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Hamstring muscle kinematics and activation during overground sprinting

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ABSTRACT

Hamstring muscle strain injury is one of the most commonly seen injuries in sports such as track and field, soccer, football, and rugby. The purpose of this study was to advance our understanding of the mechanisms of hamstring muscle strain injuries during over ground sprinting by investigating hamstring muscle–tendon kinematics and muscle activation. Three-dimensional videographic and electromyographic (EMG) data were collected for 20 male runners, soccer or lacrosse players performing overground sprinting at their maximum effort. Hamstring muscle–tendon lengths, elongation velocities, and linear envelop EMG data were analyzed for a running gait cycle of the dominant leg. Hamstring muscles exhibited eccentric contractions during the late stance phase as well as during the late swing phase of overground sprinting. The peak eccentric contraction speeds of the hamstring muscles were significantly greater during the late swing phase than during the late stance phase ($p = 0.001$) while the hamstring muscle–tendon lengths at the peak eccentric contraction speeds were significantly greater during the late stance phase than during the late swing phase ($p = 0.001$). No significant differences existed in the maximum hamstring muscle–tendon lengths between the two eccentric contractions. The potential for hamstring muscle strain injury exists during the late stance phase as well as during the late swing phases of overground sprinting.

1. Introduction

Hamstring muscle strain injury is one of the most commonly seen injuries in sports that involve sprinting such as track and field, soccer, football, and rugby (Agre, 1985; Brooks et al., 2006; Clanton and Coupe, 1998; Ekstrand and Gillquist, 1983; Garrett et al., 1989; Orchard and Seward, 2002; Stanton and Purdam, 1989; Woods et al., 2004). The prevalence rates of hamstring strain injuries are similar throughout sports in which they most frequently occur. Recent studies reported that hamstring strain injuries account for 12–16% of all injuries in Australian professional football (Arnason et al., 2004), 12% of all injuries in soccer (Woods et al., 2004), and 6–15% in rugby (Brooks et al., 2006).

Hamstring muscle strain injury is a frustrating injury because of the persistence of symptoms, slow healing, and high re-injury rate (Hawkins et al., 2001; Orchard and Seward, 2002; Petersen and Hölmich, 2005; Sherry and Best, 2004; Woods et al., 2004). Orchard and Seward (2002) reported that the re-injury rate of Australian football players who sustained their first hamstring injuries for the entire season (22 weeks) was as high as 31%. Hamstring muscle strain injury is a leading cause of lost time in these sports (Garrett et al., 1989; Petersen and Hölmich, 2005).

To prevent hamstring muscle strain injuries and improve rehabilitation outcomes, many studies have been conducted to determine the mechanisms of hamstring muscle strain injuries, especially the injuries that occur during sprinting. Mann and Sprague (1981) found the maximum knee flexion and hip extension moment during the stance phase of overground sprinting, and suggested that the potential for hamstring muscle strain injury existed during the stance phase of running. Thelen et al. (2005) found a hamstring muscle eccentric contraction during the late swing phase of treadmill sprinting, and suggested that the potential for hamstring muscle strain injury existed during the late swing phase. Their results, however, did not show a hamstring muscle eccentric contraction during the stance phase to support the notion of a potential for hamstring muscle strain injury during the stance phase (Mann and Sprague, 1981). The results by Thelen et al. (2005), however, were obtained during treadmill sprinting, which may be biomechanically different from overground sprinting (Frishberg, 1983).

The purpose of this study was to examine the potential for hamstring muscle strain injuries during overground sprinting by investigating hamstring muscle–tendon kinematics and muscle activation. We hypothesized that hamstring muscles would

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undergo an eccentric contraction which is necessary for hamstring muscle strain injuries (Lieber and Friden, 1993, 2002) during the stance phase as well as during the swing phase of overground sprinting.

2. Methods

2.1. Subjects

Twenty male runners (sprinters or middle distance runners), or soccer, or lacrosse players who practiced at least 3 times per week and had no known history of lower extremity injuries 6 months previous to the study were recruited (Table 1). The use of human subjects was approved by the Institutional Review Board.

2.2. Data collection

Surface electromyographic (EMG) electrodes were placed over the muscle belly of the dominant semimembranosus and biceps femoris of each subject. The ground electrode was placed on the ipsilateral tibial tuberosity. Manual muscle testing was performed to insure correct electrode placement. Reflective markers were placed bilaterally using a modified Helen-Hayes marker set (Kadaba et al., 1990) on both the upper and lower extremities of each subject. Reflective markers were also placed bilaterally on the acromion process, lateral epicondyle, and the dorsal side of the center of the wrist. An additional marker was place on the vertex.

