

Hamstring Muscle Kinematics during Treadmill Sprinting

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ABSTRACT

THELEN, D. G., E. S. CHUMANOV, D. M. HOERTH, T. M. BEST, S. C. SWANSON, L. LI, M. YOUNG, and B. C. HEIDERSCHEIT. Hamstring Muscle Kinematics during Treadmill Sprinting. *Med. Sci. Sports Exerc.*, Vol. 37, No. 1, pp. 108–114, 2005. **Introduction/Purpose:** The objective of this study was to characterize hamstring muscle kinematics during sprinting, so as to provide scientific data to better understand injury mechanisms and differences in injury rates between muscles. **Methods:** We conducted three-dimensional motion analyses of 14 athletes performing treadmill sprinting at speeds ranging from 80 to 100% of maximum. Scaled musculoskeletal models were used to estimate hamstring muscle-tendon lengths throughout the sprinting gait cycle for each speed. We tested the hypothesis that the biceps femoris (BF) long head would be stretched a greater amount, relative to its length in an upright posture, than the semitendinosus (ST) and semimembranosus (SM). We also tested the hypothesis that increasing from submaximal to maximal sprinting speed would both increase the magnitude and delay the occurrence of peak muscle-tendon length in the gait cycle. **Results:** Maximum hamstring lengths occurred during the late swing phase of sprinting and were an average of 7.4% (SM), 8.1% (ST), and 9.5% (BF) greater than the respective muscle-tendon lengths in an upright configuration. Peak lengths were significantly larger in the BF than the ST and SM ($P < 0.01$), occurred significantly later in the gait cycle at the maximal speed ($P < 0.01$), but did not increase significantly with speed. Differences in the hip extension and knee flexion moment arms between the biarticular hamstrings account for the intermuscle variations in the peak lengths that were estimated. **Conclusions:** We conclude that intermuscle differences in hamstring moment arms about the hip and knee may be a factor contributing to the greater propensity for hamstring strain injuries to occur in the BF muscle. **Key Words:** MUSCLE STRAIN, MOTION ANALYSIS, MUSCULOSKELETAL MODELING, MUSCLE-TENDON LENGTH, MOMENT ARM

Hamstring muscle strains are one of the most frequent injuries in sports that involve sprinting. For example, a hamstring strain incidence rate of 24% was found among a group of collegiate sprinters and jumpers over a 2-yr period (31). Similarly, high rates of hamstring muscle injuries and associated missed playing time occur in soccer, rugby, and football (16,23). Radiologic analyses of athletes postinjury indicate that a large majority of acute hamstring strains involve the biceps femoris, whereas the semitendinosus and semimembranosus muscles are less often injured (6,10,14).

Despite the frequency of hamstring muscle injuries during sprinting, it remains unclear when in the gait cycle the muscle is injured or why the biceps femoris is more susceptible to injury. Late swing (30) and early stance (19) phases of sprinting have been suggested as potentially in-

jurious phases of the gait cycle. During late swing, the hip is flexed and the knee is extending. The hamstring muscles are active at this stage (15,20) while lengthening, which could induce an eccentric contraction injury (11,29). Alternatively, hamstring muscles remain active into stance when they are presumably shortening which could induce a concentric contraction injury (19,22). As for the differences in injury rates between muscles, investigators have speculated that the biceps femoris muscle's unique dual innervation, lateral distal insertion, and/or relatively shorter fiber lengths could contribute to a greater susceptibility to injury (12,30).

Part of the current ambiguity surrounding hamstring injuries may result from difficulties in inferring the action of biarticular muscles from joint level analyses of sprinting (5,13,18,19,26,30) and anatomical descriptions of muscles. A quantitative assessment of when the hamstring muscles are actively shortening, lengthening, or acting isometrically during sprinting may be important for understanding the biomechanical mechanisms of hamstring injuries. Such information could in turn provide a scientific basis for evaluating alternative treatment strategies (24) and methods of injury prevention

The objective of this study was to characterize hamstring muscle kinematics during treadmill sprinting. Specifically, we used three-dimensional motion analyses of sprinting along with scaled musculoskeletal models to estimate hamstring muscle-tendon lengths throughout the gait cycle. We

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tested our primary hypothesis that the biceps femoris would be stretched a greater amount than the semitendinosus and semimembranosus muscles. We also tested our secondary hypothesis that increasing from submaximal to maximal sprinting speed would both increase the magnitude and delay the occurrence of peak hamstring muscle-tendon lengths in the gait cycle. To provide additional characterization of hamstring muscle kinematics, peak velocities and joint angles were also analyzed.

