PJAHS
Philippine Journal of Allied Health Sciences

Original Article

Biomechanical Parameters Assessed During Running Among Running-Related Athletes with Recurrent Hamstring Strain Injury: A Scoping Review

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Article Received: July 11, 2023

Article Accepted: September 11, 2023

Article Published: February 15, 2024

Abstract

Background: Hamstring strain injury (HSI) is the most common cause of missing practices and sporting events among running-related athletes. The incidence rate of recurrence in individuals with HSI ranges from 12% to 63%. While various risk factors for HSI have been identified, the alterations and role of biomechanical factors as potential causes of injury have been largely overlooked. **Objectives**: To report the critical biomechanical parameters assessed among running-related athletes with a recurrent HSI and to present common testing protocols in assessing the biomechanical parameters among running-related athletes with a recurrent HSI. **Methods:** ***Eligibility Criteria:*** Included studies investigated biomechanical parameters assessed among collegiate or elite running-related athletes with recurrent HSI. ***Sources of Evidence:*** This scoping review was registered in OSF and was conducted based on PRISMA-ScR. Six electronic databases were systematically searched from 1993 to May 2022. ***Charting Methods:*** The reviewers created a data charting tool for the scoping review. **Results:** Out of 874 articles, a total of 10 articles were included in the scoping review. The critical biomechanical parameters assessed include trunk flexion, hip flexion, and knee extension angles (kinematic variables), flight and stance times and velocity (spatiotemporal variables), and EMG activity of biceps femoris, semitendinosus, semimembranosus, vastus lateralis, and rectus femoris, knee flexion and extension angle peak joint torque (kinetic variables). The most common running test protocols used were the 30-meter overground repeated sprint test, a percentage of maximum running velocity (treadmill), and repeated sprints on a non-motorized treadmill. The most common protocols for isokinetic muscle testing were 60 degrees (concentric), 300 degrees (concentric), and 180 degrees (eccentric) per second angular velocities. **Conclusion:** The review demonstrated a need for more research on this topic, leading to only limited biomechanical parameters being discussed in the literature. This underscores the need for more rigorous research that could have practical applications for athletes and coaches.

***Key Words**: Hamstrings Injury; Biomechanics; athletes; scoping review*

INTRODUCTION

Muscle injuries are prevalent in athletic competitions.[1] The hamstring muscle group appears most vulnerable to injury,[2] commonly called hamstring strain injury (HSI). HSI is a non-contact muscle injury, with most cases occurring among running-related athletes,[3] including soccer (football),[4] and track and field.[5] Muscle strain caused by eccentric contractions or stretching appears to be the primary HSI mechanism.[6,7] Of the four muscles in the hamstring complex, the long head of the biceps femoris (BFlh) is most frequently injured (94%) at the proximal musculotendinous junction[8] due to the following reasons: (a) more strain experienced during sprinting compared to the semimembranosus (SM) by 2.2% and the semitendinosus (ST) by 3.3% [9], and (b) stretched at an average of 9.5% beyond its nominal upright length, which is more than the SM (7.4%) and ST (8.1%) muscles during treadmill sprinting.[10] HSI also exhibits a notable rate of re-injury [1] with a 12 to 63% recurrence rate.[11–13] One-third of these reinjuries happen within a year after the initial injury and are usually more severe.[11–14]

Although some HSI may raise the likelihood of re-injury regardless of the time gap, many early recurrence injuries could likely be ascribed to inadequate rehabilitation or premature return to play after the initial injury.[15]

Several prospective types of research have revealed that biological age,[16–26] previous injury,[17,21,23,27–31] a previous ACL injury,[17,21,23,28,34] and a previous calf strain injury are the most significant risk factors for initial HSI. [17,23,28,29,34] There is a strong likelihood that certain risk factors contributing to the possible recurrence of HSI are already associated with the initial injury. Additional factors contributing to HSI's chronic nature can arise directly from the initial injury itself. These factors may involve alterations in the muscle tissue and potential adaptive changes in the biomechanics and motor patterns of the athlete's sporting movements.[35]

Despite identifying various risk factors associated with HSI, the significance of biomechanical elements in the onset of HSI and the potential biomechanical alterations that can occur after an HSI have yet to receive considerable attention or recognition. A study that focused on the biomechanical aspects of returning athletes to sprinting following non-contact and sprint-related HSI was conducted by Daly et al.[32] During the late swing phase, there were significant reductions in EMG ratios and asymmetric movement patterns at the hip and pelvis in the sagittal plane. Due to these changes, the BFlh will likely be under more strain than the medial hamstrings.[32] This study is the first to demonstrate distinct, possible reinjury-predisposing asymmetries in kinematics and muscle engagement during running following recuperation and return to the sports.[32] Knowing the biomechanical changes for HSI is critical to managing athlete workload, preventing injuries, and deciding when an athlete can return to play after an injury.[36,37]

Several prospective studies investigate biomechanical factors to identify which are most closely linked to HSI. Several testing protocols using high-speed treadmills,[38,39] motion-capture systems,[7,40,41] dynamometers, and other isokinetic muscle testing device[42-44] have been utilized to track biomechanical asymmetries that may have occurred after HSI. These studies attempt to understand the biomechanical changes that may occur after initial HSI and how these changes might lead to the recurrence of the injury during running. Despite numerous theories, the critical biomechanical parameters that could potentially lead to asymmetries during high-speed running and contribute to recurrent HSI have not yet been identified.

Most of the studies have primarily concentrated on evaluating only a limited set of biomechanical parameters and have limited discussion about how these biomechanical parameters were altered after the injury or how they might contribute to the recurrence of HSI. Therefore, this scoping review aims: a) to report the critical biomechanical parameters in terms of kinematic, spatiotemporal, and kinetic variables assessed among running-related athletes with a recurrent HSI; and b) to present common testing protocols used in assessing the biomechanical parameters among running-related athletes with a recurrent HSI. This scoping review constitutes the initial phase of a larger research project that explicitly investigates running-related athletes who experience recurrent HSI.

METHODS

This scoping review is registered in the Open Science Framework (OSF) (osf.io/9q2cz) and conducted based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR).[45]

Eligibility Criteria.

Participants/Injury. Included studies investigated biomechanical parameters assessed among male or female collegiate or elite running-related athletes with recurrent HSI. Recurrent HSI is classified as a recurring or chronic condition characterized by repeated occurrences of strains. The review focused exclusively on recurring HSIs and the biomechanical parameters, including kinematics, kinetics, and spatiotemporal factors. Other kinds of risks, such as intrinsic factors like age, sex, and previous injuries, as well as external factors like the playing surface and footwear, were not included in the review. Furthermore, the review did not examine the effect of other musculoskeletal conditions in the lower extremities, such as tendinopathy, unspecified thigh injuries, hamstring origin avulsions, and contusion-related pathologies.

Types of Sources. This scoping review encompassed various experimental study designs, including randomized controlled trials, non-randomized controlled trials, analytic descriptive studies utilizing cross-sectional or longitudinal designs, and case studies. Furthermore, systematic reviews that meet the inclusion criteria were also considered, contingent upon the research question.

Information Sources. To find relevant publications, a limited preliminary search of PubMed was conducted. An extensive search strategy was devised for PubMed, Medline via EBSCO Host, CINAHL via EBSCO Host, Science Direct, ProQuest, and Web of Science. This strategy incorporated text words found in the titles and abstracts of relevant publications and index keywords employed to classify the articles. The search method was modified for the Science Direct database due to the limited number of words allowed in the advanced search tab. Grey literature was not included in the list of information sources due to its inaccessibility during the pandemic. The final search strategy for MEDLINE via EBSCO Host can be found in the supplemental section. Studies from 1993 until May 2022 that were published in English or with an English translation were included. The search strategy employed the following Boolean terms and keyword sets.