Each subject was asked to complete seven acceptable sprinting trials with maximum effort with a 1 min rest between trials. An acceptable trial was a trial in which the EMG and kinematic data were collected successfully. The distance between the starting line and the calibration volume was 10 m. The trajectories of the retro-reflective markers were recorded using a Motion Analysis videographic and analog data acquisition system (Motion Analysis Inc., Santa Rosa, CA) with eight cameras at a sample rate of 240 frames/s. The EMG signals were collected using a telemetry EMG system (Noraxon, Inc., Scottsdale, AZ) at a sample rate of 2400 sample/second/channel. The videographic and EMG data collections were time synchronized.

2.3. Data reduction

The data from the first three analyzable trials for each subject were reduced for analysis. An analyzable trial was a trial in which a full running gait cycle of the dominant leg was recorded. A running gait cycle was defined as the time period between two consecutive foot strikes of the same foot. The time of a foot strike was defined as the time represented by the first frame in which the vertical coordinate of the heel or toe became a constant. The time of a toe off was defined as the time represented by the frame immediately after the last frame in which the vertical coordinate of the toe was constant. The time period between a foot strike and the subsequent toe off of the same foot was referred to as the stance phase while the time period between a toe off and the subsequent foot strike of the same foot was referred to as the swing phase. The time period between a toe off and the subsequent contralateral foot strike was referred to as a flight phase.

The 3-D coordinates of all reflective markers in the laboratory reference system were filtered through a fourth order Butterworth digital filter at an estimated optimum cutoff frequency of 15 Hz (Yu, 1989). The 3-D coordinates of medial condyle, medial malleolus, and hip, knee, and ankle joint centers in the laboratory reference system were estimated as described in the literature (Kadaba et al., 1990). The reflective markers on the acromion processes, lateral epicondyles, and the dorsal side of the wrists were used as approximations of the joint centers of the shoulders, elbows, and wrists. The 3-D coordinates of the whole body center of mass were determined using the segmentation method and a 14 segment model (Hay, 1993; Hinrichs, 1990). The average forward horizontal velocity of the whole body center of mass during the flight phase was used to represent the running speed.

The pelvis segment reference frame was determined using the 3-D coordinates of the left and right anterior superior iliac spines (ASIS) and the L4–L5 joint with the right ASIS as the origin, the *x*-axis pointing anteriorly, the *y*-axis parallel to the line between the left and right ASISs pointing toward the left, and the *z*-axis perpendicular to the plane determined by left and right ASISs and L4–L5 joint pointing superiorly. The thigh reference frame was determined using the 3-D coordinates of the hip and knee joint centers, and the medial and lateral tibial condyles with the hip joint center as the origin, the *x*-axis pointing anteriorly, the *y*-axis pointing to the left, and the *z*-axis parallel to the line between the hip and knee joint centers pointing superiorly. The lower leg reference frame was determined using the 3-D coordinates of the knee and ankle joint centers, and medial and lateral tibial condyles with the knee joint center as the origin, the *x*-axis pointing anteriorly, the *y*-axis pointing toward the left, and the *z*-axis parallel to the line between the knee and ankle joint centers pointing superiorly.

Table 1
Subject descriptive information

	Mean	Standard deviation
Age (years)	21.53	3.41
Height (m)	1.81	0.06
Mass (kg)	79.91	11.11

Table 2
Normalized three-dimensional coordinates of hamstring muscle attachment points in segment reference frames

	Attachment on pelvis			Attachment on tibia		
	x	*y*	*Z*	*X*	*Y*	*z*
Biceps femoris	−0.3197	0.2686	−0.6706	−0.0269	−0.1030	−0.1132
Semimembranosus	−0.2736	0.2089	−0.6422	−0.0580	0.0605	−0.1916
Semitendinosus	−0.2827	0.2415	−0.7029	0.0200	0.0338	−0.1641

The 3-D coordinates of the attachment points of the biceps femoris, semimembranosus, and semitendinosus in the laboratory reference frame were determined from the 3-D coordinates of the attachment points of the corresponding muscles in the pelvis and tibia segment reference frames (Pierrynowski, 1995) and the orientations and locations of the segment reference frames in the laboratory reference frame. The 3-D coordinates of the attachment points of the biceps femoris, semimembranosus, and semitendinosus in the pelvis segment reference frame were normalized to the distance between the left and right ASISs while the 3-D coordinates of the attachment points in the lower leg reference frame were normalized to the distance between the knee and ankle joint centers (Table 2). Muscle–tendon length of a given muscle was determined as the distance between the two attachment points of the muscle while muscle–tendon elongation velocity was determined as the first time derivative of the muscle–tendon length.

The raw EMG signals were filtered through a band-pass digital filter at a low-pass cutoff frequency of 800 Hz and a high-pass cutoff frequency of 10 Hz, and then rectified. The band-pass filtered rectified EMGs were filtered through a low-pass digital filter again at a cutoff frequency of 20 Hz to obtain linear envelop EMG data.