METHODS

Subjects. A total of 14 athletes, 16–31 yr old, volunteered to participate in this study. All athletes were competent sprinting on high-speed treadmills, having completed a minimum of six previous treadmill training sessions of 45–60 min. Experimental testing was conducted at The Orthopedic Specialty Hospital in Murray, UT. The protocol was approved by the institutional review boards of both the testing institution and UW-Madison. Each subject provided informed consent in accordance with institutional policy.

Within 10 d before the test session, each athlete completed a speed testing protocol to establish maximum treadmill sprinting speed. The protocol consisted of five to six trials of sprinting at increasing speeds until the athlete was unable to maintain the treadmill speed for a minimum of 4 s. The athlete was allowed a full recovery between trials (heart rate < 110 bpm).

Protocol. Each test session started with the subject running at an easy speed on a high-speed treadmill, until they were acclimated to running with passive markers attached and were adequately warmed up to sprint. Motion analysis data were then recorded during treadmill sprinting at 80, 85, 90, 95, and 100% of the subject's maximum speed from the previous speed testing session. These trials were performed in a fixed, increasing speed order because it was not ethical or feasible to require athletes to attempt a maximum sprint on their first trial. If the subject was able to sprint at a maximal speed that was greater than what had been established previously, additional trials at speeds corresponding to 80–95% of the new maximum were performed in descending order. This occurred with 6 of the 14 subjects. A minimum of 3 min of rest was allotted between trials to offset effects of fatigue.

Motion analysis. An optical motion capture system (Motion Analysis Corporation, Santa Rosa, CA) was used to track the three-dimensional positions of 47 reflective markers placed on palpable anatomical landmarks. An initial recording of marker positions during quiet upright stance was performed to establish joint centers, body segment coordinate systems, and segment lengths. Kinematic data were recorded at 200 Hz.

Musculoskeletal model. A three-dimensional, 14-segment, 29 degree-of-freedom musculoskeletal model was used to compute joint angles and hamstring muscle-tendon lengths during sprinting (Fig. 1a). Six degrees of freedom described the position and orientation of the pelvis relative to the ground. Each hip was represented as a ball-and-socket

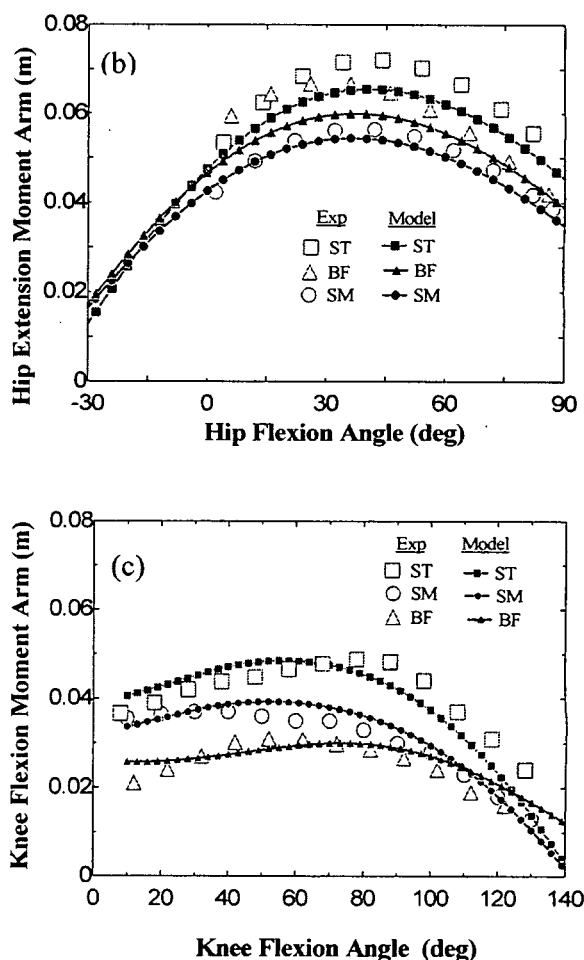
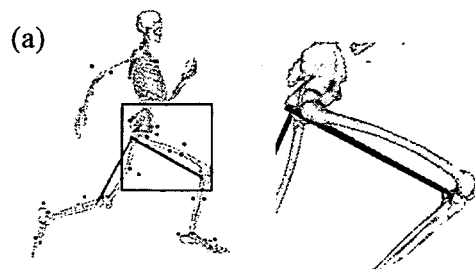


