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REVIEW

Hamstring muscle injuries in athletics

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ABSTRACT

Hamstring muscle injuries (HMI) are a common and recurrent issue in the sport of athletics, particularly in sprinting and jumping disciplines. This review summarizes the latest literature on hamstring muscle injuries in athletics from a clinical perspective. The considerable heterogeneity in injury definitions and reporting methodologies among studies still needs to be addressed for greater clarity. Expert teams have recently developed evidence-based muscle injury classification systems whose application could guide clinical decision-making; however, no system has been adopted universally in clinical practice, yet.

The most common risk factor for HMI is a previously sustained injury, particularly early after return-to-sport. Other modifiable (e.g. weakness of thigh muscles, high-speed running exposure) and non-modifiable (e.g. older age) risk factors have limited evidence linking them to injury. Reducing injury may be achieved through exercise-based programs, but their specific components and their practical applicability remain unclear.

Post-injury management follows similar recommendations to other soft tissue injuries, with a graded progression through stages of rehabilitation to full return to training and then competition, based on symptoms and clinical signs to guide the individual speed of the recovery journey. Evidence favoring surgical repair is conflicting and limited to specific injury sub-types (e.g. proximal avulsions). Further research is needed on specific rehabilitation components and progression criteria, where more individualized approaches could address the high rates of recurrent HMI. Prognostically, a combination of physical examination and magnetic resonance imaging (MRI) seems superior to imaging alone when predicting 'recovery duration,' particularly at the individual level.

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Track and field; posterior thigh muscles; sprinting; classification system; risk factor; rehabilitation; return to sport

Introduction

Hamstring muscle injuries (HMI) are common in a range of sports, most commonly those involving sprinting [1,2] or kicking [3]. There is a breadth of injuries, ranging from minor to severe [4], with a range of different classification systems in use, leading to confusion surrounding nomenclature [3,5,6]. The more severe subtypes can have a lengthy recovery, and these injuries can have high recurrence rates [4] leading to concern among athletes and support staff about the optimal way these should be considered and managed [7–9].

The hamstring muscle group is comprised of the long and short heads of biceps femoris (BFlh/BFsh respectively), the semitendinosus (ST) and the semimembranosus (SM) muscles, and they are situated in the posterior compartment of the thigh [10]. Except the BFsh which originates posteriorly from the medial femur, the other three components of the hamstrings originate from the ischial tuberosity and are biarticular muscles crossing both the hip and the knee joints. The BFlh conjoins with the BFsh distally, to insert into the fibular head laterally to the knee. The SM and ST are attached to the medial tibial condyle, the latter as part of pes anserinus (Figure 1).

This complex configuration underlies the inherent anatomical variability among the four hamstring muscles. The BFlh and SM muscles exhibit larger pennation angles, larger physiological cross-sectional area, and shorter fascicles (relative to muscle length), compared to the BFsh and ST, the latter having the longest free tendon of all [11]. These differences might play an important role in the differential distribution of strain during an eccentric action of the muscle group and could partially explain the higher incidence of injury of the BFlh (70%) and the SM (19%), compared to the ST (4%) and BFsh (2%) [8].

The hamstrings function mainly as knee flexors and hip extensors, but they also serve as knee stabilizers [10]. Compared to their antagonists, the quadriceps femoris muscles, the hamstrings are anatomically optimized for less strong but faster contractions, given their smaller physiological cross-sectional area and longer fascicle lengths, which is in accordance with their generally eccentric role and possibly contributes to higher injury risk than their antagonists [11].

Athletics (also known as 'Track and Field') is a diverse sport including road, cross-country and trail running, and the specific track-and-field disciplines, comprised of various running, hurdling, jumping, and throwing events. Each event challenges the human body in a distinct way; highlighted by the different musculoskeletal structures that are more injury-prone

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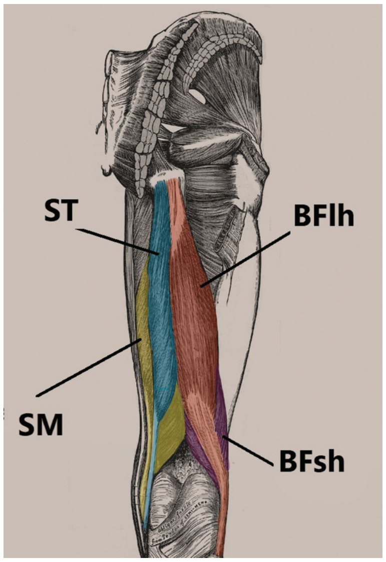

Figure 1. Schematic anatomical representation of the hamstring muscles of the right lower limb. ST: semitendinosus, SM: semimembranosus, BFlh: long head of biceps femoris, BFsh: short head of biceps femoris. Adapted from: https://teachmeanatomy.info

in each discipline, ranging from lower-leg injuries in distance runners to upper-extremity and trunk injuries in throwers [12]. The hamstring muscles are most engaged in sprinting and jumping modalities, where they are increasingly activated with increasing running speed during the late-swing and early-stance phases of the running gait cycle, when they undergo high stretching and torsional loads, respectively [13,14]. This is supported by electromyography measurements during treadmill sprinting [15] and by three-dimensional kinetic analysis of the knee joint during variable-speed running on an indoor synthetic track [16]. The key role of the hamstrings in sprinting is also indicated by results showing that among trained sprinters, best performers tend to have higher peak isokinetic eccentric strength [17] and larger muscle volumes [18] of the hamstrings.

In addition to their high incidence in athletics, HMI are also highly burdensome in other sports that involve high-speed running, such as football [19], American football [20], and rugby union [21]. However, it cannot be assumed that all sports stress the hamstring muscles the same way. In team sports, in contrast to track-and-field, athletes are required to sprint multiple times during a match, usually already in motion before they start sprinting, while their movement path is highly unpredictable and often involves changes of direction and at least potential contact with other players. This may explain why HMI in athletics involved predominantly a sprinting-type mechanism (93%) [22], while in football, the same research group found significantly less sprinting-type injuries (72%) and more stretch-type injuries (28%) [23], which may potentially have a slower recovery [24], or rugby in which HMI have been found to be caused by a range of different activities within this sport, not just sprinting [25].

