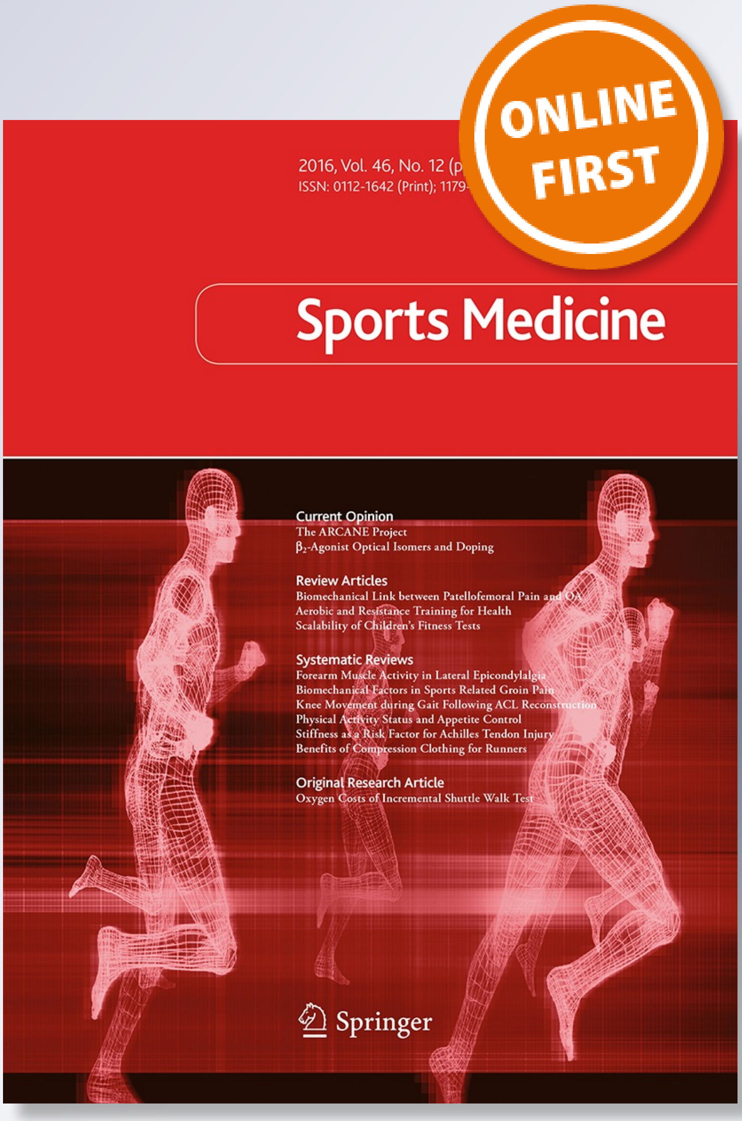
Criteria for Progressing Rehabilitation and Determining Return-to-Play Clearance Following Hamstring Strain Injury: A Systematic Review

Jack T. Hickey, Ryan G. Timmins, Nirav Maniar, Morgan D. Williams & David A. Opar

Sports Medicine

ISSN 0112-1642

Sports Med
DOI 10.1007/s40279-016-0667-x



Springer

Sports Med
DOI 10.1007/s40279-016-0667-x

SYSTEMATIC REVIEW

Criteria for Progressing Rehabilitation and Determining Return-to-Play Clearance Following Hamstring Strain Injury: A Systematic Review

Jack T. Hickey[1] · **Ryan G. Timmins**[1] · **Nirav Maniar**[1] · **Morgan D. Williams**[2] · **David A. Opar**[1]

Abstract

Background Rehabilitation progression and return-to-play (RTP) decision making following hamstring strain injury (HSI) can be challenging for clinicians, owing to the competing demands of reducing both convalescence and the risk of re-injury. Despite an increased focus on the RTP process following HSI, little attention has been paid to rehabilitation progression and RTP criteria, and subsequent time taken to RTP and re-injury rates.

Objective The aim of this systematic review is to identify rehabilitation progression and RTP criteria implemented following HSI and examine the subsequent time taken to RTP and rates of re-injury.

Methods A systematic literature review of databases MEDLINE, CINAHL, SPORTDiscus, Cochrane Library, Web of Science and EMBASE was conducted to identify studies of participants with acute HSI reporting time taken to RTP and rates of re-injury after a minimum 6-month follow-up. General guidelines and specific criteria for rehabilitation progression were identified for each study. In addition, RTP criteria were identified and categorised as performance tests, clinical assessments, isokinetic dynamometry or the Askling H-test.

Results Nine studies were included with a total of 601 acute HSI confirmed by clinical examination or magnetic resonance imaging within 10 days of initial injury. A feature across all nine studies was that the injured individual's perception of pain was used to guide rehabilitation progression, whilst clinical assessments and performance tests were the most frequently implemented RTP criteria. Mean RTP times were lowest in studies implementing isokinetic dynamometry as part of RTP decision making (12–25 days), whilst those implementing the Askling H-test had the lowest rates of re-injury (1.3–3.6%).

Conclusions This systematic review highlights the strong emphasis placed on the alleviation of pain to allow HSI rehabilitation progression, and the reliance on subjective clinical assessments and performance tests as RTP criteria. These results suggest a need for more objective and clinically practical criteria, allowing a more evidence-based approach to rehabilitation progression, and potentially reducing the ambiguity involved in the RTP decision-making process.

Key Points

- Hamstring strain injury rehabilitation progression is largely based around the alleviation of pain, and progression is typically only allowed within pain-free limits.
- Clinical assessments and performance tests are the most commonly implemented return-to-play (RTP) criteria and are often subjective.
- Implementation of the Askling H-test as RTP criteria appears to reduce rates of re-injury, but may increase the time taken to achieve RTP clearance.
- The addition of isokinetic dynamometry to clinical assessments and performance tests as RTP criteria may result in a more desirable balance between RTP times and rates of re-injury.

✉ Jack T. Hickey
jack.hickey@acu.edu.au

[1] School of Exercise Science, Australian Catholic University, 115 Victoria Parade, Fitzroy, Melbourne, VIC 3065, Australia

[2] School of Health, Sport and Professional Practice, University of South Wales, Pontypridd, Wales, UK

Published online: 29 December 2016

1 Introduction

Hamstring strain injury (HSI) is the most prevalent cause of time lost from competition in sports involving high-speed running [1–5]. Individuals with a previous HSI often exhibit deficits in hamstring muscle structure and function, well after completing rehabilitation and being cleared to return to play (RTP) [6–11]. Regardless of whether these deficits were a result or cause of injury, they suggest current rehabilitation and RTP practices may be inadequate to address these, potentially explaining the elevated risk of re-injury in those with a history of HSI [12–14]. In elite sport environments, financial [15] and performance [16] consequences of athletes remaining on the sidelines because of an injury may modify the decision to progress rehabilitation and ultimately provide clearance to RTP [17–19]. As a result, clinicians may have reduced authority over such decisions [17, 19], potentially explaining the aforementioned residual deficits in hamstring muscle structure and function [6–11].