Table 1. Key search terms

Search terms	
Keywords 1:	(Run* OR Sprint* OR Basketball OR Football OR Soccer)
Keywords 2:	(Biomechanic* OR Kinematic* OR Kinetic* OR Mechanic* OR "Peak Muscle Activation" OR "EMG" OR "Electromyography")
Keywords 3:	(injur$ or ruptur$ or avuls$ or tend#nitis or tend#nosis or strain$ or sprain$ or tear$)
Keywords 4:	(hamstring$ or semimembran$ or semitend$ or biceps femoris)

Selection of Sources of Evidence. A calibration exercise was conducted before the screening process started to ensure accuracy and reliability in selecting the correct articles for inclusion. This entailed the independent screening and data charting of a random sample of five papers by each team member. Subsequently, a pilot test was conducted by all team members. During the pilot testing session, each team member independently screened and charted data from another set of five articles. During the pilot testing, one team member took on the responsibility of being the evaluator to assess the accuracy and reliability of the screening and charting process. Any discrepancies or inconsistencies between the reviewers were addressed and resolved through discussions involving the member who assumed the role of evaluator.

During the process of evidence selection, all identified citations were collected and uploaded into a Google Sheet© following the initial search. Two independent reviewers screened titles and abstracts. The full text of any potentially relevant sources was obtained, and their citation information was imported into the Google Sheet© and Google Drive© shared folder. Two independent reviewers carefully compared the full text of chosen citations to the inclusion criteria. The rationales behind the exclusion of full-text sources of evidence that failed to meet the inclusion criteria were duly documented and reported. At each stage of the selection process, any disparities between the reviewers were resolved through discussions involving an additional reviewer. In this study, no risk of bias assessment or meta-analysis/statistical pooling was conducted. A PRISMA-ScR flow diagram was used to illustrate the search results and the study inclusion procedure in the final scoping review.[45]

Data Charting Process. The reviewers created a data charting tool (see supplemental files) for the scoping review. All the reviewers did a pilot test of the charting form. After which, when all the reviewers were comfortable with it, two independent reviewers charted the evidence, and disagreements were resolved through discussions with another reviewer. The data that was extracted contained detailed information regarding the authors, year of publication, title, objectives, study design, the language used, location, sample size, and study population characteristics (age, sex, type of sport, level of participation, type of hamstring injury, chronicity, laterality), kinematic variables (equipment used, outcome measures, method), kinetic variables (equipment used, outcome measures, method), EMG data (equipment used, outcome measure, method) and results (data analysis used and significant findings) relevant to the research question.

Synthesis of Results. The information was shown in tabular format. A narrative summary explaining how the results relate to the review aim was included with the tabulated results.

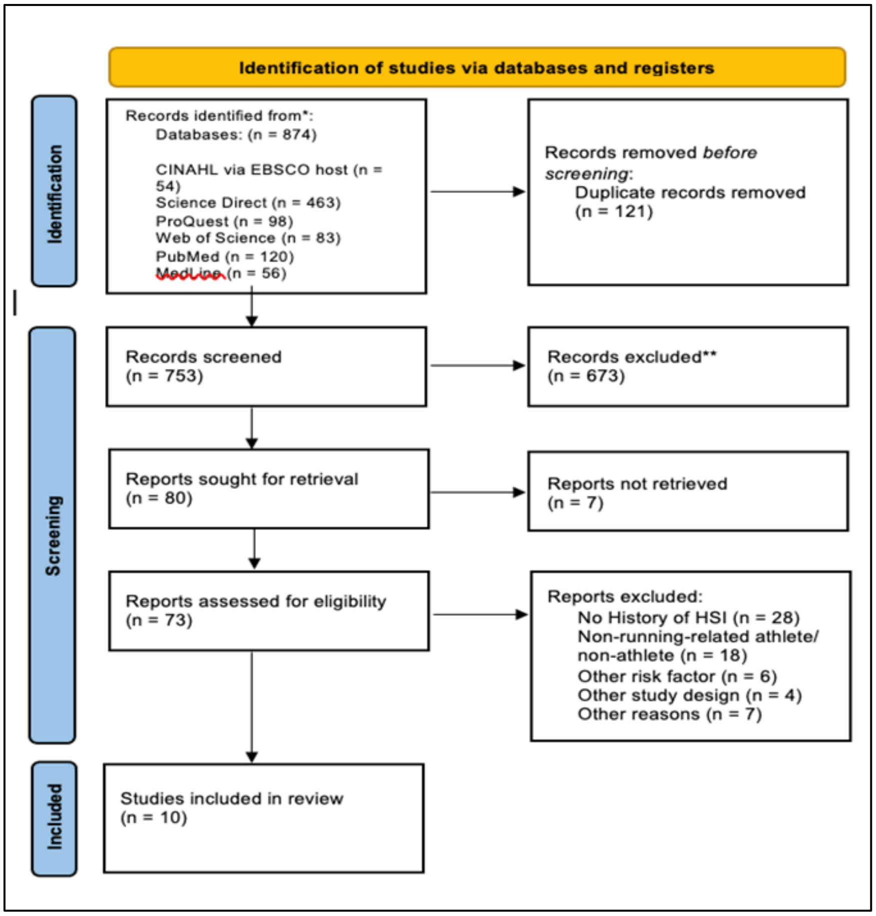

Figure 1. PRISMA diagram on study selection

RESULTS

Selection of Sources of Evidence.

A total of 874 articles were searched from six electronic databases using the identified search terms. Out of the total number of articles, 121 were duplicates. 753 papers were screened based on titles and abstracts, with 673 articles removed after the screening. The remaining 80 articles were screened based on the eligibility criteria. After this, seven papers were automatically excluded due to the non-availability of the full text online; the other 63 articles were excluded due to the following reasons: participants have no history of HSI and were non-running-related athletes, other risk factors (intrinsic and extrinsic) assessed, and other study designs not within the eligibility criteria. Finally, ten articles were included in the scoping review. Figure 1 shows the summary of searching the included article using the PRISMA flow chart 2020.[46]

Characteristics of Sources of Evidence.

Characteristics of the final ten articles included are presented in Table 2, which consists of the year of publication, geographic region, and study design. Most of the articles were published between 2020 and 2022. The papers were from Australia, the United States of America, the Czech

Republic, Qatar, France, the United Kingdom, and Denmark. Seven of the articles were cross-sectional studies, two had single-subject research, and one study had an experimental study design.

Table 2. Characteristics of included articles

		Count (%)
Year of Publication	2009 – 2011	3 (30%)
	2012 – 2015	2 (20%)
	2016 – 2019	1 (10%)
	2020 – 2022	4 (40%)
Geographic region	Australia	3 (30%)
	USA	2 (20%)
	Czech Republic	1 (10%)
	Qatar	1 (10%)
	France	1 (10%)
	United Kingdom	1 (10%)
	Denmark	1 (10%)
Study Design	Cross-sectional study (retrospective approach, exploratory, prospective, and comparative)	7 (70%)
	Single subject	2 (20%)
	Experimental	1 (10%)

The critical biomechanical parameters assessed in the included articles in the scoping review are presented in Table 3. One (1/10) article[7] discussed the kinematic parameters (trunk flexion angle, hip flexion angle, knee flexion, and extension angle), four (4/10)[39,42-44] assessed the kinetic parameters specifically on knee flexion and extension torque angle, one (1/10) article[39] evaluated the EMG activity of the biceps femoris, semimembranosus, semitendinosus, vastus lateralis, and rectus femoris, and four (4/10) papers[7,38,41,47] studied spatiotemporal variables – namely, flight time, stance time, and velocity.

In terms of the running protocol used to assess biomechanical variables among running-related athletes with recurrent hamstring strain injury, three (3/10) articles[7,40,41] used the overground repeated sprint tests, two (2/10) articles[38,39] incremental maximum treadmill sprint test, and only one (1/10) article[47] used repeated sprints on a non-motorized treadmill. Regarding Isokinetic Dynamometer muscle testing, three (3/10) articles,[42–44] used 60 degrees per second angular velocity in assessing concentric knee flexion and extension. Two (2/10) articles,[4148] used 300 degrees per second angular velocity (concentric), and only one (1/10)[44] used 180 degrees per second angular velocity (eccentric).