FIGURE 1—(a) Joint angles were computed by optimally fitting a scaled, 29 degree-of-freedom linked-segment model to measured marker kinematics. Biarticular hamstring muscles were represented by a series of line segments between origin and insertion, with wrapping surface used to represent wrapping about structures near the knee (8). (b) Semitendinosus (ST) and biceps femoris (BF) have larger hip extension moment arms than the semimembranosus (SM). This difference causes the ST and BF muscles to lengthen more than the SM as a result of hip flexion during sprinting. (c) BF has the smallest knee flexion moment arm of the biarticular hamstring muscles. Consequently, knee flexion during sprinting shortens the BF less than the SM and ST muscles. Model predictions of hip extension and knee flexion moment arms are compared with the experimental data of Arnold et al. (1) and Buford et al. (4), respectively.

joint with three degrees of freedom. A one degree-of-freedom knee was used to account for tibiofemoral and patellofemoral translations and nonsagittal joint rotations as a function of knee angle (28). The talocrural-subtalar joint was represented as a universal joint and the metatarsal joint as a

revolute, with the orientation of lower-extremity joint axes set to anatomically determined values (8). The musculoskeletal model was scaled to individual subjects using the segment lengths computed during the initial calibration trial. Both the bone and hamstring muscle geometries were based on cadaveric imaging and modeling studies conducted by Arnold et al. (1) (Fig. 1).

A nonlinear optimization algorithm (SIMM Motion Module, Motion Analysis Corporation) was used to compute the joint angles from the experimental kinematic data collected during the sprinting trials. At each time step, joint angles were computed that minimized the sum of squared differences between virtual markers on the model and experimental marker kinematics. Lengths of the biceps femoris (BF), semitendinosus (ST), and semimembranosus (SM) muscle tendons were computed from the joint angles by determining the distance from muscle origin to insertion, accounting for the wrapping of the muscles about the hip and knee joints. Muscle-tendon velocities were computed by numerically differentiating the muscle-tendon length data with respect to time. Muscle-tendon lengths and velocities were normalized to the respective muscle-tendon length in an upright posture, that is, with all lower extremity joint angles set to zero.

The occurrence of foot contact times was identified using the toe marker kinematics. A distinct oscillation in the vertical position of this marker was present at landing and was detected by determining when the vertical velocity of the toe marker exceeded a threshold value. The time (percentage of the gait cycle) and magnitude of both the minimum and maximum muscles-tendon lengths and velocities were determined from three gait cycles for both the right and left legs. The hip and knee flexion angles at the time of peak muscle-tendon lengths were also computed. Repeated measures analysis of variance was used to determine the effects of muscle and speed on the magnitude and timing of maximum muscle-tendon lengths and muscle-tendon velocities. Repeated measures analysis of variance was also used to determine the effects of muscle and speed on muscle-tendon length excursions, and to assess the effect of speed on peak hip flexion and knee extension angles. Tukey's test was used for *post hoc* analysis of significant main effects. All statistical analyses were completed with Systat (SPSS Inc., Chicago, IL) with a significance level of 0.01 used for all comparisons.

