Equation 16) (Blum et al., 2009; Forrester & Townend, 2015; Mann et al., 2014; Vernillo et al., 2017) and therefore DF carries similar information as the stiffness models. DF is a convenient measure to (visually) identify running styles as a short t_{stance} with long t_{flight} can be visually verified by an observer. DF is further suitable for making interindividual comparisons as it is a dimensionless ratio, and does not rely on many assumptions. In walking, the stance phase is longer than half the stride time, and thus the DF exceeds 0.5. In running, the DF decreases nonlinearly from 0.45 at very low running speeds to 0.28 at ~22 km/h (Forrester & Townend, 2015). For running speeds up to ~25 km/h the relation $t_{flight} < t_{stance}$ holds (Carrard et al., 2018; Chapman et al., 2012; Concejero et al., 2013; Dorn et al., 2012; Gómez-Molina et al., 2017; Hanley & Mohan, 2014; Mann et al., 2015; Nummela et al., 2007; Pavei et al., 2017; Roche-Seruendo et al., 2018; Weyand et al., 2000). A too low DF can be uneconomical given the high muscle activation during short t_{stance}, and a high DF may indicate wasteful mechanical work due to braking-propulsion accelerations (Usherwood, 2016). For a constant mechanical spring, t_{stance} would equal t_{flight}. In practice, t_{stance} is not equal to t_{flight} due to varying muscular forces during the stance phase. Therefore, a more 'symmetrical rebound', in which t_{stance} is closer to t_{flight}, is believed to indicate better usage of elastic properties of the muscular-tendon complex (Cavagna, 2006, 2010). Consistent with this belief, better runners have shorter t_{stance} and longer t_{flight} compared to less proficient runners (Concejero et al., 2013; Folland et al., 2017; Da Rosa et al., 2019; Santos-Concejero, 2014). Folland et al. (2017) found that DF, a minimal horizontal pelvis velocity (braking), shank touch-down angle, and trunk forward lean explained 31% of the variability in season-best times. In the same study, running economy was for 39% explained by VD_{stance} normalised to body height, minimum knee flexion during ground contact, and minimum horizontal pelvis velocity (Folland et al., 2017). Note that DF did not contribute significantly to the regression model for running economy. However, minimum knee flexion and VD_{stance} provide information about vertical stiffness, just as DF does.

In sum, VD_{step} is an accessible parameter that is used in feedback applications and scientific studies, but is difficult to interpret given that opposing effects are lumped into a single parameter. Instead, the ratio between VD_{stance} and VD_{flight} provides insight into the runner's ability to exploit elastic properties during running. To this end, stiffness parameters can be used. In order to categorise running styles with corresponding motions, the DF may be more straightforward. However, DF alone is not sufficient to distinguish two runners with the same stature that run in a different fashion, because both a short t_{stance} + short t_{flight} and a long t_{stance} + long t_{flight} could theoretically result in the same DF. Therefore, additional information about forward displacement is required, which can be provided by SF (or SL) at a given speed.

Landing/take-off asymmetry

Up to this point, we have assumed that the BCoM follows a symmetrical sinusoidal path during the stance phase, similar to a frictionless bouncing ball. However, it is known that due to varying muscle activation, the landing/take-off does not necessarily occur symmetrically in human running. The landing/take-off asymmetry may therefore provide additional information about variations in running styles. To this end, the stance phase is subdivided into a braking (t_{brake}) and a propulsion phase (t_{prop}) based on the sign change of the horizontal GRF component (Figures 1 and 2). For a constant stiffness spring absolute F_{brake} equals F_{prop} and t_{brake} equals t_{prop}. Assuming that the geometrical aspects remain constant, a change in the t_{brake}/t_{prop} ratio would imply that the runner changes the spring properties of the leg by means of muscle activation. Just like when t_{stance} and t_{flight} were equal as previously discussed, a more symmetrical landing/take-off may indicate that the runner is making more use of the elastic 'spring' properties of the muscle-tendon complexes (Cavagna, 2006, 2010). Since the impulse vectors during landing and take-off are oblique to the surface, a landing/take-off asymmetry could be apparent in the horizontal and vertical GRF amplitudes, or in the timing variables (t_{brake} vs t_{prop}).

When a runner accelerates, the propulsion impulse exceeds the braking impulse (Van Caekenberghe et al., 2013). At constant speed, ignoring air drag and friction, the braking impulse and propulsion impulse cancel each other out, resulting in a zero-net change of the horizontal velocity (Cavagna, 2010), i.e., $\Delta I = (-F_{x,brake} \cdot t_{brake}) + (F_{x,prop} \cdot t_{prop}) = 0$ (Appendix, Equation 24). In constant speed running up to ~14 km/h, $t_{brake} < t_{prop}$. The average GRF during propulsion is thus lower than during braking at these speeds, which is compensated by a longer t_{prop}. At higher speeds, t_{brake} approaches t_{prop}, mostly because t_{prop} becomes shorter (Cavagna, 2006, 2010; Da Rosa et al., 2019). The horizontal force and time are therefore coupled in constant speed running. For example, reducing t_{brake} will coincide with an increased amplitude of $\overline{F}_{x,brake}$. Alternatively, a runner with a large $\overline{F}_{x,brake}$ and without changes in t_{brake} will require a larger propulsion impulse to maintain a constant speed. The landing-take-off asymmetry is more pronounced in older than younger runners (Cavagna, 2010; Cavagna et al., 2008) with a longer t_{prop} in older runners and consequently longer t_{stance} (Agresta et al., 2018; Cavagna et al., 2008; Pantoja et al., 2016). In accordance with the asymmetry in timing, the leg angle at push-off is steeper (inside angle) than at touch-down angle (Figure 4.c), and the BCoM height at take-off is higher compared to touch-down height (Cavagna, 2010; Cavagna et al., 2008). Maykranz and Seyfarth (2014) were able to mimic the asymmetry of human running by introducing the foot segment with an ankle extension into the SLIP model. The ankle extension resulted in a change of effective leg length, which partly explains the landing/take-off asymmetry. Potentially, the long t_{prop} in older runners compensates for a reduced force-generating potential and diminished elasticity of the muscle-tendon complex and can be regarded as a useful strategy to cope with individual limitations. However, Da Rosa et al. (2019) found no significant differences in t_{brake} and t_{prop} between two groups divided by 3000 m performances suggesting that t_{brake} and t_{prop} are not sensitive to discriminate between running performances.