Table 3. Biomechanical variables assessed in the included articles

Biomechanical variables assessed in the included articles		Count (%)
Kinematic Variables	Trunk flexion angle	1 (10%)[7]
	Hip flexion angle	1 (10%)[7]
	Knee extension angle	1 (10%)[7]
Kinetic Variables	EMG activity of the Biceps Femoris, Semimembranosus, Semitendinosus, Vastus Lateralis, and Rectus Femoris	1 (10%)[39]
	Knee flexion angle peak torque	4 (40%)[39,42-44]
	Knee extension angle peak torque	4 (40%)[39,42-44]
	Peak Swing Hip Extension Torque	1 (10%)[7]
	Peak Vertical Ground Reaction Force (Body Weight)	2 (20%)[7,47]
	Peak Vertical Ground Reaction Force (Loading Rate)	1 (10%)[7]
	Vertical Ground Reaction Force (Impulse)	1 (10%)[7]
	Peak Posterior Ground Reaction Force (Braking)	2 (20%)[7,40]
	Peak Anterior Ground Reaction Force (Propulsive)	3 (30%)[7,40,47]
	Bilateral Strength Ratio	1 (10%)[43]
	Unilateral Strength Ratio	1 (10%)[43]
	Maximum Horizontal Force	1 (10%)[45]
	Horizontal Power Output	1 (10%)[45]

Spatiotemporal Variables	Aerial/Flight Time	2 (20%)[38,47]
	Contact/Stance Time	3 (30%)[7,38,47]
	Velocity	2 (20%)[7,45]
	Joint Displacement Angle	1 (10%)[11,48]

Table 4. Common test protocol used for assessing biomechanical variables

		Running Protocol			**Isokinetic muscle testing**		
Study	**Authors**	30 meter repeated sprints (overground)	60, 80, 90 and 100% of max running velocity (treadmill)	Repeated sprints (treadmill)	60 degrees per second angular velocity	180 degrees per second angular velocity	300 degrees per second angular velocity
1	Schache et al.[7]	✓	-	-	-	-	-
2	Silder et al. [39]	-	✓	-	-	-	-
3	Lord et al.[47]	-	-	✓	-	-	-
4	Brughelli et al.[38]	-	✓*	-	-	-	-
5	Izovska et al.[43]	-	-	-	✓	-	-
6	Seco-Calvo et al.[48]	-	-	-	-	-	-
7	Tol et al.[44]	-	-	-	✓	✓**	✓
8	Edouard et al.[40]	✓	-	-	-	-	-
9	Brukner et al.[42]	-	-	-	✓	-	-
10	Ishoi et al.[41]	✓	-	-	-	-	✓
		3/10	**2/10**	**1/10**	**3/10**	**1/10**	**2/10**

**Non-Motorized Treadmill (80% Max Velocity) **Eccentric Contractions*

Results of Individual Sources of Evidence. The results of individual sources of evidence are presented in Table 5, which includes the studies' place of origin, objectives, design, methods, participants, mean months from the last injury to assessment, rehabilitation, test protocol used, methods, outcome measures, and main findings. The data summary form for biomechanical parameters (kinematics, spatiotemporal, and kinetics) is shown in Table 6.

DISCUSSION

The primary purpose of this scoping review is to report the critical biomechanical parameters assessed and present the common test protocol for assessing biomechanical parameters among running-related athletes with recurrent HSI. This scoping review constitutes the initial phase of a larger research project that specifically investigates running-related athletes who experience recurrent HSI and was able to find ten studies on biomechanical parameters in running-related athletes with recurrent HSI (2009-2022). The critical biomechanical parameters assessed were knee flexion and extension angle peak torque, EMG/muscle activity of lower extremity muscles (kinetic variables), flight time, stance time, and velocity (spatiotemporal variables), and trunk flexion angle, hip flexion angle, and knee extension angle (kinematic variables). The most common running test protocols for assessing biomechanical parameters in running-related athletes with HSI were the 30-meter repeated sprint test, followed by a percentage of maximum running velocity on a treadmill and repeated sprints on a non-motorized treadmill. For isokinetic muscle testing, the most common protocols used were60°/s angular velocity (concentric), 300°/s angular velocity (concentric), and 180°/s angular velocity (eccentric).

Our findings indicate a research gap in understanding the impact of recurrent HSI on sprinting biomechanics. Further studies are needed to determine the specific effects and relationships, as limited information was available on kinematic, kinetic, and spatiotemporal variables in the existing research. This is in contradiction with the total number of studies published focusing on index HSI.

Table 5. Individual sources of evidence

Study	Objectives	Design	Participants	Mean months from last injury to testing	Rehabilitation	Testing Protocol used	Methods and outcome measures	Main Findings
2	○ To investigate whether pre-injury biomechanical asymmetries existed ○ To evaluate the biomechanical response to the injury and ○ To identify the timing and segmental location of the initial response.	Single Subject	○ 1 Elite Australian Rules male football player	○ Initial HSI: 67 days prior to assessment ○ 2nd HSI: 42 days later	○ Not mentioned but participating fully in his usual training activities	○ Overground 30 meters repeated sprints	○ three-dimensional (3D) motion analysis system (VICON 612, Oxford Metrics, Oxford, UK) with eight M2 cameras sampling at 120 Hz.	○ In the pre-injury trials, the right leg showed greater knee extension and hamstring muscle-tendon unit length during the terminal swing. The right leg also showed a higher peak hip extensor torque and hip power generation during the initial stance. ○ Significant biomechanical effects to the right hamstring strain were visible in the injury trial, particularly for the right leg during the subsequent swing phase after the injury started.
3	○ To investigate whether athletes with a history of a unilateral hamstring strain injury exhibit bilateral differences in (a) isokinetic strength characteristics and (b) musculotendon kinematics and neuromuscular control patterns during treadmill sprinting. ○ To determine whether the magnitude of any functional asymmetries correlate with bilateral differences in tendon volumes, as measured using magnetic resonance (MR) imaging.	Cross-sectional study	○ 18 athletes with unilateral HSI (8 athletes – atleast one re-injury; 10 athletes – index HIS)	○ 5 – 13 months prior the assessment	○ Supervised rehabilitation for at least 2 weeks and has returned to full sports participation	○ treadmill running at 60, 80, 90, and 100% of maximum sprinting speed.	○ eight-camera passive marker system (Motion Analysis Corporation, Santa Rosa, CA, USA) ○ isokinetic dynamometer (Biodex Multi-Joint System 2, Biodex Medical Systems, Inc., Shirley, NY, USA) ○ pre-amplified single differential surface electrodes (DE-2.1, DelSys, Inc, Boston, MA, USA) (Bilateral muscle activities of the rectus femoris (RF), vastus ○ lateralis (VL), BF, and medial hamstrings (MH)	○ A significantly enlarged proximal biceps femoris tendon volume was measured on the side of the prior injury. However, no significant differences between the previously injured and uninjured limbs were found in strength measures, peak hamstring stretch, or muscle activation patterns. Further, the degree of asymmetry in tendon volume was not correlated to any of the functional measures

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7	○ To compare kinetic and kinematic parameters obtained during sprints between semi-professional football players with and without recent hamstring injury, ○ To examine the fatigue-induced changes in inter-limb asymmetry, particularly with respect to horizontal force production, across repeated-sprint repetitions.	Cross-sectional study	○ 40 semi-professional footballers ○ Players were assigned to either an injured or uninjured group determined by the following criteria:(a) injury history of one or multiple hamstring injuries to one leg only, (b) the injury caused the athlete to miss at least one week of training, (c) the injury occurred less than 2 years prior to testing	○ Occurred less than 2 years prior to testing	○ Not mentioned	○ Repeated sprint test on a non-motorized treadmill ○ RST was used to elicit a fatigue response over 10 repeated sprints with the ten 6-s running bouts performed at maximum velocity with 24-s of active recovery	○ Pacer Performance System software (Innervations Solutions, Joondalup, Australia) ○ The Woodway Curve non-motorized treadmill contains four load cells (on the left and right side, at the front and rear of the treadmill belt)	○ There is a greater fatigued-induced change in mean horizontal force during a repeated-sprint test in legs with previous hamstring injury than the non-injured legs of the injured players or the legs of uninjured players.
10	○ To investigate if leg deficits exist in vertical and horizontal force in non-injured and injured Australian Rules football (ARF) players during running at 80% Vmax (maximum velocity).	Cross-sectional comparative	○ Twenty-two ARF players from the Western Australian Football League ○ Players were placed in 1 of 2 groups: previously injured and non-injured. ○ previously injured group (IG) included: (a) an injury history of 1 or multiple hamstring injuries to 1 leg only; (b) the injury caused the athlete to miss at least 1 week of	○ less than 2 years prior to the testing.	○ Not mentioned	○ Running on a non-motorized treadmill with 80% of max velocity	○ Force Treadmill Dynamometer, Woodway 3.0, Waukesha, Wisconsin, USA. ○ 2 optical speed photomicrosensors, collected by a tachometer (XPV7 PCB)	○ For the NIG, there were no significant differences between right and left legs for any of the variables. For the IG, the only variable that was significantly different between the injured and non-injured leg was horizontal force.

