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REVIEW ARTICLE

Utilizing GPS technology to identify and manage hamstring injuries during high-speed running: A scoping review

Ernest Miller. *Duke Sports Sciences Institute. Durham, NC, United States of America.*
Brandon Surber. *Duke Sports Sciences Institute. Durham, NC, United States of America.*
Lucas Vrooman. *Duke Sports Sciences Institute. Durham, NC, United States of America.*
Stephanie Hendren. *Duke Sports Sciences Institute. Durham, NC, United States of America.*
Heather Myers . *Duke Sports Sciences Institute. Durham, NC, United States of America.*

ABSTRACT

Purpose: Hamstring injuries are among the most prevalent injuries in elite sport with high rates of recurrence. Global Positioning System (GPS) technology has been widely implemented to measure the movement of athletes. The purpose of this scoping review is to examine how GPS technology is used to manage hamstring injuries during high-speed running. Methods: A scoping review was conducted within Embase, CINAHLComplete, SPORTDiscus, and Scopus. Studies were included if they used objective GPS metrics and investigated their relationship to hamstring injuries or risk factors. Studies were excluded if they did not report hamstring injuries separately. Results: 3950 articles were reviewed and 15 met inclusion criteria. Most studies were conducted with elite male soccer players. The most common GPS metrics reported included total distance traveled, high speed running distance over 24 km/hour, the acute to chronic workload ratio, and efforts exceeding 80% of maximum speed. Clinical relevance: The current literature on GPS monitoring for hamstring injury management focuses on elite male soccer players, with limitations due to varying injury definitions and a lack of prospective trials. Clinicians may consider managing high-speed running loads above 24 km/h and 80% of maximum speed to modify hamstring injury risk in elite male soccer players.
Keywords: Hamstring injury, Global Positioning System (GPS), Injury management, High-Speed running, Training load.

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Corresponding author. *Duke Sports Sciences Institute. DUMC 3965, 3475 Erwin Road, Durham, NC 27705, United States of America.*
E-mail: heather.myers@duke.edu
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INTRODUCTION

Hamstring strain injuries are among the most common and burdensome injuries in elite sports, resulting in critical time lost from competition with high rates of recurrence (Ekstrand et al., 2023; Mack et al., 2020; Okoroha et al., 2019). Professional sporting organizations are investing significant financial and technological resources (NFL, 2024) to better understand and mitigate the risk of these injuries. Despite increased research and clinical attention, injury rates appear to be on the rise (Ekstrand et al., 2023; Mack et al., 2020; Okoroha et al., 2019).

In the last twenty years, there has been rapid interest in and implementation of athlete monitoring technology including global positioning systems (GPS) to inform athletic performance and injury reduction practices. GPS utilizes a satellite navigation network that provides location and time data. In a sporting context the capabilities of GPS have been combined with accelerometers (measuring change in velocity), magnetometers (measuring orientation), and gyroscopes (measuring rotation) into commercially available tracking devices that can be noninvasively worn by athletes during live training and competition to gather data about athletic movements. The first patent for a GPS tracker for sport was obtained in 2004 and widespread authorization and adoption by multiple professional sports leagues occurred in the 2010s (French & Torres-Ronda, 2022).

Of considerable interest among the metrics reported by commercially available GPS athlete monitoring systems for their potential relationship to hamstring strain injury are those metrics related to high-speed running including total high-speed running distance and percentage of maximal velocity. It is widely accepted from both anecdotal evidence and formal investigation that hamstring strain injuries commonly occur during high-speed running efforts (Martin et al., 2022). It has also been proposed that properly progressed intensity, frequency, and volume of high-speed running may be protective against index injury and key to optimizing rehabilitation and return to play following hamstring strain (Gómez-Piqueras & Alcaraz, 2024).

To the authors' knowledge there has not been a comprehensive review of the existing literature investigating high-speed running metrics derived from GPS technology and their association with hamstring strain injury. The organization of data and identification of patterns in high-speed running metrics pertaining to the volume, intensity, and frequency of exposures at which hamstring strain injuries occur has the potential to better inform injury risk reduction and rehabilitation practices. Therefore, the purpose of this scoping review is to collate the available literature and provide a summary of lines of inquiry, conclusions, and potential avenues for further investigation in the utilization of GPS systems to identify and manage hamstring strain injuries.

METHODS

A scoping review, appropriate for exploring an emerging area of research to identify key concepts, types of literature available, and knowledge gaps, was conducted using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines and was registered with Open Science under registration number:(blinded). A systematic search on the concepts of hamstring injury and GPS was conducted on November 20, 2023. We searched MEDLINE (Ovid), CINAHL Complete (EBSCOhost), SPORTDiscus (EBSCOhost), and Scopus (Elsevier) using a combination of keywords and database-specific subject headings when available. No restrictions were placed by date or language. Editorials, letters, comments, and case reports, book chapters/reviews, theses, and pamphlets were excluded through the search. Animal-only studies were similarly excluded. No additional registries or grey literature were searched. The full, reproducible search strategies for all included databases are located in the Appendix. (Appendix 1) In addition, a manual search of reference lists of the articles screened for inclusion was performed to find relevant articles not identified in the initial search. All citations were imported into Covidence (*Covidence Systematic Review Software*, n.d.), a systematic review screening software, for de-duplication and screening.