The landing/take-off asymmetry should be visible in GRF traces. Instantaneous changes in GRF may change braking and propulsion impulse and contribute to landing/take-off asymmetry. Many studies on GRF focus on foot strike patterns (rear/mid/forefoot) or shod versus barefoot running. Most studies have focused on the vertical component only. The prevailing view is that a rearfoot striking pattern creates a characteristic first peak in the GRF_y (Kluitenberg et al., 2012; Nordin et al., 2017; Vernillo et al., 2017). Studies have shown that at high SF (or short t_{stance}) the amplitude of the initial peak in the GRF_y was reduced (Giandolini et al., 2013; Thompson et al., 2014). In some cases, the increased SF also resulted in skewing of the GRF_y towards the first half of the stance phase (Farley & Gonzalez, 1996). However, similar impact peak forces were also found at high running speeds in the absence of a rearfoot strike pattern (Bezodis et al., 2008; Bundle & Weyand, 2012; Clark et al., 2017; Clark & Weyand, 2014; Weyand et al., 2010). Clark et al. (2017) were able to accurately predict GRF_y curves over a wide range of speeds for both rear- and fore-foot striking patterns. They concluded that sprinters attained faster top speeds than non-sprinters by applying greater vertical forces during the first half of the stance phase. These greater forces led to skewing of GRF_y towards early stance that increased with speed (Clark et al., 2017; Clark & Weyand, 2014). Similar instantaneous peaks and valleys as in GRF_y during early stance are also observed in the GRF_x traces (Giandolini et al., 2013; Munro et al., 1987; Thompson et al., 2014). It seems that rearfoot (Boyer et al., 2014; Nordin et al., 2017) and forefoot strike patterns (Giandolini et al., 2013; Munro et al., 1987; Thompson et al., 2014) can be recognised from the GRF_x (Figure 5). Closer examination reveals that instantaneous changes are present in both GRF_x and GRF_y, which can be explained by changes in GRF orientation (Boyer et al., 2014; Nordin et al., 2017). Unfortunately, studies in which the horizontal and vertical GRF components are combined into a single vector are rare, which has been addressed previously as a limitation of the current literature (Boyer et al., 2014; Chang et al., 2000; Haugen et al., 2019; Moore et al., 2016). It is therefore difficult to draw strong conclusions on the need to define landing/take-off asymmetry to identify various running styles. Further research on the association between landing/take-off asymmetry and instantaneous GRF changes in relation to foot strike patterns and in fact whole-body kinematics is warranted.

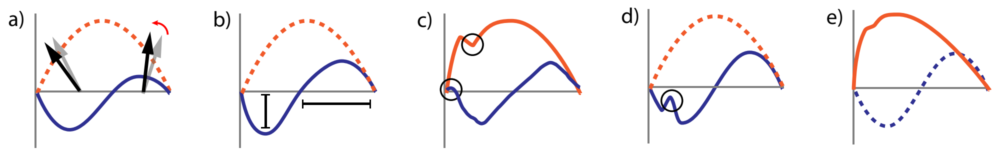

Figure 5. Examples of variations in GRF curves, the vertical GRF in orange and the horizontal GRF in blue. The dotted lines represent uncertainty. a) During downhill running and the step before a hurdle, the braking impulse vector becomes oriented more horizontally while the propulsion impulse vector becomes oriented more vertically (both visualised as grey to the black arrow). In contrast, during constant speed running the braking impulse should roughly equal the propulsion impulse; b) Increased t_{prop} during low speeds and in older runners; c) Typical curve of rearfoot striking pattern; d) Typical curve of forefoot striking pattern; e) The first peak in sprint running and skewness towards early stance. Due to running with increased SF, the first vertical peak may not be apparent.

In conclusion, the vertical and horizontal GRF curves cannot be assumed to be symmetrical and the asymmetry is speed dependent. Therefore, without taking running speed into account, the duration of both t_{brake} and t_{prop}, or GRF_x in relation to GRF_y, interpretations regarding injury risk or performance may not be valid. Therefore, high impact peak forces and steep slopes should not necessarily be interpreted as 'wrong' as some authors seem to imply (e.g., Bredeweg et al., 2013; Napier et al., 2018). The landing/take-off asymmetry was more pronounced in older runners compared to younger runners, but not in groups divided by 3000-m performances. It should be noted that these studies yielded significant differences in t_{flight}, t_{stance} and SL (Cavagna et al., 2008; Preece et al., 2018; Da Rosa et al., 2019). Presumably, inter-individual differences in landing/take-off asymmetry are, at least partly, reflected in other parameters. For example, it can be hypothesised that t_{prop} relates with t_{flight}. If so, landing/take-off asymmetry does not need to be measured in addition to the SF and DF to discriminate running styles. However, this issue should await further research to be decided.

Limb and trunk kinematics

The BCoM movements mechanically interrelate with limb and trunk kinematics. It is useful to understand the relationships between the BCoM movements and limb and trunk kinematics, because this may help to distinguish running styles and provide insight on why, where and how to make modifications in a running style.

Leg configuration at initial contact

The leg configuration at initial contact, which is characterised by hip, knee and ankle joint angles, determines the anterior foot placement distance relative to the BCoM (Figure 6). The position of the CoP relative to the BCoM and hence the anterior foot placement distance is crucial for the effects of the GRF vector on the BCoM trajectory. Excessive anterior foot placement relative to the BCoM is commonly referred to as 'overstriding'. A far anterior foot placement at initial contact results in higher braking impulses (Lieberman et al., 2010, 2015). The large moment arm of the GRF to the knee joint will force the knee into extension, or require high flexor moments around the knee (Lieberman et al., 2010, 2015). When the point of force application is located behind the ankle joint, the dorsiflexor muscles will be loaded eccentrically, potentially increasing the risk of tibial stress syndrome.

