25 Lower-Limb Muscle Function in Human Running

Anthony G. Schache, Tim W. Dorn, and Marcus G. Pandy

Abstract. This paper provides a brief summary of work completed to date in our research laboratory investigating lower-limb muscle function during human running. Muscle function has been evaluated using a variety of methods, including muscle electromyography, inverse dynamics, and computational musculoskeletal modeling. It is evident that the coordination amongst the major lower-limb muscles changes considerably when running speed is progressed from jogging through to maximum sprinting. The ankle plantarflexor muscles appear to have a dominant role up to running speeds of around 7 ms^{-1}. For running speeds beyond 7 ms^{-1}, the hip flexor and extensor muscles become far more critical. These findings provide insight into the strategies used by the lower-limb muscles to maximize running performance and have implications for the design of injury prevention programs.

1 Introduction

Running is a fundamental skill. It is a critical requirement for almost all sporting activities. Understanding the biomechanical function of the major lower-limb muscle groups during running is important for improving current knowledge regarding human high performance as well as identifying potential factors that might be related to injury. There are a variety of methodological approaches that can be taken to study lower-limb muscle function during running, including: (a) the measurement of muscle electromyographic activity [1, 2]; (b) the use of inverse dynamics to determine lower-limb joint moments of force (or torques), net joint powers, and work [3,5]; and (c) the use of computational musculoskeletal modeling to calculate certain parameters that cannot be directly measured via non-invasive experiments [6,9]. Our research group has applied a combination of these approaches to address several research questions of primary interest, for

Anthony G. Schache · Tim W. Dorn · Marcus G. Pandy
Department of Mechanical Engineering, University of Melbourne,
Parkville, Victoria 3010, Australia
e-mail: pandym@unimelb.edu.au

V. Kumar et al. (Eds.): *Adv. in Mech., Rob. & Des. Educ. & Res.*, MMS 14, pp. 323–327.
DOI: 10.1007/978-3-319-00398-6_25

example: Which lower-limb muscles are most important for increasing running speed? and How does faster running influence the mechanics of certain biarticular muscles, such as the hamstrings? Herein we provide a summary of some of the main findings from work completed to date.

2 Overview of Experimental Methods

Data were collected from nine healthy adult runners (five males, four females; age, 27.7±8.0 years; body mass, 73.1±8.6 kg, height, 176±7 cm). Each participant ran on an indoor synthetic running track at four discrete steady-state running speeds: slow running at 3.5 ms^{-1} (N=9), medium-paced running at 5.0 ms^{-1} (N=9), fast running at 7.0 ms^{-1} (N=8) and maximal sprinting at 8.0 ms^{-1} or greater (N=7). Small reflective markers were mounted at specific locations on the trunk, legs and arms and the marker trajectories were recorded using a three-dimensional motion capture system (VICON, Oxford Metrics Ltd., Oxford, UK). Ground reaction forces were measured using eight force plates (Kistler Instrument Corp., Amherst, NY, USA). Lower-limb muscle electromyographic data were acquired using a telemetered system (Noraxon Telemyo 2400T G2, Noraxon USA Inc., Scottsdale, AZ, USA).

3 Lower-Limb Muscle Function with Increasing Running Speed

To determine which muscles are most important for increasing running speed, we initially applied an inverse-dynamics approach to calculate the torques, net powers and work done at the lower-limb joints [4]. The most substantial increases in magnitude were displayed by the sagittal-plane torques, net powers, and work done at the hip and knee joints during the terminal swing phase of the stride cycle. For example, when running speed changed from 3.5 ms^{-1} to 9.0 ms^{-1}, the peak hip joint power generation and the peak knee joint power absorption during terminal swing increased 12.1-fold and 8.1-fold, respectively. In contrast, the work done at the knee joint during the stance phase of the stride cycle was not affected by running speed, whereas the work done at the ankle joint during stance increased when running speed changed from 3.5 ms^{-1} to 5.0 ms^{-1}, but plateaued thereafter. In terms of lower-limb muscle function, this study revealed that in order to progress running speed towards maximal sprinting the increase in biomechanical load generated by the hip flexor and extensor muscles during the swing phase of the stride cycle was substantially greater than that generated by the knee extensor and ankle plantarflexor muscles during stance.