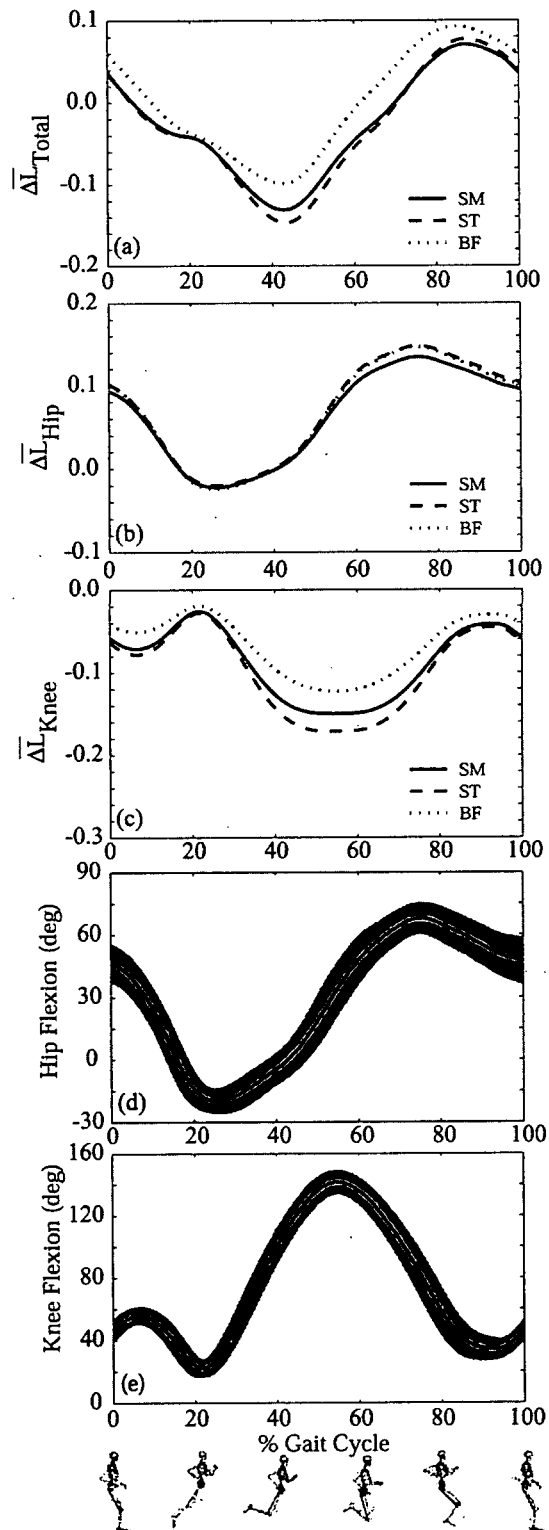


FIGURE 2—(a) The net change in length (ΔL) of the hamstring muscles during the sprinting gait cycle, relative to the respective muscle-tendon lengths in an upright configuration. Peak lengths of the hamstring muscles occurred at ~92% of the gait cycle. b) Much of the lengthening of the hamstring muscles was attributable to hip flexion (d) during the swing phase of sprinting. c) Knee flexion (e) during late swing acted to reduce the net change in muscle lengths. However, because the biceps femoris (BF) has a smaller knee flexion moment arm, it undergoes the least amount of shortening with knee flexion. These effects at the hip and knee contributed to a larger net lengthening of BF, compared with the semitendinosus (ST) and semimembranosus (SM) muscles.

TABLE 1. Subject characteristics and maximal treadmill sprinting speed of the athletes who participated in this study.

	Males Mean (SD)	Females Mean (SD)
No. of subjects	9	5
Age (yr)	18.2 (2.3)	19.6 (6.4)
Height (cm)	182.2 (4.3)	176.4 (5.3)
Body mass (kg)	84.7 (6.0)	65.7 (4.2)
V_{max} ($m \cdot s^{-1}$)	9.36 (0.61)	8.13 (0.76)

TABLE 2. Mean (SD) peak muscle-tendon lengths (\bar{L}_{max}), normalized to lengths in an upright posture, over the sprinting gait cycle. Peak lengths were significantly larger in the biceps femoris than the semimembranosus and semitendinosus muscles ($P < 0.01$) and were reached significantly later (t_{max}) in the gait cycle (GC) at the fastest speed ($P < 0.01$). Although the peak muscle-tendon lengths were invariant with speed, the corresponding posture of the limb did vary. This was evident in the hip and knee flexion angles which, at the time of peak muscle-tendon length, both significantly varied with speed ($P < 0.01$).

