The Role of Hamstring Contraction During Running: An Analysis

Theo Hu

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Bobby Bonser, D.A.T.
Thesis Chair

____
Justin Kilian, Ph.D.
Committee Member

____
David Schweitzer, Ph.D.
Assistant Honors Director

____
Date

Abstract

The hamstring muscle group, spanning the posterior aspect of the proximal lower limb, generates large amounts of contractile force during running. Researchers have examined this power generation within different phases of the stride cycle. Forces generated by the hamstrings hold implications for both running efficiency and the role of strengthening for injury prevention. The goal of this review is to examine the hamstring's unique physiology as a bi-articular muscle, its role in running stride, various training philosophies, and the specific impact on running economy contributing to overall running performance. The summation of research presented shows that the hamstring muscle group is uniquely positioned to impact overall running performance and that despite common misconceptions, shorter hamstrings are correlated with elevated running performance.

Keywords: Hamstring, Power generation, Stride cycle, Running economy

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Introduction

Hamstring Action and Role

The group of muscles commonly known as the hamstrings, made up of the biceps femoris (BF), semitendinosus (ST), and semimembranosus (SM), are crucial for human locomotion. The hamstring group is uniquely positioned to function differently during walking and running, and its specific physiology enables it to serve multiple functions within the walking and running stride. The foot ground contact time during running is much shorter than during walking, meaning the hamstring must produce much more torque over a much shorter timeframe. Indeed, the hamstring crosses both the acetabulofemoral joint (hip) as well as the tibiofemoral joint (knee) allowing its contraction to both extend the hip as well as flex the knee (Novacheck, 1998). As both movements are foundational to the running stride, the hamstring has great injury potential if underprepared and the opportunity for performance benefit when adequately trained. The unique nature and function of the hamstring group and its power and energy production have great implications for running economy and efficiency throughout the stride cycle. The ability of the hamstring group to do work enables other muscle groups of the lower leg to significantly contribute to force generation throughout the running stride.

The running stride is made up of the swing phase and stance phase. The stance phase occurs when the foot is planted on the ground, while the swing phase encompasses the time the foot is not touching the ground. This forces the hamstring to work differently within portions of those phases. Researchers have extensively examined the length and strength of contraction in different portions of the stride cycle to better understand the hamstring’s role as well as provide a basis for rehab and running performance improvement (Askling et al., 2003; Mikkola et al., 2007; Saunders et al., 2006; Spurrs et al., 2003). In the stance phase, the hamstring on the stance leg concentrically contracts for the first half and eccentrically contracts for the second half. This is the same for swing phase, however the hamstring acts primarily around the hip during stance phase and the knee during swing phase.

Researchers also show the positive effects of hamstring treatment and strengthening on running improvement. Different disciplines within running as well as levels of competition require various training methods and emphasize specific roles the hamstrings perform during the stride cycle. Recent research also reveals that there are differences observed in hamstring activation dependent on surface grade and running intensity (Cappellini et al., 2006; Dorn et al., 2012; Swanson & Caldwell, 2000; Yokozawa et al., 2007). The function of the hamstring allows it to be a crucial contributor in running form and ability, impacting sport performance and training. Contributions include both concentric and eccentric contractions during each phase of the stride cycle. Peak force was shown by Dorn et al. (2012) to increase in a nonlinear fashion when observing running velocity, placing significantly increased importance on the hamstring at increasing speeds. Because of this function and involvement throughout the stride cycle, targeted hamstring exercises have been shown to both prevent injury and increase running performance (Askling et al., 2003).

Anatomy and Physiology

Any discussion on and investigation into the performance and function of the human body must begin with examining the anatomy and physiology of the specific area. The unique structure and function of the hamstring is the foundation to many studies on its role during the running gait. Each of the three muscles that make up the hamstring group run along the posterior aspect of the thigh, and function as hip extensors and knee flexors. This is possible because of their unique position as bi-articular muscles.

Originating at the ischial tuberosity, the BF (most lateral) inserts at the fibular head, the ST at the pes anserinus tendon on the tibia, and the SM at the posterior aspect of the medial condyle of the tibia (Biel & Dorn, 2010). While functionally producing the same motion at the hip and knee joints, the three muscles of the hamstring are different lengths because of their different insertion points. Pierrynowski (1995) found that the ST has the longest fibers, followed by the BF and the SM, which has a fiber length only 78% of the BF length and 45% of the ST length. Another study by Yu et. al (2008) called the length of the hamstring the muscle-tendon length and correlated this measurement with EMG activity over the duration of the stride cycle. Hamstring length and EMG activity both peak in the hamstring during the end of swing phase while the foot is decelerating and preparing for foot strike rather than during the stance phase. The peak hamstring length difference between stance phase and swing phase is similar, whereas peak hamstring EMG activity differs widely between stance and swing phase. This is indicative of a propensity for hamstring strain during terminal stance, as higher EMG activity as seen during terminal swing is shown to reduce the risk of strain.