Two of three independent reviewers (EM,BS,LV) screened all titles and abstracts. Conflicts were resolved by a third reviewer (HM). The same process was repeated for full text review. Studies were included if they reported objective metrics derived from GPS monitoring technology and investigated their relationship to the incidence of hamstring strain injuries or proposed hamstring strain injury risk factors. Studies were excluded if they lacked GPS monitoring, did not report hamstring injuries independent of other injuries, or for wrong study design (case report, commentary, conference abstract).

Data extraction and quality assessment

Two of three (EM,BS,LV) blinded reviewers recorded relevant information regarding the study characteristics, including the study design, level of evidence (based on the guidelines of the Oxford Centre for Evidence-Based Medicine), population, outcome measures, and timing of measurement collection.

The risk of bias was performed independently by two reviewers (EM,BS) using the Methodological Items for Non-Randomized Studies (MINORS) tool, a methodological index for nonrandomized studies (Kim, 2013). A third reviewer (HM) resolved discrepancies. Each MINORS item was scored 0 if not reported, 1 if reported but inadequate, and 2 if reported and adequate. The maximum possible score was 16 for non-comparative studies and 24 for comparative studies. Scores between 13 and 16 for non-comparative studies, or between 21 and 23 for comparative studies, were considered at low risk of bias. For those scoring less than 12 for noncomparative studies or less than 20 for comparative studies were considered at high risk of bias. The level of agreeability of the risk of bias between the two reviewers was calculated using Cohen’s Kappa.

Statistical analysis

Given the non-randomized design and relative low levels of evidence of most of the included studies, pooled statistics were not reported. This group of studies demonstrates both clinical and methodological heterogeneity, making both meta-analysis and sub-group analysis unfeasible. As a result, individual results are reported for each study.

RESULTS

After 3,420 duplicates were removed, 7,420 studies were screened against eligibility criteria. Fifteen articles were included in the review (Figure 1). There was a substantial level of agreeability (96%) between full text reviewers (Cohen’s Kappa = 0.93). The median level of evidence of the included studies was Level III (15 studies) (Table 1). Based on MINORS criteria, one comparative study scored an 11 out of 24. In the fourteen non-comparative studies, scores ranged from 2-6 out of a possible 16. Mean MINORS scores were 3.5 for non-comparative studies. The level of agreeability between MINORS raters was 86.9% with Cohen’s kappa 0.722 indicating moderate agreeability.

Publication years ranged from 2017 to 2023 with data collected between 2011 and 2022. Four studies did not report the time of study activities. The included studies represent four continents and twelve countries. All but one study was observational in design. Most studies were conducted in the sport of soccer (11). All studies were of male athletes competing at the professional (14) or semi-professional (1) level. The most common GPS metrics reported included total distance travelled, high speed running distance over 24 km/hour, the acute to chronic workload ratio, and efforts exceeding 80% of maximum speed. Only two studies combined GPS metrics with some form of internal workload metric. The definition of hamstring injury varied considerably. Heterogeneous and insufficient data limits this scoping review to a narrative discussion and conclusion. A summary of outcomes for each included study is provided in Table 2.

