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HAMSTRING INJURIES IN FOOTBALL: A COMPLEX SYSTEMS APPROACH THROUGH VIDEO ANALYSIS

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List of Abbreviations

ACL – Anterior Cruciate Ligament
ACWR – Acute:Chronic Workload Ratio
AM – Adductor Magnus
APT – Anterior Pelvic Tilt
BAMIC – British Athletics Muscle Injury Classification
BFlh – Biceps Femoris Long Head
BFsh – Biceps Femoris Short Head
BW – Body Weight
CKC – Closed Kinetic Chain
CMAS – Cutting Movement Assessment Score
CoD – Change of Direction
FHS: Football Hamstring Screening protocol
FIFA – Fédération Internationale de Football Association
FIICCS – Football Injury Inciting Circumstances Classification System
GM – Gluteus Maximus
GPS – Global Positioning System
GRF – Ground Reaction Force
H:Q – Hamstring-to-Quadriceps Strength Ratio
HI – Hamstring Injury
HRV – Heart Rate Variability
IF – Injury Frame
IRA – Intra-Rater Agreement
IRR – Inter-Rater Reliability
KAM – knee abduction moments
LESS – Landing Error Scoring System
MBIM – Model-Based Image-Matching
MHF – Maximum Hip Flexion
MKVD: Maximal knee vertical displacement
MRI – Magnetic Resonance Imaging
MTJ – Myotendinous Junction
MVP: Maximal vertical projection
NHE – Nordic Hamstring Exercise
OKC – Open Kinetic Chain
QA-SIVAS- Quality of Sport Injuries Video Analysis Studies
RFD – Rate of Force Development
RTP – Return to Play
SBL – Superficial Back Line
SM – Semimembranosus

S-MAS Sprint Mechanics Assessment Score
ST – Semitendinosus
TRIPP – Translating Research into Injury Prevention Practice framework
TIP – Team-sport Injury Prevention cycle
UEFA – Union of European Football Associations
US – Ultrasound
VA – Video Analysis

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1. GENERAL INTRODUCTION

1.1 Towards a Complex System Approach

Determining the causes of natural phenomena is a key goal of science [1]. Causal knowledge provides the critical foundations on which informed and appropriate actions can take place to alter a given outcome [2]. At the heart of this scientific tradition lies the notion of determinism: the idea that in a sequence of events “only one thing can happen next, and that its evolution is governed by precise laws”. This deterministic worldview has long dominated scientific thinking, both in the past and still today.

For centuries, most scientific thinking in the West has been shaped by a mechanistic and reductionist perspective, the “microscopic lens”. We examine things by breaking them down into smaller and smaller parts, to examine each part's role. This approach, introduced by Aristotle and epitomized by Newton and Descartes, has been enormously successful in explaining natural laws and describing the human body in fine detail. Yet, while it enables precision, it also risks missing the bigger picture. We must be aware that when we reduce a complex problem into its units, the relationships are neglected, and prediction may not be possible. This mechanistic view has deeply influenced the way we think, including sports theory, practice, and research. Human beings have often been described as “machines” to be optimized, with inputs (training load), outputs (performance), and fixed feedback (adaptations, fatigue). Such linear models remain central in many areas, but in the 20th century, they began to be challenged [3].

The rise of relativity and quantum physics (Einstein, Bohr, and others) replaced the language of strict cause-and-effect with one of relationships, uncertainty, and probability. Parallel developments in information theory, cybernetics, psychology, and systems theory, among others, expanded this shift [3,4]. Complexity thinking emerged, however, it took much of the century for these ideas to influence medicine and, eventually, sports injury analysis.

Although complexity has gained traction as a scientific and philosophical concept, its definition continues to be contested. At its core lies the question of what truly defines complexity, and what does it mean to apply complex thinking to research. Complexity is difficult to define precisely because it deals with continual, transformative change. Definitions require stability, yet complexity invites us to see the world as dynamic, always in flux; but a world that does have patterns to it, patterns that structure and bind through their interplay. Thinking complexly therefore asks us to shift our perspective of world not in terms of “things” but of processes. This represents a move from the science that study particles to the sciences of relations and interactions among particles, events, and systems. In this view, cause–effect relationships are rarely linear or singular. Instead, what looks like a single cause is often the combined effect of many connected factors.

Yet, our “natural” way of interpreting change is to assume it is smooth and continuous. Humans are inclined to think in terms of mono-causality, where the final visible event (e.g., injury occurrence) is routinely interpreted as the unique cause of an outcome [5]. Such linear associations are most evident when the exposure is close in time to the outcome, which strengthens their apparent effect. The concern, however, is that this relationship reflects only a limited segment of the causal picture. When relevant influences are more distant in time, or when multiple factors at different levels (biomechanical, behavioral, physiological, contextual) interact, linear and singular explanations fail to capture the full process. This limitation is especially clear in gradual-onset injuries, where the inciting event may be distant from the outcome. In practice, however, dynamic systems such as the human body often fluctuate between stability and instability, showing both order and chaos at the same time. This makes long-term prediction impossible, while short-term forecasting remains probabilistic at best. Prediction of complex problems, whether financial crises [4], disease spread [6], athletic performance [7], or sports injuries [8], requires identifying and modelling a complex network of interacting factors. At both the cellular and organic levels, reality lies not in independent entities (Newton’s “hard, massy, impenetrable particles”) but in their relations and cooperation.

1.1.2 Characteristics of a Complex System

Biology, and medicine in particular, recognizes that living organisms are dynamic, open systems characterized by multiple interactions among units, recursive loops, self-organization, non-linearity, and emergent properties. Such systems also operate under some level of uncertainty, as the multiple scales (spatial and temporal) of interacting units are often unknown or not directly observable [3]. The key characteristics of complex systems are outlined below.

Non-linearity occurs when the effects of interacting components are not proportional to their causes. In linear systems, outputs change in direct proportion to inputs, and the superposition principle applies, two causes acting together produce an additive effect. However, linearity represents only a limited subset of complex behavior, applicable under tightly controlled conditions and minimal interactions (e.g., a direct muscle blow causing a proportional injury). In contrast, non-linear systems produce effects that cannot be predicted from individual causes: small changes may yield large consequences, and vice versa.

Emergent properties arise from the collective interactions of components, forming new levels of organization. These properties may be multiply realizable, meaning different arrangements of lower-level units can yield the same emergent function. For example, similar coordination patterns may result from different muscle activation combinations. Emergence supports hierarchical organization, where micro-level interactions shape macro-level behaviors, which in turn influence lower levels through feedback. The interaction creates something qualitatively new, “the whole is greater than the sum of its parts.” Thus, the system’s organization is irreducible to its components.

Complex systems can self-organize without external control, enhancing stability or efficiency and distinguishing them from purely chaotic systems. In living organisms, self-organization enables continuous adaptation to internal and external changes. This relates to openness: open systems exchange energy, matter, and information with their environment, whereas closed systems do not. Because most biological systems are open, modeling and experimentation must account for exogenous influences, which can be amplified over time by sensitivity to initial conditions.

Another key feature is the presence of feedback loops, where outputs are recycled as new inputs. Feedback may be positive or negative and operates across levels: micro-level interactions create macro-level patterns, which in turn influence the micro-level in continuous loops. This circular causality sustains functionality across scales and underlies coevolution, where components and their environment adapt mutually over time [9].

Synergy refers to the system’s ability to maintain function despite perturbations. When certain components lose efficiency, others adjust their contributions to preserve overall function. In motor systems, synergy manifests as compensatory adaptations to pain, injury, or fatigue, maintaining coordinated movement [10].

Equifinality denotes that a system can reach the same end state from different initial conditions or through multiple pathways. In sports, similar movement outcomes or injury types may emerge from distinct combinations of biomechanical, physiological, or environmental factors. Equifinality underscores the limitations of single-cause explanations and supports a systems-level view.

Complex systems range along a continuum from near-equilibrium (homeostasis) to far-from-equilibrium (allostasis). Near-equilibrium systems maintain stability, absorbing change; far-from-equilibrium systems operate near the edge of chaos, where small perturbations can drive major effects—sometimes adaptive, sometimes pathological (e.g., overload and injury). A complexity perspective challenges the assumption that equilibrium is the normal state, emphasizing coexistence between stability and transformative change.

Finally, in modernist thinking our tendency is to universalize, to declare as true that which fits all, all the time. Probably the most challenging of all the characteristics of thinking complexly is acceptance of and working with ambiguity and uncertainty. There is no single “correct” solution; each situation is unique. In a complex world, probability replaces certainty, interpretation replaces prediction, and interactions matter more than isolated parts. Paul Cilliers emphasizes that open systems thinking thrives on contradictions, using them as forces that vitalize the system [11]. Similarly, Michel Serres suggests that wisdom begins when we develop a “fear of a unitary solution,” cultivate humility, and abandon the compulsion to dominate or oversimplify [12].

1.1.3 Complex System and Sports Injuries

Within applied sports science and medicine, numerous challenges hinder attempts to develop detailed understandings of injury causation. Traditional research approaches have been largely shaped by study designs in which it is assumed that the parts of a system can be studied, summed up and used to represent the system as a whole [13]. In other words, the parts of the body and environment are reduced to parts of the musculoskeletal system observed under various laboratory conditions and then generalized back as if they represented the entire body in motion.

The simplification of complex problems into basic units and then make inferential leaps to explain how these parts interact to lead to the observed phenomenon is the classical science method of analysis within the reductionism paradigm [14]. Unless each part of the body and its interactions are identical, a reductionistic approach is not likely to provide a complete understanding of system behavior and may result in distorted assumptions of how the parts work together to generate a movement [15]. This approach has led to identification of isolated factors that are frequently assumed as causes of injuries or diseases. In epidemiology, ‘risk factor’ is described as any attribute, characteristic or exposure of an individual that increases the likelihood of developing an injury, and it is generally treated as a static variable with effects assumed to be proportional and additive—that is, a simple, linear relationship is assumed between the factor and the outcome proportional [16]. This has been successful in certain domains, such as establishing clear linear associations between smoking and lung cancer. However, reductionism risks oversimplifying the inherently dynamic nature of sport injuries. While linear models assume stable, proportional relationships, most injuries in reality emerge from nonlinear, context-dependent interactions that reductionist methods cannot fully capture. Moreover, linear cause–effect reasoning is particularly vulnerable to confounding factors, where a third variable influences both the presumed risk factor and the injury outcome, creating spurious or exaggerated associations. Bahr and Holme [17] discussed the influence that the power of a study has on the identification and evaluation of injury causation factors. Factors affecting the power of an epidemiological study include the size of the effect being investigated, the acceptable level of significance and the sample size.

A complex systems approach seeks to overcome these limitations by viewing injuries as emergent outcomes of dynamic, synergistic interactions among multiple interconnected risk factors [8,14,18–20]. However, as the risk factors themselves are insufficient to cause injury, some inciting event (e.g., motor action, playing situation or an opponent's behavior) is considered necessary to trigger the causal pathway. Complex systems in sport (athletes, teams, games, etc.) consist of heterogeneous components operating across different timescales (from milliseconds to decades) and levels (biomechanical, physiological, psychological, and environmental) [21]. These systems are adaptive, goal-directed, and continuously adjusting to change through self-organization [22]. This property increases immensely their level of complexity and provides a big challenge for understanding sports-related phenomena. To advance injury research meaningfully, injuries therefore must be understood not as the result of a single cause but as the product of dynamic, multilevel interactions [6].

Newell's constraints model in 1986 already distinguished between personal (e.g., physical capacity, fatigue, previous injuries), environmental (e.g., pitch surface, weather conditions, match context), and task-related (e.g., speed of play, technical and tactical demands) constraints, all of which interact dynamically to influence injury risk [22]. In relation to personal constraints, physiological, psychological, and perceptual-cognitive-motor components interact with the environment and task constraints to attempt successful achievement of the motor skill goal. The concept of constraints or boundary conditions requires probabilistic rather than deterministic reasoning: the same exposure may lead to injury in one athlete but not in another, depending on the evolving configuration of constraints. In this respect, the concept of constraint seems more suitable than that of risk factor, especially when considering sports injuries [10]. Athletes are not 'frozen' in a given time instant, their susceptibility to injury changes over time in response to shifting internal and external constraints.

Recently, several conceptual models have extended complex thinking to investigate risk factors and athlete susceptibility in sports injuries etiology [8,19,20,24]. Bittencourt and colleagues' "web of determinants" model framed injuries as the outcome of interacting risk factors, where multiple pathways may lead to similar injury outcomes [8]. This implies that the same type of injury (e.g., anterior cruciate ligament rupture) may arise through different pathways depending on context — for example, between a soldier, an elite footballer, or an art performer. Bekker and Clark [25] highlighted the role of context in shaping injury processes, showing that injuries cannot be separated from the social, cultural, and environmental systems in which athletes operate. Hulme and Finch [18] advocated embracing the complex nature of sports injuries by shifting the focus from isolated risk factors (e.g., lack of sleep, nutrition status, training surface, joint range of motion, tissue recovery state, training load) to risk pattern recognition (risk profiles). Accordingly, we need to ask ourselves, without taking away the epidemiological importance of identifying risk factors and their potential modifiability, whether we are aiming at prediction or solely at finding relationships. In order to catch patterns and be able to prevent, we need to predict. Thus, the best way to predict an injury is by understanding the interactions among the web of determinants and not just the determinants themselves.

Sport is not only a social phenomenon of our world but a real bank of human behavior experimentation. It provides a chance to effectively and efficiently study the effects of intense perturbations in complex living systems at many levels (physiological, psychological, social). The possibility of getting rapid empirical feedback in relation to formal models makes modeling sport-related phenomena a field of special interest for science and for complex systems theory [26–29]. In conclusion, the science of complex dynamical systems can contribute to changing the prevalent mechanistic view in sports injury and can make useful contributions to the understanding of complex systems. This theoretical foundation frames the specific focus of this thesis: advancing knowledge of hamstring injuries (HI) in football through a complex system perspective.

1.2 What is a Sport Injury?

Defining what constitutes a ‘recordable event’ in sport is a critical methodological consideration that strongly influences the results of injury and illness surveillance studies. Although numerous consensus statements have aimed to standardize surveillance methodology [30–33], definitions of sport injury still vary widely [34]. A single, universal definition may not be necessary, as definitions often depend on the context, objectives, and resources of the surveillance system [35–37]. In fact, underlying the choice of definition are a number of practical and theoretical issues, including the duration and setting of surveillance, the available resources, the type of injuries and illnesses of interest, how data are to be collected and what they are to be used for.

It has been well documented that variations in definitions and methodologies create significant differences in the results and conclusions obtained from studies of sports injuries [35,38–42]. While consensus-based recommendations provide guidance for standardized methodology, researchers must choose definitions that reflect the aims and context of their study, carefully considering the strengths and limitations of each approach. Any researcher planning a sports injury study needs to define the terms 'sports injury' and 'injury severity' before it can be formally established and it is also highly desirable that results are comparable between studies; both within and between sports. Bahr and Holme [17] highlighted the influence of study power on identifying and evaluating injury causation factors. Power depends on the effect size, significance level, and sample size, underscoring the importance of rigorous methodological design in sports injury research. Above all, however, surveillance data must be valid as no single definition is likely to suit all needs.

Conceptually, a sports injury can be described as the loss of body function or structural integrity resulting from sports participation [37]. Recent recommendations define injury as "tissue damage or other derangement of normal physical function due to participation in sports, resulting from rapid or repetitive transfer of kinetic energy" [30,31]. Injury epidemiology extends the classical triad of agent, host, and environment, identifying kinetic energy as the agent of injury [37,43]. From a biomechanical standpoint, injury occurs when mechanical stress or strain exceeds tissue tolerance, meaning that loading surpasses the tissue's strength [44].

Understanding tissue damage requires consideration of mechanical principles such as material fatigue and failure. Tissue stiffness and ultimate strength determine how the body responds to loads and depend on its type, magnitude, frequency, and rate of load application. Failure occurs when stress or strain exceeds material strength, either through a single high-magnitude load, repeated submaximal loads, or a combination of both. As biological tissues are materials, these principles apply, though within a dynamic physiological environment that involves remodeling and recovery. This framework conceptualizes injury as a continuum of energy exposures, integrating acute and overuse injury onset. Biomechanical explanations should clarify either how loading exceeded tissue tolerance or how tolerance was reduced, allowing otherwise normal loads to cause damage [45].

Therefore, consensus statements suggest that no single definition of injury fits all purposes. Instead, three alternative definitions are recommended for recordable events: (1) all complaints, (2) medical attention, and (3) time loss (see figure 1).

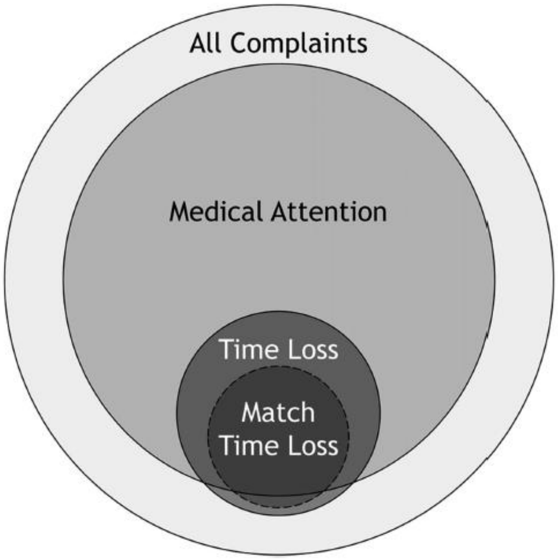


Figure 1: Interactions between various definitions of injury and illness. Circle-size represents the relative number of incidents likely to be registered (not to scale) [35].

These definitions form a hierarchy from broadest to narrowest, capturing different numbers of incidents [46]. The time-loss definition is most commonly used in football injury surveillance. It defines a recordable injury as one causing absence from training or competition [33], is relatively simple to capture, and is suitable even when data collectors are non-experts. Injury severity should be reported as the number of days the athlete is unavailable, from onset to full return. Aggregated data can report total time-loss days, with median and quartiles, while caution is advised when interpreting means due to right-skewed distributions. Severity categories may use time bins such as 0, 1–7 days, 8–28 days, 29–90 days, 91–180 days and >180 days, consistent with football-specific extensions [31]. However, the reliance on time-loss definitions introduces certain limitations, particularly in professional football. Athletes may continue training or competing despite pain or dysfunction (e.g., sore hamstrings), leading to an underestimation of injury occurrence and severity, while in other cases time-loss may be prolonged for precautionary reasons rather than medical necessity, thereby exaggerating severity. These distinctions are particularly relevant for video analysis (VA) studies, where study design and data availability limit which injuries (e.g., acute onset, official matches only) can be captured. Awareness of these limitations is essential for accurate interpretation of findings.

1.3 Conceptual Models of Sports Injury

Large scale epidemiological studies continue to report the persistent nature of sports injuries, with injury rates remaining relatively stable over time across various sports [47]. Notably, some injury types, such as HIs, have even increased in specific contexts [48,49]. This persistence raises an important question: why, despite decades of research, do injury rates remain unchanged? One possible explanation is that current approaches may be targeting the wrong aspects of the problem, measuring variables that are convenient rather than meaningful, and developing component-driven interventions that fail to address the complex, interacting nature of real-world injuries [50]. Consequently, a persistent global burden of injury remains, apparently resistant to conventional linear prevention models. Each sport carries a distinct level of risk, influenced by its inherent characteristics, governing rules, and, in team sports, by the conduct of participants toward one another. Many sports injuries are considered not unavoidable “accidents” [51] and their prevention should be a priority for sports administrators [52], physicians and scientists [53]. Managing injury risk is therefore central to maintaining athlete availability and optimizing performance. Despite this optimistic outlook, the effectiveness of prevention efforts has remained disappointingly inconsistent, underscoring the need to better understand injury etiology and to translate theoretical knowledge into effective practice.

A fundamental step in sports injury prevention is to understand both risk and underlying etiology. Since the early 1990s, several theoretical frameworks have guided clinicians and researchers in conceptualizing injury causation and developing preventive strategies. Across these frameworks, injuries are recognized as multifactorial and individual susceptibility emerges from the ongoing interactions between intrinsic (athlete-related) and extrinsic (environmental) factors [19,24,54]. Within this context, the most influential conceptual frameworks can broadly be categorized into etiological models, which seek to explain how and why injuries occur, and preventive models, which translate this understanding into strategies aimed at reducing injury risk. Two models have been particularly influential in shaping the study of sports injury: the epidemiological model of Meeuwisse [54] and the preventive framework of van Mechelen et al. [55].

1.3.1 Etiological models

Meeuwisse's original model (1994) [54] proposed a multifactorial perspective in which injuries arise from interactions between intrinsic factors, some modifiable (e.g., flexibility) and others fixed (e.g., age), and extrinsic factors such as surface, equipment, or opponent behavior (Figure 2). Injury occurs when the mechanical load of an inciting event exceeds the tissue's tolerance, with the inciting event representing the final link in the causal chain.

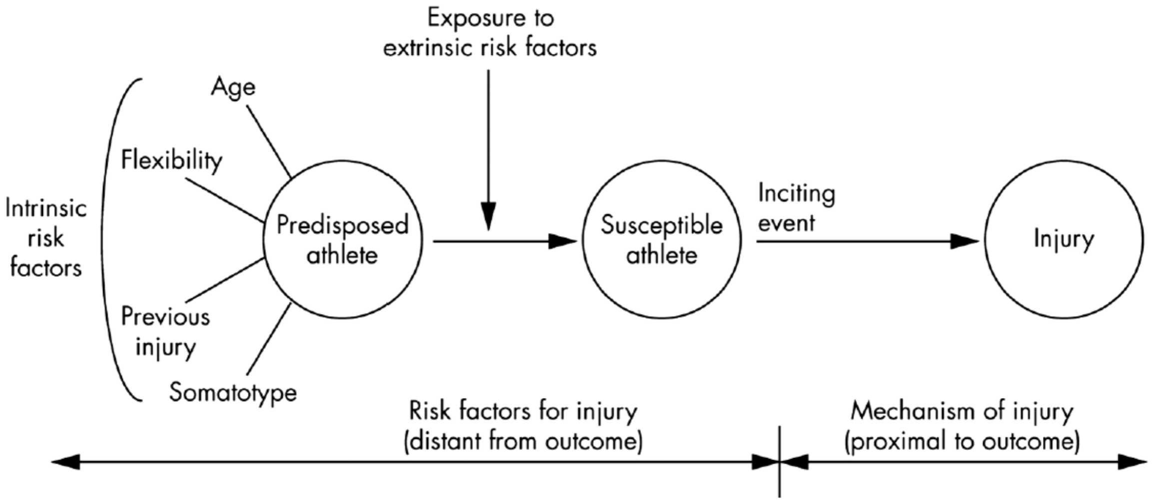


Figure 2: Meeuwisse's first multifactorial etiology model proposed in 1994 [54].

Later, Meeuwisse and colleagues [56] recognized that risk factors are interrelated and proposed a dynamic, recursive model replacing the linear "chain of events" with a cyclical process. Athlete susceptibility varies with adaptation or maladaptation to training and competition, such that similar exposures may lead to injury or continued participation depending on context [19]. This model better reflected real sporting environments, where repeated exposures and fluctuating preparedness influence injury risk. It also underscored the need for longitudinal monitoring rather than static pre-season screening to capture the evolving interaction between risk factors and outcomes.

Building on this foundation, Bahr and Krosshaug [16,24] proposed a comprehensive model of injury causation, that integrates internal and external risk factors with the biomechanical determinants of the inciting event (see figure 3). This model also incorporated elements from McIntosh's biomechanical injury model [45], providing a more granular view of how external loads and tissue tolerance interact to produce injury.

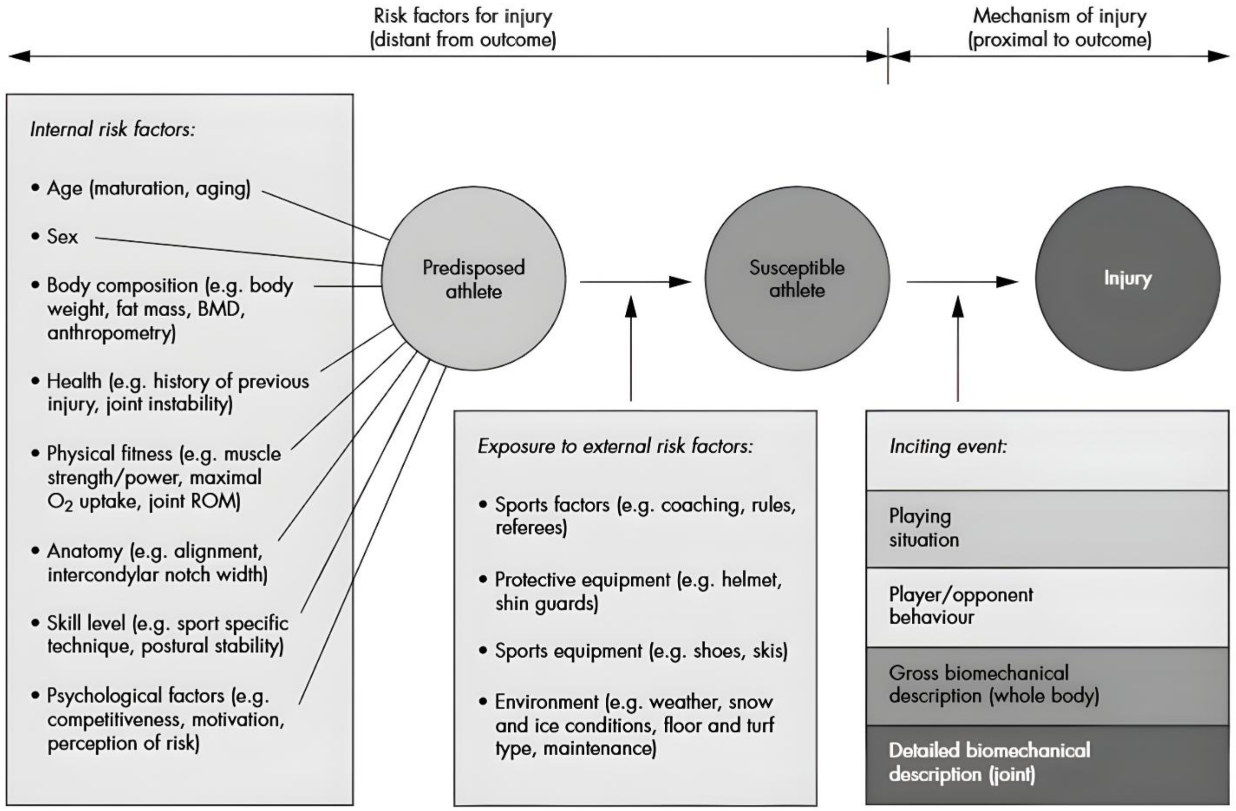


Figure 3: Comprehensive model for injury causation. BMD, body mass density; ROM range of motion [23].

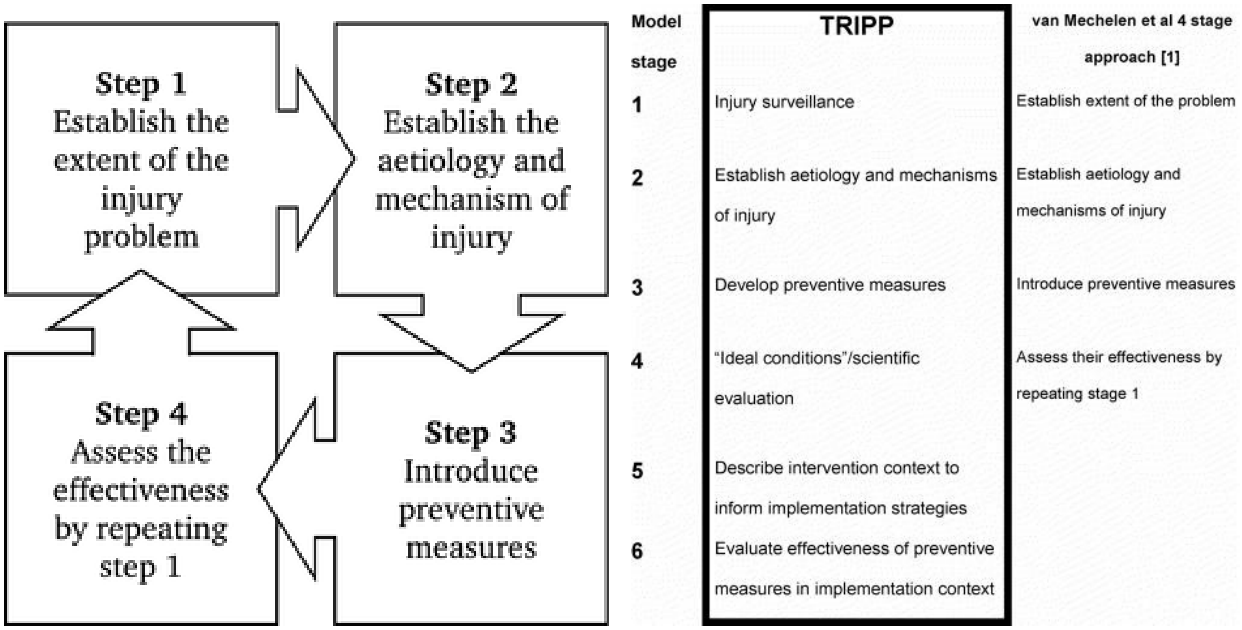
Other models address workload and adaptation. Windt and Gabbett [57] in 2016 extended the classic fitness–fatigue model, describing the paradoxical role of workload: repeated exposure may strengthen tissue and reduce risk through adaptation, or increase risk through fatigue and maladaptation, depending on the context and magnitude of stressors. Although participation in sport inherently predisposes athletes to injury, repeated exposure also modifies subsequent risk, highlighting the challenge of balancing training and competition loads to encourage adaptation while minimizing injury risk. The model and framework from Kalkhoven et al. (2020) [44] were created to move injury research beyond purely identifying associations and reduce issues such as HARK-ing (Hypothesizing After the Results are Known), toward more thorough mapping of causal-pathways. Their goal is to clarify how specific physiological and mechanical risk factors interact over time and contribute to stress-, strain-, and overuse injury onset.

This progression in understanding injury etiology reflects a shift toward complexity-informed approaches, which are more ecological, integrative, and representative of real-world sport environments [58]. Such models guide study design, inform appropriate analytical methods, and identify key variables to consider. The continuous refinement of these frameworks illustrates the importance of flexibility and openness to revising theoretical models as new evidence emerges [59].

1.3.2 Preventive models

In 1992 van Mechelen and colleagues [55] introduced, the “sequence of prevention” model which adapted principles from public health to the field of sports medicine (see figure 4a, left). The model outlines a four-step process: (1) establishing the extent of the injury problem; (2) identifying key risk factors and mechanisms; (3) implementing preventive strategies to reduce risk; and (4) evaluating their effectiveness by repeating step 1.

The first step typically involves epidemiological surveillance to quantify the problem in terms of injury profile, incidence, prevalence, severity, time loss, and associated costs, stratified by sport, sex, age, or competition level [60]. The second step focuses on identifying the key risk factors and mechanisms underlying injury occurrence. In the third step, preventive measures are designed on the basis of this knowledge, aiming to reduce either the likelihood or severity of future injuries. The final step requires evaluation of these strategies, often through time-trend analysis or randomized controlled trials, to assess the effectiveness of these measures [24].



Model stage	TRIPP	van Mechelen et al 4 stage approach [1]
1	Injury surveillance	Establish extent of the problem
2	Establish aetiology and mechanisms of injury	Establish aetiology and mechanisms of injury
3	Develop preventive measures	Introduce preventive measures
4	"Ideal conditions"/scientific evaluation	Assess their effectiveness by repeating stage 1
5	Describe intervention context to inform implementation strategies	
6	Evaluate effectiveness of preventive measures in implementation context	

Figure 4. Conceptual models for sports injuries. (a, left) The "Sequence of Prevention" model proposed by van Mechelen et al. [55]. (b, right) The Translating Research into Injury Prevention Practice (TRIPP) framework [58], which expands on van Mechelen's model by integrating research findings with real-world implementation and context-specific validation.

While highly influential, linear models like van Mechelen's have limitations. They tend to oversimplify causation by assuming direct, unidirectional relationships between risk factors and outcomes [8,18,61] and may lack operational detail [62] or contextual nuance [63]. Furthermore, interventions developed under controlled conditions often fail in applied environments, where athlete behavior, organizational culture, and resource constraints play a major role [25]. Finch emphasized that *research alone does not prevent injuries*, translation and adoption by athletes, coaches, and organizations are essential. To address these gaps, Finch proposed the Translating Research into Injury Prevention Practice (TRIPP) framework [58], which extends van Mechelen's sequence model by adding steps focused on implementation context (personal, environmental, societal, organizational) and evaluation in real-world settings (Figure 4b, right).

