Journal of Athletic Training 2022;57(2):125–135
doi: 10.4085/1062-6050-0707.20
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Hamstring Strain Injury Rehabilitation

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Hamstring strain injuries are common among athletes and often require rehabilitation to prepare players for a timely return to sport performance while also minimizing reinjury risk. Return to sport is typically achieved within weeks of the injury; however, subsequent athlete performance may be impaired, and reinjury rates are high. Improving these outcomes requires rehabilitation practitioners (eg, athletic trainers and physical therapists) to understand the causes and mechanisms of hamstring strain injury, know how to perform a thorough clinical examination, and progress loading to the site of injury safely and effectively. This narrative review discusses current clinical concepts related to these aspects of rehabilitation for hamstring strain injury, with the aim of helping practitioners improve athletes' outcomes. Collectively, this knowledge will inform the implementation of evidence-based rehabilitation interventions.

Key Points

- Mechanisms of hamstring strain injury likely involve a combination of high muscle-tendon unit forces (active or passive), extensive muscle-tendon unit lengthening beyond moderate lengths, and high-velocity movements.
- Returning to high-speed running is arguably the most important aspect of rehabilitation, given that it is fundamental to performance in many sports and a common mechanism for hamstring strain injury.
- Eccentric hamstring exercises and hip-extensor strengthening should also be implemented during rehabilitation to prepare athletes for the demands of high-speed running and address deficits in strength and muscle structure.

Rehabilitation practitioners (eg, athletic trainers and physical therapists) regularly manage athletes who have sustained acute hamstring strain injuries (HSIs). The aim of HSI rehabilitation is to prepare athletes for return to sport (RTS) performance as soon as possible while also mitigating their reinjury risk. Athletes typically complete rehabilitation and RTS within 3 weeks of HSI[1]; however, reinjuries frequently occur soon after RTS,[2] and subsequent performance may be impaired.[3] Therefore, rehabilitation practitioners need to be cognizant of current evidence-based practices so that athletes have the best opportunity for a full recovery.

This narrative review presents a brief overview of the causes and common mechanisms of HSI, the important features of the clinical examination, a detailed breakdown of different rehabilitation interventions and implementation considerations, and outcome measures to guide rehabilitation and RTS prognosis; it also identifies 2 key questions to inform future directions for research and practice. The Strength of Recommendation (SOR) Taxonomy[4] was applied during open discussion among all authors to reach consensus on our recommendations related to clinical examination, rehabilitation interventions, and outcome measures. In this article, we aim to provide practitioners with the contemporary, evidence-based information necessary to deliver best-practice rehabilitation for athletes with HSIs, promoting expeditious RTS performance while minimizing the risk of recurrent injury.

CAUSES AND MECHANISMS

Whether HSI occurs after accumulated repetitive microscopic muscle damage or in response to a single aberrant event exceeding the limits of the muscle-tendon unit is debatable.[5] Some HSIs may result from an ongoing decline in tissue integrity due to repetitive damage, leaving the athlete vulnerable to an innocuous inciting event (eg, submaximal velocity running). In other instances, HSI may be caused by a single macrotraumatic event (ie, forceful and rapid hip flexion), irrespective of underlying tissue integrity. Either way, HSI mechanisms likely involve a combination of (1) high muscle-tendon unit forces (active or passive), (2) muscle-tendon unit lengthening beyond moderate lengths, and (3) high-velocity movements.[6,7] Whether all 3 factors are necessary for an athlete to sustain an HSI remains unclear. Nonetheless, these causes should be in the forefront of the practitioner's mind when developing both HSI prevention and rehabilitation programs.

In a sporting context, the most common mechanism of HSI is high-speed running, followed by movements involving forceful and extensive hamstring lengthening, such as kicking.[8] During high-speed running, the terminal

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Table. Differential Diagnosis and Common Clinical Presentation of Possible Causes of Posterior Thigh Pain Other Than Hamstring Strain Injury

Differential Diagnosis	Common Clinical Presentation
Proximal hamstring tendon avulsion	Severe acute-onset pain occurs near the ischial tuberosity, usually due to forceful hip flexion with full knee extension, such as a fall while waterskiing. Athlete may have a palpable defect in the proximal hamstring tendon and significant bruising along the posterior thigh.
Proximal hamstring tendinopathy	Gradual onset of pain near the ischial tuberosity is provoked by repetitive loading of the proximal hamstring tendon. More common in middle-aged or older adults, particularly those who participate in activities with repetitive loading, such as long-distance running.
Lumbar spine radiculopathy	Posterior thigh pain is referred from the lower back and related to the forward-slumped posture due to sciatic nerve or lumbar nerve-root compression.
Adductor muscle injury	Acute- or gradual-onset pain is close to the posterior thigh but slightly more medial. Acute mechanisms include acceleration, change of direction, or kicking. Pain provocation during isometric adductor squeeze or hip-abduction range-of-motion testing may help differentiate it from hamstring injury.

swing phase is considered most injurious.[7,9] In the second half of the swing, the hamstring are active, rapidly lengthening, and absorbing energy to decelerate the limb in preparation for foot contact.[6] Hamstring muscle force increases approximately 1.3-fold as running velocity increases from 80% to 100% of maximum and the greatest muscle-tendon unit stretch is incurred by the long head of the biceps femoris.[10] These findings may explain why the long head of the biceps femoris is the most injured hamstring muscle,[11] often during high-speed running.

