The Science and Practice of Middle and Long Distance Running

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Chapter 2: The Biomechanics of Distance Running

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- Running speed is dictated by an athlete's step length and cadence, although step length is more important in differentiating between faster and slower runners, and reduces more with fatigue. Being able to increase cadence, however, is often the deciding factor in sprint finishes.

- Of the different components that make up step length, the distance the body travels during flight is the most important. An athlete's flight distance is determined by upward and forward impulse in late stance, which usually decrease with fatigue because of reduced leg stiffness and tolerance to repeated stretch loads.

- Middle-distance runners are more likely to land on the forefoot or midfoot at first contact, whereas marathon runners tend to land on the heel. There are potential performance benefits to landing near the front of the foot through the stretch-shortening cycle and shorter contact times, although these apply less in longer events.

- There are small gains to be made from following rival runners in terms of air resistance, although having air moving around the body for cooling is important in hot conditions. Running uphill is unsurprisingly more energy costly than running on flat courses, but running downhill can risk injury because of the increased load on the knee, hip, and shin muscles.

- Running of soft surfaces, such as in cross country running, is more difficult than on roads because the non-compliant nature of the surface reduces the effectiveness of the stretch-shortening cycle, and is more energy costly because of an increase in leg stiffness to accommodate a reduction in stability.

Introduction

A knowledge of the biomechanics of running is invaluable when describing an athlete's technique, explaining how they speed up or slow down, and understanding the external and internal forces that cause their movements. As the outward expression of movement, an athlete's biomechanics translates their underlying physiological, nutritional and psychological processes into running motion, and those who are biomechanically "better" are often those who can manage this transfer more efficiently and economically while reducing injury risk. This chapter provides a brief review of the important aspects of the running stride and its various components, the effects of different footstrike patterns and fatigue on running technique, and how racing conditions such as wind, hills and underfoot surface affect an athlete's biomechanics.

Step length and cadence

Running speed is the product of step length and cadence, the latter of which is often referred to as step rate or step frequency. Step length is the distance between successive foot contacts from a specific gait event on one foot to the equivalent event on the other foot, and is measured in metres (m). The term 'stride length' is sometimes used interchangeably with 'step length' (Enomoto et al, 2008); however, stride length is most often used to refer to the distance between a specific gait event on one foot to the equivalent event on the same foot (e.g., Cavanagh and Kram, 1989). Hence, a stride refers to two successive steps (Levine, Richards and Whittle, 2012). Cadence measures how frequently the runner completes a step in a given time, usually per second (measured in hertz, Hz). As speed is step length multiplied by cadence, an athlete with a step length of 1.50 m and a cadence of 3.00 Hz runs at 4.5 metres per second ($m \cdot s^{-1}$). To convert $m \cdot s^{-1}$ to kilometres per hour ($km \cdot h^{-1}$), we multiply by 3.6. Thus, our runner's speed of 4.5 $m \cdot s^{-1}$ is equivalent to 16.2 $km \cdot h^{-1}$.

It is clear that both step length and cadence are important to running speed. However, cadence tends to vary less between distance runners, ranging from about 2.75 to 3.25 Hz (165 to 195 steps per minute). In middle-distance running, which includes fast starts and bursts of speed (e.g., to reach the bend before other athletes, or avoid being boxed in), athletes have to accelerate to ensure a good position. Increasing cadence in middle-distance races is therefore a performance-determining factor because of these short phases of great acceleration (Reiss, Ernest and Gohlitz, 1993). Over 800 m and 1500 m, individuals usually change from sub-maximal to maximum speed by increasing cadence, as step length is already close to its maximum at competition pace (Hunter, Marshall and McNair, 2004). Cadence also increases during sprint finishes; for example, when Kenenisa Bekele won the 2007 World Championship 10,000 m, his step length was relatively constant at approximately 1.95 m throughout the race, and it was by increasing cadence during the last lap (from 3.2 Hz to 3.6 Hz) that he was able to achieve such a fast finish (Enomoto et al, 2008). At running speeds outside of the sprint finish, increases in speed normally arise from increases in step length, with an optimal step length and cadence unconsciously chosen by athletes to minimise energy expenditure (Saunders et al, 2004).

