3 Hamstrings Biomechanics Related to Running

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3.1 Introduction

Hamstring strain injuries (HSIs) occur frequently in sports characterised by high-speed running [1–4]. Subsequently, a thorough understanding of hamstring function during high-speed running may provide clinicians with a better understanding of HSI mechanisms and directly inform injury preventative and rehabilitative interventions. In sports that require high-speed running, this is by far the most frequently reported mechanism of HSI [2, 5–7]. Although there are other commonly reported mechanisms of HSI (e.g. kicking [2] and slow stretching [8, 9]), these mechanisms will not be the focus of this chapter, primarily due to a lack of biomechanical data providing insight into hamstring function during these mechanisms.

The following chapter aims to provide an overview of hamstring function during running, with a particular emphasis on high-speed running. As HSI typically occurs in the biarticular hamstrings (as opposed to the biceps femoris short head (BF_{SH}), a particular focus will be placed on these muscles. After providing a general overview

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of methods to quantify hamstring function, this chapter will describe hamstring function across the running stride cycle. Hamstring function will be described in reference to hamstring muscle activation, kinematics and kinetics. Additionally, key considerations for clinicians will be covered. These considerations include an overview of the effect of prior HSI on hamstring function during running, a brief discussion on the critical point of the running stride cycle where HSI is most likely to occur and an overview of key factors that influence strain of the most vulnerable hamstring muscle (biceps femoris long head [BF_{LH}]) during swing.

3.2 Quantification of Hamstring Function

Hamstring function during running can be quantified in multiple ways. The following section provides a brief overview of some of these methods, with a specific focus on outcome measures that reflect the loads experienced by the hamstrings during running.

3.2.1 Hamstring Activation

Muscle activation involves the measurement of the electrical activity associated with muscle contraction, which usually involves the application of surface electrodes to the skin directly over the target muscle of interest. This process is known as electromyography (EMG). The muscle EMG signal is best used to describe the onset and offset of muscle activation, e.g. with respect to other muscles or with respect to key events in the running stride cycle such as foot strike and toe-off. Whilst greater muscle activation can reflect an increase in muscle force production, the relationship between EMG signal intensity and force is difficult to determine and will be influenced by many factors, especially muscle length and muscle shortening velocity. It is also worth noting that recording EMG signals via surface electrodes can be susceptible to measurement error such as crosstalk, which is the measurement of the electrical activity of any muscle other than the targeted muscle. Due to the proximity of the hamstrings relative to each other, surface EMG can only separate the activation of the medial (semitendinosus (ST) and semimembranosus (SM)) from the lateral (BF_{LH} and BF_{SH}) hamstring group with reasonable confidence.

3.2.2 Hamstring Kinematics

Motion capture experiments have provided much of the current knowledge of hamstring function during running. These laboratory-based experiments typically involved the use of skin surface markers, placed on various anatomical locations of participants. Using multiple specialised cameras, the three-dimensional positions of these markers are tracked whilst the participant performs the required movements.

These data can then be used to calculate motion of the body, including joint angles, velocities and accelerations.

Motion capture data can be input into musculoskeletal models, which contain a detailed representation of the entire skeleton including various muscle-tendon unit (MTU) actuators that are attached to the skeleton at their anatomically correct origin and insertion sites. Such a model allows for direct estimation of the length of the hamstring MTUs during running. MTU length data are typically presented as absolute lengths (in units of metres, centimetres or millimetres) or relative lengths (usually computed as % of the MTU length assumed in upright standing). These data can also be differentiated to compute shortening and lengthening velocities of each MTU, which can be used in conjunction with muscle activation data to determine the contraction modes of each MTU. Outputs from musculoskeletal modelling can also be input into a finite element model that allows for more complex representations of muscle fibre and tendon dynamics, yielding detailed information such as region-specific strain patterns within a given MTU [10, 11].