2.4. Data analysis

Five 3 (muscle) × 2 (phase) analyses of variance with mix design were performed to compare the eccentric contraction characteristics of the biceps femoris long head, semimembranosus, and semitendinosus. The dependent variables of the analyses were (1) the maximum muscle length during the eccentric contraction, (2) the maximum eccentric contraction speed, (3) the muscle length at maximum eccentric contraction speed, (4) the magnitude of EMG at the maximum muscle length during the eccentric contraction, and (5) the magnitude of EMG at the maximum eccentric contraction speed. The independent variables of the analyses were phase (stance and swing) and muscle (biceps femoris long head and semitendinosus) with phase as a repeated measure and muscle as an independent measure. Post-hoc *t*-tests with Bonferoni adjustment were performed to locate differences when a significant main effect was detected. A Type One Error rate of 0.05 was chosen as the indication of statistical significance. The Systat computer program package for statistical analysis (Systat, Inc., Eveston, IL) was used to perform all statistical analyses.

3. Results

The mean running speed for the 20 subjects was 7.77 m/s with a mean within subject standard deviation of 0.11 m/s, and between-subject standard deviation of 0.34 m/s. The mean duration of the stance phase was 26.60% of the running gait cycle with a between-subject standard deviation of 0.02%.

The muscle–tendon length–time curve of each of the three hamstring muscles had a peak during the late stance phase as well as during the late swing phase (Table 3, Fig. 1). Each muscle also had a positive peak elongation velocity during the mid stance phase as well as during the mid swing phase (Table 3, Fig. 2).

Hamstring muscles were activated during the entire running gait cycle (Fig. 3). The maximum activations of the hamstring

Table 3
Temporal characteristics of the hamstring muscle eccentric contractions during a running gait cycle (% of running gait cycle)

Muscle	Stance phase		Swing phase	
	Maximum velocity	Maximum length	Maximum velocity	Maximum length
Biceps femoris	19.15 (0.04)	25.73 (0.02)	66.47 (0.04)	88.26 (0.04)
Semimembranosus	18.85 (0.01)	25.47 (0.02)	68.70 (0.05)	91.64 (0.03)
Semitendinosus	19.38 (0.02)	26.17 (0.02)	66.53 (0.04)	89.24 (0.04)

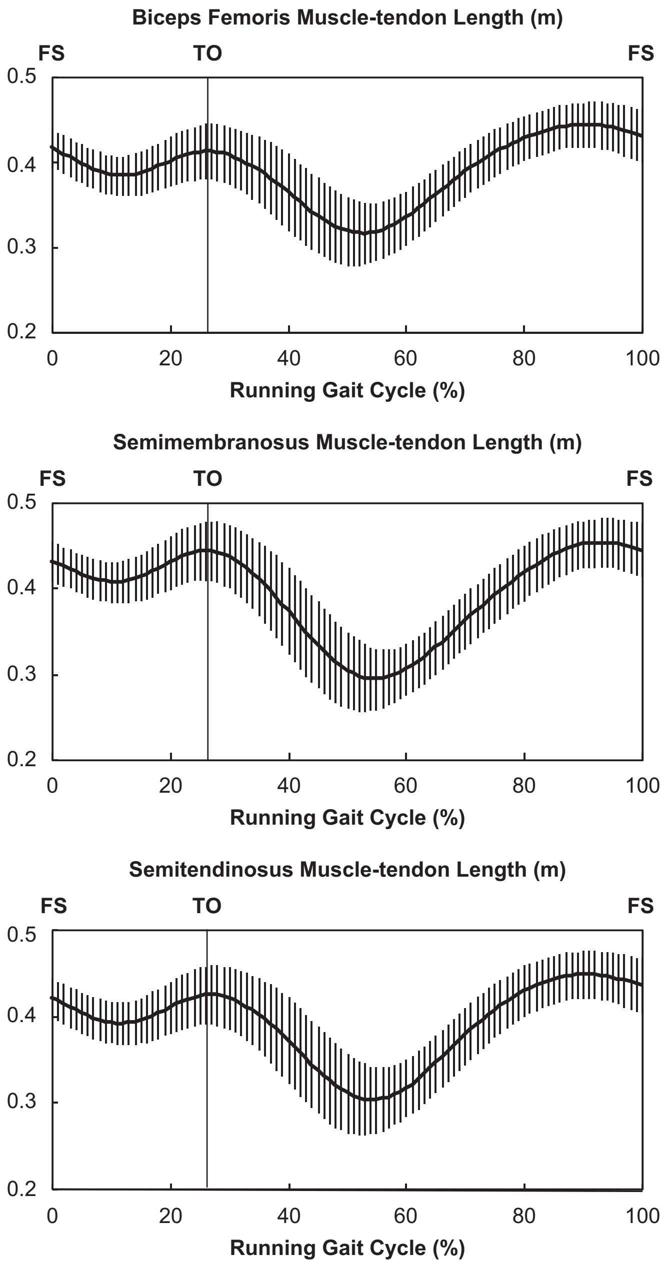

Fig. 1. Hamstring muscle lengths during a running cycle (FS = foot strike, TO = toe off).