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			training; and (c) the injury occurred less than 2 years prior to the testing.					
4	○ To identify preseason isokinetic strength differences in the knee flexors and extensors and their ipsilateral/bilateral ratios ○ To compare the results among players who subsequently overcame a hamstring strain injury (HSI) or anterior cruciate ligament (ACL) rupture during the season and those who did not.	Cross-sectional, retrospective approach	○ 134 male professional soccer players (10 players with ACL injury; 10 players with grade 3 hamstring injury, 20 healthy players)	○ Not mentioned	○ Not mentioned	○ Isokinetic strength evaluation with 90 knee flexion and extension of the knee extensors (KE) and flexors (KF) during concentric muscle contraction at a 60 degrees per sec angular velocity	○ Cybex Humac Norm dynamometer (CybexNORM®, Humac, CA, USA)	○ The results of our study show that low-angular velocity preseason testing did not result in a player's HSI or ACL injury during the season. The difference between the monitored groups ranged from 1.5% to 3%. The comparison showed low evidence for significant differences.
11	○ To explore the potential role of Joint clearance displacement as a risk factor for HTI and as a clinical predictor of reinjury and injury severity	Cross-sectional, retrospective approach	○ 100 elite US athletes (40% women, 60% men) ○ History of HTI group: n = 50 (35 males; 15 females) ○ No History of HTI group: n = 50 (25 males; 25 females)	○ Not mentioned	○ Not mentioned	○ X-rays were performed in an anterior-posterior projection and the axial projection proposed by Johnson to determine JCD	○ X-ray	○ Significant differences were found in injury severity and a number of injuries. The multivariate analysis data indicated that Joint clearance displacement was significantly associated with the number of injuries and their severity. In the stepwise regression model, JCD variability explained 60.1% of the number of injuries and 10.5% of injury severity.
5	○ To prospectively evaluate isokinetic variables in a cohort of MRI-positive hamstring-injured professional football players who had completed a six-stage rehabilitation program including functional sports-specific rehabilitation.	Experimental	○ 52 football players (27 (52%) grade 1 and 25 (48%) grade 2 injuries)	○ Not mentioned	○ progressive six stage criteria-based rehabilitation programme, including successfully completing football-specific FFT	○ Testing comprised three modes and speeds. First, five repetitions at 60°•s-1 concentric knee flexion and extension Second, 10 repetitions at 300°•s-1 concentric knee flexion/extension Third, five repetitions at 60°•s-1| 180°•s-1 eccentric knee extension/flexion	○ Isokinetic System 3, Biodex, New York, USA	○ Out of the total of 52 players, a completes set of isokinetic testing was conducted before their clinical discharge. Among them, 27 players (52%) had grade 1 injuries, while 25 players (48%) had grade 2 injuries. Among the 52 players, 35 (67%) displayed a deficit of more than 10% in at least one of the three hamstring-related isokinetic parameters. Specifically, 39% of players had a 10% deficit in hamstring concentric 60 degree/sec. 29% had a deficit at 300 degree/sec, and 28%

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								had a deficit in hamstring eccentric. Comparing players with reinjury (N=6) to those without reinjury (N=46), there was no significant difference in mean isokinetic peak torques and 10% isokinetic deficits.
8	○ To analyze the association between horizontal force production capacities during sprinting (low and high velocities) and hamstring injury occurrence in football players.	Prospective Cohort Study	○ 284 football players grouped between with history of hamstring injury or no history of hamstring injury	○ Not mentioned	○ Not mentioned	○ 2 X 10 m and 2 X 30 m sprints with increasing intensity	○ Laser distance measurement system (LDM 301, JENOPTIK, Jena, Germany; sampling rate, 100 Hz) ○ radar system (Stalker ATS Pro II, Applied Concepts, Richardson, TX, USA; sampling rate, 46.87 Hz)	○ There were no associations between FH0 (theoretical maximal force production at zero velocity) and/or V0 (theoretical velocity until which horizontal force can be produced) values at the start of the season and new HI occurrence during the season. Lower measured FH0 values were significantly associated with a higher risk of sustaining HI within the weeks following sprint measurement.
6	○ To use a clinical example to describe a treatment strategy for the management of recurrent hamstring injuries and examine the evidence for each intervention.	Single-Subject	○ 26-year-old professional footballer with 5 episodes of hamstring injury	○ 1st episode: 46 days ○ 2nd episode: 49 days ○ 3rd episode: 27 days ○ 4th episode: 35 days ○ Note: days until next episode	○ RICE ○ soft tissue massage ○ stretching ○ core strengthening ○ progressive agility ○ neuromuscular ○ control exercises ○ a graded running programme ○ an isolated hamstring strengthening ○ programme with specific emphasis on eccentric exercises	○ Concentric knee flexion and extension from 0° to 90° knee flexion at 60°/s	○ Isokinetic System 3, Biodex	○ It is impossible to be definite about which aspects of the program contributed to a successful outcome. Only limited evidence is available in most cases; therefore, decisions regarding the use of different treatment modalities must be made by using a combination of clinical experience and research evidence.
9	○ To compare sprinting performance obtained during a repeated-sprint test between football players with and without a previous hamstring strain injury.	Exploratory cross-sectional study	○ 44 sub elite football players grouped either with history of hamstring injury and no history of hamstring injury	○ Not mentioned	○ Not mentioned	○ Thirty-meter repeated sprint performance	○ High-speed 240 Hz iPhone 6 camera (Apple Inc., USA) and the MySprint application	○ A significant between-group difference was seen in favor of players having a previous hamstring injury over 6 sprints for maximal velocity and mechanical effectiveness (rate of decrease in ratio of force with increasing speed)

Table 6. Data summary of biomechanical parameters (kinematic, spatiotemporal, and kinetic Variables)

Authors		Kinematic Variable (Sagittal Plane)			Spatiotemporal Variables			Kinetic Variable (EMG Activity)					Kinetic Variable (GRF and Joint Torques)											
	Joint Clearance Displacement	Trunk Flexion Angle	Hip Flexion Angle	Knee Extension Angle	Aerial Time	Stance Time	Velocity	Biceps Femoris	Semitendinosus	Semimembranosus	Vastus Lateralis	Rectus Femoris	Peak Swing Hip Extension Torque	Peak Vertical GRF BW	Peak Vertical GRF Loading Rate	Vertical GRF Impulse	Peak Posterior GRF (braking)	Peak Anterior GRF (propulsive)	Knee Flexion Angle Peak Torque	Knee Extension Angle Peak Torque	Bilateral Strength Ratio	Unilateral Strength Ratio	Max Horizontal Force	Horizontal power output
Schache et al.[7]	-	✓	✓	✓	-	✓	✓	-	-	-	-	-	✓	✓	✓	✓	✓	✓	-	-	-	-	-	-
Silder et al.[39]	-	-	-	-	-	-	-	✓	✓	✓	✓	✓	-	-	-	-	-	-	✓	✓	-	-	-	-
Lord et al.[47]	-	-	-	-	✓	✓	-	-	-	-	-	-	-	✓	-	-	-	✓	-	-	-	-	-	-
Brughelli et al.[38]	-	-	-	-	✓	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Izovska et al.[43]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	✓	✓	✓	-	-
Seco-Calvo et al.[48]	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Tol et al.[44]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	✓	-	-	-	-
Edouard et al.[40]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	✓	-	-	-	-	-	-
Brukner et al.[42]	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	✓	-	-	-	-
Ishoi et al.[41]	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	✓	✓
	1/10	**1/10**	**1/10**	**1/10**	**2/10**	**3/10**	**2/10**	**1/10**	**1/10**	**1/10**	**1/10**	**1/10**	**1/10**	**2/10**	**1/10**	**1/10**	**2/10**	**3/10**	**4/10**	**4/10**	**1/10**	**1/10**	**1/10**	**1/10**

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Kinematic Parameters

Only one article[7] discussed changes in kinematic variables (trunk flexion, hip flexion, and knee extension angles) during sprinting. The study involved a single subject who had recently experienced two right hamstring strains. Quantitative gait analysis was utilized to investigate potential biomechanical asymmetries in the subject's sprinting gait. The subject had an initial HSI 67 days before the assessment, and a recurrence occurred 42 days later. The experiment consisted of 10 trials of 30 meters repeated sprints.