Despite such advances, many frameworks still fell short of addressing the practical needs of practitioners in team environments. To bridge this gap, O'Brien et al. [64] developed the Team-sport Injury Prevention (TIP) cycle, a pragmatic model emphasizing applied implementation. The TIP cycle integrates key concepts from previous models [55,58] with the risk management approach of Fuller et al. [42,61], stressing that prevention strategies must be tailored to specific populations, contexts, and delivery systems [63]. Finally, Bolling et al. [66] proposed a context-driven reinterpretation of van Mechelen's sequence (see figure 5). Using qualitative methods, they aimed to refine Step 1, defining and describing the injury problem, making it more sensitive to contextual realities and better suited to practical application in sport settings [41,64].

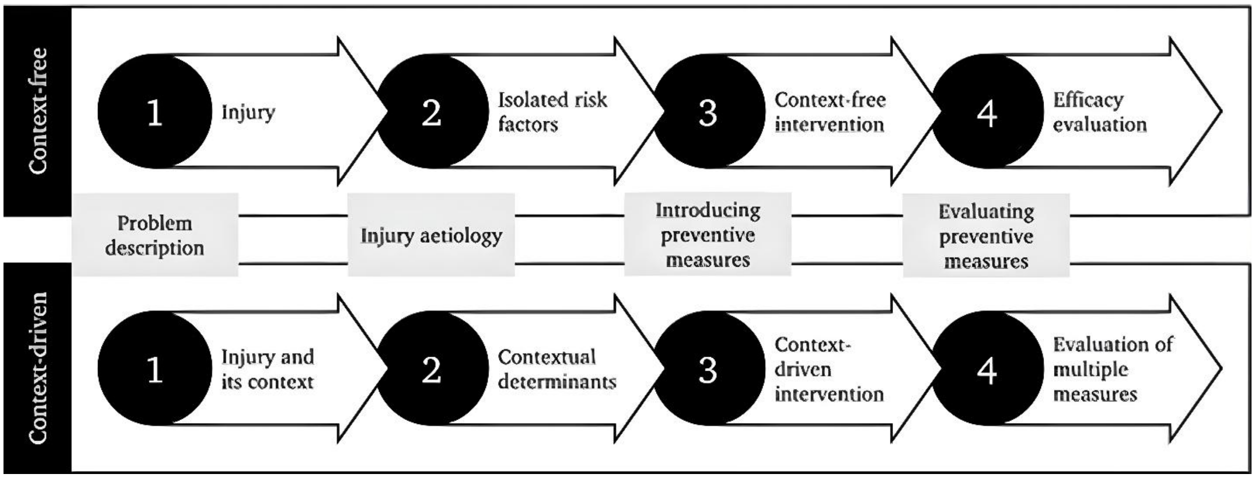


Figure 5. Contemporary, context-driven reinterpretation of the 'sequence of prevention' model proposed by Bolling et al. [66].

1.3.3 Injury-Inciting Event and Mechanisms

Regardless of whether injury causation is approached from a biomechanical or epidemiological perspective, a precise and context-specific description of the inciting event - the circumstances during which injuries occur - is essential [56,65] . The ultimate goal is to translate this knowledge into targeted preventive measures tailored to the specific sport and injury type. However, the implementation and evaluation of prevention strategies remain limited until inciting events and mechanisms are comprehensively described and understood.

Bahr and Krosshaug [23] emphasized that defining the inciting event in detail is a crucial step in understanding injury causation. They argued that traditional biomechanical analyses, while valuable, are insufficient on their own to inform effective prevention. Instead, a complete description should integrate the context (e.g., type of action, phase of play, ball possession, playing surface, pitch location etc.), player and opponent behavior, and whole-body and joint biomechanics. Importantly, these components interact dynamically: the characteristics of the playing situation and athlete or opponent behavior influence both overall movement patterns and tissue-specific loading. A reductionist focus on isolated joint or tissue mechanics therefore risks overlooking essential contextual determinants. Because behavior shapes both risk factors and mechanisms of injury, it is increasingly recognized as a central component of prevention strategies [66].

Understanding the behavioral and contextual dimensions of injury occurrence thus represents a key research priority. The sport-specific activities performed immediately before and at the moment of injury are often referred to as injury mechanisms [23,67]. However, as this terminology may be ambiguous, Aiello et al. [65] proposed distinguishing between the (injury-)inciting activity, defined as the sport-specific action during which the injury occurs, and the (injury-)inciting circumstance, defined as the surrounding environmental and situational context. At this stage, video analysis (VA) becomes particularly valuable, providing detailed insights into both injury mechanisms and situational patterns that can inform the design of more effective preventive interventions (see Section 1.10).

1.4 Injury Classification

The development of the UEFA injury classification model in 2005 [45] laid the groundwork for systematic epidemiological research in professional football. Shortly after, the first consensus statement on injury definitions and data collection procedures was published in 2006 [32]. This framework has since been continuously refined through IOC updates [29] and football-specific extensions [30], reflecting the evolving needs of injury surveillance in the sport. More recently, the Football Injury Inciting Circumstances Classification System (FIICCS) [68] was developed to categorize the specific circumstances leading to injuries, and we respond to their call by adopting and implementing the framework within VA studies. Together, these initiatives have provided a common language for researchers, standardized data collection, and enabled the creation of comparable, high-quality datasets across studies.

Traditionally, health problems in sport are categorized as having sudden or gradual onset. Sudden-onset injuries result from a clearly identifiable event, such as player collision, whereas gradual-onset problems develop without a distinct precipitating event, for example, tendinopathy from repetitive loading. The term overuse injury is often applied to gradual-onset problems, although inconsistently in the literature, and most surveillance systems lack a formal definition [69]. In practice, many health problems exist along a continuum, involving both sudden and gradual mechanisms.

The mechanism of onset has typically been defined only in the context of sudden-onset injuries. Sudden-onset injuries can result from contact and non-contact mechanisms [70,71]. Contact injuries occur through direct contact, where external force is applied immediately and locally to the injured area, or through indirect contact, where external force is applied elsewhere but contributes to the chain of events leading to injury. Non-contact injuries occur without any external force, arising instead from intrinsic biomechanical or physiological factors. Gradual-onset injuries, by their nature, are considered non-contact.

Another important aspect of injury classification is determining whether a new injury is related to a previous one. The IOC consensus statement (2020) [29] and its football-specific extension [30] recommend a standardized framework for the classification of subsequent injuries, which allows researchers to differentiate between injuries based on anatomical location, tissue involvement, and the recovery status of the player. According to this framework, a subsequent local injury affects the same anatomical site as the index injury but involves different tissues—for example, a meniscal tear following an anterior cruciate ligament rupture. In contrast, a subsequent new injury occurs at a different anatomical site and is therefore considered independent from the index injury (see figure 6). When the same location and tissue are involved, the injury is classified as a recurrence. Recurrences can occur after full recovery or during an ongoing rehabilitation process. If the athlete has fully recovered and returned to unrestricted training or competition, the subsequent event is defined as a reinjury. Reinjuries are further categorized according to the time elapsed since the return to play (RTP): early recurrences occur within two months, late recurrences between two and twelve months, and delayed recurrences after more than twelve months [32]. Conversely, if the index injury has not yet fully healed and symptoms worsen, the event is defined as an exacerbation. A player is considered fully recovered when is available for unrestricted participation in training and competition, in line with the operational definition of injury severity provided in the consensus statements [29].

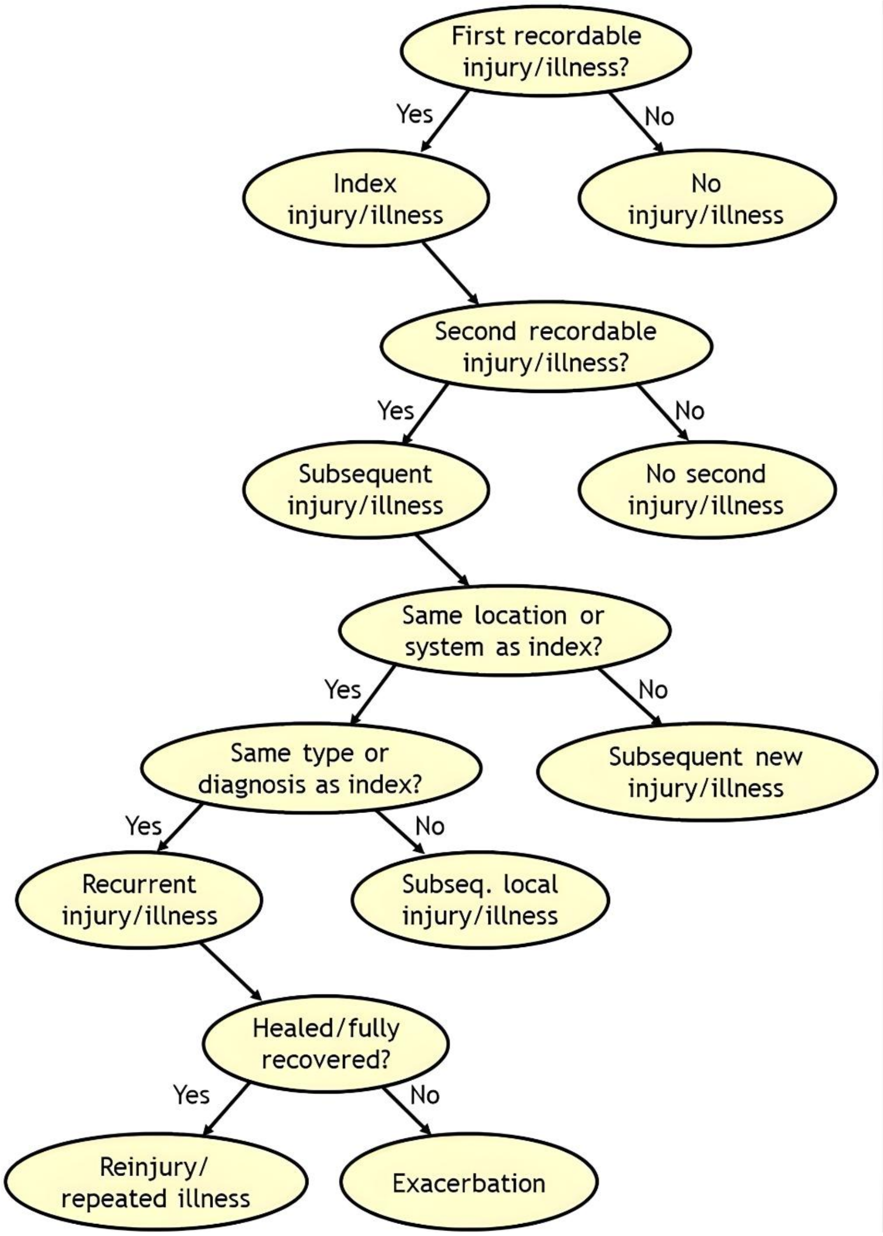


Figure 6: Classification tree for subsequent health problem. Definitions: (1) index injury (illness)=the first recorded injury (illness), (2) subsequent injury (illness)=any injury (illness) occurring after the index injury (illness) ((i) subsequent injury to a different location than the index injury (subsequent illness involving a different system than the index illness); (ii) subsequent injury to the same location but of a different tissue type than the index injury (subsequent illness of involving the same system but of a different type/ other diagnosis) or (iii) subsequent recurrent injury (illness)=subsequent injury to the same site and of the same type as the index injury (subsequent illness involving the same system and type as the index illness). Third,

fourth or more health problems should be assessed relative to the initial index health problem and all other previous ones (eg, second and third health problem) [29].

To facilitate consistency across studies, the IOC football-specific extension recommends classifying injuries across several hierarchical dimensions: body region (e.g., lower limb), body area (e.g., thigh, knee, ankle), tissue type (e.g., muscle/tendon, bone, joint/ligament, skin), injury type (e.g., strain, sprain, fracture, dislocation), and diagnosis (e.g., hamstring muscle injury, anterior cruciate ligament rupture) [30]. Accurate recording and reporting of injuries are essential for reliable surveillance. Ideally, the diagnosis should be recorded in as much detail as possible, depending on the available information and the expertise of the person responsible for data collection [29]. When data are collected by athletes themselves or by non-medical staff, reporting should generally be restricted to the affected body area, as their ability to provide reliable information on tissue type or pathology is limited [72].

Injury surveillance depends on several key epidemiological measures to characterize the scale and impact of sport injury [29]. Prevalence refers to the proportion of athletes affected by a health problem at a given point or over a defined period; incidence denotes the number of new injuries occurring in a population at risk during a specified time frame, often expressed relative to exposure (for example, injuries per 1000 hours of play). Burden combines incidence and severity, often expressed as total time-lost per unit exposure (e.g., days lost per 1000 hours), to indicate overall impact. IOC football extension consensus statement further recommends that exposure be recorded in detail and separated into distinct categories. Training exposure should be distinguished as: (1) football-specific training, (2) pre match warm-up, (3) strength and conditioning, and (4) other training (e.g., post-match cool-down), in addition to match exposure [30]. Moreover, in agreement with the IOC consensus, exact *player exposure time* should be recorded for each individual, rather than estimating team exposure from the number and duration of training sessions and matches [30].

Beyond these core measures, examining the temporal and spatial distribution of injuries provides additional insight into risk patterns. Temporal analyses may consider seasonal timing, monthly trends, or within-match distribution to identify high-risk periods, such as congested fixture schedules, early-season peaks, or the final 15 minutes of each half [73,74]. Spatial analyses assess field location and playing position, as injury likelihood varies across zones and roles [75]. Together, these standardized measures and classifications support meaningful comparisons across studies and form the foundation for targeted injury prevention strategies.

1.5 Impact of Injuries in Football

Football is the most popular team sport globally across men's, women's, and youth participation [76], making the effective management of associated risks a critical priority. Injuries remain a major concern for players, practitioners and sporting organizations due to their widespread and lasting consequences. They can have serious short- and long-term health effects, including treatment costs, time lost from sport, reduced career length [77] and a substantially increased risk of early osteoarthritis, cartilage degeneration, or tendinopathies [78–80]. Injuries also negatively affect individual performances and team success [81,82]. Teams that minimize injury incidence and burden generally achieve better outcomes, as reflected in higher league standings and improved performance in international rankings [81,83,84]. For example, lower injury burden and higher match availability were both significantly associated with a higher final league ranking and an increase in the UEFA Season Club Coefficient [83]. Similar associations have been observed in elite rugby union, where injuries negatively correlated with team success [85].

At the international level, players may face an elevated risk of injury and illness due to increased fixture congestion, variations in training load, and differing match demands compared with club football [38]. The impact of injury extends beyond physiological outcomes to include significant psychological consequences. Injured players could experience anxiety, depression, and reduced self-confidence, which can interfere with rehabilitation adherence and return-to-play readiness [86]. Fear of re-injury or uncertainty about future performance can prolong recovery, reduce motivation, and negatively influence overall athletic performance. Consequently, psychological support and monitoring should be considered integral components of injury management programs, alongside physical rehabilitation. In youth football, injuries can hinder skill acquisition, limit progression to higher levels of competition, and increase dropout rates from organized sport [87]. Early specialization and high training volumes may exacerbate injury risk, emphasizing the need for age-appropriate training loads, monitoring of growth-related vulnerabilities, and targeted injury prevention strategies for young athletes [88,89].

Finally, injuries represent a significant financial burden to football clubs (see figure 7). For instance, the average cost of a professional top-team player being unavailable for one month has been estimated at approximately €500,000 or around €17,000 a day [90]. Given that a typical squad of 25–28 players accumulates roughly 1,100 absence days per season, the total cost of injuries can exceed €20 million per club annually [90]. Additionally, diminished on-field performance can indirectly lead to reduced revenue for sporting organizations and governing bodies through lost ticket sales, broadcasting rights, and sponsorships [91,92].

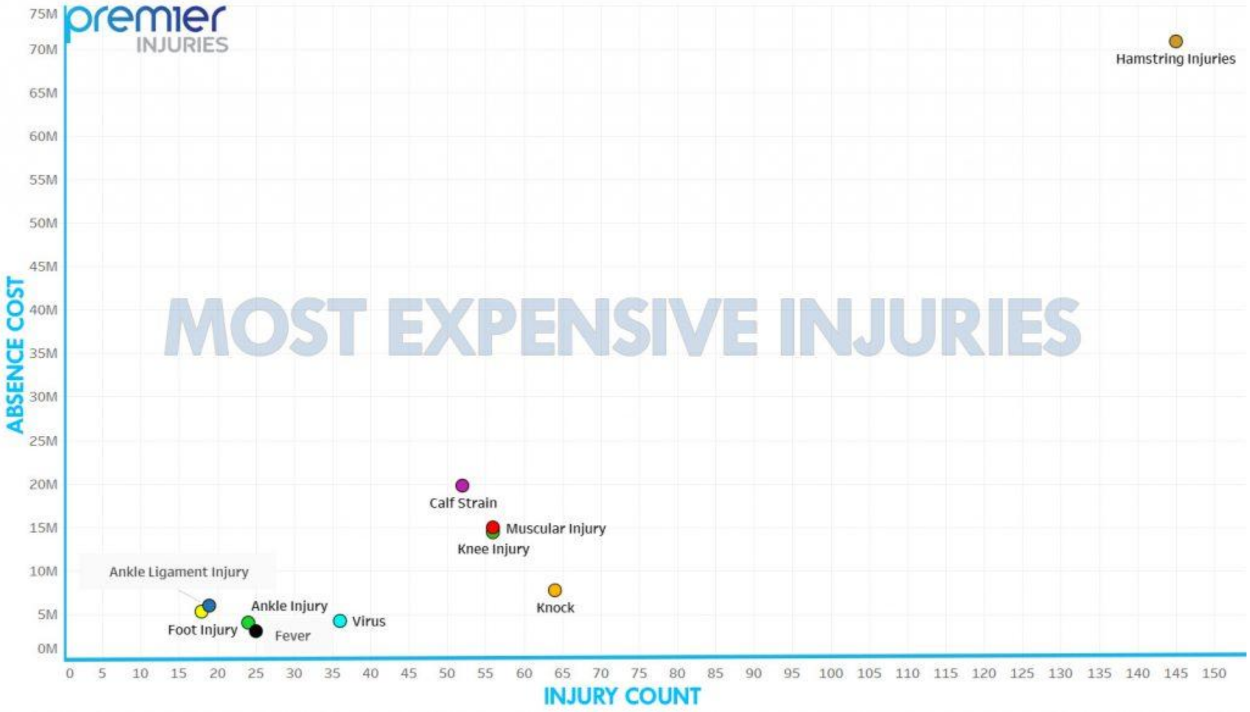


Figure 7: The 10 most expensive injury types in the English Premier League during the 2022/23 season, based on injury count and total absence cost. Source: Analytics FC, 2023.

1.6 Injury Epidemiology in Football

The incidence of injuries in professional football (number of injuries per hours of exposure) varies widely depending on context, competition level, and methodological approach [46,73,74,81,93]. More than a decade ago, Ekstrand et al. [46] reported that a typical 25-player squad could expect approximately 50 time-loss injuries per season, with an average of 12% of players unavailable at any given time. Since 2001, overall injury rates have remained relatively stable or slightly decreased, although the injury landscape has changed to some extent (Figure 8). Muscle injuries continue to represent the predominant problem, with HI the most frequent injury sub-type, while ligament injuries show a declining trend [96].

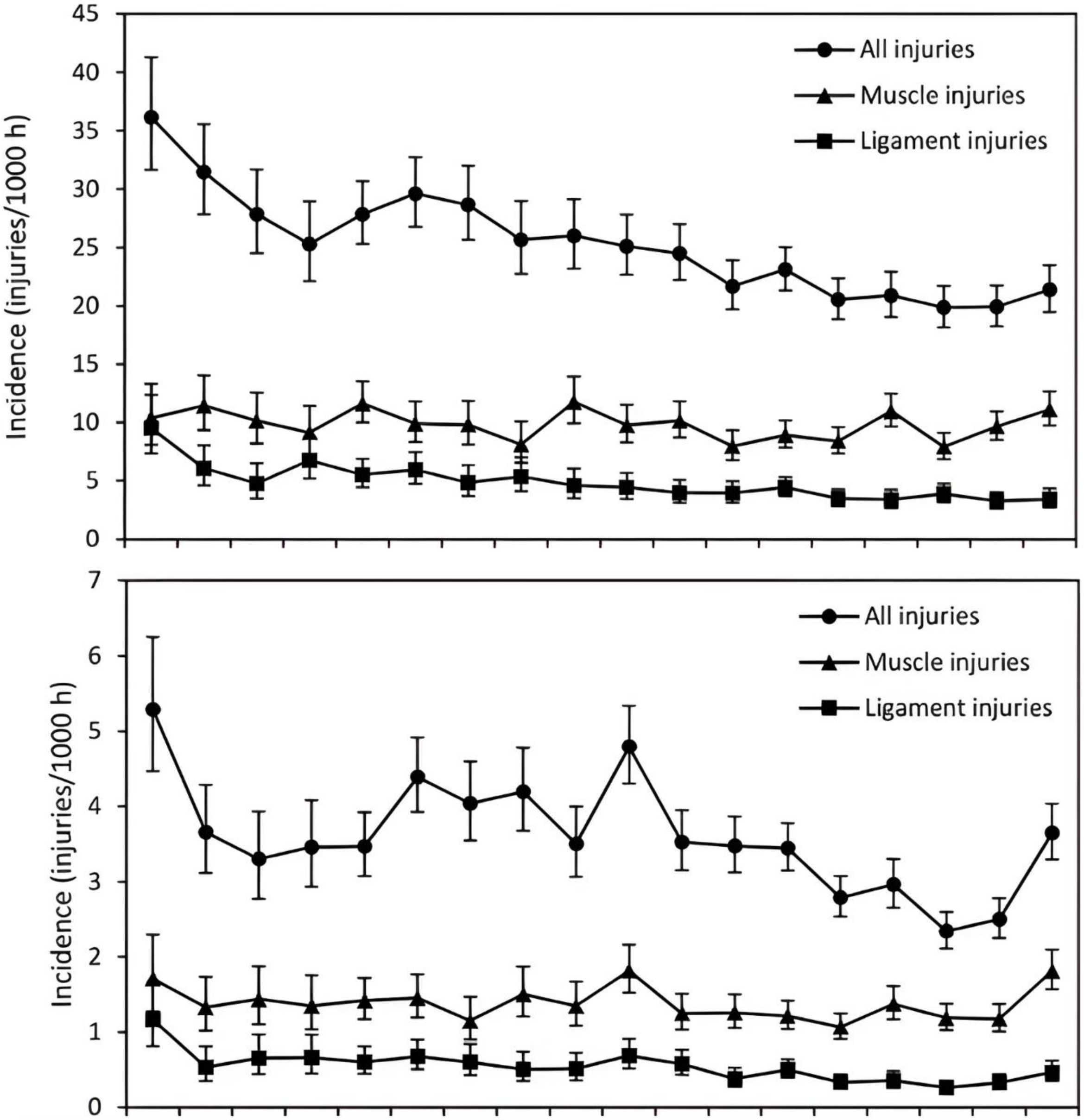


Figure 8: Match (top) and training (bottom) injuries. Injury incidence rate for all injuries, muscle injuries and ligament over 18 seasons. From Ekstrand et al., 2021 [95]

A recent systematic review and meta-analysis estimated an overall injury incidence of 8.1 injuries per 1000 h of exposure, with match incidence (36.0) nearly ten times higher than training incidence (3.7) [73]. A 2023 review reported comparable values (7.75 ± 2.28 injuries/1000 h), with match injuries occurring about 7.7 times more often than training injuries. Most injuries affected the lower extremities (83%), particularly the thigh (26%) [96]. Roughly 65% were minor, 25% moderate, and 10% severe, with muscle/tendon (40%) and joint/ligament (21%) injuries being most common [77].

League-specific cohort studies provide further granularity. In the English Premier League during the 2015–16 season, the total injury incidence was 9.11/1000 h of exposure, with match incidence substantially higher than training (24.29 vs. 6.84) [74]. Moderate severity injuries (8-28 days) were the most common (44.2%) and the highest incidence occurred in December [74]. Similarly, a media-based prospective analysis of Bundesliga players (2014/15–2020/21) found match and training incidences of 25.9 and 3.4 /1000 h, respectively, with the thigh (24%), knee (15%), and ankle (13%) most affected, and muscle/tendon injuries comprising nearly half of all cases (49%) [97].

The UEFA Elite Club Injury Study, spanning 18 seasons (2001–2019) and all UEFA Champions League teams, reported an overall incidence of 6.6/1000 h, with match injuries (23.8/1000 h) far exceeding training injuries (3.4/1000 h) [95]. Over time, overall rates decreased by ~3% per season, primarily due to fewer ligament injuries, while muscle injury rates remained stable. Reinjury incidence fell by 5% per season, mainly during matches. Despite these improvements, the overall injury burden remained unchanged, although squad availability increased modestly in both training (+0.7% per season) and matches (+0.2%) [95].

Using a similar design, the UEFA Women's Elite Club Injury Study began in 2018 [98]. A typical 23-player women's squad could expect 35 injuries per season, with an overall injury incidence of 6.7/1000 h and a fourfold higher rate during match play (18.4) compared to training (4.8). Most injuries (85%) affected the lower extremities, predominantly the thigh, knee, and ankle. Muscle injuries represented 39% of all injuries, while ligament injuries accounted for 20%. Acute injuries constituted 53%, with traumatic injuries more frequent during matches than training (63% vs 46%; $p < 0.001$), and contact injuries were more common in match play (40% vs 20%; $p < 0.001$). Severe injuries accounted for 21% of all injuries, with ACL, HI, and quadriceps being the most frequent [98]. International football studies confirm similar patterns, with match injury incidence substantially higher than training incidence in both men's (31.1 vs 4.0/1000 h) and women's (27.6 vs 5.1/1000 h) football [99]. Match injury burden also exceeds training burden (men's: 454 vs 51 days; women's: 507 vs 88 days per 1000 h).

Synthetizing lower limb injuries predominate across all cohorts in professional football players, accounting for 61–90% of all injuries, with the thigh being the most commonly affected region [46,74,100–102]. The most common injury types include muscle/tendon injuries, joint and ligament injuries, and contusions, with muscle strains representing 41.2% of all injuries [73]. Approximately two-thirds of traumatic injuries are contact-related, whereas non-contact injuries account for 26–58% of total injuries. Contact injuries predominate in matches, whereas training injuries are more frequently non-contact or cumulative [73,99–101]. This profile highlights the critical importance of monitoring and implementing injury prevention strategies tailored to the specific demands of professional football.

1.6.1 Muscle Injuries in Football

Muscle injuries constitute a major problem in professional football, accounting for nearly one-third of all time-loss injuries [103]. Most are strains rather than contusions or lacerations [104]. A typical elite men's team (25 players) can expect ~15 muscle injuries per season, leading to a mean absence of 223 days, 148 missed training sessions, and 37 missed matches [103]. These figures highlight their substantial impact on both performance and club success. About 92% of all muscle injuries affect the four main lower-limb muscle groups: hamstrings (37%), adductors (23%), quadriceps (19%), and calf (13%) [103]. In elite women's football, data show a similar distribution, with muscle injuries comprising 39% of all time-loss injuries, predominantly in the thigh region, with hamstring (12%) and quadriceps (11%) injuries equally common [98].

The incidence of muscle injuries is markedly higher during match play compared with training (8.70 vs 1.37/1000 hours) [46,103]. Notably, 66% of HIs occur during matches [103]. Congested match schedules exacerbate the risk: when players have ≤ 5 days between matches, muscle injury incidence increases by ~20%, likely due to accumulated fatigue and incomplete recovery [105]. Seasonal spikes are also observed at the start of the competitive season and after winter breaks, coinciding with condensed fixture periods [47].

Frequently injured muscles are often bi-articular [106], have complex architecture (e.g., adductor longus), undergo eccentric loading, and contain a high proportion of type II fibers [109–111]. Approximately 96% of muscle injuries occur in non-contact situations, reflecting the physiological demands of high-intensity football actions [103]. Recurrent muscle injuries represent about 16% of cases and are associated with 30% longer absences than index injuries [103]. Most are of moderate severity (8–28 days), though thigh and calf injuries generally result in longer absences than hip/groin injuries [103]. Age also influences risk: players over 22 years show significantly higher incidence rates than younger athletes, while leg dominance has little effect, except for quadriceps injuries, which occur more frequently in the dominant kicking leg (60%) [46].

1.6.2 Muscle Injury Diagnosis and Classification

Histologically, an acute muscle tear induces inflammation, edema, and sometimes hemorrhage, with infiltration of inflammatory cells and fibroblasts within the first 24–48 h [114]. Experimental models demonstrate that this destructive phase is followed by a repair and remodeling phase, involving progenitor cell recruitment, scar formation, and tissue reorganization [115].

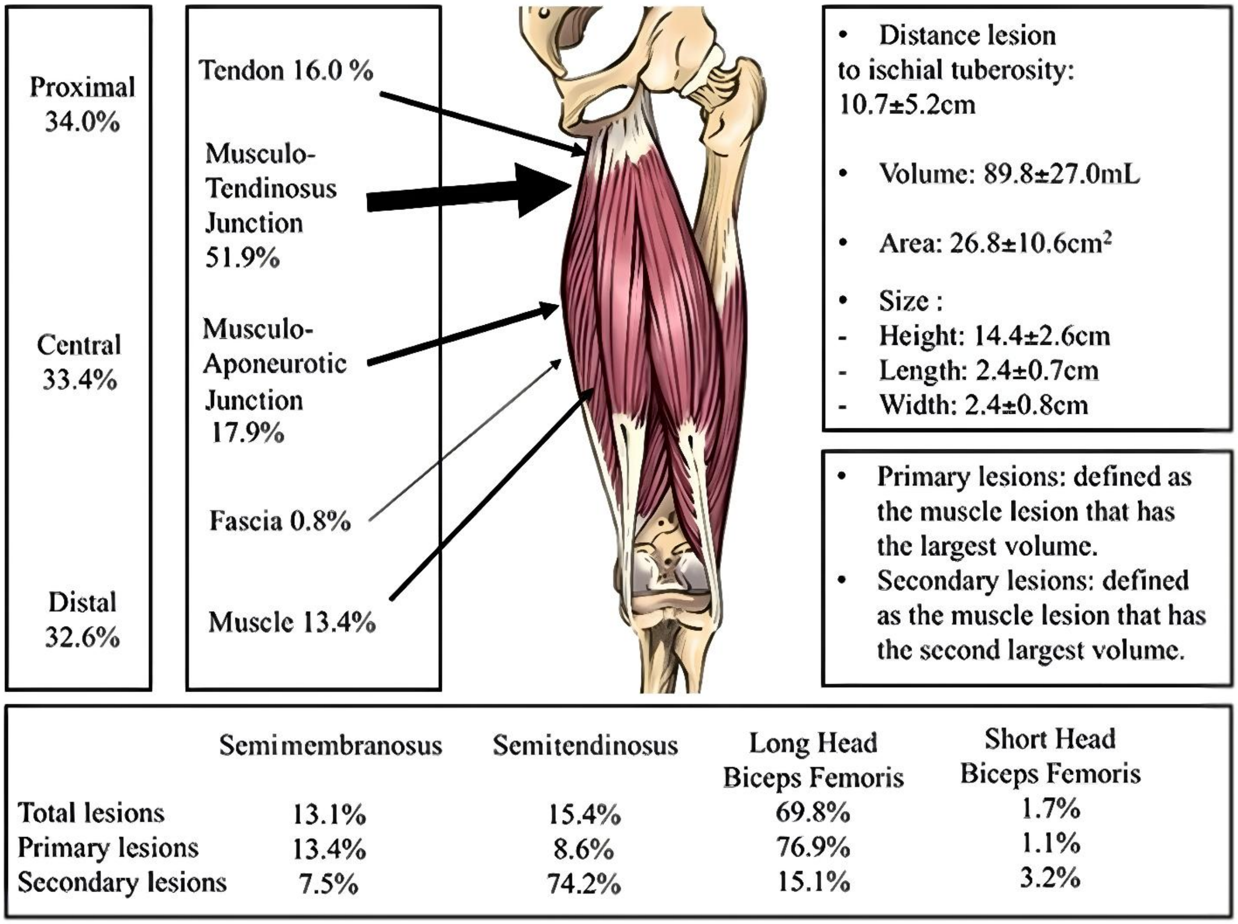
Diagnosis begins with a comprehensive history and physical examination, including inspection, palpation, and functional testing of the injured muscle with and without resistance [116–120]. While diagnosis is primarily clinical, imaging is routinely used to determine the location and extent of injury and to provide prognostic information such as recurrence risk and expected RTP timeline [121,122]. In elite sport, where rapid but safe RTP is a priority, defining prognosis is central. If a football player sustains an injury, one of the first questions from coaches and staff typically concerns when the player will be able to compete again [109]. Given the economic and competitive implications of player absences, RTP estimation holds great importance for both the individual and the club [110]. Accurate prognosis allows medical and performance staff to plan rehabilitation, future training, and team composition [90]. However, these decisions are often made under substantial pressure [110,111], and although a criteria-based approach is recommended, consistent implementation remains challenging due to the absence of validated, universally accepted criteria [112,113].time and performance pressure [110,111].