Muscle	Speed (% max)	$\bar{L}_{max}^{a,c}$	$t_{max}^{a,b}$ (%GC)	$\theta_{hip}^{a,b}$ (°)	$\theta_{knee}^{a,b}$ (°)
Biceps femoris	80	1.098 (0.026)	86.9 (4.2)	62.7 (8.3)	43.9 (12.6)
	85	1.096 (0.028)	87.1 (4.5)	63.1 (6.8)	44.3 (11.6)
	90	1.097 (0.027)	87.4 (3.8)	63.3 (7.1)	44.8 (10.2)
	95	1.094 (0.027)	88.3 (3.5)	62.6 (5.8)	45.4 (9.9)
	100	1.098 (0.028)	89.6 (3.7)	64.6 (6.7)	45.4 (8.7)
Semimembranosus	80	1.077 (0.015)	89.9 (2.9)	56.6 (7.5)	31.4 (6.6)
	85	1.075 (0.019)	90.4 (3.1)	57.2 (7.0)	32.1 (5.7)
	90	1.075 (0.015)	90.0 (2.7)	58.8 (7.4)	35.4 (5.2)
	95	1.072 (0.015)	90.8 (2.4)	58.8 (6.4)	37.1 (5.6)
	100	1.075 (0.016)	92.0 (2.7)	61.4 (8.0)	38.4 (5.3)
Semitendinosus	80	1.084 (0.017)	89.7 (2.9)	56.9 (7.5)	31.8 (6.6)
	85	1.082 (0.020)	90.1 (3.1)	57.5 (6.9)	32.7 (5.8)
	90	1.082 (0.017)	90.0 (2.7)	58.9 (7.4)	35.6 (5.3)
	95	1.078 (0.016)	90.7 (2.4)	58.9 (6.4)	37.4 (5.6)
	100	1.082 (0.018)	92.0 (2.7)	61.5 (8.0)	38.7 (5.3)

^a Significant muscle effects ($P < 0.01$); ^b significant speed effects ($P < 0.01$); ^c significant muscle by speed interactions ($P < 0.01$).

RESULTS

Maximal sprinting speeds for the subjects averaged $9.4 \text{ m}\cdot\text{s}^{-1}$ for the males and $8.1 \text{ m}\cdot\text{s}^{-1}$ for the females (Table 1). The hamstring muscle-tendons were shortening at foot contact, and continued to shorten throughout the stance phase of sprinting (Fig. 2). Hamstring muscle-tendon lengthening started at $\sim 45\%$ of the gait cycle, which was during swing just before the knee was reversing direction and starting to extend. Muscle-tendon lengthening persisted from this point until reaching peak lengths at $\sim 90\%$ of the gait cycle, which slightly preceded maximum knee extension during terminal swing.

The individual hamstring muscle-tendons were stretched an average of 7.4% (SM), 8.1% (ST) and 9.5% (BF) beyond nominal upright lengths. The normalized peak muscle-tendon length was significantly greater ($P < 0.01$) for the BF than the SM and ST (Table 2). Peak muscle-tendon lengths did not vary significantly over the range of running speeds tested. However, the corresponding hip flexion and knee flexion angles, at the time peak muscle-tendon lengths were reached, both significantly increased with speed ($P < 0.01$, Table 2). The overall excursions over a gait cycle were greater for the ST (22.8%) than the SM (20.5%) and BF (19.4%) muscles (Fig. 3). Peak hamstring lengths occurred significantly later in the gait cycle at 100% of sprinting speed compared with submaximal sprinting speeds ($P < 0.01$), with the delay amounting to $\sim 2\%$ of the gait cycle.

Peak lengthening velocities of 1.6–2.0 muscle-tendon lengths per second occurred at $\sim 60\%$ of the gait cycle (Table 3). This corresponded closely to the transition from knee flexion to knee extension during the swing phase of sprinting. Peak lengthening velocities increased significantly with speed for each of the muscles ($P < 0.01$). Lengthening velocities were greater in the ST than the BF and SM ($P < 0.01$).

Maximum hip flexion did not vary with speed, reaching approximately 70° at each of the speeds. The knee was significantly ($P < 0.01$) more flexed, by 8° , during late swing at the maximum speed than at the slowest (80% max) speed (Table 4).