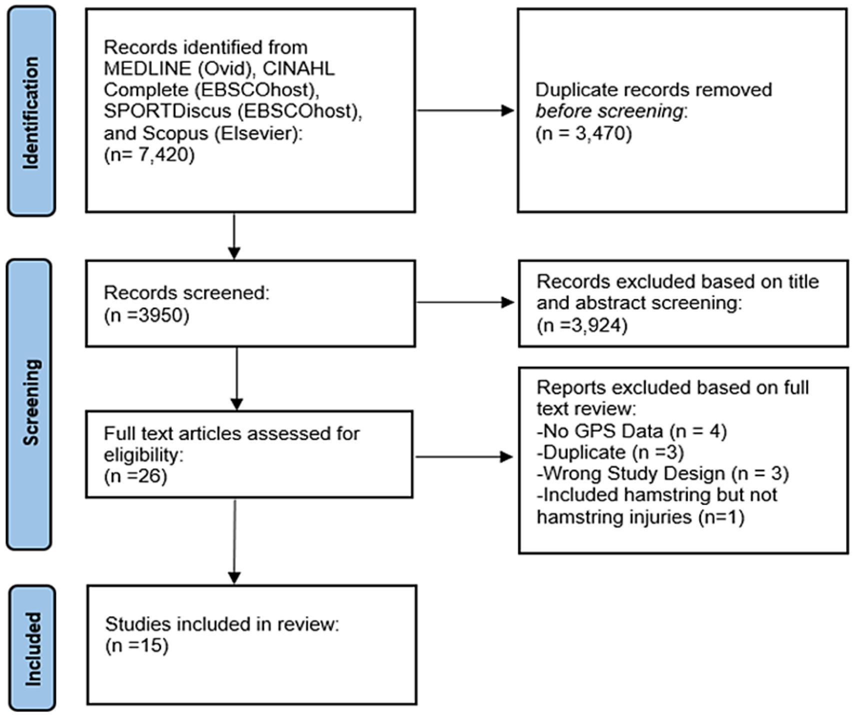

Figure 1. PRISMA Diagram for study inclusion (PRISMA, Preferred Reporting Items for Systematic Review and Meta-Analysis).

Table 1. Summary of eligible studies included for review study (Author, year).

	Journal	Country	Years	Level of Evidence	Study Design	MINORS	Mean Age ± SD (range)	Population	N
Aiello 2023	J of Science and Med in Sport	Italy	2019-2022	III	Retrospective Review	4/16	26.6±4.3	Elite male football(soccer) players	46
Buchheit 2023	Biol Sport	Ireland, France, Canada	2018-2021	III	Retrospective Review	2/16	Not provided	Elite Adult Footballers	620 players (152 injuries)
Duhig 2016	Br J Sports Med	Australia	2012-2014	III	Cohort study	3/16	22.2±3.4	Elite Australian Rules Footballers	51
Hoppen 2022	BMJ Open Sport Exerc Med	The Netherlands	2017-2020	III	Retrospective Review	4/16	20.89±3.41	Professional football (soccer club)	15 (18 injuries)
Li 2017	Orthop J Sports Med	United States	2014-2016	III	Retrospective Review	2/16	Injured Group: 26.1±2.87 Non-injured Group: 25.5±2.92	One football team in the NFL	232
Madison 2019	J Strength Cond Res	UK		III	Cohort study	6/16	23±5	Semi-professional male soccer players	10

Moreno-Perez 2021	Biol Sport	Spain	2011-2014	III	Cohort study	11/24		Professional football (soccer) players	144
Moreno-Perez 2023	Sports Health	Spain	2013-2016	III	Cohort study	4/16	26.7±3.8	Professional Football (soccer) players	144
Ribeiro-Alvares 2023	Sport Science Health	Brazil	2018-2019	III	Retrospective Review	3/16	24.6±3.6	Professional Male Soccer Players	48
Ruddy 2018	Br J Sports Med	Australia	2014-2015	III	Cohort study	5/16	23.4±3.5	Elite Australian footballers competing in AFL	220 (30 hamstring injuries)
Satkunskiene 2020	J Muscluloskelet Neuronal Interact	Lithuania		III	Cohort study	4/16	23.8±7	Professional Soccer Players	11
Shah 2022	Sports	UK	2018-2020	III	Cohort study	3/16		Professional football (soccer) players	58
Stares 2018	J Science Med in Sport	Australia		III	Cohort study	3/16		Elite Australian Rules Footballers	N = 85 (37 injuries)
Whiteley 2021	Scand J Med Sci Sports	Australia, England, Ireland, Wales		III	Retrospective Review	3/16	25.18±4.17	Professional Association Football-soccer, Rugby League, Rugby Union, and Australian rules football players	15 (22 injuries)
Whiteley 2022	Sports Health	Qatar	2013-2019	III	Retrospective Review	3/16		Professional Soccer Players	38

Table 2. Summary of outcomes for each included study.

