[CLINICAL COMMENTARY]

ANTHONY G. SCHACHE, PhD[1] • TIM W. DORN, PhD[2] • GAVIN P. WILLIAMS, PhD[3,4]
NICHOLAS A.T. BROWN, PhD[5] • MARCUS G. PANDY, PhD[1]

Lower-Limb Muscular Strategies for Increasing Running Speed

Running is a fundamental skill and a critical requirement for almost all sporting activities. Understanding the biomechanical function of the lower-limb muscle groups during running is important for improving current knowledge regarding human high performance, as well as for identifying potential factors that might be related to injury. Humans have the capacity to run at a broad spectrum of speeds. Depending on the particular protocol used to identify the preferred transition speed, locomotion has been found to switch from walking to running between speeds ranging from 2.0 to 2.7 m/s.[29,61,77] Elite athletes have the ability to achieve maximal running speeds greater than 10 m/s (or 36 km/h).[17] The purpose of this clinical commentary is to augment the way the lower-limb muscles function to increase running speed from slow jogging to sprinting.

We will present a brief synopsis of our main research findings to date, together with additional evidence obtained from other studies. It is worth noting that many thorough and valuable literature reviews and book chapters describing lower-limb muscle function during running already exist[2,19,48,52,64,68,89] and are recommended for the interested clinician who is seeking additional material. Our intention in this clinical commentary is to discuss these prior publications by highlighting some recent insights.

We will also present 2 examples to illustrate how basic science knowledge of lower-limb muscle function during running can be valuable. First, from a performance perspective, we will explore the potential mechanisms behind the decline in maximum running speed in the aging athlete. Second, from an injury perspective, we will demonstrate how this knowledge can be helpful for designing rehabilitation programs that aim to retrain the ability to run in young, previously active adults who have sustained a traumatic brain injury (TBI).

SYNOPSIS: This clinical commentary discusses the mechanisms used by the lower-limb musculature to achieve faster running speeds. A variety of methodological approaches have been taken to evaluate lower-limb muscle function during running, including direct recordings of muscle electromyographic signal, inverse dynamics–based analyses, and computational musculoskeletal modeling. Progressing running speed from jogging to sprinting is mostly dependent on ankle and hip muscle performance. For speeds up to approximately 7.0 m/s, the dominant strategy is to push on the ground forcefully to increase stride length, and the major ankle plantar flexors (soleus and gastrocnemius) have a particularly important role in this regard. At speeds beyond approximately 7.0 m/s, the force-generating capacity of these muscles becomes less effective. Therefore, as running speed is progressed toward sprinting, the dominant strategy shifts toward the goal of increasing stride frequency and pushing on the ground more frequently. This strategy is achieved by generating substantially more power at the hip joint, thereby increasing the biomechanical demand on proximal lower-limb muscles such as the iliopsoas, gluteus maximus, rectus femoris, and hamstrings. Basic science knowledge regarding lower-limb muscle function during running has implications for understanding why sprinting performance declines with age. It is also of great value to the clinician for designing rehabilitation programs to restore running ability in young, previously active adults who have sustained a traumatic brain injury and have severe impairments of muscle function (eg, weakness, spasticity, poor motor control) that limit their capacity to run at any speed. *J Orthop Sports Phys Ther 2014;44(10):813-824. Epub 7 August 2014. doi:10.2519/jospt.2014.5433*

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Background

To evaluate the biomechanical function of the lower-limb muscles during running, a variety of analytical approaches can be taken. For example, many studies have used an inverse dynamics–based analysis to quantify lower-limb net joint moments across a range of running speeds.[1,4,7,42,64,75,79] The net joint moment

[1]Department of Mechanical Engineering, University of Melbourne, Melbourne, Victoria, Australia. [2]Neuromuscular Biomechanics Laboratory, Stanford University, Stanford, CA. [3]Physiotherapy Department, Epworth Hospital, Richmond, Victoria, Australia. [4]Centre for Health, Exercise and Sports Medicine, Department of Physiotherapy, University of Melbourne, Melbourne, Victoria, Australia. [5]Performance Science and Innovation, Australian Institute of Sport, Belconnen, Australian Capital Territory, Australia. Part of the research contained in this clinical commentary was funded by the Australian Research Council (LP110100262), the Victorian Neurotrauma Initiative, and the Australian Physiotherapy Association. The authors certify that they have no affiliations with or financial involvement in any organization or entity with a direct financial interest in the subject matter or materials discussed in the article. Address correspondence to Dr Anthony G. Schache, Department of Mechanical Engineering, University of Melbourne, Melbourne, Victoria 3010 Australia. E-mail: anthonys@unimelb.edu.au