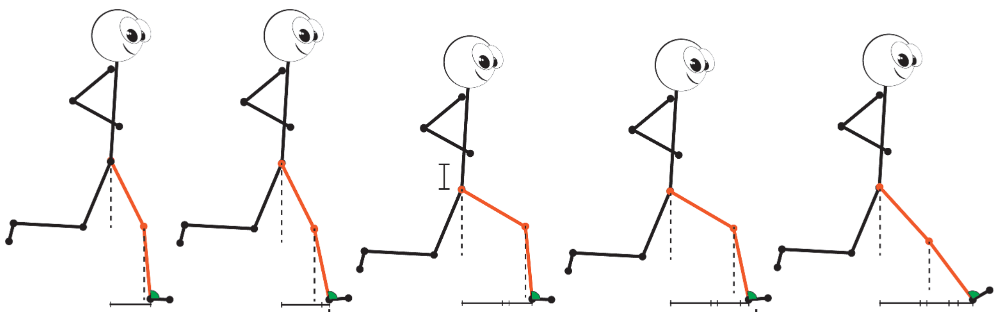

Figure 6. Geometrical relation for various leg configurations (a-e) and the horizontal distance between the hip and initial contact (length of the horizontal bars, d_{hip-ic}). This anterior foot placement position at initial contact (d_{hip-ic}) can be estimated from t_{stance} at a given horizontal speed of the hip, or alternatively, the BCoM. These figures visualise that d_{hip-ic}, and thus t_{stance}, relate to hip and knee angles. The ankle angle (green wig) is kept constant in these figures and is expected to provide a relative limited contribution to the hip height and d_{hip-ic}. Notice that runners with an average t_{stance} are expected to have the most knee flexion at initial contact.

At higher speeds, the foot is placed more anterior (Cunninghan et al., 2013). It is believed that the more anterior foot placement is most likely the result of hip flexion (Figure 6.a to 6.c) rather than knee extension (Figure 6.a to 6.b) (Orendurff et al., 2018). Accordingly, runners with larger SL (resulting in higher speeds) showed more hip flexion, but not more knee extension at initial contact (Lieberman et al., 2010). Better runners land less anterior to their BCoM despite their larger SL (Preece et al., 2018). Also, sprinters land less anterior relative to their BCoM than non-sprinters (Bushnell & Hunter, 2007; Cunninghan et al., 2013). Such larger SL's are possible by increased flight times, giving the runner time to position his or her leg before landing. Therefore, large SL should not be confused with 'overstriding'. Instead, 'overstriding' likely relates to a relatively long t_{stance} as previously discussed and potential effects of speed should be considered.

Less anterior foot placement (Figure 6a,b) can be achieved by leg retraction (rearward leg rotation) before initial contact. Leg retraction occurs mostly by rotation of the leg around the hip (Orendurff et al., 2018). As a result of leg retraction, the swing foot orients more normal-to-the ground before initial contact, the hip/BCoM is higher at initial contact, and t_{stance} is shortened. The leg retraction decreases the horizontal velocity difference of the foot relative to the surface ('matching ground speed') (Blazevich, 2017; Blum et al., 2010), which reduces impact impulses, prevents slipping (Karssen et al., 2015) and improves stability (Blum et al., 2010; Karssen et al., 2011; Seyfarth et al., 2003). As a consequence, it is expected that leg retraction redirects the GRF vector more vertically during early stance and that the vertical impact peak shifts towards early stance as observed in experienced sprinters (Clark & Weyand, 2014). According to Karssen et al. (2011), on a predictable terrain (such as a road or track) the runner can adopt a running style with fast leg retraction to deal with impact losses, impact forces, the risk of slipping and (internal) stability. However, to cope with terrain irregularities other requirements are needed. On uneven terrain, the runner may adopt a running style optimised for disturbance rejection. Disturbance rejection is the ability to follow a given trajectory in spite of unexpected external forces (Karssen et al., 2011). Their conclusions suggest that to control stability the leg retraction speed can be optimised to enhance robustness to internal (leg stiffness variations) or external disturbances (ground surface irregularities).

Knee angle at initial contact can vary within a range of anterior foot placement positions and with a given hip angle (Figure 6c,d). Knee flexion angles at initial contact were found to correlate with the maximal knee flexion later in stance phase (r = 0.67) (Derrick, 2004). Studies have shown that knee flexion during the stance phase reduces vertical peak leg acceleration and GRF_y (Derrick, 2004; Orendurff et al., 2018). Therefore, knee flexion might be regarded as a strategy to absorb the landing impact and might also help to improve disturbance rejection. The strategy to land with bent knees will load the quadriceps muscles eccentrically (Hamner et al., 2010), which may induce muscle sourness when excessive knee flexion moments are present. Since knee flexion can be used to control the leg stiffness, it can be expected that knee flexion is speed dependent. However, evidence regarding knee flexion changes during the stance phase in relation to running speed is equivocal, with some studies indicating increased knee flexion during midstance (Grimmer & Seyfarth, 2014; Orendurff et al., 2018) and others showing knee flexion to remain relatively stable across running speeds (Cunninghan et al., 2013).

Besides hip and knee angles, the runner can control ankle angles. As previously noted, foot strike patterns have drawn substantial scientific attention. However, it should be noted that the orientation of the foot mostly depends on the orientation of the lower leg. Ankle plantar or dorsal flexion will only contribute to a small extent to $d_{hip\text{-}ic}$ or hip height. Where $d_{hip\text{-}ic}$ is the anterior foot placement position at initial contact relative to the hip. Furthermore, the neuromuscular control occurs from proximal to distal (Orendurff et al., 2018), which makes striking patterns a consequence, rather than a cause of leg retraction. Therefore, despite the vast body of literature on foot strike patterns, we argue that foot strike patterns should not be regarded as a key feature of running styles.

For leg stiffness, we have discussed how t_{stance} is geometrically related to leg configuration (landing/take-off angle). Since also hip height depends on t_{stance}, it is safe to assume that leg configurations relate (at least partly) to t_{stance}. Furthermore, t_{flight} will change inversely proportional to t_{stance} for a given SF. Therefore, it is safe to assume that based on the t_{stance}/t_{flight} ratio (or DF), SF and speed, predictions on leg configuration can be made.