Overall, most distance runners have techniques that optimise performance within their physical and anthropometric builds where, ultimately, step length is limited by the athlete's stature and, more specifically, their leg length. Of course, this does not mean that short athletes cannot succeed in distance running; indeed, many of the world's best ever athletes are shorter than average, e.g., the hugely successful Ethiopian distance runners, Haile Gebrselassie and Kenenisa Bekele, are about 1.65 m tall (5' 5"). Bushnell and Hunter (2007) found that distance runners' sprinting techniques differed from trained sprinters and suggested that this might be because distance runners practise sprint technique less and are unable to change technique greatly to increase cadence during sprint finishes. Coaches are therefore advised to include sprint technique training into competitive distance runners' schedules.

Components of step length

Step length is the sum of four distinct but interrelated components. At first contact, the athlete strikes the ground with the foot, and the distance from the whole body centre of mass (CM) to the foot centre of mass is the first of these components (here, I have termed this “foot ahead”). The body then rolls forwards over the support foot until toe-off, in phases that can be most easily summarised as early stance, midstance and late stance. The distance the foot moves from its horizontal position at first contact until toe-off is the second component contributing to step length (“foot movement”). Although this action is vital for correct running gait, foot movement is a relatively small contributor to overall step length and does not differentiate between faster and slower running. The distance from the CM to the foot centre of mass at toe-off is the third of the four components, which I have termed “foot behind”. These three components occur during the contact phase, which has a shorter duration in faster running (because it leads to a higher cadence), and decreasing contact time is indeed one way by which distance runners speed up (Bushnell and Hunter, 2007). After the contact phase, the athlete has an airborne period during which the CM will experience a flight distance (the fourth and final component) before first contact occurs on the other foot and the gait cycle is repeated.

In effect, the three most important components of step length are the distance the foot lands in front of the body, the distance the foot is behind the body at toe-off, and how far the athlete travels during flight. To be successful, the athlete must cover sufficient distances during each of these phases, but running faster is not a simple case of increasing any or all of these components. First, the athlete needs to take care that the foot ahead distance is not too great (sometimes termed “overstriding”) as the increased braking forces that occur slow the runner more than necessary (Moore, 2016). However, it should be noted that braking at first contact with the ground is normal and, although it often appears in fast-moving elite athletes that the foot is landing directly under the body, it does not and to physically undertake such actions would adversely reduce step length. Second, the foot behind distance occurs during late stance when the hip, knee and ankle are extending to push the body forwards. However, as with foot ahead distance, the athlete should take care not to deliberately overextend as the increase in contact time not only decreases cadence, but also occurs when the lower limb joints are no longer particularly effective. In general, there is little difference in foot ahead or foot behind distances between elite standard athletes. Although the athlete cannot speed up during flight in the absence of anything to push forwards against, and in fact slightly slows down because of air resistance, flight distance contributes so much to step length that it is the biggest differentiator between athletes. When running slowly, by contrast, flight distance can be very small. Merely instructing an athlete to increase any of these distances is unlikely to be productive; rather, it is through training, particularly at fast speeds and supplemented appropriately with technical and resistance training, that the athlete learns to get the right balance for their stature, strength and ability.

Ground reaction forces in running

The importance of the stance phase during running is obvious given it is during ground contact that the body applies an external force to generate forward momentum. In simple terms, a force causes a change in velocity and, when running, different external forces are experienced. These include ground reaction forces in late stance that accelerate the athlete upwards and forwards, air resistance that causes slowing down, and frictional forces that provide grip. A force is a vector, which means that it has a magnitude (measured in newtons, N) and a direction (Winter et al, 2016). It can be quite difficult to analyse forces as single vectors so, in biomechanics, the ground reaction forces between the body and running surface are very often resolved into three directions: vertical (the only direction affected by gravity), forwards-backwards, and side-to-side. When a person stands still on a weighing scale, the value on the display is their vertical ground reaction force (i.e., their weight), although it is normally displayed in the technically incorrect but more familiar units of kilograms or pounds.