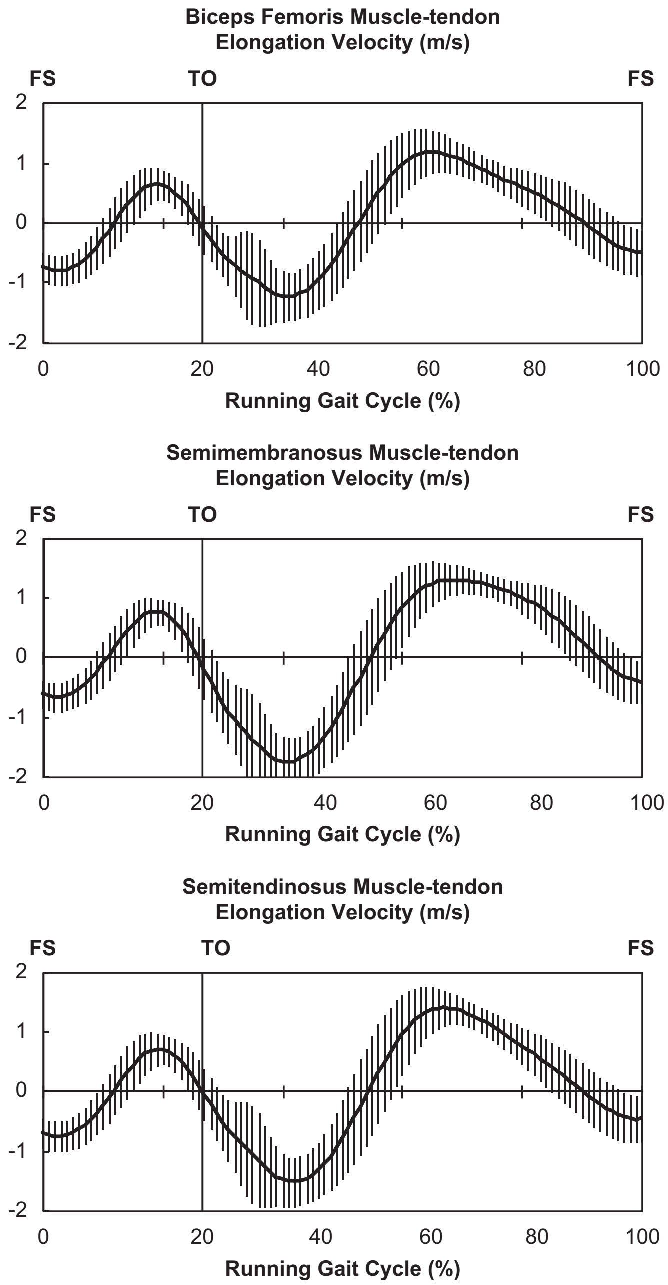

Fig. 2. Hamstring muscle elongation velocities during a running gait cycle (FS = foot strike, TO = toe off). A positive muscle–tendon elongation velocity suggests an eccentric contraction while a negative muscle–tendon elongation velocity suggests a concentric contraction.

muscles occurred during the early stance phase and late swing phase (Fig. 3). The activation of the hamstring muscles during the late swing phase was about two to three times greater than during the late stance phase and early swing phase (Fig. 3).

The peak positive elongation velocity of each hamstring muscle was significantly greater during the late swing phase than during the late stance phase ($p = 0.001$) (Fig. 4). The peak positive elongation velocities of the semimembranosus and semitendinosus were significantly greater than that of the biceps femoris during the late swing phase ($p = 0.003$, $p = 0.001$) (Fig. 4). No

