Biomechanics of Muscle Strain Injury

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Abstract

The most common muscle strains are to the hamstring, quadriceps and calf muscle groups. From anecdotal and direct video evidence, it is known that gastrocnemius (calf) strains often occur during a single-leg support phase of push-off movements with the body weight far in front of the calf. The exact moment of hamstring and quadriceps strains has not been proven, but recent video evidence suggests that hamstring strains often occur due to over-striding when at fast speed. Conversely, video evidence suggests that rectus femoris strains may often occur due to under-striding when trying to slow down. This is the likely mechanism of rectus femoris strains that occur during running, and also during the running drop punt kick in Australian football. This combination of under-striding when trying to slow down causes the body to lean backwards and the leg to move farther behind the body than normal, which places extra stress and strain on the rectus femoris. A common mechanism of hamstring strain injury is probably when the body is leaning forward trying to maintain or achieve extra speed and the foot lands too far in front of the centre of mass, stressing and stretching the hamstring muscle group. Hamstring fatigue and/or weakness probably contribute to over-striding. For both hamstring and quadriceps strains, it is not established whether strain injury actually occurs during the swing phase (when the muscle is at greater length) or the ground contact phase (when there is greater stress on the muscle from external forces). Muscle strain injury *in vivo* is probably dependent on a combination of strain (muscle length) and external stress, so that the greater the length of a muscle at any given time, the less external force (stress) it can absorb before failure.

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Introduction

Muscle strains are amongst the most common injuries in football players and sprint athletes, although little is known about the risk factors [32]. The most common strains are to the long muscles of the lower limb, particularly the hamstring muscle group, the rectus femoris (quadriceps group) and gastrocnemius (calf group) [10,32]. The assessment of risk factors is best made through a combination of epidemiological studies and biomechanical analysis. It is known that strain injury is the result of excessive forces (which can be either externally applied or passive internal forces, due to strain). In the laboratory external forces and strain can be created and measured for an isolated muscle [4,6,20,29]. The forces (moments) affecting individual joints during the gait cycle *in vivo* can be estimated using well established models [22,23,30]. There are also models which can estimate muscle length during sprinting gait [13-15,43]. However, there is no established model to determine the external force (or stress) that individual muscle groups or muscle fibres are subject to at any given time of the gait cycle, making it very hard to assess why strain injury actually occurs.

Gastrocnemius muscle strains are known to commonly occur late during the single-leg stance phase of a push-off manoeuvre. Clinical and anecdotal evidence is in agreement with direct video evidence that has recently been reported [34]. Although hamstring muscle strains are a more common injury, authors have disagreed about whether strains occur during late swing or early stance during sprinting [1,7,34]. Rectus femoris (quadriceps) strains are known to commonly occur during kicking in Australian football and soccer, but no previous study has addressed the question of whether they primarily occur during ball contact, back swing, or ground contact during the step before kicking [32].

Previously published information about the epidemiology of muscle strains has found that quadriceps strains in football players are more common in dominant kicking leg (RR 2.13, 95% CI 1.59-28.6), whereas hamstring and calf injuries are fairly evenly distributed [32]. Previous muscle strain injury is a strong risk factor for future strain injury to the same muscle group (and in some cases other muscles). Calf and hamstring (but not quadriceps) strains are more common in older players [32].

Despite the established risk factors mentioned, any model attempting to explain the pathogenesis of a muscle strain injury *in vivo* is a yet-to-be-tested hypothesis. This lecture will review the studies and theories behind muscle strain injury and suggest some of the possible and likely biomechanical factors that contribute to a muscle strain injury.

