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Sprint running: From fundamental mechanics to practice – A review

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Sprint running: From fundamental mechanics to practice – A review

Heading title: Sprint performance mechanics

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Abstract

In this review, we examine the literature in light of the mechanical principles that govern linear accelerated running. While the scientific literature concerning sprint mechanics is comprehensive, these principles of fundamental mechanics present some pitfalls which can (and does) lead to misinterpretations of findings. Various models of sprint mechanics, most of which build on the spring-mass paradigm, are discussed with reference to both the insight they provide and their limitations. Although much research confirms that sprinters to some extent behave like a spring-mass system with regard to gross kinematics (step length, step rate, ground contact time, lower limb deformation), the laws of motion, supported by empirical evidence, show that applying the spring-mass model for accelerated running has flaws. It is essential to appreciate that models are pre-set interpretations of reality; finding that a model describes the motor behaviour well is not proof of the mechanism behind the model. Recent efforts to relate sprinting mechanics to metabolic demands are promising, but have the same limitation of being model based. Further, a large proportion of recent literature focuses on the interaction between total and horizontal (end-goal) force. We argue that this approach has limitations concerning fundamental sprinting mechanics. Moreover, power analysis based on isolated end-goal force is flawed. In closing, some prominent practical concepts and didactics in sprint running are discussed in light of the mechanical principles presented. Ultimately, whereas the basic principles of sprinting are relatively simple, the way an athlete manages the mechanical constraints and opportunities is far more complex.

Key words

Running technique; kinetics; stiffness; braking; propulsion; power

Abbreviations

AOD	Accumulated oxygen deficit
CoM	Centre of mass
D_{RF}	Decrease of ratio of forces
F_{eff}%	Force effectiveness (%)
GRF	Ground reaction force
k_{leg}	Leg stiffness
P_{max}	Maximum horizontal power
RF	Ratio of forces (horizontal over total)
S_{FV}	Force-velocity slope
SR	Step rate
t_c	Contact time
t_a	Aerial time
τ	Time constant (tau)

Introduction

The mechanics of sprint running have received considerable attention in the scientific literature over the years. The first specific sprint running studies were published already in the 1920s (Best and Partridge 1928; Furusawa et al. 1927), and Mero et al. (1992) summarised several pioneering studies. However, numerous investigations have been undertaken since then, and advances in technology have allowed scientists to explore fundamental aspects of sprinting skills more closely. Although the mechanical principles of sprint running are similar to those of running in general, a major difference is the large acceleration at the start (accelerated running). This is likely why propulsive forces have received much attention in the literature. In this review, we examine the literature by using the mechanical principles that govern linear accelerated running. We feel that elaborating on fundamental mechanics is necessary, because some of these principles are often 'taken for granted' in the research literature, which could easily lead to misinterpretations of findings. Attempting to keep the content relatively orderly, we treat a number of issues separately, even though they often are entwined and in some cases mere 'different explanations of the same story'. Although the present review is specifically oriented towards sprint running (i.e., athletics), most of the content is also relevant for e.g., team sports where brief, linear accelerations frequently occur.

Braking and propulsion – two sides of the same coin

Fundamental aspects of propulsion

At the start of a sprint, i.e., in accelerated running from a standstill, the generation of forward (horizontal) acceleration is likely the most important performance-determining factor. An increase in sprinting velocity can only be achieved by upsetting the balance between propulsive and braking impulses so that the runner gains a surplus of propulsive impulse. Much research has confirmed this; the best performance is strongly correlated with high mean horizontal forces (e.g., Colyer et al. 2018a; Colyer et al. 2018b; Hunter et al. 2005; Kugler and Janshen 2010; Morin et al. 2012; Morin et al. 2011a; Morin et al. 2015a; Nagahara et al. 2018a; Rabita et al. 2015). This finding by itself is merely a confirmation of a basic law of physics yet it is still valuable because it forms the basis for further investigation about how this is accomplished and if there are any mechanical constraints that affect this accomplishment. In many of these studies, deeper analysis about how propulsive forces are brought about is indeed performed. Theoretically, for a given mean net horizontal force (i.e., a given offset between braking and propulsive force), the condition where both braking and propulsive forces are minimised (i.e., braking force equals zero and propulsive force equals the propulsion-braking offset) leads to the best performance, i.e., the shortest time to cover a given distance. Intuitively, this is not straightforward, which may be a source for misinterpretation of empirical findings. The average force (or acceleration) determines final speed, not average speed. Since (negative) braking force precedes the (positive) propulsion force at each ground contact, the resulting force fluctuation during ground contact will reduce the average speed, with the net force only determining the change in speed between touchdown and lift-off. Thus, because average speed is the direct determinant for sprint performance, the horizontal force fluctuation itself reduces performance. This principle applies to both accelerated running and sprinting at maximum velocity, the only difference being that in the latter case the propulsion-braking offset equals zero. Indeed, during the development of a sprint, peak braking forces tend to increase from ~0.2 to ~0.4 times bodyweight throughout acceleration and corresponding propulsive forces reduce from ~0.6 to ~0.4 (Nagahara et al. 2018a). Other studies by the same group (Colyer et al. 2018a; Colyer et al. 2018b) show the same tendency.

Wild turkeys seem to have perfected the principle of avoiding braking in accelerated running (Roberts and Scales 2002). This was also thought to be the case for humans. As far back as 1971, Cavagna et al. (1971) indicated that at the start of a sprint run, all energy at the onset (at low speed) originated from muscle work that was directly converted into motion of centre of mass (CoM). This finding has been refuted, at least as a general principle, by Johnson and Buckley (2001) and Debaere et al. (2013a) who found clear periods of work absorption at hip and ankle, followed by work production during the first contact period. This is supported by other studies (e.g., Bezodis et al. 2014; Mero 1988; Morin et al. 2015b). Further, unpublished personal observations on horizontal and vertical velocity development (same data as in Ettema et al. 2016; Haugen et al. 2018a; Haugen et al. 2018b) suggest that braking occurs very early in accelerated running.

