Published in final edited form as:
J Orthop Sports Phys Ther. 2010 February ; 40(2): 67–81. doi:10.2519/jospt.2010.3047.

Hamstring Strain Injuries: Recommendations for Diagnosis, Rehabilitation and Injury Prevention

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Synopsis

Hamstring strain injuries remain a challenge for both athletes and clinicians given the high incidence rate, slow healing, and persistent symptoms. Moreover, nearly one-third of these injuries recur within the first year following a return to sport, with subsequent injuries often being more severe than the original. This high reinjury rate suggests that commonly utilized rehabilitation programs may be inadequate at resolving possible muscular weakness, reduced tissue extensibility, and/or altered movement patterns associated with the injury. Further, the traditional criteria used to determine the readiness of the athlete to return to sport may be insensitive to these persistent deficits, resulting in a premature return. There is mounting evidence that the risk of reinjury can be minimized by utilizing rehabilitation strategies that incorporate neuromuscular control exercises and eccentric strength training, combined with objective measures to assess musculotendon recovery and readiness to return to sport. In this paper, we first describe the diagnostic examination of an acute hamstring strain injury, including discussion of the value of determining injury location in estimating the duration of the convalescent period. Based on the current available evidence, we then propose a clinical guide for the rehabilitation of acute hamstring injuries including specific criteria for treatment progression and return to sport. Finally, we describe directions for future research including injury-specific rehabilitation programs, objective measures to assess reinjury risk, and strategies to prevent injury occurrence. Level of evidence: Diagnosis/therapy, level 5.

Keywords

functional rehabilitation; muscle strain injury; radiology/medical imaging; running; strength training

Hamstring strain injuries comprise a substantial percentage of acute musculoskeletal injuries incurred during sporting activities at the high school, collegiate, and professional levels.[20,64,77,86] Participants in track, football, and rugby are especially prone to this injury given the sprinting demands of these sports,[14,31,40,73] while dancers have a similar susceptibility due, in part, to the extreme stretch incurred by the hamstring muscles.[6] Over a 10-year span among

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the players of 1 National Football League team (1998-2007), the occurrence of hamstring strain injuries (n=85) was second only to knee sprains (n=120).[31] The average number of days lost to this injury ranges from 8 to 25, depending, in part, on the injury severity and location.[17,31] Of potentially greater concern is that one-third of the hamstring injuries will recur with the greatest risk during the initial 2 weeks following return to sport.[71] This high early reinjury rate is suggestive of an inadequate rehabilitation program,[26] a premature return to sport,[85] or a combination of both.

The occurrence of hamstring strain injuries during high-speed running is generally believed to occur during terminal swing phase of the gait cycle,[37,70] a perception that is supported by the objective findings from 2 separate hamstring injury cases.[41,84] During the second half of swing, the hamstrings are active, lengthening and absorbing energy from the decelerating limb in preparation for foot contact.[21,93,105] The greatest musculotendon stretch is incurred by the biceps femoris,[94,96] which may contribute to its tendency to be more often injured than the other 2 hamstring muscles (semimembranosus and semitendinosus) during high-speed running (FIGURE 1).[7] Running-related hamstring strain injuries typically occur along an intramuscular tendon or aponeurosis, and the adjacent muscle fibers.[7,53] During its recovery from injury, the hamstrings must be properly rehabilitated to safely handle high eccentric loading upon return to running.

Hamstring injuries that occur during activities such as dancing or kicking can occur during either slow or fast movements that involve simultaneous hip flexion and knee extension. Such movements place the hamstrings in a position of extreme stretch, with injuries most commonly presenting in the semimembranosus and its proximal free tendon (as opposed to the intramuscular tendon).[6,8] These injuries tend to require a prolonged recovery period before an individual is able to return to the pre-injury level of performance.[8,17] Despite differences in injury mechanisms and recovery time, current examination and rehabilitation approaches generally do not consider injury location (i.e. proximal free tendon injuries versus intramuscular tendon and adjacent muscle fibers) as part of the clinical decision making process.[6]

The primary goal of a hamstring rehabilitation program is to return the athlete to sport at prior level of performance with minimal risk of injury recurrence. Achieving this objective requires consideration of the musculoskeletal deficits directly resulting from the injury (eg, swelling, pain, weakness, loss of range of motion), as well as risk factors that may have been present prior to the injury. While the age of the individual and a prior history of a hamstring strain have been consistently identified as injury risk factors,[13,32,33,74,103] each is non-modifiable. Modifiable risk factors that have been suggested include hamstring weakness, fatigue, and lack of flexibility[1,23,42,103] with a strength imbalance between the hamstrings (eccentric) and quadriceps (concentric) being most support by evidence.[3,28,104] In addition, limited quadriceps flexibility[34] and strength and coordination deficits of the pelvic and trunk muscles may contribute to hamstring injury risk.[19,87] As a result, current rehabilitation programs typically include a combination of interventions targeted at each of these modifiable factors.[65]

The purposes of this clinical commentary are: 1) to describe the diagnostic examination of the acute hamstring strain injury with emphasis on tests and measures that have prognostic value; 2) to present a comprehensive rehabilitation guide based on existing evidence aimed at minimizing both the convalescent period and risk of injury recurrence; and 3) to suggest future directions for research into injury mechanisms and recovery, with the goal of developing better prevention and more individualized rehabilitation programs.

Examination

History

The majority of individuals with hamstring strain injuries will present in the acute setting with a sudden onset of posterior thigh pain resulting from a specific activity, most commonly high-speed running.[22] Athletes may describe the occurrence of an audible pop with the onset of pain, more common to injuries involving the proximal tendon,[9] and are generally limited by the pain from continuing in the activity. Individuals may also report having pain at the ischial tuberosity when sitting, most commonly when the proximal tendon(s) is involved.[24] Because hamstring strain injuries have a high rate of recurrence, patients may report a previous hamstring injury, which is often adjacent to or near the current site of injury.

The mechanism of injury, and subsequent tissues injured, have been shown to have important prognostic value in estimating the rehabilitation time needed to return to pre-injury level of performance (TABLES 1 and 2).[6–9] That is, injuries involving an intramuscular tendon or aponeurosis and adjacent muscle fibers (biceps femoris during high-speed running[6,7]) typically require a shorter convalescent period than those involving a proximal free tendon (semimembranosus during dance and kicking[6,8,9]). This finding is consistent with prior observation that injuries involving the free tendon require a longer rehabilitation period than those within the muscle tissue.[38] Severe injuries, such as complete or partial ruptures of the hamstring muscles, typically result from extreme and forceful hip flexion with the knee fully extended (eg, water skiing),[24] and often require operative intervention with extensive post-surgical rehabilitation.[50,58,83] Although a differential examination is always recommended, the absence of a specific injury mechanism should lead the examiner to consider other potential sources of posterior thigh pain (TABLE 3).