Trunk flexion-extension

Another salient characteristic of an individual's running style is the degree of forward, or backward trunk lean. Running with consistently increased trunk inclination is sometimes advocated as it results in higher SF and reduced VD_{step} (Dallam et al., 2005). However, between 12 km/h to 20 km/h, recreational runners show trunk inclinations ranging between 5° and 7.5° (Preece et al., 2016), whereas, over the same speed range, elite runners maintain a smaller consistent thoracic inclination of around 3° (Preece et al., 2016). Accordingly, a more upright trunk posture appears to be correlated with better running performance (Folland et al., 2017). In addition, novice runners being in a fatigued state increased trunk peak flexion and decreased peak extension, resulting in an overall increase in trunk inclination (Koblbauer et al., 2013; Maas et al., 2018). Dos Santos et al. (2016) instructed participants to run with exaggerated forward trunk lean angles (normal 9°, experiment 15°) and found that runners placed their foot more anterior at initial contact. In walking, exaggerated forward trunk lean led to a posterior shift of the hip relative to the BCoM, a steeper leg touchdown angle and a steeper leg toe-off angle (Aminiaghdam et al., 2017). Also in sprinters the trunk lean angle strongly correlated with the anterior foot placement position (Cunha et al., 2002). In walking as well as sprint running, the forward trunk inclination was associated with a more forward-tilted GRF vector (more vertical during t_{brake} and more horizontal during the t_{prop}) (Aminiaghdam et al., 2017; Van Caekenberghe et al., 2013). By bringing the head, arms and trunk forward, a runner reduces the anterior BCoM position (according to an estimate by Santos by ~2–3 cm) relative to the CoP. It is possible that forward trunk lean plays a role in compensatory strategies to maintain anterior-posterior balance or to increase forward propulsion despite more anterior foot placement, but it is questionable if this should generally be advised.

Within a step, the trunk flexes and extends. This dynamic trunk flexion-extension plays a role in compensating the angular momentum in the sagittal plane generated by the legs (Hinrichs, 1987). However, the contralateral leg movement compensates most of the angular momentum and the trunk flexion-extension only partly compensates the angular momentum generated by the legs in the sagittal plane (Hinrichs, 1987). During the stance phase, trunk flexion reaches its peak around midstance while extension occurs during propulsion (Koblbauer et al., 2013; Teng & Powers, 2014). During the flight phase the trunk flexion-extension range remains relatively small. The trunk flexion-extension may therefore predominantly affect the timing and redirection of the propulsion force. It can be hypothesised that high or late propulsive forces during late stance coincide with large trunk extension moments. The acceleration of the swing leg can also promote horizontal propulsion (Kugler & Janshen, 2010; Kyrolainen et al., 2001; Schmitz et al., 2014). Therefore, insufficient swing leg velocity may be associated with more trunk extension during late push-off. Perhaps larger trunk flexion-extension range and a longer t_{prop} observed during acceleration and in fatigued runners, novice runners, and older runners may serve the same purpose: to maintain propulsion impulse without peak force generation.

It is possible that increased consistent trunk inclination may result from a different movement strategy compared to a running style with increased dynamic trunk flexion-extension moments. An increased trunk inclination seems to increase SF, whereas increased trunk flexion-extension moments rather seem an attempt to increase propulsive forces and are therefore more likely to stimulate SL instead of SF. However, a high SF may not only be associated with increased trunk inclination since a too upright trunk posture may also result in higher SF. For example, a higher SF could also result from a too vertical oriented push-off force. Based on these speculations regarding trunk posture, the association between running with increased trunk lean, an upright trunk posture and with exaggerated trunk flexion-extension with spatiotemporal parameters can be usefully investigated in future studies. Based on the studies discussed above, we expect trunk posture to be associated with vertical displacement, landing/take-off asymmetries and take-off angles.

Body torsion and arm swing

Notable differences in body rotation and arm swing can also be observed between runners. In running, the lower body (legs and lower trunk) and upper body (upper trunk, head and arms) rotate in opposite directions about the longitudinal axis, with opposite vertical angular momenta (Hamner & Delp, 2013; Hinrichs, 1987). The vertical angular momentum generated by the lower body needs to be compensated to prevent whole-body rotation resulting in a non-straight trajectory. In runners generating insufficient compensatory angular momentum using the upper body, longitudinal rotation of the upper body may be visible (Pontzer et al., 2009) with the hands tending to cross the body's midline (Strohrmann et al., 2013). At higher running speeds, the more rapid leg movements increase the angular momentum of the lower body (Hamner & Delp, 2013).

The lower body angular momentum is the result of various (related) factors in the gait cycle.

1) At initial ground contact, the braking force decelerates the hip relative to the midline, thereby creating a change in angular momentum (Arellano & Kram, 2012). For a given GRF a larger step width, or a wider pelvis, will theoretically increase the change in angular momentum, which may partly account for individual differences.

2) During the stance phase, the legs swing in the opposite direction constituting an angular momentum around the longitudinal axis (Hinrichs, 1987). This angular momentum will be greater when the mass of the leg is further away from the hip, and when the velocity of the leg is higher.

3) During late push-off, transverse plane pelvic rotation lengthens the step ('pelvic step'), thereby increasing the angular momentum around the longitudinal axis (Bruijn et al., 2008; Preece et al., 2016).

Given the effect of these factors, whole-body rotations, which are commonly seen in runners, are potentially the result of running styles with anterior placement, or emphasis on push-off (e.g., large propulsive force during late stance, or long t_{prop}). Especially during the flight phase in the absence of free moments, the upper body including the arms provides the principal source for generating compensatory angular moments (Hinrichs, 1987). The pelvic and thoracic contributions to total body angular momentum are relatively small since masses of these segments are distributed close to the longitudinal axis (Bruijn et al., 2008; Hinrichs, 1987). More importantly, high accelerations of the arms cause substantial compensatory moments (Hamner & Delp, 2013; Pontzer et al., 2009). Also, the downward acceleration of the pendular arm swing provides a small (less than 10%), but meaningful contribution to the vertical GRF. In fact, despite the additional energy required to swing the arms back and forth, arm swing reduces the net metabolic (energy) cost of running (Arellano & Kram, 2011). The role of the arms in generating compensatory moments becomes even more critical when the swing time decreases, as occurs at high running speeds (Hinrichs, 1987).

Besides compensation using the upper body, the runner can prevent whole-body rotation by generating a substantial exorotation moment around the hip at the stance-leg side. These, 'free moments' are transferred over the knee (most likely via passive tissues), which may explain why such free moments have been found to correlate with tibial stress (Milner et al., 2006; Pohl et al., 2008) and knee injuries (Willwacher et al., 2016). Large free moments may also place a high demand on the rotator muscles of the hip. Reducing the net angular momentum about the vertical axis generating angular moments using the upper body may therefore help to reduce injury risk.