Because people's weights vary considerably, it is quite normal in biomechanics to present force magnitudes in bodyweights (BW), whereby the forces measured are divided by the athlete's weight. For example, if a runner who weighs 600 N (approximately 61 kg / 135 lb) experiences a landing force of 900 N, we could express this as 1.5 BW.

At first contact with the ground, the runner experiences a large impact force of between 2 and 3 BW (Cavanagh, 1990). Because the impact force occurs very early in the gait cycle, the muscles are often unprepared for it and respond through passive deformation of body tissues (Watkins, 2010). This "muscle latency" period lasts about 70 milliseconds, and the combination of relatively large impact forces and the inability of the body to respond fully mean that there is more variability within limbs, and asymmetry between them, than during the rest of the gait cycle (Hanley and Tucker, 2018). Vertical forces during running tend to increase during early stance with a peak at midstance, associated with controlling the downwards movement of the CM, and preventing any vertical collapse during this weight acceptance phase (Winter and Bishop, 1992); lower limb joint stiffness is therefore a key factor in maintaining posture during this phase (Serpell et al, 2012). Note here that "stiffness", the relationship between the deformation of a body and a given force (Butler, Crowell III and McClay Davis, 2003), is used to explain in simple terms how much or how little the lower extremity joints bend during stance, rather than tightness or soreness in the muscles after exercise.

Although vertical forces, and probably more so side-to-side forces, are difficult to link with performance (Cavanagh, 1990), the role of forwards-backwards forces are easier to understand in terms of running speed. Both the braking and propulsive forces that occur in this force direction have peak magnitudes of between 0.3 and 0.5 BW (Cavanagh and Lafortune, 1980; Munro, Miller and Fuglevand, 1987), although what is more important is not the peak force but the total force applied during each phase. The product of force and time is impulse, defined as the change in momentum (Winter et al, 2016). Put simply, the larger the negative impulse during braking in early stance, the more the athlete will decelerate, which requires a similarly large positive impulse during late stance to speed up enough to maintain an overall constant speed (Chang and Kram, 1999). Maintaining a constant pace is therefore easier when the braking impulses are kept low, which theoretically occurs with a shorter foot ahead distance (Moore, 2016) and emphasises the biomechanical advantage of avoiding overstriding.

Movements and muscles involved in running

We have already noted that there are effectively two phases that contribute to step length and cadence during running: a contact phase and a flight phase. These arise because each leg goes through a period where it is in stance (the contact phase) and a period in swing, comprising early swing, midswing and late swing. In normal running, each leg's swing phase is longer than the stance phase, and it is during the short time when both legs are in swing that flight time occurs, whereby one leg is in early swing, just after toe-off, and the other leg is in late swing, just before first contact (Novacheck, 1998). This of course means that during normal running, there is no occasion when both feet are in contact with the ground at the same time. For ease of explanation, the following sections will describe joint and body segment movements during the stance and swing phases, although it should be remembered that these are, in reality, interdependent parts of a continuous movement. In addition, as there are hundreds of muscles involved in running, only the activity of large muscle groups will be considered.

Muscle moments and powers

Before discussing the movements of the body's joints and segments, it is useful to understand a little about the internal forces produced by muscles. Muscles act on bones to create movements at joints via tendons; for example, the soleus muscle in the calf pulls on the calcaneus (heel bone) via the Achilles tendon to plantarflex the ankle. It is often helpful to consider the muscle and tendon as part of one unit, rather than separate, and refer to it as the muscle-tendon unit (MTU). Most of the movements in running are rotational, such as knee flexion, and joint moments (or torques) indicate the amount and direction of rotational force about a joint. These are useful because they describe the relative contributions of different muscle groups during certain movement phases (Enoka, 2008). Calculations of mechanical power are used to complement the joint moment information by measuring the rate of work done by MTUs across a joint (White and Winter, 1985). MTUs that shorten when activated (often described as “concentric”) generate power, whereas those that lengthen (“eccentric”) absorb it (Vardaxis and Hoshizaki, 1989). Power that has been absorbed in MTUs stores elastic energy that can be later converted to kinetic energy with resulting power generation (Cavagna, Dusman, and Margaria, 1968) through the stretch-shortening cycle mechanism that increases running efficiency (Cavagna, Saibene, and Margaria, 1964). The stretch-shortening cycle is a complicated phenomenon, but in essence refers to the rapid lengthening and subsequent shortening of an MTU, whereby the early stretch absorbs energy that enhances performance during the concentric phase of activity (Komi, 2000).