3.2.3 Hamstring Kinetics

Joint motion data obtained from motion capture experiments can be combined with ground reaction force data (if synchronously collected) and estimates of body segment inertial properties to solve for the generalised forces and moments necessary to cause the observed motion, via a process called inverse dynamics. Since the net joint moments obtained from these calculations are considered to represent the net moment produced ‘internally’, primarily by muscles, inverse dynamics can provide some indirect insight into hamstring function during running by considering the specific joint moments to which the hamstrings can be expected to provide a dominant contribution (i.e. ‘internal’ hip extension and knee flexion moments). Nevertheless, one must be cautious about inferring muscle function via this approach, as inverse dynamics yields only the net joint moments, which could theoretically be contributed by many muscles other than the hamstrings. Whilst direct (in vivo) measurement of hamstring muscle kinetics during running cannot be achieved non-invasively, it is possible to provide estimates.

These estimates can be computed via musculoskeletal modelling, provided that each MTU actuator in the model contains representations of properties needed to provide physiologically reasonable estimates of muscle force. Whilst the level of complexity of these models varies, generic properties may include representations of activation-contraction dynamics, whilst specific properties may include representations of force-generating capacity and architectural properties, typically derived from cadaver experiments. Using these muscle models, as well as input experimental data (typically joint angles, ground reaction forces and sometimes EMG), estimates of muscle forces can be predicted using numerical optimisation algorithms. Whilst the detail of this modelling approach is beyond the scope of this chapter, the interested reader is referred to published works to obtain a more comprehensive understanding [12, 13].

Recently, innovative methods are emerging in an attempt to quantify in vivo muscle forces non-invasively [14]. In this work, researchers attached a low-profile tapper device over the distal biceps femoris tendon of two participants performing treadmill running at multiple speeds. The device is capable of measuring shear wave speed, which can be used as an indicator of tendon tensile loading. Whilst this is limited and does not yield direct muscle force estimates (i.e. in Newtons of force), the researchers demonstrated that shear wave speed is related to tendon tensile loading within physiological loads and thus could provide a useful general indicator of muscle force patterns.

3.3 Hamstring Function During Running

For the purposes of this chapter, temporal aspects of running will be described over the 'stride cycle'. The stride cycle refers to the entire sequence of events that occurs between foot strike (i.e. the first point in time the foot contacts the ground, denoted as 0% of the stride cycle) and the subsequent foot strike on the same leg (i.e. 100% of the stride cycle). This method exploits the cyclical nature of running and is commonly employed in running-based studies to compare data across conditions involving contrasting running speeds and stride durations. In the following section, hamstring function during running will be described separately for each of the two primary phases of the stride cycle: stance and swing. The decision to describe the two key phases of the stride cycle separately in this chapter is based on prior convention adopted in the literature and it permits ease of interpretation for the reader. Nevertheless, we do not want this decision to distract the reader. There is only one continuous phase of hamstring activity per stride cycle, as the hamstrings begin activating during the final third of the swing phase and continue activating throughout the stance phase until just after toe-off [15, 16]. Given that the hamstrings begin activating during the swing phase, we have decided to describe hamstring function during swing followed by that during stance.

3.3.1 Swing Phase of the Stride Cycle

The swing phase is defined as the period in which the foot is not in contact with the ground and typically accounts for ~75% of the stride cycle during maximal sprinting [16]. The swing phase is often subdivided into three sub-phases. Early swing occurs between toe-off and maximum knee flexion, mid-swing between maximum knee flexion and maximum hip flexion and late swing between maximal hip flexion and foot strike [17].

3.3.1.1 Hamstring Activation

Both the medial and lateral hamstrings are heavily recruited during the swing phase of running starting from mid-swing onwards (Fig. 3.1) [16, 17]. For both muscle