The relationship between the spatiotemporal parameters and vertical angular moment is not straightforward, given the multiple potential causes for lower body rotation and various compensatory mechanisms. A longer t_{stance} is associated with more anterior foot placement and thereby presumably results in larger braking forces. A longer t_{stance} will also relate to more pelvic rotation. Furthermore, given the effects of the downward arm swing on the vertical GRF it possible that, especially at high running speeds, a short t_{flight} may be indicative of an ineffective arm swing with potentially more upper body rotation. Therefore, runners with long t_{stance} and short t_{flight} are more likely to suffer large lower body angular moments or are unable to sufficiently compensate lower-body rotations with upper body angular moments.

Leg swing

The leg of a runner of 70 kg weighs around 12 kg (Plagenhoef et al., 1983). With SF somewhere between 160 and 190 spm (Van Oeveren et al., 2017), the swing leg moves within 1/3th of a second from its most anterior to its most posterior position. Modica and Kram (2005) estimated that swinging the legs requires ~20% of the net energy cost of running at 11 km/h. Later this estimation was adjusted to ~7% due to synergistic movements to accomplish vertical body weight support, forward propulsion and leg swing (Arellano & Kram, 2014; Chang & Kram, 2017). This adjustment highlights the effective contribution achieved by the swing leg kinematics and kinetics to both vertical and horizontal propulsive forces. One of the potential mechanisms explaining this efficiency is that the kinematic energy of the swing leg can be temporarily stored in elastic structures, such that it is not lost, but can be reused in subsequent movements. For example, Preece et al. (2018) found that, compared to less proficient runners, high-performance runners had more flexed knees during swing, but without differences in knee angles at initial contact. This finding suggests that high-performance runners have higher knee extension velocity during late swing. During late swing, the hamstrings absorb the kinetic energy, such that it reaches a maximum just before initial contact (Chumanov et al., 2012). The tension increase on the hamstrings can be regarded as a mechanism to reuse the kinetic energy of the swing leg, and contributes to the subsequent leg retraction (Morin et al., 2015). With a potential downside of increased hamstring injury risk (Hoogkamer et al., 2017; Kenneally-Dabrowski et al., 2019; Schache et al., 2013; Sun et al., 2015).

A second mechanism to potentially improve the efficiency of the swing leg is by reducing its moment of inertia. Running with extended legs has been shown to hinder the hip flexors from propelling the leg quickly forward due to the associated changes in the moment of inertia of the swing leg (Williams et al., 1987). Accordingly, experiments with weights (up to 2 kg) distally placed on the legs and with heavy shoes showed that energy consumption is affected by the distribution of limb mass and resulted in lower SF's (Breine et al., 2017; Martin, 1985; Myers & Steudel, 1985; Reenalda et al., 2016). Since both legs move in phase, a faster leg swing will be associated with a shorter t_{stance} of the contralateral leg. Therefore, in order to attain high running speeds, during which SF is high and t_{stance} is short, it becomes critical to sufficiently flex the knee during the swing phase (Hamner & Delp, 2013; Lipfert, 2010; Willems et al., 1995).

The swing leg motion is often ignored in SLIP models as they essentially describe the course of one step (technically a half-cycle). Rashty et al. (Rashty et al., 2014) showed that by modelling the pendular motion of the swing leg in the conventional SLIP model, the generated momentum of the swing leg induces sequential steps. Consequently, the forward motion becomes more stable, which led the authors to suggest that the swing leg may help to reduce muscular force provided by the stance leg (Rashty et al., 2014). The swing leg reaches its highest forward acceleration during the stance phase of the contralateral leg (Figure 2, d). Understandably, the leg swing contributes to the generation of propulsive forces (Kyrolainen et al., 2001; Schmitz et al., 2014). For example, an asymmetrical angular acceleration of body segments results in a forward-oriented GRF. A high acceleration of the lead leg at the end of the propulsion phase may consequently orient the GRF more horizontally, resulting in a change in whole-body angular momentum and more effective propulsion (Kugler & Janshen, 2010).

Runners with high SF and short t_{stance} can be expected to have higher knee flexion during the swing phase. Notably, t_{stance} can be shortened due to more leg retraction before initial contact or by reducing t_{prop}. A long t_{prop} may delay and reduce swing knee flexion, which increases the moment of inertia. During mid-swing, a faster leg swing will stimulate a shorter contralateral t_{stance} and contribute to generate propulsive forces. A relatively long t_{flight} may increase the time to flex the knee and retract the leg. All in all, we expect knee flexion to be reflected in the spatiotemporal parameters of interest.

The dual-axis framework

The characteristics of the BCoM are used in this review to identify the key parameters that define running styles. To fully describe the spectrum of running styles we argue that it is required to cover at least the horizontal and vertical component of the BCoM trajectory. The SF (or SL) and stance/flight ratio at a given speed seem to provide the necessary information. Given the possibility to vary the stance/flight ratio at a given SF or vice versa, the isolated analysis of these key parameters may not convey an unambiguous image of a running style. In addition, as stipulated, these ratios are likely to explain part of the limb and trunk kinetics and kinematics. Given the speed-dependency of all parameters considered in this review, a running style should be defined at a given speed. As a guideline for identifying running styles and interpret biomechanical parameters in running we propose the use of the conceptual Dual-axis framework (Figure 7) as explained in detail in the next section.

The vertical position in the Dual-axis framework is quantified by the t_{stance}/t_{flight} ratio. To prevent division by zero in the absence of a flight phase (as in walking), it is recommended to use the DF instead. The vertical position can be expected to be most directly related to running performance, since numerous studies have shown that a short

t_{stance}, long t_{flight}, low DF or high stiffness, relates to performance (e.g., Concejero et al., 2013; Folland et al., 2017; Da Rosa et al., 2019; Santos-Concejero, 2014). The t_{stance}/t_{flight}-axis reflects the utilisation of elastically stored energy. To achieve the highest speed possible, a running style enabling the delivery of high propulsive forces over a wider speed range would be preferred, which the runner can achieve by reusing elastically stored energy. Hence this running style is labelled as 'Bounce' and is characterised by a short t_{stance} and a relatively long t_{flight}. Both VD_{stance} can be expected to be large to enable the generation of high forces and as a result VD_{flight} can also be expected to be relatively large.