Both ultrasound (US) and magnetic resonance imaging (MRI) play important roles in the assessment of muscle injuries [110,123–125], with MRI regarded as the gold standard due to its superior soft-tissue contrast and capacity to delineate injury extent [126]. Prognostic features reported on MRI include length of tear [127], “MRI-negative” injuries [111], distance from the musculotendinous junction [128], oedema [110], and tendon involvement [112]. Nevertheless, MRI alone cannot accurately determine prognosis, management strategy, or RTP timeline in isolation. Instead, imaging findings should complement ongoing clinical reasoning and functional assessment, both of which are continuously adapted as the athlete progresses through rehabilitation. Prognosis and management should therefore be determined by an integrative clinical process that considers not only imaging results but also sport-specific demands, individual healing responses, and contextual factors [116,129]. Notably, up to 20–30% of clinically diagnosed HI present as MRI negative, highlighting the limitations of imaging alone [123,130,131].

A persistent limitation in muscle injury research has been the lack of standardized classification. Classification refers to the categorization of injury type, location, or mechanism, while grading denotes severity, often linked to expected recovery time [112,132]. Early grading systems (Grade I–III tears) [130] lacked anatomical precision and prognostic utility. Consequently, newer systems were developed to enhance diagnostic accuracy and communication among clinicians [133], several of which have been reviewed comprehensively [132,134–138]. More recent approaches also consider anatomical tissue involvement [131] and the mechanism of injury [139].

The Munich Consensus Statement (2013) was a major advance, distinguishing functional muscle disorders (without structural damage) from structural injuries (partial or complete tears) [130]. Building on this, the British Athletics Muscle Injury Classification (BAMIC) system [131] gained popularity, first in track and field and later in football. BAMIC classifies injuries by anatomical site (myofascial, musculotendinous junction, intra-tendinous, or tendon), extent of involvement, and degree of tissue disruption, and incorporates a “Grade 0” category for MRI-negative injuries. Cohort studies have confirmed its prognostic validity and inter-rater reliability [140]. More recently, the Barcelona/MLG-R classification, developed with FC Barcelona’s medical department, integrates anatomical detail, injury mechanism, and clinical presentation [139]. Although still under validation, it represents a shift toward muscle-specific, context-sensitive classification.

Despite these advances, no single system adequately captures the heterogeneity of muscle injuries [111,112,116,141]. Having a single classification system applicable to all muscle injuries may not improve communication between clinicians, given the variability in muscle anatomy and function [138]. Muscles differ in size, architecture, tendon structure, and fiber arrangement [142,143], leading to distinct healing patterns, rehabilitation demands, and reinjury risks [143,147]. For example, intratendinous injuries typically require 2–4 months for recovery and carry higher recurrence risk, whereas myofascial injuries resolve in roughly 3 weeks [112,140,145,146]. Yet most classification systems do not distinguish between proximal, distal, and intramuscular tendon injuries, despite evidence that these variations affect management (Figure 9).



- Distance lesion to ischial tuberosity: 10.7±5.2cm
- Volume: 89.8±27.0mL
- Area: 26.8±10.6cm^2
- Size :
  - Height: 14.4±2.6cm
  - Length: 2.4±0.7cm
  - Width: 2.4±0.8cm

- Primary lesions: defined as the muscle lesion that has the largest volume.
- Secondary lesions: defined as the muscle lesion that has the second largest volume.

	Semimembranosus	Semitendinosus	Long Head Biceps Femoris	Short Head Biceps Femoris
Total lesions	13.1%	15.4%	69.8%	1.7%
Primary lesions	13.4%	8.6%	76.9%	1.1%
Secondary lesions	7.5%	74.2%	15.1%	3.2%

Figure 9: Location of hamstring injuries (HIs) based on 2761 injuries detailed in the 34 included studies from Grange et al., 2023 [150].

This lack of specificity is particularly evident in HIs. A HI is not a single entity but a heterogeneous group with multifactorial etiology, and current systems remain nonspecific for the individual muscle injured. The typical clinical triad following acute HI, pain on stretch, pain on resistance testing, and localized pain on palpation [7], can present across a wide spectrum of anatomical and functional patterns. Some authors argue that each hamstring muscle should be classified separately, reflecting differences in connective tissue, fascia, and tendon architecture that influence healing time, prognosis, and management [134,138]. Indeed, myotendinous junction (MTJ) architecture and intramuscular connective tissue vary considerably among and within individuals [147,148], as do the functional roles of each hamstring muscle during movement [153,154]. Furthermore, HI inciting-activities, particularly stretching versus running-type situational pattern, may produce distinct injuries[128,151] [128,151], yet remain underrepresented in most classification systems.

Management should therefore consider the specific muscle involved, mechanism of injury, and sporting demands (e.g., sprint- versus pivot-dominant sports). Clinicians should consider these factors when prescribing rehabilitation as the management of an injury with the same classification, within a different hamstring muscle, may require individualized management to optimize outcome. In a recent Delphi study, experts reported most frequent use of the British Athletics Muscle Injury Classification (BAMIC) (58%), Munich (12%) and Barcelona (6%) classification systems for HI [152]. Issues identified to advance imaging classifications systems include detailing individual hamstring muscles, establishing optimal use of imaging in diagnosis and classification, and testing the validity and reliability of classification systems. The consensus panel recommended that future classification systems evolve to integrate imaging and clinical parameters around individual muscles, injury mechanism, sporting demands, functional criteria, and patient-reported outcome measures [152].

1.7 The Hamstring Muscle Complex

The term hamstrings originates from Old English, where ham referred to the back of the thigh and string described the prominent tendons palpable behind the knee. Historically, the expression was used to denote the tendinous structures at the knee joint, before later being extended to encompass the three biarticular muscles of the posterior thigh, biceps femoris (long head) (BFlh), semitendinosus (ST), and semimembranosus (SM), as well as the monoarticular short head of biceps femoris (BFsh) [150,157]. Although widely used, the collective term *hamstrings* is problematic, as it implies a homogeneous muscle group. In reality, these muscles differ substantially in their anatomical architecture, mechanical function, and neural control. They act synergistically in many tasks but are not functionally interchangeable, a distinction critical for both research and clinical practice. Similarly, the commonly used expression *hamstring strain injury (HSI)* is both etymologically and clinically imprecise, as it excludes injuries involving the free tendon. The broader term *hamstring injury (HI)* should be preferred when the specific muscle or structure affected is unspecified. The use of the term strain is discouraged, as it is a vague biomechanical descriptor applied indiscriminately to anatomically distinct conditions. Since the Munich consensus statement, the term tear has been recommended for structural injuries, graded as (minor and moderate) partial tears and (sub)total tears [130].

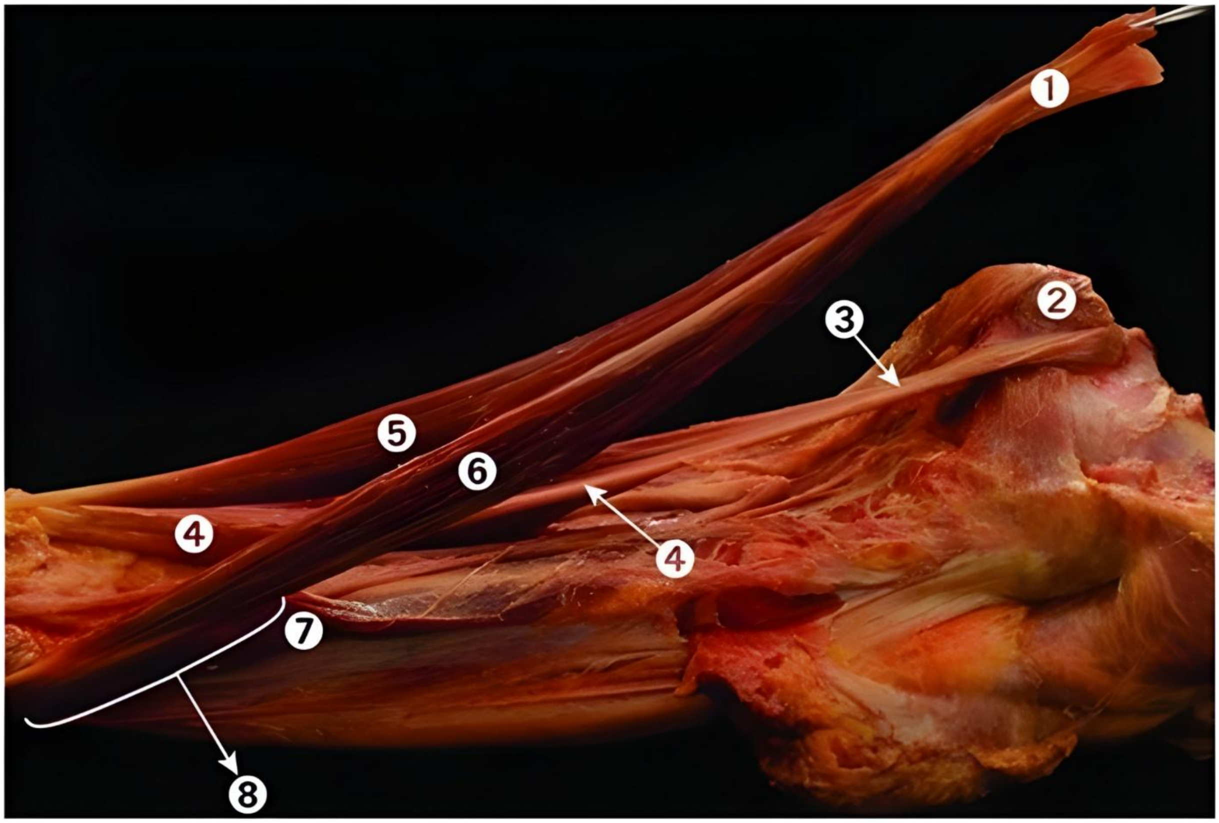


Figure 10: Posterolateral view of the hamstrings. (1) Conjoined tendon of the semitendinosus and the long head of the BF; (2) ischial tuberosity; (3) proximal tendon of the SM muscle; (4) SM muscle; (5) ST muscle; (6) long head of the BF muscle; (7) short head of the BF muscle; (8) conjoined tendon of the long and the short head of the BF [158].

The long hamstring muscles (SM, ST, BFlh) (Figure 10) cross both the hip and knee joints, contributing to hip extension, knee flexion, and tibial rotation—internal for SM and ST, external for BF. The monoarticular BFsh acts as a powerful knee flexor and tibial supinator [118]. The hamstrings are innervated predominantly by branches of the tibial division of the sciatic nerve, with BFsh supplied by the common fibular nerve [155]. Vascularization derives mainly from branches of the profunda femoris artery, with venous drainage via the profunda femoris vein.

The hamstring tendons can be divided into (1) a free tendon, devoid of fascicle insertions, and (2) the MTJ, where fascicles insert into the tendon. These parameters show high interindividual variability, and differences in tendon length and architecture are thought to influence injury susceptibility [156–158]. Both proximal and distal MTJs extend over a large portion of each muscle rather than being localized to either end.

Muscle architecture determines maximal force output, shortening velocity, and injury risk [159,160]. It includes (a) muscle size (cross-sectional area) and (b) fascicle orientation and length. BFlh and SM are hemipennate, ST is fusiform and divided into proximal and distal segments by a tendinous inscription, and BFsh is trapezoid-shaped [153,161,162]. BFlh has relatively short fascicles, which may predispose it to injury, whereas ST exhibits long fascicles and a unique tendon morphology. SM contributes differently to hip extension and knee flexion moments compared with other hamstrings. BFsh, originating from the femur, lacks a proximal free tendon. Variation in tendon proportion, fascicle length, and pennation angle among muscles leads to differences in force generation, contraction velocity, and injury susceptibility [163,164].

The hamstring complex comprises muscle, tendon, aponeurosis, MTJ, and myoaponeurotic junction, each with distinct mechanical and healing properties [153,161,162]. Injury size (area, volume, length) also affects prognosis [151]. Anatomically, the majority of HIs occur in the BFlh, with ST and SM less frequently injured sometimes with distinct mechanisms; up to 25% of cases involve multiple muscles, typically BFlh and ST, due to their anatomical proximity [154]. The BFlh's biarticular nature, dual innervation, short fascicles, and intramuscular tendon contribute to its high injury incidence and complex rehabilitation demands [159,166–168]. Therefore, HI should be viewed as a family of distinct injuries, each defined by the specific muscle, tissue location, and structural involvement, each requiring tailored prevention and rehabilitation strategies [140,165].

1.7.1 Semimembranosus (SM)

The SM originates from the lateral facet of the ischial tuberosity [158,169–172], lateral and anterior to the conjoined tendon of BFlh and ST [169,173], and posterior to quadratus femoris [158,174] (Figure 11a). Anatomical variants may present a shared tendon with the conjoined tendon [171]. An additional tendinous component from the inferior ischium connects with adductor magnus (AM) [158,169], likely aiding force dissipation and explaining the lower injury incidence of SM relative to BFlh and ST [169]. SM is typically innervated by a single branch of the tibial division of the sciatic nerve, sometimes sharing a trunk with ST [148,155]. A secondary branch often supplies the posteromedial portion of AM, which some authors consider part of the hamstrings due to its shared origin, innervation, and role in hip extension [155].

The SM tendon, the longest of all hamstrings (~32 cm), spans ~75% of muscle length, with fascicles arising distally and a large intramuscular tendinous component [172]. The proximal MTJ accounts for about two-thirds of total tendon length [148,172]. Regarding fascicular architecture, SM can be divided into three distinct regions: the proximal and middle segments are unipennate, while the distal portion is bipennate

[148]. Distally, SM has the longest MTJ among the hamstrings (16–19 cm) but a slightly shorter free tendon. The distal insertion is at the posteromedial corner of the knee, associated with the medial collateral ligament, posterior oblique ligament, and posterior horn of the medial meniscus [175,176]. Functionally, SM resists valgus stress in extension and external rotation in flexion [177]. Injuries typically involve the proximal free tendon, often from stretch-type patterns [128,178].

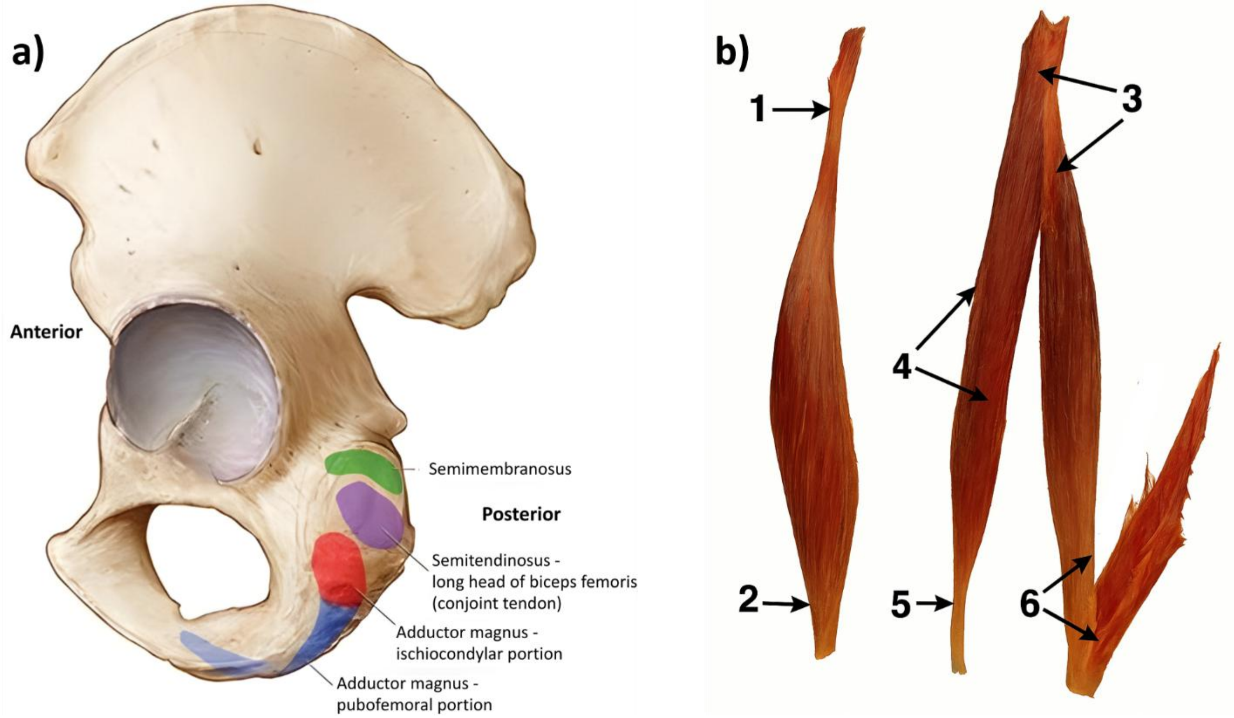


Figure 11. Anatomical representation of the hamstring muscle complex and its proximal attachments on the ischial tuberosity. (a, left) Posterior view of the pelvis illustrating the origin sites of the hamstring muscles: the semimembranosus (green), the conjoined tendon of the semitendinosus and long head of the biceps femoris (red), and the ischial and pubofemoral portions of the adductor magnus (blue) [182]. (b, right) Dissected view of the hamstring muscle complex showing: (1) proximal tendon of the SM, (2) distal tendon of the SM, (3) conjoined tendon of the ST and BFlh, (4) tendinous inscription (raphe) of the ST, (5) distal tendon of the ST, and (6) common distal tendon of the BFlh and BFsh [158].

1.7.2 Semitendinosus (ST)

The ST arises from the conjoined tendon shared with BFlh, originating from the medial facet of the ischial tuberosity (Figure 11a). The tendon is initially rounded with a smaller cross sectional area than SM [148,170,172]. The free proximal tendon is short (1–2 cm), and the proximal MTJ, the shortest among the hamstrings, measures approximately 11–12 cm, occupying about 28% of total muscle length) [148,172,179].

A distinctive feature is the tendinous inscription (raphe) dividing the muscle into proximal and distal segments (Figure 12b). Both contain parallel fascicles; the distal portion has a greater pennation angle, contributing to long fascicles comparable to sartorius and gracilis [184,185]. The distal tendon, the longest of all hamstrings [148,157,184], begins at mid-thigh as a thin aponeurosis and lies superficially over SM [148,179,183]. It passes superficial to the medial collateral ligament, inserting at the pes anserinus along with sartorius and gracilis [185]. Within this insertion, sartorius is the most proximal, gracilis intermediate, and ST the most distal [185,186].

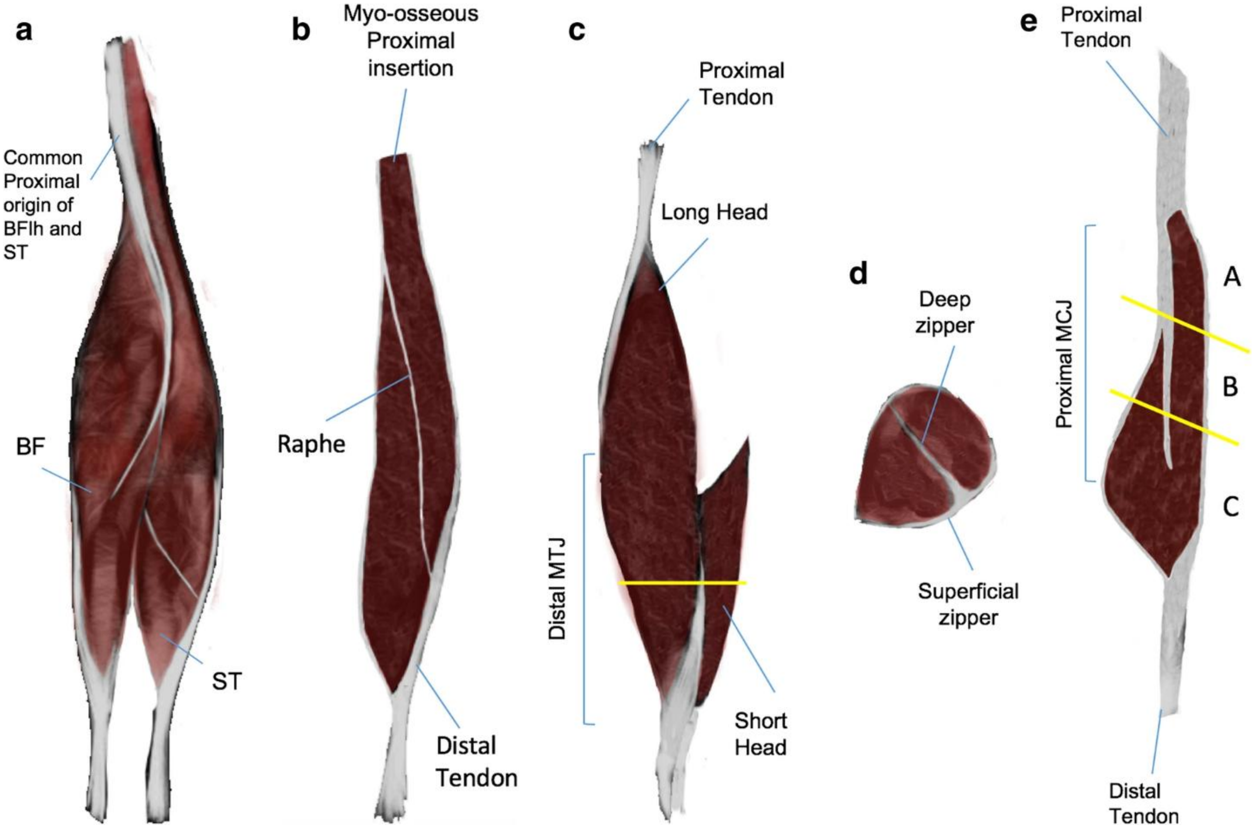


Figure 12: Hamstring complex muscles showing the distribution of connective tissue in each muscle belly. a) Frontal view of the hamstrings (BFlh, biceps femoris long head; ST, semitendinosus; BF: biceps femoris). b) Coronal section of the semitendinosus. c) Open lateral view of the biceps femoris (MTJ, myotendinous junction). d) Axial section of the distal part of the biceps femoris. E) Coronal section of the semimembranosus (MCJ, myoconnective junction) [182].

1.7.3 Biceps Femoris Long Head (BFlh)

The BFlh originates via a thick tendon from the lateral part of the medial facet of the ischial tuberosity [148,169,170], often continuous with the sacrotuberous ligament [158,169,183,185,187–189]. From a phylogenetic perspective, the sacrotuberous ligament has been proposed to represent the upper, degenerated remnant of the BFlh tendon [183]. This anatomical continuity may facilitate force transmission across the sacroiliac joint. A recently described retinaculum-like structure anchors the BFlh tendon to the ischial tuberosity and establishes a strong interface with both the sacrotuberous ligament and the epimysium of gluteus maximus [190]. Through this structure, gluteus maximus is mechanically linked to BFlh, suggesting a synergistic role in transmitting and stabilizing forces during hip extension.

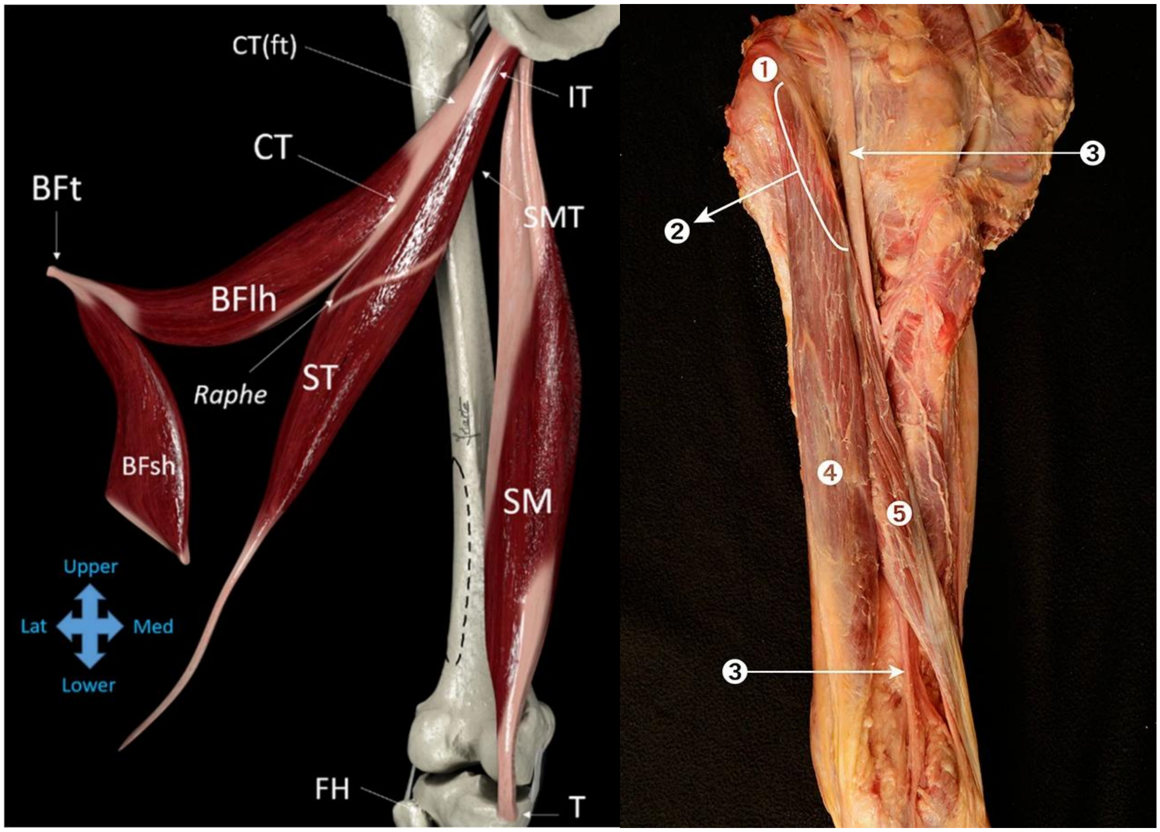


Figure 13. Anatomical representation of the hamstring muscle complex. (a) Three-dimensional schematic illustration of the expanded hamstring muscles. BFlh – long head of the biceps femoris; BFsh – short head of the biceps femoris; ST – semitendinosus; SM – semimembranosus; SMT – semimembranosus tendon; CT – common tendon; CT(ft) – free-tendon part of the common tendon. The dotted line along the femoral shaft indicates the linea aspera, the origin of the BFsh. IT – ischial tuberosity; T – medial tibial surface; BFt – distal biceps femoris tendon [191]. (b) Posterolateral view of a dissected right posterior thigh. (1) Ischial tuberosity; (2) Conjoined tendon of the semitendinosus and long head of the biceps femoris; (3) Sciatic nerve; (4) Semitendinosus muscle; (5) Long head of the biceps femoris [162].

Muscle fibres originate from the lateral surface of the conjoined tendon [148,158,183,192] (Figure 11a, left). About 9–10 cm distal to the ischial tuberosity, BFlh separates from ST [169,171,193]. The proximal tendon (~25 cm) occupies approximately

60% of muscle length; the free tendon (~5–6 cm) transitions into a long intramuscular portion (~20 cm). Architecturally, BFlh is pennate, optimized for force production rather than high-speed shortening, contrasting with the parallel-fibered ST [148]. The distal tendon is the longest among hamstrings (~27 cm, ~60–65% of muscle length) [148,157], forming a broad aponeurosis that partially covers BFsh [152,188]. The distal MTJ extends ~18 cm (~40% of total muscle length) [152]. Distally, the BF tendon inserts primarily onto the fibular head, with extensions to the lateral tibial condyle [198–200], functioning as a dynamic stabilizer against anterolateral and anteromedial knee instability [200,201].

1.7.4 Biceps Femoris Short Head (BFsh)

The BFsh originates from the posterior femur, approximately 15 cm distal to the ischial tuberosity, below the distal insertion of gluteus maximus (GM) [152]. Its fibers arise from three main sites: the linea aspera (between adductor magnus and vastus lateralis), the upper two-thirds of the lateral supracondylar line, and the posterior portion of the lateral intermuscular septum [152,188,202]. Unlike the other hamstrings, BFsh lacks a broad proximal tendon, and its MTJ is minimal. The fascicular architecture is variable, with two distinct regions: the posterior portion typically displaying longer fascicles (10–14 cm) than the anterior [152]. Pennation angles range between 10–16° [186].Distally, BFsh has two main tendinous insertions: a direct arm inserting onto the fibular head (medial to the fibular collateral ligament), and an anterior arm that passes deep to the ligament, partly blending with the anterior tibiofibular ligament before attaching to the tibia near Gerdy’s tubercle. An additional lateral aponeurotic expansion connects to the posteromedial aspect of the fibular collateral ligament [201,203].

1.8 From Individual Isolated-Muscle to Myofascial Chains

Life on this planet is built from cells, which organize into tissues, organs, and systems. A tissue is a collection of specific types of cells organized by structural and functional characteristics to perform specific roles. A system’s function is not simply the sum of its parts but emerges from their integration. This principle also applies to human movement: muscles, nerves, and connective tissues interact as networks rather than as isolated elements.

Anatomy and biomechanics have traditionally been studied through a reductionist lens. Human biomechanics has long been framed using Newtonian mechanics, with geometry reduced to levers, vectors, and inclined planes. Almost every anatomy text presents muscle function by isolating an individual muscle on the skeleton, reducing function to approximate origin and insertion, disconnected from neurological, vascular, and regional relationships. This reductionist approach fails to capture the complexities of human movement. According to Dischiavi et al. [204], movement is better understood through holism. Our understanding of anatomy has been shaped by dissection methods. With a knife, muscles are easily separated from surrounding fascia, fostering the belief that each acts independently. The very term “anatomy” derives from the ancient Greek ἀνατομή (anatomē), literally meaning “to cut up,” a reminder of this reductionist bias. In many anatomical references still in use today, fascia is removed to reveal muscles, thereby discarding its integrative role. In contrast, if fascia were left intact, the body would appear as an intricate web enveloping every organ and structure, similar to neural and vascular networks. A holistic lens, aligned with complex systems theory introduced in Chapter 1, views muscles as embedded in connective tissue networks, where function emerges from interdependence. Just as injury causation has shifted from single to multifactorial models, anatomy too must move from isolated muscles to myofascial chains.

The term *myofascial meridian* was introduced in 1997 by Tom Myers to explain how fascia contributes to structure and function. Fascia is a continuous fibrous connective tissue network that surrounds, supports, protects, and connects musculoskeletal and visceral structures [205]. It is organized in specific lines of tension that distribute mechanical strain, facilitate coordinated movement, and provide stability [206]. Beyond structure, fascia lubricates and nourishes tissues [207] and regulates tension–compression balance. In this view, muscles are components of an interconnected network, with fascia as the linking element [208] (Figure 14). Thus, muscles operate not as isolated units but as nodes within a body-wide myofascial network. The connective tissue network forms a structural framework around myofibers, coordinating the contraction of individual fibers into a collaborative action, enabling efficient movement. It means that the extracellular matrix plays a key role in muscle fiber force conduction [209,210]. This concept aided practitioners to explore how dysfunction or overload in one region can influence distant or seemingly unrelated structures. Importantly, myofascial chain theory does not discard classical muscle-based analysis; it situates it within a systemic, load-distributing model more consistent with biological reality than a purely mechanical lever model. Rather than Descartes’ “soft machines,” the body can be seen as an autopoietic (self-forming) system governed by non-linear dynamics.

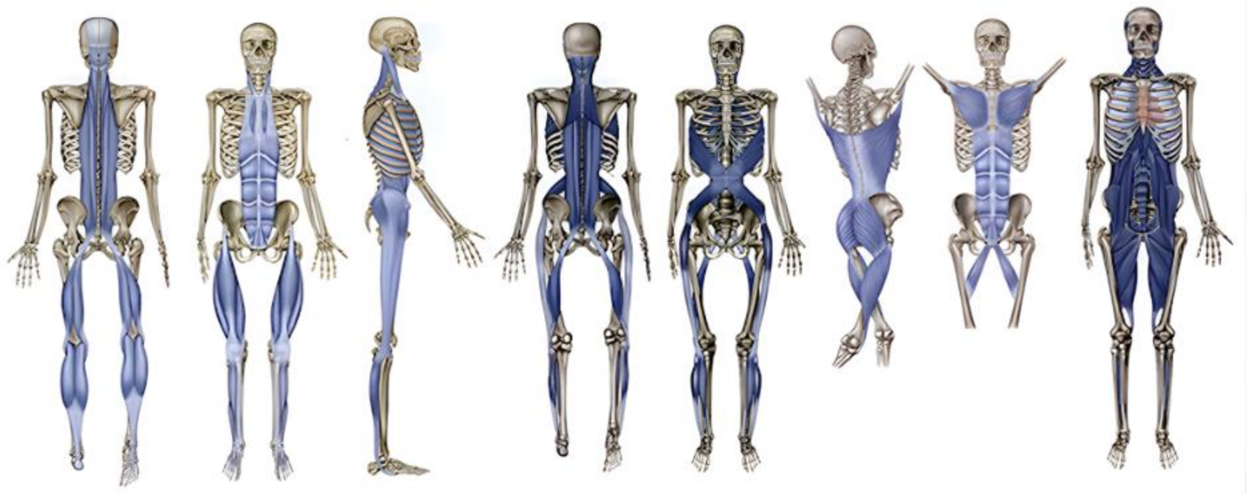


Figure 14: Schematic representation of the principal myofascial meridians described by Myers in Anatomy Trains [211].