Study ID	Population	Summary
Aiello 2023	Elite male football(soccer) players	Sixteen out of 17 hamstring injuries occurred while players were running, with a median distance of 16.75 meters and peak speeds exceeding 25 km/h, corresponding to 87.55% of their maximum speed. Players who were decelerating at the time of injury had covered 7.7 meters and were slowing down from speeds around 30.69 km/h. Overall, most hamstring injuries occurred when players were running faster than 25 km/h and over 80% of their maximum speed, often without the ball (71%) and during linear runs (88%).
Buchheit 2023	Elite Adult Footballers	The study analysed Maximum Sprinting Speed (MSS) using GPS data, averaging the top three speeds when specific testing was unavailable. It assessed hamstring injury risk based on exposures to running speeds exceeding 85%, 90%, and 95% of each player's MSS. Injuries considered were those causing over three days of missed training. Findings indicated that most players reached matches without near-to-MSS exposures in training. Notably, there were no hamstring injuries when players trained at over 95% MSS two days before matches (D-2), whereas injuries still occurred when such exposures happened earlier or not at all. The study suggests that programming >95% MSS exposures at D-2 could reduce match-related hamstring injuries.
Duhig 2016	Elite Australian Rules Footballers	In the 2013 season, injured players had a mean high-speed running distance of 22.1 km, while uninjured players averaged 22.6 km; in 2014, injured players averaged 16.6 km compared to 15.2 km for uninjured players. A higher likelihood of hamstring strain injuries was linked to greater high-speed running distances in the four weeks prior, especially the week immediately before injury (OR = 6.44). Players with more than four years of experience had a reduced risk of hamstring injury, suggesting experience offers a protective effect (OR = 0.77)
Hoppen 2022	Professional football (soccer club)	The median number of matches to reach pre-injury maximal velocity was 2, with 83% of injuries reaching this within 2 matches. Pre-injury total distance, sprint distance, and high-intensity distance were reached within 1 match for most injuries (94% for sprint distance). The median time to return to pre-injury maximal velocity was 11 days, while total distance, high-intensity distance, and sprint distance were regained in a median of 5 days.
Li 2017	One football team in the NFL	The average acute workload ratio (ACR) was significantly higher in the injured cohort compared to the uninjured cohort (2.14 vs. 1.73, p = .022), indicating a potential link between workload and injury risk. Injured players experienced a 111% increase in mean player load during the week of injury (745.6) compared to their preinjury block (523.6, p < .001), while uninjured players saw a 73% increase. Additionally, the incidence of hamstring injuries was greater during the preseason compared to the regular season, with 65.7% of injuries occurring in defensive backs and wide receivers.

Madison 2019	Semi-professional male soccer players	In a study comparing small-sided games (SSGs) with larger relative areas, significant differences were observed in peak hamstring force decrement and mean hamstring force deficits at 90 degrees, with larger games resulting in greater decrements (5.78 N and -13.62 N, respectively). The number of accelerations performed during sessions was positively correlated with reduced hamstring peak torque at 90 degrees (r = 0.46, *p* = .039), suggesting that increased acceleration may lead to greater hamstring fatigue. Overall, larger relative area SSGs elicited higher internal and external loads, contributing to hamstring force decrements that can be managed by controlling the pitch area.
Moreno-Perez 2023	Professional football (soccer) players	High-speed running distances of ≤328m and total running distances of ≤5.8km were identified as significant predictors for hamstring injury, with respective sensitivity and specificity values. Most hamstring injuries (86.4%) occurred during match situations, particularly during explosive actions such as sprints over 20m, kicking, and accelerating. Lower match-play exposure in the game or two games before an injury increased the likelihood of injury, with key thresholds being less than 95 minutes of play or covering distances under 12 km and high-speed running under 901m.
Moreno-Perez 2021	Professional Football (soccer) players	Injured players showed significantly lower accumulated match exposure time and running distances (total distance and high-speed running) in the five games before injury compared to uninjured players. The Acute to Chronic Workload Ratio (ACWR) did not differ substantially between injured and uninjured players in the 5-2 matches before injury, but uninjured players had higher ACWR in the match immediately prior to injury. These findings suggest that lower playing exposure, leading to reduced physical load, may increase the risk of hamstring injuries, particularly when players are underloaded in official matches.
Ribeiro-Alvares 2023	Professional Male Soccer Players	Of the 20 players who sustained hamstring injuries, 75% had an acute chronic workload ratio (ACWR) below 1.5 for key GPS metrics (total distance, high-speed running, very high-speed running, and actions >19 km/h) before the injury. Only 25% of players were in the "*danger zone*" (ACWR >1.5) for very high-speed running, with some also in the danger zone for high-speed running and total distance. The study concluded that using ACWR as the primary metric to determine player readiness should be approached with caution, as most injuries occurred outside the danger zone.
Ruddy 2018	Elite Australian footballers competing in AFL	Weekly distance covered above 24 km/h (>653 m) had the largest influence on the risk of hamstring strain injury (HSI) in the following week, with a relative risk (RR) of 3.4. For relative exposure, the percentage of distance covered above 24 km/h compared to distance above 10 km/h (>2.5%) also significantly increased the risk of HSI (RR = 6.3). Although these running exposure variables were associated with HSI risk, their predictive accuracy was limited, showing modest clinical utility for predicting individual injury occurrences.
Satkunskiene 2020	Professional Soccer Players	During the in-season period, hamstring passive stiffness increased, with negative correlations observed between stiffness and acceleration (r = -0.655, *p* = .004) as well as jump events (r = -0.873, *p* = .001). The changes in hamstring stiffness were linked to the intensity and volume of accelerations and jumps, suggesting biomechanical adaptations were suppressed in players exposed to higher external loads. These findings highlight that regular training and matches increase hamstring passive stiffness, but excessive mechanical stress may hinder the adaptation of the muscle-tendon unit.
Shah 2022	Professional football (soccer) players	A significant inverse relationship was found between total weekly sprint distance and the percentage change in eccentric hamstring strength, though the correlation was very small (ρ = -0.13, *p* < .01). Similarly, weekly efforts at >90% maximum velocity also showed a small inverse relationship with eccentric hamstring strength (ρ = -0.08, *p* = .01), while efforts >95% maximum velocity had no significant effect. Completing 7-8 weekly sprint efforts at >90% maximum velocity led to a significant decrease in eccentric hamstring strength, suggesting that monitoring sprint load at these intensities may help reduce hamstring injury risk in professional footballers.
Stares 2018	Elite Australian Rules Footballers	High rehabilitation workloads delayed return to play (RTP), with total distances covered above 49,775 m and sessional RPE values above 1266 AU significantly slowing recovery. Returning to running within 3-4 days increased the risk of subsequent injury, while achieving moderate-high sprint distances (427-710 m) was protective against future injuries. Monitoring training loads during rehabilitation can guide RTP decisions, balancing faster recovery with minimizing the risk of re-injury.
Whiteley 2021	Professional Association Football-soccer, Rugby League, Rugby Union, and Australian rules football players	Preinjury cumulative high-speed running distances were highly correlated across individuals, but post-injury values showed significant suppression (*p* = .0005). Upon returning to play, 7 out of 15 players experienced a sustained reduction in high-speed running distance, 7 showed no change, and only 1 player saw an increase. The study concluded that nearly half of the players did not return to their preinjury high-speed running performance, suggesting persistent deficits may exist after a hamstring strain injury.
Whiteley 2022	Professional Soccer Players	Players returning to match-play after a hamstring strain injury showed small reductions in physical performance, including a decrease in maximal speed by 0.25 km/h, a reduction in high-speed running distance by 43 meters, and a decrease in sprinting distance by 22 meters. These declines were within the normal variation typically seen between matches. Despite these changes, the performance reductions post-injury did not substantially deviate from usual match fluctuations