From a clinician's perspective, progression through stages of HSI rehabilitation (e.g. from acute to end stage) can be based on pathophysiological time frames for healing tissue [20–28] or specific criteria [29–35]. Whilst time frames for the physiological healing of muscle injury exist, much of this evidence is based on experimental animal models [20, 25, 27, 36, 37] and it remains unknown if these models are relevant to guide rehabilitation progression in humans. More recently, criteria-based rehabilitation progressions have gained popularity [29–34], as this approach is more individualised than relying on time frames for healing alone. Despite this recent interest, specific criteria to progress through stages of HSI rehabilitation have not been examined rigorously.

In contrast, criteria to determine RTP clearance following HSI have received much greater attention [18, 30, 34, 38–43], including a recent systematic review [44], which reported that RTP criteria for HSI have little evidence base. That systematic review [44], however, did not investigate the time taken to achieve RTP clearance and rates of re-injury for studies implementing different criteria. It could be argued that implementing different rehabilitation progression and RTP criteria would result in altered RTP times and the risk of subsequent re-injury, and investigation of this could help clinicians make evidence-based decisions. It is, therefore, the aim of this systematic review to identify and discuss the rationale for criteria to determine both rehabilitation progression and RTP clearance following HSI and to investigate the subsequent time taken to RTP and rates of re-injury.

2 Methods

2.1 Study Design

This review is compliant with the Preferred Reporting Items for Systematic Reviews and Meta-Analysis guidelines [45]. A comprehensive systematic literature search of MEDLINE, CINAHL, SPORTDiscus, Cochrane Library, Web of Science and EMBASE was conducted from inception until July 2015.

2.2 Search Strategy

The search terms (Table 1) aimed to identify muscle group, definition of injury, intervention and outcome. Citation tracking via PubMed was performed to identify any studies published following the original literature search as well as cross checking of reference lists. Studies identified through this search were imported into EndNote software and duplicates were subsequently removed.

2.3 Study Selection

Titles and abstracts were screened for relevance by the lead author (JH), after which full-text assessment was carried out on remaining items by two authors (JH and RT) based on pre-determined selection criteria (Table 2). Where multiple studies reported on the same data, the study with the greatest number of participants was selected for inclusion. Any disputes were discussed and resolved in consultation with a third author (DO).

2.4 Study Quality Assessment

Methodological quality was assessed using a modified version of a previously validated checklist (Table 3) [46]. Items 5, 8, 14, 15, 20, 21, 23 and 24 were removed because of their lack of applicability across all studies, so as not to unfairly favour randomised controlled trials over cohort studies and retrospective investigations. Item 27 relating to sample size calculation and statistical power was altered, so that one point was awarded if sample size was calculated and a second point if the sample size was subsequently met. An additional two items 28 and 29 were included by the authors to assess the method of injury diagnosis and level of control and supervision over rehabilitation.

2.5 Data Extraction

Participant details, each study's method of HSI diagnosis, definition of RTP time, mean RTP time in days and the number of re-injuries following RTP clearance were

Table 1 Summary of keyword grouping employed during database searches

Muscle group	Definition of injury	Intervention	Outcome
Hamstring	Strain	Rehab[a]	Return[a]
"Posterior thigh"	Injur[a]	Conserv[a]	Resum[a]
"Biceps femoris"	Tear[a]	Treat[a]	Time
Semimembranosus	Rupture	Intervention[a]	Train[a]
Semitendinosus	Pain[a]	Therap[a]	Participat[a]
	Dysfunction	Manag[a]	Recurr[a]
	Trauma[a]	Clinical[a]	Re-inj[a]
		Criteri[a]	Reinj[a]
		Progress[a]	Re-occur[a]
			Reoccur[a]
			Outcome[a]
			Sport[a]
			Function[a]
			Convalescen[a]
			Recover[a]

Boolean term OR was used within categories; AND was used between categories

[a] Truncation

Table 2 Criteria for inclusion and exclusion in the systematic review

Inclusion criteria	Exclusion criteria
Participants with acute hamstring strain injury diagnosed within 10 days of initial injury by either clinical examination or magnetic resonance imaging	Participants with complete hamstring muscle ruptures (grade 3), avulsion injuries and hamstring tendinopathy
Studies that clearly describe rehabilitation progression and return-to-play criteria	Studies involving surgical interventions
Studies reporting time taken to return to play	Individual case studies
Studies reporting rates of re-injury with a minimum 6-month follow-up period	

extracted from each study. Where data were not available or reported as median rather than mean, corresponding authors were contacted for additional information. Both general guidelines and specific criteria for rehabilitation progression and RTP clearance implemented in each study were identified.

Given the wide range of specific RTP criteria, these were subsequently categorised as either clinical assessments, which are typically implemented in regular practice, or performance tests which assess the athlete's ability to complete sports-specific movements and tasks. In addition, isokinetic dynamometry and the Askling H-test were considered in their own separate categories, as they require specialised laboratory-based equipment, are not typically implemented in regular clinical practice or have only been described in the literature recently [38].

2.6 Statistical Analysis

Where individual studies reported mean RTP times and re-injuries within different intervention groups, but implemented identical rehabilitation progression and RTP criteria across interventions, the mean RTP times and overall re-injury rates for these studies were calculated. These means were used to investigate subsequent RTP times and re-injury rates, independent of differences between interventions within studies.

Mean RTP times for these studies were calculated using the "weighted.mean" function in R [47]. Weights were chosen as the inverse of the estimated variance in RTP time for each intervention. Overall rate of re-injury was calculated by dividing the total number of re-injuries by the total number of participants who completed re-injury follow-up in each individual study and expressing this quotient as a percentage. These results along with the categories of RTP criteria implemented by each study were then plotted in a figure created using the "ggplot2" package [48] in R [47].