Braking versus propulsion

While various studies have indicated that both propulsive and braking forces are associated with performance (e.g., Morin et al. 2015b), these two periods during ground contact have hardly ever been considered as two sides of the same coin – one technique strategy. That is, an athlete may attempt to minimise braking, thereby possibly reducing the potential to generate propulsion in the second phase of the step, the combination of which may still lead to better performance. We investigated the potential of this strategy by considering empirical step force data (Bezodis et al. 2008, their figure 2). These data were digitised and velocity and displacement changes calculated by numerical integration. We then analysed the situation where braking force was nullified and propulsion force reduced correspondingly to obtain the same impulse and change of velocity. The advantage of minimising force fluctuations amounted to just below 1 cm distance covered in the same time for one ground contact period, i.e., about 0.3 - 0.4 m (or 0.03 - 0.04 s) in a 100-m sprint at an average speed of 10 ms^{-1}. While this may be a meaningful effect at the elite level, it hardly seems relevant when comparing different performance levels. When nullifying the braking period but leaving propulsion unchanged, the gain for a 100-m sprint was only doubled (by law) to about 0.6 - 0.8 m (~0.06 - 0.08 s). These calculations were done on one data set from high-level sprinters (Bezodis et al. 2008) and should thus only be considered as indicative of the approximate gain that could be obtained. The speed reduction based on the original data was about 0.13 ms^{-1}, which is in agreement with the classic study by Fenn (1930), suggesting a reduction between 0.13 and 0.24 $m \cdot s^{-1}$ when running at maximum velocity.

In the preceding theoretical analysis, neither the potentiating effect of associated eccentric contraction during braking on subsequent concentric contraction period during propulsion, i.e., in a stretch-shortening contraction (e.g., Cavagna et al. 1968; Edman et al. 1978; Ettema et al. 1990; Walshe et al. 1998), nor the attainment of high active state at onset of propulsion (Bobbert et al. 1996; Walshe et al. 1998) were considered. These and other possible technical aspects in sprinting may outweigh the relatively small mechanical downside of braking-propulsion fluctuation described above. Further, even for a passive, solid body, ground impact leads to braking and propulsive forces (e.g., Cross 2002). It is therefore not surprising that this is also the case for athletes (Bezodis et al. 2008; Colyer et al. 2018a; Colyer et al. 2018b; Hunter et al. 2005; Kugler and Janshen 2010; Nagahara et al. 2018a; Nagahara et al. 2018b; Rabita et al. 2015). In our opinion, it is not possible through empirical studies to resolve which of the abovementioned mechanisms and strategies prevail in sprinting. Still, some empirical findings indicate the importance of attenuating braking and enhancing propulsion. Morin et al. (2015b) found that sprint performance in elite level sprinters (100-m: 9.95–10.60 s) was more related to being able to generate propulsion forces and much less to minimising braking. On the other hand, Colyer et al. (2018a) found in intermediate sprinters (100-m: 10.88–11.96 s) that minimising braking when approaching maximum sprinting velocity was a major contributing factor. The comparison of these findings may indicate that, as a group, the best sprinters excel in suppressing braking as one aspect of good technique, a factor that is therefore not discriminating at this level.

As mentioned earlier, the braking-propulsion sequence is associated with the stretch-shortening contraction at the muscular level. The mechanism of storage and release of elastic energy that goes hand-in-hand with such muscular behaviour likely occurs during sprinting, particularly at maximal velocity. However, the idea that stretch-shortening contractions emerge as a strategy because of this mechanism is flawed (e.g., Lai et al. 2014). The storage and release mechanism always entails some loss of energy, if only because of viscous properties of tendons. Thus, if one were able to avoid braking, i.e., maintaining the body's kinetic energy, this would be a better strategy to 'save' energy via elastic absorption (Ettema 2001). Of course, if braking is to occur, storing most of the energy that is lost as kinetic energy elastically and reutilising it in propulsion is beneficial. This issue is discussed further in the "storage and release of elastic energy" section.

Spring-mass paradigm: leg stiffness

Even though horizontal force seems to be the obvious dynamic component to focus on in sprint running, the vertical force component is essential to elevate (in accelerated running) or maintain height of (at maximal velocity) CoM. The value of the mean vertical force during ground contact is given by the action of gravitation and equals:

$F_v = F_g \frac{t_{cycle}}{t_c}$ (Weyand et al. 2000),

where F_v is mean vertical force, F_g is gravitational force, t_{cycle} is cycle time and t_c is contact time. Note that this is a constraint dictated by Newton's laws of motion, not an empirical finding. In other words, it is not necessary to investigate effects of mean vertical forces with regard to performance because they are directly linked to relative contact time. However, the force profile, including peak forces, may give indications about the technical strategy that is applied in sprint running. Unlike in the horizontal direction, a vertical braking phase (impact) is unavoidable, which must be followed by a vertical propulsion phase. The force profile is often linked to kinematic changes of the lower limb, expressed as vertical and leg stiffness, being the ratio of peak force and vertical CoM displacement or leg length change during ground contact, respectively (Farley and Gonzalez 1996; Morin et al. 2005; Taylor and Beneke 2012). Here, we discuss leg stiffness and the related spring-mass paradigm for the vertical movement, but it also applies to the horizontal brake-propulsion dynamics. The difference between leg stiffness and vertical stiffness essentially lies in the contribution of leg rotation over the stance foot in vertical stiffness (although equations may suggest the opposite). That is, leg stiffness is more closely related to spring-like behaviour of the lower limb and its joints than vertical stiffness; vertical stiffness is the hardest variable to interpret whereas leg stiffness is likely the variable most associated with storage and release of elastic energy. For that reason, here we consider only leg stiffness.