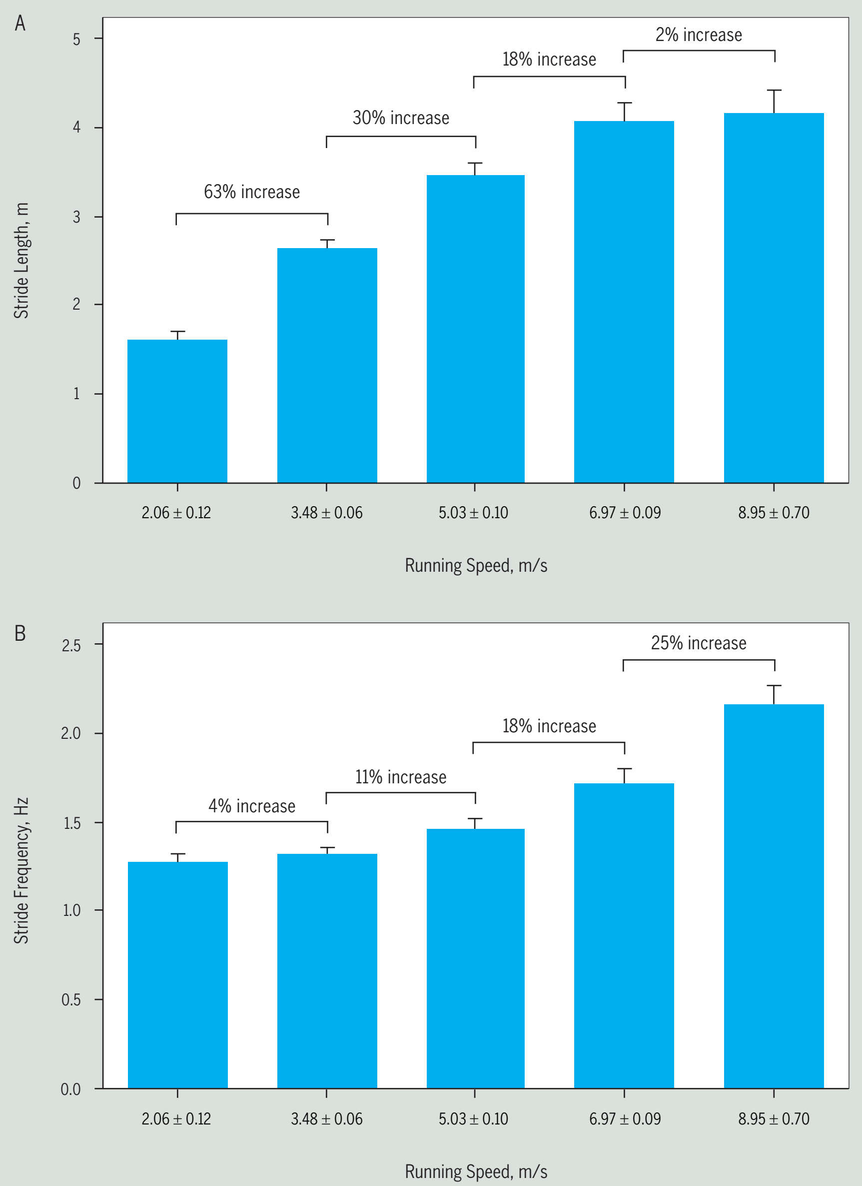

FIGURE 1. Effect of running speed on (A) stride length and (B) stride frequency. Experimental data were obtained from Dorn et al.[18]

represents the sum of the moments produced by all of the muscle-tendon units, ligaments, and contact forces spanning that joint. As the moments attributable to ligaments and contact forces are likely to be small for the primary sagittal plane joint motions during running, the net joint moment is a bulk representation of the moments produced by the muscle-tendon units spanning a joint.[19,90] Another analytical approach involves recording the electromyographic signal from muscles of interest,[7,42-45,49,63,79] which is sometimes performed in conjunction with an inverse dynamics–based analysis.[7,42,79] More recently, computational musculoskeletal models have been used to investigate how lower-limb muscles function during running.[6,18,25,55,73] The advantage of this latter approach is the ability to calculate certain variables that cannot be directly measured via noninvasive experiments, such as relative contributions from the lower-limb muscles to the generation of the ground reaction force (or the acceleration of the body's center of mass) during running. Our investigations to date have involved the simultaneous recording of trunk and lower-limb kinematics, ground reaction force, and (in most instances) lower-limb muscle electromyographic signal during overground running, using able-bodied adult athletic participants[18,46,67,75] as well as participants who have sustained a TBI.[85,86] To evaluate lower-limb muscular strategies during running in these 2 cohorts, we have used a combination of the aforementioned analytical approaches.

Many researchers have evaluated the biomechanical strategies used to increase running speed by analyzing a range of different steady-state speeds.[1,4,6,7,9,21,26,43-45,63,65] We have taken a similar approach, whereby able-bodied participants performed multiple discrete running trials at a wide spectrum of steady-state speeds.[18,46,75] Our target running speeds were 2.0 m/s (jogging), 3.5 m/s (slow-pace running), 5.0 m/s (medium-pace running), 7.0 m/s (fast-pace running), and 8.0 m/s or greater (sprinting). For these running speeds, stance-phase durations (expressed as a proportion of the stride cycle) ranged from approximately 41% for jogging to 24% for sprinting, consistent with what has been previously reported for similar running-speed categorizations.[64]

An alternative approach is to evaluate accelerated running,[11,59,60,81] which better resembles how running speed is increased in real-life sporting situations. Unfortunately, though, evaluating accelerated running over ground can be experimentally challenging, as humans require at least 40 m to reach their maximum running speed from a stationary position (eg, from the start of a 100-m race).[16,59,60] This distance is even greater for submaximal accelerations. Most studies evaluating lower-limb biomechanics during accelerated running over ground have therefore focused on the first few steps of the acceleration phase[8,15,33,41,50,51,53,54] or a single stride cycle midway through the acceleration phase.[30,31,34] At present, the only studies that have been able to record ground reaction force data for an entire acceleration phase continuously (ie, within a single trial) have involved a specialized instrumented torque treadmill.[57,58]