DISCUSSION

We used experimental joint kinematics along with a musculoskeletal model to estimate hamstring lengths during sprinting, thus providing an indication of overall stretch in the muscle-tendon unit. We found that the hamstring muscle tendons undergo lengthening from approximately 45–90% of the sprinting gait cycle, with peak lengths occurring while in flight phase before foot contact. Previous estimates of hamstring kinematics during sprinting have also concluded that peak muscle-tendon lengths occur during late swing (25,30). EMG analysis indicates that the hamstring muscles are active during the last $\sim 20\%$ of the sprinting gait cycle (15,30). Taken together, this means the hamstring muscles are likely undergoing an active lengthening contraction during late swing.

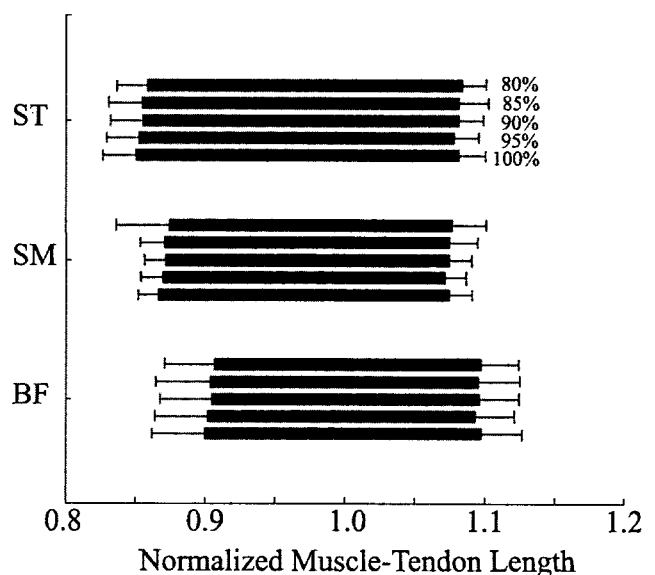


FIGURE 3—Range of normalized muscle-tendon lengths through which the hamstring muscles act during sprinting. The largest excursion is seen in the semitendinosus (ST), which is attributable to the ST having a larger knee flexion moment arm and hence greater shortening with knee flexion. Relative to respective upright lengths, the biceps femoris (BF) is stretched more than the ST and semimembranosus (SM) muscles at all speeds.

TABLE 3. Mean (SD) maximum and minimum muscle-tendon velocities, normalized to lengths in an upright posture, during the sprinting gait cycle. The magnitude of both maximum (\bar{V}_{max}) and minimum (\bar{V}_{min}) velocities increased significantly with running speed. Peak lengthening velocities were significantly larger in the semitendinosus than the biceps femoris and semimembranosus muscles. The time of occurrence of peak lengthening (t_{max}) and shortening (t_{min}) velocities within the gait cycle (GC) did not vary with speed or between muscles.

Muscle	Speed (% max)	$\bar{V}_{max}^{a,b,c}$ ($L_0 S^{-1}$)	t_{max} (%GC)	$\bar{V}_{min}^{a,b}$ ($L_0 S^{-1}$)	t_{min} (%GC)
Biceps femoris	80	1.63 (0.25)	59.0 (7.1)	-1.21 (0.22)	18.9 (18.3)
	85	1.69 (0.28)	59.0 (7.3)	-1.28 (0.20)	21.5 (17.2)
	90	1.70 (0.26)	59.0 (8.0)	-1.33 (0.22)	17.7 (14.9)
	95	1.74 (0.29)	58.6 (7.4)	-1.40 (0.23)	16.3 (17.4)
	100	1.77 (0.27)	60.5 (10.7)	-1.47 (0.24)	16.8 (15.5)
Semimembranosus	80	1.54 (0.24)	59.9 (7.1)	-1.27 (0.21)	26.4 (16.7)
	85	1.59 (0.26)	60.3 (7.2)	-1.33 (0.20)	27.1 (16.2)
	90	1.63 (0.24)	60.4 (7.9)	-1.36 (0.21)	22.0 (14.2)
	95	1.66 (0.28)	59.8 (7.3)	-1.42 (0.23)	22.4 (16.3)
	100	1.71 (0.26)	63.7 (10.2)	-1.49 (0.23)	21.4 (14.7)
Semitendinosus	80	1.74 (0.31)	60.8 (7.1)	-1.45 (0.28)	27.7 (16.8)
	85	1.79 (0.33)	60.9 (7.2)	-1.53 (0.28)	28.5 (16.3)
	90	1.83 (0.32)	60.8 (7.9)	-1.55 (0.29)	24.3 (14.4)
	95	1.87 (0.35)	61.1 (7.5)	-1.62 (0.31)	25.7 (16.7)
	100	1.93 (0.34)	64.8 (10.3)	-1.70 (0.32)	24.2 (15.0)