Leg stiffness is an outcome of running technique and can be adapted through muscle action. Even though leg stiffness often is described as an outcome of contact time, the opposite must be the case. However, ground contact time is often used to calculate stiffness (e.g., Morin et al. 2006; Taylor and Beneke 2012). The stiffer an object is, or an athlete behaves, the shorter ground contact will be. (This seems advantageous with regard to horizontal propulsion, which should be as acute as possible in sprint running.) The current use of leg stiffness (k_{leg}) has an important limitation with regard to mathematical interdependence of the variables. Most studies seem to use the same algorithm based on assumptions of how people run (spring-mass paradigm), presented by e.g., McMahon and Cheng (1990) and Farley and Gonzalez (1996), and further developed by Morin et al. (2005) as:

$$k_{leg} = \frac{F_{max}}{\Delta L} \quad (1)$$

$$F_{max} = mg\frac{\pi}{2}\left(\frac{t_a}{t_c} + 1\right) \quad (2)$$

$$\Delta L = L - \sqrt{L^2 - \left(\frac{vt_c}{2}\right)^2} + \Delta y \quad (3)$$

$$\Delta y = -\frac{F_{max}}{m}\left(\frac{t_c}{\pi}\right)^2 + g\,\frac{{t_c}^2}{8} \qquad (4)$$

where t_c is contact time, t_a is aerial time, m is body mass, F_{max} is maximum ground reaction force (GRF), L is leg length, v is running velocity and g is gravitational acceleration. Without deliberating further about the equations and the validity of the assumptions these are based on, it becomes clear that, unless all variables are measured independently, leg stiffness is merely another way of presenting how people run with regard to gross kinematics (contact time and aerial time) and a few anthropometrical parameters. Morin et al. (2005) validated this model by comparing the model force profile against measured force profiles on highly trained middle-distance runners (no 100-m personal best reported, but given the maximum velocity obtained in the study, we estimate this to be slightly above 11 s). The model may not be valid because athletes, and specialists to the highest degree, use an asymmetrical pattern of force application to maximize GRFs and attain faster speeds (Clark and Weyand 2014). At maximal velocity, specialist sprinters may technically move differently from non-specialists, particularly with regard to mimicking spring-mass behaviour. It is worth noting that in Morin et al. (2005) the actual leg length change profile during ground contact was not tested against the model's profile. The spring-mass model and the mathematical approaches to find stiffness values are useful for furthering our understanding of the mechanics of (sprint) running. However, we warn against the notion that the model is considered the analysis 'benchmark'. We argue even stronger that extreme care should be taken when applying such models in practice, particularly if based only on kinematic data. Nagahara and associates (Colyer et al. 2018a; Colyer et al. 2018b; Nagahara et al. 2018a) are the first to collect force data from start to about 50 m in a sprint. Such data in combination with detailed kinematics are needed to validate the spring-mass model in accelerated running.

With our theoretical analysis of leg stiffness in mind, we considered some of the literature using this method. Taylor and Beneke (2012) analysed the kinematic data of 100-m sprints of the three best sprinters of their era during the 2009 World Championship. The absolute best 100-200 m sprinter (ever) demonstrated the lowest stiffness, while the second best demonstrated the highest. In other words, at the highest level, results are inconclusive. When these data are compared with other studies on elite sprinters, non-specialists (100-m best time estimated 11-14+ s) and middle-distance runners (Monte et al. 2017; Morin et al. 2005; Morin et al. 2006; Nagahara et al. 2018b), leg stiffness in the world's best is considerably higher (21-31 vs. 10-18 kNm^{-1}), which is in agreement with the hypothesis that high stiffness is associated with good performance. However, no clear tendency is present from elite to non-specialist. Moreover, Morin et al. (2006) found that leg stiffness was not reduced after performance-deteriorating fatigue. In all, comparisons between these studies suggest that the world's best sprint by adopting a technique marked by a clearly higher leg stiffness value. Even though the ecological validity of the model can be questioned, especially for the world's best, the numbers are in any case an expression of kinematic characteristics, particularly contact time.

Little is known about the development of leg stiffness during the acceleration phase. For non-specialists, leg stiffness does not change during the progression of a 100-m sprint from about 20-30 m, when running speed increase flattens out (Morin et al. 2006). We calculated leg stiffness for our own data (national level sprinters) (Ettema et al. 2016; Haugen et al. 2018a; Haugen et al. 2018b) on a part of the acceleration phase according to (Taylor and Beneke 2012). The results showed stiffness values (~14 kN m^{-1}) that were in accordance with other studies (Monte et al. 2017; Morin et al. 2005; Morin et al. 2006) and varied little from the second step (the first being first ground contact out of the starting block). Taken together, these data suggest that leg stiffness remains relatively unchanged during a 100-m sprint, independent of the phase (acceleration or maximal velocity).

If we consider the origin of the findings regarding leg stiffness, that is, the interdependence of leg stiffness and contact time (and aerial time) (eqs 1-4), the finding of constant stiffness is of interest as both temporal variables change during accelerated running, in opposite direction (Čoh et al. 2006; Debaere et al. 2013a; Nagahara et al. 2014a; Nagahara et al. 2014b; Rabita et al. 2015). In that sense, presenting spatio-temporal characteristics in the form of leg stiffness (except for the very first step) may describe the same mechanism that is shown by more or less unchanged step rate, $SR = \frac{1}{t_c + t_a}$ (t_a is aerial time), during the development of a sprint.

Storage and release of elastic energy – the other side of the spring-mass coin

The notion of storage and reutilisation of elastic energy in running as an energy 'saving' and beneficial mechanism is widely accepted in the literature. We do not rebut this idea in general, but present some critical notes with regard to its usefulness for, as well as empirical evidence in, sprinting. Ample evidence exists that in steady speed running the lower extremity 'at face value' behaves as a spring (see previous section). Whether this behaviour is truly associated with a physical spring mechanism is actually far less (Latash and Zatsiorsky 1993; Morin et al. 2005). Even though some studies on spring-mass models, stiffness and spring-like behaviour warn against this simplification, it may easily be overlooked. The spring mechanism is thought to originate in muscle-tendon units that undergo stretch-shortening cycles, the ideal being the 'concerted' contraction, in which all length change is residing in the tendons and the contractile machinery is acting isometrically as a pure force generator (see Hof et al. 2002). Little direct evidence is available that contractions resembling the concerted mode actually occur during running. Still, through the combination of empirical data and model calculations it seems reasonable to assume that humans, like various other (Biewener et al. 2004; Griffiths 1989; Roberts et al. 1997), are well capable of exploiting this strategy for (re)utilising energy fairly effectively (e.g., Hof et al. 2002; Lai et al. 2014; Lichtwark and Wilson 2007). Thus, the spring-like behaviour of the leg in running is most likely linked to the meaningful use of an actual spring (read "tendon"). Evidence for accelerated running and maximal velocity sprinting is actually quite sparse (e.g., Lai et al. 2016).