2.7 Primary Outcome

The primary outcome of this systematic review was the mean RTP time and overall rate of re-injury for each study,

Table 3 Study quality assessment checklist modified from Downs and Black [27]

Category	Item	Question
Reporting	1	Was the hypothesis/aim/objective of the study clearly described?
	2	Were the main outcomes to be measured clearly described in the introduction or methods section?
	3	Were the characteristics of the patients included in the study clearly described?
	4	Were the interventions of interest clearly described?
	6	Were the main findings of the study clearly described?
	7	Did the study provide estimates of the random variability in the data for the main outcomes?
	9	Were the characteristics of patients lost to follow-up described?
	10	Were actual probability values reported for the main outcomes except where the probability value is <0.001?
External validity	11	Were the subjects asked to participate in the study representative of the entire population from which they were recruited?
	12	Were those subjects who were prepared to participate representative of the entire population from which they were recruited?
	13	Were the staff, places and facilities where the patients were treated representative of the treatment the majority of patients receive?
Internal validity (bias)	16	If any of the results of the study were based on "data dredging", was this made clear?
	17	In trials and cohort studies, do the analyses adjust for different lengths of follow-up of patients, or in case-control studies, was the time period between the intervention and outcome the same for cases and controls?
	18	Were the statistical tests used to assess the main outcomes appropriate?
	19	Was compliance with the intervention reliable?
Internal validity (confounding)	22	Were study subjects in different intervention groups (trials and cohort studies) or were the cases and controls (case-control studies) recruited over the same period of time?
	25	Was there adequate adjustment for confounding in the analyses from which the main findings were drawn?
	26	Were losses of patients to follow-up taken into account?
Power	27[a]	Did the study have a calculation of power and was this met?
Additional internal Validity (bias)	28[b]	Was diagnosis of acute hamstring strain appropriate?
Additional internal Validity (confounding)	29[b]	Was rehabilitation controlled and supervised by the authors at least once per week?

[a] Modified items

[b] Additional items

in the context of the criteria implemented to progress through stages of rehabilitation and determine RTP clearance.

3 Results

3.1 Literature Search

The literature search consisted of five steps (Fig. 1). Following full-text assessment, ten studies met the eligibility criteria, however, two of these studies reported on the same data set from a large-scale intervention [49, 50]. One study analysed a smaller subset of the data that performed follow-up testing post-RTP clearance [49]; therefore, only the study with greater participant numbers [50] was included in the review.

3.2 Study Quality Assessment

Study quality ranged from 10 [51] to 18 [52] out of a possible score of 22, with a mean (±standard deviation) score of 14.4 (±2.2). Full quality assessment results for each study are detailed in Table 4.

3.3 Participant and Study Details

A total of 601 participants with an acute HSI diagnosed by either clinical examination, magnetic resonance imaging or a combination of both within 10 days of initial injury were

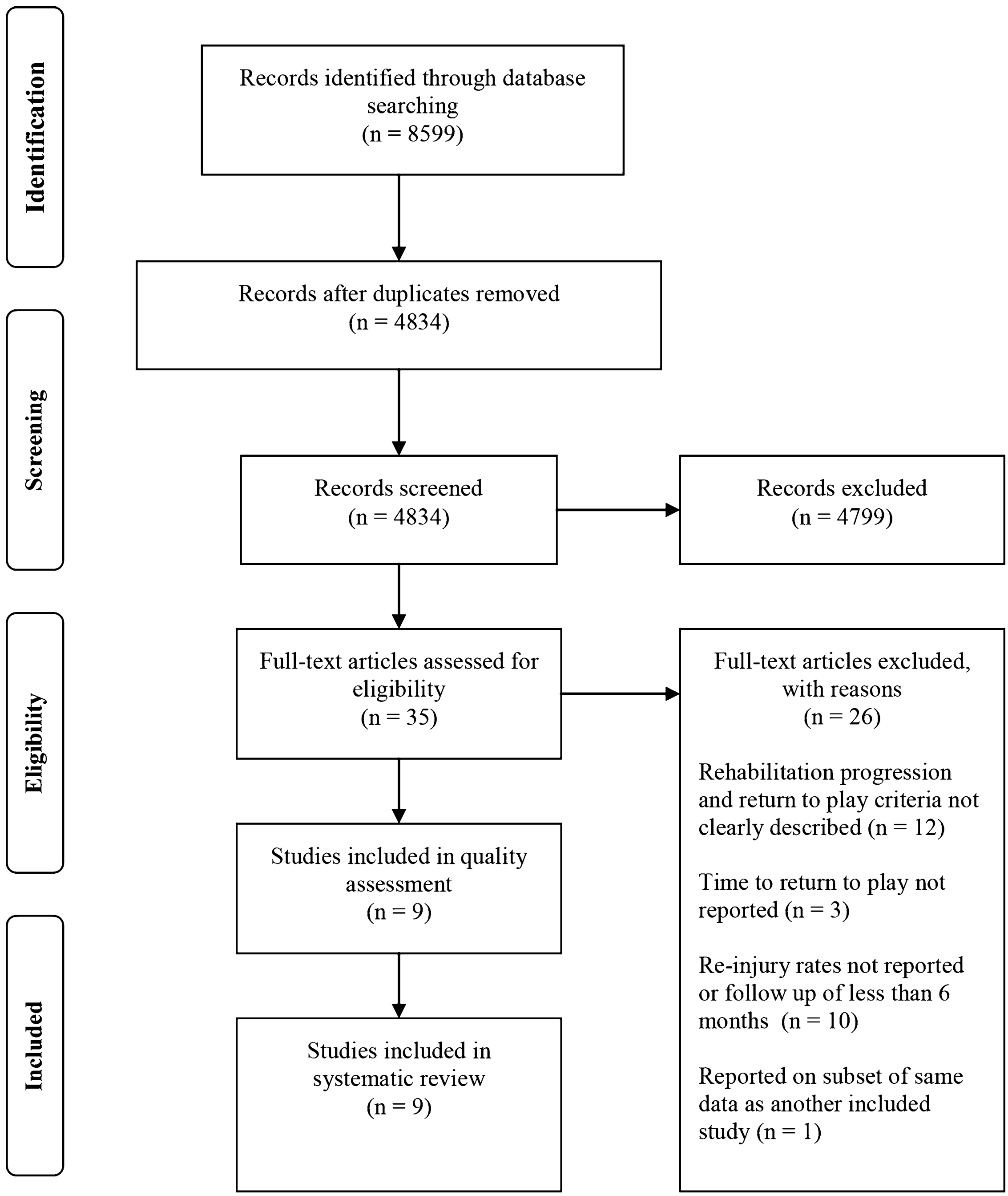


Fig. 1 Preferred Reporting Items for Systematic Reviews and Meta-Analyses flowchart outlining study selection process

recruited across the included studies. These participants included a mixture of male (80.6%) and female (19.4%) individuals participating in sports at professional, collegiate and recreational levels. Definitions of RTP time included the number of days from injury until participation in full training or availability for competition [50, 53–55], completion of rehabilitation protocol and clearance from a treating sports medicine physician [52] or meeting RTP criteria [51, 56–58] as detailed in Table 7. Further details of participants and studies included are seen in Table 5.

