doi: 10.4085/1062-6050-0707.20

**Title:** Current clinical concepts: hamstring strain injury rehabilitation

**Authors:** Jack T. Hickey, AEP, PhD⁵; David A. Opar, PhD⁵,²; Leigh J. Weiss, ATC, PT, DPT³; Bryan C. Heiderscheit, PT, PhD, FAPTA⁴

¹School of Behavioural and Health Science, Australian Catholic University, Melbourne, Australia

²Sports Performance, Recovery, Injury and New Technologies Research Centre

³New York Football Giants, East Rutherford, NJ, USA

⁴University of Wisconsin-Madison, Madison, WI, USA

**Corresponding Author:** Jack T. Hickey, AEP, PhD

School of Behavioural and Health Sciences, Australian Catholic University

115 Victoria Parade, Fitzroy, VIC 3065 Australia

+61 03 9953 3038

jack.hickey@acu.edu.au

No ethics approval was required for this clinical commentary.

No funding was provided for the development of this clinical commentary.

Dr David Opar is listed as a co-inventor on a patent filed for a field-testing device of eccentric hamstring strength (PCT/AU2012/001041.2012) as well as being a minority shareholder in Vald Performance Pty Ltd, the company responsible for commercialising the device. Dr Opar is also the Chair of the Vald Performance Research Committee, a role that is unpaid. Dr Opar has received funding from Vald Performance for research unrelated to the current manuscript. Dr Opar’s brother and brother-in-law are employees of Vald Performance. Apart from the above, the authors certify that they have no affiliations with or financial involvement in any organization or entity with a direct financial interest in the subject matter or materials discussed in the article.
Readers should keep in mind that the in-production articles posted in this section may undergo changes in the content and presentation before they appear in forthcoming issues. We recommend regular visits to the site to ensure access to the most current version of the article. Please contact the JAT office (jat@slu.edu) with any questions.
Current clinical concepts: hamstring strain injury rehabilitation

Abstract

Hamstring strain injuries are common among athletes and often require rehabilitation to prepare for timely return to sport performance, while also minimizing re-injury risk. Return to sport is typically achieved within weeks of the injury, but subsequent athlete performance may be impaired and re-injury rates are high. Improving these outcomes requires rehabilitation practitioners (e.g. Athletic Trainers and Physical Therapists) to understand the etiology and mechanisms of hamstring strain injury; know how to perform a thorough clinical examination; and progress loading to the site of injury in a safe and effective manner. This narrative review discusses current clinical concepts related to these aspects of hamstring strain injury rehabilitation, with the aim of helping practitioners improve athlete outcomes. Collectively, this knowledge will inform the implementation of evidence-based rehabilitation interventions.

Key points

- Hamstring strain injury mechanisms 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 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
Introduction

Rehabilitation practitioners (e.g. Athletic Trainers and Physical Therapists) regularly manage athletes who have suffered acute hamstring strain injuries (HSIs). The aim of HSI rehabilitation is to prepare the athlete for a return to sport (RTS) performance as soon as possible, while also mitigating their re-injury risk. Athletes typically complete rehabilitation and RTS within three weeks of HSI, but re-injuries commonly occur soon after and subsequent performance may be impaired. Therefore, rehabilitation practitioners need to be cognizant of current evidence-based practices so athletes have the best opportunity for a full recovery.

This narrative review presents a brief overview of the etiology and common mechanisms of HSI; the important features of clinical examination; a detailed breakdown of different rehabilitation interventions and implementation considerations; outcome measures to guide rehabilitation and RTS prognosis; and identifies two key questions to inform future directions for research and practice. The strength of recommendation taxonomy (Table 1) was applied during open discussion between all co-authors, to reach consensus on our recommendations related to clinical examination, rehabilitation interventions and outcome measures. This narrative review aims to provide practitioners with 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.

Etiology and mechanisms

Knowing whether HSI occurs after accumulating repetitive microscopic muscle damage or in response to a single aberrant event exceeding limits of the muscle-tendon unit, is debatable. Some HSIs may result from an ongoing decline in tissue integrity due to repetitive damage leaving the athlete vulnerable to an innocuous inciting event (e.g., sub-maximal velocity running). In other instances, HSI may be caused by a single macro-traumatic event (i.e. 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.\textsuperscript{6, 7} Whether all three factors are necessary for an athlete to sustain an HSI remains unclear.
Nonetheless, these etiological factors should be front of mind for practitioners 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.\textsuperscript{8} During high-speed
running the terminal swing phase is considered most injurious.\textsuperscript{7, 9} During the second half of swing, the
hamstrings are active, rapidly lengthening and absorbing energy to decelerate the limb in preparation
for foot contact.\textsuperscript{6} Hamstring muscle force increases \textasciitilde 1.3-fold as running velocity increases from 80% to
100% of maximum and the greatest muscle-tendon unit stretch is incurred by the biceps femoris long
head.\textsuperscript{10} These findings may explain why biceps femoris long head is the most injured hamstring muscle,\textsuperscript{11}
often during high-speed running.