Physical Examination

In the event of high suspicion of a hamstring injury based on the injury mechanism and sudden onset of symptoms, the purpose of the physical examination is more to determine the location and severity of the injury than its presence. Hamstring strain injuries are commonly classified according to the amount of pain, weakness, and loss of motion, resulting in grades of I (mild), II (moderate), or III (severe).[65,85] These injury grades are considered to reflect the underlying extent of muscle fiber or tendon damage (eg, grade I having minimal damage with grade III being complete tear or rupture), and can be used to estimate the convalescent period and to design the appropriate rehabilitation program.[46]

For injuries involving the intramuscular tendon and adjacent muscle fibers, a battery of tests that measure strength, range of motion, and pain can provide a reasonable estimate of rehabilitation duration.[85,101] In fact, the actual rehabilitation duration was shown to be as predictable from this clinical test combination as from measures of injury severity obtained from a magnetic resonance (MR) image.[85] However, for injuries to the proximal free tendon, the amount of impairment identified from these tests are not predictive of the recovery time needed to return to pre-injury level.[6] Regardless, we recommend the following specific measures, as described below, be used during the examination of all acute hamstring injuries, at the very least to serve as a baseline from which progress can be assessed. These tests should be considered as part of a comprehensive examination to identify deficits in adjacent structures that may have contributed to the hamstring injury (eg, strength of lumbopelvic muscles; quadriceps tightness).[19,36,87]

Strength—Strength assessment of the hamstring muscles is recommended through manual resistance applied about the knee and hip. Due to the biarticular nature of the hamstring muscles and the accompanying changes in musculotendon length that occur with hip and knee flexion, multiple test positions are utilized to assess isometric strength and pain provocation. For example, with the patient in a prone position and the hip stabilized at 0° of extension, knee flexion strength should be examined with resistance applied at the heel in both 15° and 90° of knee flexion. Attempts to bias the medial or lateral hamstrings by internal or external rotation of the lower leg, respectively, during strength testing may assist in the determination of the involved muscles. Because the hamstring muscles also extend the hip, we recommend that hip extension strength be assessed with the knee positioned at 90° and 0° of flexion while resistance is applied to the distal posterior thigh and heel, respectively. It is important to note that pain provocation with this assessment is as relevant of a finding as weakness, and a bilateral comparison should be performed for each measure.

Range of motion—Similar to strength testing, range of motion tests should consider both the hip and knee joints. Passive straight leg raise (hip) and active knee extension test (knee) are commonly used in succession to estimate hamstring flexibility and maximum length.[85,87,101] Typical hamstring length should allow the hip to flex 80° during the passive straight leg raise[49] and the knee to extend to 20° on the active knee extension test.[61] When assessing post-injury muscle length, the extent of joint motion available should be based on the onset of discomfort or stiffness reported by the patient. In the acutely injured athlete, these tests are often limited by pain and thus may not provide an accurate assessment of musculotendon extensibility. Once again, a bilateral comparison is recommended.

Palpation—Palpation of the posterior thigh is useful for identifying the specific region injured through pain provocation, as well as determining the presence/absence of a palpable defect in the musculotendon unit. With the patient positioned prone, repeated knee flexion-extension movements without resistance through a small range of motion may assist in identifying the location of the individual hamstring muscles and tendons. With the knee maintained in full extension, the point of maximum pain with palpation can be determined and located relative to the ischial tuberosity, in addition to measuring the total length of the painful region. While both of these measures are used, only the location of the point of maximum pain (relative to the ischial tuberosity) is associated with the convalescent period. That is, the more proximal the site of maximum pain, the greater the time needed to return to pre-injury level ($r=0.70$, $p=0.004$).[7]

The proximity to the ischial tuberosity is believed to reflect the extent of involvement of the proximal tendon of the injured muscle, and therefore a greater recovery period.[7,8]

Differential Examination—As part of the differential examination process, additional sources of posterior thigh pain should be considered (TABLE 3). For example, adverse neural tension has been implicated with posterior thigh pain and can be assessed using the active slump test.[59,85,95,101] The reproduction of symptoms related to the forward slumped posture suggests a more proximal contribution (eg, sciatic nerve, lumbar spine) to the posterior thigh pain.[59,75] This finding is more likely to be observed in individuals who have sustained recurrent hamstring injuries due to the residual inflammation and scarring that has been suggested to interfere with normal sciatic mobility.[95] In individuals with an apparent grade I hamstring strain injury, adverse neural tension may be the sole cause of the symptoms with no actual muscle injury present.[51] The absence of a specific injury mechanism should be considered in such cases.

As hip adductor strain injuries are also common during athletic events, careful differentiation of the injured muscle is required given the proximity of these muscles (eg, gracilis and adductor magnus and longus) to the hamstrings. Adductor strain injuries typically occur during movements involving quick acceleration or change of direction, as well as those requiring extreme hip abduction and external rotation.[60] Combined injury of the hamstrings (semimembranosus) and hip adductor muscles (adductor magnus) has been observed during a sagittal split motion in sports such as tennis,[9] as well as during high kicking associated with dance.[8] Pain is typically reproduced with palpation of the adductor tendons on or near their insertion to the pubic ramus, as well as with resisted hip adduction.[69] Imaging procedures may be required for the final determination of injury location and to rule out other possible causes of inguinal pain.[2]

Imaging

Unless an avulsion fracture with bony fragment or apophyseal fracture is suspected, plain radiographs are of little use in the examination of an acute hamstring injury.[22] Instead, ultrasonography (US) and MR imaging technologies have been advocated in these cases,[24,55] with the area of injury (edema; hemorrhage) depicted by echotexture and high signal intensity (T2-weighted images), respectively (FIGURE 2).[22,55] While both imaging modalities are considered equally useful in identifying hamstring injuries when edema and hemorrhage are present,[25] MR imaging is considered superior for evaluating injuries to deep portions of the muscles,[54] or when a previous hamstring injury is present as residual scarring can be misinterpreted on an US image as an acute injury.[25] Due to its increased sensitivity in showing subtle edema, measuring the size of injury (length and cross sectional area) is more accurate with MR imaging.[25]

Recent MR-imaging studies of acute grade I and II hamstring strain injuries have indicated that abnormalities (eg, edema) can confirm the presence and severity of injury, as well as provide a reasonable estimate of the rehabilitation period.[25,39] Specifically, the length and cross sectional area of the injury were directly proportional to the time away from sport necessary for recovery.[25,92] However, 2 prospective investigations demonstrated that the severity of the initial injury as determined from MR imaging was ineffective in predicting reinjury.[56,99] Thus, MR imaging of the acute hamstring injury appears useful in estimating time away from sport, but is limited in identifying individuals at risk for reinjury. Quantifying the extent of musculotendon remodeling with a repeat MR image at the time of return to sport may provide additional insight into the likelihood of muscle re-injury and should be considered an area for future research (FIGURE 2). In current clinical practice, MR imaging is often reserved for the more severe injuries where a rupture is suspected. Determining the extent (partial versus complete) and location of rupture, as well as the extent of tendon retraction in the case of complete rupture, is important in deciding whether a surgical procedure will be necessary.[54]

Prognosis

As stated above, the injury location and severity based on findings from the initial examination and MR imaging are useful at estimating the duration of rehabilitation required before the athlete returns to sport. Specifically, the following factors have been shown to require a greater convalescent period: 1) injury involving a proximal free tendon;[6,8,9] 2) proximity of the injury to the ischial tuberosity;[7,38] and 3) increased length and cross-sectional area of injury;[25,39,85,92] Despite injuries that involve the intramuscular tendon and adjacent muscle fibers initially present as more severe (eg, greater tenderness to palpation, range of motion loss, and weakness), the convalescent period is typically less than injuries involving the proximal free tendon.[6] This may be reflective of the increased remodeling time required of tendinous injuries.[38] Alternatively, post-injury scarring along the aponeurosis[88] may facilitate alternative force transmission paths that serve to protect the remodeling tissue upon return to sport.

Findings from the initial examination are less valuable in estimating risk of injury recurrence. That is, those injuries that presented as more severe based on physical examination or MR imaging findings did not have a greater rate of injury recurrence.[39,56,99,101] As previously stated, characterizing the extent of musculotendon recovery at the time of return to sport may provide prognostic value regarding reinjury risk and should be considered a direction for future research.