3.4 Rehabilitation Progression Guidelines and Criteria

Progression of rehabilitation exercises was only allowed within pain-free limits in six studies [50, 52–55, 58], whilst

Table 4 Results of itemised scoring of study quality using a modified quality assessment checklist[a]

References	1	2	3	4	6	7	9	10	11	12	13	16	17	18	19	22	25	26	27	28	29	Total	%
Askling et al. [54]	1	1	1	1	1	1	1	1	0	0	0	1	1	1	0	1	0	1	0	1	1	15	68
Askling et al. [53]	1	1	1	1	1	1	1	1	0	0	0	1	1	1	0	1	0	1	0	1	1	15	68
Hamilton et al. [52]	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	0	1	2	1	1	18	82
Kilcoyne et al. [51]	0	1	0	1	1	1	1	1	0	0	0	0	0	0	1	1	1	0	0	0	1	10	45
Malliaropoulos et al. [56]	1	1	1	0	1	1	1	1	0	0	0	1	1	1	0	1	1	0	0	0	1	13	59
Reurink et al. [50]	1	1	1	1	1	1	0	1	0	0	0	1	1	1	0	1	0	1	2	1	0	15	68
Sherry and Best [57]	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	0	1	1	0	0	1	15	68
Silder et al. [58]	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	0	1	1	0	1	16	72
Verrall et al. [55]	1	1	1	1	1	1	1	0	0	0	0	1	0	1	0	1	1	1	0	1	0	13	59

[a] See Table 3 for questions relating to the listed items

one allowed up to 1–2 out of 10 pain during their running rehabilitation protocol [51]. Five studies [50, 52, 56–58] implemented specific criteria-based progressions through stages of rehabilitation, with the alleviation of pain during walking [50, 56–58], pain-free manual assessment of isometric knee flexor strength [50, 58] and pain-free normal jogging [50, 58] most common. Further details of rehabilitation progression guidelines and criteria are shown in Table 6.

3.5 RTP Criteria

A wide range of specific RTP criteria were identified across the nine included studies with pain-free sprinting [50, 51, 57, 58], manual assessment of isometric knee flexor strength [53, 54, 57, 58], range of motion tests [50, 53, 54, 56] and pain-free palpation of the injury site [53, 54, 57, 58] most common. Clinical assessments and performance tests were the most widely implemented categories of RTP criteria, used by eight [50, 52–58] and seven [50–52, 55–58] of the included studies, respectively.

Four studies implemented a combination of clinical assessments and performance tests as their criteria for RTP clearance [50, 55, 57, 58]. In addition to performance tests [51] or a combination of clinical assessments and performance tests [52, 56], three studies implemented isokinetic dynamometry as part of RTP decision making [51, 52, 56]. Finally, two studies implemented the Askling H-test as

Table 5 Participant and study details

References	No. of participants (% male)	Population	Diagnosis	Re-injury follow-up period (months)
Askling et al. [54]	56 (68)	Elite Swedish sprinters and jumpers	CE and MRI ≤5 days of injury	12
Askling et al. [53]	75 (92)	Elite Swedish footballers	CE and MRI ≤5 days of injury	12
Hamilton et al. [52]	90 (100)	Athletes from a range of sports at a professional or competitive level	CE and MRI ≤5 days of injury	6
Kilcoyne et al. [51]	48 (83)	Athletes from a range of sports competing at a Division 1 collegiate level	CE ≤24 h of injury	6
Malliaropoulos et al. [56]	165 (59)	Elite track and field athletes	CE and US ≤48 h of injury	24
Reurink et al. [50]	80 (95)	Athletes from a range of sports competing at a recreational or competitive level	CE and MRI ≤5 days of injury	12
Sherry and Best [57]	28 (75)	Athletes from a range of sports	CE ≤10 days of injury	12
Silder et al. [58]	29 (79)	Athletes from a range of sports involving high-speed running	CE and MRI ≤10 days of injury	12
Verrall et al. [55]	30 (100)	Elite Australian Rules footballers	CE and MRI between 2 and 6 days of injury	Same and following playing season

CE clinical examination, *MRI* magnetic resonance imaging, *US* ultrasound

Table 6 General rehabilitation progression guidelines and specific criteria to progress through stages of rehabilitation

References	General guidelines		Specific criteria for progression through stages of rehabilitation									
	Within pain-free limits	Within limits of 1–2/10 pain (no sharp pain)	Pain-free single leg squat	Pain-free bike at 150 W for 5 min	Full knee extension in supine	Pain-free high knee march	Pain-free normal walking gait	Pain-free ROM or >75% of uninjured side	Pain-free normal jog	Run at 70% perceived maximum speed	Pain-free submaximal then full isometric knee flexor strength assessed manually	Pain-free change of direction and 100% speed run
Askling et al. [54]	✔											
Askling et al. [53]	✔											
Hamilton et al. [52]	✔		✔	✔	✔			✔		✔		✔
Kilcoyne et al. [51]		✔										
Malliaropoulos et al. [56]							✔	✔				
Reurink et al. [50]	✔						✔		✔		✔	
Sherry and Best [57]						✔	✔					
Silder et al. [58]	✔						✔		✔		✔	
Verrall et al. [55]	✔											
Total	6	1	1	1	1	1	4	2	2	1	2	1

ROM range of motion

RTP criteria once no signs or symptoms of HSI were present during clinical assessments [53, 54]. Further details of the specific RTP criteria included within each of these categories can be seen in Table 7.

3.6 RTP Times and Re-injury Rates

In the four studies implementing a combination of clinical assessments and performance tests as RTP criteria, mean RTP times and re-injury rates were 23 days and 34.8% [57], 26 days and 9.1% [58], 27 days and 63.3% [55], and 45 days and 34.8% [50]. Mean RTP times and rates of re-injury in the three studies implementing isokinetic dynamometry as part of RTP decision making were 12 days and 6.25% [51], 15 days and 13.9% [56] and 25 days and 9.6% [52]. In the two studies implementing the Askling H-test as RTP criteria, mean time taken to RTP and rates of re-injury were 63 days and 3.6% [54] and 36 days and 1.3% [53]. Figure 2 shows each study's mean RTP time and the rate of re-injury and indicates the combination of RTP criteria implemented in each of these studies.