As discussed, storage and release of elastic energy takes time, hence it is associated with braking and delayed propulsion. If stiffness of a spring-mass system is increased, its bouncing behaviour will show decreased deformation, unchanged peak force, shorter contact time and less storage and release of elastic energy. This can be easily verified by using Blickhan's model (Blickhan 1989). However, while the world's very best seem to sprint with higher leg stiffness, they also, admittedly based on kinematic analysis with a chance for large error (Taylor and Beneke 2012), seem to generate clearly higher peak ground forces (about 4 times body weight) than found in other studies, which is in agreement with Clark and Weyand (2014). If they only develop higher leg stiffness, these higher forces should not be expected. At the risk of taking the abstraction of the spring-mass paradigm one step further away from real mechanisms, to compare studies with regard to energy storage and release, we estimated the amount of energy involved using $E = \frac{k_{leg}\Delta L^2}{2}$, if only to obtain an approximate comparison. The findings are inconclusive: where the non-specialists (Morin et al. 2006) compare well with the world's best (~2.2 – 2.7 J kg^{-1}) (Taylor and Beneke 2012), the elite and intermediate sprinters (Monte et al. 2017) store and reutilise more energy (~3.5 J kg^{-1}). For the best sprinter ever, we estimated this value to be ~3.3 J kg^{-1}. For the sake of being clear, these data merely indicate how athletes compare in 'spring-mass-like behaviour' as observed from the outside (and here in the energy dimension). The validity of the model with regard to the importance of true storage and release of elastic energy in series-elastic structures (tendons) is still open for debate. We do not argue against that energy is stored and released in tendons during sprinting. However, the argument that because this occurs it is a key element for good performance is flawed. Humans have tendons that stretch under load, not rigid wires that connect muscle to bone. Re-utilisation of stored energy may just as well be a solution to minimise the downside of a 'side effect' of having elastic connectors, rather than a strategy for sprinting performance.

Power

In accelerated running, skeletal muscle must contribute significantly in doing work because the mechanical kinetic energy of CoM is to be increased. Thus, a pure elastic function, like in concerted contractions (Hof et al. 2002), is not possible as a general principle; some major muscles must produce work in concentric contraction. In maximal velocity sprinting, the use of elastic energy most likely occurs because of the braking phase during landing, irrespective of the direction of CoM velocity reduction, as well as to do work against drag. If the spring-mass paradigm were to be verified by identifying spring mechanisms (not just behaviour), it cannot be the only mechanism of relevance in accelerated running and maximal velocity sprinting.

Samozino et al. (2016), provide a good basis for the magnitude of power that needs to be generated in sprinting. They based their calculations on a mono-exponential development of speed during 100-m sprint, a well-validated function (Chelly and Denis 2001; di Prampero et al. 2005; Ettema et al. 2016; Furusawa et al. 1927; Morin et al. 2006). Using this method on world-level performance, peak power easily exceeds 2000 W in men (up to 2500 W) and about half in women (Slawinski et al. 2017). During maximal velocity sprinting, power against drag amounts to ~300 W (based on Samozino et al. (2016) – using 10 ms^{-1} maximum velocity). Given that some power will be lost due to segment movements relative to CoM, which are not included in the abovementioned values, total muscle mechanical power is likely higher.

We can compare these values with the (approximate) value for 'elastic' energy storage and release of 3 J kg^{-1} presented in the previous section by multiplying this with a typical step frequency of 4.5 Hz (e.g., Graubner and Nixdorf 2011; Nagahara et al. 2018b; Rabita et al. 2015). For an 80-kg athlete, this gives a value of ~1000 W. Thus, once again, if the spring-mass model reflects true spring mechanisms, this gross analysis indicates that both power production and the storage and reutilisation of elastic power are significant mechanisms in sprinting, the former most prominent during acceleration, the latter at maximal velocity sprinting.

Based on a large sample of sprinting athletes, Haugen et al. (2019) reported very large correlations between maximum horizontal power output (P_{max}) and sprint performance; the shorter the sprint distance, the higher the association was with P_{max}. However, the strength of this relationship diminishes in homogenous subsets of elite sprinters (Slawinski et al. 2017). The relationship between sprint improvement and power increase is not linear, but exponential (Seiler et al. 2007). Sprint time differences are accompanied by a threefold difference in power output (Haugen et al. 2019; Kristensen et al. 2006). Haugen et al. (2019) reported step-averaged P_{max} values in the range 13-25 and 11-21 $W \cdot kg^{-1}$ for men and women, respectively, based on sprint tests of 666 elite athletes from 23 different sports. Slawinski et al. (2017) reported that P_{max} in male and female world-class sprinters was 30.3 ± 2.5 and 24.5 ± 4.2 $W \cdot kg^{-1}$, respectively, typically attained after ~1 s of sprinting. The highest individual values were 36.1 $W \cdot kg^{-1}$ and 29.3 $W \cdot kg^{-1}$, representing current upper limits in humans (Haugen et al. 2018c).

Metabolic demands

Sprint running relies heavily on anaerobic metabolism. During a single 6-s sprint, the relative energy system contributions from stored ATP, stored phosphocreatine, anaerobic glycolysis and aerobic processes are reported to be ~ 6, 46, 40 and 8%, respectively (Girard et al. 2011). Logically, the aerobic contribution of ATP resynthesis increases with increasing sprint duration. On the basis of accumulated oxygen deficit (AOD) measures, the relative anaerobic energy system contribution is estimated to be about 80% for 100-m, 70% for 200-m and 60% for 400-m runs (Duffield et al. 2004, 2005; Nummela and Rusko 1995; Spencer and Gastin 2001; Zouhal et al. 2010). However, the AOD method has clear limitations for estimation of metabolic power during brief and intense exercise (Gastin 2001). Estimates based on lactate measures and mathematical modelling display higher anaerobic energy contribution during sprinting compared to AOD measures (Duffield et al. 2004). Although instantaneous energy delivery is mainly anaerobic in sprinting, still 80-95% of peak oxygen uptake is obtained during a 400-m run (Duffield et al. 2005; Hanon et al. 2010; Nummela and Rusko 1995) and reached after ~25 s, i.e., ~200 m (Hanon et al. 2010). Possibly due to the same challenges, no relationship is found between sprint performance and blood lactate values (3-7 minutes) after 100-m sprinting (Hautier et al. 1994; Hirvonen et al. 1987), typically being 8-10 $mmol \cdot l^{-1}$ (Duffield et al. 2004; Hautier et al. 1994; Hirvonen et al. 1987). However, significant relationships between 200 and 400-m sprint performance and physiological variables, such as AOD (Dal Pupo et al. 2013; Weyand et al. 1993; Weyand et al. 1994), blood lactate level (Lacour et al. 1990; Nummela et al. 1992; Weyand et al. 1994) and plasma enzyme activity (Ohkuwa et al. 1984) have been reported.