Rehabilitation

Returning the athlete to sport at prior level of performance with a minimal risk of injury recurrence is the primary objective of a rehabilitation program following a hamstring strain injury. The high recurrence rate of hamstring injuries has led to speculation regarding the appropriateness of commonly employed rehabilitation strategies.[1,22] Several factors have been suggested that likely contribute to the high rate of reinjury:[71] 1) persistent weakness in the injured muscle; 2) reduced extensibility of the musculotendon unit due to residual scar tissue; and 3) adaptive changes in the biomechanics and motor patterns of sporting movements following the original injury. In addition to these injury-induced risk factors, modifiable risk factors that may have contributed to the original injury (eg, strength and control of lumbopelvic muscles[19,87] or quadriceps tightness[34]) should be considered in the rehabilitation program.

With a focus on muscle remodeling, eccentric strength training has been advocated in the rehabilitation of hamstring injuries. It has been suggested that the high injury recurrence may be attributed to a shorter optimum musculotendon length for active tension in the previously injured muscle.[16,78] Such a shift in the force-length relationship could be a training effect, eg, repeated performance of strengthening with concentric exercises during rehabilitation. Alternatively, this shift could reflect the presence of residual scar tissue at the musculotendon junction.[47] Scar tissue is stiffer than the contractile tissue it replaces, and thus may alter the mechanical environment of the muscle fibers. Specifically, a decrease in series compliance would shift peak force development to shorter musculotendon lengths. In healthy control subjects, the performance of controlled eccentric strength training exercises has been shown to facilitate a shift in peak force development to longer musculotendon lengths.[15] Therefore, eccentric strength training following a hamstring injury may effectively restore optimum musculotendon length for active tension to normal, thereby reducing the risk of reinjury.

One common criticism of rehabilitation programs that emphasize eccentric strength training is the lack of attention to musculature adjacent to the hamstrings. It has been suggested that neuromuscular control of the lumbopelvic region is needed to enable optimal function of the hamstrings during normal sporting activities.[72] This has led some clinicians to utilize various trunk stabilization and progressive agility exercises for hamstring rehabilitation.[13,87] Sherry and Best[87] demonstrated a significant reduction in injury recurrence when individuals with an acute hamstring injury were treated using a progressive agility and trunk stabilization (PATS) program compared to a progressive stretching and strengthening (STST) program. The PATS program consisted primarily of neuromuscular control exercises, beginning with early active mobilization in the frontal and transverse planes, and then progressing to movements in the sagittal plane. Compared to the STST group, there was a statistically significant reduction in injury recurrence in the PATS group at 2 weeks (STST, 55%; PATS, 0%) and 1 year (STST, 70%; PATS 8%) after return to sport. It remains unclear which neuromuscular factors were responsible for the reduced reinjury risk in the PATS group. One hypothesis is that improved coordination of the lumbopelvic region allows the hamstrings to function at safe lengths and loads during athletic movement, thereby reducing injury risk.[87] An alternative explanation is that the use of early mobilization limits the residual adverse effects of scar tissue formed early in the remodeling process. For example, early mobilization has been demonstrated to promote collagen penetration and orientation of the regenerating muscle fibers through the scar tissue, as well as recapillarization of the injured area.[45,47,57]

Because of the reduced range of motion present at the knee and hip following an acute hamstring injury, flexibility exercises targeting the hamstring muscles are commonly incorporated into the rehabilitation program.[1,22,65,98] However, the influence of flexibility training on either hamstring injury prevention or recovery remains unclear.[3,13,29,62]

If a positive active slump test is found during the examination, neural mobilization techniques have been recommended as part of the rehabilitation program.[52,95] For example, the inclusion of the slump stretch has been shown to reduce time away from sport for individuals diagnosed with a grade I hamstring strain injury who also demonstrated a positive slump test.[51] The use of neural mobilization techniques in the care of more severe hamstring injuries or injuries in the acute stages of healing has not been investigated.

Additional interventions such as electrophysical agents and massage therapy have also been suggested in the management of acute hamstring strain injuries.[22,44,46,103] However, evidence to support their use is lacking.[65] For example, therapeutic ultrasound has been recommended to relieve pain following muscle injury and to enhance the initial stages of muscle regeneration, yet its use does not appear to have a beneficial influence on muscle healing.[63,80] Similarly, conflicting evidence exists regarding massage therapy and its positive effect on hamstring muscle activity and flexibility in healthy adults;[11,12,43] with no evidence regarding its effect on healing and recovery following an acute muscle strain injury.

Below is a proposed guide to the rehabilitation of grade I and II hamstring strain injuries based on current available best evidence (see Appendix for summary). The interventions employed for these injuries are typically prescribed based on the patient's status and time post-injury.[26] As such, this rehabilitation guide is divided into 3 phases with specific treatment goals and progression criteria for phase advancement and return to sport. The focus during phase I involves minimizing pain and edema while protecting the scar formation, especially during the immediate days post-injury (1-5 d).[46] Low intensity, pain-free exercises involving the entire lower extremity and lumbopelvic region are initiated through a protected (limited and painfree) range of motion to minimize atrophy and develop neuromuscular control. During phase II, the intensity and range of motion of the exercises are increased based on the patient's tolerance and improvement. Movements involving eccentric actions of the hamstring muscles are also initiated. Phase III involves more aggressive, sport-specific movements through full unrestricted range of motion to prepare the athlete for return to prior level of sporting activity. It should be noted that this guide is based primarily on the literature pertaining to hamstring injuries involving the intramuscular tendon and adjacent muscle fibers[6,7,16,87] due to the lack of published rehabilitation programs for those involving the proximal free tendon. Modifications to the exercises, sports specific movement, and progression criteria may need to be considered for injuries involving the proximal free tendons of the hamstring muscles. Further, this guide is not appropriate for the post-operative rehabilitation of a complete hamstring rupture or avulsion.

Phase I

Protection—Excessive stretching of the injured hamstrings should be avoided, as this can result in dense scar formation in the area of injury prohibiting muscle regeneration.[45] However, restricted movement of the hamstrings should be encouraged with the onset of pain used to define the range of motion limit. This may require the use of shorter strides during ambulation, or in more severe cases, the use of crutches. In addition, when crutches are used, the athlete should be instructed to avoid actively holding the knee in flexion for a prolonged period as this may place an excessive tensile load on the healing tissue. Normal gait can be resumed when pain allows.

Ice—The injured area should be iced 2-3 times/d to help decrease pain and inflammation with duration of each session dependent on the icing medium (eg, 3-5 minutes for an ice cup and 15-20 minutes for a cold pack).[22]

NSAIDS—Non-steroidal anti-inflammatory medications (NSAIDs) may be used during the initial days following muscle injury. However, investigations demonstrating a lack of benefit[82] and possibly negative effect on muscle function following recovery[67] have resulted in controversy regarding their use. Analgesics, such as acetaminophen, have been suggested as an alternative to NSAIDs given the reduced risk and cost.[79] In our experience, most athletes can control pain with ice and activity modification alone.

Therapeutic Exercise—The exercises and movements selected are designed to promote neuromuscular control within a protected range of motion, thereby minimizing the risk of damage to the remodeling muscle.[46] These initial exercises include isometrics of the lumbopelvic musculature, single-limb balance exercises, and short stride frontal plane stepping drills (eg, grapevine (ONLINE VIDEO)), while avoiding isolated resistance training of the injured hamstring muscle. The exercises should always be performed without pain, with the intensity of the exercises progressed from light to moderate as tolerated.

Progression Criteria—Progression to phase II can begin once the following criteria are met: 1) normal walking stride without pain; 2) very low speed jogging without pain; and 3) pain-free isometric contraction against sub-maximal (50-70%) resistance during prone knee flexion (90°) manual strength test. If these criteria are met at the initial visit, as may be the case with less severe injuries, then the rehabilitation program can begin at phase II.