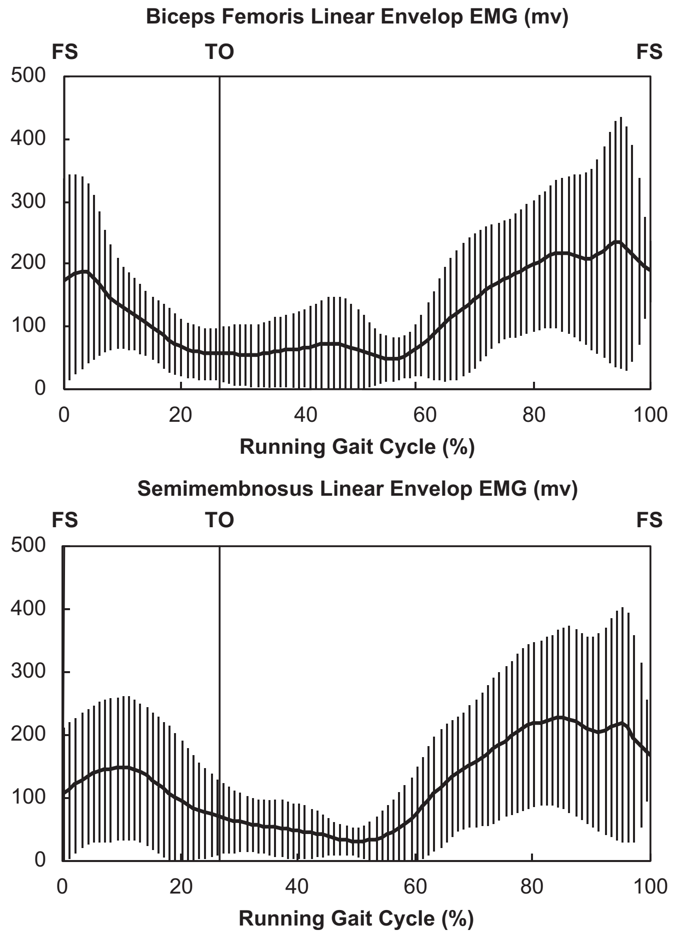

Fig. 3. Hamstring muscle linear envelop EMG during a running gait cycle (FS = foot strike, TO = toe off).

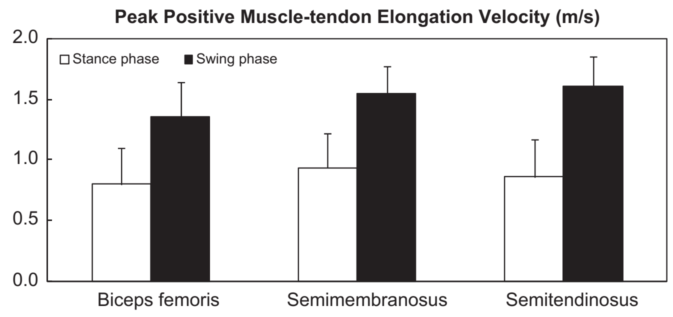

Fig. 4. Comparison of peak muscle–tendon elongation velocity. Peak muscle–tendon elongation velocities were significantly greater in the late swing phase than in late stance phase ($p = 0.001$). The muscle–tendon elongation velocities of the semimembranosus and semitendinosus in the late swing phase were significantly greater than that of the biceps femoris ($p = 0.002$, 0.003).

significant difference existed in the peak positive elongation velocity among muscles during the late stance phase ($p = 0.062$) (Fig. 4).

The muscle–tendon length of each hamstring muscle at the peak elongation velocity was significantly greater during the late stance phase than during the late swing phase ($p = 0.001$) (Fig. 5). The semimembranosus muscle–tendon length at its peak elongation velocity during the late stance phase was significantly greater than those of the biceps femoris and semitendinosus ($p = 0.001$, $p = 0.016$) (Fig. 5). No significant difference existed in the muscle–tendon length at the peak elongation velocity among muscles during the late swing phase ($p = 0.380$) (Fig. 5).

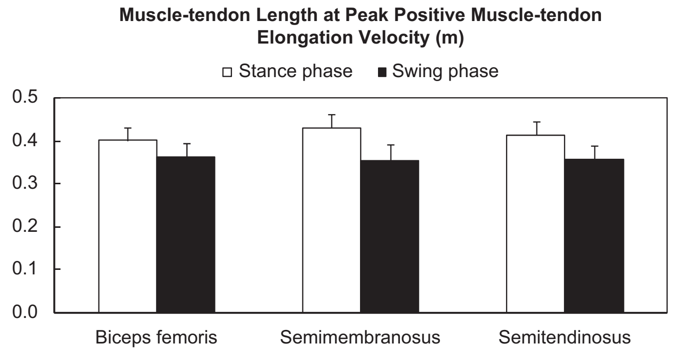

Fig. 5. Comparison of muscle–tendon length at the peak muscle–tendon elongation velocity. The semimembranosus and semitendinosus muscle–tendon lengths at their peak muscle–tendon elongation velocities were significant greater in the late stance phase than in the late swing phase ($p = 0.001$, 0.004). The semimembranosus muscle–tendon length at its peak muscle–tendon elongation velocity in the late stance phase was significantly greater than those of the biceps femoris and semitendinosus ($p = 0.001$, 0.015).

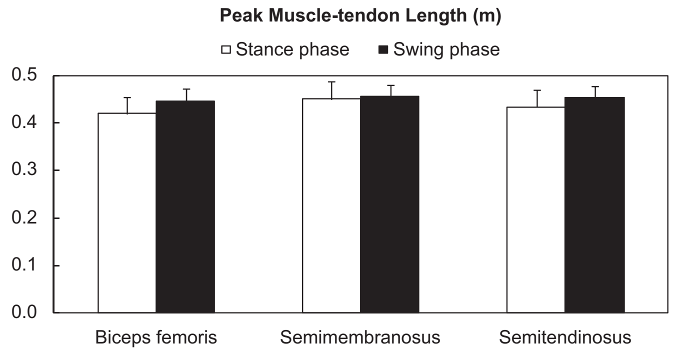

Fig. 6. Comparison of peak muscle–tendon length. The peak muscle-tendon length of the semimembranosus was significantly longer than those of the biceps femoris and semitendnosus in the late stance phase ($p = 0.001$). There was no significant difference in peak muscle–tendon length between muscles in the late swing phase ($p = 0.265$).