Another approach has been developed by considering cost of force production in sprinting and mechanical equivalents in uphill and downhill steady speed running (di Prampero et al. 2005). For the latter, physiological steady state can be achieved and a metabolic cost can be estimated. Thus, this approach avoids the inherent challenge of the physiological non-steady state in sprinting. In the model, any acceleration corresponds to a particular slope (di Prampero et al. 2005). Based on this approach, metabolic power over the first 30-m of Usain Bolt's 100-m world record race was estimated to 104 (mean) and 199 (peak) $W \cdot kg^{-1}$. Corresponding values for intermediate sprinters (100-m personal best 11.30 ±0.35 s) were 44 and 92 $W \cdot kg^{-1}$ (di Prampero et al. 2015). Beneke and Taylor (2010) made estimates on world-level sprint performance based on the same principles, but reached different peak values. Hoogkamer et al. (2014) approached this issue in more detail by taking into account several identifiable energy cost components. Even this more detailed approach relies on assumptions about efficiency of doing muscle work, which the model outcome is quite sensitive for. Thus, as Hoogkamer et al. (2014) explicitly point out as well, at present, these types of approaches should aim at understanding general principles rather than at coming to exact estimates of metabolic cost in sprinting.

Horizontal and vertical combined: one action

Decomposition of one force

The horizontal component of propulsive force is often referred to as 'effective force', because only this component leads to acceleration in the horizontal (end-goal) direction. The rationale seems logical, because one differentiates between total force production and one component that, likely through technique, can be maximised. The use of this term, however, is misleading because it implicitly suggests that the perpendicular, vertical component is 'ineffective' and should be minimised. It may be obvious that without any (or with low) vertical GRF, an athlete would not be able to keep upright, let alone sprint. We do not suggest that authors using this term mean to state that vertical force is a 'waste', but expressing effective force in percentage of total GRF (Morin et al. 2011a) can easily be misinterpreted to mean that any vertical force component could be avoided. Adding to the argument, the expression as a percentage (F_{eff}%) suggests that the other component of GRF equals 100-F_{eff}%, which obviously is incorrect. In fact, the expression is simply the cosine of the angle between total GRF and the horizontal, and thus merely indicates the direction of the GRF vector. There is nothing wrong with this kind of information, but it bears an unfortunate 'label'. The use of 'ratio of forces' (RF) (e.g., Morin et al. 2011a) is more appropriate. Force effectiveness and RF have been introduced in sprint running as an analogy to the analysis of perpendicular crank force in cycling (see e.g., Samozino et al. 2016). However, in cycling, although hardly avoidable, a force component in line with the crank arm (i.e., not contributing to crank moment) is not a mechanical requirement. In running, the perpendicular component is required, and thus, RF (or force direction) must be interpreted differently than in cycling.

Work analysis in force decomposition

The approach described above is increasingly problematic when considering work that must be done by the athlete. A proper naming of GRF components in a propulsion action is by the definition of work (W), i.e., the dot product of force (F) and associated displacement (d) of CoM: $W = \|F\| \cdot \|d\| cos\theta$, θ being the angle between the force and displacement vectors. The size of the 'effective' component of the GRF equals $\|F\| cos\theta$, i.e., the force component in the direction of movement of CoM. In accelerated running, CoM moves obliquely forward-upward, as does the propulsive component. Any component perpendicular to this movement direction is associated with change of that direction (as in centripetal force). If such a component exists, CoM's movement will be curvilinear. If this is beneficial for sprinting performance or if such a component is to be regarded as 'waste', and if so, if it is a necessary investment, are central questions that cannot be answered by only considering force components in the end-goal direction. Work is a scalar; it may be associated with movement in a particular direction (vector), but it has no direction itself. This distinction is essential for understanding that work done in a vertical movement may be (re)utilised in horizontal movement.

This issue is best exemplified by considering a perfect circular motion of an object at constant speed, driven by a centripetal force (Fig. 1). When analysing this situation, one will find that the product of centripetal force- and displacement components in 'end-goal' direction will lead to the correct amount of 'quasi work' done. That is, it equals the increase in kinetic energy associated with motion in end-goal direction. Apparently, energy has been 'transferred' from the original state to the end-state with a redirected velocity vector. Thus, work seems to be associated with the centripetal force, which by definition is not possible. The solution to this paradox is that when incorporating the same product for force - and displacement components orthogonal to the end-goal direction, the same but negative ‘work’ is obtained. The centripetal force’s only action is changing the velocity vector’s direction, while the kinetic energy associated with this vector is maintained. Mathematically this is represented as instantaneous increase in kinetic energy associated with end-goal direction motion and an identical reduction of energy associated with starting direction of motion. Both amounts are truly ‘fictive work’; they appear mathematically, but no real work is done. Consequently, decomposing forces into components in the end-goal direction (positive power) and perpendicular to it (negative power) leads to the correct outcome if all dimensions are included in the analysis. However, analysing only one (end-goal directed) dimension, and ignoring the orthogonal one(s), may lead to erroneous findings about the work done by end-goal directed ‘propulsive’ forces. We refer to e.g., van Ingen Schenau and Cavanagh (1990) and Donelan et al. (2002) for a detailed description of analysis.