The length of the specific muscles also has implication for the occurrence of hamstring strain, which takes place over 75% of the time in the BF long head (Brukner & Khan, 2016). In addition to hip extension and knee flexion activities, the hamstrings also participate in other joint actions. These actions include the BF laterally rotating the knee and hip while the SM and ST medially rotate both the knee and hip. This does not play much role in the running gait because of the linear nature of the stride cycle. Given the bi-articular nature of the hamstring group and the drastic change the knee and hip angles experience throughout the stride cycle, Yu et al. (2008) found an active requirement for high magnitude lengthening and shortening of the hamstring.

Also unique to the running stride, Mohamed et al. (2002) demonstrated that the hamstrings uphold stable mechanical advantage at one end while simultaneously promoting change in muscle length at the other. This is because of the bi-articular nature of the hamstrings and requirement during portions of the stride cycle to hold a static angle at the knee while also extending the hip. Yeow (2013) showed in his study that torque produced by the hamstrings around the knee joint during stance phase are crucial to enable full use of the quadricep muscle group. The unique anatomy of the hamstring group allows dynamic function through bi-articular force production in the stride cycle round both the hip and knee joints (Yeow, 2013). Researchers have communicated the factors that allow for its efficient function and contribution to the running stride (Mohamed et al., 2002).

Stride Function

During running, the stride functions to generate power, acceleration, deceleration, and stability to the human body. As bipeds, humans require constant stability along with force generation, and the lower limbs are specifically designed for that role. Ultimately, the stride is designed to efficiently turn cellular energy into kinetic energy through the activation of muscles. Working in harmony, the muscles of the legs do just that. The running gait utilizes nearly all of the proximal and distal leg muscles, but some muscle groups contribute a greater amount. The bi-articular nature of the hamstring group places it in a crucial position to generate force and efficiently propel athletes.

Stride Phases

The running stride has two distinct phases: the stance phase and the swing phase (Montgomery et al., 1994). The swing phase during running begins with toe-off and continues until heel-strike. The initial swing phase occurs when the body is fully unsupported, and the remaining portion occurs while the opposite leg is generating power through the stance phase. The stance phase takes place from heel-strike through toe-off. During this phase the body generates force through the leg to propel the body forward, using most of the muscles of the thigh and leg. The stance phase is slightly shorter than the swing phase, allowing the fully unsupported time of gait when neither foot is touching the ground, constituting running. In different capacities, the hamstrings generate power in both of these phases (Montgomery et al., 1994). In the swing phase, the hamstring eccentrically contracts as the hamstring lengthens. Eccentric contraction peaks just before heel-strike, according to Yeow (2013) and Chumanov et al. (2011). The hip moves from a state of extension to a state of flexion during the swing phase, and the knee extends from a state of flexion in the second half of the swing phase. This necessitates the eccentric contraction, allowing deceleration of the foot just before heel-strike. In the stance phase, the hamstrings concentrically contract and force the hip to extend while keeping the knee at the same angle of flexion through most of the stance phase (Yeow, 2013).

Ideal Torque

Because the hamstrings vary greatly in length throughout the stride cycle, different amounts of torque are generated at different portions of the stride cycle because of different hamstring lengths. This is confirmed by Montgomery et al. (1994). From a physics perspective, the lower limb is a long lever with forces accentuated by the incredible increase of impact during the running stride. Additionally, because the hip is the first joint in the movement chain of the lower leg, the amount of torque required during the running gait is incredible. This need for torque is most clearly examined in a study by Kyröläinen et al. (2001) which observed the role of different muscle groups during increased running speeds. The prolonged hamstring activation during the stance phase underpins the increased importance of this muscle group as a hip extensor during high-speed running. Researchers observed through analysis of running at different speeds that while oxygen consumption linearly increased with energy requirement, EMG activation of the BF was specifically associated with an increase in energy cost. Not only did the BF show more EMG activity during the ground contact phase, it also presented greater activation during the swing phase when compared to the ST and SM. Most vivid was the role it played as a bi-articular muscle during maximal running velocity where it was most crucial for power development.