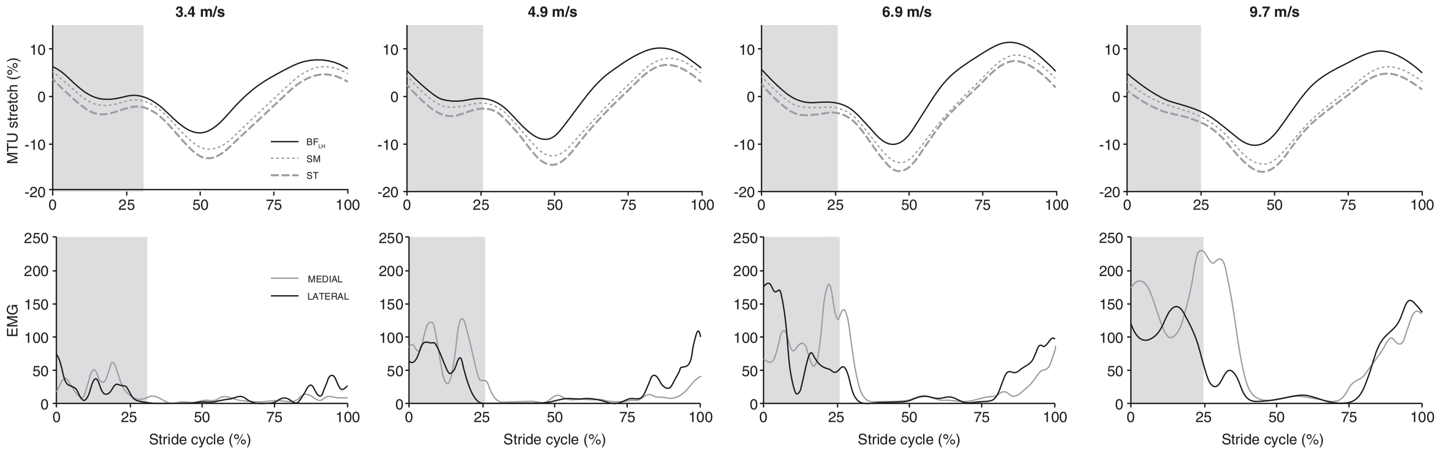

Fig. 3.1 Hamstring musculotendon unit stretch and EMG at various overground running speeds derived from Schache et al. [16]. Musculotendon unit stretch is defined as the percentage change in length from standing upright posture. Electromyography data was normalised to the mean signal obtained across the entire stride cycle for the maximum running speed (for each muscle group). Shaded region represents the stance phase. *MTU* musculotendon unit, *EMG* electromyography, BF_{LH} biceps femoris long head, *SM* semimembranosus, *ST* semitendinosus

groups, the average magnitude of muscle activity appears to increase with running velocity [16, 17]. For example, Higashihara and colleagues [17] showed that average medial and lateral hamstring activity increased 2.5- and 2.9-fold, respectively, during late swing as running velocity progressed from 50% to 95% of maximum. Similarly, Schache and colleagues [16] showed that the average medial and lateral hamstring activity during terminal swing increased 3.5- and 4.4-fold, respectively, as running velocity increases from ~30% to 100% of maximum running velocity. There is also evidence of differences in activation of the medial and lateral hamstrings, and these differences appear to be affected at least to some extent by the sprinting condition, i.e. maximal acceleration sprinting vs. maximal constant-velocity sprinting [18]. The medial hamstrings exhibit greater activation than the lateral hamstrings in both the early swing and the first half of the mid-swing phases in both sprinting conditions [18]. This difference is also evident in the second half of the mid-swing phase for maximal constant-velocity sprinting, but not maximal acceleration sprinting [18].

3.3.1.2 Hamstring Kinematics

During the swing phase, the biarticular hamstring MTUs shorten from toe-off until ~50% of the stride cycle (~33% of swing phase, Fig. 3.1) [15, 16, 19]. After this point, each MTU lengthens until reaching its peak at ~85% of the stride cycle (~60% of swing) and shortens thereafter until foot strike [16, 19, 20]. Given the hamstrings are activating during the mid- and late swing sub-phases, each hamstring MTU is therefore undergoing an active stretch-shortening cycle during this period. The magnitude of this peak MTU stretch increases when running velocity increases from low to high (~30–80%) [16], but is invariant as running speed approaches maximal sprinting (80–100%) [16, 19, 21]. Additionally, the magnitude of the peak MTU stretch during maximal sprinting (Table 3.1) is greatest for the BF_{LH}, followed by the medial hamstrings [15, 16, 19, 22]. Most studies show that peak MTU stretch is greater for SM than ST [15, 16, 19], although the reverse has been reported [22] which is most likely attributable to variability in modelling properties.