Among the many cell types present in connective tissue, fibroblasts play the central role, producing the fibrous elements—primarily collagen, elastin, and reticulin—that provide strength, elasticity, and adaptability (see figure 15). Fascia is not uniform: its characteristics vary depending on location, showing differences in thickness, elastic fiber content, adherence, and expansions into surrounding soft tissues [212]. These structural variations are particularly relevant in transition zones, where fascia integrates with tendinous, aponeurotic, and ligamentous tissues, as well as with the deep fascia itself [213]. Importantly, fascia is dynamic and adaptable. It undergoes continuous remodeling in response to mechanical stress [214,215], with strain transmission dependent on specific patterns of muscular activation [216,217]. Through mechano-transduction, the conversion of mechanical forces into cellular biochemical signals, these loads can even influence fibroblast activity and gene expression, ultimately remodeling the extracellular matrix [214,218]. In this self-organizing system, adaptation is neutral: it may be beneficial or detrimental, depending on stimuli. Excessive or maladaptive remodeling may reduce strength, coordination [213,219], or proprioception [220]. Such variability explains why joint shapes and connective tissue properties differ among individuals despite textbook “uniformity”. Clinically, this implies that musculoskeletal assessment and treatment may need to include fascia-targeted strategies, not just “the injured muscle” [221]. The growing interest in fascial interventions in musculoskeletal practice reflects this shift [222].

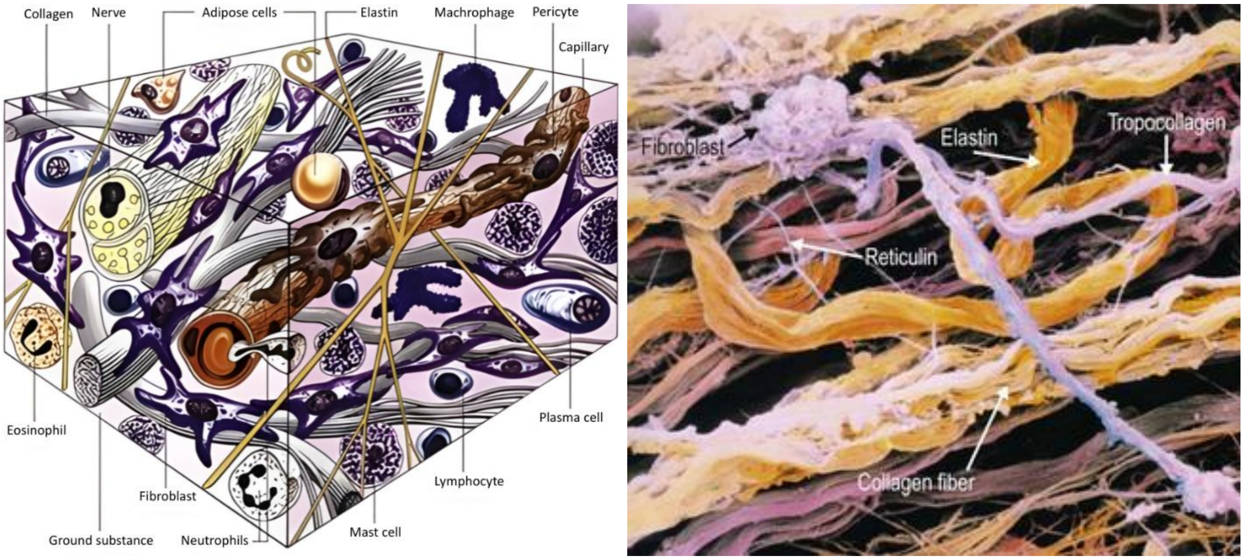


Figure 15: (a) Schematic representation of connective tissue illustrating the variable composition of cells, fibers, and interfibrillar ground substance (proteoglycans) that determine its mechanical properties [211]. (b) Scanning electron micrograph of loose connective tissue showing collagen, elastin, reticulin, and tropocollagen fibers, as well as fibroblasts. Adapted from Young B, O'Dowd G, Woodford P. Wheater's Functional Histology: A Text and Colour Atlas. 6th ed. Philadelphia: Churchill Livingstone/Elsevier; 2014.

1.8.1 Bio-tensegrity

A helpful analogy contrasts the body with a building. While we often imagine the body as a stack of bricks or blocks supported by rigid foundations, it more closely resembles a tensegrity structure. Coined by designer R. Buckminster Fuller, the term "tensegrity" (short for tensional integrity) describes systems that maintain their stability through a continuous balance of tensile forces rather than relying primarily on compressive elements such as walls or columns. In these structures, strength and integrity arise from the global interaction of tension and compression rather than from isolated components (see figure 16). Applied to the human body, this model illustrates that mechanical forces are distributed across the system rather than localized, providing a more accurate representation of how fascia and muscles operate in movement and injury [223].

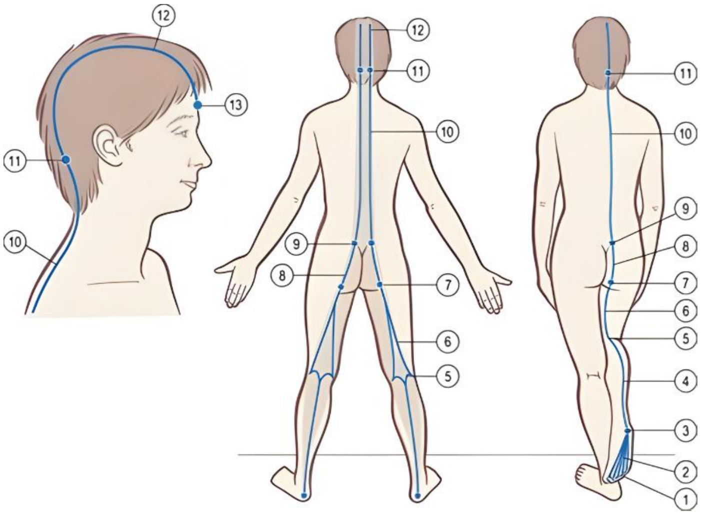
Figure 16: Example of a pelvis tensegrity model (left), and a tensegrity-inspired chair design (right).

The concept of tensegrity can guide someone who is attempting to understand the fascia and its intricate system, in order to appreciate its complexity within an apparently simple design. It is now clear that fascia distributes strain laterally to neighboring myofascial structures; thus, a tendon's pull is not absorbed solely at its insertion but shared through adjacent tissues. The focus on isolating muscles has blinded us to this phenomenon, which in retrospective represents an inefficient way to conceptualize a stress-bearing system. The stability of a tensegrity structure differs from that of a rigid compression-based structure: it is generally less stiff, but more resilient. When one "corner" is loaded, the entire structure redistributes strain, compensating small stresses across its network. However, if the load or its rate of application becomes excessive, failure may occur, not necessarily at the point of application, but at a distant weak spot where structural integrity is compromised.

In the human body, this means that an injury may manifest locally, but its origin can often be traced to long-term strain, imbalance, or dysfunction in other communicating regions. The actual site of breakdown reflects not only acute stress but also pre-existing vulnerabilities or prior injuries. From a clinical and sports perspective, this implies that muscle injuries should not be viewed merely as local tissue failures but rather as organ-level disturbances within a broader system [141]. For example, in football, asymmetries in hip rotation, pelvic control, foot strike pattern, or temporal mandibular joint mechanics [224] can propagate through fascial pathways, eventually overloading and predisposing more distant and seemingly unrelated structures, such as the hamstrings, to injury. Identifying and addressing these interconnected pathways is therefore fundamental for both understanding injury mechanisms and designing prevention strategies.

1.8.2 Hamstrings Muscle Complex and Superficial Back Line (SBL)

The concept of myofascial meridians or myofascial chains has been investigated in several studies [225–227]. The general principle is that strain, tension, trauma, and movement are transmitted along these fascial pathways, linking distant body regions through continuous connective tissue structures. A landmark systematic review by Wilke et al. (2016a) [208], conducted according to PRISMA guidelines, evaluated over a century of anatomical dissection studies (1900–2014). Using the QUACS (Quality Appraisal for Cadaveric Studies) tool, the authors classified the strength of evidence for myofascial transitions as strong, moderate, limited, conflicting, or non-existent. Their findings supported the existence of three myofascial chains described by Myers [211], with robust evidence for transitions between the plantar fascia and gastrocnemius, gastrocnemius and hamstrings, and hamstrings and lumbar fascia/erector spinae.



Bony Stations		Myofascial tracks
Frontal bone, supraorbital ridge	13	
	12	Galea aponeurotica/epicranical fascia
Occipital ridge	11	
	10	Sacrolumbar fascia/erector spinae
Sacrum	9	
	8	Sacrotuberous ligament
Ischial tuberosity	7	
	6	Hamstrings
Condyle of femur	5	
	4	Gastrocnemius/Achilles tendon
Calcaneus	3	
	2	Plantar fascia and short toe flexors
Plantar surface of toe phalanges	1	

Figure 17: Superficial Back Line myofascial ‘tracks’ and bony ‘stations tracks and stations. The shaded area shows where it affects and is affected by the more superficial fasciae (dermis, adipose, and the deeper fascia profundis) [211].

Among these chains, particular attention is given to the Superficial Back Line (SBL), where the hamstrings play a central role (Figure 17). The SBL extends continuously from the plantar fascia at the feet to the scalp fascia at the skull, functioning primarily to support upright posture and counteracting flexion forces [211]. Structurally, this requires a high proportion of slow-twitch, endurance fibers in the muscular portions and dense, load-bearing fascial structures in the connective tissue portions. Key examples include the Achilles tendon, hamstrings, sacrotuberous ligament, thoracolumbar fascia, erector spinae "cables," and the occipital ridge fascia. Importantly, although referred to as a single line, there are two mirrored SBLs, right and left, and asymmetries between them are often clinically relevant.

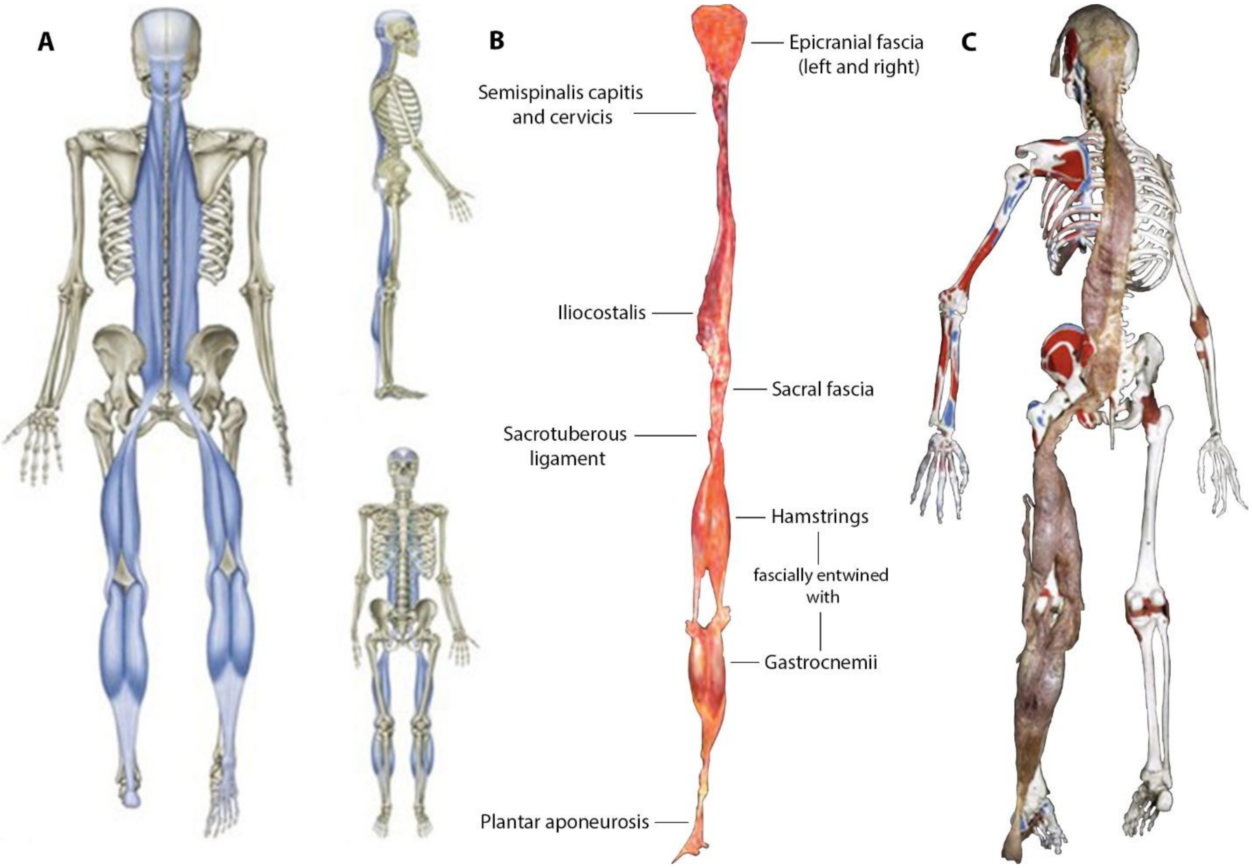


Figure 18. Representation of the Superficial Back Line (SBL) according to Myers' Anatomy Trains concept [211]. (A) Schematic visualization of the SBL illustrating its continuous myofascial connection from the feet to the head. (B) The SBL dissected and displayed as an integrated fascial chain, showing its main components. (C) The same dissected specimen reassembled on a skeleton to demonstrate the topographical continuity of the SBL along the posterior aspect of the body.

The hamstrings are particularly significant within the SBL due to their direct fascial continuity with the sacrotuberous ligament (previously described) and their connection to the gastrocnemius tendons distally. Fibers from the hamstring myofascia extend beyond their bony attachment at the ischial tuberosity, integrating into the sacrotuberous ligament and continuing toward the sacrum. Similarly, distal hamstring tendons share continuity with the gastrocnemii, further reinforcing the functional integration of the posterior chain (Figure 18). Clinically, common postural compensation patterns associated with dysfunction in the SBL include limited ankle dorsiflexion, knee hyperextension, hamstring shortness, anterior pelvic shift, sacral nutation, lumbar hyperlordosis, thoracic extensor dominance, suboccipital tightness leading to cervical hyperextension, anterior displacement of the occiput on the atlas, and disrupted eye–spine coordination. A typical pattern observed is shortening of the hamstrings and sacral stabilizers, pushing the pelvis anteriorly. This, in turn, causes compensatory tightening of anterior hip muscles that attempt to resist the forward drive from the posterior chain. It is clinically essential to differentiate between muscles tense due to concentric overloading versus those tense due to eccentric strain, as treatment strategies differ significantly. Compared to the medial hamstrings, the BFlh also belongs to the spiral line, connecting via the sacrotuberous ligament and contralateral latissimus dorsi through the thoracolumbar fascia. This linkage underlies trunk–pelvis rotational force transmission during locomotion and football-specific tasks such as kicking, changes of direction, and lateral lunges. Depending on foot dominance, one spiral line may be preferentially recruited for stabilizing or rotational actions, creating chronic asymmetry in myofascial tension. These additional contralateral coordination demands may help explain why the BFlh is the most commonly injured hamstring muscle.

Direct morphologic continuity between adjacent muscles provides a strong basis for expanding diagnostic and therapeutic perspectives beyond isolated anatomical structures [228]. For example, in patients with low back pain, interventions targeting neighboring or even remote myofascial tissues via specific fascial connectivity could prove to be effective in reducing pain [229]. Consistently, individuals with low back pain frequently present with reduced hamstring flexibility [230,231], and evidence suggests that releasing posterior thigh tension may help alleviate low back pain [225,232]. Within the framework of the Superficial Back Line (SBL), such associations are anatomically coherent, as both regions are part of the same fascial pathway extending from head to toe. Similar to previously mentioned research, Labovitz et al. (2011) and Bolivar et al. (2013) reported that limited extensibility of the gastrocnemius and hamstrings may contribute to plantar fasciitis [233,234]. Since these structures, gastrocnemius, hamstrings, and plantar aponeurosis, are all part of the SBL, they represent potential shared therapeutic targets when one region is affected by trauma or overuse.

Several randomized and controlled studies support non-local effects. Grieve et al. (2015) [225] reported that a single session of self-myofascial release applied only to the plantar surface significantly increased hamstring and lumbar spine flexibility in healthy adults. A more recent single-blind RCT in 58 asymptomatic individuals with hamstring tightness found that remote myofascial release applied to either the suboccipital region or the plantar fascia improved hamstring flexibility to a similar extent as direct stretching of the hamstrings [235]. Fousekis et al. (2019) [236] further showed that instrument-assisted soft tissue mobilization applied to either the upper or lower portion of the SBL improved hamstring flexibility equivalently across four weeks, regardless of whether the application site was local or remote local or remote. While methodological limitations warrant caution, these findings empirically support the idea that tension and adaptation propagate along organized myofascial continuities.

1.8.3 Evolutionary and Functional Perspectives on Hamstring Vulnerability

The hamstring muscle complex reflects an evolutionary compromise between efficiency and stability in bipedal locomotion. The shift from quadrupedal to upright gait required substantial modifications in pelvic tilt, lumbar lordosis, and lower limb alignment, altering hamstring function as both hip extensors and knee flexors. The transition to bipedalism shortened the ischial tuberosity lever arm, altering hamstring moment arms. Compared to quadrupedal primates, humans possess longer hamstrings that operate across two joints, enabling powerful hip extension and stride length while simultaneously predisposing them to strain injuries [237]. Humans are evolutionarily adapted to running, but primarily as endurance athletes. Compared with most animals, our efficiency in long-distance locomotion is exceptional and likely provided survival advantages during persistence hunting. Interestingly, humans are also among the slowest species to master locomotion, reflecting the complexity of our neuromuscular adaptations. Thus, while optimized for endurance, our musculoskeletal system faces a mismatch when exposed to explosive, high-speed demands characteristics of football.

Functionally, hamstrings act not only as prime movers in sprinting but also as a link in a chain that integrates force transmission between axial and appendicular skeleton; hubs where forces and compensations converge from both lower limb and lumbopelvic regions. Clinical symptoms, such as hamstring tears, can therefore mislead practitioners into focusing solely on the injured tissue, when in fact the hamstrings may represent the victim rather than the source of dysfunction [113]. From this perspective, the hamstrings muscle group should be understood within myofascial networks rather than as isolated anatomical units. Their architecture is shaped by systemic function, connective tissue interactions, and neural regulation. Injury prevention and rehabilitation should therefore focus on the integrity of chains, lines, and asymmetries, rather than the hamstring strength in isolation [238]. Applying a fundamental principle of biology, function defines structure [237]: modifying hamstring activation patterns is more effective than isolated strength work. Evidence from return-to-play studies supports this view, with superior outcomes when rehabilitation targets the whole kinetic chain instead of isolated muscle strengthening [163,196].

This approach aligns with contemporary use of the term neuromuscular function, which refers to coordinated sensorimotor control across the full movement system. Optimal performance requires predictive (“feedforward”) regulation through continuous sensory–motor loops between peripheral and central networks [239]. Prospective studies in elite football and Australian rules football have shown that neuromuscular coordination within the lumbopelvic–hip complex, and within the broader posterior kinetic chain, is associated with HI risk [240,241]. These findings suggest that protecting the hamstrings requires restoring not only structural integrity and strength, but also dynamic neuromuscular control across the entire chain.

1.9 Hamstring Injuries in Football: State of the Art

Football has the highest incidence of hamstring injuries (HI) among team sports [242], representing the most common injury in both male and female players [48,100,104]. The epidemiology of football injuries has been extensively documented, particularly over the last two decades through the UEFA Elite Club Injury Study. HI account for approximately 34% of all muscle injuries and 17–26% of all injuries sustained by football players [48,243]. Despite ongoing prevention efforts by medical staff and scientific community research, the prevalence of HI continues to rise, increasing approximately 2.3% per year in elite professional football [48]. In a large cohort of English professional football players, HIs represented the most frequent muscle group affected, responsible for 39.5% of all muscle tears and 16.3% of all injuries [76]. Similar trends are seen in women's football, where HIs account for around 12% of all reported injuries, followed by quadriceps injuries (11%) [100]. Similar results have been reported in women's football from Scandinavia [244,245], whereas a Spanish single-club study found quadriceps injuries to be slightly more prevalent [246]. It is, therefore, likely that there is a similar trend as seen in men's professional football with increasing playing intensity over time [247], and an accompanying transition from ligament to muscle injuries [97].

A male team with a 25-player squad typically sustains five to six HIs per season, resulting in approximately 80 days lost to injury [105]. Notably, average first-team squad sizes have increased in recent years, from an average of 23 to 26 players, likely reflecting a need for player rotation during congested match schedules, which are known to increase injury risk and impair team performance [248,249]. Among non-contact injuries, HIs impose also the greatest burden and highest recurrence rate, with up to 13% of all HIs representing recurrences within two months of RTP [48,243,250]. Recurrence may affect more than half of players who have sustained a previous HI, with the highest risk occurring within the first two weeks after RTP [251,252]. In women's football, recurrence rates are slightly lower but still significant, representing around 11% of all HIs [253]. Following injury, the BFlh often exhibits shorter fascicle length [163], reduced eccentric strength [254], and increased muscle–tendon stiffness [255], factors associated with reinjury risk. Preventing the initial injury is therefore paramount. In elite European football, the average absence following a functional HI is 6 days (16% reinjury rate), compared to 18 days for structural injuries (17.5% reinjury rate) [251]. Most HIs occur during matches rather than training, with 65% recorded in match play versus 35% in training [48,243]. Furthermore, match injuries impose a substantially greater burden than training injuries (88.5 vs 6.3 injury days lost per 1000 hours of exposure) [48].

According to the UEFA Elite Club Injury Study, the distribution of HIs by severity was: minimal (10%), mild (21%), moderate (54%), and severe (15%) [48]. In the Norwegian women's premier league (2020–2021 seasons), gradual-onset HIs accounted for 53% of all injuries [253], a proportion notably higher than that reported in men's football (34–36%) [47,48]. Gradual-onset complaints have previously been described as more frequent in female than in male football players [244]. Moreover, MRI findings revealed that up to 40% of injuries involved the SM muscle [253], contrasting with data from men's football, where the BFlh accounts for 69–84% of cases and the SM for only 11–12% [48,123,256]. Regarding BFlh, all cases occurred at the MTJ [253], consistent with observations in male players, a region highly susceptible to mechanical stress [257,258]. Conversely, SM injuries often involved the proximal tendon, highlighting the need for targeted preventive strategies in female players [253]. However, another study on women's football reported that most injuries (66%; 82/125) were located in the BFlh [100], underscoring variability across cohorts and the need for further investigation in larger samples. In a recent study on men's football, Ekstrand et al. [259] reported 84% of injuries involving the BFlh, 12% the SM, and 4% the ST. No significant differences in lay-off time were observed between muscles, although recurrence was higher for BFlh injuries than for SM and ST combined (18% vs 2%) [259]. Both hamstring muscle strains and avulsions tend to occur proximally rather than distally [260], although the underlying reasons and mechanisms for this proximal predominance remain unclear. Because hamstring injuries may involve multiple sites and muscles simultaneously, a comprehensive assessment along the entire length of the muscle group is essential, rather than focusing solely on the region of pain [123,129,148].

1.9.1 Injury Mechanisms and Situational Patterns

A sudden-onset HI usually involves a moment that athletes can recall as a result of a specific movement of the lower leg or pelvis. HIs typically present as sudden pain in the posterior thigh, sometimes accompanied by an audible snap, leading to immediate player impairment and inability to continue playing (although in some cases, the player remains on the pitch, and the injury is reported after the match or the following day). The unmistakable visible sign of the injured athlete is reaching for the affected region with the ipsilateral hand.

The mechanism of HI onset is often described in epidemiological studies as "non-contact", referring to the absence of a direct external impact (e.g., contusion after collision with an opponent). However, VA allows a more nuanced classification into contact (direct/indirect) and non-contact mechanisms [72,73,261–265], as detailed in Section 1.3.3. While non-contact mechanisms predominate, indirect contact accounts for 26–35% of cases in some studies [73,262,265,266], warranting closer attention. Direct-contact HIs are rare but have been occasionally documented in specific match contexts. Some studies further categorized indirect contacts by the involved body region (e.g., upper body, pelvis, injured leg) [72,261–263] and contact type (e.g., tackles, collisions) [72,73,263,266].

A meta-analysis on the prevalence of HIs in professional football identified fast hip flexion and knee extension movements under high eccentric load as the primary inciting mechanisms [105]. Consequently, HIs occur when the muscle–tendon unit (MTU) is exposed to a combination of (1) high forces, (2) lengthening action, (3) high velocity, and (4) moderate-to-long muscle length [267–271]. These movements can be categorized into run-type and stretch-type situational patterns, reflecting the action performed at the moment of injury [272]. In both running and overstretching actions, the hamstrings function eccentrically to decelerate hip flexion and knee extension. However, whereas run-type injuries occur within a normal range of motion (ROM), stretch-type injuries occur at more extreme and variable joint positions. Notably, most HIs in football, both run- and stretch-type, biomechanically occur during rapid actions involving hip flexion with knee extension, often exacerbated by concurrent ankle dorsiflexion and trunk flexion with the gaze fixed downward on the ball. This posture, especially when the hamstrings are required to lengthen eccentrically while generating high forces [273], stretches the entire posterior muscle chain, positioning the hamstrings as a weak link within a chain that integrates force transmission between the axial and appendicular skeleton.

1.9.1.1 Run-type Situational Pattern

The precise phase of the running cycle in which HIs occur during maximal or near-maximal sprinting remains debated [131]. Most studies indicate that HIs in football are most likely to occur during the late swing or the early stance phase of running, when eccentric hamstring activation peaks. This coincides with anterior pelvic tilt and maximal hamstring lengthening as the lower limb decelerates in preparation for foot ground contact [274,275]. During these phases, the hamstrings generate large active torques to counteract the passive effects of leg inertia (in swing) and the external ground reaction force (GRF) (in stance). Although distinct mechanical demands characterize each phase, it is conceptually useful to consider them together as a swing–stance transition, given the continuous nature of lower-limb motion and the hamstrings' dual role in hip extension and knee flexion throughout this interval [72,73,261–264,266].

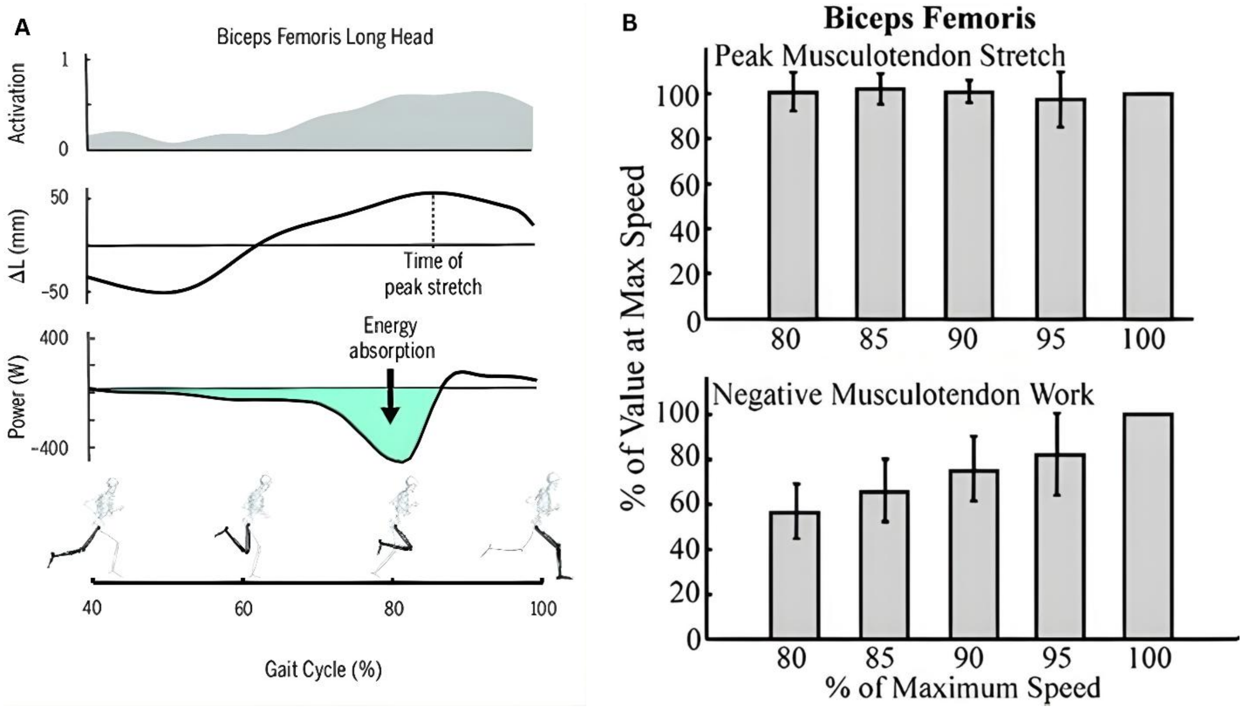


Figure 19. (A) During the late swing phase of running, the biceps femoris long head is active while undergoing stretch (ΔL, change in length relative to upright stance), resulting in substantial energy absorption as it decelerates the swing limb. This eccentric loading condition represents a critical phase associated with lengthening-contraction injuries [276]. (B) Peak musculotendon stretch (top) remains relatively constant across running speeds, whereas negative musculotendon work (bottom) increases markedly as sprint speed approaches maximal effort, reflecting greater eccentric demand on the hamstrings [277].

From a functional standpoint, the hamstrings act as primary contributors to horizontal force production, accelerating the center of mass forward during sprinting [278,279]. Modelling studies have demonstrated that the hamstrings, along with the triceps surae and gluteus medius, serve as essential accelerators throughout the sprint, particularly during the acceleration phase [279]. The hamstrings generate substantial hip extensor torques, contributing up to 15% of total propulsive impulse during sprint acceleration, with peak muscle forces reaching 3–4.2 times body weight (BW) during stance and up to 8× BW during swing [279]. During maximal velocity sprinting, forces can reach 10× BW at terminal swing [280].

The BFlh is consistently identified as the most vulnerable muscle due to its greater length changes and smaller knee flexion moment arm compared with the ST and SM [169] [274] [166,244,411] [170,273,411,412]. Peak strain and lengthening velocities occur during late swing, when BFlh acts eccentrically to decelerate the limb and stabilize the knee before foot strike [166,244]. Kinetic data also indicate that the hamstrings experience peak forces while transitioning from eccentric control during swing to concentric propulsion during stance, with muscle–tendon units lengthening by approximately 10% across all hamstring heads [267,274]. This rapid eccentric–concentric switch has long been hypothesized to predispose the tissue to acute strain injury [407] [408,409]. Intermuscular coordination also plays an important protective role. Despite their biarticular function, individual hamstring muscles demonstrate distinct neural innervation patterns and region-specific activity [152] [414] [415], suggesting variability in load-sharing strategies between and within muscles. The ST, for instance, shares a common proximal tendon with BFlh and has been proposed to act as a load buffer, potentially mitigating stress on the BFlh during high-speed running. Inefficient intermuscular coordination or asynchronous activation between these synergists could therefore amplify localized mechanical strain.

During late swing, rapid hip flexion and knee extension drive large angular accelerations of the shank, producing motion-driven torques that the hamstrings must resist eccentrically [267,274,276] (see figure 19). Following ground contact, vertical GRF rises abruptly, generating external hip flexor and knee extensor moments that must be counteracted by the hamstrings to stabilize the limb and propel the body forward [287,288]. Failure to resist these external moments may result in excessive hip flexion and knee extension, further increasing active strain within the muscle–tendon unit and predisposing it to structural failure [288,289]. The transition between late swing and early stance therefore represents a period of maximal mechanical demand, where high eccentric loads, rapid lengthening velocities, and abrupt shifts in contraction mode converge. The hamstrings are required to simultaneously control leg deceleration, stabilize the pelvis, and generate propulsive force, a complex interplay that renders the musculature particularly susceptible to overload.