^a Significant muscle effects ($P < 0.01$); ^b significant speed effects ($P < 0.01$); ^c significant muscle by speed interactions ($P < 0.01$).

We estimate that muscle-tendon stretch, relative to muscle-tendon length in an upright posture, during sprinting is greater for the biceps femoris than the semimembranosus and semitendinosus. This difference is a direct result of slight variations in hip extension and knee flexion moment arms between the individual hamstring muscles. Peak hamstring muscle lengths during sprinting occur during late swing when the hip is highly flexed ($\sim 55\text{--}65^\circ$) and the knee is slightly flexed ($\sim 30\text{--}45^\circ$) (Table 2). Experimental studies have found that the semitendinosus and biceps femoris have a slightly larger hip extension moment arm than the semimembranosus (1). Thus, hip flexion causes relatively greater lengthening of these two muscles. Conversely, knee flexion causes a reduction in the overall length of the bi-articular hamstrings. At the knee, the biceps femoris has a smaller flexion moment arm than the semitendinosus and semimembranosus (4), and a corresponding smaller reduction in overall length. The net result of these combined effects is for sprinting to require greater stretch of the biceps femoris than of the semimembranosus and semitendinosus (Fig. 2).

Intermuscle differences in hamstring muscle injury rates have been observed among sprinters. The long head of the biceps femoris is the most commonly injured (6,10,14). For example, imaging analysis of 170 athletes postinjury found that 80% of hamstring muscle strain injuries involved the biceps femoris (14). These observations are consistent with our estimate that the BF incurs the largest overall stretch

TABLE 4. Maximum hip flexion (θ_{hip}) and minimum knee flexion (θ_{knee}) angles over the sprinting gait cycle. Maximum hip flexion did not vary with speed, but was reached (t_{hip}) significantly later in the gait cycle at high speeds. The knee was more flexed at the higher speeds, with peak knee extension being reached (t_{knee}) slightly closer to heel contact as speed was increased.

Speed (% max)	θ_{hip} (deg)	t_{hip}^a (% GC)	θ_{knee}^a (deg)	t_{knee}^a (%GC)
80	71.5 (9.4)	78.0 (1.8)	24.7 (4.7)	95.5 (2.1)
85	71.4 (8.1)	78.4 (2.2)	25.8 (4.9)	95.8 (1.9)
90	70.8 (7.8)	79.0 (2.2)	28.9 (4.3)	96.4 (2.0)
95	69.5 (5.9)	80.0 (1.7)	31.0 (4.8)	96.9 (2.1)
100	70.3 (5.9)	81.6 (3.3)	32.5 (5.2)	96.7 (2.3)

^a Significant speed effects ($P < 0.01$).

during sprinting. Thus, it is possible that slight differences in muscle moment arms, particularly at the knee, may contribute to the differences in injury rates among the hamstring muscles. This potential factor has not been previously proposed, with other researchers focusing on differences in fiber lengths, pennation, and innervation (11,30). Further research is warranted to better understand how these various factors actually combine to cause differences in injury rates.

Surprisingly, we did not estimate significant changes in peak hamstring lengths as running speed was increased from 80 to 100% of maximum. However, we did find that the posture of the limb, at the time peak hamstring lengths were reached, varied significantly with speed. Both the hip and knee flexion angles were greater at faster sprinting speeds (Table 2). Therefore, the increase in hamstring muscle-tendon length due to a more flexed hip was offset by the decrease in length due to a more flexed knee at fast sprinting speeds. This result suggests that hamstring extensibility may be a limiting factor dictating postures seen during the late swing phase of running. It is also interesting to note that the pattern of muscle-tendon lengths occurring during sprinting (Fig. 2) are qualitatively similar to that seen in walking (7). However, the stretch magnitude during sprinting, from 7 to 10% beyond upright lengths, exceed the $\sim 5\%$ hamstring stretch that occurs during walking (7).