In the pre-recurrent injury trials, the trunk flexion of the right leg during foot strike was observed to be 3.3 degrees more than the left leg. Additionally, the peak knee extension at terminal swing was 5.7 degrees more for the right leg compared to the left leg. Moreover, the average hip flexion angle during sprinting was measured to be 92.6 degrees.

The right HSI resulted in significant biomechanical changes during the post-recurrent injury trial. The kinematic patterns of the trunk, hip, and knee exhibited noticeable variations compared to their usual pre-recurrent injury patterns. In the post-recurrent injury trial, the trunk flexion at foot strike for the injured right leg showed a negative value (-11.85 degrees). In contrast, for the uninjured left leg, the value decreased to almost half (7.09 degrees) of the pre-recurrent injury trial values (14.91 degrees). Moreover, the peak knee extension at the terminal swing for the injured leg was greater (5.55 degrees) than for the uninjured leg (17.50 degrees). Consequently, due to the increased knee extension, the injured leg's hamstring muscle-tendon unit length was longer and occurred earlier during terminal swing compared to the uninjured leg.[7]

During the post-recurrent injury trial, the hip flexion angle during sprinting decreased to an average of 35.5 degrees. The authors of the study identified biomechanical asymmetries in the running gait analysis during both the pre-recurrent and post-recurrent injury trials. However, establishing a cause-and-effect relationship between the observed biomechanical asymmetries and the recurrent HSI remains challenging. Furthermore, unilateral HSI might impact the mechanics of both lower limbs, making the use of the unaffected lower limb as a reference point for comparison potentially inappropriate. Nevertheless, such understanding was initially considered clinically practical for identifying potential contributing factors and creating subject-specific therapeutic interventions.

Spatiotemporal Parameters

Two articles[38,47] investigated the differences in flight time (FT) during running between football players with and without a history of HSI. Both studies found no significant difference in FT between the two groups.

Regarding stance time (ST), three articles[7,38,47] examined this parameter among football players. All three studies concurred that there were no significant differences in ST between the injured and non-injured groups or between the injured and non-injured leg during the injury trial conducted by Schache et al.[7]

Flight time (FT) and stance time (ST) are important factors that influence running efficiency, performance, and injury risk.[49] Maintaining a stable pattern of spatiotemporal variables has been associated with better running mechanical efficiency.[50] However, these parameters during running can affect impact shock and, consequently, the risk of injury.[51]

Changes in spatiotemporal parameters during the stance phase of running can alter the intensity and rate of impact force loading, which may be linked to running injuries.[51] Moreover, it is suggested that the ability of the athlete to efficiently maximize FT and minimize ST with effective energy transfer during ground contact will lead to better running economy, resulting in an efficient forward projection of the body's center of mass.[51]

Two articles[7,41] investigated the differences in velocity during running between football players with and without a history of HSI. Both studies reported no significant differences in velocity between the two groups. The observed data from the articles did not show any discrepancies in sprinting velocity between subjects with and without a history of HSI.

The study conducted by Ishøi et al.[41] provided some reasons for this finding. Firstly, during the sprint acceleration and maximum velocity phases, the body's transition from a crouched to an upright position may limit the ability of the hamstring muscles to efficiently apply horizontal forces onto the ground to increase sprinting velocity. Secondly, the ability to quickly transfer horizontal propulsive force onto the ground at high sprinting velocity might depend not only on hamstring muscle function but also on other muscle groups[52] or the improved technical ability of the athlete[53]. As a result, players who had experienced HSI in the past exhibited marginally better mechanical effectiveness, defined as less loss of horizontal force application with increasing sprinting velocity.[41,53].

Kinetic Parameters

A total of four articles[39,42-44] investigated knee isokinetic strength measurements in relation to HSI. All the articles [39,42-44] reported that there were no significant bilateral differences in peak knee flexion and extension torque.

However, the study conducted by Silder et al.[39] revealed a noteworthy finding when a subgroup analysis was performed. In nine subjects whose bilateral difference in tendon size exceeded the 95% confidence interval observed for uninjured athletes using an isokinetic dynamometer at 60 degrees/second, there was an average increase of 8° for the knee flexion angle of peak torque. The authors explored how a previous hamstring injury and the presence of scar tissue might impact the strength and functionality of the musculotendon unit. For those with BF long head strain injury, a significant amount of scar tissue can develop along the proximal musculotendon junction, potentially shortening the length for active force generation.

Despite these observations, it should be noted that the angle of peak torque did not show consistent variations across all subjects.[39] Similarly, the study by Izovska et al.[43] did not find isokinetic concentric and eccentric strength deficits to be reliable indicators of risk factors for hamstring strain injuries. According to their findings, using isokinetic strength measurements (isokinetic dynamometer at 60 and 300 degrees/seconds for both concentric knee flexion and extension) to predict hamstring damage remains inconclusive.[43]

On the contrary, Tol et al.[44] conducted a study comparing players with and without reinjury and found no significant difference in mean isokinetic peak torque for any mode of testing or the percentage of players with at least one isokinetic deficit higher than 10%. Similarly, the study by Brukner et al.[42] demonstrated that prior HSI did not have a significant impact on peak torque.

These findings raise doubts about peak torque's validity as a reinjury risk factor, especially in relation to eccentric strengthening, as it was not significantly affected. Tol et al.[44] suggest that after completing a progressive football-specific rehabilitation program, normalization of isokinetic hamstring function is not always guaranteed. Further examination of individuals who suffered an injury within two months of being discharged from clinical rehabilitation revealed no variations in isokinetic strength metrics.

It remains uncertain whether an isokinetic functional deficit at the end of rehabilitation is linked to a higher risk of subsequent injuries. Nevertheless, for an effective return to sport, complete restoration of isokinetic function is deemed essential. This information highlights the importance of appropriately working the hamstring muscle during rehabilitation, taking into account the type of contraction, knee angle, and parameter-specific effects of a prior injury and eccentric exercise on hamstring muscle performance.[42]

Electromyographic Activity

Regarding EMG activity, only one article[39] examined the differences in muscle activity between limbs during running at 60, 80, 90, and 100% of the maximum running speed among subjects with a history of HSI. The study did not find any substantial interactions between limbs or across running speeds in muscle activity onset, offset, or duration. Additionally, there were no significant limb-by-speed interactions or notable effects for the Rectus Femoris (RF), Biceps Femoris (BF), Vastus Lateralis (VL), or Medial Hamstrings (MH) activity magnitudes.

However, the study did reveal a speed-by-phase relationship for the VL, MH, and BF muscles, but not for RF. The MH and BF muscles exhibited notably higher activity during the terminal swing and early stance phase of running. Specifically, the BF activity during terminal swing increased on average by 67%, and the MH increased by 37% as the speed increased from 80 to 100% based on the root-mean-square (RMS) activity observed between the two lower extremities. In contrast, BF activity increased by just 34%, and MH activity climbed to 66% during the early stance phase of running.

These findings suggest that BF is more prone to injury than MH during the terminal swing phase of running, as BF activity increased nearly twice as much compared to MH. However, it is essential to interpret these results cautiously, considering that only one study has investigated the EMG activity in subjects with a history of HSI during various running speeds.[39] Further research is needed to validate and confirm these findings in larger and more diverse populations.