Also compared to team sports, athletics are characterized by relatively longer training periods and shorter competitive seasons. The total training exposure was measured as 25 times larger than the respective in competitions [26]. So, even though only one-fourth of seasonal injuries occurred during competitions [27], when standardized for total time exposure, injury incidence was 3.8 times greater during competitions than training [26]. For HMI particularly, nearly half were competition-related [26], representing ~17% of the total injuries sustained during international athletics championship competitions [1]. Given that competitions usually include only one or two maximal sprints, while sprint training sessions can be comprised of much more, this may reflect the greater significance of maximal effort during short-duration performance tasks than that of muscle fatigue in eliciting HMI in athletics.

Hamstring muscle fatigue appears to be accumulated more rapidly during change-of-direction than straight-line sprinting [28] which may lead to decrements in lumbo-pelvic control, leg stiffness, knee stability, and/or energy transfer through the muscle-tendon unit that may predispose to HMI [29] if sprinting is repeated under fatigued state as is often the case in the later stages of team sport matches, as evidenced by higher HMI incidence the last minutes of each half-time interval in football [30]. In athletics, the role of hamstring fatigue is less researched, although a 3-year observational study noted higher incidence of HMI in the 4x400m compared to the 4x100m relays [31], which could indicate some involvement of muscle fatigue in the injury risk profile of longer sprints, but more research is warranted in this area.

Another unique feature of athletics found only in the 200 m and the 400 m disciplines is curved sprinting. It is speculated that sprinting while on an anti-clockwise swerve, as undertaken during a 200 m or 400 m race, might demand greater strength of the ST and SM muscles of the outer (right) leg and stronger BF muscles of the inner (left) leg [32]. Kinematic studies have pointed the stabilizing role of the left leg and the accelerating role of the outer leg during curved sprints [33]. However, the only study examining the muscle activation patterns on curved track sprinting has shown similar surface EMG values compared to straight sprinting of the BF muscle, though this could be attributed to methodological issues such as the measurement of the BF activity during acceleration only and before maximal velocity was obtained [34]. More research is necessary to elucidate how the observed biomechanical differences are explained by distinct activation patterns during curved sprinting and what are the possible implications on HMI.

Therefore, the distinct differences between athletics and team sports regarding sprinting may also lead to important differences in the clinical aspects of HMI. This may render the evidence about the etiology, prevention, and management of HMI not directly transferable from one sport to another. Thus, a sport-specific review of the literature is necessary to extract best-practice recommendations and identify future research perspectives.

This narrative review summarizes the latest literature on HMI in the disciplines of athletics with the highest injury incidence (i.e. sprints and jumps), from a clinical perspective. This sport-specific evidence synthesis can be used as a guide by practitioners. The discussion spans from the injury's epidemiology to the contemporary classification systems, and from the factors contributing to higher injury and reinjury risk, to the current preventive and therapeutic strategies that may be advantageous in risk mitigation and faster return to sport (RTS). An outline of the evidence referenced in the following discussion is provided, highlighting the involvement or not of track-and-field athletes to emphasize the sport-specific nature of this review (Table 1).

Burden of injury

The great heterogeneity in injury definitions and methodologies of injury reporting (e.g. self-reporting [27] vs medically- or imaging-confirmed diagnoses [1,26]) among epidemiological studies makes direct comparison of results challenging between studies. This is compounded further by the methods of recording of athlete exposures, with some studies reporting incidence data based per 1 athlete-year (i.e. the exposure of one athlete in one competitive season), while others reporting data as incidence per 1000 athlete exposures (AE) [35], considering every distinct training session or competition as 1 AE [26].

Hamstring muscle injuries (HMI) are not equally frequent across different athletics disciplines. These injuries are believed to be rare in trail-running [36] but are the most frequent diagnoses in sprints and jump disciplines, accounting for 23.5% and 10.2% of injuries reported annually in international-level athletes, respectively [27]. Cumulatively, HMI represented 61% of all muscle strains across all track-and-field disciplines with an incidence of 0.5 injuries per 1000 athlete-exposures (AE) [26], which approximates to 0.2 injuries per athlete-year, given that this cohort of adolescents accumulated ~8 sessions weekly. Comparably, in a adults' cohort of the British team, the incidence was calculated as 0.3 new cases per athlete-year [35]. A direct comparison of HMI across different age groups of the Swedish national athletics team has also shown that adult athletes were more susceptible to injury than youth athletes [27]. The reasons behind the higher injury rates in adults have not been properly researched yet, as discussed in more detail later. Overall, it seems that approximately one out of four elite track-and-field athletes are sustaining a new HMI each year.

However, the actual 'burden' of injury may be better reflected on the combination of both incidence and time lost due to injury [37]. For HMI in adolescent athletes, the time lost due to injury was estimated from ~2 to ~6 weeks depending on the severity, resulting in ~13 days lost/1000AE (~5.2 days lost per athlete-year, assuming 8AE per week), which amounted to 16.5% of the overall injury-burden in track-and-field [26]. Similarly, in adults, the mean time loss was estimated at 2.7 weeks (95%CI 2.2–3.2 weeks), resulting in an annual burden of 5.3 days lost per athlete-year, across all disciplines and both sexes [35]. Specifically for sprint disciplines, HMI were both more frequent and severe (about 5 times) with a burden of 62 days lost/1000AE [26]. This is equivalent to saying that a typical high-level sprinter training ~8 times per week is expected to miss ~25 days each year due to HMI.