Collectively, these findings highlight the multi-factorial biomechanical origin of HI during sprinting. Injuries most commonly occur during the swing–stance transition, when high eccentric demands combine with unfavorable trunk or pelvic postures and neuromuscular coordination errors. VA studies have further refined this understanding by differentiating between linear and curved runs, changes of direction (CoD), and running phases (acceleration, deceleration, high-speed running), suggesting that the precise mechanism may vary with the task's spatiotemporal demands. Further studies should focus on running kinematics and ball interaction (e.g., ball conduction, receiving a pass, etc.).

1.9.1.2 Stretch-type Situational Pattern

Although HIs in football are traditionally described as sprint-related and have received most of the research and preventive attention, VA evidence challenges this view, highlighting the importance of mechanisms occurring beyond high-speed running. The stretch-type situational pattern encompasses movements such as twisting, lunging, reaching, slide tackling, and kicking, all of which impose substantial eccentric demands on the hamstrings and contribute meaningfully to injury risk. While run-type HIs represent the majority, but not the overwhelming majority, in some cohorts (56–68%) [100,262,266], other studies report comparable or even higher proportions of stretch-type cases (52–54%) [73,261], suggesting that non-running injuries are both common and underrepresented. Taken together, current evidence suggests that non-running injuries are both common and underrepresented, with HIs appearing almost evenly distributed between run- and stretch-type mechanisms. This challenges the long-standing assumption that sprinting represents the dominant pattern.

Stretch-type injuries arise from heterogeneous, context-dependent movements, often involving ball interaction and opponent duels that complicates classification and may have led to previous underestimation. As shown in figure 20, duel-type injuries consistently occur during player–ball interactions, whether pressing, protecting, or intercepting, and often involve indirect contacts [265]. Accordingly, classification based on ball possession and player behavior provides a more ecologically valid framework [290]. Importantly, stretch-type HIs in football differ from those observed in dancers [155], as they typically occur during dynamic movement rather than static elongation. Because these mechanisms frequently overlap with running actions (e.g., lateral lunge after a 10-meter run), some authors have proposed intermediate or “mixed” categories to better capture their continuum [263,266].

While external load monitoring (e.g., Global Positioning System, GPS) offers useful context, player velocity or running intensity at the time of injury provides an incomplete indicator of mechanical load. In stretch-type injuries particularly, limb swing velocity may be high, for example during a rapid lunge to intercept the ball, even when overall running speed is moderate. Thus, GPS-derived metrics may underestimate true eccentric load exposure. Emerging technologies, such as instrumented shin guards incorporating GPS, gyroscopes, and accelerometers (e.g., Xseed, Soccerment srl © 2024), could enable quantification of instantaneous lower-limb kinematics and loading during match play, enhancing our understanding of real-time mechanical conditions at injury.

The situational pattern of injury also influences both location and tissue involvement [291]. Run-type HIs typically affect the BFlh near the MTJ, reflecting high force production demands. In contrast, stretch-type HIs more often involve the proximal SM free tendon [131,181]. The affected tissue type and lesion site may influence healing time and recurrence risk [155,171]. These mechanisms differ biomechanically and clinically: stretch-type injuries often present with milder acute pain, proximity to the ischial tuberosity, multiple muscle involvement, and prolonged healing compared with sprinting injuries [131,155,256].

Figure 20: Examples illustrating the variability of stretch-type hamstring injury mechanisms within the football-specific duel-type subcategory. Frames progress from left to right, showing (a) the push-off phase of the injured leg, (b) the transition movement, and (c) the suspected injury frame. Yellow arrows indicate the injured leg. Classification follows the method proposed by Pellegrini et al. [264]. Example 1 depicts a defensive press, with the player lunging toward an opponent in possession. Example 2 shows an offensive press, characterized by indirect contact during a lunge toward the opponent. Examples 3 and 4 illustrate protect actions involving indirect contact

while shielding the ball, performed in closed and open kinetic chains, respectively. Example 5 represents an intercept action (open kinetic chain), where ball possession is contested and the player performs a reaching movement toward the ball.

Given this variability, the term HI should be understood as an umbrella category encompassing diverse lesions characterized by specific combinations of muscle involvement, tissue type, biomechanical context, and situational demands, each with unique prognoses and recurrence profiles [157,158,165]. From an applied perspective, developing ecologically valid preventive strategies requires moving beyond isolated, linear sprint models to also include stretch-type and run-type injuries that do not occur while sprinting (acceleration and deceleration phases). Otherwise, prevention programs will prepare athletes for only a subset of HIs. Targeting technical proficiency in high-risk tasks such as lunging, tackling, and reaching, treating these as trainable motor skills, may help reduce tensile overload, mirroring the progress made in sprint mechanics training (see section 1.10.4). Coaches should emphasize joint control within mid-range positions, enabling athletes to absorb contact forces without excessive elongation and to maintain a margin of safety during dynamic duels. Addressing these aspects is essential for the next generation of VA-based preventive strategies in football.

1.9.2 Hamstring Injury Risk Factors

Understanding the risk factors for hamstring injuries (HIs) is a cornerstone for effective prevention and rehabilitation strategies in athletes [271]. Despite the substantial research effort devoted to this topic, the evidence remains inconsistent, and the relative contribution of each factor is still debated. Hamstring injuries are recognized as multifactorial in origin [292], with both intrinsic and extrinsic influences playing a role [293]. Extrinsic risk factors are external to the individual and include variables such as the type of sport, exposure level, training and match load, surface type, and playing environment [55]. Intrinsic risk factors, in contrast, are personal and can be further classified as modifiable or non-modifiable. Non-modifiable factors—such as previous injury, age, sex, and ethnicity—cannot be altered but are crucial for identifying at-risk populations. Modifiable intrinsic factors include physical fitness characteristics (e.g., strength, flexibility, and neuromuscular control) that can be improved through training and targeted interventions. Moreover, as discussed previously, the unique anatomical and functional features of the hamstring muscle group may themselves constitute an intrinsic risk factor for injury.

Several systematic reviews and meta-analyses have synthesized the evidence on hamstring injury risk factors [196,294,295]. The most comprehensive meta-analysis identified increased age, previous hamstring injury, and greater quadriceps strength as significant risk factors [294], while other reviews have reported up to 21 potential risk factors associated with injury occurrence [296]. However, the coexistence of conflicting results across studies underscores the complexity and multifactorial nature of hamstring injuries [8,297]. The frequent tendency to examine variables in isolation may further obscure interactions among biomechanical, physiological, and contextual determinants, limiting our ability to understand and manage this multifaceted problem effectively.

The continuing rise in hamstring injury incidence likely reflects multiple interrelated factors, including the absence of consensus on RTP criteria following hamstring muscle injury [298], high variability in recovery times [123,298], increasing physical demands during matches [247], and the negative effects of match congestion on player health and recovery [299]. Ultimately, the risk profile of each athlete must be interpreted within the context of individual sporting demands, injury history, and dynamic workload patterns, while also considering psychological and well-being factors and the inherent limitations of existing risk-factor evidence.

1.9.3 Non-modifiable Intrinsic Factors

A wide range of non-modifiable and potentially modifiable intrinsic risk factors have been examined and discussed in the literature (see figure 21).

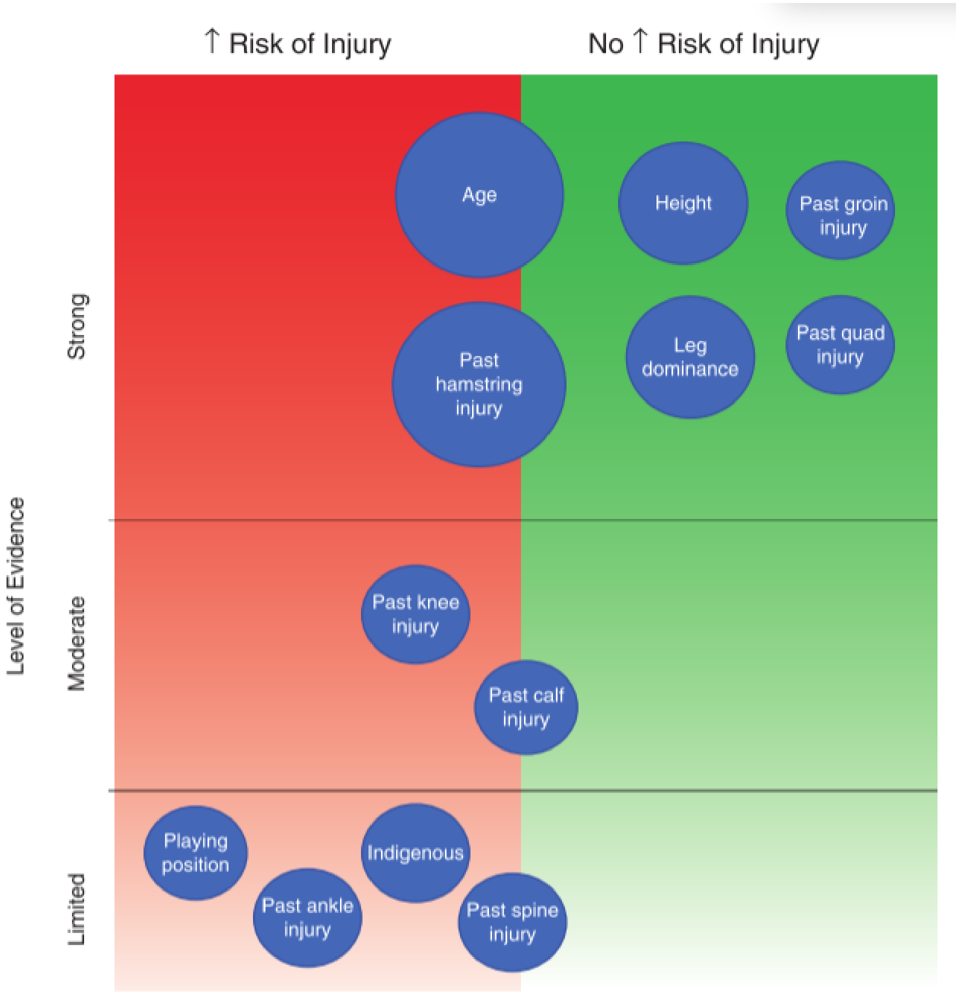


Figure 21: Intrinsic, non-modifiable risk factors for hamstring injury, levels of evidence, and relationship to injury risk. The size of each circle in the figure reflects the volume of research for each factor, while overlap across the midline indicates conflicting evidence [177].

Age is a commonly reported risk factor for hamstring strain [294,296], though the underlying mechanisms remain unclear. Older athletes typically have greater cumulative exposure to sport, increasing the likelihood of previous HI. Additionally, age-related declines in strength [300,301], power [300,302], and running capacity [303] may limit the ability to meet sport-specific demands, thereby increasing injury risk.

Previous HI is consistently recognized as the strongest predictor of future injury [294]. Athletes with a prior hamstring strain face an approximately threefold increased risk, which rises to fivefold if the previous injury occurred in the same season [296]; some studies report up to 11.6-fold risk of recurrence in football [85]. The period of greatest vulnerability is often within the first four weeks after return to sport [304]. Proposed mechanisms for recurrence include muscle scarring, suboptimal muscle length, and neuromuscular inhibition, a reduction in force output in the hamstrings and synergistic muscles due to decreased neural stimulation [177,305–307] (see figure 22). Numerous studies [305,308–310] have demonstrated altered activation patterns in the hamstrings and synergistic muscles controlling pelvic girdle position following HI. While neuromuscular inhibition initially protects the injured muscle, prolonged inhibition may impair rehabilitation outcomes and muscle function post-RTP [177]. Techniques such as surface electromyography, transcranial magnetic stimulation (TMS), and twitch interpolation have been used to detect altered neuromuscular activation patterns following HI [278] [279] [280]. The precise duration of heightened risk following injury remains unknown and is likely to be individual-specific.

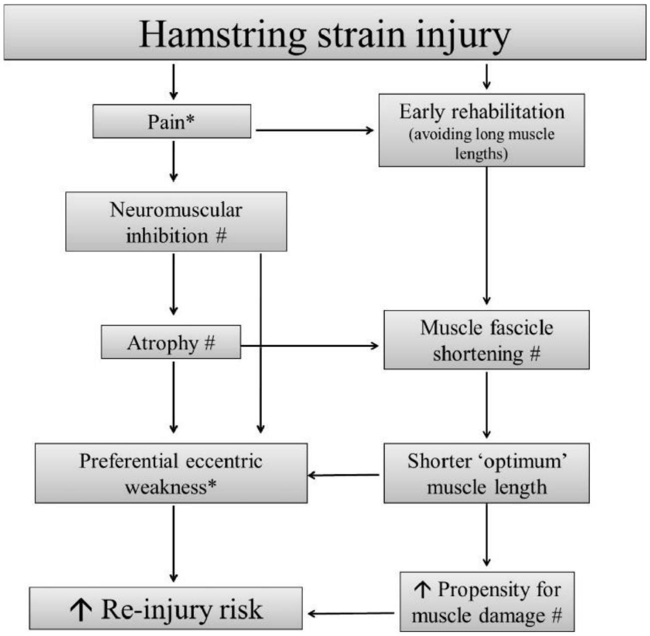


Figure 22: Conceptual framework for the putative role of neuromuscular inhibition following hamstring strain injury in the development of several maladaptations associated with increased re-injury risk. ∗ = Particularly at long muscle lengths, # = biceps femoris (BF) specific [307].

Prior joint injuries also influence hamstring injury risk. Moderate evidence suggests that previous knee injury increases risk [311,312], and limited evidence supports a role for ankle injury [313]. Conflicting evidence exists for the relationship between HI and previous ACL injury or previous calf strain and no evidence for a relationship with previous groin injury, quadriceps injury, or adductor strain [163,292,314–316].Hamstring injury may also arise iatrogenically, such as following hamstring autografts for ACL reconstruction.

Sex and ethnicity contribute to risk, though evidence is limited [196]. Male athletes are approximately 64% more likely to sustain an acute HI than females [317], though recent studies indicate rising HIs in women’s football, likely reflecting increased playing intensity [318]. Indigenous Australian [312] and Black African or Caribbean [170,319] athletes have been suggested to be at higher risk, potentially due to differences in muscle fiber composition and anterior pelvic tilt [170,312]. Although several epidemiological studies have been conducted in women’s football [244,245,320–322], there is currently limited data on female-specific HI mechanisms, and caution is needed when extrapolating findings from men’s football [323,324]. Consequently, injury prevention programs may be less effective for female athletes, particularly if developed from male-focused datasets [325].

Prognostic indicators at the time of injury may also reflect intrinsic risk. Athletes who hear a popping sound or must stop playing within 5 minutes of injury tend to experience longer recovery times [114,326], and the severity of pain at injury onset correlates with prolonged rehabilitation [327]. In summary, among non-modifiable intrinsic factors, older age and previous hamstring injury are the most consistent and strongest risk factors for HI [296], while sex, ethnicity, and prior joint injuries may contribute variably depending on individual and contextual circumstances.

1.9.3 Modifiable Intrinsic Factors

Within modifiable intrinsic risk factors, poor muscle strength has long been considered important for muscle injury [294]. Intuitively, if an activity requires loading beyond the capacity of the MTU, it could result in structural damage. Research on strength as a risk factor for HI is extensive, encompassing multiple lower-limb muscles, contraction modes, speeds, athlete populations, and joint positions [294,328] (see figure 23).

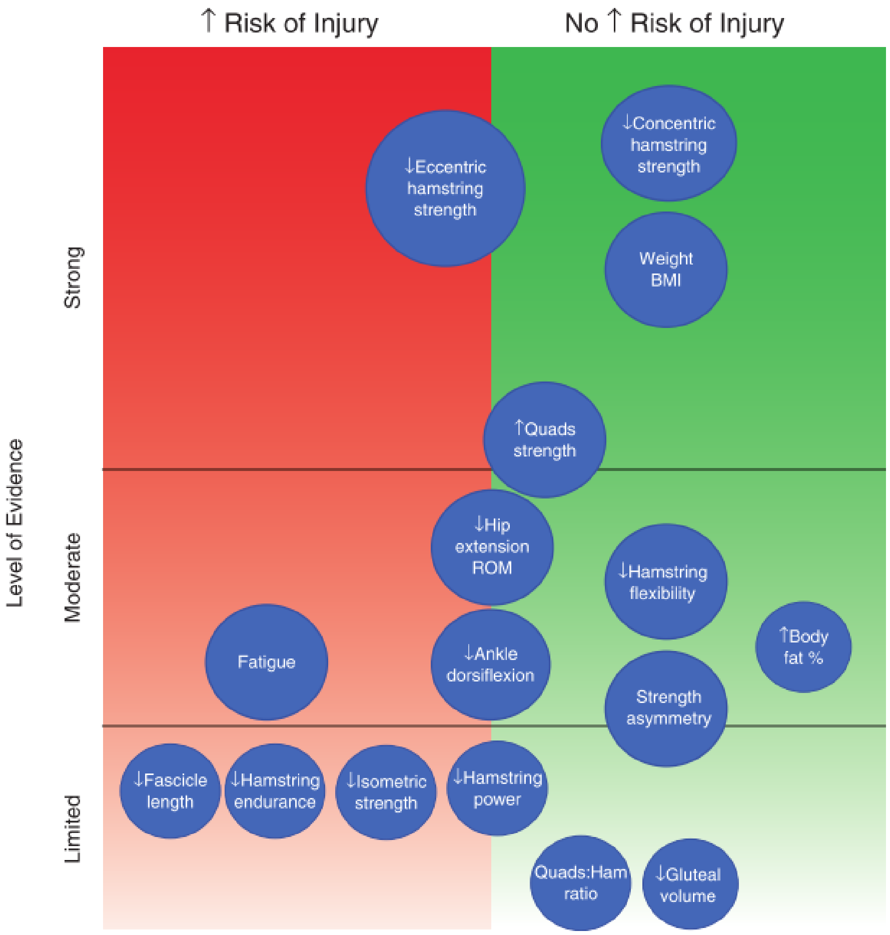


Figure 23: Intrinsic, modifiable risk factors for hamstring injury, levels of evidence, and relationship to injury risk. The size of each circle reflects the volume of research for each factor, while overlap across the midline indicates conflicting evidence [177].

Recently, attention has focused on eccentric hamstring strength, given persistent deficits post-injury [309,329–331] and the common mechanisms of injury [131,332]. Evidence indicates that targeted eccentric strengthening can reduce HI incidence [333]. The Nordic Hamstring exercise (NHE) program has been widely promoted for prevention [334–338]. Although using NHE to measure eccentric hamstring strength has also gained popularity, some studies in football [339] and rugby union [314] found no relationship between peak NH force and future injury risk. Nonetheless, increases in match intensity over recent years may counteract preventive benefits. For example, Barnes et al. [247] reported a 30% increase in high-intensity running distance and a 35% increase in sprinting in the English Premier League from 2006/2007 to 2012/2013. Despite some inconsistencies between studies, the overall evidence suggests eccentric hamstring strength remains an important consideration for injury risk screening [328,340,341]. In contrast, concentric and isometric strength measures generally show limited association with hamstring injury [328]. Importantly, regular strength monitoring is recommended for injury prevention [342], as reductions in isometric strength may precede injury [343]. Regardless of the mode of contraction, strength fluctuations occur within a match cycle [344,345] and across a season [346], so serial monitoring can identify abnormal deviations, signaling failed recovery and allowing early interventions [342,347].

Between-limb strength asymmetries have traditionally been considered potential risk factors, under the assumption that the weaker side may be more susceptible to injury or re-injury [348,349]. While some asymmetry may be normal, substantial differences may indicate reduced proficiency in coping with sport demands [350]. A study of 462 professional soccer players found low hamstring strength relative to quadriceps strength associated with injury [351]. Over the past 15 years, hamstring-to-quadriceps (H:Q) ratios and bilateral asymmetries have been extensively studied. Overall, when all data and evidence are combined, these ratios show no consistent association with injury risk [328]. Muscle imbalance may pose risk only when bilateral deficits exceed 10% or H:Q ratios fall below 0.6 [351,352], but current evidence is weak [296,339,353].

Flexibility, mobility, and range of motion (ROM) have also been evaluated as potential risk factors. Movements such as sprinting and kicking involve large stresses at reasonably long MTU lengths [131,350], suggesting a minimum ROM requirement for safe performance. However, most traditional tests do not predict hamstring injury risk, including: (1) active or passive knee extension [85,240,354–358], (2) straight leg raise (active, passive) [355,357,359,360], (3) slump [355,358], and (4) lumbar flexion (standing, seated) [240,355,357,358,361,362]. Isolated findings do show some tests are associated with risk of injury to the hamstrings, although the association, albeit significant, is best described as weak [363,364]. Hip extension ROM in the modified Thomas test shows mixed evidence as a risk factor [240,355,358]. Reduced hip extension may increase the risk profile due to alterations in the mechanical loading conditions of the hamstrings during running, which are influenced by the lengthening and activation characteristics of the iliopsoas [350]. Other hip ROM measures (flexion, internal/external rotation) generally lack predictive value [240,355,358]. Reduced ankle dorsiflexion ROM may also indicate risk of future hamstring injury, although research findings are conflicting [311,355,358,363]. Adequate ankle dorsiflexion mobility is necessary in football and decreased ankle mobility changes the touchdown position of the foot, reducing the horizontal force production [365]. As hamstring muscle activity is highly correlated with increased horizontal force production [278], limited ankle dorsiflexion mobility might lead to increased work required from the hamstring muscle, predisposing it to injury [366]. Overall, ROM assessment is best suited for periodic health evaluations and rehabilitation staging [115,254,342,344,345].

Muscular fatigue, defined as a decline in muscle performance associated with muscle activity [367], is a well-recognized risk factor. The absorption of energy before structural failure is reduced in fatigued muscles [268]. Reduced hamstring strength-endurance may predispose athletes to injury [345], particularly during match play and high workloads [368]. Neuromuscular fatigue [369] induces altered biomechanics [370,371] reduced eccentric strength, rate of force development (RFD), and decreased activation of hamstrings in players subjected to soccer-specific exercise protocols designed to simulate match-day fatigue levels [372–374]. Eccentric and isometric hamstring deficits are greater than concentric deficits [371,374–377], and hamstring strength declines more than quadriceps post-match [378]. Fatigue also alters running kinematics: reduced hip flexion and knee extension ROM, increased anterior pelvic tilt, and decreased hamstring excursion [310,370]. Single and repeated sprint performances are also impaired during and after match play [379], and players experience reduced range of hip and knee motion [370], reduced BF activation [380], reduced passing and shooting accuracy [381,382], and inferior jump performances after games [371]. All these changes may overload the hamstrings, particularly late in games or during congested schedules or high workloads, where the muscle does not have a chance to return to its pre-fatigued functional state [342].

Recent evidence suggests that peripheral fatigue contributes more substantially than central mechanisms to post-match fatigue, likely as a consequence of match-induced muscle damage [369]. Central fatigue, defined as a reduced capacity of the central nervous system to activate skeletal muscle [383], also plays a role, particularly in the immediate aftermath of competition. In football, mental fatigue has been shown to impair players' decision-making abilities during match situations and to reduce physical and technical performance following cognitively demanding tasks [384] [385]. Central fatigue tends to be most pronounced immediately after matches, with marked recovery within 24 hours and complete restoration typically observed by 48 hours post-match. In contrast, peripheral fatigue affecting the hamstring muscles can persist for several days. Deficits in hamstring function are often evident acutely post-match and may remain unresolved up to 72 hours after competition [368,369,386–388]. Considering that approximately one-third of matches in elite football are scheduled within a 72-hour interval [248], it is plausible that players often enter subsequent matches without full physiological or psychological recovery, thereby increasing their vulnerability to hamstring injury. Finally, load management encompasses both physiological and psychological stressors [389]. Players with residual fatigue or impaired decision-making are exposed to higher-risk situations, further increasing the likelihood of hamstring injury.

1.9.4 Modifiable Sprinting Kinematics Risk Factors

Beyond neuromuscular and strength-related parameters, movement technique itself represents a modifiable intrinsic factor influencing hamstring injury risk. As strain is the primary mechanism of muscle injury, the kinematic and kinetic characteristics of sprinting directly determine the magnitude of stretching and loading on the hamstrings. Current evidence indicates that no single biomechanical variable alone explains hamstring strain; rather, it is the interaction between multiple kinematic and kinetic features that contributes to injury risk. Coaches and practitioners commonly identify several technical parameters as important for HI prevention [390], including an overstride running pattern, anterior pelvic tilt, poor lumbo-pelvic control, lumbar extension, back-kicking of the trailing leg, and forward trunk lean. These factors alter force transmission between the trunk, pelvis, and lower limbs, influencing hamstring loading and strain. A widely accepted technical model of sprinting, known as front-side mechanics, describes how movements occurring anterior to the body's center of mass are associated with better sprint performance and potentially lower injury risk [391]. Specifically, front-side mechanics seek to maximize leg motions occurring in front of the vertical torso line while minimizing actions occurring behind that line throughout the sprint cycle (see figure 24). This model emphasizes maintaining an upright trunk and neutral pelvic position, achieving higher knee lift, and striking the ground beneath the body. These features reduce the touchdown distance (TDd), the horizontal distance between the center of mass and the foot at ground contact, resulting in lower braking forces and higher vertical components of GRF [392,393]. The outcome is greater stiffness, shorter stance duration, which have been associated with higher maximal sprinting speeds [392].

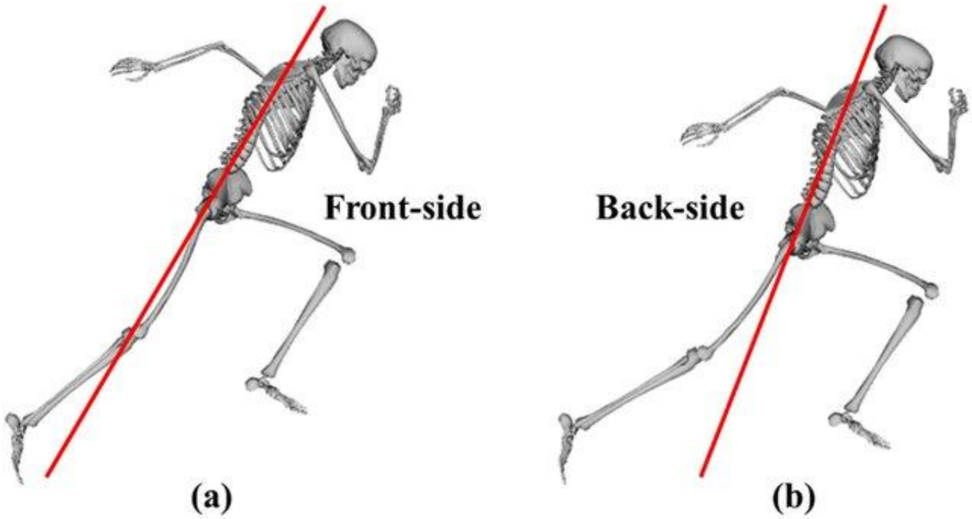


Figure 24: Front-side (a) and back-side (b) mechanics schematic during the second step stance phase of a maximal effort sprint. The red line indicates whether the thigh

segment is positioned in front of or behind the torso, representing front- or back-side mechanics, respectively. Images generated using OpenSim 3.3 software [394].

In contrast, back-side mechanics involve excessive trailing leg extension at toe off, “back-kicking” actions during swing, and large thigh separation angles (inter-thigh angle) [391,395] (Figure 25). These movements occur behind the center of mass and are thought to increase hamstring strain by promoting anterior pelvic tilt and lengthening of the BFlh. Although few studies have directly linked back-side mechanics to HI [395,396], the concept remains biomechanically plausible, supported by modeling studies showing a mechanical coupling between the hip flexors and contralateral hamstrings during sprinting. When the trailing leg’s hip flexors (particularly the iliopsoas) contract and lengthen to accelerate the swing phase, they induce an anterior rotation of the pelvis, which simultaneously increases anterior pelvic tilt and the stretch of the contralateral BFlh [276,397,398]. This illustrates how back-side mechanics, through excessive hip extension and contralateral hip flexor activity, can amplify pelvic rotation and hamstring strain on the opposite limb.

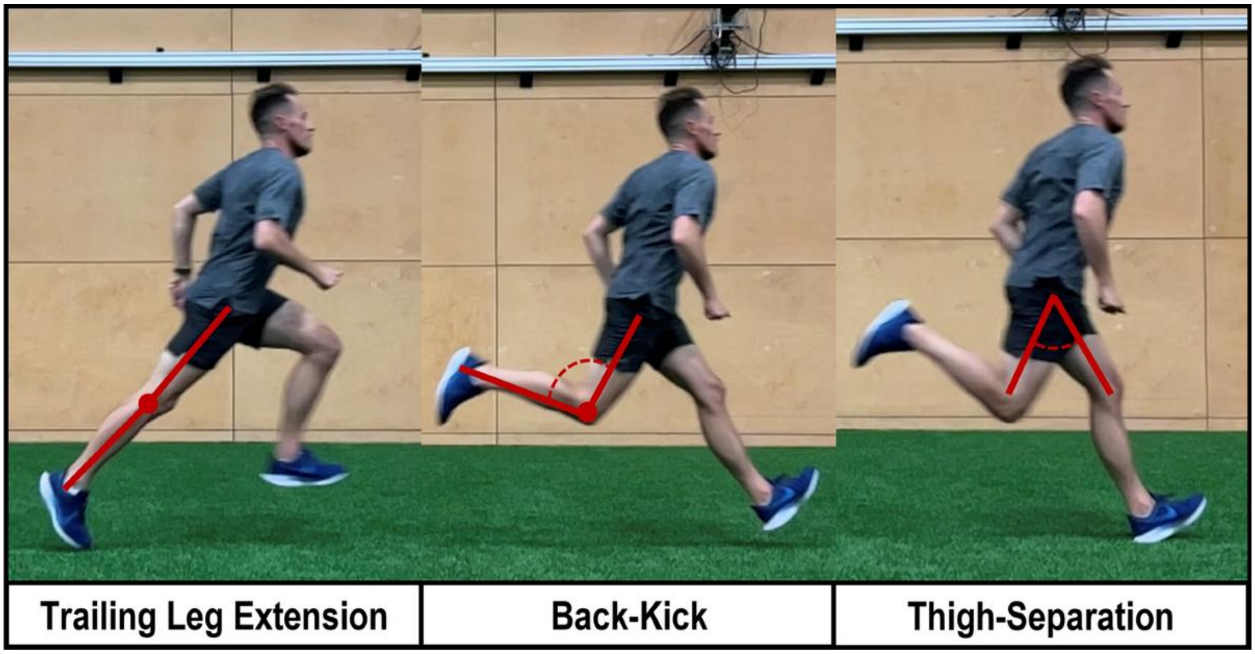


Figure 25: Pictorial representation of key features of back-side running mechanics [399].

Excessive trailing leg extension (triple extension) at toe off is a common mechanical feature during acceleration but may be detrimental during maximal-velocity sprinting [390,391]. Because peak GRF occur during the first half of the stance phase [393], continuing to extend the leg and push against the ground beyond this point, often referred to as triple extension, is considered an inefficient force production strategy [391]. Once the peak GRF has already passed, this late push-off no longer contributes meaningfully to propulsion and instead prolongs stance duration while shortening flight time [391]. The reduced flight time limits the opportunity to reposition the limb for the next stride, thereby increasing the demand for rapid leg recovery and swing. As a result, athletes may adopt over-striding mechanics, a more forward-leaning trunk posture, and exaggerated back-side leg movements, all of which can heighten mechanical stress on the hamstrings. Although direct evidence linking trailing leg extension to injury is limited, modeling work suggests that excessive knee extension at late stance may create an additional peak of hamstring strain [400]. Therefore, minimizing trailing leg extension is recommended for both performance and injury risk reduction.

Over-striding refers to a running pattern in which the foot strikes the ground in front of the body's center of mass. Kinematically, this manifests as increased hip flexion at initial contact, a more extended knee, greater tibial and foot inclination angles, and reduced thigh and leg retraction during the late swing phase [401,402]. These characteristics alter the runner's interaction with the ground, affecting both performance and injury risk. From a mechanical standpoint, over-striding shifts the point of foot contact forward relative to the center of mass, which increases braking forces and the braking impulse generated during early stance [401,403]. Since the hamstrings play a major role in reaccelerating the center of mass horizontally [278,279], greater braking requires proportionally higher hamstring activation to restore forward momentum. Together, these factors expose the hamstrings to greater tensile loads in an elongated position, increasing both the magnitude and rate of strain applied to the muscle-tendon unit [404]. When repeated across multiple sprinting efforts, this increased workload can accelerate neuromuscular fatigue, diminishing the muscle's ability to resist strain and increasing susceptibility to fatigue-induced microdamage or tissue failure [405]. Therefore, whilst the contribution of over-stride mechanics to hamstring tissue strain is plausible, there is a lack of data investigating the association between the two [310,406].