CLINICAL EXAMINATION

When athletes experience acute-onset posterior thigh pain in response to a common mechanism of HSI, the clinical examination is less about diagnosis and more about the rehabilitation needs or RTS prognosis.[12,13] Athletes presenting with posterior thigh pain resulting from either a mechanism not typical of HSI or a more chronic onset require a differential diagnosis to either confirm or rule out the presence of other pathologies (Table). In this section, we highlight the important features of an initial clinical examination of HSIs in athletes.

Subjective History

In our collective clinical experiences, athletes with a suspected HSI typically report the sudden onset of posterior thigh pain, sometimes accompanied by an audible or sensory pop, causing the immediate cessation of activity. Athletes should be asked to rate their pain at the time of suspected HSI, which is associated with the RTS prognosis[12] and may be used as a reference point when monitoring symptoms throughout rehabilitation. Recording a thorough history of the athlete's injuries before this incident is important, as previous HSI increases the risk of future HSI by 2.7 times[14] and recurrence at the site is common in the weeks after RTS.[2] Concurrent or previous injuries to other areas, particularly the lower back, hip or groin, and knee, should also be noted, as these findings could alter the clinical examination or rehabilitation protocol. *SOR: A*

Palpation of the Injured Area

With the athlete lying prone and the knees in full extension, the practitioner can palpate the posterior thigh to assess defects in the muscle-tendon unit and identify the possible injury site by establishing the point of maximal pain provocation. Distance from the ischial tuberosity to the site of maximal pain provocation by palpation and the total length of palpable pain should be measured and monitored throughout rehabilitation. Palpable pain that is closer to the ischial tuberosity or of greater total length has some association with an increased duration of HSI rehabilitation.[13,15] *SOR: B*

Range-of-Motion Testing

Hip-flexion and knee-extension range of motion (ROM) should be evaluated during the clinical examination to determine hamstring flexibility and tolerance to muscle lengthening. In our experience, pain may limit the accurate assessment of actual muscle-tendon unit extensibility, but ROM comparison with the contralateral uninjured limb may still provide an indication of HSI severity.[8] Between-limbs deficits in knee ROM and pain during the active knee-extension tests are useful measures in providing a prognosis for RTS[16] and the progression of running intensity throughout HSI rehabilitation.[13] The active knee-extension test can be performed with the hip flexed to either 90° or the maximal angle of flexion possible for each athlete[13] (Figure 1).

Assessment of hip-flexor flexibility and ankle-dorsiflexion ROM may also be warranted, as these measures have some association with HSI risk.[17,18] In a prospective study of Australian rules footballers, the HSI risk increased by 15% for every 1° increase in hip flexion during the modified Thomas test.[17] The average dorsiflexion lunge test distance reported by van Dyk et al[18] was less in soccer players who sustained HSIs (9.8 ± 3.1 cm) than in their uninjured counterparts (11.2 ± 3.1 cm). However, practitioners must be aware that these group-level associations are limited in their ability to predict HSI at the individual level. *SOR: B*

Strength Testing

Hamstring strength is usually evaluated during isometric contractions at the initial clinical examination,[19] and practitioners should ask athletes to rate their pain on a numeric rating scale (range = 0–10) during these tests.[20] Strength can be objectively measured if practitioners have access to equipment such as a handheld dynamometer,[21] load cells,[22] or force plates.[23] Practitioners without access to such equipment may consider using manual muscle testing to subjectively characterize strength, but we encourage exploration of relatively cheap alternatives, such as crane scales, which can objectively measure force.[24]

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Figure 1. Active knee-extension tests performed with the athlete lying supine and holding the thigh at either A, 90° or B, maximal hip flexion. Range of motion can be assessed by placing an inclinometer on the anterior tibial border and instructing the athlete to extend the knee until the maximal tolerable stretch is achieved.