While our inverse-dynamics analysis generated some important and interesting observations, the ability of this approach to quantify the biomechanical load experienced by an individual lower-limb muscle is limited by the mechanical redundancy of the human musculoskeletal system. In other words, because many muscles cross each lower-limb joint, a net joint torque can be satisfied by an infinite combination of muscle forces. It is therefore not possible to discern the actions of individual muscles from net joint moments alone [10]. Hence, our next step was to apply computational musculoskeletal modeling [6]. Such an approach allows the contributions of individual lower-limb muscles to joint and center-of-mass accelerations to be determined, information which perhaps best describes the functional role of a muscle.

When running speed progressed from slow to fast, stride length displayed a greater percentage increase in magnitude than stride frequency; however, beyond 7.0 ms^{-1} the opposite occurred. This result is consistent with what has been reported by others [11]. Thus, faster running is initially achieved by increasing stride length at a greater rate than stride frequency, but eventually a threshold is reached and a shift in strategy occurs whereby the progression to maximum running speed is achieved by increasing stride frequency at a greater rate than stride length. Our computational modeling indicated that the ankle plantarflexor muscles were primarily responsible for this strategy shift. Specifically, for running speeds up to 7 ms^{-1}, the ankle plantarflexors (i.e., the gastrocnemius and soleus muscles) provided a significant contribution to vertical support and hence increases in stride length. For speeds beyond 7 ms, these muscles likely shortened at relatively high velocities and had less time to generate forces needed for support. Consequently, running speed was progressed to maximum by having the hip flexors and extensors (i.e., the iliopsoas, gluteus maximus, and hamstring muscles) accelerate the hip and knee joints more vigorously during swing, thus increasing stride frequency. These findings offer insight into the strategies used by the lower-limb muscles to maximize running performance. The function of the ankle plantarflexor muscles appears critical, and it could be theorized that a key difference between elite and sub-elite sprinting athletes relates to the rate at which these muscles produce maximum force [12]. Compared to their sub-elite counterparts, elite sprinters may have the capacity to produce maximum force from the ankle plantarflexor muscles in a much shorter period of time, thus allowing them to reach higher speeds of running before needing to shift strategies.

4 Hamstring Muscle Function during Sprinting

One consequence of the switch to a hip-dominant strategy as running speed approaches maximum sprinting is that the magnitude of the forces (gravity and centrifugal) acting about the hip and knee joints during the terminal swing phase of the stride cycle increase dramatically. Large ‘external’ hip flexor and knee extensor torques are produced, which are primarily opposed by the hamstring muscles. It is therefore not surprising that the majority of hamstring muscle strain-type injuries occur when running at maximal or close to maximal speeds [13]. In order to aid in the development of rehabilitation and prevention strategies that are specific to the mechanism of injury, musculoskeletal modeling has been used to understand the mechanics of the human hamstring muscles during sprinting by our research group [14] and others [15, 16]. The consistent finding from all studies completed to date is that during the terminal swing phase of the stride cycle the hamstrings reach peak muscle-tendon unit stretch, produce peak force, and perform much negative work (energy absorption). It has therefore been proposed that for sprinting the biarticular hamstrings are at greatest risk of injury during terminal swing when they are contracting eccentrically [17]. Such a proposal is consistent with what has been concluded from two independent case studies that analyzed biomechanical data collected during an acute *in vivo* hamstring muscle strain-type injury [18, 19]. The main implication is that interventions for rehabilitating and preventing hamstring strain injuries should be biased towards fast eccentric contractions performed at long muscle-tendon unit lengths.

5 Summary and Future Directions

This review has provided a brief summary of work completed to date in our research laboratory investigating lower-limb muscle function during human running. Evidence has been presented demonstrating that the coordination amongst the major lower-limb muscles changes considerably when running speed is progressed from jogging through to maximum sprinting. Our future work is directed at investigating lower-limb muscle function for continuous maximal accelerations and comparing results to those already obtained by analyzing a spectrum of discrete steady-state speeds. We are currently also using ultrasound imaging to directly evaluate muscle-fiber strain, and endeavour to integrate such measurements with a computational modeling approach to generate a more complete understanding of lower-limb muscle function during running.