Phase II

Protection—While a return to full range of motion is encouraged during this phase, end range lengthening of the hamstrings should be avoided if weakness persists. In the presence of a significant strength deficit, the musculotendon unit may not be able to guard against passive musculotendon lengthening, potentially limiting fiber repair.[46]

Ice—Icing should be performed after the rehabilitation exercises to help decrease the possible associated pain and inflammation.

NSAIDS—NSAIDs are generally not used during this phase due to the potential negative side effects associated with prolonged NSAID use.[10,66] In addition, masking pain during rehabilitation may result in an overly aggressive progression of the rehabilitation exercises due to the patient being unable to accurately self-assess a potentially painful response.

Therapeutic Exercise—Exercises employed in phase II promote a gradual increase in hamstring lengthening, compared to the limited range of motion allowed in phase I. This approach is based on observations that mobilization of skeletal muscle 5-7 days after injury can enhance fiber regeneration.[45,47,48] With the emphasis on neuromuscular control, agility drills, and trunk stabilization, exercises are performed with a progressive increase in speed and intensity, respectively. Movements are begun primarily in the transverse and frontal planes to avoid overstretching the injured muscle (eg, rotating body bridge (ONLINE VIDEO), boxer shuffle (ONLINE VIDEO)), but progressively transitioned to the sagittal plane based on the patient's tolerance and improvement (eg, supine bent knee bridge walk outs (FIGURE 3)). Sub-maximal eccentric strengthening exercises near mid-length of the muscle are initiated as part of functional movement patterns rather than through exercises isolating the hamstrings. In preparation for the athlete's return to sport, anaerobic training and sport skills are initiated taking care to avoid end range lengthening of the hamstrings or substantial eccentric work.

This typically precludes the athlete from running at a speed greater than 50% of their maximum. In our experience, the above exercises in combination with the reduction in pain and edema, restores full range of motion of the recovering muscle without the need to incorporate specific stretching.

Progression Criteria—Progression to Phase III can begin once the following criteria are met: 1) full strength (5/5) without pain during a 1 repetition maximum effort isometric manual muscle test in prone with the knee flexed at 90°; and 2) forward and backward jogging at 50% maximum speed without pain.

Phase III

Protection—Range of motion is no longer restricted as sufficient hamstring strength without accompanying pain should now be present. However, sprinting and explosive acceleration movements should be avoided until the athlete has met return to sport criteria.

Ice—Icing should be performed after the rehabilitation exercises, as needed, to help decrease possible associated pain and inflammation.

Therapeutic Exercise—Given the athlete's impending return to sport, agility and sport-specific drills should be emphasized that involve quick direction changes and technique training, respectively. Trunk stabilization exercises should become more challenging by incorporating transverse plane motions and asymmetrical postures. With the emphasis remaining on functional movement patterns, eccentric hamstring strengthening should be progressed toward end range of motion with appropriate increases in resistance (eg, supine single limb chair-bridge (FIGURE 4), single limb balance windmill touches with dumbbells (FIGURE 5 and ONLINE VIDEO), lunge walk with trunk rotation opposite hand dumbbell toe touch and T lift (ONLINE VIDEO)). Incorporating sport-specific movements that involve a variety of head and trunk postures, as well as quick changes in those postures is encouraged.

Return to Sport Criteria—Establishing objective criteria for determining the appropriate time to return an athlete to sport remains challenging and an important area for future research. Based on the best available evidence[72,87,99] and our experience, we recommend that athletes be cleared to return to unrestricted sporting activities once full range of motion, strength, and functional abilities (eg, jumping, running, cutting) can be performed without complaints of pain or stiffness. When assessing strength, the athlete should be able to complete 4 consecutive pain-free repetitions of maximum effort manual strength test in each prone knee flexion position (90° and 15°). If possible, isokinetic strength testing should also be performed under both concentric and eccentric action conditions. Less than a 5% bilateral deficit should exist in the ratio of eccentric hamstring strength (30°/s) to concentric quadriceps strength (240°/s).[27] In addition, the knee flexion angle at which peak concentric knee flexion torque occurs should be similar between limbs.[16,78] Functional ability testing should incorporate sport-related movements specific to the athlete, with intensity and speed near maximum.

Future Directions

Injury-specific Rehabilitation

While recent findings have demonstrated the significance that injury location and mechanism have on the duration of the convalescent period, these injury sub-types have not been considered in the investigations involving rehabilitation strategies. That is, hamstring strains have received the same treatment regardless of specific injury location or mechanism, despite a substantial difference in treatment duration (TABLE 2).[6,87] With the majority of rehabilitation programs being designed almost exclusively for running-related injuries involving primarily muscular tissue, future investigations need to be performed to identify the most appropriate rehabilitation strategy for the injuries involving the proximal free tendon. It may be reasonable to consider interventions commonly employed to treat tendinopathies (eg, Achilles tendinopathy) in the latter injury type. Given the lengthy recovery period associated with proximal free tendon injuries, there is the potential for a significant impact by reducing the time needed to recover.

Evaluating Re-injury Risk

Clinicians face considerable pressures to return an athlete to competition as quickly as possible, often times at the expense of completing a comprehensive rehabilitation program. This early return to sport is not only met with a high risk of reinjury,[56,74] but also reduced performance by the athlete.[97] Despite these risks, athletes commonly return early to sport as the risk of reinjury is often considered a reasonable compromise compared with the extended time away from sport required of a more cautious rehabilitation program.[72] However, it is worth noting that should the hamstring injury recur, the second injury is usually more severe than the first, typically requiring the time away from sport to double.[17,56] While there is no consensus on when an athlete can safely return to sport following a hamstring strain injury,[72] once full range of motion, strength and functional activities (eg, jumping, running, cutting) can be performed, the athlete is typically regarded as being ready to return to play. However, these criteria are likely too vague as pain and stiffness associated with the injury typically resolve within 1 to 2 weeks, while the underlying injury and risk of reinjury may persist for several more weeks.[25] Recent prospective studies have revealed that physical exam findings at the time of injury were ineffective at predicting injury recurrence.[99,101] The development of quantitative post-treatment parameters to objectively characterize musculotendon recovery and readiness to return to sport is therefore an important avenue of future research.

Several investigations have previously looked at the potential of using strength imbalance or bilateral strength deficit measures to identify those at risk of a hamstring re-injury.[26-28] These studies suggest that eccentric hamstring strength and angle of peak strength seem to be the most promising measures. For example, despite a normal concentric strength profile of the hamstring muscles following rehabilitation, Croisier and colleagues[27] observed that 18 of 26 athletes with recurrent hamstring injuries demonstrated persistent bilateral deficits in eccentric hamstring strength, as determined by the ratio of eccentric hamstring strength (30°/s) relative to concentric quadriceps strength (240°/s). Following an isokinetic training program emphasizing eccentric exercises, individuals recovered full hamstring strength (less than 5% bilateral deficit), returned to pre-injury level of play and did not re-injure themselves during the subsequent 12 months.[27] Despite these promising findings, it is important to note that 31% of the individuals with a recurrent hamstring injury in this study displayed normal hamstring strength. Determining the knee angle at which peak torque occurs may further assist in identifying those at risk of re-injury. The occurrence of peak torque at a greater knee flexion angle (ie, shorter optimum musculotendon length for active tension) compared to the contralateral side has been suggested to increase the risk of injury recurrence due to an increased susceptibility to damage from eccentric exercise.[16,78]

In addition to persistent strength deficits within the previously injured muscle, we have recently demonstrated the substantial influence that lumbopelvic muscles can have on the overall stretch of the hamstrings.[21] For example, activation of the uniarticular hip flexors (iliopsoas) during high-speed running induces stretch in the contralateral hamstrings. In particular, the iliopsoas muscle force directly induces an increase in anterior pelvic tilt during early swing phase, which in turn necessitates greater hamstring stretch of the contralateral limb which is simultaneously in late swing phase. This coupling may, in part, explain why rehabilitation exercises targeting neuromuscular control of muscles in the lumbopelvic region are effective at reducing hamstring re-injury rates.[87] In addition, it is possible that passive tension due to stretch of the iliopsoas during late stance phase may have a similar effect (ie, produce anterior tilt of the pelvis and a stretch of the contralateral hamstrings). Future investigations are needed to determine if strength or flexibility deficits in the lumbopelvic muscles at the time of return to sport increase the risk of hamstring injury recurrence.