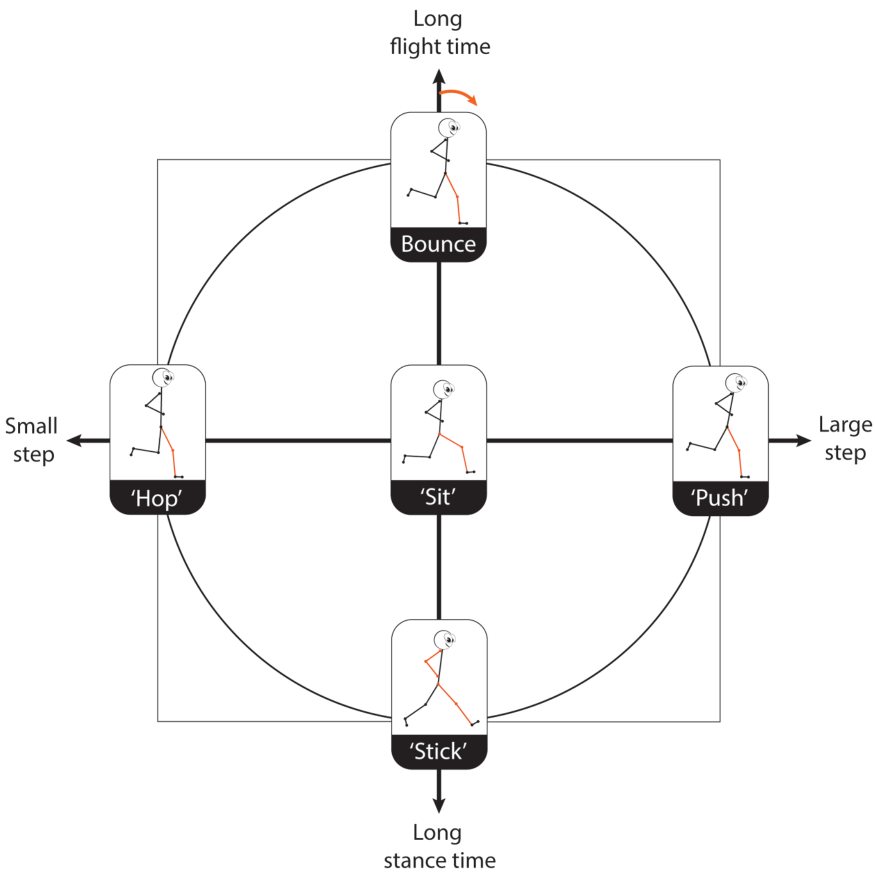

Figure 7. Visualisation of the proposed Dual-axis framework to characterise the fundamental differences in running styles as assessed at a given speed. The horizontal axis is defined by SF corrected by leg length and signifies the forward BCoM displacement per step. With at the left a high SF and at the right a low SF. The vertical axis represents the ratio between the stance and flight phase, which is quantified by the DF. With at the top a running style having a low DF. Together the axes describe a continuous spectrum of running styles with on the extremes 'Walk', 'Bounce', 'Hop', and 'Push' styles. Based on the horizontal distance between initial contact and the hip, a running style labelled 'Sit' is positioned in the centre, which is characterised by a flexed knee at initial contact. The curved orange arrow at the top indicates the expected effect of running speed on the interdependency between DF and SF.

In contrast, the running style at the low end of the vertical axis, coined ‘Stick’, is characterised by a long t_{stance} with a short t_{flight}. The associated low VD_{step} can be beneficial at low running speeds, or in conditions in which high vertical peak forces are unbeneficial (such as while running with a heavy bag or in loose sand). With increasing speed, t_{flight} increases relative to t_{stance}, but plateaus around ~20 km/h (Figure 3). In the Stick, this plateau can be expected to occur earlier, because the ability to generate propulsive forces during the short t_{stance} may limit some runners to increase t_{flight} further.

The horizontal position in the Dual-axis framework for a given speed is determined by either SF or SL. Note that both SF and SL can be chosen given their inverse relationship with speed. With a large SL/low SF on the right side and small SL/high SF on the left side. The position of a runner on the horizontal axis strongly depends on the runner’s ability to generate propulsion forces. Since taller runners naturally have larger SL, normalisation to leg length is strongly recommended. Methods include expressing SL as a percentage of leg length (Cavanagh & Williams, 1982; Hof, 1996). If SF is used, SF can be rendered dimensionless by dividing SF by $\sqrt{(g/L_0)}$ (Hof, 1996). Note that these two normalisation methods will lead to the same conclusions since gravitational acceleration can be assumed to be constant for this purpose.

The Hop (left) has a relatively high SF (Figure 8), with a low to medium DF. This combination suggests that the runner generates relatively limited forward propulsion during the stance phase. The resultant propulsion force is directed too vertical. As a result, the push-off angle is not optimal, resulting for a given speed in a non-maximal t_{flight}. This phenomenon can have multiple causes, among which insufficient leg extension, too upright trunk orientation, or insufficient leg swing velocity.

The Push (right) involves large steps, and a DF that is medium to large. The large DF occurs at the expense of a long t_{stance}. The t_{flight} is shorter than maximally possible, since the propulsion force is oriented more horizontally or lower. The long t_{stance} may be the result of a movement strategy that includes prolonged t_{prop} to prevent peak force generation.

In the centre of the model a running style with intermediate DF and SF is described. This running style is likely to be characterised by a relatively large knee-flexion at initial contact (Figure 6.c, d) since leg configuration is associated geometrically with t_{stance} and, hence, t_{flight}. Due to the expected ‘sitting posture’ this running style is coined ‘Sit’. Note that three visually distinctive running styles (Bounce, Sit and Stick) are possible with similar SF’s. The range of styles with corresponding SF may explain why some previous studies might not have find significant differences in SF’s between runners despite considerable variation in performance levels (Van Oeveren et al., 2019) or experience (Agresta et al., 2018; Luedke et al., 2018; Van Oeveren et al., 2019).