Given the biarticular nature of the hamstring, knee-flexion and hip-extension strength should be tested with the athlete lying both prone and supine (Figure 2), ideally with the hamstring in a lengthened position,[19,21] which appears most useful for RTS prognosis.[12,13] Internal and external rotation of the tibia can be added to knee-flexion strength tests to differentiate between medial and lateral hamstring muscle injury, respectively.[25] Hip-extension strength can be assessed with the knee flexed to identify muscles other than the hamstring, such as the gluteus maximus, that require strengthening during rehabilitation.[26] Practitioners may also consider testing the strength of movements not involving the hamstring based on the athlete's injury history (eg, hip adduction in those with hip and groin pain[27]), which may inform exercise selection during rehabilitation. *SOR: A*

Magnetic Resonance Imaging

Beyond the subjective and physical clinical examinations mentioned, magnetic resonance imaging (MRI) may be used to confirm the HSI diagnosis by identifying the location and extent of tissue damage. Several MRI-based muscle-injury classification and grading systems have been proposed and applied to HSI to provide the RTS prognosis.[28] Prolonged RTS after HSI may occur when MRI scans show signs of tissue damage compared with no damage or if the proximal tendon is disrupted compared with intact.[29] However, further detailed classification or grading of HSI based on MRI findings appears to offer negligible prognostic value beyond that of routine clinical examination.[12]

An emerging recommendation is that HSI rehabilitation should be more conservative when MRI reveals disruption to the intramuscular tendon,[30,31] which was originally based on retrospective observations of prolonged RTS and greater recurrence rates with this diagnosis.[32] More recent prospective work[31] has shown that when rehabilitation is informed by the MRI diagnosis, recurrence rates can be kept similarly low across all types of HSI, but RTS time is prolonged by at least 2 weeks in athletes with intramuscular tendon disruption. This prolonged RTS was likely the result of the 2-week delay in progression of eccentric loading and running intensity that was applied to HSIs with intramuscular tendon disruption in the study by Pollock et al.[31] Yet

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Figure 2. Isometric strength testing of the knee flexors in A, prone position at 0° of hip and 15° of knee flexion and B, supine position at 90° of hip and 90° of knee flexion and of the hip extensors in C, prone position at 0° of hip and 90° of knee flexion and D, supine position at 0° of hip and 0° of knee flexion.

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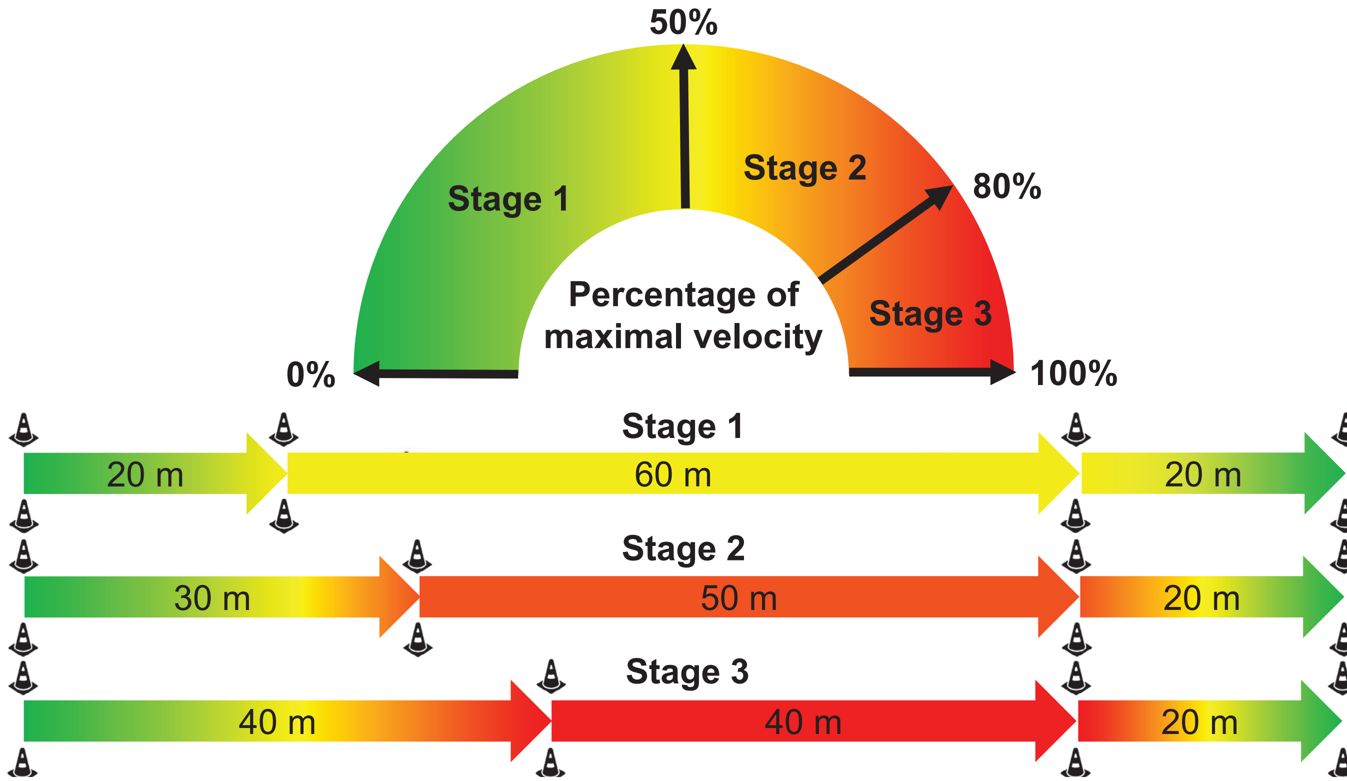