DISCUSSION AND CONCLUSIONS

Despite the widespread use of GPS technology and the near ubiquitous issue of hamstring injuries in elite level sport, there is a dearth of existing experimental literature in a narrow population of athletes to inform clinical decision-making. Of the fifteen studies included in this review, eleven (Aiello et al., 2023; Buchheit et al., 2023; Hoppen et al., 2022; Madison et al., 2019; Moreno-Perez et al., 2021; Moreno-Pérez et al., 2023; Ribeiro-Alvares et al., 2023; Satkunskiene et al., 2020; Shah et al., 2022; Whiteley et al., 2021, 2022) examined professional male soccer players, despite hamstrings injury also being of high concern in women's professional soccer (Hallén et al., 2024) and in additional sports such as baseball (Okoroha et al., 2019) and American football (Mack et al., 2020). Notably, there were no studies that met the inclusion criteria that were conducted on female athletes of any sport. While there was an approximately equal representation of prospective (Duhig et al., 2016; Madison et al., 2019; Moreno-Perez et al., 2021; Moreno-Pérez et al., 2023; Ruddy et al., 2018; Satkunskiene et al., 2020; Shah et al., 2022; Stares et al., 2018) and retrospective (Aiello et al., 2023; Buchheit et al., 2023; Hoppen et al., 2022; Li et al., 2020; Ribeiro-Alvares et al., 2023; Whiteley et al., 2021, 2022) (n = 8 and n = 7, respectively) investigations, most studies meeting the inclusion criteria were observational, with only three studies containing experimental designs (Madison et al., 2019; Moreno-Perez et al., 2021; Moreno-Pérez et al., 2023) and only two possessing control groups (Moreno-Perez et al., 2021; Moreno-Pérez et al., 2023).

Eight (Aiello et al., 2023; Buchheit et al., 2023; Duhig et al., 2016; Li et al., 2020; Moreno-Perez et al., 2021; Moreno-Pérez et al., 2023; Ribeiro-Alvares et al., 2023; Ruddy et al., 2018) of the included studies investigated the incidence of hamstring injuries directly, while seven (Hoppen et al., 2022; Madison et al., 2019; Satkunskiene et al., 2020; Shah et al., 2022; Stares et al., 2018; Whiteley et al., 2022) of the studies examined proposed hamstrings injury risk factors including hamstrings eccentric strength (Shah et al., 2022) and stiffness (Satkunskiene et al., 2020). Of importance, the definition of a hamstring injury varied considerably across studies from a relatively low diagnostic threshold of *"acute pain in the posterior thigh that caused immediate cessation of exercise"* (Duhig et al., 2016) to a relatively high diagnostic threshold of injuries that caused "*absence of training and competition of at least seven days*"(12) or "*disruption of hamstring fibres confirmed by magnetic resonance imaging*" (Ruddy et al., 2018). Such heterogeneity of injury definition would pose challenges to future attempts to collectively synthesize data.