Test Protocols

Three articles[7,40,41] utilized overground repeated sprint tests to evaluate biomechanical parameters. An overground repeated-sprint bout refers to a sequence of at least three consecutive sprints with an average rest period of no more than 21 seconds between each sprint.[54]

According to the study by Spencer et al.[55] the total sprint time showed high reliability, as indicated by a typical error of measurement of 0.7% (with a 95% confidence interval between 0.5% and 1.2%). The reliability of this test is comparable to other running tests involving repeated sprints on level ground that have also measured the total sprint time.[54] However, it is important to note that one study presented a contradictory result, which may have potentially lowered the reliability.[56] Further research is needed to better understand the factors influencing the test's reliability and its implications for assessing biomechanical parameters during overground repeated sprint tests.

In the study by Pimenta et al.[57] architectural differences in the biceps femoris long head muscle were investigated between injured and non-injured football players before and after repeated sprint tasks.[58] After an injury, sprinting ability and strength may decline, and there could be changes in muscle structure even after the player has returned to competition. The previously injured group in the study exhibited a shorter fascicle length, greater pennation angle at rest and during activity, and differences between limbs, along with significantly higher sprint performance speed. These findings highlight the importance of being cautious when comparing architectural parameters between the limbs of different subjects. The observed disparities in fascicle length between limbs with prior injuries and their uninjured counterparts during periods of rest or activity may be a consequence of the injury and not necessarily a predictive measure. This difference could also indicate an increased risk of re-injury in the same limb.[58]

Similarly, in another study by Pimenta et al.[57] the effects of a repeated sprint protocol on sprint performance were compared between football players with and without previous hamstring strain injuries.[57] The researchers found no significant difference in sprint performance between the previously injured and healthy control groups.[57] However, the intriguing result of their study was the early rate of torque development observed in the previously injured limb, showing a higher rate compared to the contralateral limb.[57] This finding suggests that despite similar sprint performance between the two groups, there may be distinct neuromuscular characteristics in the previously injured limb that warrant further investigation.

In the assessment of biomechanical parameters, two articles[38,39] utilized an incremental maximum treadmill sprint test. Although the specific test protocols were not detailed in these studies, the authors justified the use of this test by incorporating various running speeds to examine the potential impact of speed on the existence of a bilateral asymmetry.[39] Moreover, the choice of using 80% of maximum velocity in the treadmill sprint test is widely adopted in the literature and has been employed in previous research involving athletes who had previously experienced hamstring strain injuries and anterior cruciate ligament (ACL) injuries.[38,59,60]

Out of the reviewed articles, only one study[47] employed repeated sprints on a non-motorized treadmill. In their research, Lord et al.[47] investigated the reliability of this protocol utilizing a non-motorized treadmill. The study revealed that performance indicators such as maximum speed and average force can be effectively measured and used to conduct a repeated sprint protocol, yielding accurate results.[47] Moreover, the use of a curved non-motorized treadmill demonstrated high consistency when applied in short-duration sprints.[47]

Isokinetic Muscle Testing

In the context of Isokinetic muscle testing, three articles [42–44] utilized an angular velocity of 60 degrees per second to assess concentric knee flexion and extension. Two articles[41,44] employed 300 degrees per second angular velocity, while only one study[44] utilized 180 degrees per second angular velocity. Notably, isokinetic testing at a low angular speed (60 degrees per second) has been deemed a reliable indicator of non-contact leg injuries in National College American Association athletes, as demonstrated by Kim et al.[61]. Additionally, Sugiura et al.[62] observed a strong correlation between hamstring injuries in elite sprinters and hamstring muscle weakness when testing at lower speeds.[62]

Several considerations must be made in synthesizing the results of the included articles. First, the number and severity of HSI of the participants included in the study are diverse, which might affect the results seen in each of the articles included. A minor HSI might not have the same impact on sprinting biomechanical factors as a more severe injury would. Second, the mean number of months from injury before assessment, the presence or absence of rehabilitation after the injury, and the protocols and training programs implemented after HSI might affect the participants' response during the assessment. The papers did not determine whether the biomechanical asymmetries observed were already present before injury or might be the results of the incurred injury. More prospective research investigating the association between biomechanical variables and recurrent HSI must be conducted.

Prospective vs. Retrospective Study Designs

The prospective study design evaluates baseline exposure and monitors subjects over time to examine disease progression or mortality. It is suitable for assessing associations between exposures and outcomes, minimizing recall bias, and allowing the calculation of vulnerable population size.[63] However, loss to follow-up can skew results.[64] In contrast, retrospective study designs assemble cohorts, find eligible subjects, and evaluate baseline exposures after follow-up is completed.[63]

Prospective study design offers precise data collection on exposures, confounders, and outcomes, but it is costly, time-consuming, and less efficient due to the long follow-up period.[63] In retrospective designs, not all relevant risk factors may be recorded, potentially impacting the validity of reported associations when confounding is controlled for.[64]

Out of the seven cross-sectional studies included in this review, only one has a prospective cohort study design. Edouard et al.[40] examined how the ability to generate horizontal force during sprinting at both low and high speeds is related to the incidence of HSI in football [4]4. The study followed a group of 284 football players throughout the season; all participants were required to perform 30-meter sprints on the field at the start of the season and at various points during the season. Over the course of the season, prospective injury data on players were collected.[40] Their findings suggest that low horizontal force production capacities at low velocity during early sprint acceleration could be a potential additional factor associated with an increased risk of HSI when considering a comprehensive, multifactorial, and individualized approach.[40] The same outcomes cannot be observed in other cross-sectional study designs. The remaining six cross-sectional studies employed a combination of retrospective, exploratory, and comparative methodologies with the primary objective of investigating the effects of recurrent hamstring strain injuries (HSI). These studies encompassed a range of variables, namely the lower extremity strength characteristics,[39] muscle activity,[39] kinematics,[7] kinetics, [39,42,44,48] and spatiotemporal alterations or patterns during running.[7,43,48,51] Additionally, these studies explored deficits in the vertical forces[7] and horizontal forces,[43] as well as asymmetries and bilateral differences between the injured and uninjured limbs[44] within the same individuals.

Strengths and Limitations

Our scoping review adhered to the PRISMA-ScR guidelines and ensured that all the studies included in our review underwent peer review. However, it is important to note that our review has certain limitations. While we made efforts to include a wide range of published articles and grey literature relevant to our topic, it is possible that some relevant sources may have been missed.

CONCLUSION

This scoping review was able to report the common biomechanical variables (kinematic, kinetic, and spatiotemporal) assessed and the testing protocol used in assessing these biomechanical variables among running-related athletes with recurrent HSI. Nevertheless, the present review has uncovered a scarcity of studies dedicated to investigating this specific domain, resulting in a restricted examination of kinematic, kinetic, and spatiotemporal variables. Therefore, it is highly recommended that forthcoming research endeavors in this field adhere to established protocols, aiming to acquire a more exhaustive comprehension of hamstring strain injury (HSI) recurrence. Such comprehensive insights would then serve as valuable guidance for coaches and sports medicine professionals, facilitating the development of effective preventive and treatment strategies.

Individual Author's Contributions

All authors contributed significantly to this study and its reporting.

Disclosure Statement

This study is not affiliated with any funding agency.

Conflicts of interest

RVE, CS, and DM are part of the editorial board of PJAHS.

Supplementary Files

Supplementary File A. PRISMA-P Checklist

Supplementary File B. Data Charting Tool.