Mohamed et al. (2002) found that the greatest torque generated by the hamstrings on knee flexion and hip extension occurred when the hamstrings were lengthened. This is confirmed in Chumanov et al. (2011), Kyröläinen et al. (2001), Yeow (2013), and Yu et al. (2008). Results of these studies show that in a more lengthened state, the hip either neutral or flexed, and the knee extended, the EMG activity in the hamstring group was significantly lower than at joint angles requiring short hamstrings. Of particular note are findings by Lunnen et al. (1981) who found that while EMG activity in the hamstrings decreased with length, torque generated increased. The mechanical advantage held by the hamstrings is important to note in the discussion on running economy which will be examined later, as less EMG activity means less muscle activation and more efficient torque production.

Yeow (2013) examined further the specific roles of each of the three muscles of the hamstring group during each phase of the stride cycle. He found that all three muscles were major contributors to power generation during the stance phase around the knee joint. This is the point in the stride cycle that positive work is being done to accelerate the knee into a flexed position. Additionally, the BF long and short heads contributed to both dissipation and power generation during extension of the knee during the latter half of stance phase. During the swing phase, however, the SM and ST are responsible for generating and dissipating energy for both knee flexion and extension. With great amounts of torque generated when hamstrings are in a more lengthened state, loading occurs at different magnitudes throughout the stride cycle.

Chumanov et al. (2011) examined the loading of the hamstrings at different portions of the stride cycle specifically in relation to the incidence of hamstring strain. Hamstrings shorten while under load from the last 10% of the swing phase through the entirety of the stance phase (Chumanov et al., 2011). Additionally, during the first 40% of the swing phase the hamstring lengthens under load because of increased hip flexion (Chumanov et al., 2011). The literature on hamstring torque and force production at different lengths, during different speeds, and provided by different muscles shows that a lengthened hamstring position provides the greatest amount of torque around both the hip and knee joints. This is notable concerning the function of the hamstring in the stride cycle and the incidence of strains given high torque on long muscles increase the likelihood of strains.

Force Production at Variable Speed

The force production and energy use by the hamstring at increasing running speeds is a linear progression as reported by Kyröläinen et al. (2001). This is an intuitive fact, that an increase in speed will require more work to be done by the muscles and muscle groups providing that power. However, concentric force produced during the stance phase remains constant over increased speeds (Kyröläinen et al., 2001). Examining both different running speeds and the specific hamstring muscles, it was observed that the BF increases greatly in loading as the running intensity increases, resulting in greater risk of strain when compared to the SM and ST. A study by Yeow (2013) also showed the greater load placed on the hamstring during the late swing phase when compared to the stance phase, a key fact in the later examination of hamstring strains. Researchers found that force generated during the stance phase remained constant at increased running speeds while the force during the latter half of the swing phase increased significantly. Finally, in examination of each individual hamstring muscle, the force generated by the SM and BF was significantly greater than that produced by the ST over any of the speeds observed (Yeow, 2013).

Running Economy Biomechanics

In examination of the function and efficiency of any aspect of the human body, biomechanics must be considered. The unique relationship between the skeletal system and the muscular system to provide the body with locomotion is dynamic and begs analysis. The stride cycle and phases discussed above are the framework by which we can understand the economy and efficiency of human running. Compared to walking, running requires more energy, but more efficiently propels the body than at the same speed walking (Cappellini et al., 2006). Hip motion during walking moves in a convex arc with the high point coming when the lower limb is directly beneath the hips. Conversely, the hips during running move in a concave arc with the high points coming at heel-strike and toe-off. The hips dipping lower during the middle of the stance phase allows loading of muscles in preparation of explosive thrust during toe-off. This is a stark contrast to the walking stride and emphasizes the need of the hamstring group during the running gait (Cappellini et al., 2006). Running is not a two-dimensional movement, and because of that the stride adapts to various speeds and angles of running surface. These slight alterations impact the use and function of the hamstrings within the gait.

Additionally, the hamstring group is one of the most strained muscle groups in athletics and certain portions of the stride cycle increase the likelihood of these strains (van den Tillar et al., 2017). Eccentric contractions during the terminal portions of each phase coupled with mechanical work and power production contribute to the likelihood of strains. The specific role of the hamstring during the running stride positions enables it to perform efficient mechanical work during running. Because of the bi-articular nature of the hamstrings, Jacobs et al. (1996) found significant contribution to explosive leg extension power transfer. These researchers expounded on previous theories of bi-articular muscles efficiently transferring power and force from proximal ends of limbs to distal portions, enabling explosive movement. It was observed that the hamstrings transferred much more power from the hip to the knee than vice versa. The overall conclusion of this study was that bi-articular muscles, hamstrings included, are important for power transfer from the hip joints to knee joints.