High speed running distance (Duhig et al., 2016; Hoppen et al., 2022; Moreno-Perez et al., 2021; Moreno-Pérez et al., 2023; Ribeiro-Alvares et al., 2023; Ruddy et al., 2018; Shah et al., 2022; Stares et al., 2018) (n = 8), total distance travelled (Aiello et al., 2023; Hoppen et al., 2022; Moreno-Perez et al., 2021; Moreno-Pérez et al., 2023; Ribeiro-Alvares et al., 2023; Stares et al., 2018) (n = 6), and an acute to chronic workload ratio (ACWR) measure (Duhig et al., 2016; Li et al., 2020; Ribeiro-Alvares et al., 2023) (n = 3) were the most investigated metrics. Within the last decade, much research and practical focus has been placed on the concept of the ACWR, where the acute workload, most often operationalized as the total workload over the course of one week, is divided by the chronic workload, most commonly a four-week training or competition block (Hulin et al., 2016). An ACWR between 0.8-1.3 is proposed to be optimal, with a ratio of less than 0.8 putting athletes at risk due to undertraining and a ratio greater than 1.3 or an acute spike in workload greater than 10% increasing injury risk due to fatigue or inadequate preparation (Hulin et al., 2016). Despite its widespread usage, Impellezeri et al. offered a substantive critique of the research in this area to date, identifying several methodological and conceptual flaws in the ACWR and calling into question its uncritical adoption into practice (Impellizzeri et al., 2020). "*Load*" is a general term, with variable definitions depending on the context, but can be understood as a psychophysiological stress on the athlete, which is further subdivided into "*internal*" and "*external*" load. External load is in reference to measurable characteristics of work the athlete has completed and in the context of this review, would include such measures as high-speed running distance and total distance travelled. The internal load is the perceptual or physiological response to the external load and may include measures like heart rate, blood lactate, or rating of perceived exertion and has been proposed as a critical component to a comprehensive understanding of the total load experienced by athletes (McCall et al., 2018). Only two studies (Duhig et al., 2016; Stares et al., 2018) included in this review used both internal and external load metrics. Given the complex ethology of athletic injuries, it is possible that combining external GPS metrics with measures of internal load and other proposed risk factors may aid in better identifying athletes at higher risk of injury. Novel study types such as the study by Aiello et al included in this review which combined a GPS and video-based method to examine high-speed running metrics at the time of injury may additionally provide greater context for the ethology of an injury including kinematic and environmental variables (Aiello et al., 2023).

The Nordic hamstring curl, an eccentric strengthening exercise, rose to prominence in the injury prevention and rehabilitation literature as an effective intervention, with several individual studies (Mjølsnes et al., 2004; Petersen et al., 2011; Seagrave et al., 2014; van der Horst et al., 2015) and two meta-analyses (Al Attar et al., 2017; van Dyk et al., 2019) suggesting that implementation of the exercise resulted in a clinically significant reduction in injury rates. However, a recent reappraisal (Impellizzeri et al., 2021) of the meta-analyses in this area concluded that the preventive effects of the Nordic hamstring curl proposed from the existing literature were questionable due to high risk of publication bias, variable and contradictory effects, and limited available evidence outside the sport of soccer. While the effectiveness of the Nordic hamstring exercise in improving eccentric hamstring strength and hamstring fascicle length, two modifiable risk factors supported in the hamstring injury risk literature, appears evidenced (Alonso-Fernandez et al., 2018; Cuthbert et al., 2020; Gérard et al., 2020; Opar et al., 2012, 2015; Timmins et al., 2016), it is likely that the exercise is only one important component of a comprehensive rehabilitation and prevention program rather than a panacea. The continuing rise of hamstring injuries suggests that more comprehensive risk reduction and rehabilitation programs are warranted.

Utilizing GPS for monitoring and progressing high-speed running training as a preventative and rehabilitative measure may have certain advantages or complement Nordic hamstring training as the kinetic and kinematic profile of high-speed running programs may more closely approximate the demands placed on the hamstrings in the sporting environment. However, to date, there have been no prospective controlled trials comparing GPS monitored high-speed running dosage in relation to the incidence of hamstring injuries. The current literature provides no evidence to guide management of high-speed running in female athletes and is limited in its application outside of the unique demands of soccer. Future research may benefit from more experimental study designs and utilizing other purported risk factors in conjunction with GPS monitoring.

AUTHOR CONTRIBUTIONS

EM and HM developed the research question. SH conducted the systematic search. EM, HM, BS, and LV screened articles, extracted data, performed risk of bias assessment, and prepared the manuscript. All authors read and approved the final manuscript.

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No potential conflict of interest was reported by the authors.

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APPENDIX 1. SEARCH STRATEGIES.

Date of completed search: November 20, 2023.

Total number of articles (before de-duplication): 7420.

Total number of articles (after de-duplication): 3950.