Figure 3. Example of 3-stage progressive running protocol over 100 m, accounting for greater acceleration distances and more gradual-intensity increases at higher percentages of maximal velocity.

it remains unclear if delayed progression of eccentric loading and running intensity is truly necessary in HSIs with intramuscular tendon disruption, as the rehabilitation practitioners were not blinded to the MRI findings.[31]

In a prospective study that did blind rehabilitation practitioners to the MRI findings, time to RTS and recurrence rates were not different when comparing HSIs with and those without intramuscular tendon disruption.[33] However, RTS was prolonged in participants with full-thickness intramuscular tendon disruption (31.6 ± 10.9 days) versus those with no disruption (22.2 ± 7.4 days) as well as in participants with waviness of the intramuscular tendon (30.2 ± 10.8 days) versus those with no waviness (22.6 ± 7.5 days).[33] Nonetheless, athletes can successfully RTS despite persistent signs of intramuscular tendon disruption on follow-up MRI scans without increasing their risk of reinjury.[34]

Based on current evidence, practitioners who can refer patients for MRI may be able to provide a more accurate prognosis for RTS by differentiating between HSIs with and those without visible tissue damage or proximal tendon involvement. Still, the need to alter rehabilitation and RTS decision making based purely on other MRI findings, such as intramuscular tendon disruption, requires further investigation before being recommended as standard practice. *SOR: B*

REHABILITATION

As soon as HSI has been confirmed, rehabilitation interventions aimed at preparing the athlete for a timely, safe, and effective RTS should be implemented without delay. In this section, we discuss the current evidence related to different exercise interventions and passive treatments used in HSI rehabilitation and considerations for their implementation.

Exercise Interventions

Progressive Running. A progressive return to high-speed running and sprinting is likely the most important aspect of rehabilitation, given that it is fundamental to performance in many sports and a common HSI mechanism. Figure 3 provides an example of a 3-stage progressive running protocol based on our collective clinical experience, understanding of biomechanical demands placed on the hamstring during running,[6,10] and application of similar protocols in HSI rehabilitation.[20,35] Stage 1 can be safely introduced after athletes can walk with minimal pain (eg, pain ≤4 on a numeric rating scale ranging from 0 to 10),[20] progressing from a slow jog (approximately 25% of maximal velocity) to moderate-speed running (approximately 50% of maximal velocity) as tolerated.[35] When moderate-speed running is tolerated, athletes can gradually progress through stage 2 but should only advance to stage 3 when high-speed running (approximately 80% of maximal velocity) can be performed without pain to minimize the HSI risk. During stage 3, progression toward maximal sprinting (100% of maximal velocity) should occur in relatively small increments (approximately 5%) to account for the substantial increase in negative (ie, eccentric) work required by the hamstring at running intensities >80% of maximal velocity.[10]

When high-speed running and sprinting have been achieved, subsequent exposure during HSI rehabilitation and RTS should be individualized to the needs of each