Approaches calculating power directly from horizontal forces and horizontal velocity (e.g., Morin et al. 2011a), not accounting for CoM movement direction, only provide information about propulsion outcome, not about instantaneous power, i.e., where and when power that leads to propulsion is generated. As long as only mean power over a whole movement cycle is considered (e.g., Samozino et al. 2016; Slawinski et al. 2017), the outcome is valid because mean power associated with vertical movement (perpendicular to propulsion) will be zero. However, such approaches may give misleading results regarding power delivered by the athlete through GRF and will not provide insight into the mechanisms leading to power generation and end-goal directed motion. This issue on dynamics analysis is not restricted to sprint running. Interesting parallels can be found in speed skating, cross-country ski-skating (both entailing zig-zag motion of CoM in the horizontal plane) and ski poling (Göpfert et al. 2016; Smith 1992; Stöggl and Holmberg 2016).

Force direction: technique or strength capacity?

Having emphasised the mechanical importance of the vertical component of GRF in sprinting, ultimately, only the horizontal component leads to acceleration (and maintenance of speed) in the horizontal direction, and, therefore, should be as large as possible. Given the vertical component being equal to $F_v = F_g \frac{t_{cycle}}{t_c}$, the direction of the total GRF equals $\alpha = \text{asin}\left(\frac{F_g \frac{t_{cycle}}{t_c}}{F_h}\right)$, F_h being horizontal force. If we assume that the GRF should be directed through (or close to) the CoM, the line between CoM and ground contact point (of push-off) should have approximately the same angle. The typical start position allows for making α as small as possible (e.g., Morin et al. 2011a; Morin et al. 2011b; Samozino et al. 2016). The angle increases during accelerated running and approaches 90° (RF=0) at maximum sprint velocity, and is linearly dependent on velocity (Samozino et al. 2016). Similar results can be deduced from (Haugen et al. 2018a) and (Ettema et al. 2016), showing that touchdown and lift-off angles gradually increase throughout the acceleration phase. That is, the sprinter's support area shifts forward relative to CoM with increasing sprint velocity. When assuming start position, sprinting athletes typically lower their CoM ~20 cm (compared to upright position), which is accomplished by a combination of lowering the hips (i.e., bending the knees) and leaning the upper body forward (Haugen et al. 2018a; Nagahara et al. 2014b; Otsuka et al. 2016; Slawinski et al. 2010). Competitive sprinters are able to sprint with their CoM in front of the support area during the 3-4 initial steps (Haugen et al. 2018a; Mero et al. 1983). However, given the muscle force-velocity characteristics in motion, the upper body must gradually be moved upright because one is simply not strong enough to generate the same required forces at high speed. Haugen et al. (2018a) reported that trunk angle (relative to the horizontal) in well-trained sprinters increased from 36 ±7 (first step) to 84 ±3° (maximum velocity) throughout acceleration, and (Nagahara et al. 2014b) observed a similar development.

Generating a larger horizontal force cannot be obtained by simply changing the direction of a given total GRF (in conjunction with changing body angling, i.e., CoM-support line). On the contrary, it can only be obtained by a combination of a larger horizontal force and upholding at least the same vertical component. Thus, the total GRF must increase. Once more, as a sprint develops and speed increases, given the force-velocity characteristics in motion, this will be even harder. We do not suggest that technical ability does not play a role, but we disagree with the notion that RF and its decrease during accelerated running (D_{RF}) describes a pure technical ability in which a small absolute D_{RF} value, i.e., small decline of RF over velocity, relates to good performance (Morin et al. 2011a; Samozino et al. 2016). In the abovementioned, recently developed models, possibly most completely described by Samozino et al. (2016), running speed is assumed to develop according to a mono-exponential function given a time constant, τ. Thus, τ is a measure of acceleration capability independent of the maximum velocity. As mentioned earlier, the general validity of this model is well established. In the model, D_{RF} is the outcome of the combination of maximum velocity and τ. In other words, D_{RF} is a different way of looking at performance outcome and does not discriminate between capacity and technical ability. The relationship between D_{RF} and performance depends on which parameter – acceleration capability (τ) or maximum velocity – that is affected in the description of athletic capacity and performance. If τ is improved, absolute D_{RF} is increased; if maximum sprint velocity is improved, the opposite occurs. The extremely high correlation (r=0.99, n=666) found between D_{RF} and the slope of the constructed force-velocity development during sprinting (S_{FV}) for athletes in a wide range of sports (Haugen et al. 2019) points in the same direction of strong mathematical interdependence of these variables because they are model outcomes from the same measurement data.

On a sprint track, using spikes, one may assume that horizontal friction is not a delimiting factor. The placement of the CoM far in front of the push-off area (feet at ground contact) allows for a large horizontal force component while the total force is directed towards CoM. The ability to keep the body in this angled position depends on forces the athlete is able to generate, not vice versa. Interestingly, kinematic data from Ettema et al. (2016), their S1 – supporting information file, suggest an average D_{RF} value of -0.048 (% sm^{-1}) for national level sprinters, which is very close to the lowest absolute value reported by Morin et al. (2011a) on non-specialists (-0.051). These data indicate that τ is correlated with performance when comparing athletes (Morin et al. 2011a) and effect of fatigue (Morin et al. 2011b), which suggests that in practice the impact of maximum velocity supersedes that of acceleration capability. In the data by Ettema et al. (2016) τ shows no relationship with performance at all (r=0.06, n=24). The latter may be caused by the rather homogeneous performance level in the group of participants, but not by a lack of differences between athletes regarding D_{RF} (range -0.039 to -0.062). In conclusion on D_{RF} and related mechanisms, in light of the above-presented model, it is not possible to alter D_{RF} given the performance capacity of a sprinter as expressed in τ and maximum velocity. Of course, the model is nothing more than that, a model, even if it describes velocity development during sprinting very well.