3.3.1.3 Hamstring Kinetics

Model-based studies have predicted that peak muscle forces for all of the biarticular hamstrings occurs during the late swing phase of running (~60% of swing or ~85% of stride cycle), regardless of running velocity (Fig. 3.2) [15, 19, 21]. The magnitude, however, is sensitive to running velocity as well as the specific hamstring muscle. As running velocity increases from 80% to 100% of maximal sprinting velocity, hamstring muscle force increases ~1.3-fold [19, 21]. Regardless of running velocity, the SM produces the most force, followed by the BF_{LH} and the ST (Table 3.1) [15, 19, 21, 23]. As each hamstring MTU is also actively lengthening for a certain portion of the late swing sub-phase, the hamstrings perform negative work at this stage of the stride cycle (Fig. 3.2). The magnitude of negative work is also

Table 3.1 Hamstring kinematics and kinetics during the swing phase of maximal sprinting

	Running velocity (m/s)	$\mathrm{BF}_{\mathrm{LH}}$	SM	ST
Peak MTU strain (%)[a]				
Schache et al. [16]	9 ± 0.7	11.5 ± 2.5	9.4 ± 14	8.3 ± 1.5
Chumanov et al. [19]	8.0 and 7.1[b]	13 ± 2	11 ± 3	10 ± 3
Thelen et al. 2005 [22]	9.4 and 8.1[b]	9.8 ± 2.8	7.5 ± 1.6	8.3 ± 1.8
Schache et al. [15]	9.0 ± 0.7	12.0 ± 2.6	9.8 ± 1.2	8.7 ± 1.3
Peak force (N/kg)				
Schache et al. [15]	9.0 ± 0.7	26.4 ± 5.2	46.8 ± 6.3	5.5 ± 0.8
Thelen et al. 2005 [23]	9.3	17.6	NR	NR
Chumanov et al. [21]	9.1 ± 6 and 8.2 ± 0.8	21.4 ± 5.4	27.9 ± 7.6	7.9 ± 1.8
Chumanov et al. [19]	8.0 and 7.1[b]	13.2 ± 1.5	23.9 ± 3.5	5.9 ± 1.9
Negative work (J/kg)				
Schache et al. [15]	9.0 ± 0.7	0.3 ± 0.1	1.1 ± 0.3	0.1 ± 0.1
Chumanov et al. [21]	9.1 ± 6 and 8.2 ± 0.8[b]	0.8 ± 0.3	1 ± 0.4	0.4 ± 0.2

BF_{LH} biceps femoris long head, *SM* semimembranosus, *ST* semitendinosus, *MTU* musculotendinous unit, *NR* not reported

[a] Expressed as % of length in upright static standing

[b] Reported as velocities for males and females

related to both running velocity and muscle. The SM produces the greatest amount of negative work, followed by the $\mathrm{BF}_{\mathrm{LH}}$ and ST (Table 3.1) [15, 21]. As running velocity increases from 80% to 100% of maximal sprinting velocity, the negative work during swing increases 2-fold for the SM, 1.7-fold for the ST and 1.6-fold for the $\mathrm{BF}_{\mathrm{LH}}$ [21].

3.3.2 Stance Phase of the Stride Cycle

The stance phase is defined as the period in which the foot is in contact with the ground (i.e. from foot strike to toe-off) and typically accounts for ~25% of the full stride cycle during sprinting [16]. Although it is widely believed that HSIs occur during the swing phase, some have suggested that the high ground reaction forces that occur during stance can also cause HSI [24]. Additionally, previous research has shown that hamstring function during stance plays an important role in running performance [25, 26], which can be a key component of HSI rehabilitation progression and return to play (RTP) decisions [27, 28]. Subsequently, an understanding of hamstring function during stance is important for practitioners.