**Clinical examination**

When athletes have suffered acute onset posterior thigh pain in response to a common mechanism of
HSI clinical examination is less about diagnosis, but more relevant to inform practitioners about
rehabilitation needs or RTS prognosis.\textsuperscript{12, 13} Athletes presenting with posterior thigh pain that is either the
result of a mechanism not typical of HSI or more chronic onset will require differential diagnosis, to
either confirm or rule out the presence of other pathologies (Table 2). The following section highlights
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 sudden onset of
posterior thigh pain, sometimes accompanied by an audible or sensory pop, causing immediate
cessation of activity. Athletes should be asked to rate their pain at the time of suspected HSI, which is associated with RTS prognosis\textsuperscript{12} and may be used as a reference point when monitoring symptoms throughout rehabilitation. Recording a thorough history of the athlete’s injuries prior to this incident is important, as previous HSI increases risk of future HSI by 2.7 times,\textsuperscript{14} and recurrence at the same site is common in the weeks after RTS.\textsuperscript{2} Concurrent or previous injuries to other areas, particularly the lower back, hip/groin and knee should also be noted, as these findings could alter clinical examination or rehabilitation. \textit{Strength of recommendation: A}

\textbf{Palpation of the injured area}

With the athlete lying prone with knees in full extension, practitioners can palpate the posterior thigh to assess for defects in the muscle-tendon unit and identify the potential injury site by establishing 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 a greater total length, both have some association with increased duration of HSI rehabilitation.\textsuperscript{13, 15} \textit{Strength of recommendation: B}

\textbf{Range of motion testing}

Hip flexion and knee extension range of motion (ROM) should be assessed during clinical examination, to indicate hamstring flexibility and tolerance to muscle lengthening. In our experience, pain may limit accurate assessment of actual muscle-tendon unit extensibility, but ROM comparison to the contralateral uninjured leg may still provide an indication of HSI severity.\textsuperscript{8} Between leg deficits in knee ROM and pain during the active knee extension tests are useful measures to provide prognosis for RTS\textsuperscript{16} and progression of running intensity throughout HSI rehabilitation.\textsuperscript{13} The active knee extension test can be performed with the hip flexed to either 90° or maximal hip flexion ROM\textsuperscript{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. In a prospective study of Australian rules footballers, HSI risk increased by 15% for every 1° increase in hip flexion during the modified Thomas test. Average dorsiflexion lunge test distance was significantly less in soccer players who prospectively suffered HSIs (9.8 ± 3.1cm) compared to their uninjured counterparts (11.2 ± 3.1cm). However, practitioners must be aware that these group level associations are limited in their ability to predict HSI at the individual level. Strength of recommendation: B

**Strength testing**

Hamstring strength is usually assessed during isometric contractions during the initial clinical examination due to pain, which practitioners should ask athletes to rate on a 0 to 10 numeric rating scale during testing. Strength can be objectively measured if practitioners have access to equipment such as a hand-held dynamometer, load cells or force plates. Practitioners without access to such equipment may consider using manual muscle testing to subjectively evaluate strength, but we encourage exploration of relatively cheap alternatives, such as crane scales, which can objectively measure force.

Given the biarticular nature of the hamstrings, both knee flexion and hip extension strength should be tested with the athlete in prone and supine (Figure 2), ideally with the hamstrings in a lengthened position, which appears most useful for RTS prognosis. Internal and external rotation of the lower leg can be added to knee flexion strength tests, to differentiate between medial and lateral hamstring muscle injury, respectively. Hip extension strength can be assessed with the knee flexed to identify the need to strengthen muscles other than the hamstrings during rehabilitation, such as gluteus maximus. Practitioners may also consider assessing strength of movements not involving the
hamstrings based on the athlete’s injury history (e.g. hip adduction in those with hip and groin pain\textsuperscript{27}), which may inform exercise selection during rehabilitation. \textit{Strength of recommendation: A}

**Magnetic resonance imaging**

Beyond the subjective and physical clinical examinations mentioned above, magnetic resonance imaging (MRI) may be used to confirm 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 with the intention of providing RTS prognosis.\textsuperscript{28} There is evidence of prolonged RTS following HSI, when MRI shows visible signs of tissue damage compared to no damage, or if the proximal tendon is disrupted compared to intact.\textsuperscript{29} But further detailed classification or grading of HSI based on MRI findings appears to offer negligible prognostic value additional to routine clinical examination.\textsuperscript{12}

There is an emerging recommendation that HSI rehabilitation should be more conservative when MRI reveals disruption to the intramuscular tendon,\textsuperscript{30, 31} originally based on retrospective observations of prolonged RTS and greater recurrence rates with this diagnosis.\textsuperscript{32} More recent prospective work shows that when rehabilitation is informed by MRI diagnosis, recurrence rates can be kept similarly low across all types of HSI, but RTS time is prolonged by at least two weeks in athletes with intramuscular tendon disruption.\textsuperscript{31} This prolonged RTS is likely a result of the two week delay in progression of eccentric loading and running intensity applied to HSIs with intramuscular tendon disruption in this study.\textsuperscript{31} However, it remains unclear if delayed progression of eccentric loading and running intensity are truly necessary in HSIs with intramuscular tendon disruption, as rehabilitation practitioners were not blind to MRI findings.\textsuperscript{31}

In a prospective study that did blind rehabilitation practitioners to MRI findings, time to RTS and recurrence rates were not significantly different when comparing between HSIs with and without intramuscular tendon disruption.\textsuperscript{33} However, RTS was significantly prolonged when comparing between
participants with full-thickness intramuscular tendon disruption (31.6 ± 10.9 days) and those with no
disruption (22.2 ± 7.4 days) as well as waviness of the intramuscular tendon (30.2 ± 10.8 days) compared
to no waviness (22.6 ± 7.5 days).\textsuperscript{33} Athletes can, however, successfully RTS despite persistent signs of
intramuscular tendon disruption on follow-up MRI, without increasing their risk of re-injury.\textsuperscript{34}

Based on current evidence, practitioners with scope to refer for an MRI may be able to provide a more
accurate prognosis for RTS by differentiating between HSIs with and without visible tissue damage or
proximal tendon involvement. However, 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. \textit{Strength of recommendation: B}

\textbf{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. The following section discusses
the current evidence related to different exercise interventions and passive treatments used in HSI
rehabilitation and considerations for their implementation.