The peak muscle–tendon length of the biceps femoris and semitendinosus were significantly greater during the late swing phase than during the late stance phase ($p = 0.001$, $p = 0.008$) (Fig. 6). The peak muscle–tendon length of the semimembranosus was significantly longer than those of the biceps femoris and semitendinosus during the late stance phase ($p = 0.001$, $p = 0.015$) (Fig. 6). No significant difference existed in the peak muscle–tendon length among muscles during the late swing phase ($p = 0.156$) (Fig. 6).

4. Discussion

The results of this study support our hypothesis that the hamstring muscles undergo an eccentric contraction during the late stance phase as well as during the late swing phase of overground sprinting. These results are qualitatively consistent with those reported by Wood (1987). Using animal models, (Garrett et al., 1987; Lieber and Friden, 1993, 2002) demonstrated that muscle strain injuries were due to the magnitude of the strains, not the force the muscles experienced during the eccentric contractions. Recent MRI studies on hamstring muscle strain injuries demonstrated that over 90% of hamstring strain injuries occurred at the muscle belly or the muscle–tendon junction (Askling et al., 2007; Koulouris et al., 2007), which are similar to the muscle strain injuries simulated using animal models (Garrett et al., 1987; Lieber and Friden, 1993, 2002; Best et al., 1995). The results of our study combined with the literature indicate that hamstring muscles have the necessary condition and thus a potential for strain injuries during the late stance phase as well as during the late swing phase of overground sprinting.

Hamstring muscles may be more likely to sustain strain injuries during the late swing phase than during the late stance phase. Although muscle strain injuries are mainly due to muscle strains during eccentric contractions (Garrett et al., 1987; Lieber and Friden, 1993, 2002; Hasselman et al., 1995) demonstrated that the muscle strain that could cause a muscle strain injury decreased if the muscle was highly activated. The results of the current study showed that the maximum hamstring muscle–tendon length was similar during the late stance phase and the late swing phase while the muscle activation was higher during the late swing phase than during the late stance phase. These results combined with the literature indicate that hamstring muscles could sustain strain injuries at shorter muscle–tendon lengths during the late swing phase than during the late stance phase.

The likely hamstring strain injury site may be different between late stance phase and late swing phase. Best et al. (1995) showed that strain injury occurred at the muscle–tendon junction when strain rate was low but occurred at the distal muscle belly when the strain rate was high. The results of the current study showed that hamstring muscle elongation velocity was higher during the late stance phase than during the late swing phase. These results combined with the results of Best et al. (1995) indicate that a strain injury may be more likely to occur at the hamstring muscle–tendon junction during the late stance phase than during the late swing phase while it may be more likely to occur at the muscle belly during the late swing phase than during the late stance phase.

The eccentric contractions of the hamstring muscles during the late swing phase of overground sprinting observed in the current study were consistent with that reported by Thelen et al. (2005). Although Thelen et al. (2005) reported the changes in hamstring muscle–tendon lengths relative to the muscle–tendon lengths in a standing position while we reported the absolute muscle–tendon lengths of the hamstring muscles, the results of both studies suggest that hamstring muscles were in eccentric contractions during the late swing phase. The results of this study and the study by Thelen et al. (2005) support previous studies by (Simonsen, et al., 1985; Wood, 1987) in which they suggested that peak hamstring muscle–tendon lengths occurred during the late swing phase of overground sprinting.

The eccentric contractions of the hamstring muscles during the late stance phase of overground running found in the current study were qualitatively similar to what Wood (1987) showed, but were not reported by Thelen et al. (2005). This discrepancy in the hamstring muscle contraction pattern during the stance phase of sprinting between studies is most likely due to differences in lower extremity kinematics between treadmill and overground sprinting. A comparison of the knee flexion angle at the takeoff between overground and treadmill sprinting in Frishberg's study (1983) showed that the knee flexion angle at the takeoff during the overground sprinting was significantly smaller than that of the treadmill sprinting (Table 4). The mean difference in the knee flexion angle at the takeoff was 5.2° with a 95% confidence interval between 1.9° and 8.5° (Table 4). A smaller knee flexion angle means that the knee is in a straighter position and that the hamstring muscle–tendon unit is longer during the late stance phase in the overground sprinting when compared to the treadmill sprinting. The estimated muscle–tendon lengths could also be affected by the data smoothing procedure, the 3-D coordinates of muscle attachment points in corresponding segment reference frames, and the method of calculating muscle–tendon length.