The maximum hip flexion (MHF) angle represents the thigh's peak elevation during late swing and is a marker of effective sprint mechanics [391,407]. Greater MHF allows more powerful leg retraction and greater GRF during stance [393,402]. However, while higher MHF enhances performance, it may also increase hamstring strain due to greater muscle length and force during terminal swing. Findings across studies are mixed: some report lower MHF in previously injured limbs [406,408], others higher [310]. This may reflect post-injury adaptations, where athletes subconsciously limit MHF to reduce strain, compensating for deficits in eccentric strength [406]. Consequently, MHF likely represents a performance–injury paradox, balancing improved speed with increased tissue load.

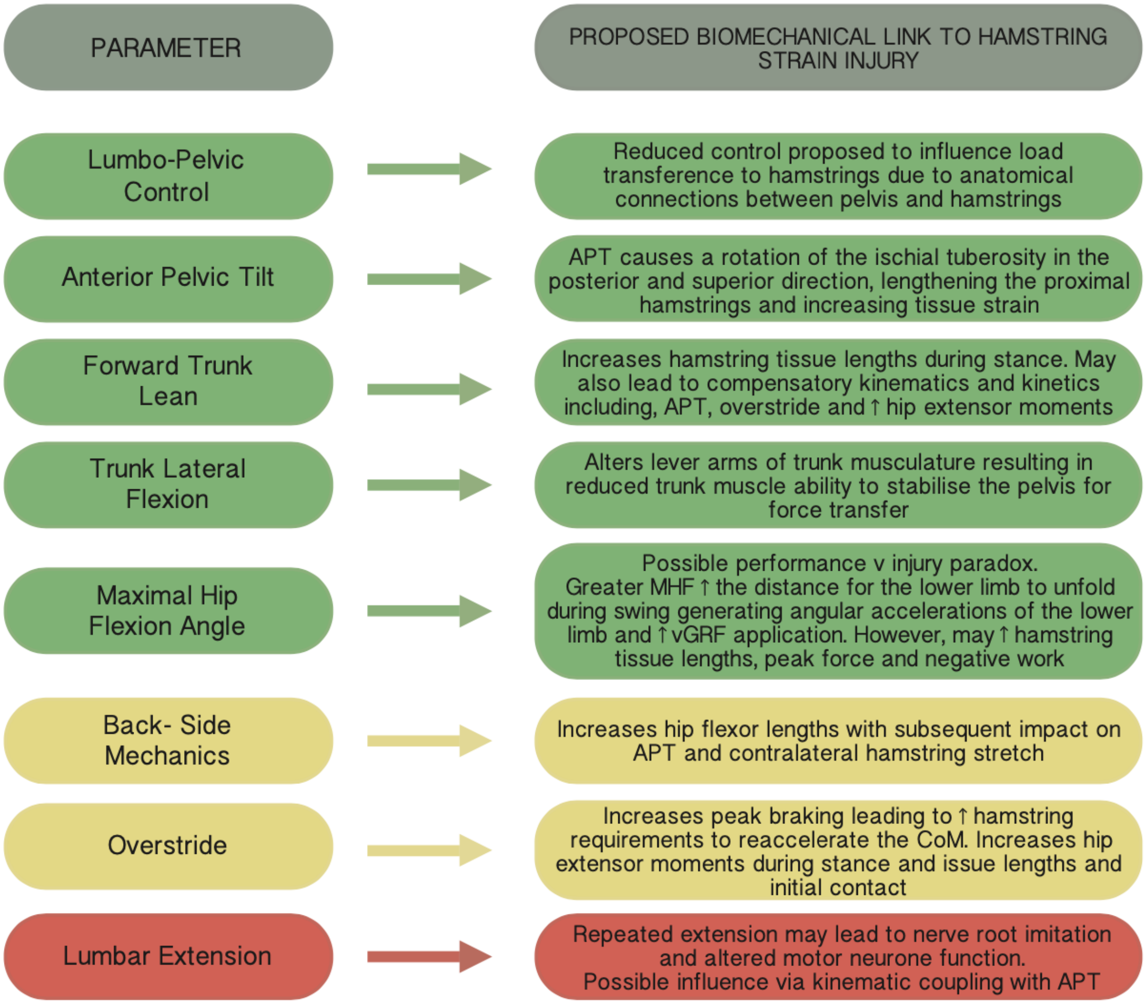


Figure 26: Current evidence linking kinematic variables with hamstring injury. Green boxes: experimental and modeling evidence; yellow: modeling only; red: theoretical association. ↑ increased, ↓ decreased, APT: anterior pelvic tilt, CoM: center of mass, vGRF: vertical ground reaction force [399].

Lumbo-pelvic control refers to the ability to stabilize and coordinate movements of the lumbar spine and pelvis during dynamic activities [409] (Figure 26). Given the hamstrings' proximal insertion on the ischial tuberosity, this control plays a central role in modulating strain [297,317,348,390]. The pelvis acts as a functional lever between the trunk and lower limbs; thus, any imbalance or delayed activation of muscles spanning these regions can alter intersegmental coordination and increase hamstring loading. Modeling studies have shown that the contralateral iliopsoas can increase BFlh stretch by more than 25 mm by accelerating the pelvis into anterior rotation, while the gluteus maximus, adductor magnus, and obliques counteract these forces [276]. Experimental evidence supports this link: athletes who later sustained a HI showed altered trunk and pelvic muscle activity, including reduced activation of the gluteus maximus and obliques and delayed onset of gluteus maximus and erector spinae activity [241,354,410–412]. These findings suggest that improving lumbo-pelvic control, also with perturbation training, should be a key focus in injury prevention and rehabilitation programs.

Anterior pelvic tilt is one of the most consistently reported kinematic features linked to HI [370,413,414]. From a functional anatomy standpoint, anterior pelvic tilt causes a rotation of the ischial tuberosity posteriorly and superiorly, resulting in a disproportionate active lengthening and passive tension demand, especially for the proximal region of the posterior thigh musculature [160,397]. This mechanical relationship is supported by modeling and elastography studies showing that anterior pelvic tilt increases hamstring tension by 13–32%, depending on the specific muscle [415]. Prospective research shows mixed results: some studies found greater anterior pelvic tilt in players who later sustained injuries [310,410], while others reported no association [411]. However, recent intervention studies on football players demonstrate that reducing anterior pelvic tilt by ~5° during late swing phase of sprinting through targeted technique training can lower hamstring strain and potentially injury risk [416]. Thus, anterior pelvic tilt remains a modifiable mechanical factor that can be addressed through movement retraining focused on pelvic control.

Deficits in trunk control, particularly in lateral flexion and rotation, are frequently associated with poor lumbo-pelvic stability [390]. Excessive side flexion or rotation alters trunk muscle length–tension relationships, impairs pelvic stabilization, and disrupts sacroiliac joint force transfer [417], increasing hamstring tension [348,409]. Trunk muscle activity contributes to sacroiliac joint stiffness [418], which directly affects hamstring torque and load distribution [419,420]. Prospective studies have shown that athletes who later sustained a HI exhibited greater trunk side flexion toward the injured limb during late swing [410,411]. Reduced oblique activation during the same phase [354] further supports this association. The obliques' anatomical attachments allow them to resist trunk motion while compressing and stabilizing the pelvis, thereby reducing anterior pelvic tilt [192,409]. Consequently, diminished oblique function may reduce pelvic stability and increase proximal hamstring strain [276,419].

Forward trunk lean during sprinting can markedly affect hamstring loading by altering both kinematics and kinetics (Figure 27). Increasing trunk flexion shifts the center of mass anteriorly and is accompanied by greater anterior pelvic tilt and hip flexion, which together lengthen the hamstrings and elevate tissue strain [404]. This anterior shift also increases the external hip flexor moment, requiring greater activation of the hip extensors to maintain propulsion [421]. Over repeated sprints, this heightened mechanical demand may promote fatigue, microtrauma, and ultimately, injury development. Additionally, the forward displacement of the center of mass may induce a compensatory over-stride, further amplifying hamstring strain [422]. Although coaches and clinicians often link excessive trunk lean to hamstring injury risk, empirical evidence remains limited. Schache et al. [423] reported increased trunk flexion and corresponding rises in GRF, hip extensor moments, and hip power in a case of acute HI, while Kerin et al. [424] observed similar trunk positions in all sprint-related injuries analyzed via 2D video. Collectively, these findings suggest that excessive forward trunk lean may exacerbate hamstring strain, but more robust prospective studies are needed to clarify its causal role in injury mechanisms.

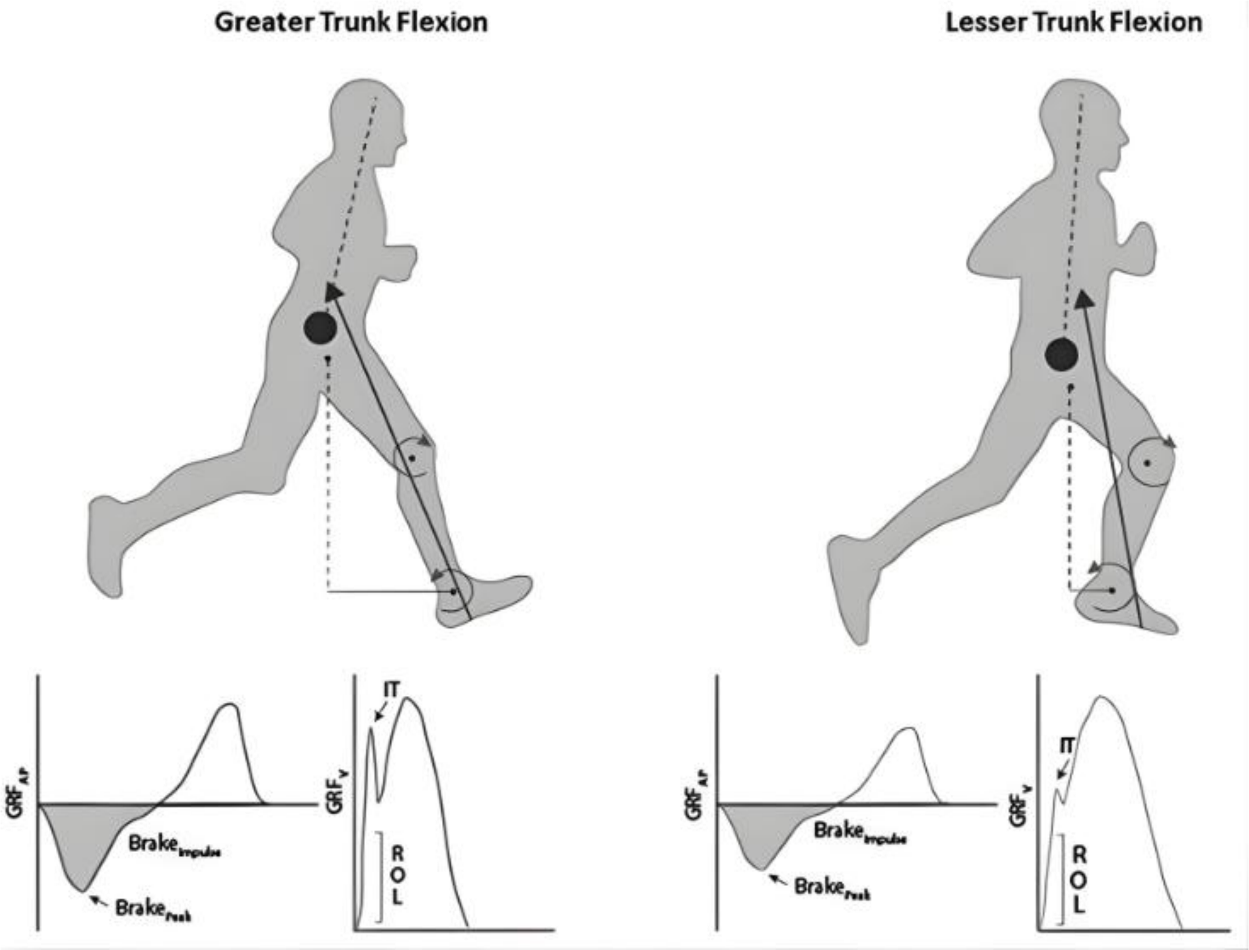


Figure 27: Biomechanical model illustrating the relationship between trunk flexion and lower-limb kinetics. Greater trunk flexion increases over-stride and stride length while decreasing stride frequency, elevating hip extension moments and braking force, rate of loading (RoL) and impact transient peaks (IT). Reducing trunk flexion has the opposite effects on these parameters [421].

Despite the recognized role of sprinting in both performance and injury prevention, few intervention studies using high-speed sprinting as a direct training method to reduce HI risk [425]. This is noteworthy given that suboptimal sprinting kinematics [410,426], lack of exposure to maximal velocity [427], and lower sprint performance [428] have all been associated with increased risk of lower-limb and HI in team sports. Importantly, hamstring activation during sprinting exceeds that observed in most traditional strengthening exercises [429,430], supporting sprint training as a time-efficient, sport-specific strategy to enhance both performance and injury resilience [431].

1.9.4 Extrinsic Risk Factors

Environmental and contextual conditions have been examined as potential contributors to HI risk [432,433]. To date, however, there is no consistent evidence that match-day temperature, wind speed, playing altitude, surface type, match time, or pre-match time zone change significantly influence future HI risk [432–434]. Shoe–surface interaction has been associated with an increased risk of overall lower-limb injury, particularly through excessive rotational traction, although its specific effect on hamstring injury remains unclear [435]. Interestingly, barefoot-style football boots have recently gained popularity, though their implications for injury risk are yet to be thoroughly evaluated.

Importantly, injury risk is not uniform across the pitch: positional demands correspond to different exposures and injury patterns. Multiple studies have demonstrated that injury frequency, type, burden, and mechanism differ markedly across positions [436–438]. As expected, goalkeepers exhibit a lower risk of hamstring injury[98] [363], likely due to their reduced exposure to match-related kicking volumes and velocities [440], as well as lower overall running and high-speed running demands [441,442]. Nonetheless, isolated cases of punt-kick–related hamstring injuries have been reported [265]. Beyond positional factors, playing level, geographical, and contextual influences also appear relevant. For instance, northern European teams show higher overall and training-related injury incidence compared to southern European teams, suggesting that climate, training culture, and environmental conditions may modulate injury risk [443].

Football has evolved substantially over recent decades, with greater match frequency and increased physical demand. Objective data indicate that players now cover longer distances and perform more frequent high-speed efforts than in the past [247]. Hamstring injury rates tend to increase during congested fixture periods [248], particularly when two matches are separated by four or fewer days compared with six or more [299,444]. Muscle injury rates are especially sensitive to short recovery intervals [248].

Consequently, quantifying acute and chronic load exposure has become essential in athlete monitoring and in assessing the dynamic evolution of injury risk throughout the season. Advances in sports performance science have enhanced understanding of how acute workload, chronic training history, and match characteristics interact with injury susceptibility [445–449]. The acute:chronic workload ratio (ACWR), along with 1- to 4-week load histories, is often evaluated to determine how fluctuations in training load affect risk. A sudden, unaccustomed increase in high-speed running volume is thought to heighten injury risk, particularly in muscles critical for sprinting such as the hamstrings [445–449].

Empirical evidence supports this view. Duhig et al. [450] found the strongest association between injury and the total high-speed running distance in the week preceding injury, while Ruddy et al. [445] reported that both absolute high-speed running (>24 km/h) and week-to-week changes in total high-speed running distance were most predictive of injury. Similarly, Aiello et al. [264] observed that most hamstring injuries occurred when players exceeded 25 $km \cdot h^{-1}$ or at >80% of maximal sprint speed. Another study found that hamstring injuries during matches were often preceded by five minutes of unusually intense running (>21 km/h) compared with control matches [375]. Collectively, these findings suggest that brief periods of atypically high running intensity can markedly increase hamstring injury risk. Additional extrinsic factors include inadequate warm-up routines and preseason conditioning [352].

Recent evidence indicates that a substantial portion of HI risk is extrinsic, arising from club-level and organizational factors rather than the player alone [376,377](see figure 28). For example, team communication quality has been correlated with injury rates, training attendance, and match availability [88]. Other influential external factors include the stability of coaching, medical, and managerial staff [66]. Teams characterized by frequent staff turnover or inconsistent management structures may inadvertently expose players to varying training methodologies, recovery strategies, and performance expectations, conditions that collectively increase the likelihood of hamstring injury.

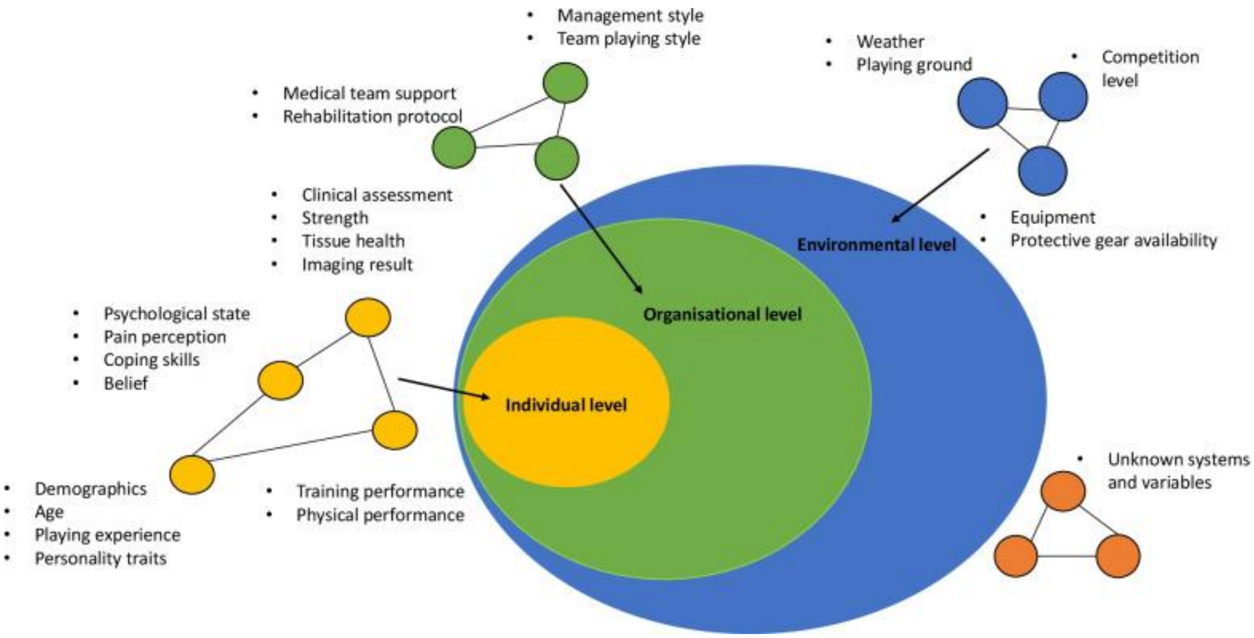


Figure 28: An example of multilevel system map with factors related to return to sport decision in anterior cruciate ligament injury [454].

1.9.5 Football-Specific Injury Profile

Performance in football relies on a combination of individual, technical, and tactical skills, as well as the dynamic interaction between players within a team. It is a high-intensity, intermittent sport requiring players to repeatedly perform physically demanding actions such as unipedal-dominant movements, sprints, accelerations, decelerations, ball-specific skills, jumping, and player-to-player duels—all while simultaneously engaging in complex cognitive processes such as tactical decision-making [378]. On average, professional players perform approximately 600 cutting movements of 0°–90° per match [456] and more than 70 directional changes ≥45° at speeds exceeding 4 m/s [457]. Importantly, changes of direction (≥50°) followed by sprints often precede decisive moments such as goal-scoring or assists [458]. At the elite level, where players operate under extreme time and space constraints, speed and mechanical efficiency are critical determinants of performance. Given these requirements, it is unsurprising that professional football is characterized by a high incidence of injury, with muscle injuries representing the most common injury type [96].

Football is unique among major sports in that it is played almost exclusively with the lower limbs, with the upper limbs contributing only to specific circumstances such as goalkeeper interventions and throw-ins. By contrast, all other sports (e.g., basketball, volleyball, tennis, handball, golf, etc.) rely on the upper limbs for ballistic, coordinated actions, while the lower limbs primarily provide locomotion and stability. In football, however, the lower limbs have to simultaneously generate locomotor output and perform precise technical actions; this dual role places them under exceptional high-risk situations. Football is also unique because it replaces the natural human pattern of oculo-manual coordination (eye–hand) with oculo-podalic coordination (eye–foot), requiring players to control and manipulate the ball using the lower limbs while maintaining visual tracking and spatial awareness. From an anthropological perspective, in fact, football poses an *"anti-evolutionary challenge"* and the design of the human body illustrates these contrasts. Around six million years ago, humans began to walk upright, shifting weight-bearing responsibilities to the lower limbs and freeing the forelimbs for manipulation. Although arms and legs share a common structural blueprint, with a ball-and-socket joint connecting to the axial skeleton and a hinge joint in the middle, their functions diverged markedly. The leg is optimized for stability and propulsion, while the arm evolved for mobility and precision. For instance, the bones of the forearm rotate to permit wrist mobility, whereas the bones of the lower leg are constrained for stability; the ankle is specialized for shock absorption and push-off, while the shoulder evolved for high-mobility tasks such as throwing. Football challenges these evolutionary adaptations by requiring the lower limbs to fulfill both roles, propulsion/stability and skill execution/motor control, placing unique demand on the musculoskeletal system.

Beyond these evolutionary and biomechanical constraints, the postural and positional demands of the game introduce further complexity. Evidence suggests that hamstring morphology and function may adapt to sport-specific loading patterns, with measurable differences between athletes of different disciplines—for example, sprinters versus rugby players—reflecting distinct muscular use profiles [459,460]. Within football, certain positions, such as defenders engaged in repeated one-versus-one duels or pressing actions, spend extended periods in a semi-squat posture. This stance facilitates rapid reactivity but maintains the pelvis and hamstrings under sustained tension at sub-optimal lengths, potentially shifting muscle activation toward the quadriceps and altering the H:Q strength ratio. Biomechanically, this posture embodies a trade-off between readiness for explosive action and chronic disadvantage for the posterior chain. These examples challenge the conventional pursuit of an "ideal" anatomical alignment. In reality, no athlete conforms perfectly to textbooks of Anatomy. Each body represents the cumulative result of personal motor history, injury background, and lifestyle, continuously shaped by the repetitive mechanical demands of sport and training. From a postural and performance standpoint, every player constitutes a unique adaptive system that requires individualized assessment and training strategies. Conditioning and rehabilitation should therefore aim to respect each athlete's functional asymmetries and compensatory patterns rather than enforcing standardized corrective models at the group level.

Finally, football is remarkably “democratic” in its anthropometric diversity. Unlike sports such as basketball or volleyball, where height and limb proportions impose more rigid selection pressures, football accommodates a wide variety of body types and movement strategies. Anthropometric, biomechanical, and neuromuscular profiles vary greatly among players, leading to substantial differences in optimal training methods, recovery capacity, and injury susceptibility. This diversity enriches the game’s tactical and technical dimensions but also complicates injury prevention, as load distribution, fatigue tolerance, and tissue resilience differ across individuals. Understanding and integrating this variability is fundamental for developing personalized conditioning, load management, and rehabilitation programs that minimize injury risk while maximizing performance potential.

1.10 Video Analysis: A Window into Sports Injuries

Understanding how injuries occur in sport requires multiple complementary approaches, each offering a different perspective on the injury process. A comprehensive understanding must integrate both the sequence of events leading to the injury and a biomechanical description of the whole body and joint at and before the moment of injury.[24]. This knowledge is critical for identifying targets for preventive interventions [62,384]. Methods commonly used to describe injury mechanisms include athlete interviews, clinical and in vivo studies, cadaveric testing, motion analysis of non-injury situations, mathematical modeling, and video analysis (VA). In rare cases, injuries have even occurred during biomechanical experiments (Figure 29). Since no single method can fully capture the multifactorial nature of sports injuries, these approaches are best applied complementarily to address both mechanical and contextual factors [69].

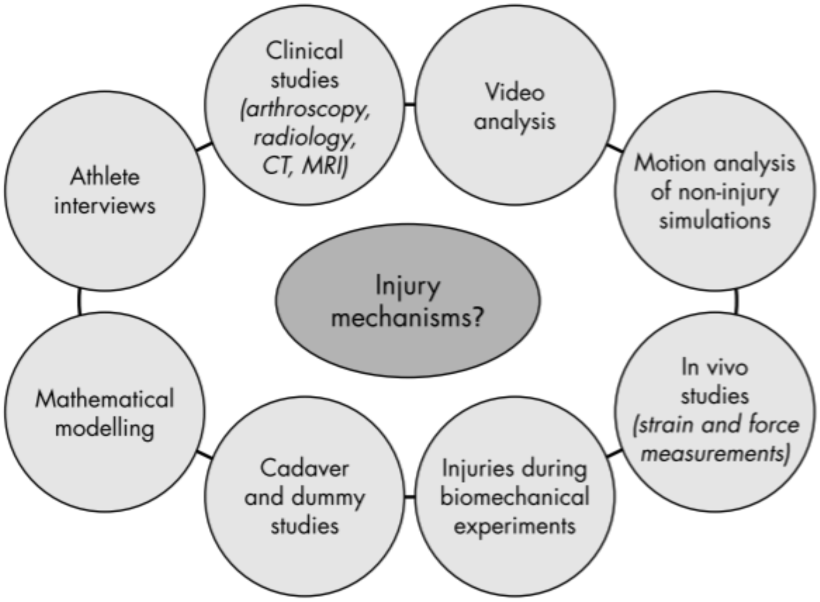


Figure 29: Research approaches to describe the mechanism of injuries in sports [69].

Among these, VA stands out as a unique tool for linking biomechanics and real-world sport scenarios. The widespread broadcasting of elite competitions provides a rich and largely untapped source of real-world injury footage, allowing researchers to study actual injury events under natural, competitive conditions. Although the first VA study dates back nearly 40 years (Silver & Gill, 1980s, on cervical spine injuries in rugby [462]), systematic approaches have only gained traction in recent decades. In most team settings, routine VA work falls within the coaching/performance department, but its application to medical and injury research has gained increasing recognition [73,261,463].

Bi-dimensional (2D) VA involves systematic examination of injury footage to identify key events, such as ground contact, push-off, or the suspected injury frame (IF), and to describe both biomechanical and contextual features surrounding the incident (e.g., opponent behavior, technical action with the ball, attacking or defending phase of play, pitch location, etc.) [24]. This method provides accessible, non-invasive, and cost-effective insight into the interplay between the player, the task, and the environment. The introduction of standardized evaluation tools such as the QA-SIVAS scale [464] has further strengthened the methodological rigor, enhancing reproducibility and reliability. Therefore, 2D VA in sport represents a methodological bridge between biomechanics and performance analysis, combining qualitative observation with measurables parameters to improve objectivity and reduce observer bias [463,465].

From a conceptual perspective, VA is a tool that fits perfectly with the complex-systems model of sports injury (macroscopic lens), acknowledging that multiple mechanical, behavioral, and contextual factors converge in time and space to influence player's injury constraint. In this sense, VA resonates with the way humans naturally perceive and interpret physical phenomena, such as motion, in the real world. Vision, our dominant and most refined sensory modality, enables us to understand not only *what* happens but *how* it happens. VA applies this innate perceptual ability in a systematic and analytical manner. Just as football players continuously scan their environment during play to anticipate opponents' movements, ball trajectory, and spatial constraints, researchers use VA to retrospectively analyze these same interactions. The key difference lies in the temporal dimension: athletes must interpret complex visual information in fractions of a second under pressure, whereas analysts can slow, replay, and view footage from multiple angles to dissect the sequence of events and reveal biomechanical and contextual details invisible in real time. In this way, VA provides a structured extension of human visual cognition, transforming perception into data-driven understanding. It supports the second step of the "sequence of prevention" model [69] by generating hypotheses about injury risk factors and guiding subsequent quantitative research.

In football, VA has been successfully applied to study muscle–tendon injuries such as those involving the ACL [466,467], Achilles tendon [468,469], adductor longus [470], rectus femoris [471], and HI [73,263,265,290]. A systematic approach to VA enables the development of an "injury passport", a multidimensional profile describing the injury mechanism, inciting activities, inciting circumstances, and biomechanics of each injury. This structured approach contributes to identifying the main pattern of events leading to injury and allows for meaningful comparisons across players, teams, and competitions. Beyond movement analysis, VA also provides insight into the cognitive and emotional dimensions of injury. Careful frame-by-frame inspection allows researchers to infer attentional focus, body language, and facial expressions. Arnason et al. [472] reported that in 93% of football injury cases, players' attention was directed away from the challenging opponent, suggesting that momentary lapses in situational awareness may contribute to injury occurrence. Similarly, heightened aggressiveness or frustration can reduce cognitive inhibition and increase behavioral risk. Facial pain reactions captured within milliseconds after injury can also help approximate the precise moment of tissue damage, aligning perceptual and mechanical indicators. Moreover, recent findings highlight the role of neurocognitive mechanisms, such as attentional control and motor-response inhibition, in the milliseconds preceding injury. Many football injuries, particularly ACL injuries, are thought to stem from neurocognitive prediction errors occurring approximately 250 ms before ground contact [473]. Together, these insights reinforce that injuries are not purely mechanical phenomena but the product of complex interactions between perception, cognition, and movement. Integrating these perspectives within VA underscores the need for both *hardware-based* (biomechanical) and *software-based* (neurocognitive) approaches to fully capture the perceptual and contextual demands of actual play [474–478].

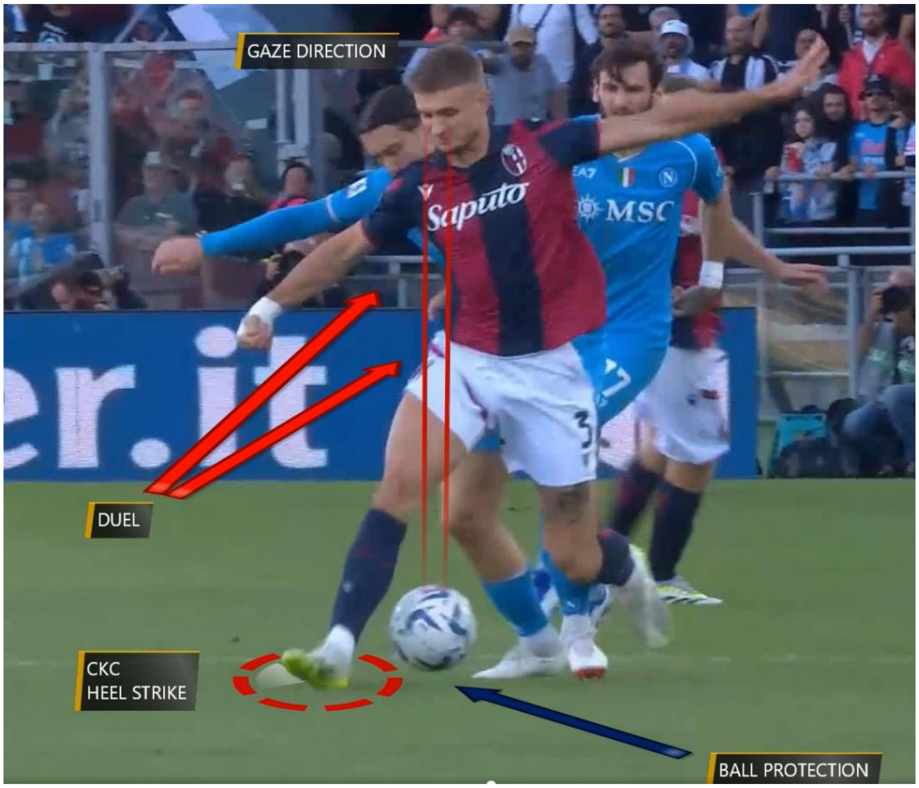


Figure 30: An example of video analysis (VA) application in describing injury context at initial ground contact.

One of the major advantages of VA lies in its ecological validity. Injury footage provides real-world, non-invasive observations of players performing unconditioned and under natural competitive stress. Laboratory analyses, while capable of quantifying forces and joint angles with high precision, often fail to capture the behavioral, perceptual, and tactical components that shape movement in real team sports. Movement cannot be reduced to a series of numerical variables (e.g., GPS metrics, GRF, joint angles) or to a single time frame. Injuries are inherently sport- and context-specific: for instance, in football, ACL injuries tend to occur more frequently during defensive actions [386], whereas HIs are often sustained in attacking phase [73]. On the other hand, sports like basketball and rugby tend to have a higher incidence of offensive ACL injuries [387,388]. A simple yet illustrative example is that HIs are often reported to occur in combination with ball interaction or duels with opponents [265,290]. These events take place when the player is in an active phase of play and must simultaneously process environmental cues, make rapid decisions, and execute precise motor actions, a scenario of multitasking under time constraint and high cognitive demand. No current HI screening or clinical test reproduces these contextual factors, highlighting the unique value of VA in bridging the gap between laboratory assessment and real-world injury mechanisms.