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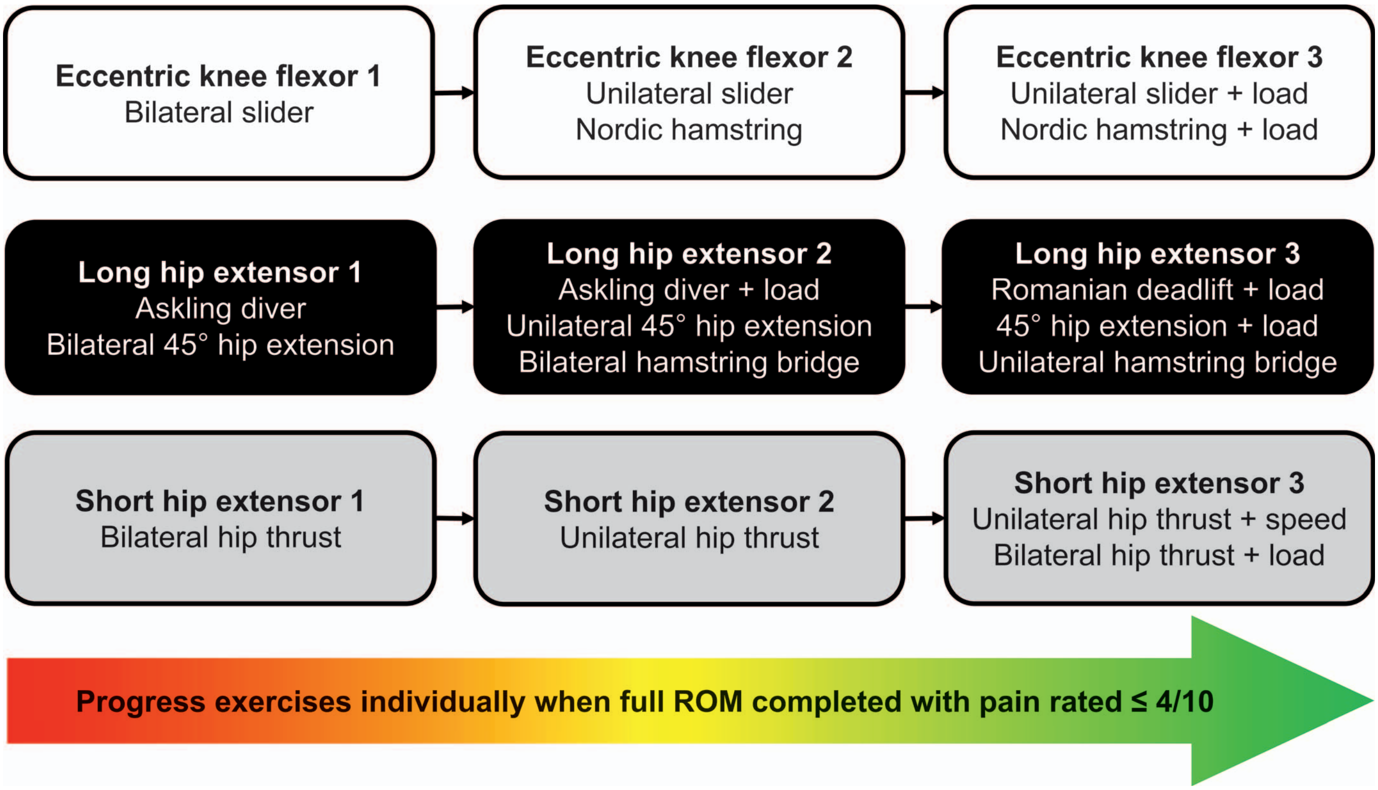

Figure 4. Example of progression of exercises targeting eccentric knee-flexion (white) and hip-extensor strength at long (black) and short (gray) hamstring muscle lengths. Abbreviation: ROM, range of motion.

athlete. Where possible, large spikes in high-speed running volume should be avoided to reduce the subsequent HSI risk.[36] The emergence and availability of wearable sensors (eg, global positioning systems, inertial measurement units) and other technologies (eg, timing gates, smartphone apps) make quantifying progressive running during HSI rehabilitation easier.[37] Practitioners can use these approaches to gather outcome measures at RTS to objectively individualize running progressions, safely reintegrate athletes into regular training, and prepare them for sport performance. *SOR: A*

Eccentric Hamstring Exercises. Eccentric hamstring exercises are a common HSI rehabilitation intervention to prepare athletes for the demands of high-speed running and address deficits in strength and muscle structure. Emphasizing mainly eccentric actions and hamstring lengthening via the extender, diver, and glider exercises, the Askling L-protocol reduced RTS time compared with conventional[15] and multifactorial[38] interventions. However, none of the Askling L-protocol exercises load the hamstring to a high intensity during eccentric contractions,[39] and high-intensity loading appears to be a key component of interventions proven to increase hamstring strength, lengthen long head of the biceps femoris muscle fascicles, and reduce the HSI risk.[40,41] As deficits in hamstring strength and long head of the biceps femoris muscle fascicle length are seen after RTS,[42] more progressive eccentric loading, such as the Nordic hamstring exercise (NHE), should be implemented during rehabilitation.

Although eccentric loading is frequently recommended as a rehabilitation intervention, the challenge for practitioners is knowing how and when to safely introduce exercises such as the NHE after HSI. Eccentric hamstring exercises are often avoided in the early stages of HSI rehabilitation and only introduced after pain and between-limbs strength deficits during isometric knee flexion have resolved.[35,38] Nevertheless, eccentric loading can be safely progressed based on individual exercise performance, regardless of pain and between-limbs strength deficits during isometric knee flexion after acute HSI.[20] For example, the submaximal bilateral eccentric slider exercise can be introduced at the very start of HSI rehabilitation (Figure 4), and when athletes can perform this exercise through full ROM, they can progress to a unilateral variation and begin the NHE (see Supplemental Video 1, available online at http://doi.org/10.4085/1062-6050-0707.20.S1).[20] This progressive approach to eccentric loading has been shown to increase hamstring strength and long head of the biceps femoris muscle fascicle length in relatively brief periods of rehabilitation after acute HSI.[20] Examples of these eccentric hamstring exercises and descriptions of when they should be introduced and progressed on an individual basis during HSI rehabilitation are provided in Figure 4 and Supplemental Video 1. *SOR: A*