4 Discussion

4.1 Statement of Main Findings

The main findings of this systematic review are (1) progression of HSI rehabilitation is largely based around the injured individual's perception of pain and progression is typically only allowed within pain-free limits; (2) the most commonly implemented RTP criteria, performance tests and clinical assessments, are generally based on either the injured individual's perception of pain, or a clinician's subjective interpretation, such as manually resisted strength testing; (3) studies implementing the Askling H-test had the lowest rates of re-injury but prolonged RTP times; and (4) studies implementing isokinetic dynamometry typically had faster mean RTP times and lower rates of re-injury compared with studies implementing a combination of clinical assessments and performance tests as RTP criteria.

4.2 Rehabilitation Progression Guidelines and Criteria

In all included studies, the injured individual's perception of pain was used to guide rehabilitation progression to some extent, either through general progression guidelines [50–55, 58] or specific criteria to advance through stages of rehabilitation [50, 52, 56–58]. With the exception of one study [51], which was of the lowest methodological quality, rehabilitation was kept completely pain free, consistent with conventional clinical practice and guidelines for the treatment of muscle injury [20–23, 28, 31–35, 43]. However, as acknowledged in some of these articles [20–23], such guidelines lack a solid scientific basis, and the efficacy of remaining completely pain free during HSI rehabilitation has never been scientifically investigated.

Specific criteria for rehabilitation progression, such as the alleviation of pain during isometric knee flexor contraction, also reflect the aforementioned treatment guidelines, which advise that isometric muscle contractions should be pain free prior to implementing concentric before eccentric exercises [20–23, 26, 28]. As mentioned above, such guidelines lack empirical evidence, leaving the possibility that this approach may unnecessarily delay and reduce exposure to eccentric exercise. This is of critical importance, as eccentric knee flexor exercise reduces HSI risk [59–62], likely owing to improving known risk factors such as eccentric hamstring strength [63, 64] and muscle fascicle length [65, 66]. A potential lack of exposure to eccentric exercise during rehabilitation may partly explain residual deficits in such variables seen in those with a previous HSI [6, 7], potentially contributing to elevated risk of re-injury in this population [12, 13].

4.3 RTP Criteria

The RTP decision was also heavily weighted to the resolution of signs and symptoms of HSI during performance tests and clinical assessments, consistent with recently published work [42, 44]. Being able to sprint and perform sports-specific movements without pain is a logical milestone prior to RTP clearance; however, these performance tests do not directly assess any known risk factors for HSI. Therefore, although such performance tests should be included to indicate readiness to RTP, they do not necessarily provide any information as to the subsequent risk of re-injury [67].

Clinical assessments were frequently implemented as both rehabilitation progression and RTP criteria, and these have been shown to provide a relatively time and cost-effective indicator of recovery from HSI [11, 68, 69]. However, the subjective nature of clinical assessments implemented by the studies identified in this review, such as manual muscle testing, lack reliability and sensitivity in detecting deficits in strength [70, 71]. The use of more objective measures of isometric strength, such as hand-held and externally fixed dynamometry, has been shown to provide a more reliable guide to clinical recovery and may indicate risk of re-injury [49, 68]. In addition to isometric strength testing, the implementation of range of motion tests may also provide a good guide to clinical recovery [11] and indicate an increased risk of re-injury [49].

Compared with the prevalence of performance tests and clinical assessments, isokinetic dynamometry was only implemented as RTP criteria in three of the included

Table 7 Specific criteria for return to play (RTP) within each category

References	Clinical assessments				Performance tests				Isokinetic dynamometry			Askling H-test
	Manual assessment of isometric knee flexor strength	Pain-free palpation of injury site	ROM tests	"Normal" clinical assessment (details of assessment not reported)	Pain-free and subjective readiness following sprinting	Pain-free and subjective readiness following agility tests or sports-specific movements	Pain-free full training	"Equal" single-leg triple hop for distance	Isokinetic strength difference ≤5% at 60 and 180°/s	Results of isokinetic strength test considered	Perceived equal between limb isokinetic strength	No pain or insecurity during ballistic hip flexion with full knee extension in supine
Askling et al. [54]	✔	✔	✔									✔
Askling et al. [53]	✔	✔	✔									✔
Hamilton et al. [52]				✔		✔				✔		
Kilcoyne et al. [51]					✔						✔	
Malliaropoulos et al. [56]			✔					✔	✔			
Reurink et al. [50]			✔		✔	✔						
Sherry and Best [57]	✔	✔			✔	✔						
Silder et al. [58]	✔	✔			✔							
Verrall et al. [55]				✔			✔					
Total	4	4	4	2	4	3	1	1	1	1	1	2

ROM range of motion

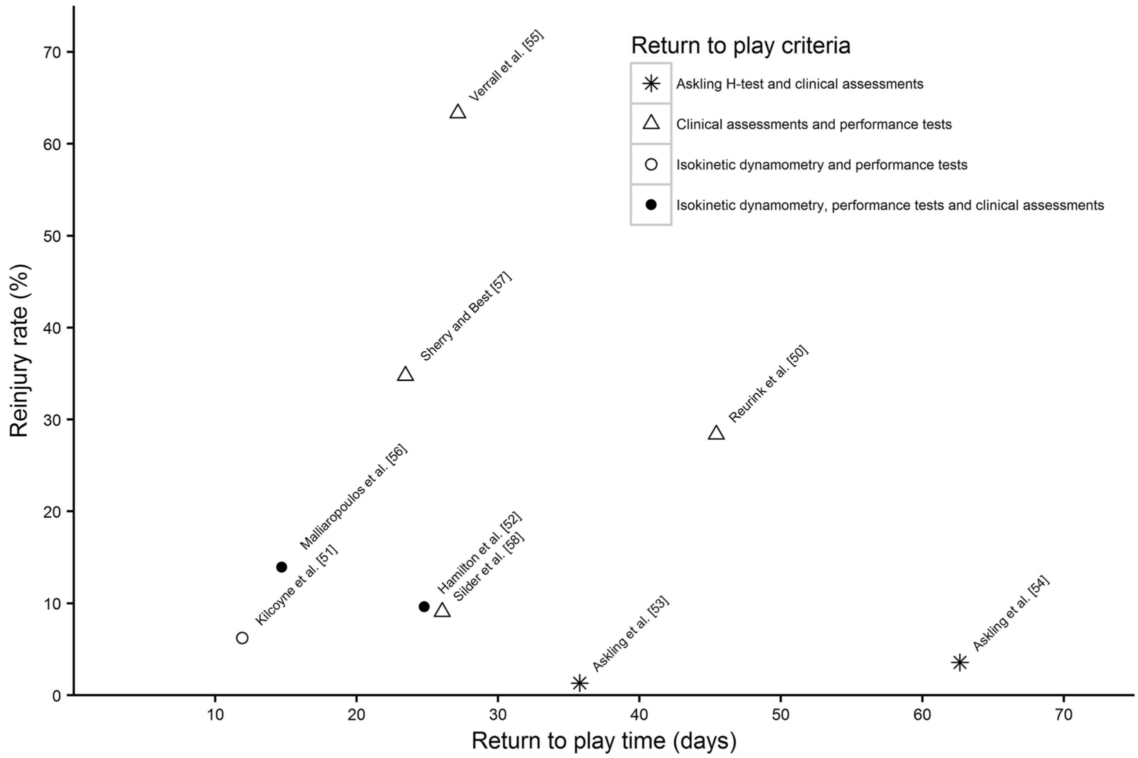


Fig. 2 Mean time taken to return to play (RTP) and overall rates of re-injury for each individual study are plotted on the *x* and *y axis*, respectively. The combination of RTP criteria implemented by each study is indicated by the *shape* of the data point as per the key in the top right-hand corner of the figure