Table 4
Comparison of knee flexion angle (degrees) at the toe off between overground and treadmill sprinting

Subject no.	Overground			Treadmill			Difference in knee angle
	Thigh	Leg	Knee	Thigh	Leg	Knee	
1	147.5	116.8	30.7	146.2	113.3	32.9	2.2
2	139.3	122.3	17.0	145.8	119.3	26.5	9.5
3	140.7	120.7	20.0	140.8	120.2	20.6	0.6
4	144.2	114.8	29.4	144.7	109.5	35.2	5.8
5	142.0	121.8	20.2	144.8	116.5	28.3	8.1
Mean	142.7	119.3	23.5	114.4	115.8	28.7	5.2
SD	3.2	3.3	6.2	2.1	4.4	5.7	3.8

The thigh and leg angles at the toe off were reported by Frishberg (1983). The knee flexion angle at the toe off was determined as the leg angle minus thigh angle. The knee flexion angle at the toe off in treadmill sprinting was 5.2° greater than that in overground sprinting with a 95% confidence interval from 1.9° to 8.5°.

Although both the current study and the study by Mann and Sprague (1981) suggested a potential for hamstring muscle strain injuries during the stance phase of the overground sprinting, the suggested possible time when an injury occurs was different. Mann and Sprague (1981) suggestion was based on the maximum knee flexion moment during the early stance phase while the current study's suggestion was based on the eccentric contraction of the hamstring muscles during the late stance phase. As previously mentioned, muscle strain injury is a function of muscle strain, not muscle force (Lieber and Friden, 1993). Although the maximum knee flexion moment during the early stance phase observed by Mann and Sprague (1981) suggested a maximum hamstring muscle force that is supported by the EMG data obtained in this study, hamstring muscles do not seem to be in a danger of strain injury because the hamstring muscles were not in eccentric contraction during this phase as the current study and literature showed (Wood, 1987; Thelen et al., 2005).

The results of the current study and studies by Thelen et al., 2005 and Mann and Sprague (1981) provide significant information for qualitatively determining the time when a hamstring injury occurs. Mann and Sprague (1981) reported the maximum knee flexion moment during the early stance phase indicating the maximum hamstring force. A hamstring muscle strain injury has likely occurred during late swing phase if the athlete starts to quit running during early stance phase because of the pain due to high hamstring muscle loading during the early stance phase. A hamstring muscle strain injury has likely occurred during the late stance phase if the athlete starts to quit running during the swing phase because of the pain due to increased hamstring muscle strain during the late swing phase.

Further studies are needed to determine why the biceps femoris is the most frequently injured muscle among the hamstring muscles. Wood (1987) and Thelen et al. (2005) concluded that the biceps femoris is the most frequently injured muscle in hamstring muscle strain injuries because its muscle–tendon unit is the most strained among the hamstring muscles during the late swing phase of sprinting. The current study did not show this result because the absolute muscle–tendon lengths of the hamstring muscles were not converted to the muscle–tendon strains as Wood (1987) and Thelen et al. (2005) did. As Best et al. (1995) and Thelen et al. (2005) pointed out, besides muscle–tendon length and strain, muscle fiber lengths and pinnation angles also need to be considered when determining the relative risk for strain injuries among muscles. Although pinnation angles of the three hamstring muscles are very similar, muscle fiber lengths of these muscles are significantly different. Semimembranosus has the shortest muscle fiber length among hamstring muscles, which is only 78% of the biceps femoris muscle fiber length and 45% of the semitendinosus muscle fiber length (Pierrynowski, 1995). Considering the significant difference in muscle fiber length among the hamstring muscles, the difference in the muscle–tendon strain among these muscles reported by Wood (1987) and Thelen et al. (2005) may not be sufficient to explain why the biceps femoris is the most frequently injured muscle among the hamstring muscles. Further studies on the mechanical properties of the hamstring muscles may be needed to explain why the biceps femoris is the most prone to injury among the hamstring muscles.

Further studies may also be needed to investigate the hamstring kinematics and kinetics during the accelerating phase of sprinting. Sprinters have more forward trunk lean while accelerating to full speed sprinting. This may result in increased hamstring strains during the stance phase, and thus increased risk for a hamstring strain injury. Studies on the hamstring kinematics and kinetics during this phase of sprinting may provide significant information for a comprehensive understanding of hamstring strain injuries.

Conflict of interest statement

None of the authors has any conflict of interest in this study.

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References

Agre, J.C., 1985. Hamstring injuries: proposed aetiological factors, prevention and treatment. Sports Medicine 2, 21–33.

Arnason, A.S.S., Gudmundsson, A., Home, I., Engebretsen, L., Bahr, L., 2004. Risk factors for injuries in football. American Journal of Sports Medicine 32, 5S–16S.

Askling, C.M., Tengvar, M., Saartok, T., Thorstensson, A., 2007. Acute first-time hamstring strains during high-speed running: a longitudinal study including clinical and magnetic resonance imaging findings. American Journal of Sports Medicine 35, 197–206.

Best, T.M., McElhaney, J.H., Garrett Jr., W.E., Myers, B.S., 1995. Axial strain measurements in skeletal muscle at various strain rates. Journal of Biomechanical Engineering 117, 262–265.