Nonetheless, these results were found predominantly in studies involving male athletes, and the evidence on the burden of HMI on female athletes and any gender differences is much more limited. Recent data from both training and competition injuries in elite track-and-field athletes suggest that females present lower overall and thigh-located injury risk compared to males [1,27], although the causative factors for any such difference have not yet been fully explored in the literature, and the implications in female athletes remain unclear as many of the prevalence and interventional studies have included male athletes only [25,38].

There needs to be better consensus on the presentation of epidemiological findings and a collaborative secondary data analysis could provide greater insight into the actual burden of HMI in different subpopulations of elite track-and-field athletes, and whether different demographic information (age, gender, ethnicity, etc.) may have specific impact on risk factors, and the strength of these associative risks.

Classification systems and terminology

Developing and implementing a classification system for muscle injuries with prognostic validity (i.e. an accurate estimation of the injury's severity and prediction of return-to-sport time) [6], which guides clinical decision-making and optimizes rehabilitation is of paramount importance [8]. Despite the best endeavors, a single, universally accepted injury-grading system has yet to be established despite more than 60 years have passed since the first published attempts [39,40]. The earliest grading systems relied solely on the clinical manifestations of muscle injury (e.g. for indirect tearing injury: sharp, localized, stretch-aggravated pain following a 'snap' sound, loss of muscle function, ± fall of the athlete, ± palpable muscle defects or gaps, ± hematoma) [3] but they lacked validity and objectivity [39,40]. The addition of ultrasound [41–44] and, primarily, magnetic resonance imaging [45,46] criteria resulted in less subjective grading systems, but the typical 3-stage categorization of severity maintained its limited clinical significance, with vast differences in what constituted a 'Grade 1,' 'Grade 2,' and 'Grade 3' injury reported between different classification systems [39,40]. Within the last decade, however, there have been multiple cooperative efforts to create classification systems with evidence-based prognostic potency, originally focused on HMI but potentially applicable to any muscle injury (Table 2) [3,5,6].

A. Munich classification

[3,5,6] The 'Munich classification' [3] was an expert-derived consensus-based grading system seeking to bring clarity to nomenclature and terminology. It distinguished between 'structural' injuries (further subdividing those in indirect & direct) and 'functional' injuries, and the system has been validated in football [47] but not yet in athletics. This consensus meeting set specific definitions and recommendations for terminology to be used, seeking to declutter the terminology around the description of muscle injuries. Given the long history, public/lay knowledge and terms, frequency, and considerable burden of muscle injuries in sports generally, the diverse wealth of words defining or describing a muscle injury is not surprising. Ranging from layman's terms such as 'pulled muscle' to commonly used words in the clinical setting (e.g.

Table 1. Summary of the research articles referenced in the discussion. The sport population of each study and the summary findings are presented, categorized by section. HMI: hamstring muscle injuries, BAMIC: British Athletics Muscle Injury Classification, ACL: anterior cruciate ligament, BFlh: biceps femoris long head, ST: semitendinosus, NHE: Nordic hamstring exercise, RTS: return-to-sport, PRP: platelet-rich plasma, MRI: magnetic resonance imaging.

Section	Author (year)	Study design	Sport population	Summary finding
Burden of injury	Viljoen et al. (2021) [36]	systematic review	trail running	HMI are rare in trail running
	Jacobsson et al. (2013) [27]	prospective cohort study	track-and-field	HMI are the most frequent injuries in elite sprinters (20%) and jumpers (10%)
	Martínez-Silván et al. (2021) [26]	prospective cohort study	track-and-field	HMI incidence was calculated at 0.5 cases per 1000 AE
	Kelly et al. (2022) [35]	prospective cohort study	track-and-field	HMI incidence was calculated at 0.3 cases per athlete-year
	Bahr et al. (2018) [37]	critical review	n/a	Burden of injury accounts for both incidence and time lost due to injury
	Edouard et al. (2016) [1]	observational study	track-and-field	HMI were the most common injuries in world athletics championships and more frequent in males
Classification systems and terminology	Mueller-Wohlfahrt et al. (2013) [3]	consensus-based	n/a	A newly proposed nomenclature and classification system for muscle injuries
	Hamilton et al. (2015) [39]	narrative review	n/a	HMI classification systems have low clinical and radiological validity
	Grassi et al. (2016) [40]	narrative review	n/a	Recent HMI classification systems could improve clinical practice
	Pollock et al. (2014) [5]	n/a	track-and-field	A newly proposed classification system for HMI
	Valle et al. (2017) [6]	consensus-based	n/a	A newly proposed classification system for muscle injuries
	Tol et al. (2013) [50]	editorial	n/a	"Functional" injuries might not be separated from "structural" injuries in the "Munich consensus"
	Patel et al. (2015) [51]	retrospective study	track-and-field	BAMIC is a reliable classification system for HMI in athletics
	Pollock et al. (2021) [8]	prospective cohort study	track-and-field	BAMIC-guided rehabilitation has low (3%) re-injury rate of HMI
	Pollock et al. (2016) [52]	retrospective study	track-and-field	Intratendinous HMI are of higher severity
	Paton et al. (2023) [55]	consensus-based Delphi study	n/a	BAMIC is the mostly used (58%) classification system by clinicians currently
Risk factors	Green et al. (2020) [61]	systematic review	33% football 27% Australian football 9% track-and-field	Past HMI, ACL and calf muscle injury are the strongest risk factors of HMI
	Malliaropoulos et al. (2018) [62]	observational cohort study	track-and-field	Past ankle ligamentous injury is a strong risk factor of HMI
	Afonso et al. (2021) [60]	narrative review	n/a	Certain anatomic and physiological variations of the hamstring muscles may predispose to HMI
	Huygaerts et al. (2021) [63]	narrative review	n/a	
	Sugiura et al. (2008) [64]	prospective cohort study	elite sprinters	Eccentric weakness of the hamstring muscles is associated with HMI
	Kalema et al. (2021) [65]	literature review	sprinters	No strong evidence linking any biomechanical parameter to higher HMI risk
	Higashihara et al. (2018) [68]	cross-sectional study	sprinters	BFlh is more engaged in acceleration while ST is more activated during maximal speed sprinting
Risk mitigation	Rudisill et al. (2022) [71]	systematic review	multiple sports	HMI risk mitigation is primarily achieved by exercise-based programs implementation currently
	Vatovec et al. (2021) [72]	systematic review	team sports	Eccentric loading of the hamstring muscles seems effective in preventing HMI
	van Dyk et al. (2019) [73]	systematic review	team sports	Performing the NHE seems to halve the HMI risk
	Malliaropoulos et al. (2012) [75]	narrative review	track-and-field	Proposal of exercise selection criteria for HMI prevention in track-and-field
	Alt et al. (2021) [17]	repeated measures longitudinal study	sprinters	Performing the NHE improves the late-swing mechanics of sprinting
	van Hooren et al. (2017) [32]	narrative review	n/a	The activation of the hamstring muscles in sprinting might be primarily isometric rather than eccentric
	van Hooren et al. (2017) [32]	narrative review	n/a	Proposal of primarily isometric exercises for HMI risk mitigation
	Pincheira et al. (2022) [76]	cross-sectional study	n/a	The NHE results in considerable stretching of the musculotendinous unit
	Alt et al. (2022) [77]	case study	male long jumper	Variations of the NHE can provide a stepwise framework for HMI rehabilitation and risk mitigation
	Bourne et al. (2018) [78]	narrative review	n/a	Specific structural adaptations might be key for exercise selection during HMI prevention
	van Hooren et al. (2022) [80]	cross-sectional study	n/a	The Biceps femoris and the Semimembranosus are more activated during hip-dominant exercises, while the Semitendinosus is primarily activated during knee-dominant exercises