3.3.2.1 Hamstring Activation

Across the stance phase of running, both the medial and lateral hamstring groups continue to activate (Fig. 3.1) [16, 20]. As the hamstrings are considered to be important contributors to forward propulsion of the centre of mass during the stance phase of running [25], it is unsurprising that the magnitude of hamstring activation during stance appears to increase as running velocities progress from low to high

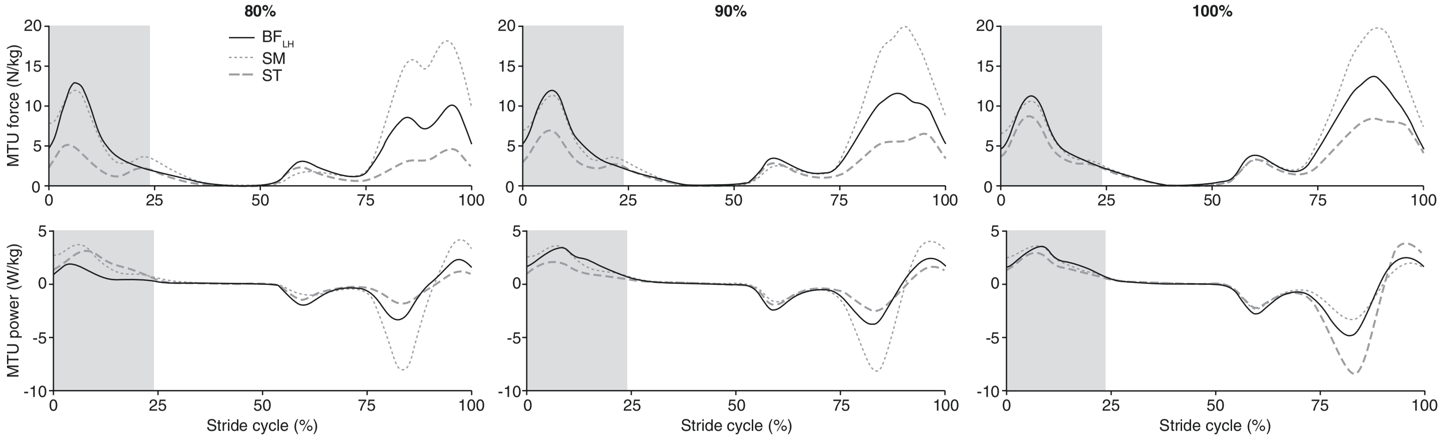

Fig. 3.2 Hamstring musculotendon unit force and power at various treadmill running speeds (expressed as % of maximum running speed) derived from Chumanov et al. [19]. Shaded region represents the stance phase. *MTU* musculotendon unit, *EMG* electromyography, BF_{LH} biceps femoris long head, *SM* semimembranosus, *ST* semitendinosus

[17]. For example, the average lateral and medial hamstring activity during stance increases 2.8- and 4.1-fold, respectively, as running velocity increases from 50% to 95% of maximum speed [17]. Within higher running velocities (≥85% of maximum velocity), mean muscle activity for both hamstring groups remains relatively unchanged during stance [17]. Differences between muscle groups appear to vary across sprinting conditions, i.e. maximal acceleration sprinting vs. constant-velocity sprinting [18]. Lateral hamstring activation is greater than medial hamstring activation in the early stance phase of maximal acceleration sprinting, whereas no differences between muscle groups appear to exist in this phase for maximal constant-velocity sprinting [18]. In contrast, medial hamstring activation exceeds lateral hamstring activation in the late stance phase of maximal constant-velocity sprinting, whereas no differences appear to exist in this phase for maximal acceleration sprinting [18].

3.3.2.2 Hamstring Kinematics

The length of each hamstring MTU during stance is less than that experienced during swing (Fig. 3.1) [15, 16, 19]. Studies have shown that hamstrings' MTU length at initial contact is approximately 5% greater than its length in upright stance [15, 16, 19]. Throughout stance, the MTU length of the biarticular hamstrings progressively shortens such that by toe-off the hamstrings' MTU length is approximately 5% shorter than its length in upright stance [15, 16, 19]. This trend appears to be consistent regardless of running velocity, and similar patterns exist for each of the different biarticular hamstring muscles [16, 19].