There is an important distinction in the way the lower-limb muscles operate when running at a steady-state speed, compared to when accelerating, that needs to be highlighted. When running at a steady-state speed, the lower-limb muscles function like springs storing and recovering energy with each step, and thus there is no net change in the average mechanical energy of the body. When accelerating, the lower-limb muscles function like motors doing positive work and generating power to increase the kinetic energy of the body.[69,70] It should therefore be kept in mind that observations generated from studies that have compared a range of incremental steady-state running speeds may not necessarily hold true for accelerated running. One would anticipate that differences in the function of the lower-limb muscles compared to steady-state running are likely to be most apparent when beginning to accelerate. During the first 3 to 4 steps when maximally accelerating, the trunk is inclined forward and the foot contacts the ground behind the body's center of mass.[59] Thus, the biomechanical objective is to maximize the propulsive component of the ground reaction force.

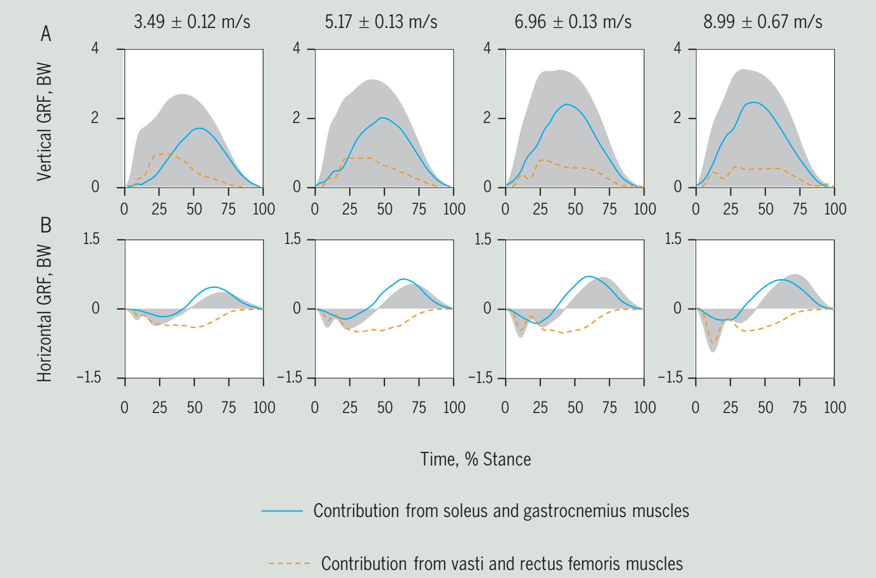

FIGURE 2. The contributions from the ankle plantar flexors and knee extensors to the generation of the GRF (gray shading) when running at 4 different steady-state speeds. (A) The GRF in the vertical direction. (B) The GRF in the anterior/posterior direction, where the anterior (propulsive) component is positive and the posterior (braking) component is negative. Data represent the mean values obtained from a cohort (n = 9, 3.49 ± 0.12 m/s and 5.17 ± 0.13 m/s; n = 8, 6.96 ± 0.13 m/s; and n = 7, 8.99 ± 0.67 m/s) of able-bodied adult athletic participants. Note that in the anterior/posterior direction (B), the combined contribution from the soleus and gastrocnemius muscles during the middle portion of stance becomes positive before the development of the propulsive component of the GRF, because these muscles must counter the opposing effects from other lower-limb muscles (eg, the vasti and rectus femoris muscles) that are still providing a contribution to the braking component at this time. Experimental data were obtained from Dorn et al.[18] Abbreviations: BW, body weight; GRF, ground reaction force.

Lower-Limb Muscular Strategies for Increasing Running Speed

Running speed can be increased by pushing on the ground more forcefully (strategy 1), pushing on the ground more frequently (strategy 2), or combining these 2 strategies. When running speed is initially increased, strategy 1 appears to be the priority. A more forceful ground contact results in a longer stride length because the body spends more time in the air,[18] and this response is exactly what we have observed to occur. When running speed changed from jogging (2.06 ± 0.12 m/s) to slow-pace running (3.48 ± 0.06 m/s), stride length increased by 63% (from 1.62 ± 0.09 m to 2.65 ± 0.08 m), whereas stride frequency increased by only 4% (**FIGURE 1**).[18] The lower-limb muscles largely responsible for pushing on the ground forcefully during running are the major ankle plantar flexors (soleus and gastrocnemius muscles).[18,25]

By combining experimentally recorded motion analysis and ground reaction force data during running with computational musculoskeletal modeling, it is possible to calculate the contribution of each individual muscle force to the total ground reaction force in both the vertical and the anterior-to-posterior directions. The data clearly demonstrate that the soleus and gastrocnemius muscles combined are responsible for a large portion of the ground reaction force in the vertical direction (between 49.0% and 62.3%), and nearly all of the propulsive component of the ground reaction force in the anterior/posterior direction (**FIGURE 2**).[18] This relative reliance on the soleus and gastrocnemius muscles to generate the necessary ground forces during jogging and slow- to medium-pace running is certainly advantageous. The soleus and gastrocnemius muscles are attached to the calcaneus via a long, compliant Achilles tendon, which has the ability to store elastic strain energy during the first half of stance and then return this energy during the second half of stance, thereby reducing the amount of power that must be generated by the soleus and gastrocnemius muscle fibers to propel the body in the air.[20,27,46,74]