Traditional Clinical Model of Muscle Strain Injury

Clinical sports medicine teaching asserts that two-joint muscles strain during sprint activities when undergoing eccentric contractions, which is well summarized in the works of Garrett [10,11]. However, Garrett admits in these reviews that he is merely summarizing popular opinion of the clinical sports medicine literature rather than stating proven fact, for example[10] "most clinicians would agree that muscle strain injuries occur when the muscle is either stretched passively or activated during stretch.[18,40,45]". This paradigm suggests that hamstring muscles are prone to strain injury in late swing phase (eccentric phase) rather than early ground contact (when the hamstring contraction is concentric) [1]. This model would also suggest that the rectus femoris is prone to strain in the early swing phase of sprinting and early backswing of the kicking motion. These phases are when the rectus femoris is eccentrically contracting [27,39].

Biomechanical Model of Muscle Strain Injury

Change of movement (angular velocity) of a joint is determined by a sum of the forces (moments) acting on the joint. These forces can be divided into the net moment generated by muscles acting on the joint ('muscle moment') and the net moment generated by external forces ('external moment') such as ground reaction forces and gravity. It is quite complicated to consider these forces for a single joint, such as the knee, and it is extremely complicated to consider how these forces interact for two joint muscles such as the hamstrings and rectus femoris.

The first author to measure muscle moments during sprinting and declare a period in the gait cycle where the hamstrings were prone to tear was Ralph Mann [23,24]. He measured muscle moments for hip, knee and ankle during sprinting and found that knee flexion moment and hip extension moment were both highest in the early ground contact phase of sprinting [23,24]. This establishes that the hamstring muscle group is generating the most force during this phase of gait (initial ground contact), and Mann concluded from this that hamstring strains are most likely to occur at this time. Mann's theory is most plausible if it is considered that the hamstring group is able to generate maximum joint moments during the initial contact phase because it is being stressed by net external moments in the opposite directions. Mann and other authors, when publishing muscle moments, have not generally published the external moments, although during the initial contact phase of sprinting these will tend to reflect the muscle moments. Angular velocity of the hip and knee are not changing rapidly during this phase [2], from which the conclusion can be made that the muscle and external moments are acting in opposite directions and are tending to neutralize each other. That is, during the initial contact phase of maximal sprinting there is a high hip extensor muscle moment counterbalancing a hip flexor external moment, with the converse occurring at the knee. Complicating this explanation is the fact that other muscles, such as the vasti and gastrocnemius, are also actively contracting during the initial ground contact phase [27], although as mentioned the net muscle moment at the knee is one of flexion. The hamstring muscle is also very active during the late swing phase [1,27] but in this phase it acts against relatively little external force, so its action results in a much greater change of angular velocity at the hip (which changes from flexing to extending during this phase) and knee (which changes from extending to flexing). Even though the hamstring contracts at least as much during the early ground contact phase, there is less resulting change in joint angular velocity due to the resisting external forces.

To summarise, in real life activities such as sprinting and kicking, the greatest lengths (stretches or strains) of the hamstring and rectus femoris muscles occur during swing phases. However, maximum external joint moments (forces which oppose muscle action) and consequent stress on muscles occurs during ground phases. Clinical teaching that stretch (strain) is most responsible for muscle strain injuries [10], suggests that the hamstring and rectus femoris muscles are most prone to failure when most stretched which is when they are contracting eccentrically during the swing phases. The model of Mann based on kinetics suggests that the hamstring muscles are most prone to failure when they are most stressed and also generating the most force, when opposing external forces during ground contact.

Laboratory Model of Muscle Strain Injury

A human muscle strain injury model can be simulated in the laboratory [20,29] by over-stretch of *isolated* animal muscle (i.e. *not* animal muscle during a running activity). Injury generally occurs at the musculo-tendinous junction (as seen in human in vivo strains) although can sometimes occur in the muscle belly [4,10].

Almost all laboratory simulated muscle strain injury experiments have found that strain (amount of lengthening of the muscle or muscle fibre, expressed in units of mm/mm) is the property that correlates most with muscle damage. Strain has been shown to have a greater correlation with muscle damage than muscle force [20], velocity [6], strain rate [4] and contraction status of the muscle [12]. These findings suggest that amount of strain (muscle length) should be the property that correlates most with risk of muscle strain injury *in vivo*.