We have recently presented evidence that both tendon and muscle remodeling can persist for many months following a hamstring injury.[88] In our study, high resolution bilateral MR images were obtained from 13 athletes who sustained a clinically diagnosed grade I/II strain injury of the biceps femoris between 5 and 19 months prior but were pain-free and back to full sports participation at the time of the study. Atrophy of the biceps femoris long head was observed often with an accompanying hypertrophy of the biceps femoris short head. Scarring adjacent to the prior injury was also detected, represented by increased low-intensity signal on both T1 and T2 weighted images (FIGURE 6). We believe that this remodeling may be occurring within the first few weeks following initial injury, as evidence by scar tissue formation in athletes just following a successful return to sport (FIGURE 2).

We conducted biomechanical testing on a subset of these same athletes with a prior hamstring injury, with the intent of identifying functional bilateral differences between the previously injured and uninjured limbs.[89] Three-dimensional full body kinematics and electromyographic signals were recorded while subjects ran on a treadmill at speeds ranging between 60 and 100% of maximum. Because scar tissue is thought to influence both the passive and active force-length properties of muscle, the passive force-length relationship of the hamstrings was also measured in each limb.[91] Despite significant bilateral asymmetries being present in hamstring and tendon morphology in these athletes, our preliminary findings showed no consistent asymmetries in joint kinematics or muscle activity during sprinting, or in passive hamstring musculotendon stiffness.[89] While it is possible that joint level analyses are inadequate at detecting changes that occur at the musculotendon level, continued investigations are needed to determine the influence that post-injury remodeling may have on functional performance and the resulting contribution to re-injury risk.

Dynamic MR imaging has the ability to measure the motion of muscle fascicles, tendon, and aponeurosis *in vivo*;[4,76,106] which cannot be done using standard joint level analyses. We recently designed and built a MR compatible device capable of inducing shortening and lengthening muscle contractions within the bore of a standard MR scanner.[102] Dynamic MR imaging techniques (eg, cine phase contrast) can be used in conjunction with the device to image the muscle under the 2 loading conditions. Our preliminary dynamic image data clearly reveal non-uniform shortening throughout the muscle, and differences between the loading conditions.[90] Our future studies are designed to look at how this non-uniform shortening can contribute to shear strains along the musculotendon junction as muscle undergoes an eccentric contraction, a situation which may contribute to injury risk at this location. We also intend to dynamically image previously injured hamstring muscles with the goal of better understanding the influence that altered musculotendon morphology has on *in vivo* contraction mechanics. Imaging of previously injured subjects will enable a more comprehensive characterization of the impact of scarring on the strain distribution, particularly along the proximal musculotendon boundary, lending valuable insight into the effects that persistent scarring may have on functional performance and reinjury risk.

Injury Prevention Strategies

Given the high incidence of hamstring strain injuries that occur across a variety of sports and activities and the substantial tendency for injuries to recur, the greatest impact may be achieved by developing improved techniques for preventing initial injury. Several investigations have been conducted to identify risk factors associated with injury occurrence.[34,36,74,100,104] Based on these associations, prevention strategies have been suggested that target specific risk factors, such as deficits in hamstring flexibility and strength. However, the effectiveness of these proposed prevention programs at reducing the occurrence of hamstring strain injuries is limited to a few investigations.

Despite hamstring stretching being commonly advocated for injury prevention, the inclusion of a flexibility program has not been shown to reduce the incidence of hamstring strain injuries.[3,17] However, the duration and frequency of hamstring stretching have been suggested as important factors in the effectiveness of a flexibility program at reducing injury occurrence.[29] While a decrease in quadriceps flexibility has been identified as a risk factor for hamstring strain injury,[36] the effect of a quadriceps or hip flexor stretching program on the incidence of hamstring injury remains unknown. Randomized controlled trials are needed to compare between specific flexibility programs, as well as against a control group to determine if stretching should remain as part of the injury prevention strategy.

Conversely, the incorporation of eccentric hamstring exercises as part of routine training has been found to substantially reduce the incidence of hamstring strain injuries.[3,5,17] A recent prospective investigation determined through isokinetic testing that a strength imbalance (≥ 20% bilateral deficit) between the eccentric hamstrings (30°/s) and concentric quadriceps (240°/s) ratio resulted in a 4-fold increase in risk of hamstring injury (risk ratio, 4.66; 95% confidence internal, 2.01-10.8) compared to a normal strength profile.[28] The authors suggested that an insufficient eccentric capacity of the hamstring muscles to offset the concentric action of the quadriceps during terminal swing resulted in the increased injury risk.[27] The addition of eccentric hamstring strength exercises as part of preseason and in-season training for elite soccer players reduced the incidence of hamstring strain injuries (risk ratio, 0.43, 95% confidence interval, 0.19-0.98).[3] While this may simply be attributed to the increase in peak hamstring eccentric strength,[68] it has also been suggested that the injury risk-reduction benefit from eccentric training may be due, in part, to the resultant shift in peak force development to longer muscle lengths.[15] Because of the increased occurrence of delayed onset muscle soreness resulting from eccentric training, and therefore potential for reduced patient compliance,[35] a gradual increase in training load and intensity is strongly recommended to minimize these effects.[3]

Finally, because of its demonstrated importance to injury recovery,[87] neuromuscular control exercises targeting the lower extremities and lumbopelvic region have been suggested for inclusion in hamstring injury prevention programs.[19,98] Examples of such movements include high knee marching, quick support running drills, forward falling running drills, and explosive starts, with the focus being on postural control and power development. Following a 6 week training period of these exercises, improvements in lower extremity control and movement discrimination have been observed, with the authors suggesting a potential contribution to injury prevention.[19] In addition, a program emphasizing varying trunk movements during running (eg, upright posture, forward flexed, forward flexed and rotated) reduced hamstring injury occurrence by 70% on average over a 2 year period.[98] Given these promising findings, additional prospective studies need to be performed on a larger scale and involve athletes from all levels of competition (eg, high-school, collegiate, professional). Further, the relevance of such exercises to the prevention of hamstring injuries involving the proximal free tendons needs to be determined.

Summary

Hamstring strain injuries are common in the athletic population and have a high rate of recurrence. Considering the multifaceted nature of hamstring injuries, the strength in local and adjacent muscles, as well as range of motion at the hip and knee should be evaluated during the physical examination. Findings pertaining to the mechanism of injury and injury location within the musculotendon unit are important in determining an accurate prognosis. An emphasis on neuromuscular control and eccentric strengthening is suggested for the successful return of the athlete to sport while reducing the risk of re-injury. Future research should include evaluating the effectiveness of current rehabilitation programs, identifying appropriate return to sport criteria that can accurately predict risk of reinjury, and developing effective strategies to prevent injury occurrence.