References

1. Chan O, Del Buono A, Best TM, Maffulli N. Acute muscle strain injuries: A proposed new classification system. Knee Surgery, Sport Traumatology, Arthroscopy. 2012;20(11):2356-2362. doi:10.1007/s00167-012-2118-z
2. Heiderscheit BC, Sherry MA, Silder A, Chummanov ES, Thelen DG. Hamstring strain injuries: Recommendations for diagnosis, rehabilitation, and injury prevention. Journal of Orthopaedic & Sports Physical Therapy. 2010;40(2):67-81. doi:10.2519/jospt.2010.3047
3. Beltran L, Ghazikhanian V, Padron M, Beltran J. The proximal hamstring muscle-tendon-bone unit: A review of the normal anatomy, biomechanics, and pathophysiology. European Journal of Radiology. 2012;81(12):3772-3779. doi:10.1016/j.ejrad.2011.03.099
4. Elliott MCCW, Zarins B, Powell JW, Kenyon CD. Hamstring muscle strains in professional football players: A 10-year review. American Journal of Sports Medicine. 2011;39(4):843-850. doi:10.1177/0363546510394647
5. Edouard P, Pollock N, Guex K, et al. Hamstring Muscle Injuries and Hamstring Specific Training in Elite Athletics (Track and Field) Athletes. International Journal of Environemntal Research and Public Health. 2022;19(17). doi:10.3390/ijerph191710992
6. Yu B, Liu H, Garrett WE. Mechanism of hamstring muscle strain injury in sprinting. Journal of Sport and Health Science. 2017;6(2):130-132. doi:10.1016/j.jshs.2017.02.002
7. Schache AG, Wrigley T V., Baker R, Pandy MG. Biomechanical response to hamstring muscle strain injury. Gait Posture. 2009;29(2):332-338. doi:10.1016/j.gaitpost.2008.10.054
8. Kenneally-Dabrowski CJB, Brown NAT, Lai AKM, Perriman D, Spratford W, Serpell BG. Late swing or early stance? A narrative review of hamstring injury mechanisms during high-speed running. Scandinavian Journal of Medicine & Science in Sport. 2019;29(8):1083-1091. doi:10.1111/sms.13437
9. Schache AG, Dorn TW, Blanch PD, Brown NAT, Pandy MG. Mechanics of the human hamstring muscles during

sprinting. Medicine & Science in Sports & Exercise. 2012;44(4):647-658. doi:10.1249/MSS.0b013e318236a3d2

10. Thelen DG, Chumanov ES, Hoerth DM, et al. Hamstring muscle kinematics during treadmill sprinting. Medicine & Science in Sports & Exercise. 2005;37(1):108-114. doi:10.1249/01.MSS.0000150078.79120.C8
11. Brukner P. Hamstring injuries: Prevention and treatment - An update. British Journal of Sports Medicine. 2015;49(19):1241-1244. doi:10.1136/bjsports-2014-094427
12. Lempainen L, Banke IJ, Johansson K, et al. Clinical principles in the management of hamstring injuries. Knee Surgery, Sport Traumatology, Arthroscopy. 2015;23(8):2449-2456. doi:10.1007/s00167-014-2912-x
13. Wangensteen A, Tol JL, Witvrouw E, et al. Hamstring Reinjuries Occur at the Same Location and Early after Return to Sport. American Journal of Sports Medicine. 2016;44(8):2112-2121. doi:10.1177/0363546516646086
14. Silvers-Granelli HJ, Cohen M, Espregueira-Mendes J, Mandelbaum B. Hamstring muscle injury in the athlete: State of the art. Journal of ISAKOS. 2021;6(3):170-181. doi:10.1136/jisakos-2017-000145
15. Hägglund M, Waldén M, Ekstrand J. Previous injury as a risk factor for injury in elite football: A prospective study over two consecutive seasons. British Journal of Sports Medicine. 2006;40(9):767-772. doi:10.1136/bjsm.2006.026609
16. Arnason A, Sigurdsson SB, Gudmundsson A, Holme I, Engebretsen L, Bahr R. Risk Factors for Injuries in Football. American Journal of Sports Medicine. 2004;32(SUPPL. 1). doi:10.1177/0363546503258912
17. Bourne MN, Opar DA, Williams MD, Shield AJ. Eccentric knee flexor strength and risk of hamstring injuries in rugby union. American Journal of Sports Medicine. 2015;43(11):2663-2670. doi:10.1177/0363546515599633
18. Fousekis K, Tsepis E, Poulmedis P, Athanasopoulos S, Vagenas G. Intrinsic risk factors of non-contact quadriceps and hamstring strains in soccer: A prospective study of 100 professional players. British Journal of Sports Medicine. 2011;45(9):709-714. doi:10.1136/bjsm.2010.077560
19. Freckleton G, Cook J, Pizzari T. The predictive validity of a single leg bridge test for hamstring injuries in Australian rules football players. British Journal of Sports Medicine. 2014;48(8):713-717. doi:10.1136/bjsports-2013-092356
20. Henderson G, Barnes CA, Portas MD, Christopher M, Barnes A. Factors Associated with Increased Propensity for Hamstring Injury in English Premier League Soccer Players. Running Head: Hamstring Injury in Soccer.; 2010.
21. Ruddy JD, Pollard CW, Timmins RG, Williams MD, Shield AJ, Opar DA. Running Exposure Is Associated with the Risk of Hamstring Strain Injury in Elite Australian Footballers.; 2018.
22. Schuermans J, Danneels L, Van Tiggelen D, Palmans T, Witvrouw E. Proximal Neuromuscular Control Protects Against Hamstring Injuries in Male Soccer Players: A Prospective Study with Electromyography Time-Series Analysis during Maximal Sprinting. American Journal of Sports Medicine. 2017;45(6):1315-1325. doi:10.1177/0363546516687750
23. Timmins RG, Bourne MN, Shield AJ, Williams MD, Lorenzen C, Opar DA. Short biceps femoris fascicles and eccentric knee flexor weakness increase the risk of hamstring injury in elite football (soccer): A prospective cohort study. British Journal of Sports Medicine. 2016;50(24):1524-1535. doi:10.1136/bjsports-2015-095362
24. van Dyk N, Bahr R, Burnett AF, Verhagen E, von Tiggelen D, Witvrouw E. No association between rate of torque development and onset of muscle activity with increased risk of hamstring injury in elite football. Scandinavian Journal of Medicine & Science in Sports. 2018;28(10):2153-2163. doi:10.1111/sms.13224
25. Verrall GM, Slavotinek JP, Barnes PG, Fon GT, Spriggins AJ. Clinical risk factors for hamstring muscle strain injury: A prospective study with correlation of injury by magnetic resonance imaging. British Journal of Sports Medicine. 2001;35(6):435-439. doi:10.1136/bjsm.35.6.435
26. Yeung SS, Suen AMY, Yeung EW. A prospective cohort study of hamstring injuries in competitive sprinters: Preseason muscle imbalance as a possible risk factor. British Journal of Sports Medicine. 2009;43(8):589-594. doi:10.1136/bjsm.2008.056283
27. Gabbe BJ, Bennell KL, Finch CF. Why are older Australian football players at greater risk of hamstring injury? Journal of Science and Medicine in Sport. 2006;9(4):327-333. doi:10.1016/j.jsams.2006.01.004
28. Opar DA, Williams MD, Timmins RG, Hickey J, Duhig SJ, Shield AJ. Eccentric hamstring strength and hamstring injury risk in Australian footballers. Medicine & Science in Sports & Exercise. 2015;47(4):857-865. doi:10.1249/MSS.0000000000000465
29. Orchard JW. Intrinsic and extrinsic risk factors for muscle strains in Australian football. The American Journal of Sports Medicine. 2001 May;29(3):300-3.
30. Orchard JW, Kountouris A, Sims K. Risk factors for hamstring injuries in Australian male professional cricket players. Journal of Sport & Health Science. 2017;6(3):271-274. doi:10.1016/j.jshs.2017.05.004
31. Roe M, Murphy JC, Gissane C, Blake C. Hamstring injuries in elite Gaelic football: an 8-year investigation to identify injury rates, time-loss patterns and players at increased risk. British Journal of Sports Medicine. 2016 Oct 20;52:982-988. DOI: 10.1136/bjsports-2016-096401

32. Daly C, Mccarthy Persson U, Twycross-Lewis R, Woledge RC, Morrissey D. The biomechanics of running in athletes with previous hamstring injury: A case-control study. Scandinavian Journal of Medicine & Science in Sport. 2016;26(4):413-420. doi:10.1111/sms.12464

33. Orchard JW, Kountouris A, Sims K. Risk factors for hamstring injuries in Australian male professional cricket players. Journal of Sport & Health Science. 2017;6(3):271-274. doi:10.1016/j.jshs.2017.05.004

34. Orchard JW, Driscoll T, Seward H, Orchard JJ. Relationship between interchange usage and risk of hamstring injuries in the Australian Football League. Journal of Science & Medicine in Sport. 2012;15(3):201-206. doi:10.1016/j.jsams.2011.11.25

35. Gabbe BJ, Bennell KL, Finch CF, Wajswelner H, Orchard JW. Predictors of hamstring injury at the elite level of Australian football. Scandinavian Journal of Medicine & Science in Sport. 2006;16(1):7-13. doi:10.1111/j.1600-0838.2005.00441.x

36. Ardern CL, Glasgow P, Schneiders A, Witvrouw E, Clarsen B, Cools A, Gojanovic B, Griffin S, Khan KM, Moksnes H, Mutch SA. 2016 Consensus statement on return to sport from the First World Congress in Sports Physical Therapy, Bern. British journal of sports medicine. 2016 May 25.