Unfortunately with respect to real life human activities, strain alone does not explain why muscles sustain injury. The greatest strain (displacement) that a muscle can undertake is a movement from being fully shortened to fully lengthening, for example during a slow muscle stretching exercise, yet a slow stretch rarely if ever results in a muscle strain injury. As a muscle is stretched towards its maximum length, it passively resists the stretch [21]. In activities that typically cause muscle strain injuries (e.g. hamstring strains during sprinting) maximal range of motion of muscle groups (and hence maximal strain) is not nearly reached, yet a muscle strain injury can result. This implies that one or more of stress (tension), velocity, strain rate and/or contraction status are also relevant to creating a muscle strain injury in real life.

The laboratory studies, in showing that amount of strain is an important factor, suggest that muscles probably need to be in a relatively stretched state in order to create a strain injury. Certainly this is the case during a calf strain in the push-off manoeuvre described earlier. They also suggests that muscles are unlikely to be injured in a shortened state, irrespective of the forces involved, such as the rectus femoris muscle during ball contact in kicking.

Gastrocnemius (Calf) Strain Injury

The biomechanical milieu during a gastrocnemius strain injuries can be summarised more easily than the other muscle strains, as the time of occurrence of the common gastrocnemius strain in the gait cycle is well established. 'Tennis leg' in which the gastrocnemius suffers strain injury during the push-off movement after a tennis serve, was described over 30 years ago [9]. A video has recently been published which reveals a gastrocnemius strain at the exact moment of occurrence captured on a cricket 'StumpCam' [34]. In this case (Figure 1) the muscle strain injury occurs during the commencement of the second step of take-off (single leg support) towards the end of ground contact cycle. The gastrocnemius muscle is close to, but probably not at, maximum length. It is also presumably contracting quite strongly as it appears likely that ground reaction forces are tending to dorsi-flex the ankle and extend the knee. It is difficult to determine whether the muscle is undergoing any change in length at the time of the strain injury [34]. The muscle-tendon unit appears to be almost isometric. A recent study has shown that the muscle and tendon components of a muscle-tendon unit are not necessarily moving in the same direction [19]. When the gastrocnemius changes length during jumping, that there is a phase after eccentric contraction where musculo-tendinous unit as a whole appears to be isometric. However, realtime ultrasound reveals that during this phase the muscle component is contracting while the tendon component continues to lengthen, with the overall appearance of no change in length of the muscle-tendon unit [19].

Hamstring Strain Injury

Video analysis of hamstring strains, whilst not revealing the time of injury during the gait cycle, shows that they are likely to occur during overstriding when close to maximum speed and trying to maintain speed. During this type of movement, the hamstring muscles are relatively more stretched than during a stride of normal length at maximum speed, although they do not reach maximum muscle length. As mentioned previously, authors have disagreed about whether the actual muscle injury occurs during late swing or early stance during sprinting [1,7,34]. This is because the external forces and consequent muscle stress are greater during the ground phase, whereas the maximum length (muscle strain) is in the swing phase.

Hamstring strain injuries have been the subject of many epidemiology studies, but despite this there are few agreed risk factors for injury. The most established risk factors are age and injury history and unfortunately these are not reversible [3,32]. The most controversial risk factor is low strength (usually measured by reduced hamstring to quadriceps (H:Q) ratio). Many prospective studies have found a significant correlation between poor strength and risk of hamstring injury [8,36,44]. However, none of these studies measured past injury history as a confounder, and it is possible that low H:Q ratio was simply a marker for those athletes that had a past history of hamstring strain. A more recent study with superior sample size to those cited previously

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suggested that H:Q ratio was not a risk factor for hamstring strain [3]. This paper used an eccentric protocol, which has become standard for new generation isokinetic machines. However, a possible problem with this methodology is that an eccentric protocol on an isokinetic machine can actually cause a hamstring strain itself [38], so athletes may not give 100% effort when performing the eccentric protocol out of self-preservation.