Acknowledgments

Acknowledgment of funding sources: National Football League Medical Charities, National Institutes of Health (grant nos. AR 56201, RR 250121), University of Wisconsin Sports Medicine Classic Fund

Appendix

Proposed guide for the rehabilitation of acute hamstring strain injuries. Suggested exercises, including sets and repetitions, should be individualized to the patient. Progression through the 3 phase program is estimated to require approximately 2-6 weeks but should be progressed on a patient-specific basis using criteria as indicated.

Phase I
Goals: **1** Protect scar development **2** Minimize atrophy
Protection: Avoid excessive active or passive lengthening of the hamstrings
Ice: 2-3 times/d
Therapeutic Exercise (performed daily): **1** Stationary bike × 10 min **2** Side step × 10 m, 3 × 1 min, low to moderate intensity, pain-free speed and stride **3** Grapevine × 10 m, 3 × 1 min, low to moderate intensity, pain-free speed and stride (ONLINE VIDEO) **4** Fast feet stepping in place, 2 × 1 min **5** Prone body bridge, 5 × 10 s **6** Side body bridge, 5 × 10 s **7** Supine bent knee bridge, 10 × 5 s **8** Single limb balance progressing from eyes open to closed, 4 × 20 s
Criteria for Progression to Next Phase: **1** Normal walking stride without pain **2** Very low speed jog without pain **3** Pain-free isometric contraction against sub-maximal (50-70%) resistance during prone knee flexion (90°) manual strength test
Phase II
Goals: **1** Regain pain-free hamstring strength, beginning in mid-range and progressing to a longer hamstring length

2. Develop neuromuscular control of trunk and pelvis with progressive increase in movement speed

Protection: Avoid end-range lengthening of hamstrings while hamstring weakness is present

Ice: Post-exercise, 10-15 min

Therapeutic Exercise (performed 5-7 d/wk):

1. Stationary bike × 10 min
2. Side shuffle × 10 m, 3 × 1 min, moderate to high intensity, pain-free speed and stride
3. Grapevine jog × 10 m, 3 × l min, moderate to high intensity, pain-free speed and stride
4. Boxer shuffle × 10 m, 2 × 1 min, low to moderate intensity, pain-free speed and stride (ONLINE VIDEO)
5. Rotating body bridge, 5 s hold each side, 2 × 10 reps (ONLINE VIDEO)
6. Supine bent knee bridge with walk outs, 3 × 10 reps (FIGURE 3)
7. Single limb balance windmill touches without weight, 4 × 8 reps per arm each limb (ONLINE VIDEO)
8. Lunge walk with trunk rotation, opposite hand-toe touch and T lift, 2 × 10 steps per limb (ONLINE VIDEO)
9. Single limb balance with forward trunk lean and opposite hip extension, 5 × 10 s per limb (ONLINE VIDEO)

Criteria for Progression to Next Phase:

1. Full strength (5/5) without pain during prone knee flexion (90°) manual strength test
2. Pain-free forward and backward jog, moderate intensity

Phase III

Goal:

1. Symptom-free (eg, pain and tightness) during all activities
2. Normal concentric and eccentric hamstring strength through full range of motion and speeds.
3. Improve neuromuscular control of trunk and pelvis
4. Integrate postural control into sport-specific movements

Protection: Avoid full intensity if pain/tightness/stiffness is present

Ice: Post-exercise, 10-15 min, as needed

Therapeutic Exercise (performed 4-5 d/wk):

1. Stationary bike × 10 min
2. Side shuffle × 30 m, 3 × 1 min, moderate to high intensity, pain-free speed and stride
3. Grapevine jog × 30 m, 3 × 1 min, moderate to high intensity, pain-free speed and stride
4. Boxer shuffle × 10 m, 2 × 1 min, moderate to high intensity, pain-free speed and stride
5. A and B skips, starting at low knee height and progressively increasing, pain-free
    a. A skip is a hop-step forward movement that alternates from leg to leg and couples with arm opposition (similar to running). During the hop, the opposite knee is lifted in a flexed position and then the knee and hip extend together to make the next step. (ONLINE VIDEO)
    b. B skip is a progression of the A skip, however the opposite knee extends prior to the hip extending re-creating the terminal swing phase of running. The leg is then pulled backward in a pawing type action. The other components remain the same as the A skip. (ONLINE VIDEO)
6. Forward-backward accelerations, 3 × 1 min, start at 5 m, progress to 10 m then 20 m (ONLINE VIDEO)
7. Rotating body bridge with dumbbells, 5 s hold each side, 2 × 10 reps
8. Supine single limb chair-bridge, 3 × 15 reps, slow to fast speed (FIGURE 4)
9. Single limb balance windmill touches with dumbbells, 4 × 8 reps per arm each leg (FIGURE 5)
10. Lunge walk with trunk rotation, opposite hand dumbbell toe touch and T-lift, 2 × 10 steps per limb
11. Sport-specific drills that incorporate postural control and progressive speed

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Criteria for Return to Sport:

1. Full strength without pain
   a. 4 consecutive repetitions of maximum effort manual strength test in each prone knee flexion position (90° and 15°)
   b. Less than 5% bilateral deficit in eccentric hamstrings (30°/s):concentric quadriceps (240°/s) ratio during isokinetic testing
   c. Bilateral symmetry in knee flexion angle of peak isokinetic concentric knee flexion torque at 60°/s
2. Full range of motion with pain
3. Replication of sport specific movements near maximal speed without pain (eg, incremental sprint test for running athletes)

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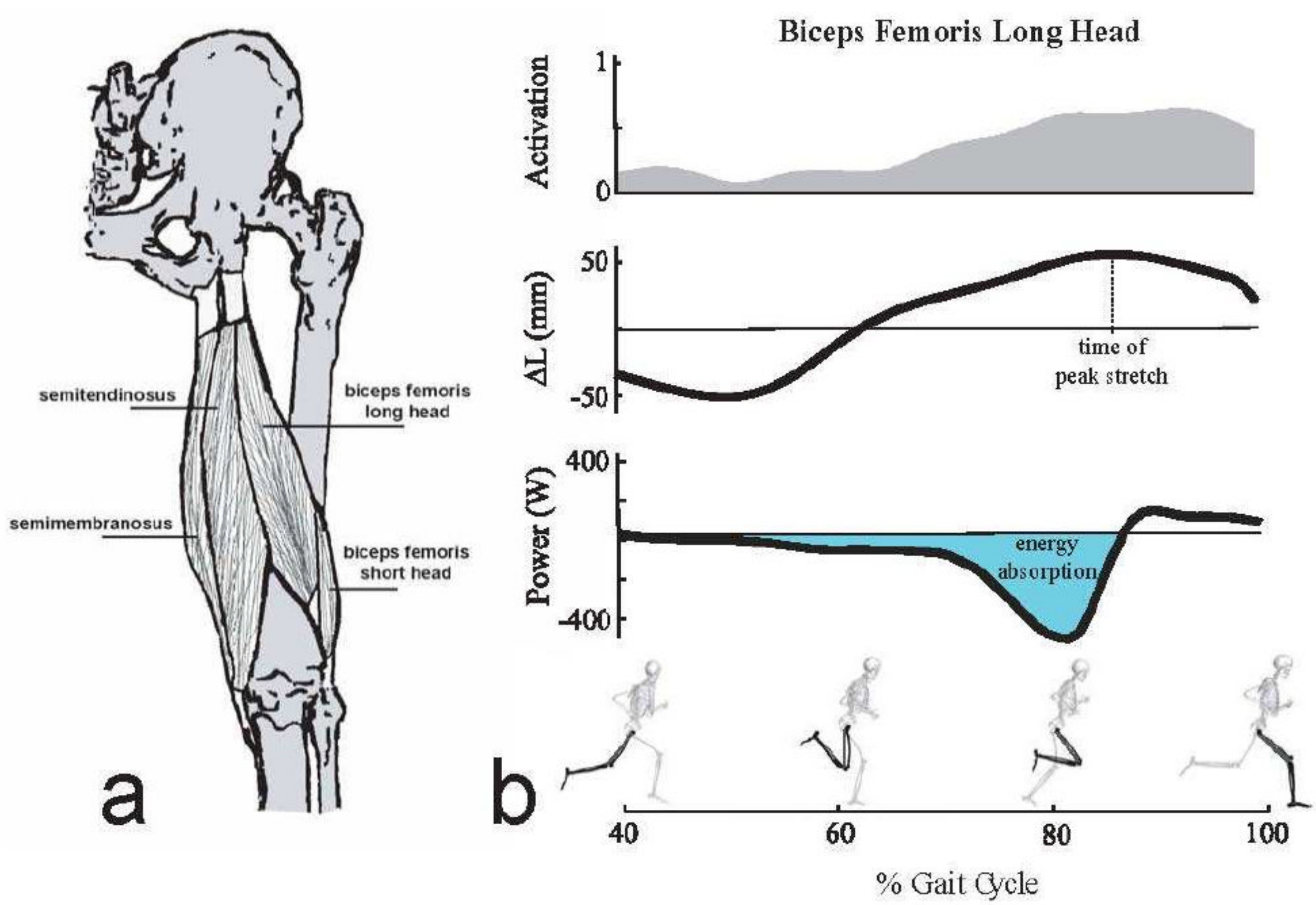