(*Continued*)

Table 1. (Continued).

Section	Author (year)	Study design	Sport population	Summary finding
Management of injury and return to sport	Dubois et al. (2022) [81]	editorial	n/a	Early management of muscle injuries should emphasize protection, elevation, avoidance of anti-inflammatory medication, compression and patient education (P.E.A.C.E.)
	Fournier-Farley et al. (2016) [24]	systematic review	n/a	Rehabilitation after HMI that included eccentric hamstring loading led to faster RTS
	Chang et al. (2020) [82]	narrative review	n/a	Higher grade HMI and tendon avulsions might be better managed by surgical repair, especially in elite athletes
	MacDonald et al. (2019) [9]	expert-based proposition	track-and-field	The BAMIC classification of HMI may guide the rehabilitation process, based on the specific anatomic injured structure
	Askling et al. (2014) [22]	prospective randomized clinical trial	track-and-field	Including hamstring lengthening exercises in the rehabilitation protocol led to faster RTS after HMI
	Erickson et al. (2017) [83]	narrative review	n/a	Sport specificity is a key parameter for exercise selection and progression criteria selection during rehabilitation of HMI
	Paton et al. (2023) [57]	consensus-based Delph study	n/a	Experts agree on the underlying principles of HMI rehabilitation, but specifically defined RTS criteria are not yet universally accepted
	Bayer et al. (2016) [84] Bayer et al. (2017) [85]	randomized controlled trial	recreational athletes	Early rehabilitation quickened RTS, but functional and structural outcome progression was similar in both early and late rehabilitation after thigh or calf muscle injury
	Mendiguchia et al. (2011) [86]	clinical commentary	football	proposal of a progression model through rehabilitation after HMI
	Askling et al. (2013) [23]	prospective randomized clinical trial	football	Including hamstring lengthening exercises in the rehabilitation protocol led to faster RTS after HMI
	Mendiguchia et al. (2017) [87]	prospective randomized clinical trial	football	Individualized, multifactorial rehabilitation after HMI led to slower RTS but lower re-injury rates in male footballers
	Vermeulen et al. (2022) [7]	prospective randomized clinical trial	multiple sports 5% track-and-field	Introducing lengthening exercises early in the rehabilitation process after HMI did not have an impact on RTS or re-injury rates
	Aspetar Hamstring Protocol (2023) [88]	expert-based proposition	multiple sports	clinical guide to rehabilitation after HMI
	Kayani et al. (2021) [89] Ayuob et al. (2022) [90]	Case series	professional athletes from multiple sports	Surgical repair of distal musculotendinous HMI led to faster RTS and improved clinical outcomes Surgical repair of proximal Biceps femoris injuries led to faster RTS and low re-injury rates
	Bodendorfer et al. (2018) [91]	systematic review	multiple sports	Surgical repair of proximal avulsion HMI led to improved clinical outcomes but with high (23%) complication rate compared to nonoperative management
	van der Made et al. (2022) [92]	prospective non-randomized clinical trial	n/a	Similar outcomes at 1 year follow-up between surgical and non-surgical management of HMI
	Plastow et al. (2023) [56]	consensus-based Delphi study	n/a	Agreement that higher grade HMI, especially in elite athletes, may be considered for surgical repair
	Grassi et al. (2018) [93]	systematic review	n/a	There is no conclusive evidence that PRP plays a role in the management of HMI
	Moen et al. (2014) [94]	prospective comparison studies	multiple sports	Clinical parameters and straight leg raise deficit is better predicting time to RTS compared to MRI, especially in low grade HMI
	Jacobsen et al. (2016) [95]			Baseline and follow-up physical examination post HMI is better predicting time to RTS compared to MRI
	de Vos et al. (2014) [96]			Clinical parameters after HMI were better reflecting re-injury risk compared to MRI
	Wangensteen et al. (2016) [97]	case series	multiple sports	Recurrent HMI occurred in the same anatomic location with the index HMI, early after RTS
	Reurink et al. (2015) [98]	prospective cohort study	multiple sports	Fibrosis is commonly seen in MRI after HMI and is not associated with re-injury risk

Table 2. A summary of the three main HMI classification systems. The year of first publication, the primary grading tool, the determining factors of classification, and the validation in athletics are compared.