Finally, Heise et al. (1996) observed through EMG activity and running economy that during the swing phase, shorter hamstring reactivation was correlated with higher running economy. The running stride when specifically compared to the walking stride differs mainly in the loading and potential energy stored as tension in the muscles and allows for high-velocity contractions propelling the body forward in the sagittal plane.

Stance Phase

The stance phase of the stride cycle begins at heel-strike and ends at toe-off. Heel-strike is called such because around 89% of distance runners strike with their heels when their foot first touches the ground (Larson et al., 2011). Novacheck (1998) further reported that toe off usually takes place at around 39% of the total stride cycle for distance running and around 36% for sprinting. Maximal hip extension occurs right at toe-off during running rather than slightly before while walking. The hip extends and accelerates throughout the stance phase and generates power and propulsion as the first joint in the kinetic chain transferring force into the ground. At the knee, flexion occurs as the kinetic chain is loaded with stored force preparing for extension. The knee flexes around 45^o during the loading portion and extends to around 25^o towards toe-off (Novacheck, 1998). This angle during loading and terminal portion of the stance phase are decreased near maximal running speeds during sprinting (Mann & Hagy, 1980). The knee also extends more during sprinting to produce more power. While the hamstrings are most active in the terminal swing phase before heel strike, immediately after heel strike the quadricep group takes precedence and the hamstrings act more as stabilizers and hold the knee in a loaded position. The hamstring’s role during the stance phase begins primarily with stabilization and progresses to explosive concentric power generation near terminal stance phase. Hips during the stance phase dip towards the ground as a function of muscular loading. Mann and Hagy (1980) showed that the center of gravity becomes lower as speed increases because of the increased hip flexion and extension. These investigators also found that while in running the knee flexes to store energy, in sprinting the ankle was a greater focal point of energy storage.

Swing Phase

The swing phase, making up the other roughly 64% of the stride cycle begins at toe-off and ends at heel-strike (Novacheck, 1998). Just as the stance phase bares great differences to the walking stance phase, the running swing phase optimizes efficiency over faster ambulatory speeds. During the first half of the swing phase, the hip flexes from maximum extension, however during the second half the hip extends and prepares for foot strike and immediate power production. Observing the knee during swing phase, flexion occurs during the first portion of swing and extends at high velocity in the terminal portion. Degree of flexion normally reaches around 60^o during the swing phase during running and closer to 105^o during sprinting (Novacheck, 1998). The hamstring becomes dominant during the late swing phase in preparation for the heel strike and to decelerate knee extension but becomes significantly less active immediately after heel strike. The key role of the hamstring in swing phase begins by controlling the flexion of the hip but ends by eccentric contraction to control knee extension. As the speed of the runner increased, Mann and Hagy (1980) found that maximal knee flexion increased in a linear fashion while maximal knee extension decreased.

Hamstring Role in Speed Differences

Given the vast range of speeds athletes run at, the hamstring and its role within the running stride must adapt and optimize to provide the utmost efficiency for the athlete. Jacobs et al. (1996) found the hamstring produces most torque in a lengthened position and thus has much more influence on upright running as opposed to sprint starts which were analyzed in this study.

In sprint starts, the hamstrings act more as stabilizers enabling the quadricep group and gluteus maximus to produce most of the force production. In elite distance runners, a greater coactivation of the hamstring and quadricep muscle groups was observed (Heise et al., 1996). In running other than in sprint starts, the role of the hamstring is much more significant because of its position as well as coactivation with the quadricep group.

In steady state or at-speed running there are two distinct ways the human body can increase running speed. Firstly, the body can increase the stride frequency but keep the intensity and power of each step consistent. Inversely, the body can keep the stride frequency similar while increasing the power and thrust generated by each stride. Cappellini et al. (2006) examined differences between the running and walking gaits but also reported that speed increases during running were due to an increase in the intensity of muscle contraction rather than an increase in stride frequency. However, Dorn et al. (2012) found that at speeds over 7 m/s the stride length no longer increased, necessitating an increase in stride frequency and a parallel increase in power generated by leg muscles. This is especially true of the hamstring as peak knee flexion and hip extension velocities continue to increase with faster speeds. The bi-articular nature of the hamstring in particular crossing both the knee and hip joints is crucial to this increased joint velocity.

Of particular note was the peak force development of the hamstring during the terminal swing phase when the hamstring is eccentrically contracting. The force at 9 m/s nearly doubled when compared to running at 7 m/s, showing the nonlinear correlation between running speed and force development of the hamstring approaching maximal velocity (Dorn et al., 2012). Additionally, increases in hip angular velocity with increased running speeds paralleled increases in joint angles more distally on the lower limb. While it is possible that this correlation is due to the increased work of the agonists and synergists about those distal joints, another hypothesis views the increased joint angle velocity of distal joints as a function of dynamic coupling. Dynamic coupling views the increased knee and ankle velocities as a function of the increased hip angle velocity. This is supported by the findings of both studies which reported that the BF and ST increased their intensity over faster running speeds while distal leg muscle activation remained constant.