\textbf{Exercise interventions}

\textit{Progressive running}

A progressive return to high-speed running and sprinting is likely the most important aspect of
rehabilitation, given it is fundamental to performance in many sports and a common HSI mechanism.
Figure 3 provides an example three stage progressive running protocol, which is based on our collective
clinical experience, understanding of biomechanical demands placed on the hamstrings during running\textsuperscript{6,10} and application of similar protocols in HSI rehabilitation.\textsuperscript{20,35} Stage one can be safely introduced once
athletes can walk with minimal pain (e.g. pain ≤ 4/10),\textsuperscript{20} progressing from a slow jog (~25%) to
moderate-speed running (~50%), as tolerated.\textsuperscript{35} Once moderate-speed running can be tolerated,
athletes can gradually progress through stage two as tolerated, but only advance to stage three once
high-speed running (~80%) can be performed without pain, to minimise HSI risk. Within stage three
progression towards maximal sprinting (100%) should be done in relatively small increments (~5%) to
account for the substantial increase in negative (i.e. eccentric) work required by the hamstrings at
running intensities above 80% of maximal velocity.\(^1\)

Once high-speed running and sprinting has been achieved, subsequent exposure during HSI
rehabilitation and RTS should be individualized to the needs of each athlete. Where possible, large
spikes in high-speed running volume should be avoided to reduce subsequent HSI risk.\(^3\) The emergence
and availability of wearable sensors (e.g. global positioning systems, inertial measurement units) and
other technologies (e.g., timing gates, smart phone apps) make quantifying progressive running easier
during HSI rehabilitation.\(^3\) Practitioners can use these approaches to gather outcome measures at RTS
to objectively individualize running progressions, safely re-integrate athletes into regular training and
prepare them for sports performance. \textit{Strength of recommendation: A}

\textbf{Eccentric hamstring exercises}

To prepare for the demands of high-speed running and address deficits in strength and muscle
structure, eccentric hamstring exercises are a common HSI rehabilitation intervention. Emphasizing
mainly eccentric actions and hamstring lengthening via the extender, diver and glider exercises, Askling’s
L-protocol reduces RTS time compared to conventional\(^1\)\(^5\) and multifactorial interventions.\(^3\) However,
none of the L-protocol exercises load the hamstrings to a high intensity during eccentric contractions,\(^3\)
and high intensity loading appears a key component of interventions proven to increase hamstring
strength, lengthen biceps femoris long head fascicles and reduce HSI risk.\(^4\)\(^,\)\(^1\)\(^5\) As deficits in hamstring
strength and biceps femoris long head fascicle length are seen beyond RTS,\(^4\)\(^,\)\(^2\) more progressive eccentric
loading, such as the Nordic hamstring exercise (NHE), should be implemented during rehabilitation.

Although eccentric loading is commonly recommended as a rehabilitation intervention, the challenge for
practitioners is knowing how and when to safely introduce exercises like the NHE following HSI.
Eccentric hamstring exercises are often avoided in the early stages of HSI rehabilitation and only introduced once pain and between-leg strength deficits have resolved during isometric knee flexion.\textsuperscript{35, 38} However, eccentric loading can be safely progressed based on individual exercise performance, regardless of pain and between-leg strength deficits during isometric knee flexion following acute HSI.\textsuperscript{20} For example, the sub-maximal bilateral eccentric slider exercise can be introduced from the very start of HSI rehabilitation (Figure 4), before progressing to a unilateral variation and introducing the NHE, once this exercise can be performed through full ROM (Supplementary video 1).\textsuperscript{20} This progressive approach to eccentric loading has been shown to increase hamstring strength and biceps femoris long head fascicle length in relatively brief periods of rehabilitation following acute HSI.\textsuperscript{20} Figure 4 and supplementary video 1 provides examples of these eccentric hamstring exercises and describes when they should be introduced and progressed on an individual basis during HSI rehabilitation. \textit{Strength of recommendation: A}

\textit{Hip extensor strengthening}

In addition to eccentric knee flexor exercises, the hamstrings should be loaded at longer muscle lengths during hip extension. Sub-maximal exercises, such as Askling’s diver\textsuperscript{15} can be introduced from the start of HSI rehabilitation (Figure 4), before progressing to hamstring bridges,\textsuperscript{20} 45° hip extensions,\textsuperscript{41} or Romanian deadlifts (Supplementary video 2). Apart from the hamstrings, single-joint hip extensors, such as gluteus maximus and adductor magnus should be targeted if clinical examination shows weakness in these muscles, as they are key contributors to horizontal force production during sprint acceleration.\textsuperscript{43} These single-joint muscles may be preferentially loaded over the injured hamstrings during HSI rehabilitation by performing hip extension exercises with greater knee flexion angles.\textsuperscript{26, 44} Bilateral bodyweight hip thrusts can be introduced from the start of rehabilitation (Figure 4) and progressed to unilateral, loaded and explosive variations (Supplementary video 3), which are linked to increased hip extensor strength and improved sprinting performance in uninjured athletes.\textsuperscript{45} Figure 4 and
supplementary videos 2 and 3 provide examples these hip extensor strengthening exercises and describes when they should be introduced and progressed on an individual basis during HSI rehabilitation. *Strength of recommendation: 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 acutely following HSI. However, these acute ROM deficits typically recover within the first two weeks after HSI and may not require direct intervention. Nevertheless, 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 increased risk of subsequent HSI. Recovery of active knee extension ROM can be slightly accelerated by implementing passive hamstring stretching four times per day, compared to once daily, from 48 hours after HSI. Other hamstring flexibility exercises prescribed in HSI rehabilitation include supine active knee extensions and dynamic hamstring mobility exercises, although the effectiveness of these different interventions are not clear. *Strength of recommendation: B*