Hip-Extensor Strengthening. In addition to eccentric knee-flexor exercises, hip-extension exercises should be used to load the hamstring at longer muscle lengths. Submaximal exercises, such as the Askling diver,[15] can be introduced at the start of HSI rehabilitation (Figure 4) before progressing to hamstring bridges,[20] 45° hip extensions,[41] or Romanian deadlifts (see Supplemental Video 2, available online at http://doi.org/10.4085/1062-6050-0707.20.S2). Apart from the hamstring, single-joint hip extensors, such as the gluteus maximus and adductor magnus,

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should be targeted if clinical examination shows weakness in these muscles, as they are key contributors to horizontal force production during sprint acceleration.[43] These single-joint muscles may be preferentially loaded over the injured hamstring during HSI rehabilitation by performing hip-extension exercises with greater knee-flexion angles.[26,44] Bilateral body-weight hip thrusts can be introduced at the onset of rehabilitation (Figure 4) and progressed to unilateral, loaded, and explosive variations (see Supplementary Video 3, available online at http://doi.org/10.4085/1062-6050-0707.20.S3), which have been linked to increased hip-extensor strength and improved sprinting performance in uninjured athletes.[45] Figure 4 and Supplemental Videos 2 and 3 supply examples of these hip-extensor strengthening exercises and describe when they should be introduced and progressed on an individual basis during HSI rehabilitation. *SOR: B*

Hamstring Flexibility Exercises. Exercises aimed at improving hamstring flexibility are regularly prescribed during rehabilitation to address deficits in hip-flexion and knee-extension ROM seen immediately after HSI.[46] However, these acute ROM deficits typically recover within the first 2 weeks after HSI[46] and may not require direct intervention. Yet hamstring flexibility exercises may be required if deficits persist during rehabilitation, as greater deficits in active knee-extension ROM at RTS have been associated with an increased risk of subsequent HSI.[47] Recovery of active knee-extension ROM can be slightly accelerated by implementing passive hamstring stretching 4 times per day, compared with once daily, starting at 48 hours after HSI.[16] Other hamstring flexibility exercises prescribed in HSI rehabilitation include supine active knee extensions[15] and dynamic hamstring mobility exercises,[38] although the effectiveness of these interventions is not clear. *SOR: B*

Progressive Agility and Trunk Stability Exercises. Exercises proposed to improve agility and trunk stability came to prominence after they were shown to lead to fewer reinjuries versus a relatively conservative hamstring strengthening and stretching intervention during HSI rehabilitation.[48] In a subsequent HSI rehabilitation study, RTS time and reinjury rates were no different between progressive agility and trunk stability (PATS) exercises and an intervention emphasizing progressive running and eccentric strengthening.[35] The purported benefits of PATS exercises are that they promote controlled early loading through frontal-plane movements while avoiding end-range hamstring lengthening.[48] It has also been argued that PATS exercises target other muscles of the lumbopelvic region, which could reduce the stretch placed on the hamstring during high-speed running, at least according to biomechanical models.[10] Although these potential benefits have not been directly investigated after implementing PATS exercises, relative success in achieving timely RTS and acceptable rates of recurrence[35,48] strengthens this otherwise theoretical rationale for their inclusion in HSI rehabilitation. *SOR: B*

Running Technique Drills. Practitioners may implement running technique drills as tolerated during the early stages of HSI rehabilitation to replicate discrete phases of the sprinting gait cycle at reduced intensities and in a controlled environment. Running technique drills are perceived to reduce potentially unwanted movements, such as excessive anterior pelvic tilt, which is often linked to a risk of HSI because of increased hamstring length in this position. Some prospective evidence has shown an elevated HSI risk in athletes who sprint with greater anterior pelvic tilt and lateral trunk flexion[49] or less gluteus maximus and trunk muscle activity.[50] Yet, similar to PATS exercises, no direct evidence supports the use of technique drills to reduce HSI risk, improve running performance, or alter any other rehabilitation outcomes. Therefore, technique drills should be viewed as a nonessential accessory to progressive running that may be implemented if a sound clinical or performance-oriented rationale is provided. *SOR: C*

Passive Treatments

Platelet-Rich Plasma Injections. Some athletes may receive platelet-rich plasma injection therapy during HSI rehabilitation, depending on their access to resources and the practices of medical personnel involved in their management. Platelet-rich plasma injections have been suggested to enhance tissue healing and have been evaluated in the treatment of acute muscle injuries, with multiple studies including athletes with HSIs.[51] In a recent meta-analysis, Seow et al[51] showed no reduction in the RTS time or reinjury rate when platelet-rich plasma injections were added to exercise interventions during HSI rehabilitation. They also reported a lack of consensus on the timing, volume, and composition of platelet-rich plasma injections,[51] and there is potential for resulting muscle soreness, which could affect exercise rehabilitation. Platelet-rich plasma injections appear, at best, to be a nonharmful yet ineffective treatment in accelerating RTS or mitigating the subsequent HSI risk. *SOR: A*