Grade Differences

Speed increases place increased demand on the hamstrings and similarly, steeper grades of running surfaces do as well. Key to understanding the role of the hamstring during incline running are the findings of studies by Swanson and Caldwell (2000) and Yokozawa et al. (2007). These researchers observed that the hamstring strength requirement increases because the stance phase is longer than running the same speed on level ground. Hamstring strength differs from speed of contraction and is thus different than the requirement for increased contraction velocity and intensity over increased speeds. Joint flexion over incline also increased for both the knee and the hip, using the hamstring in a slightly less efficient angle regarding peak torque potential. Overall findings on incline running compared with level ground running also show that the percentage of time spent in stance phase during each stride cycle increases with grade (Swanson & Caldwell, 2000; Yokozawa et al., 2007). Viewing the hamstring specifically, these researchers showed that hip flexion impacts hamstring length more than knee extension does. This fact and measured joint angles during incline running show that the hamstring contributes more to hip extension during incline running and more to dissipating force at the knee during level ground running. However, total time spent in stance phase actually decreases slightly because of the simultaneous increase in stride frequency and decrease in peak stride length. Overall, Yokozawa et al. (2007) concluded that incline running places a greater load on the muscles of the lower leg and is observed in EMG and torque increases.

Stance Phase

Of particular note regarding the motion of the hip during incline running was its motion at the moment of footstrike. Over flat ground the hip flexes slightly at footstrike to absorb energy but during incline running the hip extends explosively from just before the moment of footstrike through the first portion of the stance phase (Mann & Hagy, 1980). This means that the hamstring must transition quickly from eccentric contraction to slow the extension of the knee to concentric contraction, extending the hip. Overall, hip flexion was greater throughout the entire stride cycle during incline running, changing the angle of torque for the hamstring. This increased hip flexion is due to a greater forward lean when compared to a vector perpendicular to the ground during incline running. Researchers also observed knee flexion changing only small amounts until extending explosively at toe-off (Swanson & Caldwell, 2000). This contrasts with level ground running where the knee begins extension from around halfway through the stance phase. The lowering of the center of gravity during the middle of the stance phase also decreased in magnitude. Because the stance phase is longer during incline running, total power generation of the hamstring is greater than during level running (Yokozawa et al., 2007). Overall, the mechanical function of stance phase during incline changes significantly and demands more power generation from the hamstrings which must do work with different torque angles than during level ground running.

Swing Phase

The swing phase during incline running is notedly shorter than during level running. However, the total power produced is similar because of the parallel of increased demand and shorter force development time. Knee flexion during incline running was significantly less than during level running as opposed to hip extension which was significantly greater during incline running when compared to level ground running (Swanson & Caldwell, 2000). EMG activity also showed significant increases in hamstring stimulation in the second half of swing phase, especially in the terminal phase near footstrike (Swanson & Caldwell, 2000). This is consistent with the angular analysis showing an end to eccentric contraction and a beginning of concentric hamstring contraction during the terminal stage of the swing phase. Hamstring velocities of both concentric and eccentric contraction were shown to be higher during incline running due to the shortened swing phase and increased stride frequency. In conjunction with the decreased center of gravity drop, the vertical oscillation of the hips and torso during the swing phase also decreased with incline (Swanson & Caldwell, 2000). Overall, the swing phase during incline varies greatly when compared to level ground.

Cause of Strains

Hamstring strains are a prevalent injury in running sports at roughly 12% of all athletics injuries (Agre, 1985; Clanton & Coupe, 1998; Garrett et al., 1989; van den Tillar et al., 2017). It is one of the most common injuries the body experiences to soft tissue. Despite this prevalence, researchers have historically disagreed about at which portion of the stride cycle hamstring strain occurrence is most prevalent. More recently, researchers agree that eccentric contraction at high speeds is the largest cause of hamstring strains. For instance, Mann (1981) hypothesized that hamstring strains occurred at the point of maximum knee flexion and hip extension during the stance phase of near-maximal running. Conversely, Thelen et al. (2005) examined the eccentric contraction portion of the swing phase as the point of most hamstring strains. This is now the most widely held belief relating to the timing of hamstring strains.