Progressive agility and trunk stability exercises
Exercises proposed to improve agility and trunk stability came to prominence after they led to less re-injuries compared to a relatively conservative hamstring strengthening and stretching intervention, during HSI rehabilitation. In a subsequent HSI rehabilitation study, RTS time and re-injury rates were no different between progressive agility and trunk stability (PATS) exercises and an intervention emphasizing running and eccentric strengthening. The proposed benefits of PATS exercises, is that they promote controlled early loading through frontal plane movements, while avoiding end-range hamstring lengthening. It has also been argued that PATS exercises target other muscles of the lumbo-pelvic region, which could reduce stretch placed on the hamstrings during high speed running, at least according to biomechanical models. Although these potential benefits have not been directly...
investigated following implementation of PATS exercises, relative success in achieving timely RTS and acceptable rates of recurrence\textsuperscript{35,48} strengthens this otherwise theoretical rationale for their inclusion in HSI rehabilitation. \textit{Strength of recommendation: B}

\textit{Running technique drills}
Practitioners may implement running technique drills, as tolerated during 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 HSI risk due to increased hamstring length in this position. There is some prospective evidence of increased HSI risk in athletes who sprint with greater anterior pelvic tilt and lateral trunk flexion,\textsuperscript{49} or less gluteus maximus and trunk muscle activity.\textsuperscript{50} Yet, similar to PATS exercises, there is no direct evidence that technique drills can reduce HSI risk, improve running performance or alter any other rehabilitation outcomes. Therefore, technique drills should be viewed as a non-essential accessory to progressive running, which may be implemented if a sound clinical or performance-oriented rationale is provided. \textit{Strength of recommendation: C}

\textit{Passive treatments}

\textit{Platelet-rich-plasma injections}
Some athletes may receive platelet-rich-plasma injection therapy during HSI rehabilitation, depending on access to resources and practices of medical personnel involved in their management. Platelet-rich-plasma injections have been proposed to enhance tissue healing and have been investigated in the treatment of acute muscle injuries, with multiple studies including athletes with HSIs.\textsuperscript{51} Meta-analysis shows no significant reduction in RTS time or re-injury rate when platelet-rich-plasma injections are added to exercise interventions during HSI rehabilitation.\textsuperscript{51} There is also a lack of consensus on the timing, volume or composition of platelet-rich-plasma injections\textsuperscript{51} and resulting muscle soreness could
impact on exercise rehabilitation. Platelet-rich plasma injections appear, at best, to be a non-harmful, yet ineffective treatment in accelerating RTS or mitigating subsequent HSI risk. Strength of recommendation: A

Manual therapy
Evidence for manual therapy as a rehabilitation intervention following HSI rehabilitation is scarce. Acute increases in knee flexor torque have been observed after applying sacroiliac joint mobilizations to individuals with a recent HSI, but these findings are limited by pre-intervention differences between those who did and did not receive this treatment.\textsuperscript{52} Lumbar spine facet joint mobilizations and soft tissue massage were included in a multifactorial HSI rehabilitation algorithm, which led to fewer re-injuries but slightly prolonged RTS compared to Askling’s L-protocol exercise intervention.\textsuperscript{38} This study did not assess outcomes often proposed to be influenced by manual therapies (e.g. pain or ROM) and the extensive nature of the rehabilitation algorithm make it difficult to know if these passive interventions were of any value.\textsuperscript{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. Strength of recommendation: C

Implementation considerations
Implementing any of the above interventions requires careful consideration of various factors, both intrinsic (e.g. age and injury history) and extrinsic (e.g. pressure to expedite RTS) to the athlete. Older athletes with a history of HSI or injuries to other areas may require longer rehabilitation, due to the need to address pre-existing deficits and account for their increased risk of subsequent injury.\textsuperscript{14} Elite and professional athletes may be under more pressure to RTS, which truncates HSI rehabilitation. These factors must be considered by practitioners responsible for different aspects of rehabilitation, in collaboration with coaches, the athlete and other stakeholders in the shared RTS process.\textsuperscript{53}
As rehabilitation progresses to include more sports-specific training and high-speed running, it is important to not completely neglect key exercise interventions. Complete cessation of eccentric hamstring exercise leads to biceps femoris long head fascicle shortening,\(^\text{54}\) which can be avoided by continuing to perform these interventions, even at low training volumes.\(^\text{55}\) The impact 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 makes high-speed running difficult to perform during the subsequent 48 hours. The timing of these interventions may depend on the number of days an athlete can complete rehabilitation around their other commitments. If prescribed on the same day, we advise performing high speed running prior to eccentric hamstring exercise, to ensure 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.\(^\text{53}\) The following section briefly covers pain, patient reported outcomes, apprehension and eccentric hamstring strength, along with their associated assessment tools, which can be used during HSI rehabilitation.