In distance running, some joint stiffness is required for optimal usage of the stretch-shortening cycle, although too much or too little can lead to reduced performances and injury (Butler, Crowell III and McClay Davis, 2003). Greater running economy has been associated with greater lower limb stiffness (Dutto and Smith, 2002) because of a better use of elastic energy, and Arampatzis et al (2006) found that runners with better economy had a more compliant quadriceps femoris tendon and higher triceps surae (gastrocnemius and soleus) tendon stiffness. It is also possible that less economical athletes have techniques that lead to unnecessary and wasteful vertical motion (Nummela, Keränen, and Mikkelsson, 2007). Similarly, these authors found that shorter contact times were associated with better running economy at several speeds typical of elite 5000 and 10,000 m runners, and reasoned that this was because shorter contact times tend to feature shorter braking phases.

The swing phase

The function of the swing phase is to allow the foot to clear the ground after toe-off and be repositioned in front of the CM ready for first contact (Levine, Richards and Whittle, 2012). During early swing, the hip flexes so that the thigh moves from a position slightly behind the body to one in front of the body, with considerable activity by the rectus femoris and iliopsoas muscles. Because of the mass of the thigh and its location as the nearest joint to the trunk, this movement of the hip is important to the whole leg's contribution to overall running speed, with Bushnell and Hunter (2007) reporting that distance runners sped up by flexing the hip 14° more during midswing. The knee moves from a straightened angle of about 160° at toe-off to a very flexed position during midswing (55-60°) by concentric activity of the hamstrings, and then straightens again to about 150° in preparation for landing. The main knee extensors on the front of the thigh, the quadriceps femoris group, are mostly responsible for this movement, although runners should note that the hamstrings are often under considerable stress during late swing because of how they act to control knee extension (Chumanov, Heiderscheit, and Thelen, 2011). As well as helping the foot to clear the ground, the decrease in knee angle during swing acts to reduce the leg's moment of inertia (its resistance to rotation), and enhances the flight phase because the recovery leg's energy requirements are lowered (Kong and de Heer, 2008; Smith and Hanley, 2013). Some of the necessary actions taken to clear the ground are made by the ankle, which is plantarflexed at toe-off and moves to a more dorsiflexed position at landing, caused by activity of the tibialis anterior and other shin muscles. Along with the knee extensors, a key role of the ankle plantarflexors is to create high joint stiffness before and after first contact (Hanon, Thépaut-Mathieu and Vandewalle, 2005) to enhance the stretch-shortening cycle.

The stance phase

The purpose of the stance phase is to generate the impulse the body needs to move forwards. At first contact with the ground, the hip is flexed so that the thigh is ahead of the body and then extends to a position behind the body (usually a small amount of hyperextension). The main muscles involved are the hip extensors, comprising gluteus maximus and the three hamstring muscles, which mostly act concentrically during this motion and provide the “drive” for moving forwards. The knee flexes about 15-20° from its more straightened position at first contact until midstance and is associated with enabling a more level path of the CM (Saunders et al, 1953), although it has been found that elite runners flex their knees less and have shorter durations of knee flexion during stance (Leskinen et al, 2009). These differences in knee motion mean elite runners have greater knee stiffness (Heise, Smith and Martin, 2011), and are thus able to use elasticity better, allowing them to achieve faster times in competition and withstand tiredness for longer (Leskinen et al, 2009). This elasticity occurs because the decrease in knee angle at midstance results in energy absorption through the lengthening of the quadriceps femoris, which subsequently shortens to extend the knee and propel the body forwards and upwards.