Translation to practice – directly observable variables

Spatiotemporal variables

The world's fastest male and female track sprinters reach maximum velocities of ~12 and ~11 $m \cdot s^{-1}$, respectively (Graubner and Nixdorf 2011; Slawinski et al. 2017). The duration of the acceleration period is well documented and varies as a function of athlete performance level. International and national 100-m track sprinters achieve maximum velocity after 50-80 and 40-50 m of sprinting, respectively (Arsac and Locatelli 2002; Bae et al. 2011; Debaere et al. 2013b;

Graubner and Nixdorf 2011; Nagahara et al. 2014a; Nagahara et al. 2014b; Taylor and Beneke 2012), and men peak at ~20% further in distance than women (Debaere et al. 2013b; Graubner and Nixdorf 2011; Slawinski et al. 2017). In contrast, non-specialists typically achieve maximum velocity at ~30 m of linear accelerated running (Babić et al. 2011; Chatzilazaridis et al. 2012; Haugen et al. 2012, 2013).

Sprint speed is a product of step length and step rate. Step length development follows a hyperbolic pattern, similar to velocity, with steep increases in the early acceleration phase (Bae et al. 2011; Chatzilazaridis et al. 2012; Čoh et al. 2006; Graubner and Nixdorf 2011; Haugen et al. 2018a; Hay 2002; Nagahara et al. 2014a; Nagahara et al. 2014b), stabilising at the time of maximum velocity (Chatzilazaridis et al. 2012; Debaere et al. 2013b; Nagahara et al. 2014a; Nagahara et al. 2014b). Step length at the end of the acceleration phase in male and female world-class sprinters is in the range 2.3-2.8 m and 2.05-2.3 m, respectively, while corresponding values for step rates are in the range 4.5-5.0 Hz for both men and women (Graubner and Nixdorf 2011; Rabita et al. 2015). Men have longer absolute step lengths than women, but these differences diminish or reduce considerably when normalised for body height (Debaere et al. 2013b). There is a large inter-subject variability regarding when maximum step rate is achieved (Bae et al. 2011; Chatzilazaridis et al. 2012; Čoh et al. 2001; Debaere et al. 2013b; Graubner and Nixdorf 2011; Nagahara et al. 2014a; Nagahara et al. 2014b; Nummela et al. 2007), but step rate exceeds 90% of the rates attained at maximum velocity for most athletes already by the first step (Debaere et al. 2013b; Haugen et al. 2018a; Nagahara et al. 2014a; Nagahara et al. 2014b).

Several studies have shown that step length remains stable over time in well-trained sprinters, and individual performance-changes across competitions, trials or between training and competition are mainly regulated by step rate (Bezodis et al. 2018; Haugen et al. 2018a; Hunter et al. 2004a; Otsuka et al. 2016). Anecdotally, the classic Ben Johnson steroid abuse case has gained considerable attention among practitioners over the years. Visual inspections of television recordings reveal that his 0.65-s improvement over 100-m sprint, from 10.44 s in 1983 (World Championships in Helsinki) to 9.79 s in 1988 (Olympic Games in Seoul), was caused exclusively by increased step rate as he used 46.5 steps over the distance in both of these competitions. Overall, step rate seems to be the speed modulator in well-trained sprinters at an intra-individual level. However, differences in step length between fast and intermediate sprinters are more pronounced than differences in step rate (Babić et al. 2011; Brughelli et al. 2011; Hay 2002; Korhonen et al. 2009). Contact time in well-trained sprinters reduces gradually from 0.15-0.20 s in the first step to nearly half at the time of maximum velocity, whereas aerial time increases gradually throughout acceleration (Čoh et al. 2006; Debaere et al. 2013b; Ettema et al. 2016; Haugen et al. 2018a; Nagahara et al. 2014a; Nagahara et al. 2014b; Rabita et al. 2015). Faster athletes achieve shorter ground contact times during sprinting, without significant differences in aerial time, compared to slower athletes (Chatzilazaridis et al. 2012; Čoh et al. 2001; Lockie et al. 2013; Murphy et al. 2003; Otsuka et al. 2016). Because contact time is strongly associated with step rate, it is not surprising that changes in individual sprint performance across trials are accompanied by changes in contact time, at least when approaching maximum velocity (Haugen et al. 2018a). Indeed, contact time is without any overlap the lowest (<0.1 s) in the world's best (Taylor and Beneke 2012) and higher in all other studies used here (> 0.1 s). In all, the above suggests that sprint conditioning in most well-trained senior sprinters should be targeted to enhance step rate.

Link to coaching philosophies

These main characteristics of sprinting can be summarised as follows: to sprint fast, for starters, one needs to be able to generate large strides (step length), which requires strength. Using this principal ability, generating a high step rate will lead to further development of performance.

Moving the swing leg forward quickly allows for a rapid preparation for the next propulsion. Moreover, such strong forward movement of the swing leg (while the contralateral leg has ground contact) contributes to propulsion, similar to arm swing in jumping, a mechanism that has been overlooked in most sprint literature. The kinematics of the swing leg action should be executed purposefully so that during initial ground contact, braking forces are kept low and forceful propulsion may occur as quickly as possible. Logically, this leads to low contact times as an outcome, not as an aim by itself. These principles are described in different educational terms in practice. The focus on what happens at the front of the body's midline, referred to as 'front-side mechanics' (Mann and Murphy 2015), reflects the notion of bringing the swing leg forward quickly. This philosophy should not be mistaken as saying that what happens at the 'back-side' is of no importance. After all, the propulsive push-off happens at the 'back-side'. Indeed, recent observations by Haugen et al. (2018a) do not support the notion that variables related to the 'front-side' are better performance predictors than spatiotemporal variables and variables related to segment configurations and - velocities at touchdown. This suggests that although the 'front-side mechanics' philosophy can be defended with sound mechanics, the kinematics that are focused on may be of educational value rather than an end-goal. However, on a critical note, the notion that since the force generated during the very last part of ground contact is minimal, sprinters could move to the 'front-side' earlier by skipping this 'unproductive' part (Mann and Murphy 2015) is flawed; at the end of push-off, force is, 'by law', bound to be low and will reach zero at lift-off independent of running technique.