As running speed approaches sprinting, the ability to push on the ground more forcefully appears to become less effective. There are many biomechanical observations that provide evidence to

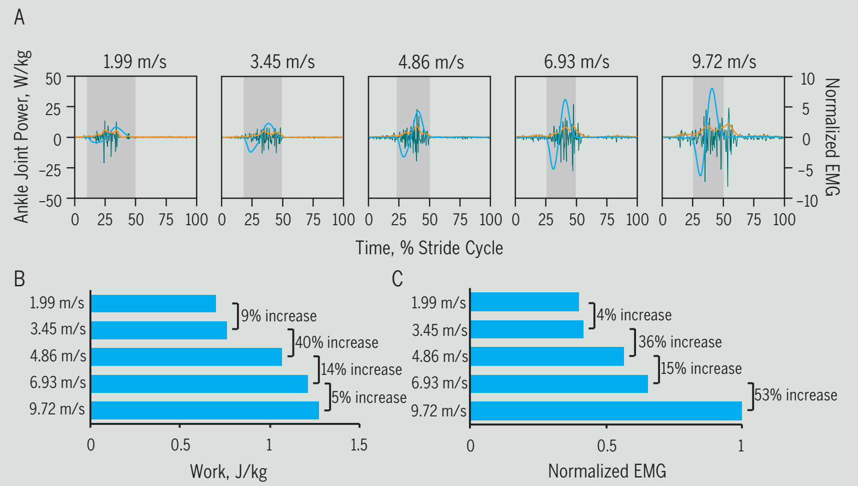

FIGURE 3. Ankle joint power and soleus EMG signal with increasing running speed for a single representative, able-bodied, adult athletic participant. (A) The temporal relationship between ankle joint power (blue line) and soleus EMG signal. Data for soleus EMG signal are presented at 2 stages through the signal-filtering process: first, after being high-pass filtered at 20 Hz (green wavy lines); and second, after being full-wave rectified and then low-pass filtered at 20 Hz, that is, the linear envelope (orange line). All EMG signal data are normalized as a fraction of the mean of the linear envelope for the maximum running-speed trial (9.72 m/s). The stance phase is indicated by the vertical gray-shaded bar. (B) The energy generated by the ankle joint for each running-speed condition. The energy generated (or positive work done) represents the area under the positive portion of the ankle joint power curve displayed in (A). (C) The magnitude (mean of the linear envelope) of the soleus EMG signal for each running-speed condition. Ankle joint power data were obtained from Schache et al.[75] Abbreviation: EMG, electromyographic.

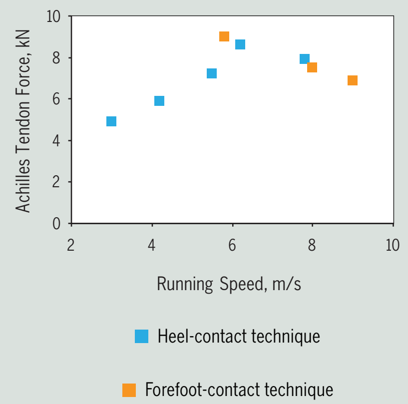

FIGURE 5. Effect of running speed on peak Achilles tendon forces during running for a single participant. The graph displays the recorded peak force for a range of discrete steady-state running speeds using both a heel-contact technique (blue squares) and a forefoot-contact technique (orange squares). All data obtained from Komi[37] and Komi et al.[38]

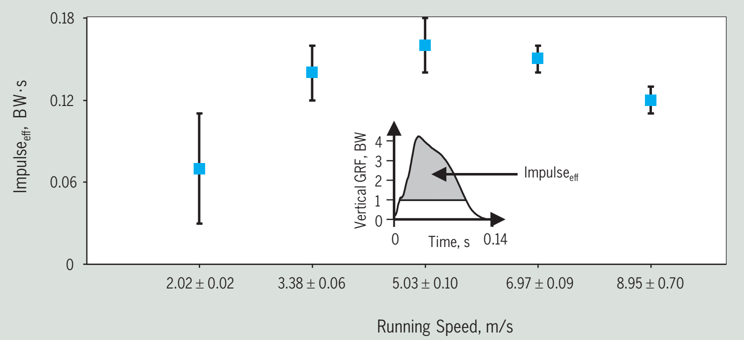

FIGURE 4. Effect of running speed on the effective impulse (impulse$_{eff}$) of the vertical GRF. The effective impulse represents the area underneath the vertical GRF that exceeds BW (as indicated by small caption inside main plot). Data represent the mean ± SD values obtained from a cohort (n = 9, 2.02 ± 0.02 m/s, 3.38 ± 0.06 m/s, and 5.03 ± 0.10 m/s; n = 8, 6.97 ± 0.09 m/s; n = 7, 8.95 ± 0.70 m/s) of able-bodied adult athletic participants. Experimental data were obtained from Dorn et al.[18] Abbreviations: BW, body weight; GRF, ground reaction force.