		Munich consensus [3]	British Athletics'BAMIC' [5]	Aspetar & Barcelona FC'MLG-R' [6]
	Year published	2013	2014	2017
	Primary grading tool	Patient history and physical examination	MRI (24–48 hr post-injury)	MRI (24–48 hr post-injury)
Determining factors	Grading	1 to 4	0 to 4	0 to 3
	Anatomic location within muscle	No	Intramuscular Myofascial Intratendinous	Proximal Medial Distal
	Injury mechanism	Yes	No	Yes
	Injury history	No	No	New vs recurrent
	Validated in athletics	Not yet	Yes [51,52]	Not yet

'tear,' 'strain,' 'hardening,' 'laceration'), they have all infiltrated in the academic literature to various extents without ever being succinctly evaluated for appropriateness, causing miscommunication among clinicians and researchers [3]. The 'Munich classification' has proposed that for structural muscle injuries, particularly hamstring injuries, 'tear' is the most suitable term, whereas 'strain' should be avoided as it relates to the transmission of force rather than the injury itself, originating as it does from the field of biomechanics [3]. Despite this international position, recent published studies have readily identified that continue to use the term 'strain' as a muscle injury descriptor [48,49], highlighting the resistance among some researchers to accept these recommendations universally.

Another important discrimination was made between 'structural' injuries, which are subclassified by severity of the structural damage seen on imaging, and 'functional muscle disorders' without imaging evidence of a tear, further classified as overexertion-related (i.e. fatigue-induced or delayed-onset muscle soreness) and neuromuscular (i.e. spine-related or muscle-related). However, it is questioned whether all functional disorders are indeed free from structural damage, and not merely minor structural injuries undetectable by current imaging techniques [50]. Considering that such diagnoses, albeit not firmly defined, might still account for lost days of training or competition, future research should aim to explore the functional/structural overlap of muscle injuries and inform classification and decision-making.

B. British athletics muscle injury classification (BAMIC)

Another recent attempt to give a reliable approach to muscle injury classification with a direct focus on HMI in athletics was proposed by British Athletics, which was based on key anatomical features of the injury on MRI (e.g. length of tear, cross-sectional area of edema and injury location) with proven prognostic significance [5]. This grading system expands on the traditional 3-stage categorization by distinguishing between intramuscular, musculotendinous, and intratendinous lesions, independently of their magnitude. Notably, zero-grade injuries (MRI negative) are included in this system, but the term 'functional disorder' is avoided [5]. Contrary to the 'Munich classification,' the BAMIC has been shown to be both reliable [51] and valid [8,52] in track-and-field HMI, and it has started being generalized to other muscle groups [53] and sports [54]. However, its reliance on very early imaging results (<2 days post-injury) may limit its application in some settings.

C. Barcelona FC & Aspetar clinic

Most recently, a proposed classification system by Barcelona FC and the Aspetar clinic [6] classifies muscle injuries based on the **M**echanism (direct or indirect), **L**ocation (proximal, medial, distal), **G**rade (MRI-based), and **R**ecurrent episode of injury (i.e. the 'MLG-R' system) [6]. The latter factor, that of 'recurrence,' which is not included in the BAMIC, potentially adds significant prognostic value as recurrent injuries tend to have worse prognosis than index ones [6]. However, validation of the MLG-R classification system is pending, while, as with BAMIC, the need for an MRI scan early-on post-injury may limit its wider application.

D. 'London consensus' on HMI

In 2020, a Delphi study comprised two online surveys of 35 and 99 experts on diagnosing and/or managing HMI interspersed by a face-to-face meeting for 15 of them that took place in London, recently published its results [55–57]. Regarding current classification systems, most clinicians preferred the BAMIC system (58%), followed by the 'Munich classification' (12%), although they agreed that no single system is entirely adequate to guide clinical decision-making and further development should incorporate details on the exact muscle injured, injury mechanism, and patient-related outcomes [55]. Sport-specificity was one of the features that experts deemed necessary during classification to guide management while acknowledging the limited research on this area [55].

Risk factors

The detection of risk factors has been established as an essential step for the prevention of injuries for more than three decades [58]. Using a 'dynamic recursive model of sports injuries' model, risk factors can be athlete-related (intrinsic) which predispose to injury, or sport/environment-related (extrinsic) which make the already predisposed athletes even more susceptible to injury [59]. Sub-categorization is then possible as to whether these factors are potentially modifiable (e.g. bodyweight, strength deficits), which could lead to the development of targeted interventions that could mitigate the risk, or non-modifiable (e.g. age, history of injuries), whose presence could imply different strategies, such as training/racing load management to minimize the exposure to potential injury inciting events [60]. The following discussion is summarized in Table 3.

A. Non-modifiable risk factors

Regarding HMI, the latest systematic review of risk factors, pooling data from more than 8000 injury incidents showed that athletes with previously sustained HMI have a 2.7–4.8 times greater risk of sustaining a new HMI, with more recent injuries lying on the higher end of this spectrum [61]. Counterintuitively, the risk of HMI has been found higher in elite track-and-field athletes with a sustained ankle ligamentous injury than in those with a previous HMI as shown by a 17-year observational study, but no explanation for this finding has yet been identified [62]. Other injuries that increase the risk of subsequent HMI are of the ipsilateral ACL (RR = 1.7) and the calf muscles (RR = 1.5), but not to the quadriceps or the groin, though the evidence is not as strong yet [61]. Moreover, older age was also associated with a higher HMI risk, yet 'old' was not formally arithmetically specified [61], although in an elite sprinting population who are most at risk, this value may be younger than many readers would consider as 'old.' It is not yet known if this is attributed to the biological effects of aging itself, or the increased training and competition exposure that is accumulated in older athletes with confounding previous injury history [61].