The ankle lands in a slightly dorsiflexed position at first contact (Buczek and Cavanagh, 1990) and dorsiflexes more in midstance largely because of knee flexion (as the tibia moves forwards relative to the foot). The plantarflexors, such as gastrocnemius and soleus, are an important energy generator as they act concentrically in late stance to create positive impulse. During the stance phase, there are also important foot movements, such as pronation and supination, which are each effectively a combination of rotational movements. These are often described as ankle motions, but actually occur at the subtalar joint, which is between the talus bone and heel bone (calcaneus), located under it. In general, the runner lands on the outside of the foot (hence the wearing down of this part of the shoe first), pronate during the early, loading part of stance so that the foot is placed flat on the ground, and then supinate (moves the weight back to the foot’s outside) during late stance. The function of the pronation and supination movements is to place the foot so that it is in the best position to provide support and guide correct movement, for example as a shock absorber (Novacheck, 1998).

Upper body movements

The movements of the upper limbs generally act in opposition to the ipsilateral (same-side) lower limbs to counteract moments of the swinging legs around the vertical axis (Hinrichs, 1987; Pontzer et al, 2009). Furthermore, Hinrichs (1987) stated that the arm swing provides a meaningful contribution to lift and subsequently flight, and although the arms do not provide forward propulsion of the CM, they minimise changes in horizontal velocity during stance. However, it is debated as to whether the shoulder muscles are primarily responsible for the swinging motion of the arms or whether their movement is mostly a passive response to the legs' movements (Pontzer et al, 2009). Regardless of the exact contribution of the upper limbs, and as elbow angles are generally more variable between runners than lower limb angles (Hanley, Smith and Bissas, 2011), the ungainly arm movements often adopted even by elite athletes should be avoided in providing balance and propulsion to the body, and are frequently an indicator of a problem elsewhere in the body.

The movements of the arms complement those of the torso, where the upper part of the trunk can be seen to act in opposite and counterbalancing motion to the lower part (Novacheck, 1998), and indeed trunk rotation in running has been associated with increased efficiency (Bramble and Lieberman, 2004). Pelvic rotation is the way in which the pelvis twists about a vertical axis, moving each hip joint forwards as that hip flexes, and backwards as the hip extends (Levine, Richards and Whittle, 2012), meaning that less hip flexion and extension are required because a portion of step length is achieved by the forwards-backwards movements of the pelvis instead (Inman, Ralston and Todd, 1981). Another important movement at the lower end of the torso is pelvic obliquity, where one side of the pelvis drops below the other (Levine, Richards and Whittle, 2012). This occurs during midstance, where the gluteus medius muscle on the outside of the hip acts to stabilise the pelvis whilst allowing a small drop to occur on the opposite side so that the overall path of the CM does not fluctuate too greatly (Saunders, Inman and Eberhart, 1953).

Footstrike patterns

Distance runners make first contact with the rearfoot (heel-striking), midfoot or forefoot (Stearne et al, 2014). Middle-distance runners are more likely to land with an anterior footstrike pattern (either midfoot or forefoot) (Hayes and Caplan, 2012), with the percentage of athletes making first contact with the rearfoot increasing as the race distance gets longer (Hanley et al, 2019; Hasegawa, Yamauchi and Kraemer, 2007). When grouped across sex and race distance, forefoot and midfoot strikers had shorter ground contact times and faster finishing times in 800 m and 1500 m races (Hayes and Caplan, 2012). Similarly, at the 15-km distance of a half-marathon, rearfoot strikers had longer contact times than forefoot and midfoot strikers (Hasegawa, Yamauchi and Kraemer, 2007) and these shorter contact times could be seen as a performance benefit from landing more forwards on the foot, possibly because footstrike pattern is a factor that affects the stretch-shortening cycle (Cavagna, Saibene and Margaria, 1964; Cavagna and Kaneko, 1977). As faster distance runners are more likely to be mid- or forefoot strikers (Stearne et al, 2014), it has been suggested that running economy is positively influenced by effective exploitation of this elastic energy (Di Michele and Merni, 2014). However, Stearne et al (2014) found no differences for total lower limb mechanical work or mean power between foot-strike patterns when running at 4.5 $m \cdot s^{-1}$. This might be because whereas forefoot striking has been associated with greater stiffness at the knee, rearfoot striking has been associated with greater stiffness at the ankle (Butler, Crowell III and McClay Davis, 2003). Indeed, the lower prevalence of midfoot and forefoot striking over longer distances amongst both recreational and world-class marathon runners (Hanley et al, 2019;

Larson et al, 2011) could be because carbohydrate oxidation rates are greater during forefoot striking (Gruber et al, 2013).