studies [51, 52, 56]. The high-cost, laboratory-based nature and technical requirements of this methodology likely explain its low rate of implementation. Whilst potentially providing a more objective measure than manual strength assessment, the ability of isokinetic dynamometry to assess the risk of initial and recurrent HSI at the individual level has been shown to be limited [29, 72].

A more recent and less frequently implemented criterion for RTP was the Askling H-test, which provides an assessment of the athlete's ability to tolerate dynamic lengthening of the hamstring muscles without pain or apprehension [38]. The H-test has been shown to be both reliable and sensitive to detect differences in the active range of motion in athletes recovering from HSI [38] and can also potentially be implemented with relatively little and inexpensive equipment.

4.4 RTP Times and Re-injury Rates

It has been established that RTP times and re-injury rates following HSI are influenced by a multitude of factors such as injury type/severity [68, 73, 74] and mode of rehabilitation [53, 54, 57, 75]. The current systematic review, for the first time, provides data related to the implementation of different rehabilitation progression and RTP criteria and subsequent RTP times and re-injury rates.

The combination of the Askling H-test and clinical assessments as RTP criteria appears to be associated with the lowest risk of re-injury [53, 54]. These findings do require further validation, as the H-test has only been implemented in two studies by the same author, who is also credited with developing the assessment. These studies also demonstrated extended mean RTP times, which may be seen as too conservative in an elite sport environment, where non-medical decision modifiers often mean accepting an increased risk of re-injury instead of missing an important game [15–19, 76]. By comparison, studies implementing a combination of clinical assessments and performance tests were generally associated with shorter mean RTP times but increased rates of re-injury of up to nearly two thirds of participants [55]. However, it should be noted that of these studies, the study with the highest re-injury rate [55] was of low methodological quality and rehabilitation was not fully controlled by the investigators.

Despite this apparent trade-off between RTP times and re-injury rates, the implementation of isokinetic dynamometry as part of RTP criteria appears to be associated with a more desirable balance between these variables. Reduced rates of re-injury may be owing to the fact that isokinetic dynamometry provides a more objective measure of eccentric knee flexor strength, which is a known risk factor for HSI [63, 64]. Unfortunately, the aforementioned limitations of isokinetic dynamometry (see Sect. 4.3) reduce the practicality of its implementation, highlighting the need to develop and implement more clinically practical and objective measures of variables such as eccentric hamstring strength.

The improved balance between RTP time and re-injury rates seen with the implementation of isokinetic dynamometry may be further reduced with more aggressive rehabilitation progression guidelines. The single study in this review to allow a low level of pain during rehabilitation running drills also had the fastest mean RTP time and a relatively low rate of re-injury [51]. There is potential that these outcomes may be the result of greater exposure to rehabilitation stimuli, driving beneficial adaptation to rehabilitation [77]. However, this study was of the lowest methodological quality [51], lacked a comparison group and did not objectively measure desired adaptations, leaving this as mere speculation.

4.5 Limitations

The major limitation of this systematic review is that RTP times and re-injury rates have been reported regardless of factors such as injury type/severity and rehabilitation intervention. Studies confirmed HSI diagnosis via either clinical examination, magnetic resonance imaging or a combination of both, making it difficult to differentiate between structural and functional HSI, which are known to influence the time to RTP and rates of re-injury [74]. To truly investigate the time taken to achieve RTP clearance and re-injury rates in response to different rehabilitation progression and RTP criteria, the aforementioned factors must be accounted for in randomised controlled trials.

The categories chosen to group specific RTP criteria were selected by the authors and are somewhat open to interpretation. However, this categorisation allowed for straight forward interpretation of results owing to the wide range of specific RTP criteria implemented across different studies. Mean RTP time and re-injury data should also be viewed with some caution as definitions of RTP time and follow-up periods varied across the included studies. However, the definitions of RTP time have been discussed in Sect. 3.3 and the inclusion criterion of a minimum 6-month follow-up should account for the majority of re-injury risks following RTP clearance. It is also acknowledged that although the original Downs and Black quality assessment has been validated [46], the modified version implemented in the current systematic review has not. These modifications are, however, similar to those implemented in another recently published systematic review [11]. Finally, our literature search was limited to articles published in the English language only, and we are not able to account for non-English literature that would have otherwise fit the inclusion criteria.

5 Conclusions

This systematic review highlights the strong emphasis placed on the alleviation of pain to allow HSI rehabilitation progression and the reliance on subjective clinical assessments and performance tests as RTP criteria. Implementation of the Askling H-test appears to reduce rates of re-injury, although this requires further validation, whilst implementing isokinetic dynamometry as part of RTP criteria may result in a more desirable balance between RTP times and rates of re-injury when compared with relying on a combination of clinical assessments and performance tests alone. These results suggest a need for more objective and clinically practical criteria, allowing an evidence-based approach to rehabilitation progression, and potentially reducing the ambiguity involved in the RTP decision-making process.

Acknowledgements The authors thank Mr. Nicol van Dyk and Dr. Peter Hickey for reviewing this manuscript prior to submission.

Compliance with Ethical Standards

Funding No sources of funding were required in the preparation of this article.

Conflict of interest Jack Hickey, Ryan Timmins, Nirav Maniar, Morgan Williams and David Opar declare that they have no conflicts of interest relevant to the content of this review.