While 2D VA facilitates the identification of contextual variables and movement patterns associated with football injuries, such as dynamic knee valgus, anterior pelvic tilt, or heel-strike position, it remains limited in kinematic accuracy [464,481]. Player video camera angles are rarely perfectly aligned with the planes of motion (frontal, sagittal, transverse), making parallax error a significant concern when estimating physical parameters from 2D footage. Moreover, simple visual inspection of video sequences can introduce subjective interpretation errors, as it is unclear to what extent segment orientations and joint angles in three planes can be reliably inferred. To address these limitations, advanced methods such as the Model-Based Image-Matching (MBIM) technique have been introduced [393–395]. MBIM reconstructs three-dimensional movement from uncalibrated video footage, enabling time-based analyses of joint kinematics and improving biomechanical precision [482,484].

From a methodological standpoint, the integration of systematic VA into injury surveillance systems represents a critical step forward. Football authorities and video producers should ensure that injury events are captured from multiple camera angles, including replays, and should collaborate to develop a centralized, open-access video injury database. Making the technical specifications of broadcast cameras publicly available would facilitate the combination of video data with other analytical tools, such as positional tracking and wearable sensors. Long-term epidemiological programs, such as the UEFA injury study, should include systematic VA components to capture contextual and mechanical information otherwise inaccessible. Furthermore, biomechanical studies must address the persistent issue of small sample sizes by incorporating power analyses and robust statistical planning in future designs.

In conclusion, VA represents far more than a descriptive tool; it is a bridge between real-world sport behavior, biomechanics, and clinical application [485]. By combining ecological validity with biomechanical insight, VA enhances our understanding of injury causation and informs more sport-specific prevention, rehabilitation, and return-to-play strategies. Integrating VA findings into clinical reasoning marks a critical step toward a modern, holistic model of football medicine.

1.10.1 Limitations of Video Analysis

A critical methodological aspect of VA is the clear description and definition of actions and events to reduce bias and improve reliability [385]. However, concerns exist regarding the objectivity, reliability, and validity of qualitative analysis due to strong reliance on the observer’s perspective, experience, and preparation [487]. Using video to observe body positions and actions is inherently challenging, and reliability across descriptors may vary [390]. To address these concerns, it has been suggested that qualitative analysis protocols be developed systematically to increase objectivity and limit dependence on observer knowledge or perspective [487]. The first step is to use a valid and standardized framework for VA, which specifies the frames of interest (e.g., initial ground contact, suspected IF) and the categorical and continuous variables to include in the dataset (often in a structured Excel sheet or database). This framework acts as a checklist that ensures all raters assess the same phenomena in a consistent and comparable way. At present, there is no research consensus on a comprehensive checklist for HI VA in football, which would provide consistent and objective observation forms across studies. Developing such a checklist is essential to promote transparency, replicability, and comparability of findings across studies.

Once the variables are defined, reliability testing across raters becomes critical. Each variable needs to be evaluated for intra-rater agreement (IRA) (consistency of a rater over time) and inter-rater reliability (IRR) (consistency across raters) [481]. Without IRR assessment, it is not possible to evaluate the reliability of the specific checklist designed for the VA study, nor to understand how each variable is scored. This limits the ability to refine the checklist and improve its accuracy in future studies. Reliability estimates depend on the type of variable assessed (continuous vs categorical), the number of raters, number of trials, and whether the index is expressed in absolute or relative terms. Recent guidelines clearly ask to state the number of video observers and their background and experience within VA studies, the specific sport, and the type of injury investigated [464]. To date, many VA studies have relied instead on mutual or consensus agreement between raters rather than formal IRR measures. In this approach, raters discuss each video clip and agree on the coding or identification of events, rather than scoring independently. While this can be practical for small datasets (20–40 injuries), it has several limitations [390]: it does not provide a quantitative measure of reproducibility, prevents evaluation of each variable individually, and limits the ability to refine the checklist for future studies. Therefore, achieving acceptable IRR should be considered an iterative process: if reliability is insufficient on the first round, raters should discuss discrepancies, clarify ambiguities, and repeat the scoring [390,391]. This iterative reliability testing not only improves consistency across raters but also enhances the methodological rigor and validity of VA studies.

Probably the main challenge is to determine the exact moment of the injury, the so-called injury frame (IF). In other words, each observer should identify the same exact IF (expressed in ms) from the video. It is in this fundamental variable that higher intra- and inter-rater reliability is particularly important to obtain. Otherwise, that specific injury case should be considered for exclusion from the study. This is also connected to another obvious limitation of VA: the quality of the video recording, which should be adequately reported, for example, image resolution (pixels), sampling frequency (frames per second), and the number and perspectives of views available. For example, injuries occur within a few milliseconds, and a low sampling frequency could fail to capture the exact moment of the injury. The increased quality of modern football broadcast footage partly explains the recent rise in VA studies on sports injuries.

Another limitation, which must be kept in mind when interpreting the results, is that even with a systematic approach (identification of all injuries within the study period), not all of the injuries reported by team medical personnel can be identified on video. In fact, about half of all injuries in football can be found on video [396]. The proportion of identified incidents ranges from nearly all head injuries to about half of ankle and knee injuries. Depending on the study design, it is possible to capture only a subset of all HI, usually those resulting in match time loss; of which typically only about half are available for VA. For injury types for which a significant proportion of cases cannot be found on video, it is possible that the mechanisms of the missing injuries differ from the recorded ones, a limitation that should always be considered. Also, even though most VA studies on HI declared a focus on acute or better sudden onset HI, it is impossible to certain distinguish between gradual/mix/sudden onset HI from the video only, unless in direct contact with medical staff. This means that studies based solely on VA, without reliable medical information, must be interpreted with caution. Most VA studies underestimating gradual or mixed-onset injuries and training-related HI. Thus, VA should be considered complementary but inherently less comprehensive than epidemiological studies in defining injury prevalence. Moreover, unlike other injury types, HI may be difficult to identify because they are mainly non-contact in nature. They often result from movements involving rapid accelerations such as sprinting, lunging, or kicking, which may not always lead to immediate and obvious functional impairment (e.g., the player might continue playing briefly before substitution) or may occur outside the camera’s field of view. A portion of injuries is also typically discarded in VA studies due to player obstruction issues.

Most VA studies only describe events and situations leading to injury. Unless there is a representative control sample of non-injury situations, it cannot be determined if the characteristics of the injury situations are different from what normally takes place without resulting in injury [381]. It is common for specific player actions, such as tackling, landing, sprinting, kicking, to be associated with specific injuries. As these actions are essential to football and performed thousands of times throughout a career, it is crucial to understand what distinguishes the specific situations leading to injury from similar ones that do not. A focus on high-risk situations may improve our ability to conduct such comparative analyses and, in turn, to refine prevention strategies [397]. Assessing non-injury situations should ideally be done in a blinded fashion, although this may be difficult in some cases, for example, for HI, where the player immediately after clearly reaches the affected areas. Although not yet described as a non-linear phenomenon, the literature reports that 60% of HIs in professional soccer are produced by the ‘same’ inciting event or action (eg, eccentric action of hamstrings during the late swing or stance phase of the sprint) which has been performed thousands of times without causing a muscle strain [405].

Finally, studies should ideally adopt a prospective cohort design to minimize recall bias, a known issue in retrospective research. In sports injury research, a recurrent methodological concern is HARKing. This occurs when researchers generate or present hypotheses after examining data but report them as if predetermined. While often unintentional, HARKing undermines transparency and inflates apparent evidence strength by blurring the line between exploratory and confirmatory research. This issue is particularly relevant in retrospective VA studies, where hypotheses about injury mechanisms or contextual factors may be inferred *post hoc* from observed patterns. To enhance robustness and reproducibility, future VA research should prioritize prospective designs, preregistered hypotheses, and standardized analytical frameworks to reduce bias and promote clearer causal understanding of injury mechanisms.

In conclusion, analysis of video recordings of actual injuries can provide detailed, ecologically valid insights into sports injuries. However, studies must be carefully designed to obtain representative video samples, include rigorous reliability testing, and acknowledge the limits of describing detailed joint biomechanics.

1.10.2 Integration with Additional Data Sources

As the volume of objective physical demands data collected from diverse sources, such as wearable sensors, GPS tracking, and motion capture technologies, continues to expand, there is an increasing need for advanced analytical frameworks to effectively interpret and integrate these datasets [398]. Traditional approaches to injury analysis and prediction often rely on limited, manually coded data, which may fail to capture subtle or emerging patterns preceding injury events [493]. Within conventional VA, biomechanists typically (1) identify key events, (2) annotate joint centers, and (3) compute spatiotemporal and kinematic parameters to generate performance and injury-risk profiles for coaches and athletes. Recent advances in machine learning and computer vision, together with the development of open-source pose estimation models (PEMs) trained on large-scale image datasets, have introduced new opportunities to automate substantial components of this workflow. Such automation reduces labor-intensive tasks, enhances processing efficiency, and allows experts to focus on data interpretation, athlete feedback, and applied injury prevention. The integration of VA with external data sources offers a powerful means to overcome these limitations by combining contextual, kinematic, and physiological information within a unified analytical framework.

Prospective cohort studies that track player exposures can reveal associations between injury incidence and potential risk factors within a population, highlighting the value of combining multiple data modalities to achieve more valid and accurate insights. For example, Aiello et al. [264] combined VA with GPS-derived workload metrics to examine the physical demands preceding injury, such as peak acceleration, high-speed running, and deceleration loads, providing a more complete description of the injury event than either dataset alone. From a biomechanical perspective, advances in markerless motion analysis and video-based modeling tools offer promising pathways for low-cost, automated biomechanical assessment [494–496]. While most biomechanical studies have focused on kinematics (e.g., joint angles, segment velocities), few have examined joint kinetics or underlying forces. Emerging video-based force estimation technologies (e.g., Forceteck systems) may soon enable the estimation of internal loading patterns directly from 2D footage, providing deeper insight into the mechanical contributors to injury.

The validity of VA findings can also be strengthened by integrating qualitative, surveillance, and clinical data. For instance, Olsen et al. [399] combined player interviews with VA in handball to validate visual interpretations and enhance analytical depth. Similarly, incorporating athletes' narratives, through post-injury interviews or questionnaires, can clarify ambiguous footage and provide valuable information on perceptual and sensorimotor aspects such as pain onset, awareness, or fatigue. Linking VA to injury surveillance databases from the same population and period (e.g., club, league, or national team) allows systematic cross-validation between video-detected and epidemiologically recorded injuries. This process improves the accuracy and representativeness of VA samples, quantifies the video capture rate (the proportion of visible and analyzable injuries), and helps identify biases such as missing training or off-camera events.

Equally important is the diagnostic accuracy of the medical dataset itself. VA studies should specify how injury data were collected and verified—whether diagnoses were made by medical professionals, confirmed by imaging (MRI, ultrasound), or obtained through self-report or media sources. Detailed diagnostic data are critical for linking the specific football action performed at the time of injury (e.g., tackling, kicking, sprinting) to the characteristics of the HI (e.g., muscle involved, tissue affected, lesion grade). Such distinctions are essential for prognosis and rehabilitation, given the heterogeneity of HIs. For example, a semitendinosus proximal free tendon injury in open kinetic chain (OKC) while stretching to reach the ball requires a different rehabilitation approach than a biceps femoris long head injury at the musculotendinous junction (MTJ) in closed kinetic chain (CKC) during heel strike after contact with an opponent. Adherence to consensus-based definitions of injury reporting, classification, and severity (e.g., the Football Injury Inciting Circumstances Classification System [70], the IOC consensus statement [29] and its football-specific extension [30]) is therefore essential in VA study design to ensure consistency across studies. Additionally, player's demographics, leg dominance, playing position, age at the injury event, and history of previous HI and other severe lower limbs injuries are relevant factors to include in the overall risk assessment. By combining video-derived movement patterns with contextual, clinical, and workload data, researchers can build multidimensional representations of injury events that are more ecologically valid, reproducible, and actionable for prevention and rehabilitation strategies. Such multimodal approaches enable triangulation of information—linking *what happened* (context from video), *how it happened* (biomechanical characteristics), and *under what conditions* (workload and exposure metrics).

Beyond biomechanical and contextual parameters, future developments in injury monitoring should aim to integrate a broader spectrum of physiological, behavioral, and psychological data to build a truly individualized "injury passport." Such an approach would represent the evolution from multimodal datasets to holistic, player-specific health profiles. For instance, incorporating metrics such as sleep quality and duration, heart rate variability (HRV), perceived exertion (RPE), nutritional status, menstrual cycle phase, and biochemical markers (e.g., from blood or saliva samples) would enable continuous tracking of recovery, fatigue, and stress responses. Psychological profiling through validated questionnaires could further provide insight into emotional regulation, fear of injury, motivation, or stress tolerance, factors known to influence both performance and injury susceptibility. While such multidimensional integration currently remains feasible only within elite environments equipped with the necessary resources and governance structures, it represents the next frontier in building comprehensive models of injury risk and recovery that extend well beyond the current scope of VA.

1.10.3 Much More Than Injury Analysis

Given the importance of neuromuscular coordination and motor control in injury prevention, VA can serve as a valuable feedback tool to enhance movement efficiency and technical execution [498]. Traditionally employed in football for tactical purposes, VA can be equally powerful in helping athletes identify and correct biomechanical flaws or risky movement behaviors, thereby reducing injury risk while optimizing performance [383]. Motor learning theory emphasizes the central role of observational feedback in skill acquisition [500]: observing others perform a movement facilitates imitation and refinement, whereas observing one's own performance produces even stronger feedback through self-recognition mechanisms. Integrating VA into regular training sessions can therefore accelerate athletes' awareness of suboptimal movement patterns and facilitate self-regulated technique correction [501]. In practice, VA enables athletes and coaches to analyze both minor technical adjustments and major mechanical or strategic deviations, fostering a deeper understanding of movement quality through visual feedback and informed discussion. From a dynamical systems perspective, VA can also be used to study the complex and time-dependent interactions between players and their environment [382,400]. This includes examining how spatial–temporal coordination emerges within and between teams, how perceptual coupling guides player movement, and how attentional focus influences the likelihood of exposure to contact or non-contact injury. Because athlete behavior directly affects both risk factors and injury mechanisms [25,66], effective prevention strategies must be built around behavior, not merely imposed from external control. In this sense, VA represents a tool not only for the second step of the prevention model (identifying mechanisms and risk factors) but also for the third step, helping to introduce interventions that reduce injury risk or severity and to develop sport-specific, task-relevant screening protocols for HIs and other lower-limb injuries (see figure 30).

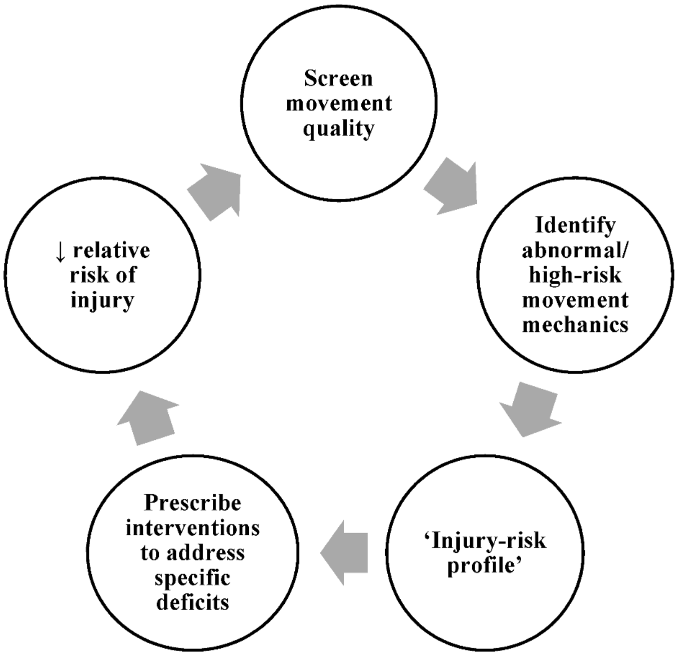


Figure 30: Screening movement quality process [503].

In addition to tactical review, footage showing typical injury patterns could be incorporated into coach and athlete education programs. Such material can help players recognize and anticipate high-risk situations associated with hamstring or other lower-limb injuries, considering contextual elements such as playing position, movement style, and environmental constraints. Education and awareness play a central role in injury prevention: if athletes are unaware of the relevance of specific countermeasures for their own safety, there is little motivation to adopt them. VA-based feedback fosters self-monitoring and self-awareness, encouraging players to regulate their workloads and to participate actively in injury-risk reduction strategies.

Injuries themselves can also be reframed as opportunities to improve bodily awareness and preventive behavior. Athletes should be educated to recognize early warning signs such as fatigue, discomfort, or mild pain, thereby promoting a culture of *listening to the body*. Although full recovery between matches is often unrealistic in professional sport, improving athletes' capacity to detect and report early symptoms may help prevent recurrent or chronic overload injuries. This educational component complements the biomechanical focus of VA, linking physical performance with cognitive and emotional self-regulation. Effective injury prevention therefore requires a multidisciplinary approach that integrates biomechanical, clinical, behavioral, and motivational perspectives [58]. Within this framework, VA provides a visual and objective foundation for communication between coaches, performance analysts, and medical staff, bridging the traditional gap between performance analysis and injury-risk management. Immediate visual feedback allows athletes to see, in real time or shortly after a session, what movements place them at higher risk and how specific technique modifications can reduce those risks. Over time, longitudinal video monitoring across a season can reveal evolving movement patterns or early-warning signs of fatigue or maladaptation, opening new opportunities for proactive surveillance and individualized intervention. Within this framework, VA represents a central element of a continuous feedback loop: footage from training and match play informs technical and behavioral corrections, which are implemented and re-evaluated through subsequent VA sessions. This cyclical process supports both skill optimization and injury risk mitigation.

1.10.4 2D Field-Based Video Analysis

As practitioners implement training interventions to reduce “high-risk” mechanics, it is essential that their effectiveness can be monitored using valid and reliable screening tools. The increasing accessibility of 2D VA tools, particularly open-source software such as Kinovea, has transformed VA from a purely observational research method into a practical screening and feedback instrument for technical skill evaluation. These systems enable frame-by-frame, slow-motion analysis of movement patterns using low-cost cameras or smartphones, making them ideal for field-based assessments of sport-specific motor tasks.

Although 3D motion capture remains the gold standard for biomechanical analysis [504], it is complex, time-consuming, and expensive, limiting its use to laboratory settings. This has created a growing need for field-based, video-supported screening methods that can identify “at-risk” mechanics under realistic conditions. 2D VA offers a cost- and time-efficient alternative for evaluating kinematic variables linked to both performance and injury risk. Parallel to these developments, the increasing accuracy of markerless motion capture systems, such as OpenCap, now enables the reconstruction of 3D kinematics from 2D videos recorded on the field [494]. These tools use computer vision and machine learning algorithms to estimate joint kinematics, kinetics, and muscle forces with increasing accuracy, allowing practitioners to capture and analyze complex movements in their natural environment [505–509]. Screening tools that simultaneously assess performance and injury-risk outcomes are particularly valuable in contemporary football, as they reduce false positives and ensure that preventive interventions remain functionally relevant [414]. Furthermore, repeated testing throughout the season is essential [296,363], since players' neuromuscular and physical status fluctuate over time [510,511].

Qualitative movement screening using 2D VA has led to the development of assessment tools such as the Landing Error Scoring System (LESS) [512], the Cutting Movement Assessment Score (CMAS) [513], the Sprint Mechanics Assessment Score (S-MAS) [514], and single-leg loading evaluations [515]. These systems have demonstrated good reliability and ecological validity, making them increasingly popular for practical application in football. They allow practitioners to identify deficits in movement quality, such as excessive trunk lean, knee valgus, or asymmetrical loading, that may predispose athletes to injury. Altogether, these findings illustrate a paradigm shift: from static or strength-based screening toward dynamic, sport-specific assessments of movement quality.

The CMAS, for example, is a validated field-based VA screening tool for identifying high-risk postures associated with non-contact ACL injuries during side-step cutting. It uses Kinovea software and correlates ($\rho = 0.63–0.80$, $p < 0.001$) against 3D motion analysis with peak knee abduction moments (KAM), a key biomechanical variable related to knee joint loading [516]. High CMAS scores, indicating poor technique, reflect risk factors such as wide lateral foot plant distance, limited knee flexion, and excessive knee valgus, trunk lean, or hip internal rotation [517,518]. Importantly, these postures not only elevate injury risk but also fail to provide performance advantages [518]. Therefore, technique-modification training (i.e., coaching cues and feedback to reduce postures associated with increased knee joint loads), guided by VA feedback, can reduce hazardous joint loading while maintaining or even improving cutting efficiency [518–520].

Similarly, the S-MAS is a 12-item qualitative movement screening tool assessing the overall movement quality of an individual's sprint running mechanics. Using a slow-motion video on software Kinovea, sprint running trials were segmented into key phases of the gait cycle. Movement kinematic features (e.g., hip position, trunk alignment, kick-back) were then evaluated and rated for the presence (1 point) or absence (0 point) of select kinematic features. Lower scores indicate more efficient sprint mechanics and reduced mechanical strain on the hamstrings (see figure 31). A recent study identified an association between sprint running kinematics and prospective sprint-related HI in elite male football players [521]. Sprint running mechanics assessed using the S-MAS were associated with both past and future HSIs, with a 33% increase in the risk of a new HSI with every one-point increase in S-MAS.

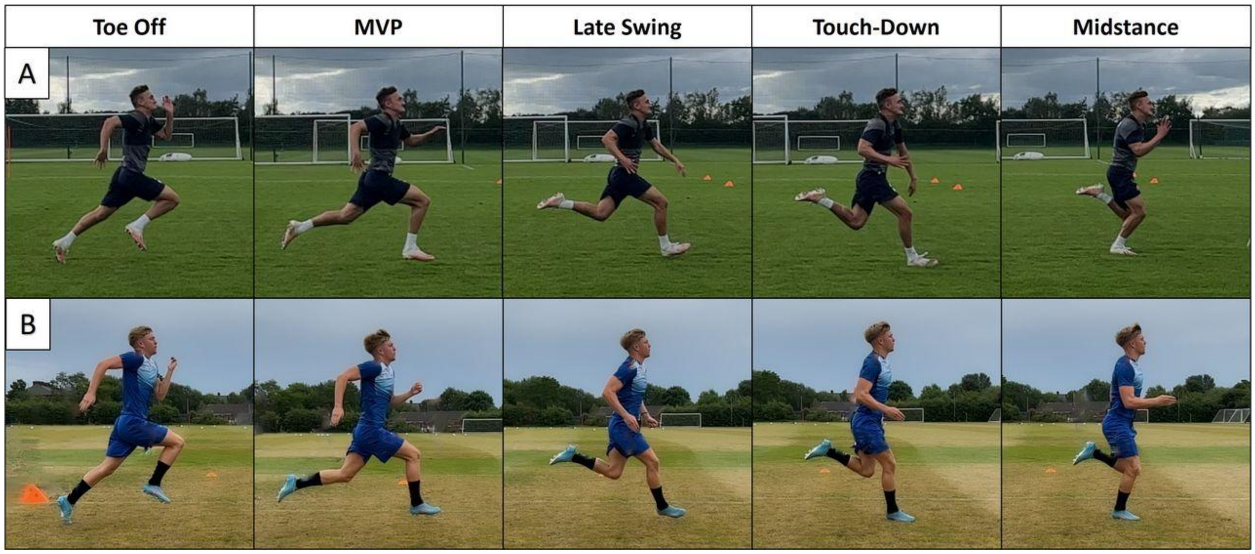


Figure 31: Illustrative example of S-MAS scoring for an injured player (A) and uninjured player (B). Using S-MAS criteria, player A would score a total of 7 points out of 12, with 1 point awarded for each of the following criteria: trailing leg extension, lumbo-pelvic rotation, thigh separation at late swing, thigh separation at touch-down, shin angle and foot v centre of mass position at touch-down and vertical collapse at midstance. Player B would score 0 out of 12 points. MVP, maximal vertical projection; S-MAS, Sprint Mechanics Assessment Score [521].

A particularly innovative example of VA-driven screening and feedback is the Football Hamstring Screening (FHS) protocol [414]. This multifactorial, football-specific protocol integrates clinical strength, ROM, and sprint-mechanics tests into an efficient 30-minute battery, using affordable equipment (~3000 USD). Its four screening categories, posterior-chain strength, lumbopelvic control, range of motion, and sprint mechanical output, reflect the multifactorial nature of HI risk [414]. A percentile method within each team is used in all categories to define whether a player's test outcome is positive or negative. Preliminary intra-rater reliability studies have shown promising consistency within football cohorts [522]. Importantly, the FHS includes a sprint-based test of sagittal-plane kinematics to evaluate lumbo-pelvic control, using 2D high-speed video (240 fps) analyzed with Kinovea software. This test aims to indirectly assess suboptimal sagittal plane lumbo-pelvic movement in sprinting by focusing on the hip and knee angles at touchdown and toe-off (see figure 32b). Excess rotational work being completed by the lower limbs ‘behind the body’ (center of mass) is associated with the ‘kick-back’ mechanism.

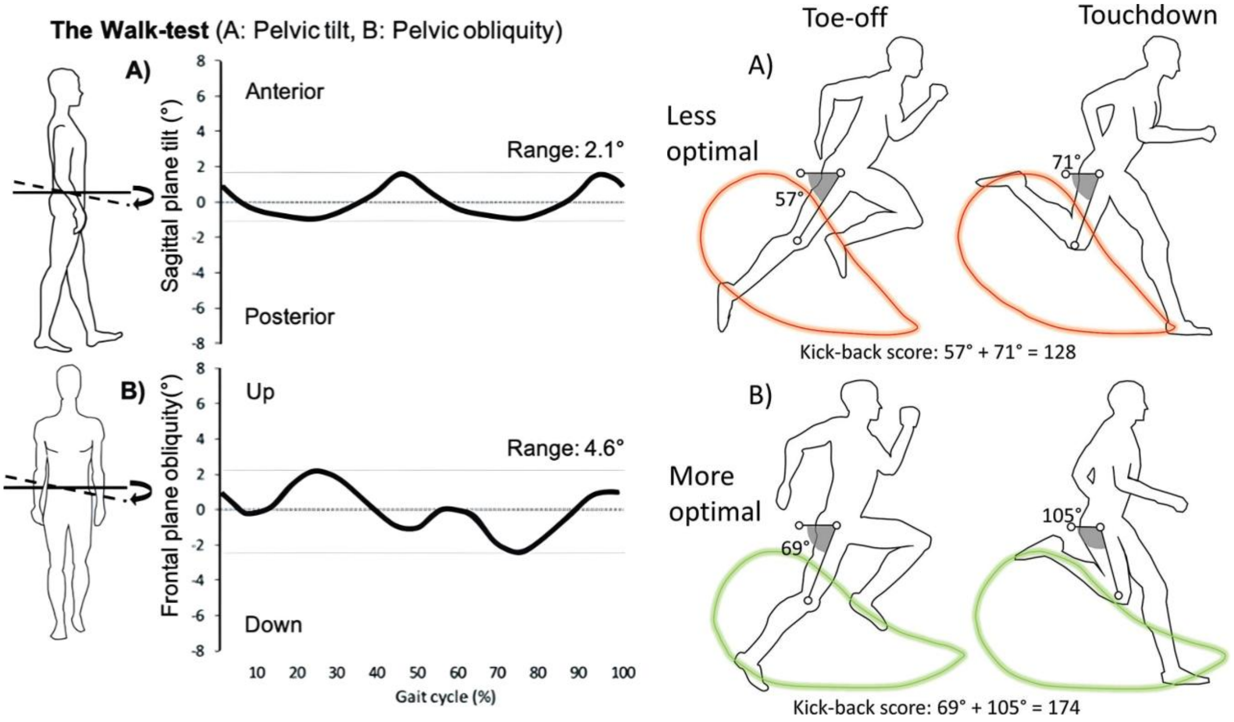


Figure 32. Football Hamstring Screening (FHS) lumbopelvic control tests. (a, left) The Walk Test assesses lumbopelvic control based on a composite score derived from the sagittal and frontal plane kinematic range of pelvic motion during walking. (b, right) The Kick-back Mechanism is quantified using a composite angle score calculated from the contralateral thigh angle at touchdown and the ipsilateral thigh angle at toe-off within the sprint stride. Joint angles were determined after manual digitization of hip and knee joint centers. Examples of less optimal (A) and more optimal (B) movement patterns. The foot trajectory during the sprint stride is shown to illustrate these differences in movement coordination. Within each team, players’ kick-back mechanisms are classified as positive if ranked at or below the 33rd percentile, corresponding to increased lumbo-pelvic loading and training demands [414].

Recently a prospective cohort study has applied the FHS to analyze the potential association with the occurrence of HI during the season [396]. The study identified that 1) no single screening test was sufficient to identify players at risk of HI within the entire season, while 2) low horizontal force production was associated with increased risk of HI when occurring closer to the moment of screening.

Recent work by Mendiguchia et al. [416] and Astrella et al. [523] further demonstrates the potential of combining VA with targeted training interventions. Their six-week multimodal program, integrating lumbopelvic control and running technique exercises, induced significant changes in the sagittal and frontal plane kinematics of the pelvis at maximal speed and discussed the implications for hamstring injury management (see figure 33). This resulted in a lower anterior pelvic tilt during the late swing phase and a higher pelvic obliquity on the free leg side during the early swing phase. Similarly, the kinematics of the lower extremities were also modified according to the front-side mechanics principles, resulting in an increase in the maximum height reached by the knee, followed by an increase in the thigh angular retraction velocity, as well as a decrease in the distance between knees at initial contact, along with a shorter landing distance and contact time. These biomechanical modifications were accompanied by improved sprint performance and potentially lower hamstring strain during late swing phase, suggesting that technique re-education can simultaneously enhance performance and reduce injury risk.

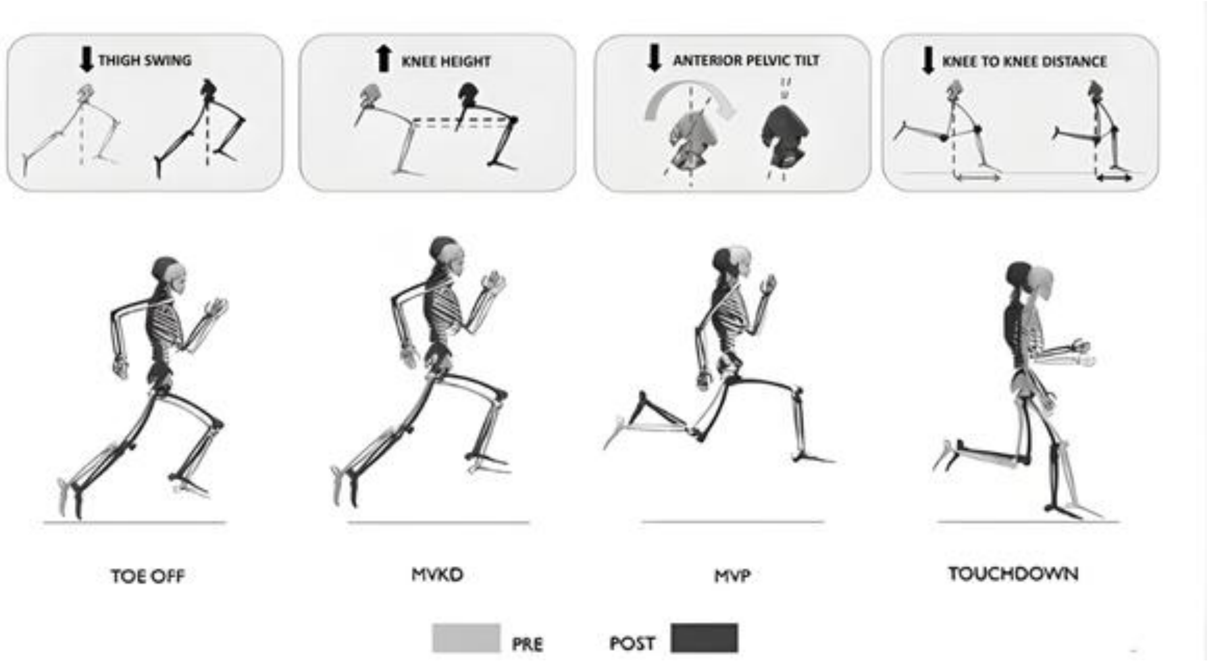


Figure 33: Visual representation of the identified changes between PRE and POST for the intervention group. MVP: Maximal vertical projection; MKVD: Maximal knee vertical displacement [416].