In examination of muscle stretch and velocity changes, Schache et al. (2013) presented that at higher running speeds, maximum stretch does not increase, but velocity of contraction does. This is the cause of hamstring strain at high speeds. Hamstring strains are a function of the interaction of muscle-tendon length in conjunction with peak muscle elongation velocity. Yu et al. (2008) found in examining the length-tension relationship that both the maximum length and maximum velocity were significantly greater during the swing phase than during the stance phase. Length was shown to be around four times greater in swing phase and velocity three times greater. Additionally, the velocity of the SM and ST were greater than the peak velocity of the BF at the point of terminal swing. Significant for hamstring strains is the fact that the muscle length of the SM is significantly greater than the ST and BF at each of their peak elongation velocities.

Despite this, Thelen et al. (2005) found that the most strained hamstring is the BF rather than the SM which has the shortest fiber length. Pennation angle of each hamstring is also similar, removing that as a possible reason for higher incidence in any one hamstring over another. Disagreement in literature mainly comes because it has been shown that increased muscle activation decreases the chance for strains, and muscle activation of the hamstring is greater during the late swing phase than during late stance phase. However, the significantly greater muscle elongation velocity often cancels out this activation preventing hamstring strains as the eccentric contraction is a factor contributing to the incidence of strains (Schache et al., 2013). One limitation in attempting to examine the occurrence of hamstring strains reported in Yu et al. (2008) and Thelen et al. (2005) is the difference between treadmill and overground running. Differences reported in these two types of running have a large degree to do with the degree of knee extension during the terminal stance phase. In treadmill running the knee does not extend as far as during overground running. This is significant for studies on hamstring strains because it is much easier to study subjects running on a treadmill rather than over ground when using an EMG. Therefore, length of hamstrings during terminal stance phase does not completely reflect actual values of overground running. An actual greater value for hamstring length in the stance phase gives more value to the theory of strains occurring more often in stance phase rather than swing phase. Overall, hamstring strains are a function of both musculotendinous lengthening coupled with eccentric contraction. Researchers show the occurrence of these two stipulations in both the late stance and late swing phase but disagree on the location of greater occurrence.

Strengthening and Flexibility

Hamstrings are one of the most often targeted muscles for static stretching among the general population and one of the least targeted for strengthening purposes. For both injury prevention, optimal performance, and overall athletic ability strengthening and flexibility of the hamstrings plays a large role. While hamstring injuries in sprinters are 10 times more likely than in middle distance and long-distance runners, injury prevention techniques are beneficial because of their impact on performance (Agre, 1985). Specifically observing distance running, researchers have investigated questions of hamstring length and the ideal level of flexibility for coaches and athletes to target and train.

Injury Prevention

Because of the incidence of hamstring strains, the foundational role of the hamstring during running, and the lack of strengthening among the general population and many athletes, hamstring strengthening has been extensively investigated in literature. Given the susceptibility for hamstring strain, especially in the BF and at high speeds, hamstring strengthening has been shown to be effective in reducing injury risk for running. Askling et al. (2003) examined soccer players and their incidence of injury after a concentric and eccentric hamstring strengthening program. The program consisted of prone curls utilizing both concentric and eccentric work and strength improvements were measured by isokinetic testing before and after the exercise programming. After the season, incidence of hamstring injuries among the control and strengthening group were tabulated and the strengthening group had an injury rate of less than 1/3 the injury rate of the control group. Van den Tillaar et al. (2017) found in a comparison of different exercises and their activation of the hamstrings in comparison to maximal sprinting EMG activity that Nordic hamstring exercise variations were most similar to maximal sprinting. The most activation of the hamstrings were found in these activities and this activation occurred at angles closely resembling the angles observed in maximal sprinting. However, the EMG activity in the strengthening exercises still did not reach the levels of maximal sprinting. While not perfect, this supports the claim that Nordic hamstring exercises are the most beneficial for hamstring injury prevention and strengthening for improved performance. In another study by Naclerio et al. (2013), a control group of athletes were compared to a group who completed a program of stable open kinetic chain single leg hamstring strengthening exercises and unstable closed kinetic chain. Researchers specifically measured torque primarily around the knee joint. It was found that after the strengthening program, torque increased at 80º and 35º of knee flexion (Naclerio et al., 2013). This study shows the importance of both stable and unstable exercises as well as open and closed chain exercises for the prevention of injuries.