References

1. Orchard JW, Seward H, Orchard JJ. Results of 2 decades of injury surveillance and public release of data in the Australian Football League. Am J Sports Med. 2013;41(4):734–41.
2. Ekstrand J, Hagglund M, Walden M. Injury incidence and injury patterns in professional football: the UEFA injury study. Br J Sports Med. 2011;45(7):553–8.
3. Opar D, Drezner J, Shield A, et al. Acute injuries in track and field athletes: a 3-year observational study at the Penn relays carnival with epidemiology and medical coverage implications. Am J Sports Med. 2015;43(4):816–22.
4. Elliott MC, Zarins B, Powell JW, et al. Hamstring muscle strains in professional football players: a 10-year review. Am J Sports Med. 2011;39(4):843–50.
5. Woods C. The Football Association Medical Research Programme: an audit of injuries in professional football: analysis of hamstring injuries. Br J Sports Med. 2004;38(1):36–41.
6. Timmins RG, Shield AJ, Williams MD, et al. Biceps femoris long head architecture: a reliability and retrospective injury study. Med Sci Sport Exerc. 2015;47(5):905–13.

7. Opar DA, Williams MD, Timmins RG, et al. Knee flexor strength and bicep femoris electromyographical activity is lower in previously strained hamstrings. J Electromyogr Kinesiol. 2013;23(3):696–703.
8. Opar DA, Williams MD, Timmins RG, et al. Rate of torque and electromyographic development during anticipated eccentric contraction is lower in previously strained hamstrings. Am J Sports Med. 2013;41(1):116–25.
9. Silder A, Heiderscheit BC, Thelen DG, et al. MR observations of long-term musculotendon remodeling following a hamstring strain injury. Skeletal Radiol. 2008;37(12):1101–9.
10. Opar DA, Piatkowski T, Williams MD, et al. A novel device using the Nordic hamstring exercise to assess eccentric knee flexor strength: a reliability and retrospective injury study. J Orthop Sport Phys. 2013;43(9):636–40.
11. Maniar N, Shield AJ, Williams MD, et al. Hamstring strength and flexibility after hamstring strain injury: a systematic review and meta-analysis. Br J Sports Med. 2016;50(15):909–20.
12. Opar DA, Williams MD, Shield AJ. Hamstring strain injuries: factors that lead to injury and re-injury. Sports Med. 2012;42(3):209–26.
13. Freckleton G, Pizzari T. Risk factors for hamstring muscle strain injury in sport: a systematic review and meta-analysis. Br J Sports Med. 2013;47(6):351–8.
14. Bourne MN, Opar DA, Williams MD, et al. Eccentric knee flexor strength and risk of hamstring injuries in rugby union: a prospective study. Am J Sports Med. 2015;43(11):2663–70.
15. Hickey J, Shield AJ, Williams MD, et al. The financial cost of hamstring strain injuries in the Australian Football League. Br J Sports Med. 2014;48(8):729–30.
16. Hagglund M, Walden M, Magnusson H, et al. Injuries affect team performance negatively in professional football: an 11-year follow-up of the UEFA Champions League injury study. Br J Sports Med. 2013;47(12):738–42.
17. Creighton DW, Shrier I, Shultz R, et al. Return-to-play in sport: a decision-based model. Clin J Sport Med. 2010;20(5):379–85.
18. Orchard J, Best TM. The management of muscle strain injuries: an early return versus the risk of recurrence. Clin J Sport Med. 2002;12(1):3–5.
19. Shrier I. Strategic Assessment of Risk and Risk Tolerance (StAART) framework for return-to-play decision-making. Br J Sports Med. 2015;49(20):1311–5.
20. Jarvinen TA, Jarvinen TL, Kaariainen M, et al. Muscle injuries: biology and treatment. Am J Sports Med. 2005;33(5):745–64.
21. Maffulli N, Oliva F, Frizziero A, et al. ISMuLT guidelines for muscle injuries. Muscles Ligaments Tendons J. 2013;3(4):241–9.
22. Page P. Pathophysiology of acute exercise-induced muscular injury: clinical implications. J Athl Train. 1995;30(1):29–34.
23. Fernandes TL, Pedrinelli A, Hernandez AJ. Muscle injury: physiopathology, diagnosis, treatment and clinical presentation. Rev Bras Ortop. 2011;46(3):247–55.
24. Jarvinen TA, Jarvinen M, Kalimo H. Regeneration of injured skeletal muscle after the injury. Muscles Ligaments Tendons J. 2013;3(4):337–45.
25. Jarvinen MJ, Lehto MU. The effects of early mobilisation and immobilisation on the healing process following muscle injuries. Sports Med. 1993;15(2):78–89.
26. Kujala UM, Orava S, Järvinen M. Hamstring injuries: current trends in treatment and prevention. Sports Med. 1997;23(6):397–404.
27. Jarvinen TA, Jarvinen TL, Kaariainen M, et al. Muscle injuries: optimising recovery. Best Pract Res Clin Rheumatol. 2007;21(2):317–31.
28. Drezner JA. Practical management: hamstring muscle injuries. Clin J Sport Med. 2003;13(1):48–52.
29. Tol JL, Hamilton B, Eirale C, et al. 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.
30. Mendiguchia J, Brughelli M. A return-to-sport algorithm for acute hamstring injuries. Phys Ther Sport. 2011;12(1):2–14.
31. Schmitt B, Tim T, McHugh M. Hamstring injury rehabilitation and prevention of reinjury using lengthened state eccentric training: a new concept. Int J Sports Phys Ther. 2012;7(3):333–41.
32. DeWitt J, Vidale T. Recurrent hamstring injury: consideration following operative and non-operative management. Int J Sports Phys Ther. 2014;9(6):798–812.
33. Sherry MA, Johnston TS, Heiderscheit BC. Rehabilitation of acute hamstring strain injuries. Clin Sport Med. 2015;34(2):263–84.
34. Valle X, Tol JL, Hamilton B, et al. Hamstring muscle injuries, a rehabilitation protocol purpose. Asian J Sports Med. 2015;6(4):e25411.
35. Heiderscheit BC, Sherry MA, Silder A, et al. Hamstring strain injuries: recommendations for diagnosis, rehabilitation, and injury prevention. J Orthop Sport Phys. 2010;40(2):67–81.
36. Garrett WE Jr, Safran MR, Seaber AV, et al. Biomechanical comparison of stimulated and nonstimulated skeletal muscle pulled to failure. Am J Sports Med. 1987;15(5):448–54.
37. Jarvinen MJ, Einola SA, Virtanen EO. Effect of the position of immobilization upon the tensile properties of the rat gastrocnemius muscle. Arch Phys Med Rehab. 1992;73(3):253–7.
38. Askling 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.
39. 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.
40. Orchard J, Best TM, Verrall GM. Return to play following muscle strains. Clin J Sport Med. 2005;15(6):436–41.
41. Fournier-Farley C, Lamontagne M, Gendron P, et al. Determinants of return to play after the nonoperative management of hamstring injuries in athletes: a systematic review. Am J Sports Med. 2016;44(8):2166–72.
42. Delvaux F, Rochcongar P, Bruyere O, et al. Return-to-play criteria after hamstring injury: actual medicine practice in professional soccer teams. J Sport Sci Med. 2014;13(3):721–3.
43. Clanton TO, Coupe KJ. Hamstring strains in athletes: diagnosis and treatment. J Am Acad Orthop Sur. 1998;6(4):237–48.
44. van der Horst N, van de Hoef S, Reurink G, et al. Return to play after hamstring injuries: a qualitative systematic review of definitions and criteria. Sports Med. 2016;46(6):899–912.
45. Moher D, Liberati A, Tetzlaff J, et al. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. Ann Intern Med. 2009;151(4):264–9.
46. Downs SH, Black N. The feasibility of creating a checklist for the assessment of the methodological quality both of randomised and non-randomised studies of health care interventions. J Epidemiol Commun Health. 1998;52(6):377–84.
47. Team RC. R: a language and environment for statistical computing. Vienna: R Foundation for Statistical Computing; 2016.
48. Wickham H. ggplot2: elegant graphics for data analysis. New York: Springer; 2009.
49. De Vos RJ, Reurink G, Goudswaard GJ, et al. 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.
50. Reurink G, Goudswaard GJ, Moen MH, et al. Rationale, secondary outcome scores and 1-year follow-up of a randomised trial