#### Pain

Rehabilitation is most commonly progressed following HSI, when the athlete reports no pain during exercise, clinical examinations or functional tasks.\(^\text{56}\) An eleven point (0 to 10) numeric pain rating scale can be used to evaluate the level of pain reported by the athlete. Compared to the conventional practice of pain avoidance,\(^\text{56}\) allowing exercise in the presence of pain rated ≤ 4 on a 0-10 numeric rating scale during HSI rehabilitation is safe and may allow earlier exposure and progression of beneficial stimulus.\(^\text{20}\)

**Strength of recommendation: B**
Patient reported outcomes

The importance of patient reported outcomes is highlighted by evidence that RTS prognosis is associated with self-predicted time to RTS and the number of days taken for the athlete to report pain-free walking.\textsuperscript{12,57} In addition to asking the athlete these questions, the functional assessment scale for acute hamstring injuries is a self-administered questionnaire, which can be used to assess severity and impact of symptoms.\textsuperscript{58} Initial research into psychometric testing show this scale has good reliability and validity but the minimal clinically important difference is unknown. \textit{Strength of recommendation: B}

Apprehension

Askling’s H-test can be used to assess athlete’s apprehension during rapid hamstring lengthening by performing explosive unilateral hip flexion with the knee fixed in extension by a brace.\textsuperscript{59} An electrogoniometer can also be used to quantify hip flexion ROM during the H-test, which may identify deficits that are otherwise undetected by clinical examinations of hamstring flexibility during later stages of HSI rehabilitation.\textsuperscript{59} Implementing the H-test as a final RTS criteria is associated with low risk of re-injury but prolonged HSI rehabilitation time\textsuperscript{56} and practitioners may need to consider which outcome is a higher priority for each individual athlete. \textit{Strength of recommendation: B}

Eccentric hamstring strength

Depending on resources, eccentric hamstring strength can be objectively tested using several tools including isokinetic dynamometry,\textsuperscript{60} hand-held dynamometry\textsuperscript{21} or during the Nordic hamstring exercise using externally fixed load cells.\textsuperscript{61} The evidence for eccentric hamstring strength as a risk factor for HSI is conflicting\textsuperscript{14} and asymmetries after RTS are not associated with re-injury.\textsuperscript{60} Eccentric hamstring strength is associated with sprint acceleration mechanics,\textsuperscript{43} which is important for performance in running-based sports.\textsuperscript{62} Therefore, maximizing eccentric hamstring strength and relative between-leg symmetry is
currently considered a desirable rehabilitation outcome for sports performance but not an essential RTS criteria to reduce re-injury risk.\textsuperscript{63} \textit{Strength of recommendation: 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. The following section identifies two 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 HSI risk and improving athlete performance, but requires more time to implement during rehabilitation and this could delay RTS.\textsuperscript{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. 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. However, the absence of evidence does not necessarily equate to evidence of absence. In these cases, practitioners need to carefully apply critical thinking and consider a sound rationale for why a proposed intervention may improve HSI rehabilitation outcomes. For example, there may not be direct evidence that a certain intervention improves outcomes when...
implemented during HSI rehabilitation. Instead, there may be evidence in uninjured athletes that an intervention leads to desirable adaptations, which is presumed to lead to improved rehabilitation outcomes.

Can we assess re-injury risk at return to sport?

Another challenge of HSI rehabilitation is uncertainty regarding which modifiable variables, if any, are associated with re-injury risk, when assessed at RTS. Deficits in hamstring muscle structure and function are commonly observed at the time of RTS or even later following HSI, but there is little evidence to suggest these variables are associated with re-injury. When measured at RTS, risk of re-injury is increased with greater between-leg deficits in active knee extension ROM and isometric hamstring strength, but unaltered by residual deficits on MRI or isokinetic strength testing. These findings are limited to relatively small sample sizes, highlighting the need to conduct multi-site studies, employing a standard suite of RTS assessments, over several years, to identify variables associated with re-injury risk.

Until this research is conducted, practitioners need to be cognizant of the limited evidence available and employ a pragmatic, heuristic approach, which considers the need for athletes to be able to 1) exceed pre-injury levels (if this data exists) in variables thought to be contributing factors for the initial injury (e.g., biceps femoris long head fascicle length); 2) allow for the resolution of between-leg asymmetry that arise in response to the pathology (e.g., ROM and strength asymmetry); and 3) ensure a sufficient exposure to key variables required to maximize performance upon RTS (e.g., high speed running). While clear consensus related to RTS is lacking, resolution of pain, symmetry (<10-15% asymmetry) with ROM and strength testing, completion of on-field performance/functional testing, and confirmed psychological readiness are the most pragmatic variables for practitioners to consider. Further, it is widely accepted that the RTS process should involve shared decision between the player, team medical staff (physicians, Athletic Trainers, Physical Therapists) and strength and performance staffs.
1. Ekstrand J, Krutsch W, Spreco A, et al. Time before return to play for the most common injuries in professional football: a 16-year follow-up of the UEFA Elite Club Injury Study. Br J Sports Med. 2020;54(7):421-426.

2. Wangensteen A, Tol JL, Witvrouw E, et al. Hamstring Reinjuries Occur at the Same Location and Early After Return to Sport: A Descriptive Study of MRI-Confirmed Reinjuries. Am J Sports Med. 2016;44(8):2112-21.

3. Whiteley R, Massey A, Gabbett T, et al. Match High-Speed Running Distances Are Often Suppressed After Return From Hamstring Strain Injury in Professional Footballers. Sports Health. 2021;13(3):290-295.

4. Ebell MH, Siwek J, Weiss BD, et al. Strength of recommendation taxonomy (SORT): a patient-centered approach to grading evidence in the medical literature. Am Fam Physician. 2004;69(3):548-56.