Increased Speed and Performance

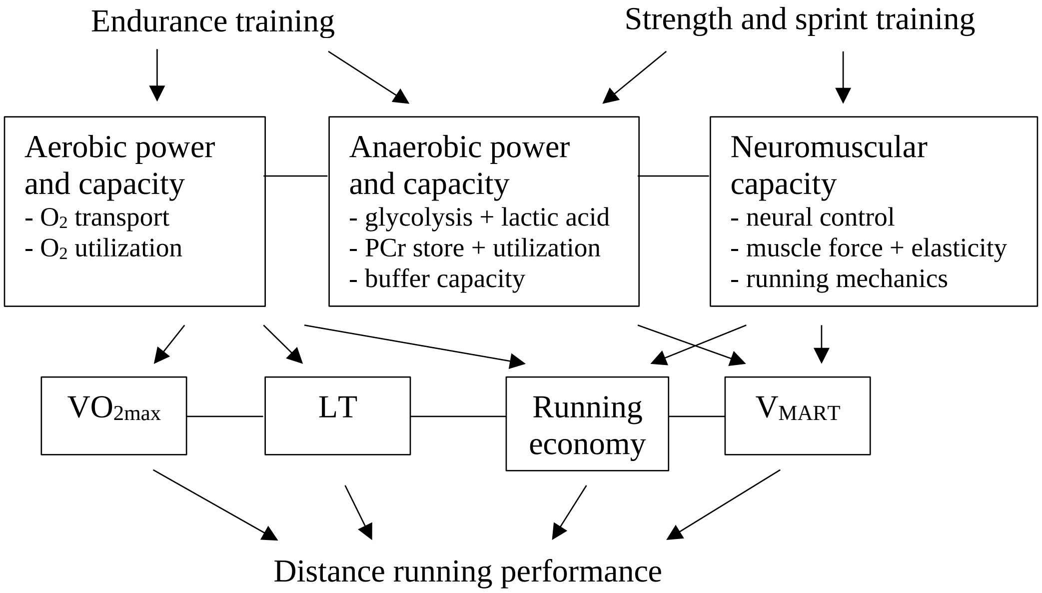
Beyond injury prevention, hamstring strengthening also benefits running performance. Researchers agree that plyometric and eccentric training as used in subsequent studies clearly strengthens hamstrings as expected (Clark et al., 2005). In a study examining maximal running speed, Askling et al. (2003) found that improvements in hamstring strength from specific training directly improves running speed. Here researchers found that there was a 2.4% improvement after a concentric and eccentric hamstring strengthening program when compared to the control group. However, investigators do not agree on the benefit of hamstring strengthening on running performance. Mendiguchia et al. (2015) and Duhig et al. (2019) found that slim to no improvements were found after hamstring strengthening. This reporting of no improvements to running performance after resistance training were generally studies that examined groups that exclusively trained with either distance training or resistance training. On the other hand, researchers report improvement to distance running performance in conjunction with continued endurance training, rather than alone. Spurrs et al. (2003) reported a 2.7% decrease in 3-kilometer time over the course of 6 weeks for athletes completing a plyometric training program in conjunction with their regular endurance training. VO_2 max did not increase over that time for either the control group or the plyometric training group. Another study by

Saunders et al. (2006) confirmed the benefit of plyometric training in a similar fashion by examining middle- and long-distance runners. Again, no improvement in VO_2 max was observed over the 9-week training plan but increases in running economy were observed at the conclusion of the study for those who trained with plyometric exercises. Rather than simply adding resistance training on top of endurance training for a group of runners, Mikkola et al. (2007) replaced 19% of the endurance training of one group with the resistance training program. Researchers in this study focused on explosive training including some plyometrics and repetitions at high speed of movement. At the conclusion of the study, anaerobic running ability improved but cardiovascular measures remained unchanged. This may be of benefit to runners who are participating in races because of the ability to elevate speed at the end of races to pass competitors. Finally, Paavolainen et al. (1999) examined the conjunction of strength and sprint training in addition to endurance running. These researchers examined the possible causes of the observed improvement to 5-kilometer running time, overall running economy, and 20-meter speed in the strength training group.

Figure 1 shows the hypothesized direct benefit of different aspects of training and their direct benefits on various aspects of running performance. Overall, VO_2 max, lactate threshold (LT), running economy, and maximal anaerobic running (V_{MART}) all contribute to distance running performance. Paavolainen et al. (1999), however, found that neither LT or VO_2 max improved despite improvement in 5-kilometer running time. Improvement in this study was attributed to the leg stiffness theory that states an increase in leg stiffness improves running economy and energy return. Clark et al. (2005) and others show the strength improvements from plyometric and eccentric exercises, allowing researchers to examine these strength benefits in relation to distance running. Overall, researchers evidence the benefit and impact of different forms of resistance training on distance running performance, running economy, increased anaerobic speed, and increased maximal speed.