this effect. First, we found the percentage increase in stride length to become progressively smaller with each increment in running speed, such that stride length changed very little between fast-pace running (6.97 ± 0.09 m/s) and sprinting (8.95 ± 0.70 m/s) (**FIGURE 1A**). This relationship between stride length and running speed has also been reported in other studies.[28,62,65,72] Second, in a similar manner to stride length, the increase in the positive work done (or the energy generated) at the ankle joint during stance becomes progressively smaller with faster running, despite dramatic rises in the magnitude of soleus activation (**FIGURE 3**). Third, the time a runner spends in the air is determined by the effective impulse applied by the lower limb to the running surface.[82,83] The effective impulse represents the area underneath the vertical ground reaction force that exceeds body weight (**FIGURE 4**). The effective impulse increases in magnitude from slower to intermediate running speeds before decreasing at fast running speeds. This relationship has been reported in several studies investigating running at a range of discrete steady-state speeds,[65,82,83] and we also found an identical result (**FIGURE 4**). Fourth, when increasing running speed beyond 6.96 ± 0.13 m/s, the peak magnitude of the combined contribution from the soleus and gastrocnemius muscles to the ground reaction force can be seen to plateau in the vertical direction (**FIGURE 2A**), whereas in the anterior/posterior direction it decreases slightly for the propulsive component (**FIGURE 2B**). Fifth, perhaps the most compelling evidence of all is provided by the relationship between running speed and the peak force developed in the Achilles tendon. These highly unique data were recorded under in vivo conditions by surgically inserting a buckle-type transducer around the tendon.[37,38] As is

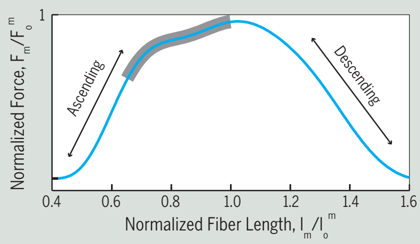

FIGURE 6. The muscle force-length relationship. The gray shading indicates the operating region for the soleus muscle when running at 3.0 m/s, as reported by Rubenson et al.[71]

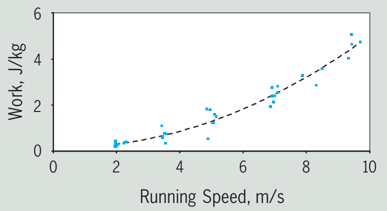

FIGURE 7. Effect of running speed on the positive work done (or energy generated) at the hip joint during swing. The blue squares represent individual participant data. A second-order polynomial equation was fitted to the data (black dashed line), demonstrating that almost all of the variability in the energy generated at the hip during swing could be explained by running speed alone (work = 0.052 × speed^2 – 0.034 × speed + 0.180) (R^2 = 0.96). Experimental data were obtained from Schache et al.[75]

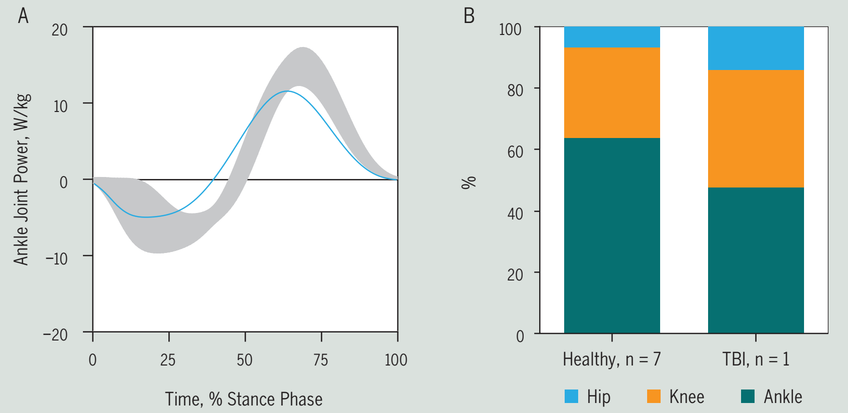

FIGURE 8. Lower-limb joint power during running for an individual with TBI compared to a cohort (n = 7) of able-bodied adult athletic participants. All data were collected at a running speed of 3.5 m/s. (A) The ankle joint power during stance. Mean ± SD data for the able-bodied participants are indicated by the gray shading, whereas data for the individual with TBI are indicated by the blue line. (B) The distribution of the average joint power generated in the lower limb during stance for the able-bodied participants and the individual with TBI. The average joint power generated at the hip (blue), knee (orange), and ankle (green) throughout stance was summed to obtain the total average joint power generated in the lower limb. The average joint power generated at the hip, knee, and ankle was then expressed as a percentage of the total average joint power generated in the lower limb. Experimental data for the able-bodied participants were obtained from Schache et al,[75] whereas the experimental data for the individual with TBI were obtained from Williams et al.[85] Abbreviation: TBI, traumatic brain injury.

evident in **FIGURE 5**, the peak Achilles tendon force was found to be highest at running speeds of approximately 6.0 m/s and decreased in magnitude thereafter. The profile of the peak Achilles tendon force plotted against running speed (**FIGURE 5**) has a remarkable degree of similarity to that evident for the effective impulse (**FIGURE 4**), substantiating our model prediction that the soleus and gastrocnemius muscles are responsible for generating a large proportion of the ground reaction force during running.