5. Opar DA, Williams MD, Shield AJ. Hamstring strain injuries: factors that lead to injury and re-injury. Sports Med. 2012;42(3):209-26.

6. Chumanov ES, Heiderscheit BC, Thelen DG. Hamstring musculotendon dynamics during stance and swing phases of high-speed running. Med Sci Sports Exerc. 2011;43(3):525-532.

7. Heiderscheit BC, Hoerth DM, Chumanov ES, Swanson SC, Thelen BJ, Thelen DG. Identifying the time of occurrence of a hamstring strain injury during treadmill running: a case study. Clin Biomech. 2005;20(10):1072-8.

8. Askling C, Saartok T, Thorstensson A. Type of acute hamstring strain affects flexibility, strength, and time to return to pre-injury level. Br J Sports Med. Jan 2006;40(1):40-4.

9. Kenneally-Dabrowski CJB, Brown NAT, Lai AKM, Perriman D, Serpell BG. Late swing or early stance? A narrative review of hamstring injury mechanisms during high-speed running. Scand J Med Sci Sports. 2019;29(8):1083-1091.

10. Chumanov ES, Heiderscheit BC, Thelen DG. The effect of speed and influence of individual muscles on hamstring mechanics during the swing phase of sprinting. J Biomech. 2007;40(16):3555-62.

11. Ekstrand J, Healy JC, Walden M, Lee JC, English B, Hagglund M. Hamstring muscle injuries in professional football: the correlation of MRI findings with return to play. Br J Sports Med. 2012;46(2):112-7.

12. Jacobsen P, Witvrouw E, Muxart P, Tol JL, Whiteley R. A combination of initial and follow-up physiotherapist examination predicts physician-determined time to return after hamstring injury, with no added value of MRI. Br J Sports Med. 2016;50(7):431-9.

13. Whiteley R, van Dyk N, Wangensteen A, Hansen C. Clinical implications from daily physiotherapy examination of 131 acute hamstring injuries and their association with running speed and rehabilitation progression. Br J Sports Med. 2018;52(5):303-310.

14. Green B, Bourne MN, van Dyk N, Pizzari T. Recalibrating the risk of hamstring strain injury (HSI): A 2020 systematic review and meta-analysis of risk factors for index and recurrent hamstring strain injury in sport. Br J Sports Med. 2020;54(18):1081-1088.

15. Askling CM, Tengvar M, Tarassova O, Thorstensson A. Acute hamstring injuries in Swedish elite sprinters and jumpers: a prospective randomised controlled clinical trial comparing two rehabilitation protocols. Br J Sports Med. 2014;48(7):532-9.

16. Malliaropoulos N, Papalexandris S, Papalada A, Papacostas E. The Role of Stretching in Rehabilitation of Hamstring Injuries: 80 Athletes Follow-Up. Med Sci Sports Exerc. 2004:756-759.

17. Gabbe BJ, Bennell KL, Finch CF. Why are older Australian football players at greater risk of hamstring injury? J Sci Med Sport. 2006;9(4):327-33.
van Dyk N, Farooq A, Bahr R, Witvrouw E. Hamstring and Ankle Flexibility Deficits Are Weak Risk Factors for Hamstring Injury in Professional Soccer Players: A Prospective Cohort Study of 438 Players Including 78 Injuries. *Am J Sports Med.* 2018;46(9):2203-2210.

Reurink G, Goudswaard GJ, Moen MH, Tol JL, Verhaar JA, Weir A. Strength Measurements in Acute Hamstring Injuries: Intertester Reliability and Prognostic Value of Handheld Dynamometry. *J Orthop Sports Phys Ther.* 2016;46(8):689-96.

Hickey JT, Timmins RG, Maniar N, et al. Pain-Free Versus Pain-Threshold Rehabilitation Following Acute Hamstring Strain Injury: A Randomized Controlled Trial. *J Orthop Sports Phys Ther.* 2020;50(2):91-103.

Whiteley R, Jacobsen P, Prior S, Skazalski C, Otten R, Johnson A. Correlation of isokinetic and novel hand-held dynamometry measures of knee flexion and extension strength testing. *J Sci Med Sport.* 2012;15(5):444-50.

Hickey JT, Hickey PF, Maniar N, et al. A Novel Apparatus to Measure Knee Flexor Strength During Various Hamstring Exercises: A Reliability and Retrospective Injury Study. *J Orthop Sports Phys Ther.* 2018;48(2):72-80.

McCall A, Nedelec M, Carling C, Le Gall F, Berthoin S, Dupont G. Reliability and sensitivity of a simple isometric posterior lower limb muscle test in professional players. *J Sports Sci.* 2015;33(12):1298-304.

Urquhart MN, Bishop C, Turner AN. Validation of a crane scale for the assessment of portable isometric mid-thigh pulls. *Journal of Australian Strength & Conditioning.* 2018;26(5):28-33.

Beyer EB, Lunden JB, Russell Giveans M. Medial and Lateral Hamstrings Response and Force Production at Varying Degrees of Knee Flexion and Tibial Rotation in Healthy Individuals. *Int J Sports Phys Ther.* 2019;14(3):376-383.

Kwon YJ, Lee HO. How different knee flexion angles influence the hip extensor in the prone position. *J Phys Ther Sci.* 2013;25(10):1295-7.

Thorborg K, Reiman MP, Weir A, et al. Clinical Examination, Diagnostic Imaging, and Testing of Athletes With Groin Pain: An Evidence-Based Approach to Effective Management. *J Orthop Sports Phys Ther.* 2018;48(4):239-249.