3.3.2.3 Hamstring Kinetics

Whilst the hamstrings generate force across the stance phase (Fig. 3.2), the peak force production appears invariant to running speed at higher running velocities (80–100% of max sprinting speed) [19]. Regardless of running velocity, peak MTU forces are greatest for the SM, followed by the BF_{LH} and ST (Table 3.2) [15, 19], similar to what has been found during the late swing phase. As the hamstring MTUs are shortening during this same period, the hamstrings primarily perform positive work [15, 19].

Table 3.2 Hamstring kinematics and kinetics during the stance phase of maximal sprinting

	Running velocity (m/s)	BF_{LH}	SM	ST
Peak force (N/kg)				
Schache et al. [15]	9.0 ± 0.7	4.6 ± 1.0	6.5 ± 1.6	3.6 ± 0.7
Chumanov et al. [19]	8.0 and 7.1[a]	11.6 ± 1.9	12.1 ± 2.4	6.2 ± 2.2
Positive work (J/kg)				
Schache et al. [15]	9.0 ± 0.7	0.05 ± 0.02	0.06 ± 0.02	0.04 ± 0.02

BF_{LH} biceps femoris long head, *SM* Semimembranosus, *ST* Semitendinosus

[a] Reported as velocities for males and females, respectively

3.4 Effect of Prior Injury on Hamstring Function During Running

Although this chapter has described ‘typical’ hamstring function during running, it is important to recognise that some of these observations appear to be different in individuals with a history of HSI. It is well known that residual deficits in hamstring strength and flexibility persist well beyond apparent ‘successful’ RTP following HSI [29]. As running ability is an important component of rehabilitation progression [28] and RTP decisions [27], understanding residual deficits in hamstring function during running is also warranted. Although available data on this topic are limited and often heterogeneous, a brief overview is provided below. To explore this issue, some studies have specifically targeted participants with a history of unilateral hamstring injury and thus compared the previously injured side to the contralateral injury-free side. Other studies have adopted a between-subjects design, comparing people with a past history of hamstring injury to a matched group who have never previously sustained a hamstring injury.

3.4.1 Muscle Activation

It is unclear whether the hamstrings of previously injured legs exhibit altered muscle activation patterns during running. One investigation involving participants with prior unilateral HSI found no differences in the magnitude, onset time, offset time or duration of medial or lateral hamstring EMG activity at running velocities of 60%, 80%, 90% or 100% of maximum compared to the contralateral uninjured leg [30]. However, the lack of observed differences may be nullified to some extent by normalising the EMG data to the maximum value obtained by the same (injured) muscle. Another study instead normalised hamstring EMG to values obtained from other uninjured muscles during treadmill running at 20 km/hr [31]. This study found a lower magnitude of lateral hamstring EMG ratios (along with the ipsilateral gluteus maximus, erector spinae, external oblique and contralateral rectus femoris) during the late swing phase in the injured leg compared to the uninjured control group.

3.4.2 Kinematics

Several studies have compared joint or hamstring MTU kinematics during running in unilaterally injured participants to their contralateral uninjured leg [30–32]. In an investigation of treadmill running at 80% of maximal velocity, Lee and colleagues [32] observed a lower peak hip flexion angle in previously injured legs during TU late swing. This decreased hip flexion was thought to be a strategy to reduce MTU stretch in the injured muscle group. However, in contrast, Silder et al. (2010) did not observe any between-leg differences in BF_{LH} stretch when investigating previously injured participants running at velocities of 60–100% of maximum [30]. Finally, Daly et al. (2016) collected joint kinematics during treadmill running at a steady-state speed of 20 km/hr from a previously injured group of athletes and a group who had never suffered a hamstring injury. These authors reported greater asymmetries in previously injured participants compared to uninjured participants favouring increased peak hip flexion angles, as well as increased anterior pelvic tilt and internal tibial rotation during late swing in previously injured legs [31]. These results implied that the previously injured athletes put their hamstrings in a more lengthened position during late swing, thus opposite to the findings from Lee and colleagues [32]. When results from all studies are considered together, no systematic findings regarding the effect of prior HSI on hamstring kinematics during running are evident.