FIGURE 1.

a) The hamstring muscle group consists of the semimembranosus, semitendinosus, and biceps femoris muscles, with the biceps femoris long head being injured most often in high-speed running.[30] b) During the swing phase of high-speed running, the hamstrings are active, stretched (ΔL, change in length relative to upright stance) and absorbing energy from the swing limb, creating the potential circumstances for a lengthening contraction injury.[21] Reproduction of a) is with permission of Springer Science+Business Media, © 2008.

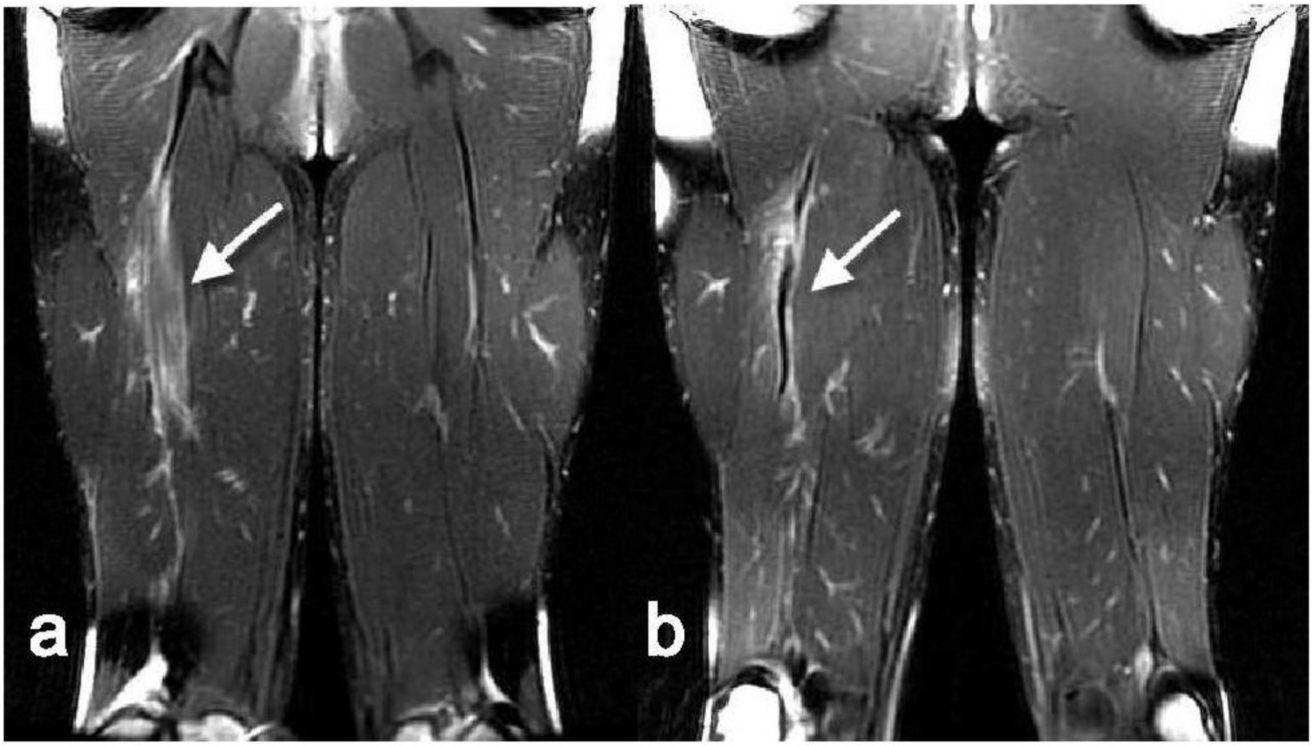

FIGURE 2.
T2-weighted coronal images at a) 10 days and b) 30 days following injury to the right biceps femoris long head sustained during high-speed running. Considerable edema and hemorrhage (high-intensity signal) are evident at the site of injury (arrow) on day 10 with persistent fluid remaining at day 30. In addition, a substantial amount of scar tissue (low-intensity signal) is present by day 30. Of note, this individual was cleared to return to sport 23 days after the injury.