Database: Medline (via PubMed)

Set #	Search Strategy	Results
1.	"Running"[Mesh] OR runs[tiab] OR running[tiab] OR ran[tiab] OR sprint[tiab] OR sprints[tiab] OR sprinting[tiab] OR accelerat*[tiab] OR deaccelerate*[tiab] OR "player load"[tiab] OR "player loads"[tiab] OR workload[tiab] OR workloads[tiab]	488661
2.	"Hamstring Muscles"[Mesh] OR "Hamstring Tendons"[Mesh] OR "Thigh"[Mesh] OR hamstring[tiab] OR hamstrings[tiab] OR "biceps femoris"[tiab] OR semitendinosus[tiab] OR semitendinous[tiab] OR semimembranosus[tiab] OR thigh[tiab] OR thighs[tiab]	58738
3.	"injuries" [Subheading] OR "Wounds and Injuries"[Mesh] OR "Sprains and Strains"[Mesh:NoExp] OR "Tendinopathy"[Mesh] OR "Fractures, Avulsion"[Mesh] OR injur*[tiab] OR strain[tiab] OR strains[tiab] OR stress*[tiab] OR sprain[tiab] OR sprains[tiab] OR pull[tiab] OR pulls[tiab] OR pulled[tiab] OR tear[tiab] OR tears[tiab] OR tendinopathy[tiab] OR tendinopathies[tiab] OR tendinitis[tiab] OR tendinosis[tiab] OR avulsion[tiab] OR avulsions[tiab] OR overuse[tiab] OR overusing[tiab] OR myositis[tiab] OR compress*[tiab] OR inflamed[tiab] OR inflammation[tiab] OR inflammations[tiab] OR inflaming[tiab] OR syndrome[tiab] OR syndromes[tiab] OR pain*[tiab] OR weak[tiab] OR weakness[tiab] OR weakened[tiab] OR stiff*[tiab] OR neuropathy[tiab] OR neuropathies[tiab] OR rupture[tiab] OR ruptures[tiab] OR rupturing[tiab] OR ruptured[tiab] OR overload[tiab] OR overloads[tiab] OR overloaded[tiab] OR overloading[tiab]	6337699
4.	1 AND 2 AND 3	1363

Database: Embase (via Elsevier)

Set #	Search Strategy	Results
1.	'running'/exp OR 'sprinting'/exp OR (runs OR running OR ran OR sprint OR sprints OR sprinting OR accelerat* OR deaccelerate* OR "player load" OR "player loads" OR workload OR workloads):ti,ab	635392
2.	'hamstring muscle'/exp OR 'biceps femoris muscle'/exp OR 'semimembranosus muscle'/exp OR 'semitendinous muscle'/exp OR 'hamstring tendon'/exp OR 'thigh'/exp OR (hamstring OR hamstrings OR "biceps femoris" OR semitendinosus OR semitendinous OR semimembranosus OR thigh OR thighs):ti,ab	113218
3.	'injury'/exp OR 'tendinitis'/exp OR 'avulsion injury'/exp OR 'avulsion fracture'/exp OR 'myositis'/exp OR 'rupture'/exp OR 'inflammation'/exp OR (injur* OR strain OR strains OR stress* OR sprain OR sprains OR pull OR pulls OR pulled OR tear OR tears OR tendinopathy OR tendinopathies OR tendinitis OR tendinosis OR avulsion OR avulsions OR overuse OR overusing OR myositis OR compress* OR inflamed OR inflammation OR inflammations OR inflaming OR syndrome OR syndromes OR pain* OR weak OR weakness OR weakened OR stiff* OR neuropathy OR neuropathies OR rupture OR ruptures OR rupturing OR ruptured OR overload OR overloads OR overloaded OR overloading):ti,ab	11959662
4.	1 AND 2 AND 3	2746

Note: all searches run in "results" tab.

Database: CINAHL Complete (via EBSCOhost)