References

1. Cappellini, G., Ivanenko, Y.P., Poppele, R.E., Lacquaniti, F.: Motor patterns in human walking and running. J. Neurophysiol. 95, 3426–3437 (2006)
2. Kyröläinen, H., Avela, J., Komi, P.V.: Changes in muscle activity with increasing running speed. J. Sports Sci. 23, 1101–1109 (2005)
3. Belli, A., Kyrolainen, H., Komi, P.V.: Moment and power of lower limb joints in running. Int. J. Sports Med. 23, 136–141 (2002)
4. Schache, A.G., Blanch, P.D., Dorn, T.W., Brown, N.A.T., Rosemond, D., Pandy, M.G.: Effect of running speed on lower limb joint kinetics. Med. Sci. Sports Exerc. 43, 525–532 (2011)
5. Winter, D.A.: Moments of force and mechanical power in jogging. J. Biomech. 16, 91–97 (1983)
6. Dorn, T.W., Schache, A.G., Pandy, M.G.: Muscular strategy shift in human running: dependence of running speed on hip and ankle muscle performance. J. Exp. Biol. 215, 1944–1956 (2012)
7. Hamner, S.R., Seth, A., Delp, S.L.: Muscle contributions to propulsion and support during running. J. Biomech. 43, 2709–2716 (2010)
8. Glitsch, U., Baumann, W.: The three-dimensional determination of internal loads in the lower extremity. J. Biomech. 30, 1123–1131 (1997)

9. Sasaki, K., Neptune, R.R.: Muscle mechanical work and elastic energy utilization during walking and running near the preferred gait transition speed. Gait Posture 23, 383–390 (2006)
10. Pandy, M.G., Andriacchi, T.P.: Muscle and joint function in human locomotion. Annu. Rev. Biomed. Eng. 12, 401–433 (2010)
11. Weyand, P.G., Sternlight, D.B., Bellizzi, M.J., Wright, S.: Faster top running speeds are achieved with greater ground forces not more rapid leg movements. J. Appl. Physiol. 89, 1991–1999 (2000)
12. Weyand, P.G., Sandell, R.F., Prime, D.N.L., Bundle, M.W.: The biological limits to running speed are imposed from the ground up. J. Appl. Physiol. 108, 950–961 (2010)
13. Askling, C.M., Tengvar, M., Saartok, T., Thorstensson, A.: Acute first-time hamstring strains during high-speed running. Am. J. Sports Med. 35, 197–206 (2007)
14. Schache, A.G., Dorn, T.W., Blanch, P.D., Brown, N.A.T., Pandy, M.G.: Mechanics of the human hamstring muscles during sprinting. Med. Sci. Sports Exerc. 44, 647–658 (2012)
15. Chumanov, E.S., Heiderscheit, B.C., Thelen, D.G.: Hamstring musculotendon dynamics during stance and swing phases of high-speed running. Med. Sci. Sports Exerc. 43, 525–532 (2011)
16. Thelen, D.G., Chumanov, E.S., Sherry, M.A., Heiderscheit, B.C.: Neuromusculoskeletal models provide insights into the mechanisms and rehabilitation of hamstring strains. Exerc. Sport Sci. Rev. 34, 135–141 (2006)
17. Chumanov, E.S., Schache, A.G., Heiderscheit, B.C., Thelen, D.G.: Hamstrings are most susceptible to injury during the late swing phase of sprinting. Br. J. Sports Med. 46, 90 (2012)
18. Heiderscheit, B.C., Hoerth, D.M., Chumanov, E.S., Swanson, S.C., Thelen, B.J., Thelen, D.G.: Identifying the time of occurrence of a hamstring strain injury during treadmill running: A case study. Clin. Biomech. 20, 1072–1078 (2005)
19. Schache, A.G., Wrigley, T.V., Baker, R., Pandy, M.G.: Biomechanical response to hamstring muscle strain injury. Gait Posture 29, 332–338 (2009)