Given the considerable inter-individual variability of most anatomical features of the hamstring muscles, particularly in the small numbers of elite athletes studied, it is only speculated that athletes with specific variations (e.g. smaller tendon–muscle ratio, smaller aponeurosis–muscle ratio, and larger proportion of type II fibers) could be at higher risk of injury [60]. The already unique anatomical complexity of the hamstring muscles, such as the different innervation between BFsh and BFlh which might complicate the motor control of hamstring muscles, or the larger pennation angles of the BFlh closer to its origin which could result in an unequal distribution of tensile stress, could partially explain their higher vulnerability to injury [63]. However, there is no evidence to categorically establish the contribution of such factors to the risk profile of HMI.

Table 3. Summary of HMI risk factors, categorized by whether they are modifiable or not, and whether they are athlete-related (intrinsic) or environment-related (extrinsic). The level of evidence for each factor is also provided.

	Modifiable		Non-modifiable	
	Risk factor	Evidence	Risk factor	Evidence
Extrinsic	Larger exposure to high-speed running	weak [61]		
Intrinsic			Past HMI	strong [61]
	Eccentric weakness of knee flexors	moderate [61]	Past ankle ligamentous injury	moderate [62]
			Past ACL injury	moderate [61]
	Concentric weakness of hip extensors	moderate [61]	Past calf muscle injury	moderate [61]
			Older age	weak [61]

B. Modifiable risk factors

Regarding modifiable risk factors, there is some evidence that inferior eccentric strength of knee flexion and concentric strength of hip extension predispose [64] track-and-field sprinters to HMI, but no explicit relationship between any strength or flexibility deficit and risk of HMI has been established yet, according to the latest systematic review [61]. Other studies attempted to identify certain features of sprinting mechanics and techniques that could expose athletes to HMI, but the results were equivocal and the evidence conflicting possibly due to the suboptimal study designs used in most of the available studies [65].

Lastly, exposure to faster running was associated with higher HMI risk, although this was identified from work done in team sports and may not reflect the actual effect of high-speed running in athletics [61]. Besides, this systematic review included only a few studies conducted in track-and-field athletes (i.e. 8 out of 78) [61], and so further and more sport-specific research is needed to elucidate which factors, and to what extent, increase the risk of HMI in athletics. Such research should acknowledge the limitations of studying each factor in isolation, as has been done so far, and embrace a multifactorial model, where each factor affects HMI risk both directly and indirectly, by modifying other factors' effect on HMI [66].

Despite the unique characteristics of block-start acceleration in sprinting disciplines compared to accelerating from a standing, or often jogging state in team sports, not much is known about the HMI risk during the early acceleration phase of track sprinting. Biomechanical studies have shown that the high-force/low-velocity acceleration phase is relying more on the 'push-off' action of the calf, knee extensors, and hip extensors [67], while only the BFlh seems to be highly engaged, highlighting its hip extending role [68]. In contrast, during maximal speed running the ST is relatively more engaged, as a primary knee flexor during the late swing phase [68]. However, no study has directly compared the injury incidence of acceleration vs maximal speed sprinting and/or associated it with individual muscle injury distribution. Potentially, a retrospective video-analysis study of HMI sustained during sprint competitions identifying the distance covered until injury while noting which muscle was injured each time could shed light on the relative importance of block-start acceleration in HMI risk.

Finally, it should be highlighted that despite the insight that identified risk factors bring on the etiology and the mechanisms of HMI, it is not yet believed that they can be reliably used as screening tools with predictive potency [69,70].

Risk mitigation

Even though strength deficits have not yet been considered as undisputed risk factors for HMI [61], exercise-based programs that focus on loading the hamstring muscles have been considered the primary preventive intervention [71]. Provided the eccentric role of the hamstring muscles during the late-swing phase of running, eccentrically strengthening exercises have gained much focus on the literature for HMI prevention and they are generally shown to be effective, although compliance is recognized to be poor in clinical settings which limits their efficacy [72]. The commonly used and extensively researched Nordic hamstring exercise (NHE) has been shown to reduce HMI risk in half (RR = 0.49, 95% CI: 0.32–0.74) [73], though this has been criticized to be an overestimation due to methodological errors in the meta-analysis, mainly regarding inclusion of ineligible studies [74]. After narrowing down the included studies, the updated effect of the exercise was not conclusively protecting, with RR = 0.59 (95% CI: 0.27–1.29). Regardless, the NHE is not the only component of such exercise programs, with alternative ones that do not include the NHE to be equally protective with those that include it [72]. However, most of the data behind these results comes mainly from footballers who may have a different injury profile than track-and-field athletes, which raises concerns about the validity of the effectiveness of such exercises to other sports. Particularly in athletics, an experts' review has proposed similar exercises for primary prevention of HMI, based on indirect evidence from biomechanical studies and clinical trials in athletes of other sports, mainly football [75]. A recent study in track sprinters sheds light on the transferability of adaptations derived from intensive NHE training in the late-swing phase mechanics of sprinting, which could partially explain the protective effect of such exercises, beyond muscle strength gains [17]. However, prospective clinical trials in track-and-field athletes are needed to establish the true magnitude of injury protection of the NHE and other similar exercises.

In accordance with the assumption that the hamstring muscles are isometrically, rather than eccentrically, activated during the late-swing phase of running [32], the inclusion of high-load isometric exercises such as single-leg roman-chair holds and split-step squats with forward lean, which challenge the hamstring muscles in both the hip and knee joints simultaneously, are suggested to have a similar prophylactic effect on the hamstring muscles, but this has not been properly investigated yet [32]. This non-inferiority of one exercise type to the other probably stems from the fact that, in the fascicle level, even the NHE seems to engage the BFlh in an isometric way, while the lengthening is originated primarily by the elastic elements of the musculotendinous unit [76]. However, this should not discourage from the use of eccentric exercise for injury risk mitigation, rather a holistic approach should be adopted, provided the benefits that may stem from the muscle engagement throughout a wide joint range of motion during an eccentric exercise [17,77], though this is beyond the scope of this review.