Set #	Search Strategy	Results
1.	MH "Running+" OR MH "Running, Distance" OR MH "Sprinting" OR TI (runs OR running OR ran OR sprint OR sprints OR sprinting OR accelerat* OR deaccelerate* OR "player load" OR "player loads" OR workload OR workloads OR overload OR overloads OR overloaded OR overloading) OR AB (runs OR running OR ran OR sprint OR sprints OR sprinting OR accelerat* OR deaccelerate* OR "player load" OR "player loads" OR workload OR workloads OR overload OR overloads OR overloaded OR overloading)	114568
2.	MH "Hamstring Muscles" OR TI (hamstring OR hamstrings OR "biceps femoris" OR semitendinosus OR semitendinous OR semimembranosus OR thigh OR thighs) OR AB (hamstring OR hamstrings OR "biceps femoris" OR semitendinosus OR semitendinous OR semimembranosus OR thigh OR thighs)	15820
3.	MH "Wounds and Injuries+" OR MH "Running Injuries+" OR (MH "Sprains and Strains+") OR (MH "Tears and Lacerations+") OR (MH "Tendon Injuries+") OR MH "Tendinopathy+" OR MH "Avulsion Fractures" OR TI (injur* OR strain OR strains OR stress* OR sprain OR sprains OR pull OR pulls OR pulled OR tear OR tears OR tendinopathy OR tendinopathies OR tendinitis OR tendinosis OR avulsion OR avulsions OR overuse OR overusing OR myositis OR compress* OR inflamed OR inflammation OR inflammations OR inflaming OR syndrome OR syndromes OR pain* OR weak OR weakness OR weakened OR stiff* OR neuropathy OR neuropathies OR rupture OR ruptures OR rupturing OR ruptured) OR AB (injur* OR strain OR strains OR stress* OR sprain OR sprains OR pull OR pulls OR pulled OR tear OR tears OR tendinopathy OR tendinopathies OR tendinitis OR tendinosis OR avulsion OR avulsions OR overuse OR overusing OR myositis OR compress* OR inflamed OR inflammation OR inflammations OR inflaming OR syndrome OR syndromes OR pain* OR weak OR weakness OR weakened OR stiff* OR neuropathy OR neuropathies OR rupture OR ruptures OR rupturing OR ruptured)	1320855
4.	1 AND 2 AND 3	753

Database: SPORTDiscus (EBSCOhost)

Set #	Search Strategy	Results
1.	DE "RUNNING" OR DE "SPRINTING" OR TI (runs OR running OR ran OR sprint OR sprints OR sprinting OR accelerat* OR deaccelerate* OR "player load" OR "player loads" OR workload OR workloads) OR AB (runs OR running OR ran OR sprint OR sprints OR sprinting OR accelerat* OR deaccelerate* OR "player load" OR "player loads" OR workload OR workloads)	128646
2.	DE "HAMSTRING muscle" OR TI (hamstring OR hamstrings OR "biceps femoris" OR semitendinosus OR semitendinosus OR semimembranosus OR thigh OR thighs) OR AB (hamstring OR hamstrings OR "biceps femoris" OR semitendinosus OR semitendinosus OR semimembranosus OR thigh OR thighs)	14691
3.	DE "INJURY risk factors" OR DE "WOUNDS & injuries" OR DE "OVERUSE injuries" OR DE "AVULSION fractures" OR DE "SPRAINS" OR DE "PHYSIOLOGIC strain" OR DE "TENDINOPATHY" OR TI (injur* OR strain OR strains OR stress* OR sprain OR sprains OR pull OR pulls OR pulled OR tear OR tears OR tendinopathy OR tendinopathies OR tendinitis OR tendinosis OR avulsion OR avulsions OR overuse OR overusing OR myositis OR compress* OR inflamed OR inflammation OR inflammations OR inflaming OR syndrome OR syndromes OR pain* OR weak OR weakness OR weakened OR stiff* OR neuropathy OR neuropathies OR rupture OR ruptures OR rupturing OR ruptured OR overload OR overloads OR overloaded OR overloading) OR AB (injur* OR strain OR strains OR stress* OR sprain OR sprains OR pull OR pulls OR pulled OR tear OR tears OR tendinopathy OR tendinopathies OR tendinitis OR tendinosis OR avulsion OR avulsions OR overuse OR overusing	301203

	OR myositis OR compress* OR inflamed OR inflammation OR inflammations OR inflaming OR syndrome OR syndromes OR pain* OR weak OR weakness OR weakened OR stiff* OR neuropathy OR neuropathies OR rupture OR ruptures OR rupturing OR ruptured OR overload OR overloads OR overloaded OR overloading)	
4.	1 AND 2 AND 3	1015

Database: Scopus (via Elsevier)

Set #	Search Strategy	Results
1.	TITLE-ABS(runs OR running OR ran OR sprint OR sprints OR sprinting OR accelerat* OR deaccelerate* OR "player load" OR "player loads" OR workload OR workloads)	2244421
2.	TITLE-ABS(hamstring OR hamstrings OR "biceps femoris" OR semitendinosus OR semitendinous OR semimembranosus OR thigh OR thighs)	69955
3.	TITLE-ABS(injur* OR strain OR strains OR stress* OR sprain OR sprains OR pull OR pulls OR pulled OR tear OR tears OR tendinopathy OR tendinopathies OR tendinitis OR tendinosis OR avulsion OR avulsions OR overuse OR overusing OR myositis OR compress* OR inflamed OR inflammation OR inflammations OR inflaming OR syndrome OR syndromes OR pain* OR weak OR weakness OR weakened OR stiff* OR neuropathy OR neuropathies OR rupture OR ruptures OR rupturing OR ruptured OR overload OR overloads OR overloaded OR overloading)	10620849
4.	1 AND 2 AND 3	1543