Although the weight of studies at least suggest that low H:Q ratio may be a risk factor for hamstring strain, it is not readily apparent that attempting to reverse H:Q deficits can reduce the incidence of hamstring strain. One study from two decades ago suggested that this approach may work, but used a non-randomised methodology [17]. This has not been repeated by any follow-up studies, although recently Tyler et al. reported similar results in adductor strains to the method of Heiser et al. with hamstring strains [42]. The lack of follow-up studies to support the success of Heiser's method makes it unlikely that the majority of hamstring injuries could be prevented by addressing strength deficits.

Rectus Femoris (Quadriceps) Strain Injury

Quadriceps strains are a common injury in Australian football [37] and soccer [16]. A relatively high proportion of these injuries occur during training [37] and the most commonly injured of the four quadriceps muscle is rectus femoris [11]. Quadriceps strains are more common in matches where there has been low rainfall over the previous week, which suggests a ground contact rather than a ball contact mechanism [32]. If quadriceps strains occurred during ball contact, it would be expected that these injuries would be more common on wet days, when the ball may be heavier. Quadriceps strains are also more likely after a recent hamstring strain [32].

If a rectus femoris strain injury occurred during the ball contact phase of kicking, it would be when the muscle was in a relatively shortened state, inactive and shortening further[27,39], apparently conditions where muscle is able to withstand greater force. A comparative set of conditions in the upper limb, where the shortening triceps muscle is resisted by the ball when serving or spiking in volleyball, does not lead to muscle strain injury.

Another anecdotal observation which suggests that the rectus femoris is not susceptible to strain injury by ball contact is that the speed of the run-up, rather than the distance the ball is kicked, is associated with a greater risk of strain. The amount of foot-ball impact force is roughly proportional to the distance that the ball travels, yet long kicks with a slow run-up do not tend to cause rectus femoris strain. In Australian football, quadriceps strains are rare on long kick-outs from goal or kicking after a mark. They are also rare in punters in American football and goalkickers in rugby union and league, where kicks for maximum distance are often attempted. However, punters and kickers in these sports use a short and/or slow run-up. In contrast, rectus femoris strain injuries often occur during short kicks in Australian football when the player is running at high speed.

Video analysis of rectus femoris strain injuries shows similarity between the quadriceps strains occurring during running and those occurring during kicking. The common factor is deceleration of the kicking or standing leg with a relatively short stride. Normally during deceleration the leg providing the loss of momentum overstrides and lands well in front of the body, directing a strong ground reaction force backwards. However, this method cannot be used by the stance leg during a running kick, as the hips would also lower during this manoeuvre and the kicking leg could not swing through without hitting the ground. In fact, the opposite effect is needed, with a slightly short step in order to raise the hips to provide clearance for the kicking leg.

Although video evidence suggests that the 'under-stride' during deceleration is the gross mechanism for rectus femoris strain, as with the hamstring strain it is not clear whether the actual muscle failure occurs during the ground contact phase or swing phase. Like the hamstring, the swing phase is associated with the greatest muscle length (stretch), whereas the ground phase is associated with the greatest potential impact of external force (ground reaction force). In contrast to the hamstring strain injury, with rectus femoris strain injury the ground contact phase of risk precedes, rather than follows, the swing phase of greatest stretch.