37. Wollin M, Thorborg K, Pizzari T. Monitoring the effect of football match congestion on hamstring strength and lower limb flexibility: Potential for secondary injury prevention?. Physical Therapy in Sport. 2018 Jan 1;29:14-8.

38. Brughelli M, Cronin J, Mendiguchia J, Kinsella D, Nosaka K. Contralateral leg deficits in kinetic and kinematic variables during running in A running in Australian Rules F alian Rules Football pla ootball players with pr ers with previous hamstring injuries. Journal of Strength & Conditioning Research. 2010;24(2010):77-91. doi:10.1007/978-3-319-18245-2_9

39. Silder A, Thelen DG, Heiderscheit BC. Effects of prior hamstring strain injury on strength, flexibility, and running mechanics. Clinical Biomechanics. 2010;25(7):681-686. doi:10.1016/j.clinbiomech.2010.04.015

40. Edouard P, Lahti J, Nagahara R, et al. Low horizontal force production capacity during sprinting as a potential risk factor of hamstring injury in football. International Journal of Environmental Research & Public Health. 2021;18(15). doi:10.3390/ijerph18157827

41. Ishøi L, Thorborg K, Hölmich P, Krommes K. Sprint Performance in Football (Soccer) Players With and Without a Previous Hamstring Strain Injury: an Explorative Cross-Sectional Study. International Journal of Sports Physical Therapy. 2020;15(6):947-957. doi:10.26603/ijspt20200947

42. Brukner P, Nealon A, Morgan C, Burgess D, Dunn A. Recurrent hamstring muscle injury: Applying the limited evidence in the professional football setting with a seven-point programme. British Journal of Sports Medicine. 2014;48(11):929-938. doi:10.1136/bjsports-2012-091400

43. Izovska J, Hank M, Cabell L, et al. The Hamstring and ACL Injury Incidence during a Season Is Not Directly Related to Preseason Knee Strength Ratios in Elite Male Soccer Players. Applied Sciences. 2022;12(3). doi:10.3390/app12031272

44. Tol JL, Hamilton B, Eirale C, Muxart P, Jacobsen P, Whiteley R. At return to play following hamstring injury the majority of professional football players have residual isokinetic deficits. British Journal of Sports Medicine. 2014;48(18):1364-1369. doi:10.1136/bjsports-2013-093016

45. Tricco AC, Lillie E, Zarin W, et al. PRISMA Extension for Scoping Reviews (PRISMA-ScR): Checklist and Explanation. Annals of Internal Medicine. 2018;169(7):467-473. doi:10.7326/M18-0850

46. Page MJ, McKenzie JE, Bossuyt PM, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. Systematic Reviews. 2021;10(1):1-11. doi:10.1186/s13643-021-01626-4

47. Lord C, Blazevich AJ, Drinkwater EJ, Ma'ayah F. Greater loss of horizontal force after a repeated-sprint test in footballers with a previous hamstring injury. Journal of Science & Medicine in Sport. 2019;22(1):16-21. doi:https://doi.org/10.1016/j.jsams.2018.06.008

48. Seco-Calvo J, Palavicini M, Rodríguez-Pérez V, Sánchez-Herráez S, Abecia-Inchaurregui LC, Mielgo-Ayuso J. The role of hip joint clearance discrepancy as other clinical predictor of reinjury and injury severity in hamstring tears in elite athletes. Journal of Clinical Medicine. 2021;10(5):1-16. doi:10.3390/jcm10051050

49. Nijs A, Roerdink M, Beek PJ. Running-style modulation: Effects of stance-time and flight-time instructions on duty factor and cadence. Gait & Posture. 2022 Oct 1;98:283-8.

50. Casado A, Tuimil JL, Iglesias X, Fernández-del-Olmo M, Jiménez-Reyes P, Martín-Acero R, Rodríguez FA. Maximum aerobic speed, maximum oxygen consumption, and running spatiotemporal parameters during an incremental test among middle-and long-distance runners and endurance non-running athletes. PeerJ. 2022 Oct 5;10:e14035.

51. Roche-Seruendo LE, García-Pinillos F, Haicaguerre J, Bataller-Cervero A V., Soto-Hermoso VM, Latorre-Román P. Lack of influence of muscular performance parameters on spatiotemporal adaptations with increased running velocity. Journal of Strength & Conditioning Research. 2018;32(2):409-415. doi:10.1519/jsc.0000000000001845

52. Wisløff U, Castagna C, Helgerud J, Jones R, Hoff J. Strong correlation of maximal squat strength with sprint performance and vertical jump height in elite soccer players. British journal of sports medicine. 2004 Jun 1;38(3):285-8.

53. Morin JB, Samozino P. Interpreting power-force-velocity profiles for individualized and specific

training. International journal of sports physiology and performance. 2016 Mar 1;11(2):267-72.

54. Spencer M, Lawrence S, Rechichi C, Bishop D, Dawson B, Goodman C. Time-motion analysis of elite field hockey, with special reference to repeated-sprint activity. Journal of sports sciences. 2004 Sep 1;22(9):843-50.
55. Spencer M, Fitzsimons M, Dawson B, Bishop D, Goodman C. Reliability of a repeated-sprint test for field-hockey. Journal of science and medicine in sport. 2006 May 1;9(1-2):181-4.
56. Wragg CB, Maxwell NS, Doust JH. Evaluation of the reliability and validity of a soccer-specific field test of repeated sprint ability. European journal of applied physiology. 2000 Sep;83:77-83.
57. Pimenta R, Lopes T, Bruno P, Veloso A. Effects of Repeated Sprints on Hamstring Active Shear Modulus Pattern and Neuromuscular Parameters in Football Players with and without Hamstring Strain Injury History—A Retrospective Study. Applied Sciences. 2023 Feb 27;13(5):3099.
58. Pimenta R, Antunes H, Lopes T, Veloso A. Do Repeated Sprints Affect the Biceps Femoris Long Head Architecture in Football Players with and without an Injury History?—A Retrospective Study. Biology. 2023 Jan 8;12(1):96
59. Hewett TE, Myer GD, Ford KR, Heidt Jr RS, Colosimo AJ, McLean SG, Van den Bogert AJ, Paterno MV, Succop P. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. The American journal of sports medicine. 2005 Apr;33(4):492-501.
60. Myer GD, Paterno MV, Ford KR, Quatman CE, Hewett TE. Rehabilitation after anterior cruciate ligament reconstruction: criteria-based progression through the return-to-sport phase. Journal of Orthopaedic & Sports Physical Therapy. 2006 Jun;36(6):385-402.
61. Kim D, Hong J. Hamstring to quadriceps strength ratio and noncontact leg injuries: A prospective study during one season. Isokinetics and Exercise Science. 2011 Jan 1;19(1):1-6.
62. Sugiura Y, Saito T, Sakuraba K, Sakuma K, Suzuki E. Strength deficits identified with concentric action of the hip extensors and eccentric action of the hamstrings predispose to hamstring injury in elite sprinters. Journal of orthopaedic & sports physical therapy. 2008 Aug;38(8):457-64.
63. Euser AM, Zoccali C, Jager KJ, Dekker FW. Cohort studies: Prospective versus retrospective. Nephron - Clinical Practice. 2009;113(3). doi:10.1159/000235241
64. Sedgwick P. Prospective cohort studies: advantages and disadvantages. Bmj. 2013 Nov 8;347.