of platelet-rich plasma injections in acute hamstring muscle injury: the Dutch Hamstring Injection Therapy study. Br J Sports Med. 2015;49(18):1206–12.
51. Kilcoyne KG, Dickens JF, Keblish D, et al. Outcome of grade I and II hamstring injuries in intercollegiate athletes: a novel rehabilitation protocol. Sports Health. 2011;3(6):528–33.
52. Hamilton B, Tol JL, Almusa E, et al. Platelet-rich plasma does not enhance return to play in hamstring injuries: a randomised controlled trial. Br J Sports Med. 2015;49(14):943–50.
53. Askling CM, Tengvar M, Thorstensson A. Acute hamstring injuries in Swedish elite football: a prospective randomised controlled clinical trial comparing two rehabilitation protocols. Br J Sports Med. 2013;47(15):953–9.
54. Askling CM, Tengvar M, Tarassova O, et al. 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.
55. Verrall GM, Slavotinek JP, Barnes PC, et al. Assessment of physical examination and magnetic resonance imaging findings of hamstring injury as predictors for recurrent injury. J Orthop Sport Phys. 2006;36(4):215–24.
56. Malliaropoulos N, Papacostas E, Kiritsi O, et al. Posterior thigh muscle injuries in elite track and field athletes. Am J Sports Med. 2010;38(9):1813–9.
57. Sherry MA, Best TM. A comparison of 2 rehabilitation programs in the treatment of acute hamstring strains. J Orthop Sport Phys. 2004;34(3):116–25.
58. Silder A, Sherry MA, Sanfilippo J, et al. Clinical and morphological changes following 2 rehabilitation programs for acute hamstring strain injuries: a randomized clinical trial. J Orthop Sport Phys. 2013;43(5):284–99.
59. Askling C, Karlsson J, Thorstensson A. Hamstring injury occurrence in elite soccer players after preseason strength training with eccentric overload. Scand J Med Sci Sports. 2003;13(4):244–50.
60. van der Horst N, Smits D-W, Petersen J, et al. The preventive effect of the Nordic hamstring exercise on hamstring injuries in amateur soccer players: a randomized controlled trial. Am J Sports Med. 2015;43(6):1316–23.
61. Petersen J, Thorborg K, Nielsen MB, et al. Preventive effect of eccentric training on acute hamstring injuries in men's soccer: a cluster-randomized controlled trial. Am J Sports Med. 2011;39(11):2296–303.
62. Arnason A, Andersen TE, Holme I, et al. Prevention of hamstring strains in elite soccer: an intervention study. Scand J Med Sci Sports. 2008;18(1):40–8.
63. Opar DA, Williams MD, Timmins RG, et al. Eccentric hamstring strength and hamstring injury risk in Australian footballers. Med Sci Sport Exerc. 2015;47(4):857–65.
64. Croisier JL, Ganteaume S, Binet J, et al. Strength imbalances and prevention of hamstring injury in professional soccer players: a prospective study. Am J Sports Med. 2008;36(8):1469–75.
65. Timmins RG, Bourne MN, Shield AJ, et al. Short biceps femoris fascicles and eccentric knee flexor weakness increase the risk of hamstring injury in elite football (soccer): a prospective cohort study. Br J Sports Med. 2016;15(24):1524–35.
66. Timmins RG, Ruddy JD, Presland J, et al. Architectural changes of the biceps femoris long head after concentric or eccentric training. Med Sci Sport Exerc. 2016;48(3):499–508.
67. Hegedus EJ, Cook CE. Return to play and physical performance tests: evidence-based, rough guess or charade? Br J Sports Med. 2015;49(20):1288–9.
68. 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. 2006;40(1):40–4.
69. Jacobsen P, Witvrouw E, Muxart P, et al. A combination of initial and follow-up physiotherapist examination predicts physician-determined time to return to play after hamstring injury, with no added value of MRI. Br J Sports Med. 2016;50(7):431–9.
70. Bohannon RW. Manual muscle testing: does it meet the standards of an adequate screening test? Clin Rehabil. 2005;19(6):662–7.
71. Wadsworth CT, Krishnan R, Sear M, et al. Intrarater reliability of manual muscle testing and hand-held dynametric muscle testing. Phys Ther. 1987;67(9):1342–7.
72. van Dyk N, Bahr R, Whiteley R, et al. Hamstring and quadriceps isokinetic strength deficits are weak risk factors for hamstring strain injuries: a 4-year cohort study. Am J Sports Med. 2016;44(7):1789–95.
73. Brukner P, Connell D. 'Serious thigh muscle strains': beware the intramuscular tendon which plays an important role in difficult hamstring and quadriceps muscle strains. Br J Sports Med. 2016;50(4):205–8.
74. Pollock N, Patel A, Chakraverty J, et al. 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.
75. Pas HI, Reurink G, Tol JL, et al. Efficacy of rehabilitation (lengthening) exercises, platelet-rich plasma injections, and other conservative interventions in acute hamstring injuries: an updated systematic review and meta-analysis. Br J Sports Med. 2015;49(18):1197–205.
76. Verrall GM, Brukner PD, Seward HG. 6. Doctor on the sidelines. Med J Aust. 2006;184(5):244–8.
77. Khan KM, Scott A. Mechanotherapy: how physical therapists' prescription of exercise promotes tissue repair. Br J Sports Med. 2009;43(4):247–52.