Why does the force-generating capacity of the ankle plantar flexors become less effective with faster running? It is clearly not due to a reduction in activation. Activation of the ankle plantar flexors increases dramatically as running speed approaches sprinting, as we (**FIGURE 3C**) and other studies[43,63] have found. The less effective force-generating capacity of the soleus and gastrocnemius muscles with faster running must therefore be explained on the basis of an unfavorable muscle-fiber force-velocity or force-length relationship (or both). As running speed increases, the duration of the stance phase becomes shorter,[82,83] thus greater force must be applied to the ground (strategy 1) in ever-decreasing periods. From a force-velocity perspective, shorter ground contact times mean that the soleus and gastrocnemius muscles are required to contract with progressively increased shortening velocities, thereby potentially reducing the peak forces that can be generated under such conditions.[18] Both experimental and modeling-based studies support this notion. For example, Weyand et al[82] compared maximum sprinting with maximum one-legged forward hopping to demonstrate that if stance-phase time is allowed to increase (as is evident in hopping), the lower limb does indeed have the ability to generate a much greater effective impulse than that observed during sprinting. Furthermore, Miller et al[55] used computer simulations to quantify the effects of muscle mechanical properties on maximum sprinting speed. They found the muscle fiber force-velocity relationship to be the most critical factor limiting sprint performance. From a force-length perspective, Rubenson et al[71] have shown that when running at 3.0 m/s, the soleus primarily operates near the top, flatter portion of the ascending limb of the force-length relation (**FIGURE 6**). It is possible that the greater level of activation with faster running causes muscle fiber shortening, and thus the operating region on the force-length curve shifts to the left, down the steeper portion of the ascending limb.[46] While such a shift might seem counterproductive in terms of the efficiency with which force is generated, it may be advantageous in terms of facilitating the utilization of tendon stretch and recoil. Tendon has the capacity to recoil at a much faster velocity than muscle fibers can shorten,[3,36] which could be a mechanism used by the ankle plantar flexors to help push on the ground as quickly as possible.

Running speeds beyond approximately 7.0 m/s can be achieved despite little change in the energy generated at the ankle joint during the second half of stance (**FIGURE 3**) and a reduction in the effective impulse (**FIGURE 4**). As running speed approaches sprinting, the dominant lower-limb muscular strategy shifts toward one that is concerned with swinging the lower limbs and thereby pushing on the ground more frequently (strategy 2). When progressing from fast-pace running (6.97 ± 0.09 m/s) to sprinting (8.95 ± 0.70 m/s), we found stride frequency to increase by 25%, whereas stride length changed very little (**FIGURE 1**). Nummela et al[65] also found that running speeds beyond 7 m/s were achieved by increasing stride frequency rather than stride length. Additional evidence of the shift toward strategy 2 is provided by the relationship between running speed and the amount of positive work done or energy generated at the hip during swing (**FIGURE 7**). A second-order polynomial equation fitted to the data in **FIGURE 7** demonstrates that almost all of the variability in the energy generated at the hip during swing could be explained by running speed alone (work = 0.052 × speed^2 – 0.034 × speed + 0.180) (R^2 = 0.96). Greater stride frequency (strategy 2) therefore increases the biomechanical demand on the hip muscles dramatically. Energy is generated by the iliopsoas during the first half of swing to accelerate the hip into flexion, and then energy is generated by the gluteus maximus during the second half of swing to accelerate the hip into extension and shift the foot underneath the body in preparation for ground contact.[18] One of the consequences of switching from strategy 1 to strategy 2 as running speed approaches sprinting is that the forces (gravity and centrifugal) acting about the hip and knee joints during terminal swing increase in magnitude dramatically. Large "external" hip flexor and knee extensor torques develop at this time in the stride cycle,[75] which are primarily opposed by the hamstrings.[12,13,76] This biomechanical function may be of clinical relevance in terms of understanding the apparent injury risk for the hamstrings during high-speed running.[14]

FIGURE 9. Performing a slow jogging action on the slide shuttle.

Does Aging Affect the Ability to Increase Running Speed?

Maximum running speed is known to deteriorate with aging.[24,56] For example, Hamilton[24] found maximum running speed to decrease from approximately 9 m/s for runners aged 30 to 39 years to approximately 5 m/s for runners aged over 90 years. Thus, with older age, the spectrum of running speeds that can be achieved becomes progressively smaller. What is the reason for this decline in performance? Does aging adversely affect the ability to push on the ground forcefully (strategy 1) or more frequently (strategy 2), or both? To answer these questions, several studies have compared stride-cycle parameters during sprinting for athletes across a broad age range.[24,39,40] With aging, stride rate was found to remain relatively invariant,[24,39,40] whereas stride length decreased[24,39,40] and stance-phase time increased.[39,40] Hence, such findings suggest that the decline in maximum running speed in the aging athlete is mostly related to a reduction in the effectiveness of the stance limb to push on the ground forcefully (strategy 1). Further evidence for this premise is provided by results from studies comparing the running biomechanics of older (greater than 60 years of age) versus younger (less than

FIGURE 10. Performing a single-leg hop on the slide shuttle.