Brooks, J.H.M., Fuller, C.W., Kemp, S.P.T., Reddin, D.B., 2006. Incidence, risk and prevention of hamstring muscle injuries in professional rugby union. American Journal of Sports Medicine 34, 1297–1306.

Clanton, T.O., Coupe, K.J., 1998. Hamstring strains in athletes: diagnosis and treatment. Journal of American Academy of Orthopaedic Surgeons 6, 237–248.

Ekstrand, J., Gillquist, J., 1983. Soccer injuries and their mechanisms: a prospective study. Medicine and Science in Sports and Exercise 15, 267–270.

Frishberg, B.A., 1983. An analysis of overground and treadmill sprinting. Medicine and Science in Sports and Exercise 15, 478–485.

Garrett Jr., W.E., Safran, M.R., Seaber, A.V., Glisson, R.R., Ribbeck, B.M., 1987. Biomechanical comparison of stimulated and nonstimulated skeletal muscle pulled to failure. American Journal of Sports Medicine 15, 448–454.

Garrett Jr., W.E., Rich, F.R., Nikolaou, P.K., Vogler, J.B., 1989. Computed tomography of hamstring muscle strains. Medicine and Science in Sports and Exercise 21, 506–514.

Hasselman, C.T., Best, T.M., Seaber, A.V., Garrett Jr., W.E., 1995. A threshold and continuum of injury during active stretch of rabbit skeletal muscle. American Journal of Sports Medicine 23, 65–73.

Hawkins, R.D., Hulse, M.A., Wilkinson, C., Hodson, A., Gibson, M., 2001. The association football medical research programme: an audit of injuries in professional football. British Journal of Sports Medicine 35, 43–47.

Hay, J.G., 1993. The Biomechanics of Sports Techniques. Prentice-Hall, Inc., Englewood Cliffs, NJ.

Hinrichs, R.N., 1990. Adjustments to the segment center of mass proportions of Clauser et al. (1969). Journal of Biomechanics 23, 949–951.

Kadaba, M.P., Ramakrishnan, H.K., Wootten, M.E., 1990. Measurement of lower extremity kinematics during level walking. Journal of Orthopaedic Research 8, 383–392.

Koulouris, G., Connell, D.A., Brukner, P., Schneider-kolsky, M., 2007. Magnetic resonance imaging parameters for assessing risk of recurrent hamstring injuries in elite athletes. American Journal of Sports Medicine 35, 1500–1505.

Lieber, R.L., Friden, J., 1993. Muscle damage is not a function of muscle force but active muscle strain. Journal of Applied Physiology 74, 520–526.

Lieber, R.L., Friden, J., 2002. Mechanisms of muscle injury gleaned from animal models. American Journal of Physical Medicine and Rehabilitation 81, S70–S79.

Mann, R.V., Sprague, P.G., 1981. A kinetic analysis of sprinting. Medicine and Science in Sports and Exercise 13, 325–328.

Orchard, J., Seward, J., 2002. Epidemiologhy of injuries in the Asutralian Football League, seasons 1997–2000. British Journal of Sports Medicine 36, 39–45.

Pierrynowski, M.R., 1995. Analytic representation of muscle line of action and geometry. In: Allard, P., Stokes, I.A.F., Jean-Pierre, Blanchi (Eds.), Three-Dimensional Analysis of Human Movement. Human Kinetics, Champaign, IL.

Petersen, J., Hölmich, P., 2005. Evidence based prevention of hamstring injuries in sports. British Journal of Sports Medicine 39, 319–323.

Sherry, M.A., Best, T.M., 2004. A comparison of 2 rehabilitation programs in the treatment of acute hamstring strains. Journal of Orthopaedics and Sports Physical Therapy 34, 116–125.

Simonsen, E.B., Thomsen, L., Klausen, K., 1985. Activity of mono- and biarticular leg muscles during sprint running. European Journal of Applied Physiology Occupational Physiology 54, 524–532.

Stanton, P., Purdam, C., 1989. Hamstring injuries in sprinting: the role of eccentric exercise. Journal of Orthopaedics and Sports Physical Therapy 10, 343–349.

Thelen, D.G., Chumanov, E.S., Hoerth, D.M., Best, T.M., Swanson, S.C., Li, L., Young, M., Heiderscheit, B.C., 2005. Hamstring muscle kinematics during treatmill sprinting. Medicine and Science in Sports and Exercise 37, 108–114.

Wood, G.A., 1987. Biomechanical limitations to sprint running. Medicine and Sport Science 25, 58–71.

Woods, C., Hawkins, R.D., Maltby, S., Hulse, M., Thomas, A., Hodson, A., 2004. The football association medical research programme: an audit of injuries in professional football—analysis of hamstring injuries. British Journal of Sports Medicine 38, 36–41.

Yu, B., 1989. Determination of the optimum cutoff frequency in the digital filter Data smoothing procedure. In: Proceedings of XII International Congress of Biomechanics, Los Angeles, CA.