The hypothesized adaptations derived from such programs that contribute to the risk mitigation of injury are not limited to strength gains, but also structural modifications such as fascicle lengthening and functional changes such as achieving peak knee-flexion torque at longer muscle-tendon lengths [78]. Some of the important parameters to be considered when selecting strengthening exercises for such programs are the mode of activation (i.e. concentric, isometric, or eccentric), the intensity (i.e. high load vs. low load), the joint of focus (i.e. hip vs knee), and the targeted muscles [75,78]. For example, NHE variations with the hip flexed may be ideal for introductory strengthening sessions since the hamstrings are loaded considerably less, while other variations can differentially engage the BFlh and/or ST, as an exploratory case study has recently shown [77]. In comparison, the volume and frequency of these sessions are of minor importance, as biweekly implementation seems to provide large enough a benefit [72] without compromising the athletes' compliance [78].

The complexity of the hamstrings' function because of each muscle's distinct force–length relationships, moment arms in both the hip and the knee, and activation patterns has been highlighted recently in an extensive review [79], which entails that sport-specificity is an important principle that should guide exercise selection [32,75]. In athletics, for example, it is speculated that sprinting while on an anti-clockwise swerve, as undertaken during a 200 m or 400 m race, might demand greater strength of the ST and SM muscles of the outer (right) leg and stronger BF muscles of the inner (left) leg [32]. Similarly, selected exercises should mimic the simultaneous hip flexion and knee extension movement during the highly injurious late-swing phase of sprinting [32,75]. One such example can be the razor curl exercise [76]. Alternatively, both hip-dominant (e.g. deadlift), which predominantly activate the BF and SM, and knee-dominant (e.g. prone leg curl) exercises, which mainly activate the ST, should be incorporated into the prevention programs [78,80].

Management of injury and return to sport (RTS)

A. Acute phase

As with most soft-tissue injuries, the early management of HMI aims at minimizing the extent of damaged tissue while preserving the healing potential for the tissue repair later [81]. According to recent expert opinions, a new, acute HMI should be initially treated with protection, compression, and elevation of the injured limb, while the athlete should be educated on the natural healing process whilst, where possible, avoiding the use of ice and anti-inflammatory drugs (e.g. NSAIDs) for better long-term healing outcomes (i.e. 'PEACE and LOVE' approach) [81]. Any therapeutic decision thereafter should aim at reducing the time to RTS unrestrictedly while minimizing the risk of a recurrent injury [24,82].

B. Subacute phase until RTS

A graded rehabilitation approach with a staged protocol lies at the heart of recovery and RTS, allowing the athlete to return to pre-injury performance levels, as soon as possible and with minimal reinjury risk [9,22,83]. Such a protocol should be guided by an accurate diagnosis/classification of the injury and executed by an interdisciplinary team, in line with the principle of sport-specificity [9,83]. Progressive loading dependent on and adapted to individual capacities and needs is another important principle to be considered upon designing and implementing such protocols, which can be applied not only across rehabilitation stages but also at the single-exercise level by modulating its intensity, as nicely shown regarding the NHE in a recent case-study [77]. However, there remains debate among experts as to what the different aspects of such protocols should include (e.g. mode of activation, dosing of load, etc.), and it is likely an individualized approach may be 'optimal' basing the progression through stages on a phased return on athletes' symptoms and regular clinical monitoring of strength capacities rather than flexibility [57]. At the elite end, this is facilitated by a closely integrated support team, but even at the amateur end, where such support is rare, evidence suggests that early rehabilitation can hasten RTS [84,85]. However, unknown remains why delaying the onset of rehabilitation from 2 to 9 days post-injury prolongs RTS by ~30% (i.e. 2–3 weeks in this study), since no structural (i.e. MRI-based), functional (i.e. isokinetic strength testing), or patient-reported subjective (i.e. symptoms' intensity) outcome could explain the benefits of early rehabilitation [84]. Several different hamstring rehabilitation protocols have been published, primarily in football, which contain various components to them [23,86,87]. Particularly for track-and-field athletes, evidence suggests that whatever specific protocol is used, it should consist of lengthening (mainly eccentric) exercises as they have been shown to reduce both the time to RTS and the recurrence rates compared to more conventional protocols (e.g. stretching and concentric strength exercises) [22]. However, introducing such lengthening exercises earlier in the rehabilitation program (i.e. before the athlete manages to run at ~70% of maximal speed pain-free) may not shorten the RTS significantly, as was shown in a diverse athletic population (6% track-and-field) [7].

A recently published review of rehabilitation undertaken within the British Athletics team over a 4-year period was published [8], which used the MRI-based BAMIC classification scale to grade injury by severity and location (i.e. myofascial, musculotendinous junction, intratendinous) and guide rehabilitation using principles published in earlier work by the same team [9]. In this approach, a progression through rehabilitation exercises was undertaken, aiming at generating high eccentric force, increasing muscle fascicle length, and developing fatigue resistance whilst overcoming selective muscle inhibition [9]. This approach led to a low re-injury rate of 2.9% over the 4-year period in this elite athletic population [8]. An alternative rehabilitation program for hamstring injuries has been made available by the clinicians at the Aspetar Clinic, Doha, Qatar [88]. This uses a 6-stage progression with set criteria that needs to move from one stage to another. Early goals are to promote initial healing, before regaining normal muscle function and control, with a progression back into sport-specific training [88]. Specific assessment testing is recommended throughout the rehabilitation journey, with exercises specified including the NHE, as well as 'Divers,' 'Gliders,' and variations of the 'bridge' exercises [88]. Whilst some of these exercises are utilized in other hamstring rehabilitation protocols, this formalized approach can help structure a progressive return to sport journey, although it has not yet been studied in a formalized trial setting or published in peer-reviewed literature. (*For details of the stages of the protocol, readers are directed to the open access document available through the clinic homepage* [88].)