3.4.3 Kinetics

Although no studies have estimated hamstring muscle forces in participants with a history of HSI, one study [32] provided some insight into hamstring muscle force production through the evaluation of the net hip extension and knee flexion joint moments during running. This study found no differences in lower limb joint moments between the injured and contralateral uninjured legs when running at 80% of maximum sprinting velocity.

Another way to grossly infer biomechanical load on the hamstrings is through the evaluation of horizontal ground reaction force production, as the hamstrings are considered to be a key contributor to the forward propulsion of the body’s centre of mass during stance [25, 26]. During non-motorised treadmill sprinting at 80% of maximum sprinting velocity, previously injured legs have been shown to display substantial deficits in maximal horizontal ground reaction force production compared to the uninjured contralateral leg and an uninjured control group [33]. However, a similar study failed to replicate these findings in maximal effort non-motorised treadmill sprinting [34]. Results from a third study [35] suggest that deficits in horizontal ground reaction force production exist during maximal velocity overground sprinting at the time of RTP, but tend to resolve within 10 weeks post RTP. Further to this, when performing ten maximal effort sprints (6 seconds each) on a non-motorised treadmill, the decrement in horizontal ground reaction force production between the first and tenth sprint has been shown to be significantly greater in previously injured legs compared to the contralateral uninjured leg and an uninjured control group [36].

Whilst some emerging evidence is available that horizontal ground reaction force production may be reduced following hamstring injury, further research is required to fully elucidate the exact function of hamstrings during the stance phase of running and whether or not a reduction in horizontal ground reaction force for the recently injured limb is a valid indicator of a persisting deficit in hamstring performance and thus a potential warning sign of likelihood for re-injury.

3.5 When Is the Critical Point in the Running Stride Cycle Where the Hamstrings Are Most Vulnerable to Injury?

Muscle strain injury is most likely limited to periods of stride cycle when hamstrings are highly activated and thus the muscle-tendon junction is subjected to high tensile loads, which based on EMG recordings is during late swing and stance. As previously documented, each hamstring MTU undergoes an active stretch-shortening cycle during late swing; hence this time of the stride cycle has been identified as a potential critical time point for injury. Circumstantial evidence is available from two case studies [37, 38], both of which suggest that the onset of injury occurred during the late swing phase.

Alternatively, early stance has also been proposed as a potential critical time point for injury, based on the proposed role of the hamstrings as a key contributor to forward propulsion of the body's centre of mass at this time [25, 26, 39]. Evidence of potentially high loads being imparted onto the hamstrings during early stance has been provided by some inverse dynamics-based studies [40, 41]. Specifically, for a brief period immediately following foot contact, the ground reaction force may pass in front of the knee joint thereby creating an 'external' extension moment at the knee which will be directly opposed by the hamstring muscles. Nevertheless, the presence of this specific joint moment in sprinting remains somewhat controversial, because it could simply be a by-product of a mismatch in cut-off frequencies when digitally filtering the kinematic and ground reaction force data [42].

Ongoing debate on this issue persists in the literature [43–46]. Whilst further research on this topic is warranted, ultimately it may simply be an academic argument. The critical point in the stride cycle might well vary from person to person, dependent upon contextual factors such as the presence of compromised tissue thresholds (e.g. from recent heavy training) and/or the exact nature of the functional activity being performed at the time of injury. It is noted that the majority of the literature covered in this chapter is derived from analysis of constant-speed running, and additional work in acceleration and deceleration efforts is warranted, as well as efforts requiring change of direction.

3.6 Factors That Influence Biceps Femoris Long Head Strain During Sprinting

Given that (a) HSI most commonly involves BF_{LH} [47], (b) HSI commonly occurs during high-speed running [48] and (c) peak MTU stretch during the terminal swing phase of high-speed running has been shown to be greatest for BF_{LH}, researchers have understandably been tempted to link these observations [15, 16, 19, 21, 22]. Understanding factors that may modulate peak MTU stretch may have important implications for interventions aiming to alter risk of HSI.