Landing on the front of the foot has been proposed as less likely to lead to injury (Kulmala et al, 2013) as it reduces peak impact forces (Cavanagh and Lafortune, 1980; Lieberman et al, 2010). This is because the wider forefoot allows impact forces to be distributed over a larger area (Rooney and Derrick, 2013), although these forces are also reduced during heel-strike in appropriate footwear (Whittle, 1999). However, it is not conclusive that vertical loading forces are directly responsible for lower limb injury (Nigg, 1997), especially given the multiplanar and complicated movements involved in running. Furthermore, whereas rearfoot striking might be associated with certain injuries (e.g., at the knee), forefoot striking is associated with injury to other areas (e.g., ankle) (Kulmala et al, 2013). Higher loads to the gastrocnemius were found in forefoot striking (Shih, Lin and Shiang, 2013), and Stearne et al (2014) stated that forefoot striking thus might actually increase the risk of Achilles tendinopathy and triceps surae injury. It is therefore inadvisable for habitual rearfoot strikers to switch footstrike pattern as it can increase the injury risk to untrained muscles (Stearne et al, 2014).

Effects of fatigue

It is well understood that one of the main limits on performance in distance running is fatigue, characterised by a reduction in power output and a decline in performance (Kellis and Liassou, 2009). There are three potential sites of failure: those within the central nervous system; those concerned with neural transmission from the central nervous system to muscle; and those within the individual muscle fibres (Bigland-Ritchie and Woods, 1984). Local muscular fatigue occurs because of intensive activity in that muscle (Mizrahi, Verbitsky and Isakov, 2000), and is one of many forms of fatigue that affect distance runners. Even though the competitive distances are shorter, middle-distance runners are more susceptible to fatigue in some ways than long-distance runners, possibly because those who specialise over shorter distances have a greater proportion of fast-twitch muscle fibres (Nummela, Keränen, and Mikkelsson, 2008) and because their pacing profiles in championship competition feature several bursts of great acceleration (Hettinga, Edwards and Hanley, 2019).

Change in running speed is the most obvious outcome of fatigue, resulting from decreases in either step length and cadence, or both (Buckalew et al, 1985; Elliott and Ackland, 1981). However, athletes racing over different distances sometimes suffer decreases in only one of these two factors; for example, in a 5 km road race, Hanley, Smith and Bissas (2011) found that the men had reduced cadence only, whereas in a men's 10,000 m track race, Elliot and Ackland (1981) found decreases in step length (from 1.76 m on the second lap to 1.66 in the second-last lap), whereas cadence did not change. In a high-quality women's marathon, Buckalew et al (1985) found that, as faster finishers had longer step lengths, maintenance of step length over the full distance was the deciding factor in the outcome of the race. This means the marathon differs from shorter distance races (i.e., changes in cadence are not as important for race success) because the physiological changes that occur in the second half mean that maintaining step length is the key to avoiding great reductions in speed to the finish.

Dutto and Smith (2002) reported that during running to exhaustion, leg stiffness decreased with fatigue and this might have caused step length to increase (rather than because of a conscious decision by the athletes), with a resulting increase in energy cost. A similar decrease in leg stiffness, found during exhaustive running by Hayes and Caplan (2014), was believed to be more likely due to changes in ankle stiffness, rather than at the knee. A decrease in leg stiffness results in a failure to fully use the stretch-shortening cycle (Chan-Roper et al, 2012), such as during the push-off phase in running. Repeated stretch-shortening cycle exercise itself induces fatigue, leading to increased lower leg stiffness to protect passive biological structures (Debenham et al, 2016), and which affects force production as there is a reduction in the amount of storage of elastic energy (Nicol, Komi and Marconnet, 1991a). It is possible that this reduction is caused by an increase in transition time from stretch to shortening (e.g., between braking and push-off phases) (Nicol, Komi and Marconnet, 1991a).