The two axes of the Dual-axis framework should not be considered strictly orthogonal as visualised since DF and SL are dependent. The stance phase is limited by geometrical constraints (leg length, touch-down and take-off angles). Therefore, at high running speeds, SL becomes more dependent on the flight phase. Consequently, with increasing speed, the vertical axis will tilt to the right. Individual variation in dependencies across speeds may reveal individual limitations and strengths. Note further that because of the

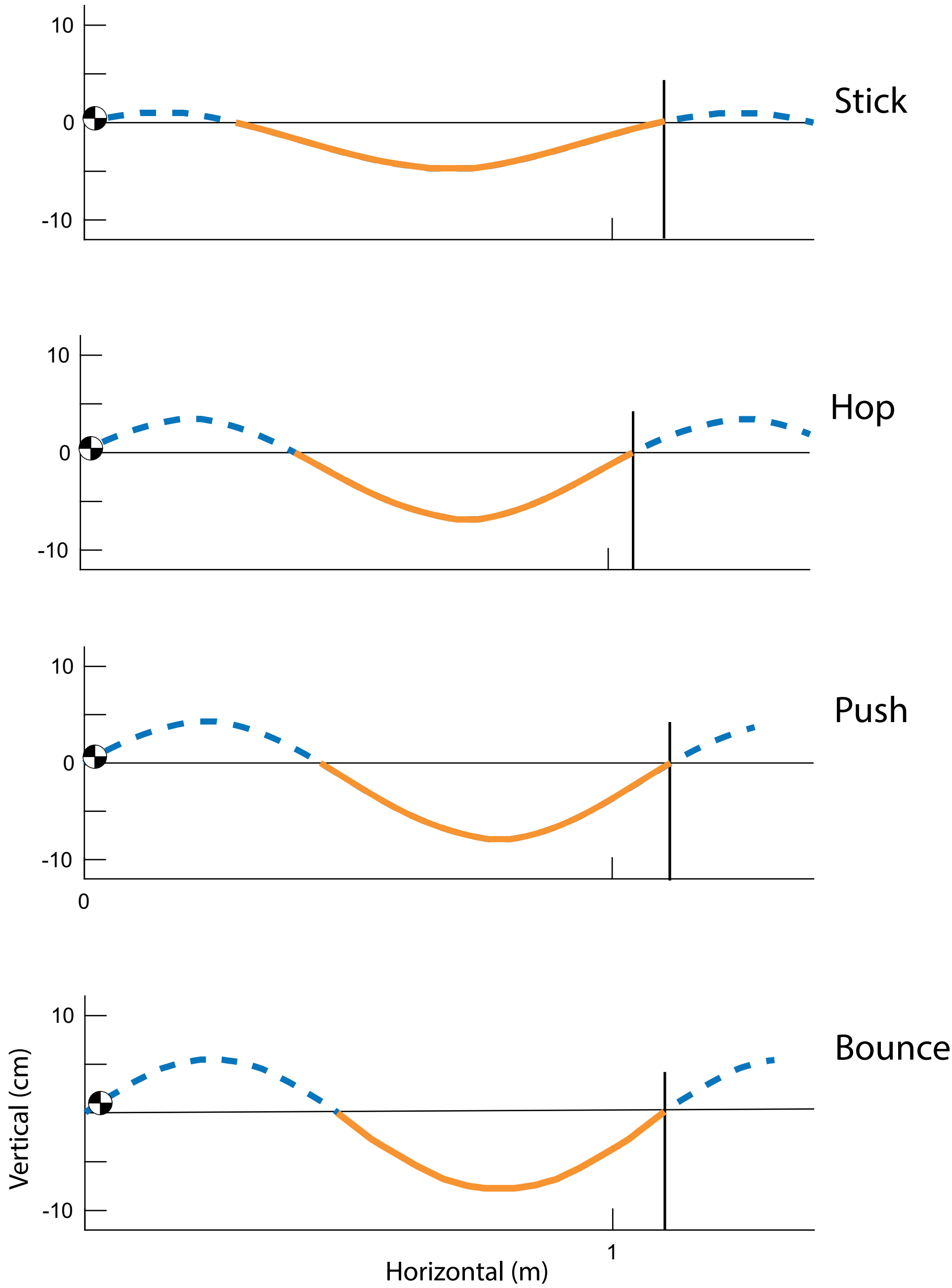

Figure 8. Illustration of the BCoM trajectories for the four most extreme styles with variations in step frequency at a given speed (black vertical bar), flight phase (blue dashed line) and stance phase (orange solid line). As a result of the expected BCoM trajectories each running style will display different spatiotemporal parameters and runners can try to modify each style accordingly. Walk: long t_{stance}, short t_{flight} resulting in a medium SF and a low VD_{step}. Bounce: short t_{stance}, long t_{flight} resulting in a medium SF and a high VD_{step}. Hop: short t_{stance}, short t_{flight} resulting in a high SF and a medium VD_{step}. Push: long t_{stance}, long t_{flight} resulting in a low SF and a large VD_{step}.

interdependency between parameters, the same running styles can be obtained theoretically from other parameter settings as well.

Biomechanical predictors of performance and individual running economy can differ (Folland et al., 2017; Kyrolainen et al., 2001; Nummela et al., 2007; Pizzuto et al., 2019; Tawa & Louw, 2018; Williams & Cavanagh, 1985). Accordingly, the running style associated with the highest absolute performance and the individually most economical running style may diverge. To allow performance-oriented comparisons, proper normalisation for individual characteristics is required. The height or leg length normalisation assumes proportionally scaled body anthropometrics, which could make runners with different body sizes run in a dynamically similar fashion. In running, the leg length normalisation is a logical first step since the pendulum length of the fast-moving limbs will have more influence on the motion than the variation in body mass (Alexander, 1989).

To assess the biomechanical predictors for running economy, additional normalisation by mass may be appropriate. In the Dual-axis framework, this would imply that the DF on the vertical axis is replaced by vertical stiffness, thereby taking into account variation in body mass. The SL or SF may not require mass normalisation additional to leg length normalisation since the natural frequency of a pendulum system depends on its length, not on its mass (Alexander, 1989). Still, in a previous study, we found that a 7.5 kg increase in body mass was associated with a reduction of SF by one step per minute (Van Oeveren et al., 2019). Differences in SF were also found due to age. It seems that, in general, stronger and potentially heavier runners prefer larger steps. This suggest that when running style is evaluated in relation with running economy, gender differences and age should be considered to account for potential differences in mass distribution or strength. Ultimately, it will be unfeasible to take all individual and situational factors into account that collectively determine the most economical running style. Therefore, caution should be exerted in generalising across running populations and in using generic reference values in feedback applications. In general, it might be more effective to design feedback systems that promote self-optimisation as suggested in some of the SF-studies.