Manual Therapy. Evidence endorsing manual therapy as a rehabilitation intervention after HSI is scarce. Acute increases in knee-flexor torque have been observed after sacroiliac-joint mobilizations were applied to individuals with a recent HSI, but these findings were limited by preintervention differences between those who did and those who did not receive this treatment.[52] Lumbar spine facet-joint mobilizations and soft tissue massage were included in a multifactorial HSI rehabilitation algorithm; fewer reinjuries were noted but RTS was slightly prolonged compared with the Askling L-protocol exercise intervention.[38] Mendiguchia et al[38] did not assess outcomes often thought to be influenced by manual therapies (eg, pain or ROM), and the extensive nature of the rehabilitation algorithm made it difficult to know if these passive interventions were of any value.[38] In the absence of clear evidence, practitioners need to consider the potential time cost of implementing manual therapies during HSI rehabilitation against any perceived benefit of these interventions. *SOR: C*

Implementation Considerations

Implementing any rehabilitation intervention requires careful consideration of factors both intrinsic (eg, age and injury history) and extrinsic (eg, pressure to expedite RTS) to the athlete. Older athletes with a history of HSI or injuries to other areas may require longer rehabilitation times because of the need to address preexisting deficits and account for their increased risk of subsequent injury.[14] Elite and professional athletes may be under more pressure to

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RTS, which can truncate HSI rehabilitation. Practitioners must consider these factors in various aspects of rehabilitation in collaboration with coaches, the athlete, and other stakeholders in the shared RTS process.[53]

As rehabilitation progresses to include more sport-specific training and high-speed running, it is important to avoid neglecting key exercise interventions. Complete cessation of eccentric hamstring exercise leads to shortening of long head of the biceps femoris muscle fascicles,[54] which can be averted by continuing to perform these interventions, even at low training volumes.[55] The effects of fatigue and muscle soreness must be considered when implementing both high-speed running and eccentric hamstring exercises. For example, eccentric hamstring exercises may cause fatigue and muscle soreness, which make high-speed running difficult during the subsequent 48 hours. The timing of these interventions may depend on the number of days an athlete can complete rehabilitation around other commitments. We advise that, if these interventions are prescribed for the same day, high-speed running should be performed before eccentric hamstring exercise to ensure that maximal sprinting is not compromised by fatigue or muscle soreness.

OUTCOME MEASURES

Throughout rehabilitation, follow-up clinical examinations and additional outcome measures should be used to monitor an athlete's recovery and inform the shared RTS decision-making process.[53] In this section, we briefly cover pain, patient-reported outcomes, apprehension, and eccentric hamstring strength, along with assessment tools that can be used during HSI rehabilitation.

Pain

Rehabilitation is most commonly progressed after HSI when the athlete reports no pain during exercise, clinical examination, or functional tasks.[56] A numeric pain rating scale (range = 0–10) can be used to evaluate the level of pain reported by the athlete. As opposed to the conventional practice of pain avoidance,[56] allowing exercise in the presence of pain rated $\leq$4 on this scale during HSI rehabilitation is safe and may allow earlier exposure to and progression of beneficial stimuli.[20] *SOR: B*

Patient-Reported Outcomes

The importance of patient-reported outcomes is highlighted by findings that RTS prognosis was associated with self-predicted time to RTS and the number of days taken for the athlete to begin pain-free walking.[12,57] In addition to asking the athlete these questions, practitioners can use the Functional Assessment Scale for Acute HSIs, a self-administered questionnaire, to assess the severity and effect of symptoms.[58] Initial research into psychometric testing has shown this scale has good reliability and validity,[58] but the minimal clinically important difference is unknown. *SOR: B*

Apprehension

The Askling H-test can be used to evaluate an athlete's apprehension during rapid hamstring lengthening by performing explosive unilateral hip flexion with the knee fixed in extension by a brace.[59] An electric goniometer can also be used to quantify hip-flexion ROM during the Askling H-test, which may identify deficits that are otherwise undetected via clinical examinations of hamstring flexibility during the later stages of HSI rehabilitation.[59] Implementing the Askling H-test as a final RTS criterion is associated with a low risk of reinjury but prolonged HSI rehabilitation time,[56] and practitioners may need to consider which outcome is a higher priority for each athlete. *SOR: B*

Eccentric Hamstring Strength

Depending on resources, eccentric hamstring strength can be objectively tested using several tools, including isokinetic dynamometry[60] and handheld dynamometry,[21] or during the NHE using externally fixed load cells.[61] The evidence for eccentric hamstring strength as a risk factor for HSI is conflicting,[14] and asymmetries after RTS were not associated with reinjury.[60] Eccentric hamstring strength is associated with sprint acceleration mechanics,[43] which are important for performance in running-based sports.[62] Therefore, maximizing eccentric hamstring strength and relative between-limbs symmetry is currently considered a desirable rehabilitation outcome for sports performance but not an essential RTS criteria to reduce the reinjury risk.[63] *SOR: B*

FUTURE DIRECTIONS FOR PRACTITIONERS AND RESEARCHERS

Despite the proliferation of HSI research in recent times, key questions related to improving rehabilitation outcomes for athletes remain unanswered. In this section, we identify 2 key questions for both practitioners and researchers to consider in shaping the future directions of HSI rehabilitation.