The purposeful landing movement of the swing leg is often referred to as the 'active touchdown' and 'foot speed' philosophy (Hunter et al. 2004b, 2005). While these terms may seem redundant or uncommunicative for the scientist, from a didactic perspective they indicate that foot placement at initial ground contact must be executed consciously and is not a part of the step cycle that just happens automatically. 'Foot speed' refers to the notion that the foot should have minimal velocity at ground contact, which from a mechanical perspective seems like an 'open door', but from a didactic point of view ensures that the athlete initiates a movement of the leg backwards relative to CoM, such that propulsion can be initiated early during ground contact and braking is minimised. The same applies for the 'hip extension - knee flexion' philosophy, which is the joint kinematics translation of the same principle (see e.g., Mann et al. 1984; Mann and Sprague 1980). Scientific support for these 'hip extension' or 'foot speed' philosophies also arises from the association between sprint performance and angular kinematics of the stance thigh (Kunz and Kaufmann 1981; Mann and Herman 1985; Mann and Sprague 1980), hip extension strength (Guskiewicz et al. 1993) and hip extensor activity (Wiemann and Tidow 1995). Hunter et al. (2005) observed a significant relationship between an 'active' touchdown (low horizontal ankle velocity relative to the ground immediately prior to touchdown) at the 16-m mark and magnitude of braking forces, but did not relate this variable to sprint performance. Haugen et al. (2018a) observed significant correlations (moderate to large effect magnitudes) between horizontal ankle velocity relative to CoM and mean step speed during accelerated running. Inevitably, horizontal ankle velocity relative to CoM during support must be equal to forward velocity (i.e., performance). Therefore, it would be reasonable to expect a significant relationship between sprint performance and lower-limb segment velocities immediately prior to touchdown as well.

Final remarks

We have described sprint running from a mechanics perspective, and critically reviewed (part of) the literature, highlighting some pitfalls regarding interpretation and consequences for the practical field. The basic principles of accelerated running are relatively simple, the way an athlete handles the mechanical constraints and utilises the opportunities is far more complex. Well established didactic philosophies on the technical execution may at face-value seem awkward in the eye of the scientist, but still make sense when analysed keeping ‘translation’ in mind.

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Figure legend

Figure 1: Analysis of power of constant speed circular motion, driven by a centripetal force (F). Power equals the dot product of force (F) and velocity (v) vectors. This analysis can be performed on the decomposed vectors in original (o) and end (e) direction, but should never be considered in isolation. Fictitious loss of kinetic energy (negative power P_o) associated with the original movement direction is instantaneously nullified by the fictitious gain of kinetic energy (positive power P_e) in the end direction. Thus, no work is done at any time by the total (centripetal) force.

Figure

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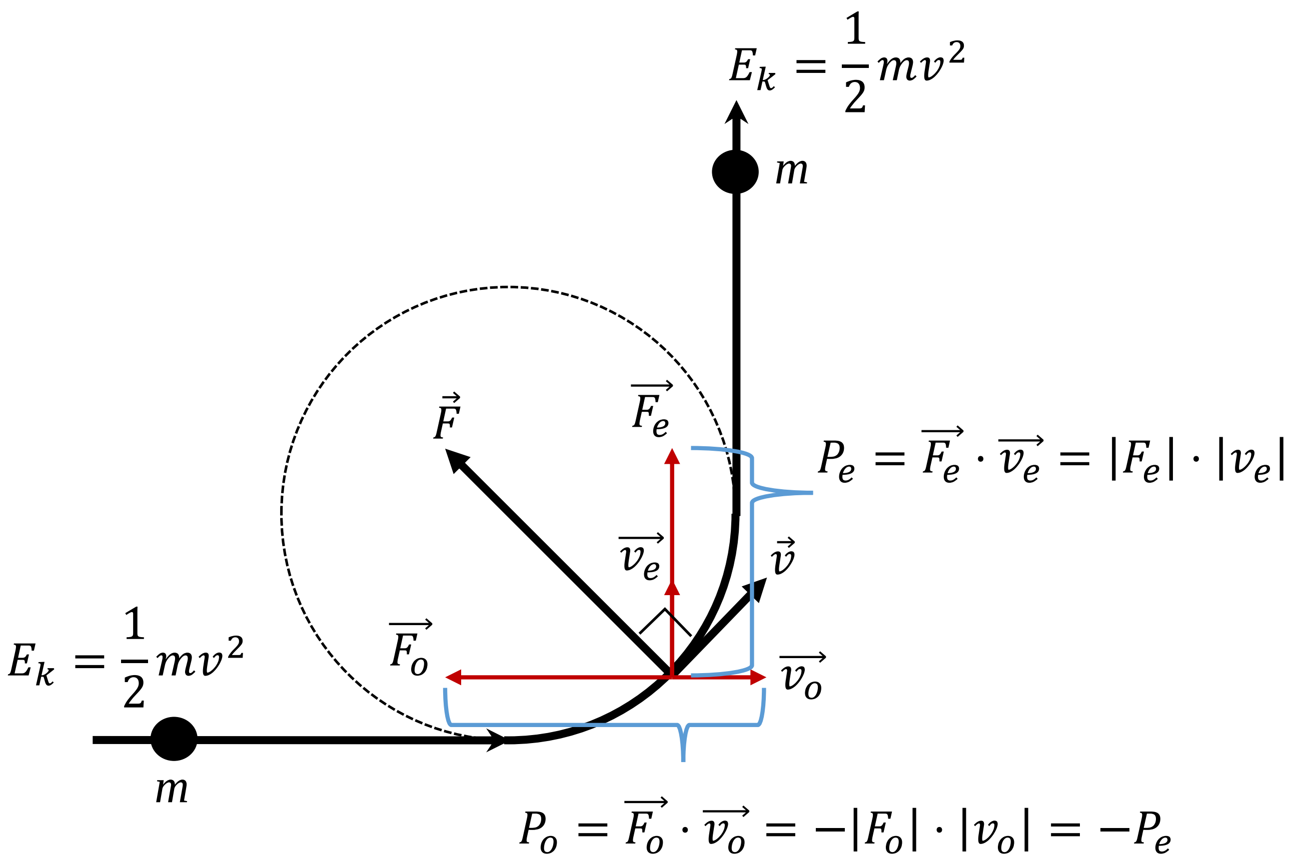

Authors contribution statement

All the authors (TH, DM, GE) contributed significantly in editing, compiling evidence, synthesizing, proof reading, and revising the manuscript. All authors read and approved the final manuscript.