Indeed, Hayes and Caplan (2012) found that contact times in high-calibre club athletes increased from the first lap to the last lap of both 800 m and 1500 m races, and given its association with cadence, the ability to maintain or decrease contact time in the later stages might be crucial for success. Nicol, Komi and Marconnet (1991b) found that longer contact times occurred after a marathon because of increased maximal knee flexion that suggested a reduction in tolerance to repeated stretch loads, which led to increased muscular work when the knee extended during a longer push-off phase to maintain a constant running speed. As this increased work requirement in itself increases the rate of fatigue, the most common outcome of stretch-shortening cycle fatigue is simply for the athlete to slow. In treadmill tests where runners exercised to exhaustion, those athletes who ran for longer were those who had more stable running styles (Gazeau, Koralsztein and Billat, 1997), and it is possible that detrimental changes in stride mechanics can be avoided to some extent through the development of local muscular endurance of key lower limb muscles, particularly the knee flexors and hip extensors (notably, the hamstrings fulfil both of these roles) (Hayes, Bowen and Davies, 2004). The changes that occur from running to exhaustion (or considerable fatigue) could lead to overuse injuries (Riazati et al, 2020), and indeed changes often occur to reduce pain in those already suffering patellofemoral pain syndrome (Bazett-Jones et al, 2013). Many of these gait alterations relate to muscle strength before and after high-intensity exercise; by contrast, with regard to changes in joint angles with fatigue over short race distances, Hanley, Smith and Bissas (2011) found that hip, knee, ankle and shoulder angles at both first contact and toe-off did not alter throughout a 5 km road race, and Elliot and Ackland (1981) reported very small or no changes in lower limb joint angles with fatigue in 10,000 m track running. Thus, even when fatigued, many athletes maintain their usual technique and coaches should note that running form, whether “good” or “bad”, is not necessarily a robust guide as to whether an athlete is tiring.

Air resistance

Air resistance occurs when an athlete runs overground and, as noted above for external forces, causes a change in the athlete's speed. An athlete running in still air (wind speed of 0.0 $m{\cdot}s^{-1}$) experiences a headwind equal to their running speed (Davies, 1980); compared with no wind conditions, headwinds increase total energy consumption, whereas tailwinds decrease it. Very strong tailwinds can cancel out the effects of running through the air, although they can also have a negative effect on the ability to maintain correct running posture (Davies, 1980). Running closely behind rivals is a very common tactic as it allows less physiologically capable athletes to maintain the pace of faster, front-running athletes (Brisswalter and Hausswirth, 2008), and is one of the principles behind pre-arranged pacemakers. Davies (1980) found that the energy cost of overcoming air resistance on a calm day was approximately 4% for middle-distance running (at 6 $m{\cdot}s^{-1}$), and 2% for marathon running (5 $m{\cdot}s^{-1}$). He recommended athletes shield behind a front runner until the closing stages of a race, although they need to be in very close proximity. However, many athletes deliberately choose to avoid following others too closely as it can eliminate the cooling effects of moving air, especially in hot conditions (Noakes, 2003). Additionally, Kyle (1979) calculated that middle- and long-distance runners reduced energy consumption by only 2 – 4% by shielding from the wind, and Trenchard, Renfree and Peters (2016) calculated that distance runners in competitive situations actually gain little from drafting. Ultimately, air resistance is very small at speeds below 4.44 $m{\cdot}s^{-1}$ (Léger and Mercier, 1984), and might be of great importance for the distance runner only in strong headwinds. In weather conditions where the relative humidity is high (at or close to 100% saturation), rainfall can negatively affect performance, particularly in the marathon (Ito et al, 2013). However, as with wearing loose clothing, some athletes might benefit from light rain because of a cooling effect. Overall, the best conditions for distance running are generally a combination of sea-level elevation, little or no wind, cool but dry conditions, and athletes of similar ability to act as pacemakers.