30 years of age) people at matched submaximal running speeds. Compared to their younger counterparts, older people run with shorter stride length[10,22,35] and a propulsive deficit at the ankle joint (ie, reduced energy generated or positive work done by the ankle joint during the second half of stance).[23,35] It has been proposed that the main characteristics that are likely to be responsible for the deterioration in maximum running speed with aging are decreased muscle strength, slower rate of muscle force development and transmission, and reduced storage and recovery of tendon elastic strain energy.[5] Given that the soleus and gastrocnemius muscles have a dominant role in producing the necessary ground forces during running (**FIGURE 2**) and that these muscles rely heavily on the utilization of tendon elastic strain energy for generating power during stance,[20,27,46,74] it would seem likely that the rate at which maximum running speed declines with aging is critically dependent on the function of the soleus and gastrocnemius muscles. Optimizing the function of the ankle plantar flexors (ie, higher force-generating capability, faster rate of force development, and increased tendon stiffness) via targeted resistance training and explosive plyometric drills would therefore appear to be of high priority for veteran sprinting athletes endeavoring to counterbalance the effect of aging.

Acquired Impairments of Lower-Limb Muscle Function

While aging appears to impair lower-limb muscle function and lead to a decline in maximum running speed, such a process occurs very slowly and only begins beyond age 30.[56] In contrast, there are other situations in which impairments of lower-limb muscle function occur suddenly and are considerably more severe. One such example is TBI. People who have sustained a TBI (eg, from a motor vehicle accident) represent an ideal model for understanding how lower-limb muscular strategies for increasing running speed are influenced by impairments of muscle function. The reason is 2-fold. First, it is adolescents and young adults who are most at risk of TBI,[80] many of whom were participating in running-based sports prior to their injury and therefore have the desire to return to similar activities. Second, it is quite common for people following TBI to experience persisting difficulties with high-level mobility tasks, such as running.[66] Our research has involved participants who have typically sustained an extremely severe TBI. This classification is based on the length of posttraumatic amnesia,[78] which for our cohort averaged 61.3 days.[85] One of our key objectives thus far has been the identification of factors that relate to improved functional outcome, and we have found that peak power generation at the ankle during walking is a strong predictor of a better high-level mobility outcome in people following TBI.[88] In other words, people subsequent to TBI who are able to use their calf muscles to push on the ground adequately when walking are far more likely to be capable of recovering the ability to run.

How do people subsequent to TBI run in comparison to their healthy, able-bodied counterparts? Even at relatively slow running speeds, people subsequent to TBI appear to have greater reliance on proximal muscle function, not just

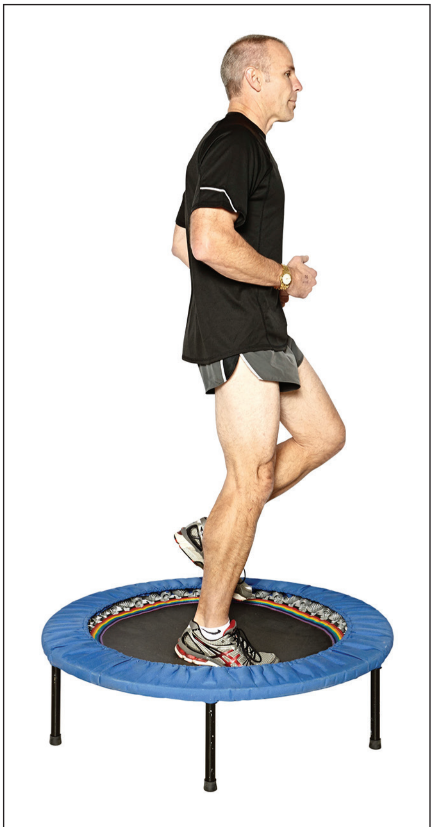

FIGURE 11. Slow jogging on the mini-trampoline.

FIGURE 12. The fast-feet running drill.

for leg swing (strategy 2) but also to aid with force generation during stance (strategy 1). Williams et al[85] found that when people run subsequent to TBI, they do so with a decreased stride length and an increased stride rate, and they generate less power at the ankle on their more affected side, when compared to healthy adults running at the same speed. To further illustrate some of the typical disparities observed, we have compared the data of a single representative participant who sustained a TBI (17-year-old male, 16 months postinjury) and successfully regained the ability to run at 3.5 m/s to those of a group of able-bodied adult athletic participants (**FIGURE 8**). Peak power generation at the ankle for the participant with TBI was found to be 11.5 W/kg, which was approximately 25% less than that for the able-bodied adult athletic participants running at the same speed (**FIGURE 8A**). To determine how this participant with TBI compensated for reduced power generation at the ankle (and thus was able to run at 3.5 m/s), we calculated the percentage contributions from the hip, knee, and ankle to the average joint power generated by the lower limb during stance. Compared to the able-bodied adult athletic participants, the distribution of average joint power generation in the lower limb during stance for the participant who had sustained a TBI was different: reduced power generation at the ankle was compensated for by greater power generation at the knee and the hip (**FIGURE 8B**). Thus, when running at 3.5 m/s, the participant who had sustained a TBI was dependent on using proximal muscles to generate power in the lower limb, which would suggest that this participant's capacity to run at speeds beyond 3.5 m/s was very limited.

While adequate calf muscle function is a critical determinant of recovering the ability to run in people subsequent to TBI, the approach taken to retrain running in this population focuses on the restoration of strategy 2 before strategy 1.[87] Distal muscle function is usually more severely impaired than proximal muscle function, thus in people subsequent to TBI it is easier to learn the skills to increase stride frequency (strategy 2) than those to generate greater ground forces

FIGURE 13. The claw exercise, used to simulate the lower-limb swing action and thereby develop the skills for pushing on the ground more frequently (strategy 2). The participant starts with the hip and knee joints flexed to approximately 90°. The hip and knee joints are extended simultaneously before rotating back to the start position again. The sequence of the images is from left to right.