Toward the end of the rehabilitation period, there is little doubt among experts that gradual introduction and progression of sport-specific sprinting drills and sprint running based on a more austere pain-threshold should be the main ingredient of the protocols [57]. However, no specific criteria for RTS are yet widely accepted, but pain-free near-maximal sprinting and athletes' confidence seem to be of most importance [57].

C. Interventional treatment options

Whilst the vast majority of HMI are managed non-operatively, there remains a debate on which, if any, types of HMI could benefit from a surgical intervention prior to rehabilitation. It seems that for both distal [89] and proximal [90] high-grade HMI (i.e. BAMIC 3b, 3c, and 4) in professional athletes, operational management is followed by an average time to RTS of 11.7 and 13.4 weeks, respectively, while reinjury rates were below 5% [89,90]. Higher grade injuries, especially proximal avulsions, are potentially an indication for surgical treatment [82], with equivocal and weak evidence showing either superior [91] or similar [92] outcomes compared to non-operative management, but evidence from randomized controlled trials is lacking [82]. Given such lack of evidence, the multidisciplinary panel of experts of the 'London consensus' on HMI highlighted the agreed indications for surgical reconstruction of HMI which were in line with the available literature recommendations [56]. For example, injuries with anatomic gaps, loss of tension, and those that are not healing after a rehabilitation period are good candidates for operational management, as well as proximal bony avulsions [56]. Any decision-making, however, should be guided by the athlete's personal demands and the odds of a full functional recovery with rehabilitation only [56]. However, particularly for track-and-field athletes, non-operational management still seems to be preferred, even for high-grade injuries [9,22].

Platelet-rich plasma injection is another extensively researched (and promoted) treatment option for HMI; however, a systematic review published a couple of years ago has questioned its value and has shown no additional benefit to the clinical outcomes, the time to RTS, or the risk of reinjury [93].

D. Prognosis and re-injury risk

From a prognostic perspective, the athlete's own estimation of time to RTS [94], knee ROM deficits [24,94], delayed medical consultation, increased pain ratings and delayed pain-free walking in the acute phase [24] and during the first week [95] of rehabilitation can predict a delayed RTS. MRI-based prognosis is debated not to be of value [94,95], although it appears valid when performed no later than a week post-injury [22,52]. Indeed, a 4-year prospective study using the MRI-based BAMIC classification found a good correlation between the length and cross-sectional area of muscular edema and time to RTS [8].

Recurrent HMI are a recognized issue, with approximately one in every five athletes sustaining an additional injury after RTS [52,96], with the vast majority of these (~80%) occurring at the same anatomical location and relatively soon after RTS [97]. Despite this high recurrence rate, there are no single, standardized RTS criteria yet, even though all proposals are based on the same evidence [9,83]. For example, it is evident that MRI before [96] or after [98] rehabilitation does not predict recurrence of injury. However, risk factors of reinjury could be identified on clinical assessment, such as tenderness on palpation, isometric weakness at 15° of knee-flexion, and active knee-extension ROM deficit [61,96]. The researchers who developed the BAMIC classification suggest that athletes with myofascial injuries could be cleared by only using similar clinical assessment criteria, while for intratendinous injuries, more extensive criteria (e.g. eccentric strength measurements, biomechanical assessment) should be added [9]. Their suggested rehabilitation protocol and RTS criteria seem to reduce the reinjury rates below 3% in elite track-and-field athletes [8]. Comparably, other researchers propose a single clinical algorithm for all injuries which relies on similar clinical outcomes and additionally the H-test, which estimates the athlete's apprehension during active stretching of the hamstring muscles [83]. Alternative work in footballers with HMI has shown that an individualized program based on criteria to progress from one rehabilitation stage to another delayed RTS, but significantly reduced the risk of reinjury compared to a 'standard' protocol [87].

It can therefore be seen that precise RTS criteria and progression of training into competition remain elusive, with more work needed. Although it may be optimal that rehabilitation progression is individually determined, particularly at the elite end of athletics, there is uncertainty regarding the duration of RTS and any risk of subsequent re-injury.

Conclusion

The hamstring muscles play an important role in the sport of athletics and their injury is both frequent and burdensome, and potentially have a high risk of recurrence. Research on identifying risk factors of HMI has not yielded great insight into the etiology of injury, but this has not refrained prevention programs from being successfully implemented, at least in settings with high input from practitioners. Although differences in the proposed classification systems in the past years are certainly noted, potentially causing additional confusion, the recently developed classification systems have improved the communication of research findings, and have also provided clinicians, in combination with physical examination, with prognostic value in their decision-making process. Rehabilitation is still considered the optimal treatment strategy guiding return to sport, although more research is needed to optimize treatment protocols. Since it remains unknown to what extent the conclusions about the prevention and management of HMI derived from studies on team sports, such as football, are transferrable to athletics, the notable scarcity of studies involving track-and-field athletes, particularly in under-represented groups in the literature, should be addressed in the future.

Future research should attempt to answer if there is an actual effect of gender and/or age in sustaining HMI and what are the unique risks associated with anti-clockwise curved sprinting and/or block-start acceleration. Additionally, epidemiological studies should agree on how best to present their results so as to facilitate comparison and reflect clinically significant variables. Researchers on classification systems of muscle injuries could examine the added value of subclassifying HMI sport, specifically on the clinical decision-making, and efforts should be made toward a unified and universally accepted classification system. Moreover, there is certainly a lack of well-designed clinical trials regarding the early management of HMI to provide evidence for the expert-based recommendations (e.g. avoidance of anti-inflammatory medication and ice). Finally, rehabilitation research could focus on how best to blend symptom-based with time-based progression RTS criteria.

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