Patel A, Chakraverty J, Pollock N, Chakraverty R, Suokas AK, James SL. British athletics muscle injury classification: a reliability study for a new grading system. *Clin Radiol.* Dec 2015;70(12):1414-20.

Reurink G, Brilman EG, de Vos RJ, et al. Magnetic resonance imaging in acute hamstring injury: can we provide a return to play prognosis? *Sports Med.* Jan 2015;45(1):133-46.

Macdonald B, McAleer S, Kelly S, Chakraverty R, Johnston M, Pollock N. Hamstring rehabilitation in elite track and field athletes: applying the British Athletics Muscle Injury Classification in clinical practice. *Br J Sports Med.* 2019;53(23):1464-1473.

Pollock N, Kelly S, Lee J, et al. A 4-year study of hamstring injury outcomes in elite track and field using the British Athletics rehabilitation approach. *Br J Sports Med.* 2021;Epub ahead of print.

Pollock N, Patel A, Chakraverty J, Suokas A, James SL, Chakraverty R. Time to return to full training is delayed and recurrence rate is higher in intratendinous (‘c’) acute hamstring injury in elite track and field athletes: clinical application of the British Athletics Muscle Injury Classification. *Br J Sports Med.* 2016;50(5):305-10.

van der Made AD, Almusa E, Whiteley R, et al. Intramuscular tendon involvement on MRI has limited value for predicting time to return to play following acute hamstring injury. *Br J Sports Med.* 2017;52(2):83-88.

Vermeulen R, Almusa E, Buckens S, et al. Complete resolution of a hamstring intramuscular tendon injury on MRI is not necessary for a clinically successful return to play. *Br J Sports Med.* 2020;Epub ahead of print.

Epub ahead of print.
35. Silder A, Sherry MA, Sanfilippo J, Tuine M, Hetzel SJ, Heiderscheit BC. Clinical and Morphological Changes Following 2 Rehabilitation Programs for Acute Hamstring Strain Injuries: A Randomized Clinical Trial. J Orthop Sports Phys Ther. 2013;43(5):284-299.

36. Ruddy JD, Pollard CW, Timmins RG, Williams MD, Shield AJ, Opar DA. Running exposure is associated with the risk of hamstring strain injury in elite Australian footballers. Br J Sports Med. 2018;52(14):919-928.

37. Samozino P, Rabita G, Dorel S, et al. A simple method for measuring power, force, velocity properties, and mechanical effectiveness in sprint running. Scand J Med Sci Sports. 2016;26(6):648-58.

38. Mendiguchia J, Martinez-Ruiz E, Edouard P, et al. A Multifactorial, Criteria-based Progressive Algorithm for Hamstring Injury Treatment. Med Sci Sports Exerc. 2017;49(7):1482-1492.

39. Severini G, Holland D, Drumgoole A, Delahunt E, Ditroilo M. Kinematic and electromyographic analysis of the Askling L-Protocol for hamstring training. Scand J Med Sci Sports. 2018;28(12):2536-2546.

40. van Dyk N, Behan FP, Whiteley R. Including the Nordic hamstring exercise in injury prevention programmes halves the rate of hamstring injuries: a systematic review and meta-analysis of 8459 athletes. Br J Sports Med. 2019;53(21):1362-1370.

41. Bourne MN, Duhig SJ, Timmins RG, et al. Impact of the Nordic hamstring and hip extension exercises on hamstring architecture and morphology: implications for injury prevention. Br J Sports Med. 2017;51(5):469-477.

42. Timmins RG, Shield AJ, Williams MD, Lorenzen C, Opar DA. Biceps femoris long head architecture: a reliability and retrospective injury study. Med Sci Sports Exerc. 2015;47(5):905-13.

43. Morin JB, Gimenez P, Edouard P, et al. Sprint Acceleration Mechanics: The Major Role of Hamstrings in Horizontal Force Production. Front Physiol. 2015;6:404.

44. Ho IMK, Ng LPC, Lee KOL, Luk TCJ. Effects of knee flexion angles in supine bridge exercise on trunk and pelvic muscle activity. Res Sports Med. 2020;28(4):484-497.

45. Neto WK, Vieira TL, Gama EF. Barbell Hip Thrust, Muscular Activation and Performance: A Systematic Review. J Sports Sci Med. 2019;18(2):198-206.

46. Maniar N, Shield AJ, Williams MD, Timmins RG, Opar DA. Hamstring strength and flexibility after hamstring strain injury: a systematic review and meta-analysis. Br J Sports Med. 2016;50(15):909-20.

47. De Vos RJ, Reurink G, Goudswaard GJ, Moen MH, Weir A, Tol JL. Clinical findings just after return to play predict hamstring re-injury, but baseline MRI findings do not. Br J Sports Med. 2014;48(18):1377-84.

48. Sherry MA, Best TM. A comparison of 2 rehabilitation programs in the treatment of acute hamstring strains. J Orthop Sports Phys Ther. 2004;34(3):116-25.

49. Schuermans J, Van Tiggelen D, Palmans T, Danneels L, Witvrouw E. Deviating running kinematics and hamstring injury susceptibility in male soccer players: Cause or consequence? Gait Posture. 2017;57:270-277.

50. Schuermans J, Danneels L, Van Tiggelen D, Palmans T, Witvrouw E. Proximal Neuromuscular Control Protects Against Hamstring Injuries in Male Soccer Players: A Prospective Study With Electromyography Time-Series Analysis During Maximal Sprinting. Am J Sports Med. 2017;45(6):1315-1325.