3.6.1 Muscle Coordination

In an effort to identify the influence of muscle force on peak BF_{LH} stretch during swing, one study [21] conducted a perturbation analysis of musculoskeletal simulations of the double float phase (i.e. when both legs are simultaneously in swing) during maximal sprinting. These authors found that greater stretch in the BF_{LH} was induced by muscle force from the ipsilateral rectus femoris and iliopsoas, as well as the contralateral iliopsoas, erector spinae and rectus femoris. Muscles with the greatest potential to decrease BF_{LH} stretch were the ipsilateral adductor magnus and hamstrings, as well as the contralateral internal oblique. It is currently unclear to what extent these simulation results reflect reality and therefore whether they can be used to directly inform rehabilitative and preventative interventions.

3.6.2 Series Elastic Component Stiffness

This chapter has provided evidence from multiple studies describing MTU stretch of the hamstrings during running. Although MTU stretch during running may well be a relevant variable for understanding the biomechanics of HSI, it is important to recognise that this term describes length changes of the entire MTU. Due to elastic properties of the series elastic component (i.e. tendon, aponeurosis), length changes of the entire musculotendinous unit are not necessarily accurate representations of length changes within the muscle fibres. The decoupling of muscle fibre and series elastic component length changes during dynamic activities is well established in vivo for other human lower limb muscle groups such as the ankle plantar flexor muscles (e.g. [49–51]). Equivalent in vivo data for the human hamstrings during running are not presently available; however, musculoskeletal modelling studies have shown that, across a range of physiologically reasonable tendon stiffness values, the relative strain experienced by the BF_{LH} muscle fibres during swing is directly related to the stiffness of the series elastic component [23]. This may suggest that tendon stiffness is an important regulator of muscle fibre strains experienced during swing and might therefore be important for injury risk. It is currently unknown, however, whether alteration of tendon stiffness will provide meaningful change in the risk of HSI.

3.6.3 Non-Uniform Strain Distribution

Musculoskeletal modelling studies describing MTU stretch during sprinting use simplified representations of muscle-tendon architecture and therefore dynamics, assuming uniformity in fibre strain distribution across the entire MTU. Whilst human in vivo data for the hamstrings is currently lacking, non-uniform muscle tissue strain distributions have been observed in the human biceps brachii muscle during loaded elbow flexion [52]. As these non-uniformities are due to the complex architecture of skeletal muscle, it is plausible that the human hamstrings may exhibit similar non-uniformity during running. To examine this, prior studies [10, 11] have utilised advanced imaging techniques to develop finite element models of the BF_{LH}, which contain more physiologically accurate complex representations of muscle fibre and tendon architecture and dynamics than what is typically accounted for in musculoskeletal modelling studies. Using these complex models and input experimental data from sprinting (i.e. MTU kinematics and muscle activation data), these studies have been able to provide insight into region-specific BF_{LH} muscle fibre strain patterns during the swing phase of sprinting. These data suggest that local muscle fibre strains exhibit non-uniformity across the MTU, with the greatest strains observed at the proximal musculotendinous junction [11]. This observation may provide an explanation as to why the proximal musculotendinous junction is the most frequently reported site of BF_{LH} strain injury [53]. Additionally, both the magnitude and non-uniformity of local fibre strain appear to increase as running velocity is increased [11].

3.7 Conclusion

In summary, the current evidence base suggests that the hamstrings are recruited for the entire stance phase, as well as during a portion of the swing phase (from mid-swing onwards). The late swing phase has been identified as the most likely period of injury, as the hamstrings undergo active lengthening and experience peak lengths. The forces produced by each hamstring muscle during this period increase with increasing running velocity, whilst the peak length experienced during this same period is largely invariant amongst high running velocities (>80% max). Whilst hamstring function is likely compromised following HSI, the findings from investigating studies are often conflicting; thus, more research is needed to identify which specific parameters need the most consideration during rehabilitation. Overall, the information in this chapter may inform clinicians aiming to develop HSI preventative and rehabilitative interventions.

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