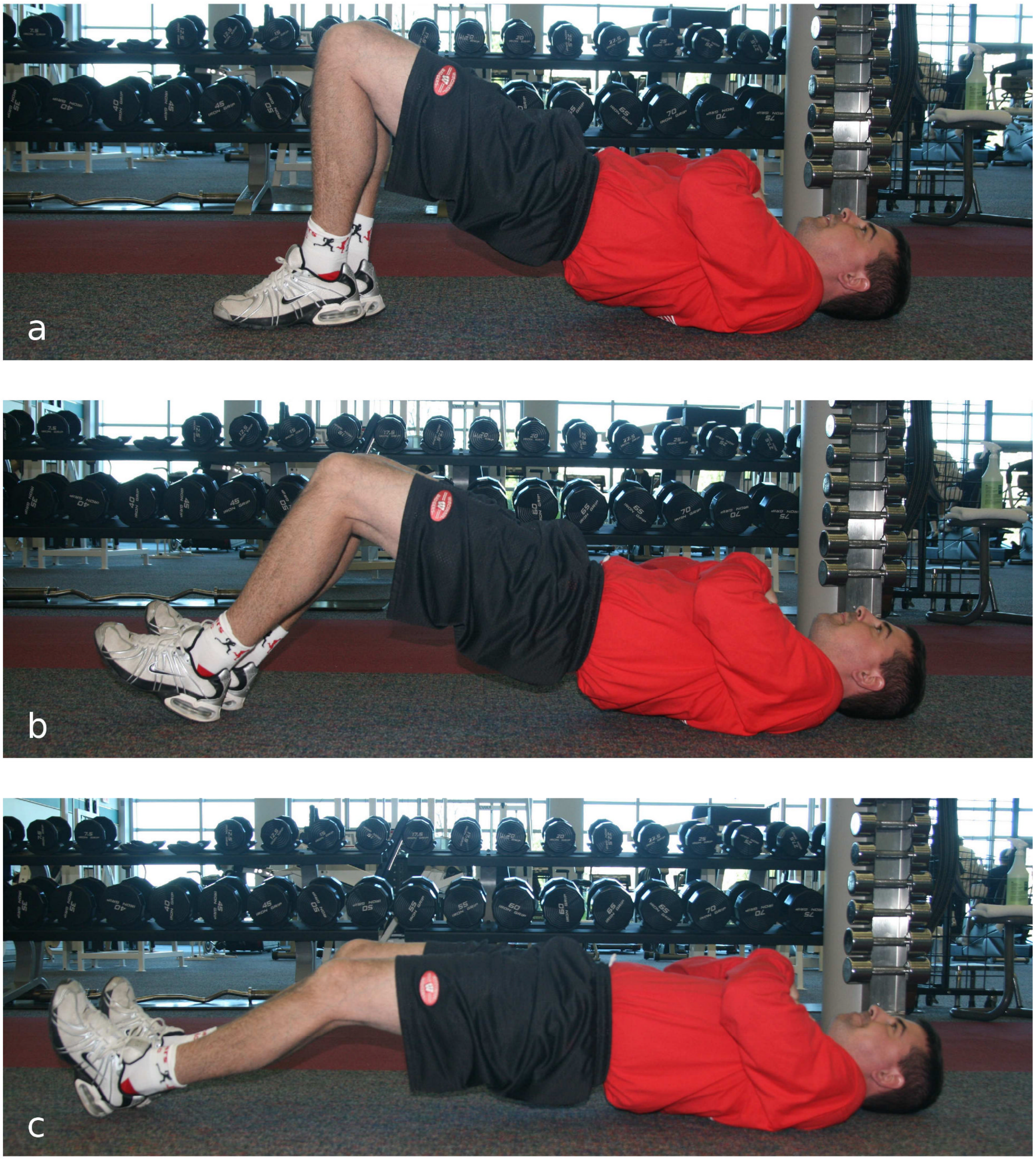

FIGURE 3.
Supine bent knee bridge walk out: starting in a) supine bridge position, b and c) progressively move feet away from hips while maintaining bridge position.

FIGURE 4.
Supine single limb chair-bridge: a) Starting with 1 leg on stationary object, b) raise hips and pelvis off ground.

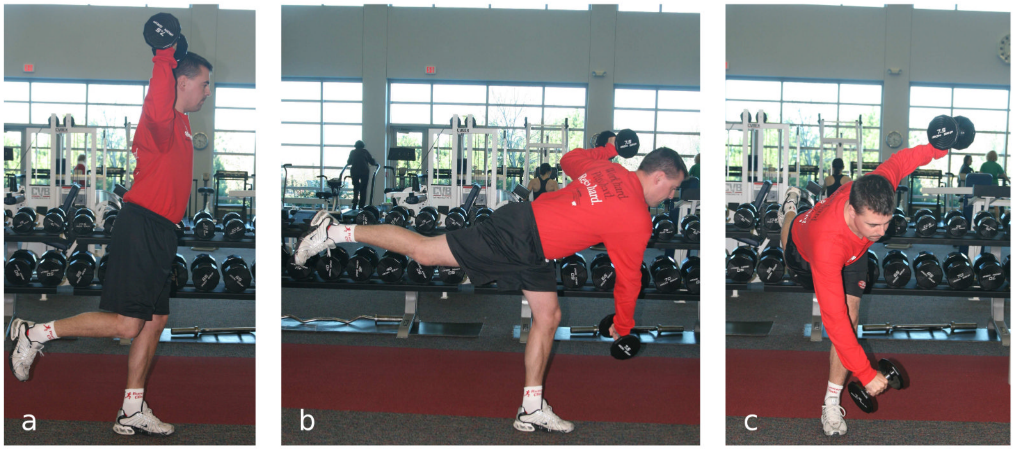

FIGURE 5.

Single limb balance windmill touches with dumbbells: Begin in a) single limb stance position with dumbbells overhead and b) perform windmill motion under control with end position of c) touching dumbbell to floor.

FIGURE 6.
Persistent scar tissue, depicted by low-intensity signal (arrow), is evident adjacent to the site of prior injury along the proximal musculotendon junction of the biceps femoris long head in the a) T2-weighted fast spin echo axial and b) recombined in-phase image acquired with 3D-IDEAL-SPGR* coronal views. Such scarring has been observed to persist on a long-term basis (5-23 months post-injury).[88] Reproduced with permission of Springer Science+Business Media, © 2008.
*Coronal images were obtained using a 3D T1-weighted spoiled gradient-echo (SPGR) chemical shift based water-fat separation technique known as IDEAL (Iterative Decomposition of water and fat with Echo Asymmetry and Least-squares estimation). Images shown are recombined water+fat (in-phase) images acquired and reconstructed with IDEAL.[81]

TABLE 1

Categories of hamstring strain injuries based on injury mechanism with associated findings from magnetic resonance imaging.[7,8]

Injury Mechanism	Sports or Activities	Involved Muscle(s)	Location	Distance from Ischial Tuberosity (cm)*	Length of Injury (cm) †
Running at maximal or near-maximal speed	sports involving high-speed running	primary - biceps femoris, long head secondary - semitendinosus	aponeurosis and adjacent muscle fibers, proximal > distal	6.7 ± 7.1 (range, -2.1-21.8)	18.7 ± 7.4 (range, 6.0-34.6)
Movement involving extreme hip flexion and knee extension	dancing or kicking	semimembranosus, proximal tendon	proximal tendon and/or musculotendon junction	-2.3 ± 0.8 (range, -3.4-1.1)	9.8 ± 5.0 (range, 2.7-17.2)

*distance between most caudal aspect of ischial tuberosity to most cranial aspect of injury.

†measured in cranial-caudal direction.

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TABLE 2

Typical acute presentation and outcomes of hamstring strain injuries based on injury mechanism.[7,8]

Injury Mechanism	Ecchymosis	Straight Leg Raise Deficit*	Knee Flexion Strength Deficit*	Level of Pain	Site of Maximum Pain† (cm)	Length of Painful Area‡ (cm)	Median Time to Pre-Injury Level (wks)§
Running at maximal or near-maximal speed	minimal	40%	60%	moderate	12 ± 6 (range, 5-24)	11 ± 5 (range, 5-24)	16 (range, 6-50)
Movement involving extreme hip flexion and knee extension	none	20%	20%	minor	2 ± 1 (range, 1-3)	5 ± 2 (range, 2-9)	50 (range, 30-76)

* percent deficit of injured limb compared to non-injured limb

† distance from point of maximum palpatory pain to the ischial tuberosity

‡ measured in cranial-caudal direction

§ time needed for athletic performance to return to pre-injury level

TABLE 3

Common signs and symptoms of a hamstring strain injury compared to those referred to the posterior thigh from another source. Modified from Brukner and Khan.[18]

Symptom/Sign	Hamstring Strain Injury	Referred to Posterior Thigh
Onset	Sudden	Sudden or gradual
Pain	Minimal to severe	Minimal to moderate pain May describe feeling of tightness or cramping
Function	Difficulty walking or running	Able to walk or run with minimal change in symptoms during the activity; may even reduce symptoms during the activity but increase after
Local Hematoma, Bruising	Likely with more severe injuries	None
Palpation	Substantial local tenderness Possible defect at site of injury	Minimal to none
Decrease in Strength	Substantial	Minimal to none
Decrease in Flexibility	Substantial	Minimal
Slump Test	Negative	Frequently positive
Gluteal Trigger Points	Palpation does not influence hamstring symptoms	Palpation may reproduce hamstring symptoms
Lumbar/Sacroiliac Exam	Occasionally abnormal	Frequently abnormal
Local Ultrasound or Magnetic Resonance Image	Abnormal, except for very mild strains	Normal