(strategy 1). Also, the risk of falling is minimized if people subsequent to TBI are initially reintroduced to running by developing the ability to swing their lower limbs correctly before they attempt to accelerate their body's center of mass in the forward direction. People who have sustained a TBI present with 3 common impairments of muscle function: weakness, spasticity, and poor motor control (or quality of movement). Nevertheless, impairment-based interventions rarely translate to improvements in physical function; for example, resistance training in people with neurological conditions increases muscle strength but does not necessarily improve locomotion performance.[84] Therefore, our approach concentrates on the development of functional skills that simulate the biomechanical demands of running.[87] While the mechanisms behind improvement in running performance in people who have sustained a TBI remain unclear, it is most likely attributable to neuroplasticity. The following is a brief summary of the primary exercise interventions and the milestones for progression.

The first objective is to teach the necessary skills to be able to run on the spot (in place). This objective is achieved in 3 stages. The first stage aims to restore the ability of the lower-limb muscles to decelerate and then accelerate the body's center of mass in a vertical direction (or support the weight of the body). This skill is initially practiced in a gravity-eliminated or gravity-reduced condition using a slide shuttle. The individual with TBI performs a slow jogging action, pushing off one limb and landing on the other limb, absorbing impact by landing on the forefoot and flexing the knee (**FIGURE 9**). With improvement, progression can be made to single-legged hopping (**FIGURE 10**). Also, the inclination of the slide shuttle can be gradually increased so that the individual with TBI begins to work against gravity more so than across gravity. Once competent in the slide shuttle, the second stage involves progressing to slow jogging on a mini-trampoline, holding onto a rail or pole with the upper limbs for stability before eventually performing this activity without support (**FIGURE 11**). The third stage involves a fast-feet running drill, where the individual with TBI practices running on the spot (in place) on level ground (**FIGURE 12**). The focus is initially on achieving a rapid cadence with minimal knee lift before gradually including high knee lift.

The second objective is to teach the ability to safely move the body's center of mass in the forward direction while running, initially at slow speeds but then at gradually increasing speeds as the individual becomes more skilled. For the aforementioned reasons, this objective is achieved by focusing on developing the skills for strategy 2 before strategy 1. Progressing in this way allows the individual with TBI to better dissociate swing-phase lower-limb speed from forward speed of the body. To practice strategy 2, the individual with TBI holds onto a rail or pole with the upper limb while the body weight is supported on the contralateral lower limb. The swing limb starts in a position of 90° of hip and knee flexion and is rotated through to full hip and knee extension before returning to hip and knee flexion again, that is, simulating the lower-limb swing action in running (**FIGURE 13**). This activity is repeated continuously and is advanced by executing the movement with greater precision and speed. The final skill that is restored is the ability of the lower-limb muscles to propel the body's center of mass both upward and forward (strategy 1). Bounding is introduced, initially as a single effort from one leg to the other (**FIGURE 14**) be-

FIGURE 14. The bounding drill aims to retrain the ability of the lower-limb muscles to propel the body's center of mass upward and forward, and thereby develop the skills for pushing on the ground more forcefully (strategy 1). The sequence of the images is from right to left.

fore performing several bounds in series. Once capable of successfully bounding, the individual with TBI can then begin to practice running with increasing stride lengths. Ultimately, the ability of an individual following TBI to be able to run at faster speeds is dependent on how well this final skill, which is largely determined by the function of the ankle plantar flexor muscles, can be restored.

Future Research Directions

Although some important insights regarding the lower-limb muscular strategies to increase running speed have been gleaned from the research completed to date, it is clear that many aspects are yet to be fully understood. As previously discussed, the vast majority of studies investigating the biomechanics of increasing running speed have used an experimental design that involves a range of discrete steady-state running speeds. However, such an approach may not resemble what occurs when accelerating, especially in the initial steps of the acceleration, when the trunk is inclined forward. Current knowledge regarding lower-limb muscle function during accelerated running is somewhat limited, and thus represents a valuable direction for future research. Also, another relatively new and potentially powerful way to study lower-limb muscle function during running is the use of dynamic ultrasound imaging.[20,32,47] This modality can quantify in vivo muscle fiber dynamics, and therefore has the potential to determine how increasing running speed influences the force-length and force-velocity relationships for certain muscles. Finally, further research is required to fully realize the biomechanical determinants of maximum running speed. Is the ability to push on the ground forcefully and quickly important? Evidence provided by many researchers[9,65,82,83] would suggest so, in which case muscular properties such as physiological cross-sectional area and percentage distribution of type IIx fast-twitch fibers (especially for the major ankle plantar flexors) are likely to be key characteristics. However, the way in which the lower limb pushes on the ground would appear to be important too, with a number of studies reporting significant correlations between maximum running speed and the magnitude of the propulsive component of the anterior/posterior ground reaction force.[9,30,57,58,65] Such a relationship suggests that technique is also likely to be a critical factor in determining sprint performance. Understanding what limits maximum running speeds in humans has considerable implications for designing optimal sprint training programs.

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