Figure 1

Specific Effects of Endurance and Strength Training on Running Performance



Note: Adapted from “Explosive-strength training improves 5-km running time by improving running economy and muscle power,” by L. Paavolainen, K. Hakkinen, I. Hamalainen, A. Nummela, and H. Rusko, 1999, *Journal of Applied Physiology*, *86*(5), 1527-1533 (https://doi.org/10.1152/jappl.1999.86.5.1527).

Ideal Hamstring Length

Besides strengthening, researchers have also examined what length of hamstring is most optimal for running, given the previous discussion on most force production occurring in the lengthened hamstring position. A common notion in the general population is that more flexibility is always of benefit, but this is not the case. Investigators have shown an inverse relationship (negative correlation) between hamstring flexibility and running speed (Craib et al., 1996; Jones, 2002; Sundby & Gorelick, 2014; Trehearn & Buresh, 2009). This is consistent with other researchers showing that the maximum force production occurs when the hamstrings are in an elongated position. In shorter muscles, this point is reached more quickly, therefore explaining performance improvement. In a study by Jones (2002), male distance runners were assessed below the LT to observe possible correlation between hamstring flexibility and running economy. The results of this study confirmed a negative correlation with hamstring flexibility metrics and running economy. Runners who scored lower on the hamstring flexibility test were found to have a higher running economy. Craib et al. (1996) examined both the flexibility of the hip, but also similarly found increases in running economy with less flexibility in the areas of trunk rotation as well as ankle dorsiflexion. Hip and ankle stiffness was correlated with increased running economy in this study. On another hand, Sundby and Gorelick (2014) found no correlation between hamstring flexibility and running economy but did find positive correlation between both hamstring torque and strength and increased running economy. Finally, Trehearn and Buresh (2009) examined hamstring flexibility correlation to both running economy and 10-kilometer running time. Researchers here found sex-related trends and differences, but data from both men and women pointed to less hamstring flexibility correlating with improved 10-kilometer time as well as running economy. Running economy being defined as how much work can be done using as little energy as possible. Researchers hypothesize in these studies that a possible explanation for the correlation is that runners with shorter hamstrings benefit from an increased energy return given the greater elasticity potential (Saunders et al., 2004). Greater elasticity potential is achieved through the stretch-shortening cycle and the energy release it affords muscles. This would require a lower energy cost and subsequently increase running economy. Current literature and findings related to the role of flexibility in distance running suggests that flexibility is not as important a component as previously thought and can even be detrimental to ideal running performance.

Conclusion

The function of the hamstring as a bi-articular muscle requires it to perform in a unique role within the running gait. Hamstrings work to both flex the knee and extend the hip forcefully. As a foundational component in the energy transfer chain from the torso to the feet, efficiency in hamstring motion elevates ability of muscles farther down the chain. Because of the bi-articular nature of the hamstring, it is important in both the stance and swing phases of the stride cycle. It performs concentric contraction in the first portion of each stride phase, with significantly more concentric force generated during stance. Eccentric contraction takes place during the terminal portion of each phase and is the main cause of strains. Impacting the knee joint, the hamstring stabilizes and disallows extension during the stance phase while it flexes the knee during the first half of the swing phase. In the second half of the swing phase, the hamstring dissipates energy and slows extension. For the hip joint, the hamstring explosively extends throughout the stance phase. Studies have shown that torque production is optimized in a lengthened position, impacting both the incidence of strains and optimal performance. Researchers report increased hamstring activation, torque, and power generation at increased running speeds and as the stride changes to sprinting. Relating more to distance disciplines, running on an incline changes both phases of the running gait and requires the hamstring to generate power from a less ideal angle. This increased power generation, especially at increased velocity impacts the incidence of strains. Investigators disagree on whether the swing or stance phase produce more strains but affirm that high-velocity eccentric contractions place greatest stress on the hamstring group. Observing the necessity of the hamstring within the running gait as well as the incidence of hamstring strains as one of the most common soft tissue injuries, researchers affirm the benefit of resistance training. They show the benefit of various types of strengthening exercises on distance running performance over multiple distances. Additionally, eccentric exercises have been shown to decrease the incidence of strains. Investigation into hamstring flexibility and its correlation to running performance contradicts a widely held belief that more flexibility is beneficial and will improve distance running performance. Investigators show clearly that there is an inverse relationship between hamstring flexibility and distance running performance over various distances. These studies on strengthening, injury prevention, and flexibility hold implications for athletes, coaches, and trainers seeking to optimize running economy and distance running performance. Despite the extensive literature on the role of the hamstring during running, there remains a need for investigation. Specifically relating to distance running, examining different types of strengthening exercises, specifically targeting different hip and knee angles and their effect on performance seems to be of benefit. Additionally, examining ideal activation ratios of the gluteus maximus and hamstring group may hold implications for training and performance benefit.

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