Future studies

The running styles defined by the Dual-axis framework may guide future research to answer questions regarding performance improvement, injury prevalence. Also, questions regarding certain environmental contexts in relation to running biomechanics can be answered more pointedly and consistently than has hitherto been possible. The proposed framework has practical and heuristic value as it only requires that speed, SF (normalised for leg length) and DF are measured and modelled in conjunction. We acknowledge that even within each position in the framework small variations still exist because of potential compensating moments generated by the trunk, arms and legs. The landing/take-off asymmetry would additionally specify the BCoM trajectory. However, current research on the landing/take-off asymmetry is limited. Therefore, strong conclusions regarding the additional value of the landing/take-off asymmetry to the framework remain to be determined. Nevertheless, we expect the Dual-axis framework to capture the most fundamental differences in running styles, since it will cover most of the variations in runners' BCoM trajectories. We further expect that measuring whole-body kinematics will result in the same definition of running styles. The Dual-axis framework will help explain variation between running styles and it provides a firmly motivated and rich basis for defining and testing new hypotheses (which we have presented in this review as expectations). Ideally, future research on running biomechanics will be done over a range of speeds to identify potential individual speed-dependent differences. Gait modifications to mimic the various running styles can be imposed by means of instructions requiring combinations of long/short t_{stance} with small/large SL. In addition, future research may want to focus the effects of specific gait modifications emphasising limb movements such as leg retraction, trunk lean, knee lift and arm swing to gain practical insights for runners and their coaches.

Conclusion

Based on the current literature, we expect that the full spectrum of running styles can be distinguished on the basis of SF, normalised by leg length, and DF for given speeds, as stipulated in the proposed Dual-axis framework. Given that the goal of locomotion is to transport the BCoM, the framework uses the sinusoidal BCoM trajectory in the sagittal plane as the guiding principle. We expect that the framework will help to describe the most fundamental differences in running styles since the BCoM movements depend mechanically on the GRF patterns and limb and trunk kinematics. The categorisation of the five styles, coined 'Stick', 'Bounce', 'Push', 'Hop', and 'Sit', can be used to study the effects of gait modification and to help the interpretation of study results. By identifying the key characteristics to differentiate running styles, this review and the synthesised Dual-axis framework are intended to provide a unified concept for interpreting measurements, for conducting future research on performance, running economy and injury risk, as well as for designing and testing coaching interventions.

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Appendix

m is the participant's body mass in kilograms.

L_0 leg length in metres at rest. This can be measured from trochanter major to the ground.

g is the acceleration due to gravity (-9.81 m/s^2)

7.1 Transformations between speed, SF, SL

$$V_x = \frac{SL}{t_{step}} \tag{1}$$

$$SF = \frac{60}{t_{step}} \tag{2}$$

$$t_{step} = t_{stance} + t_{flight} \tag{3}$$

$$t_{flight} = t_{step} - t_{stance} \tag{4}$$

$$t_{swing} = t_{flight} + t_{stance} \tag{5}$$

$$d_{stance} = v_x \cdot t_{stance} \tag{6}$$

$$d_{flight} = SL - d_{stance} \tag{7}$$

$$d_{BCoM-ic} = \frac{1}{2} \cdot v_x \cdot t_{stance} \tag{8}$$

7.2 Normalisation for body length

$$SF_{norm} = \frac{SF}{\sqrt{L_0/g}} \tag{9}$$

$$t_{stance,norm} = \frac{t_{stance}}{\sqrt{L_0/g}} \tag{10}$$

7.3 Equations based on the ballistic trajectory

$$t_{lift} = \frac{1}{2} \cdot t_{flight} \tag{11}$$

$$v_{yi} = g \cdot t_{lift} \tag{12}$$

$$VD_{flight} = v_{yi} \cdot t_{lift} + \frac{1}{2} g \cdot t_{lift}{}^2 \tag{13}$$

v_{yi} represents the initial vertical speed at the onset of the flight phase; the estimated time to reach the peak of the flight phase. These equations assume that there is no difference between landing and take-off height and air resistance can be neglected.

$$\text{Steptangle} = g \cdot t_{swing} \cdot \frac{2}{8} \tag{14}$$

$$\text{Vertical ratio} = \frac{VD_{step}}{SL} \tag{15}$$

7.4 ***Spring properties***
Duty factor

$$DF = \frac{t_{stance}}{2 \cdot (t_{stance} + t_{flight})} \tag{16}$$

Hooke's law (linear spring)

$$-F = y \cdot k \tag{17}$$

Where in the case of running F = F_{max}, y = VD_{stance}. Note that F is in opposite direction of y.
The estimate of peak vertical force during contact (Morin et al., 2005)

$$F_{max} = m \cdot g \cdot \frac{\pi}{2} \left(\frac{t_{flight}}{t_{stance}} + 1 \right) \tag{18}$$

Vertical displacement of the BCoM during the stance phase Morin et al., 2005)

$$VD_{stance} = -\frac{F_{max}}{m} \cdot \frac{t_{stance}{}^2}{\pi^2} + g \cdot \frac{t_{stance}{}^2}{8} \tag{19}$$

$$VD_{flight} = VD_{step} - VD_{stance} \tag{20}$$

The estimate of vertical stiffness (Morin et al., 2005)

$$K_{vert} = \frac{F_{max}}{VD_{stance}} \tag{21}$$

The estimate of leg stiffness (Morin et al., 2005)

$$\Delta L = L_0 - \sqrt{{L_0}^2 - \left(\frac{v_x \cdot t_{stance}}{2}\right)^2} + VD_{stance} \tag{22}$$

$$K_{leg} = \frac{F_{max}}{\Delta L} \tag{23}$$

with ΔL representing the change in leg length, and v_x the constant horizontal velocity.

7.5 Braking and propulsion

In constant speed running the netto impulse (ΔI) equals zero.

$$\Delta I = \int \left(-F_{x,brake} \cdot \ t_{brake}\right) + \int \left(F_{x,prop} \cdot \ t_{prop}\right) = 0 \tag{24}$$