51. Seow D, Shimozono Y, Tengku Yusof TNB, Yasui Y, Massey A, Kennedy JG. Platelet-Rich Plasma Injection for the Treatment of Hamstring Injuries: A Systematic Review and Meta-analysis With Best-Worst Case Analysis. Am J Sports Med. 2021;49(2):529-537.

52. Cibulka MT, Rose SJ, Delitto A, Sinacore DR. Hamstring muscle strain treated by mobilizing the sacroiliac joint. Phys Ther. 1986;66(8):1220-3.

53. Ardern CL, Glasgow P, Schneiders A, et al. 2016 Consensus statement on return to sport from the First World Congress in Sports Physical Therapy, Bern. Br J Sports Med. 2016;50(14):853-64.
54. Timmins RG, Ruddy JD, Presland J, et al. Architectural Changes of the Biceps Femoris Long Head after Concentric or Eccentric Training. *Med Sci Sports Exerc.* 2016;48(3):499-508.

55. Presland JD, Timmins RG, Bourne MN, Williams MD, Opar DA. The effect of Nordic hamstring exercise training volume on biceps femoris long head architectural adaptation. *Scand J Med Sci Sports.* 2018;28(7):1775-1783.

56. Hickey JT, Timmins RG, Maniar N, Williams MD, Opar DA. Criteria for Progressing Rehabilitation and Determining Return-to-Play Clearance Following Hamstring Strain Injury: A Systematic Review. *Sports Med.* 2017;47(7):1375-1387.

57. Moen MH, Reurink G, Weir A, Tol JL, Maas M, Goudswaard GJ. Predicting return to play after hamstring injuries. *Br J Sports Med.* 2014;48(18):1358-63.

58. Malliaropoulos N, Korakakis V, Christodoulou D, et al. Development and validation of a questionnaire (FASH--Functional Assessment Scale for Acute Hamstring Injuries): to measure the severity and impact of symptoms on function and sports ability in patients with acute hamstring injuries. *Br J Sports Med.* 2014;48(22):1607-12.

59. Asking CM, Nilsson J, Thorstensson A. A new hamstring test to complement the common clinical examination before return to sport after injury. *Knee Surg Sports Traumatol Arthrosc.* 2010;18(12):1798-803.

60. Tol JL, Hamilton B, Eirale C, Muxart P, Jacobsen P, Whiteley R. At return to play following hamstring injury the majority of professional football players have residual isokinetic deficits. *Br J Sports Med.* 2014;48(18):1364-9.

61. Opar DA, Piatkowski T, Williams MD, Shield AJ. A novel device using the Nordic hamstring exercise to assess eccentric knee flexor strength: a reliability and retrospective injury study. *J Orthop Sports Phys Ther.* 2013;43(9):636-40.

62. Faude O, Koch T, Meyer T. Straight sprinting is the most frequent action in goal situations in professional football. *J Sports Sci.* 2012;30(7):625-31.

63. van der Horst N, Backx F, Goedhart EA, Huisstede BM, Group HI-D. Return to play after hamstring injuries in football (soccer): a worldwide Delphi procedure regarding definition, medical criteria and decision-making. *Br J Sports Med.* 2017;51(22):1583-1591.
Legends to figures

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

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

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

Figure 4. Example progression of exercises targeting eccentric knee flexion (white) and hip extensor strength at long (black) and short (grey) hamstring muscle lengths. Supplementary videos show the technique and recommended repetition ranges for each of these exercises.
Table 1. The Strength of Recommendation Taxonomy

| Strength of recommendation | Definition                                                                 |
|----------------------------|---------------------------------------------------------------------------|
| A                          | Recommendation based on consistent and good-quality patient-oriented evidence |
| B                          | Recommendation based on inconsistent or limited-quality patient-oriented evidence |
| C                          | Recommendation based on consensus, usual practice, opinion, disease-oriented evidence, or case series for studies of diagnosis, treatment, prevention or screening |
Table 2. Differential diagnosis and common clinical presentation of potential causes of posterior thigh pain other than hamstring strain injury.

| Differential diagnosis                  | Common clinical presentation                                                                                                                                 |
|----------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Proximal hamstring tendon avulsion     | Severe acute onset pain near the ischial tuberosity, usually as a result of forceful hip flexion with full knee extension, such as a fall while water skiing. Athletes may have 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, provoked by repetitive loading of the proximal hamstring tendon. More common in middle-aged or older adults, particularly those that participate in activities with repetitive loading, such as long-distance running. |
| Lumbar spine radiculopathy             | Posterior thigh pain that refers from the lower back related to the forward-slumped posture as a result of sciatic nerve or lumbar nerve root compression.              |
| Adductor muscle injury                 | Acute or gradual onset pain that 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 from hamstring injury. |
Eccentric knee flexor 1
Bilateral slider

Eccentric knee flexor 2
Unilateral slider
Nordic hamstring

Eccentric knee flexor 3
Unilateral slider + load
Nordic hamstring + load

Long hip extensor 1
Askling’s Diver
Bilateral 45° hip extension

Long length hip extensor 2
Askling’s Diver + load
Unilateral 45° hip extension
Bilateral hamstring bridge

Long hip extensor 3
Romanian deadlift + load
45° hip extension + load
Unilateral hamstring bridge

Short hip extensor 1
Bilateral hip thrust

Short hip extensor 2
Unilateral hip thrust

Short hip extensor 3
Unilateral hip thrust + speed
Bilateral hip thrust + load

Progress exercises individually once full ROM completed with pain rated ≤ 4/10