Relation of Calf and Hamstring Strains to L5 Nerve Supply

Hamstring and calf strains have a relationship with advancing age and also share a common nerve supply (L5 and S1/sciatic nerve), whereas quadriceps strains are not related to age [32]. In anatomical dissections, a structure in the pelvis called the lumbosacral ligament shows a correlation between L5/S1 degenerative changes and compression of the L5 nerve root (by the ligament) [5]. The lumbosacral ligament and its propensity for extraforminal entrapment of the L5 nerve root was first described by Nathan et al. and by other anatomists since [28,31,41]. This anatomical configuration is quite possibly present in some of the older football players who find that they have recurrent hamstring and calf tears despite regular maintenance. If a nerve entrapment such as this were present, it could also explain the correlation between hamstring injury risk and low strength, but the difficulty in reducing the increased risk by strengthening. This anatomical configuration is also compatible with an at-risk athlete that has no restriction of lumbar and hip flexion, as it is most possible that any entrapment by the lumbosacral ligament would be worse in extension. 'Piriformis syndrome' has been described as a cause of recurrent posterior thigh pain, with inconsistent (although some excellent) results from division of the piriformis muscle to release the sciatic nerve [26]. Unfortunately, the lumbosacral ligament is not easily accessible. The best method for reaching it would probably be through an anterior approach, possibly with an abdominal laparoscope. This type of surgery has recently been decribed [25]. It remains to be seen whether it would be technically easy to divide the ligament to free an entrapped L5 nerve root, and whether this procedure would reduce the risk of hamstring strain injury in a highly susceptible athlete, without causing side effects. It also remains to be seen whether such an entrapment could be confirmed with investigations (such as MRI) prior to surgery.

Interaction Between Hamstring and Quadriceps Strains

Previous epidemiological study of the AFL has revealed that quadriceps strains (like many other non-contact lower limb injuries) are relatively more likely on northern AFL grounds, where ground traction and hardness are greater [33]. By contrast, hamstring strains follow an opposite trend and are more common on southern grounds [33]. It is possible that on grounds with less traction available, alterations are made to gait including over-striding to increase ground contact time, which make hamstring strains more likely and quadriceps strains less likely. In grounds where traction is greater, the stride length may be relatively shorter, which makes an under-stride, and consequently a quadriceps strain, more likely.

In addition, recent hamstring strain has been found to be a risk for quadriceps strain [32]. It is possible that during recovery from a hamstring strain, alterations are made to gait [35], which include reducing the stride length, protecting the weakened hamstring muscle from re-strain but increasing the chance of a secondary quadriceps strain.

Conclusion

Rectus femoris strains may often occur due to under-striding when trying to slow down, either during a kicking motion, or in normal running. This combination of under-striding when trying to slow down causes the body to lean backwards and the leg to move farther behind the body than normal, which places extra stress on the rectus femoris. The mechanism of hamstring strain is probably when the body is leaning forward trying to achieve extra speed and the foot lands too far in front of the centre of mass ('overstriding'), stressing the hamstring muscle group. If this hypothesis is correct, the mechanism of muscle strains is probably increased stress when at greater than a certain proportion past resting length. Fatigue, lack of warm-up and decreased strength of a muscle group probably contributes to this failure, as quadriceps fatigue, weakness or dysfunction may contribute to an under-stride (by failing to progress the leg fully during the preceding swing phase) and hamstring dysfunction to an over-stride (by failing to halt the forward progression of the leg during the swing phase).

The exact timing of the 'typical' gastrocnemius strain is known, during a ground contact phase when the muscle is also under high strain. For hamstring and rectus femoris strains, it is not established whether strain (muscle length) or stress (secondary to the external ground reaction forces) is primarily responsible for the injury, and hence the exact timing during the gait cycle is not known.

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Table 1 - Parameters influencing two-joint muscles during movements at high risk for muscle strain injury

	Hamstring	Rectus femoris	Gastrocnemius
Highest risk movement	Overstriding during maximum velocity	Understriding during deceleration (esp. kicking on the run)	Single contact phase at mid second stride of push-off
Body position	Forward lean	Backward lean	Forward lean
Upper joint position	Flexed hip	Extended hip	Extended knee
Lower joint position	Extended knee	Flexed knee	Dorsi-flexed ankle
Maximal strain/ stretch occurs	Late swing phase	Early backswing	Pre-take-off single leg support
Maximal tension/ stress occurs	Early ground contact phase	Late ground contact phase	Pre-take-off single leg support

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Figure 1 - Time of left gastrocnemius strain during a push-off movement.

Figure 2 - Time of high risk for left rectus femoris strain during kicking.

Figure 3 - Tim of high risk for left hamstring strain during sprinting and bending.

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