Are There Key Rehabilitation Interventions or Is a Multifactorial Approach Essential?

The concept of multifactorial rehabilitation is logical, given the plethora of known and potential contributors to HSI risk and athletic performance. Implementing multiple intervention types increases the likelihood of reducing the HSI risk and improving athlete performance but requires more time to implement during rehabilitation, which could delay RTS.[38] Practitioners dealing with time constraints need to prioritize rehabilitation interventions that actively contribute to improved outcomes for athletes over those that may add little benefit. However, it can be difficult to identify the most effective interventions when these are implemented as just one part of a multifactorial approach to rehabilitation. In the future, researchers need to better delineate the individual components of HSI rehabilitation to identify key interventions and their minimum effective dosage to improve outcomes for athletes.

Unfortunately for practitioners, many interventions still lack an evidence base to support or refute their implementation during HSI rehabilitation. Still, the absence of evidence does not necessarily equate to the evidence of absence. In these cases, practitioners need to carefully apply critical thinking and consider a sound rationale for

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why a proposed intervention may improve HSI rehabilitation outcomes. For example, direct evidence may not demonstrate that a certain intervention improves outcomes when implemented during HSI rehabilitation. Instead, evidence from uninjured athletes may indicate that an intervention leads to desirable adaptations, which is presumed to lead to improved rehabilitation outcomes.

Can We Assess The Reinjury Risk at Return to Sport?

Another challenge of HSI rehabilitation is uncertainty regarding which modifiable variables, if any, are associated with the reinjury risk when assessed at RTS. Deficits in hamstring muscle structure and function have been observed at the time of RTS or even later after HSI,[42,60] but currently little evidence addresses whether these variables are associated with reinjury. When measured at RTS, the risk of reinjury increased with greater between-limbs deficits in active knee-extension ROM and isometric hamstring strength[47] but was unaltered by residual deficits on MRI scans[34] or isokinetic strength.[60] These results were limited to relatively small sample sizes, highlighting the need to conduct multisite studies and use a standard suite of RTS assessments over several years to identify variables associated with the reinjury risk.

Until this research is conducted, practitioners must be cognizant of the limited evidence available and employ a pragmatic, heuristic approach that considers the need for athletes to be able to (1) exceed preinjury levels (if these data exist) in variables thought to be factors contributing to the initial injury (eg, long head of the biceps femoris muscle fascicle length), (2) allow for the resolution of between-limbs asymmetry that arises in response to the pathology (eg, ROM and strength asymmetry), and (3) ensure sufficient exposure to key variables required to maximize performance at RTS (eg, high-speed running). Although a clear consensus related to RTS is lacking, resolution of pain, symmetry ($<$10%–15% asymmetry) with ROM and strength testing, completion of on-field performance and functional testing, and confirmed psychological readiness are the most pragmatic variables for practitioners to take into account.[63] Furthermore, it is widely accepted that the RTS process should involve shared decision making among the player, team medical staff (physicians, athletic trainers, physical therapists), and strength and performance staffs.[53]

FINANCIAL DISCLOSURE

David A. Opar, PhD, is a co-inventor on a patent, filed by the Queensland University of Technology (QUT), for a field-testing device of eccentric hamstring strength, which is now known commercially as the NordBord. Dr Opar has received revenue distributions from QUT based on revenue that QUT has generated through the commercialization of his intellectual property.

Dr Opar is a minority shareholder in Vald Performance Pty Ltd, the company responsible for commercialization of the NordBord, among other devices. He has received research funding from Vald Performance for work unrelated to the current manuscript and is also the Chair of the Vald Performance Research Committee, a role that is unpaid. Dr Opar has family members who are minor shareholders or employees (or both) of Vald Performance.

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SUPPLEMENTAL MATERIALS

Supplemental Video 1. Eccentric knee-flexor exercise options and progressions.
http://doi.org/10.4085/1062-6050-0707.20.S1

Supplemental Video 2. Long hip-extensor exercise options and progressions.
http://doi.org/10.4085/1062-6050-0707.20.S2

Supplemental Video 3. Short hip-extensor exercise options and progressions.
http://doi.org/10.4085/1062-6050-0707.20.S3

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