We did find a delayed occurrence of peak hamstring lengths within the gait cycle and an increased muscle-tendon lengthening velocity at the maximum sprinting speed. It has been suggested that increasing from submaximal to maximal speed may be accomplished by delaying the reduction of swing leg energy within the gait cycle, with eccentric knee moment capacity being a potential limiting factor (5). Similarly, *post hoc* analysis of our data indicated that increasing from 95 to 100% of sprinting speed involved a delay in when the peak hamstring muscle-tendon lengths occurred in the gait cycle. Given that there were no significant changes in the timing of peak lengths at speeds below 95%, the delay seen at the highest speed may well result

from reaching a limiting neuromuscular factor at a maximum running speed.

There are some limitations of our study that are important to consider when interpreting the results. Our estimates of hamstring muscle-tendon kinematics are based on generic musculoskeletal models that do not account for individual differences in muscle origins and insertions, or the effects of loads on joint kinematics. Accounting for these factors would likely alter the absolute magnitudes of the muscle-tendon lengths but is unlikely to impact either the timing or intermuscle differences of peak muscle-tendon lengths. This is because the timing of peak lengths depends primarily on the simultaneous occurrence of near maximal hip flexion and knee extension, rather than on the geometry. Dynamic joint and muscle loading could alter the instantaneous joint axes and/or muscle paths. However, the anthropometric relationship among the muscles would still be retained meaning the relative differences in lengths and velocities between muscles would likely remain similar.

Our subjects were running on a treadmill rather than overground, as treadmill running allowed us to capture multiple trials that improved the strength of our statistical comparisons. Nigg et al. (21) found biomechanical differences between treadmill and overground running to be highly subject dependent, such that it is difficult to infer how hamstring kinematics may differ between the two conditions. Frishberg (9) found that at foot contact, sprinters tended to have a more upright leg but less upright thigh when sprinting overground compared with on a treadmill. This could indicate the athletes were running with greater hip and knee flexion during terminal swing. Because hip flexion lengthens the hamstrings and knee flexion shortens the hamstrings, these two factors could potentially combine to produce similar muscle-tendon kinematics as seen in treadmill sprinting.

Animal models have demonstrated that muscle fiber strain is a primary determinant of injury during active lengthening contractions (2,3,17). For example, Best et al. (2) found that acute strain injuries occurred when fiber strain reached ~60% across strain rates ranging from 4 to 100 $\text{cm}\cdot\text{s}^{-1}$. Therefore, although we found intermuscle differences in both the stretch and lengthening velocity of the muscle tendons, the peak stretch measures may be more

relevant as indicators of injury potential. Based on the stretch measures, our data would support the idea that injury potential is greatest during the late swing phase of sprinting and is higher for the biceps femoris than the medial hamstrings (27). However, it is important to recognize that muscle-tendon stretch does not equate directly to fiber strain due to the dynamic interactions between muscle contraction properties and tendon elasticity (32). For example, a recent experimental study demonstrated that gastrocnemius muscle fascicles remain at a relatively constant length while the muscle tendon and tendon undergo substantial lengthening and shortening during the stance phase of walking (10). It is similarly feasible that the hamstring muscle fibers undergo different motion than the muscle-tendon unit during the late swing phase of sprinting, contracting isometrically while the tendon stretches and then recoils before foot contact. Accounting for these dynamic muscle-tendon interactions is important for estimating actual fiber strain during functional movement such as sprinting. Given that the vast majority of hamstring strain injuries occur at or near a myotendinous junction (6), such analyses are highly relevant for furthering our understanding of injury mechanisms *in vivo*.

In summary, our results suggest that peak hamstring muscle-tendon lengths occur during late swing before foot contact, tend to be larger in the biceps femoris than in the semitendinosus and semimembranosus muscles, but do not vary significantly as sprinting speed is increased from submaximal to maximal. Combining these analyses with an assessment of hamstring muscle-tendon interactions may lend insights into the biomechanical mechanisms of hamstring injuries, and thus provide a scientific basis for evaluating clinical treatment strategies and methods of injury prevention.

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