Effects of gradient

Changes in gradient frequently occur in road racing, and are a common feature of cross country and other off-road running. Even though running downhill is generally faster because of gravitational forces contributing to propulsion (Paradisis and Cooke, 2001), it can also have negative consequences. These effects can be exacerbated because athletes are unfamiliar with running downhill and alter their gait to accommodate the slope, including applying more braking impulse than necessary (Gottschall and Kram, 2005). Although it has a lower metabolic cost than running on a level surface (Minetti, Ardigò and Saibene, 1994), running downhill on shallow slopes still requires some positive mechanical energy generation because elastic energy storage is insufficient to meet all energy demands (Snyder, Kram and Gottschall, 2012).

Aside from the risk of falling, the mechanics of running downhill can also increase the risk of injury. Although not necessarily direct causes of injury, greater vertical impact peak forces were found during downhill running (Gottschall and Kram, 2005; Telhan et al, 2010), and peak tibial impact accelerations increased on downhill gradients because of higher vertical velocities at impact (Chu and Caldwell, 2004). Because of the greater loading in early stance, running downhill increases the load on the knee extensors, hip extensors, and anterior and posterior shin muscles (Eston et al, 1995). Appell, Soares and Duarte (1992) stated that this mechanical stress during downhill running causes disruption of the myofibrils in the affected muscles, and the accrued muscle damage can affect running form and muscle function for up to three days afterwards (Chen, Nosaka and Tu, 2007). The loss of strength in the quadriceps femoris is caused by morphological damage during exercise (Lieber and Friedén, 1993) and is associated with the relative length of the muscle; for example, the quadriceps femoris does more work at its longer length during downhill running than during uphill running (Eston et al, 1995). Small uphill sections (of 1% gradient or less) often have little effect on the maintenance of running speed (Angus and Waterhouse, 2011). However, anyone who has run uphill knows intuitively that it is more difficult than running on level surfaces because energy cost increases with greater inclines (Minetti, Ardigò and Saibene, 1994), with a more forward lean of the trunk and shorter step lengths. Of course, some athletes deliberately choose hilly courses because of the challenge involved, or because hill running suits their abilities. Training to run downhill before competition can help prevent muscle damage (Eston et al, 1995) and coaches are thus advised to include it in their athletes' training regimens.

Cross country and off-road running

Running on natural terrain in the form of cross country running, trail running, orienteering and fell running are popular with athletes of all abilities. On soft ground, the surface absorbs energy and returns little, which can be particularly detrimental to those distance athletes who rely to a greater extent on lower limb muscle elasticity (Canova, 1998). In general, running on surfaces such as sand, grass and trails requires greater metabolic energy expenditure than running on smooth, flat, hard surfaces (Voloshina and Ferris, 2015). Increases in energy cost of between 26% and 72% have been estimated when running in forests (typical of orienteering and trail running), dependent on the underfoot conditions (Creagh and Reilly, 1997). The energy cost of running through long grass on rough terrain is increased because of decreased step lengths, greater hip flexion during swing, and larger vertical displacements of the CM (Creagh and Reilly, 1997). Pinnington and Dawson (2001) found that running on sand had a greater energy cost than running on grass and proposed that this was because of a reduction in elastic energy potentiation, caused partly by an increase in contact time. They also suggested that the increase in energy cost could be because sand's compliant nature requires increased leg stiffness that increases muscle activity to stabilise the lower limb joints (Pinnington and Dawson, 2001). Although running on such surfaces might reduce performance (e.g., time to complete a particular distance compared with athletics tracks or roads), they can provide a beneficial training stimulus, and can suit some athletes' running styles better than more stable, harder surfaces.

Conclusion

Running is a highly complex movement, requiring years of refinement to become automated and efficient, and a good understanding of biomechanics is indispensable in trying to improve performance. Although the running stride has been broken down into its various components, a holistic view of an athlete's biomechanics is essential in good coaching so, for example, understanding that increasing step length is beneficial to performance should be tempered with the risk of overstriding or decreasing cadence. Training improvements in technique take time and are best viewed as part of a whole-body exercise, where what occurs during swing in one leg is seen as complementing what happens during stance in the other. Distance running is, of course, an endurance activity and external factors such as the effects of wind, hills, surface and rival athletes' tactics can influence the rate of fatigue. Indeed, the manner in which an athlete accommodates these potential challenges can be affected by tiredness, and coaches are recommended to incorporate technically sound practice in training to prepare the body biomechanically for these race elements.

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