Although musculoskeletal screening protocols capable of accurately predicting HI risk are still in their infancy [347,524], the growing body of 2D VA applications demonstrates its practicality, reliability, and ecological validity for assessing and enhancing movement quality in football. By integrating such screening into continuous feedback loops, coaches and medical staff can track adaptations, refine preventive strategies, and translate biomechanical insights directly into on-field practice [504,525,526].

1.11 Future Perspectives

1.11.1 Individualized Approach and Applied Implications

Recent perspectives in sports science have emphasized the importance of moving beyond traditional, one-size-fits-all approaches toward individualized and context-specific frameworks for assessing injury risk and optimizing performance [63]. Within a team environment, each athlete possesses unique physical, biomechanical, and psychological characteristics that modulate susceptibility to injury. Consequently, implementing generic prevention protocols or clustering players solely on shared variables may be insufficient if individual-specific constraints are overlooked (see figure 35). Although ecological dynamics and constraints theory predicts performance based upon the individual, sports science researchers have focused upon group designs, rather than sub-groupings (e.g., playing position) or analyses that can reveal individual differences [527]. Groups of participants who can differ in characteristics such as age, skill level, gender, posture undertake performance tests or training programs, and the results are compared. Although some group-based initiatives have been shown to be effective it is possible that injury risk management may be enhanced with personalized interventions [416].

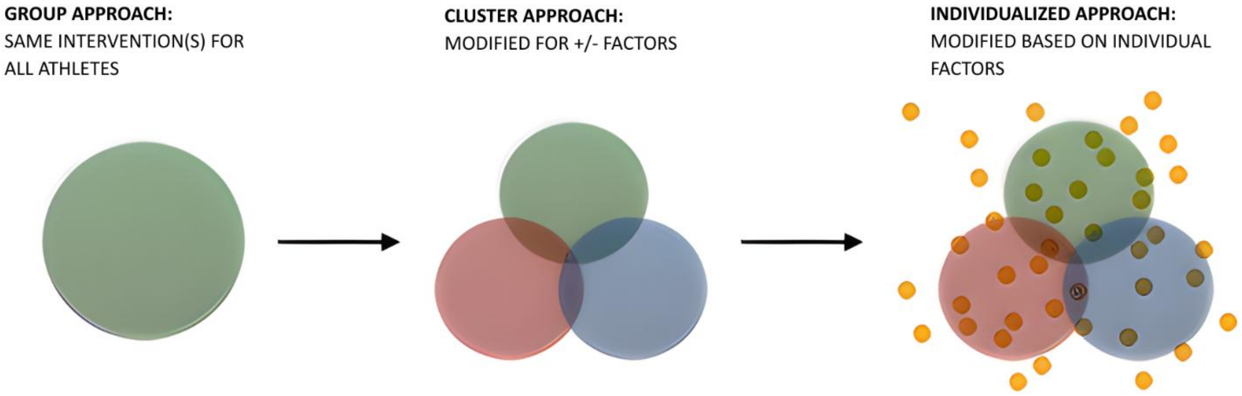


Figure 35: Strategic approaches to injury risk management [63].

Applying a complexity lens encourages researchers and practitioners to consider not only whether an intervention works, but how, for whom, under what conditions, and why it may be effective. This perspective acknowledges that interventions interact with multiple components, physiological, biomechanical, behavioral, and environmental, producing variable outcomes across athletes and contexts. Importantly, it has been argued that interdisciplinary research should investigate how individuals exploit task and environmental constraints to achieve a goal [529], and that the tasks undertaken in research should be representative of the actual game setting [530]. According to the principle of representative task design, the properties and constraints of performance tests should mirror those of the competition environment to which the findings are intended to generalize [502]. Therefore, an individual level of analysis can provide information of individualized solutions and/or deficiencies to achieve the task goal at either the ecological or execution scales [529]. Investigation of individual differences has important practical implications, as coaches are interested in the strengths, deficiencies, and development of individual athletes, so that interventions can be tailored [531].

1.11.2 Transdisciplinary Approach

Sports performance is inherently complex, as elite competition depends on the dynamic interaction of multiple factors, including physiological fitness, psychological preparedness, physical development, and perceptual-cognitive motor skills [530]. Understanding such interactions requires the integration of knowledge across domains; however, sports science research has historically remained monodisciplinary, often confined within distinct subfields [465]. Traditional studies on sports injury typically adopt a single-disciplinary lens, for example, biomechanics, physiology, or psychology, each applying its own assumptions, tools, and analytical paradigms in isolation. Biomedical researchers, for instance, often conceptualize injury as the outcome of identifiable physical or biological factors and apply quantitative methods to examine relationships between strength, previous injury, or maturation and injury risk [305,421,422]. In contrast, sport sociologists may frame injury as a socially constructed phenomenon, exploring the cultural and organizational factors influencing athlete behavior through qualitative inquiry [423,424]. Sport psychology scholars frequently address the emotional and cognitive dimensions of injury experiences, using quantitative, qualitative, or mixed-methods approaches. While each discipline offers valuable insights, this fragmented approach fails to capture the nonlinear, context-dependent interactions that characterize injury emergence. Consequently, preventive strategies often become component-based, isolating strength, flexibility, or proprioception, without sufficiently reflecting the dynamic and football-specific demands that underpin real injury mechanisms. Embracing a complex-systems perspective therefore requires moving beyond traditional disciplinary boundaries.

The call for interdisciplinary research in sport injury was first articulated by Burwitz et al. in the early 1990s [417]. Since then, several scholars have argued that safeguarding athlete health and wellbeing demands holistic, multidimensional inquiry [418,419]. Interdisciplinarity refers to a process through which complex problems, unsolvable within a single discipline, are addressed collaboratively by integrating distinct perspectives and methodological toolkits [7,17,23,425]. The different disciplinary insights foster an integrated understanding of sport injuries in relation to individual players' context and situation, potentially extending existing knowledge [7,17,23,425].

True integration, however, cannot follow an algorithm; rather, it is an iterative and complex process which requires analytical reasoning, creative thinking, and iterative collaboration across professional silos. Working beyond professional silos promotes better research questions, more appropriate study design and more rigorous statistical analysis [420]. Importantly, interdisciplinarity should not be limited to sub-disciplines within sports science. Disciplines that may appear distant, such as architecture (tensegrity) and mathematics (dynamic models), can also contribute valuable insights into the study of complex phenomena like sport injuries. A transdisciplinary approach goes even further, seeking to transcend disciplinary boundaries by creating shared conceptual models that link biological, psychological, social, and environmental dimensions. It combines quantitative and qualitative traditions into mixed-method frameworks, enabling researchers to move from isolated risk factors toward the identification of dynamic risk patterns. In doing so, transdisciplinarity does not merely integrate data and methods, it merges epistemologies and knowledge systems, producing a more comprehensive understanding of injury etiology and, ultimately, more effective, context-sensitive prevention strategies.

1.11.3 Statistical analysis and qualitative methods

Applying systems-based principles to sports injury research has important analytical implications. Traditional epidemiological and statistical models, such as correlation- or regression-based analyses, tend to be reductionist, focusing on isolated relationships between variables rather than on the interacting network of factors that contribute to injury risk [13]. Such approaches are well suited for identifying linear associations but are limited in their ability to represent causal webs, feedback loops, and conditional dependencies inherent to complex systems [540]. Injury etiology, including that of HI, is inherently multifactorial. Consequently, the effect of any single variable may not reach conventional statistical significance (e.g., $p < 0.05$) when examined independently, yet it may be highly relevant when considered as part of a multivariate or nonlinear model. This limitation likely explains why screening tools designed to predict injury risk have shown poor validity: traditional models are not designed to address class imbalance problems, where the number of injured athletes (minority class) is much smaller than non-injured athletes (majority class) [541,542]. This imbalance biases regression-based analyses toward the majority class, increasing misclassification of the very cases, injured players, that matter most.

To overcome these issues, machine learning and data mining techniques (e.g., ensemble, cost-sensitive, and class-balance learning algorithms) have been developed to model nonlinear, high-dimensional, and imbalanced datasets [430,431]. These approaches can process large numbers of interdependent variables and capture dynamic interactions between intrinsic and extrinsic risk factors, potentially yielding more robust predictive models. In addition, dynamic systems methods, such as Bayesian probability models, stochastic time-series analyses, agent-based models, and network analyses, enable researchers to explore time-varying relationships and multilevel causal mechanisms that underlie injury emergence [9,26]. These methods allow simultaneous examination of interactions within and between hierarchical levels (individual, team, environment), offering a more realistic understanding of injury development and resilience. Importantly, adopting a complex systems perspective does not necessitate abandoning reductionist approaches altogether. Instead, system-driven analyses can complement traditional methods, integrating insights from both linear statistics and dynamic modeling [544]. While the predictive accuracy of any model depends on data quality and assumptions, complex systems approach expands the methodological toolkit available to sports medicine and can advance causal thinking in injury epidemiology.

Beyond quantitative modeling, qualitative methods offer additional means to capture the contextual and behavioral dimensions of sports injuries. Injuries arise within complex sport environments that involve movement variability, decision-making, and player interactions, which are difficult to quantify precisely. Qualitative analyses, long used in human movement, ergonomics, and clinical research [545] can uncover the nuanced interplay between technical execution, situational context, and player behavior. These methods are especially valuable because they require minimal equipment, preserve ecological validity, and can complement quantitative data by providing rich contextual insights [546]. Embracing complexity therefore requires expanding the evidence base beyond purely quantitative paradigms to include mixed-methods approaches. Qualitative analyses can help explain why certain injury mechanisms occur, how athletes perceive and adapt to constraints, and which contextual factors modulate injury risk, insights often missed by traditional statistical models [27]. By integrating quantitative modeling, machine learning, and qualitative analysis, researchers can build a holistic and context-sensitive understanding of injury mechanisms, ultimately informing more individualized and effective prevention strategies [426,427].

2. SCIENTIFIC PUBLICATIONS

Paper 1

Systematic Video Analysis of 57 Hamstring Injuries in Women's Football (soccer): Injury Mechanisms, Situational Patterns and Biomechanics

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Abstract

Objective: To investigate the occurrence and inciting events of hamstring injuries (HSIs) in elite women's football through video analysis, describing the mechanism, situational patterns, and biomechanics of the sport-specific activities performed before and at the time of injury.

Methods: A descriptive observational study was conducted using video analysis of HSIs from top national and international women's football competitions across seven seasons (2017/18 to 2023/24). Three raters independently categorized HSIs following the Football Injury Inciting Circumstances Classification System (FIICCS) and analyzed joint and trunk kinematics.

Results: Among 109 identified HSIs, 57 (52%) were eligible for analysis. Most injuries (74%) were non-contact, with 51% occurring during running and 49% during stretch-type movements, including kicking and dueling. These patterns involved ball interaction in 68% and duels in 51% of cases. Injuries predominantly occurred in offensive situations (72%), with moderate to high horizontal speed and minimal vertical movement. Biomechanical analysis indicated frequent knee extension and hip flexion.

Conclusion: HSIs in women's football predominantly occur during movements with high eccentric demand of the hamstring muscles, with non-contact mechanisms being most common. HSIs are not solely linked to high-speed running but can also occur during propulsion and braking phases, or overstretching activities with an open or closed kinetic chain. HSIs often resulted from complex movements involving multiple tasks simultaneously under high physical and mental demands, in unpredictable and evolving scenarios.

Keywords: football, women, hamstrings, muscle injury, video analysis

Summary Box

What is already known on this topic

- Hamstring injuries are the most common type of injury in football, typically require weeks for recovery, and exhibit a high recurrence rate.
- These injuries are predominantly non-contact or result from indirect contact, often occurring during running or stretch movements.
- While different video analysis studies have described hamstring injuries in male football, female players remain largely underrepresented. This gap limits our understanding of potential sex-specific differences in injury mechanisms and situational patterns.

What this study adds

- This study is the first to use video analysis to explore HSIs in elite female footballers, filling knowledge gaps compared to male counterparts.
- We introduced a new classification for the type of mechanical perturbation, distinguishing them as either “hold/pull” (e.g., tackling, body block, hand on shoulder, shirt pulling) or “hit/push” type (e.g. shoulder-to-shoulder, hand or forearm push, body check while pressing).
- A football-specific classification of HSIs was developed, detailing three main situational patterns: run-type, kick-type, and duel-type.
- The study highlights that HSIs in match scenarios were often accompanied by technical (ball handling) and/or coordinative (opponent interaction and contact) challenges.

How this study might affect research, practice or policy

- Future research and practice strategies may benefit from combining hamstring strength training within drills that also replicate the technical and coordinative demands of real injury scenarios. This involves integrating specific situational patterns (run- and stretch-type), mechanical perturbations (hold- and push-type contacts), and contextual factors (e.g., ball interaction, tactical positioning, and decision-making under time constraints) into dynamic and unpredictable training tasks.

- Future research and practice strategies may benefit from combining hamstring strength training within drills that also replicate the technical and coordinative demands of real injury scenarios. This involves integrating specific situational patterns (run- and stretch-type), mechanical perturbations (hold- and push-type contacts), and contextual factors (e.g., ball interaction, tactical positioning, and decision-making under time constraints) into dynamic and unpredictable training tasks.
- In addition to tactical video analysis, footage of typical injury patterns should be integrated into trainer education programs to help players recognize and navigate high-risk situations for hamstring injuries, considering individual characteristics like playing position.

Introduction

Sports injuries result from complex interactions of factors (biomechanical, behavioral, and physiological, and more) which influence each other over time [20]. In football, this dynamic interplay places players at potential risk [2,8,25], with hamstring injuries (HSIs) being among the most common injuries in female players [244,245,322], resulting in significant performance and economic burden [101], potentially affecting career longevity, as observed in male counterpart [271]. Despite efforts from medical staff and the scientific community, HSIs now account for 12% of all time-loss injuries in women's football [100]. Although these injuries generally result in shorter lay-off periods, they impose a notable burden, with approximately 20 days lost per 1000 hours of exposure [549]. Additionally, 11% of players who suffer an HSI experience a recurrence [253], a rate comparable to the 12–16% observed in men's football [48]. Comparative studies showed that male players are about twice as likely as female players to sustain HSIs, especially during match play [246]. However, as women's football rapidly evolves, elite players now face significantly greater physical demands than in the last decade, particularly in terms of high-speed distance covered and number of sprints [318]. This escalating match play demands may have heightened the susceptibility to muscle-tendon injuries among female footballers [322,550].

Developing effective injury prevention programs requires understanding the nature and mechanisms of specific injuries [491]. However, there is currently a significant scientific gender gap in hamstring injury research, with much of the available data derived from studies on men [551]. Applying findings from men's to women's football may not translate effectively, as sex-based differences in biomechanical properties, hormone profiles, and sporting environments can alter injury risks and patterns [324]. To be effective, preventive measures should be sport-specific and consider sex, level of competition and injury profile [325].

A more precise description of injury-inciting events would be of great help to improve risk mitigation strategies by more accurately targeting the specific injury mechanisms [68]. Video analysis is a commonly adopted technique to describe the injury context and the players' activities around the time of injury [23], allowing both the biomechanical analysis and the assessment of technical and cognitive demands. In football, video analysis has been used in previous studies to investigate HSIs mechanism (non-contact vs indirect contact) and situational patterns (sprint-related vs stretch-related), as well as joint and trunk kinematics [73,261,263,264]. Despite sufficient description of HSIs events in male football, only one comparative video analysis study [262] provided some evidence on HSIs in female players.

Thus, this study aims to fill this gap by investigating the inciting events of HSIs through video analysis, describing the mechanism, situational pattern, and biomechanics of the sport-specific activities performed before and at the time of injury.

Methods

This study was a descriptive observational video analysis of HSIs in top national and international women's football competitions, at both club and national team levels. The competitions were selected based on their FIFA ranking, and included a total of thirteen club matches from the USA, eight from Italy, eight from Spain, eight from England, six from France, and three from Germany, covering both domestic (n=30) and international (n=6) league and cup (n=10) competitions. Additionally, we analyzed eleven matches from national team competitions. Data collection covered seven seasons from 2017/18 to 2023/24. The study design used the Quality Appraisal for Sports Injury Video Analysis Studies (QA-SIVAS) scale [464] and the Football Injury Inciting Circumstances Classification System (FIICCS) [70].

Injury identification and video extraction

The reports of each HSI case were identified through online database searches. Subsequently, the corresponding full-match video was retrieved to confirm and identify the injury event. Player data, including baseline characteristics and injury details, were collected from FBref.com (Sports Reference LLC, Philadelphia, USA) and supplemented with a Google search [name of player AND (hamstring OR semitendinosus OR semimembranosus OR biceps femoris) * AND injury]. It is not uncommon for players experiencing muscular injuries to continue playing and report the incident afterward; consequently, injuries were included only if the player was forced to leave the pitch and be substituted, ensuring precise identification of the injury frame (IF). Videos were obtained from YouTube and Wyscout platforms. Each video clip included approximately one minute before and 30 seconds after the suspected IF.

Video assessment

Three reviewers with documented experience in video analysis studies—a sports medicine physician, a biomechanics professor and professional UEFA A licensed coach, and a PhD candidate and sport scientist—evaluated all injury videos in real-time, slow motion, and frame-by-frame to identify key injury details. Each reviewer independently classified the injury mechanism, situational patterns and biomechanical characteristics, blinded to each other’s assessments. Discrepancies were resolved through a consensus meeting with the research team, which also included a former professional women’s basketball player with expertise in video analysis and a medical doctor and professor with experience in injury-related research. During this meeting, the videos were critically reviewed again until agreement was reached following established methodologies [73,261].

A predetermined checklist, developed from existing observation forms, was used to ensure consistent and objective analysis. This checklist included the following categories: (I) anthropometric data; (II) match conditions and characteristics; (III) injury distribution; (IV) diagnosis and potential risk factors; (V) injury mechanism; (VI) situational pattern; and (VII) biomechanics. The use of this standardized form ensured consistency and comprehensiveness in the analysis. The software Kinovea (version 0.9.5) was used for video analysis; the number and resolution of camera views were registered.

Two injury mechanism categories were identified: (1) non-contact and (2) indirect contact, defined as an injury resulting from an external force applied to the player, but not directly to the muscle injured. Indirect contact mechanisms were further classified into hold-type and push-type contacts, based on the direction and intent of the applied force. In hold-type contacts, the opponent applies force against the injured player’s movement direction, aiming to slow him down or restrict forward motion. In push-type contacts, the force is applied in the same direction as the player’s trajectory, often to disrupt balance by accelerating the player unexpectedly. The situational patterns were classified as run-type or stretch-type, based on previous literature [73]. The stretch-type pattern was further divided into duel, kick and other types. The run-type pattern was classified based on the player’s velocity profile and movement mechanics from video analysis. Three phases were identified for injury occurrence: acceleration, high-speed, and deceleration. The acceleration phase occurs when the player rapidly increases speed in the first few meters (0-10 meters) after a standing or jogging start, often exhibiting a forward lean. The high-speed phase refers to the player reaching a high to near-maximal speed, typically associated with high- or very-high-speed running and sprinting over longer distances. The deceleration phase begins when the player reduces speed, often in preparation for a change in direction, to avoid a tackle, or to stop after a high-velocity action. Kick-type injuries occurred during the preparation, execution, or balance recovery phases of a kick, while duel-type injuries involved the attempts to change/maintain possession of the ball. This includes situations where a player presses to steal the ball from an opponent, intercepts to gain control of a contended/dead ball, and protects/attacks to retain possession. This situational pattern involves football-specific actions such as lunging, breaking, sliding, shielding, landing, and regaining balance. Additional injury context information included: duels, ball interactions, number of opponents near the injured player, opposing team, game result, pitch size and surface, home/away/neutral stadium, kick-off time, weather, attendance. When available, diagnostic information (including injury location, level, and type) and a history of previous severe lower limb injuries (defined as injuries occurring at the hip, groin, thigh, knee, lower leg, ankle, or foot, involving muscles/tendons, ligaments/joint capsules, and cartilage/synovium/bursa, with a lay-off of more than 28 days) were collected from official injury reports, in accordance with the Football-specific extension of the IOC consensus statement [30].

Joint and trunk kinematics were analyzed using videos with at least one clear quasi-sagittal plane view (Figure 1). Due to parallax distortion and the limitations of 2D video analysis, angles were reported in ranges of 30°, with flexion as positive and extension as negative values. The kinematic analyses included the hip and knee angles of the injured leg, the inter-limb angle (the angle between the thigh segments in the sagittal plane), and the trunk position (forward, neutral ±10°, or backward, with the earth vertical as a reference).

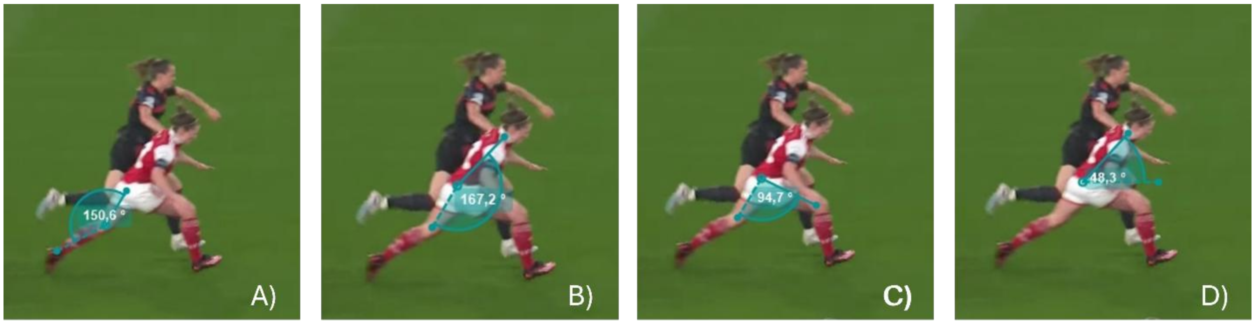

Figure 1. Example of kinematic analysis using Kinovea software. A) knee angle B) hip angle C) inter-limb angle D) trunk tilt.

Seasonal, match and field distribution

Seasonal, match and field distribution were obtained in relation to the injured player's position, including: 1) the competition period and month of the injury, 2) the phase of the game (minute and half), 3) the minutes played by the injured athlete and 4) the field location at injury, 5) player's position.

Patient and public involvement

All the videos we accessed are publicly available and no personal player information was accessed. Therefore, ethical permission and patient consent for publication were not required. The study's findings are expected to be shared through publicly accessible platforms (newspaper articles, television interviews, podcasts, blogs) to educate the community on how hamstring injuries occur and how this knowledge may inform future prevention strategies.

Equity, diversity, and inclusion statement

We responded to the growing call for more research on women's football players, aiming to bridge the gap in knowledge compared to their male counterparts. Our study included women's professional football players from diverse national championships and teams, all from high-income countries. The Authors' team consists of professionals from medicine, sports science, and biomechanics, including both female and male researchers from high-income countries, fostering diversity in expertise. This study is an important step in addressing gender imbalances in football research.

Statistical analysis

Categorical data were presented as absolute and relative frequencies. To compare variable frequency distributions, we used the Chi-squared (χ^2) test. The significance threshold was set at alpha=0.05. Effect sizes were computed using Cramer's V (φc), with interpretations as follows: φc=0.00-0.10 (little to no association), φc=0.10-0.30 (weak association), φc=0.30-0.50 (moderate association), and φc=>0.50 (strong association). Statistical analyses of this study are consistent with the CHecklist for statistical Assessment of Medical Papers (CHAMP statement) [552].

Results

A total of 109 HSIs were identified as match injuries, with 57 (52%) videos eligible for analysis involving 50 players (7 recurrences). Reasons for exclusion included cases where the video was available but the injury was not captured or the IF was unclear (n=28), where the match reportage was available but no video (n=12), where the video was available but the license did not cover the competition or league (n=8), and where the match was absent from the WyScout archive (n=4). Of the eligible videos, three had four camera views, seven had three, 24 had two, and 23 had one. The camera angles comprised semi-frontal anterior (n=14), semi-frontal posterior (n=26), semi-sagittal right (n=36), and semi-sagittal left (n=26) views. Injuries occurred during national club competitions (n=40), the Champions League (n=6), and national team competitions (n=11). Video resolution (pixels) was 640×360 (n=1), 1280×720 (n=24), and 1920×1080 (n=32). The sampling frequency (frames per second) was 25 (n=12), 30 (n=29), 50 (n=7), and 60 (n=9).

The players (age: 28±4 years; height: 1.68±0.05 m; weight: 60±5 kg; right-footed n=43) were goalkeepers (4%), center-backs (14%), full-backs (9%), midfielders (28%), wingers (12%), and strikers (33%). The lay off time was 76±93 days, significantly increased by four surgical cases and one career-ending recurrence. Excluding these, the lay-off was 53±37 days. Injuries were severe (>28 days) in 74% of cases, moderate (8-28 days) in 21%, and mild (4-7 days) in 5%. Thirty-one cases (54%) involved the dominant leg (21 right leg). Recurrent HSIs made up 30% (mostly delayed >12 months), and 42% of players had a history of severe lower limb injuries. Injury location was reported in only 23% of cases, with the biceps femoris most affected (12 out of 13). Other diagnostic details, such as injury level and type, were often incomplete.

Injury mechanism analysis

Of the total injuries, 74% were classified as non-contact ($p<0.001$, $\varphi c=0.47$) and 26% indirect contact (Table 1). Among the indirect contacts, the upper body was the most affected area (60%), followed by the lower body (27% uninjured leg and 13% injured leg). Contact occurred 407±256 milliseconds before the injury. Contact type was classified as hold/pull (40%), where force was applied against the injured player's running direction and hit/push (60%), where force was applied in the same direction (Figure 2).

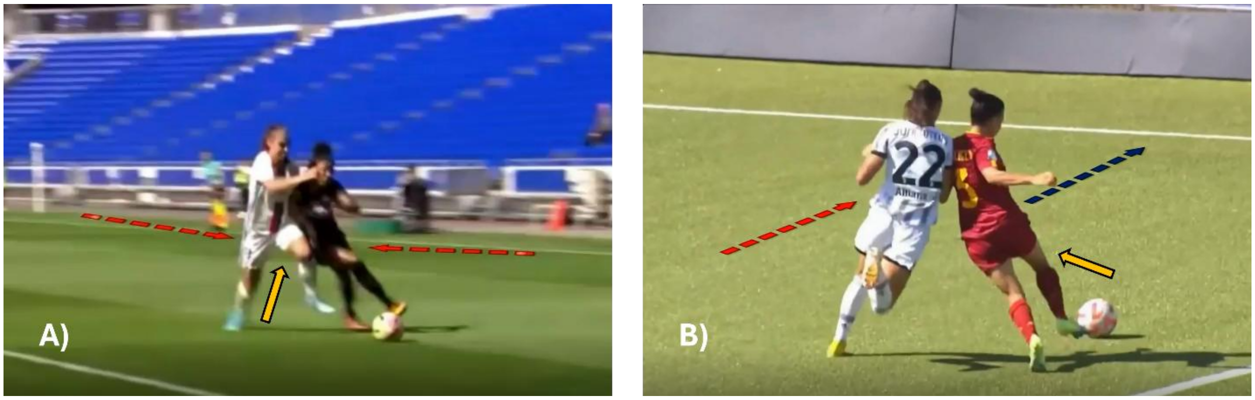

Figure 2. Examples of the two common mechanical perturbations observed in indirect contact cases: A) hold/pull and B) hit/push. The yellow arrow indicates the injured leg in the subsequent frames.

In 72% of cases (*p*<0.01, *φc*=0.44), at least one opponent was within the player's action area (3.14 m^2). Among these, 51% involved direct duels, predominantly side-by-side rather than frontal 1vs1. Ball interaction was observed in 68% of cases, indicating the injured player was attempting to engage with the ball, with or without direct contact. Further details are in Table 1.

Table 1- Distribution of injury mechanisms categorized based on a predefined checklist. The table presents the absolute number (n) and percentage (%) of each category, along with chi-square (χ^2) values, p-values, and effect size (φc). Contact characteristics include the body region involved and the type of contact. The presence of an opponent, involvement in a duel, and ball interaction are also reported.

VARIABLE	**Category**	**n**	**%**	**χ2**	**p-value**	**φc**
MECHANISM	Non-contact	42	74	12.789	<0.001	0.47
	Indirect	15	26			
CONTACT	Injured leg	2	13	5.2	0.074	0.21
	Uninjured leg	4	27			
	Upper body	9	60			
TYPE OF CONTACT	Hit/Push	9	60	0.6	0.439	0.10
	Hold/Pull	6	40			
OPPONENT(S)	Yes	41	72	10.97	0.001	0.44

	No	16	28			
DUEL	Yes	29	51	0.018	0.895	0.02
	No	28	49			
BALL INTERACTION	Yes	39	68	7.737	0.005	0.37
	No	18	32			

Situational pattern and inciting activities

Two main situational patterns were identified for non-contact and indirect contact HSIs: run-type (n=29, 51%) and stretch-type (n=28, 49%). The stretch-type injuries were further divided into kick-type (26%) and duel-type (28%). Additionally, two cases (landing from a wall jump) were categorized as stretch-type but did not fit into the aforementioned subcategories (Figure 3).

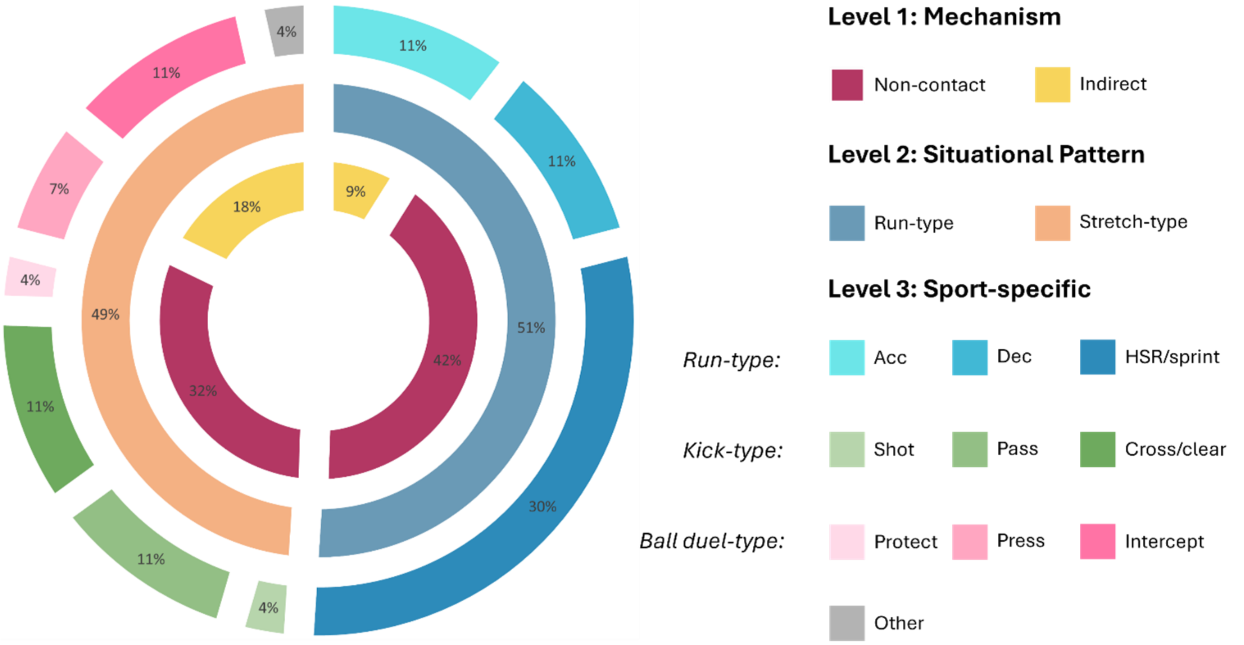

Figure 3. Classification of hamstring injury mechanisms (level 1 – inner circle), situational patterns (level 2 – middle circle), and sport-specific for football (level 3 – outer circle).

Injuries occurred more frequently in offensive, compared to defensive situations (72%, $p<0.0001$, $\varphi c=0.44$). Inciting activities are detailed in Table 2.

Table 2- Situational patterns and inciting activities performed at the injury frame. The table details the playing phase and biomechanical variables such as kinetic chain,

loading leg, foot strike pattern, and speed (horizontal and vertical). Absolute numbers (n), percentages (%), chi-square (χ^2) values, p-values, and effect size (φc) are reported for each variable.

VARIABLE	CATEGORY	n	%	χ2	p-value	φc
SITUATIONAL PATTERN	Run-type	29	51	0.018	0.895	0.02
	Stretch-type	28	49			
FOOTBALL-SPECIFIC	Run	29	51	26.158	< 0.0001	0.39
	Kick	14	25			
	Duel	12	21			
	Other	2	4			
PLAYING PHASE	Attack	41	72	10.965	< 0.0001	0.44
	Defend	16	28			
KINETIC CHAIN	Open	15	26	3.895	0.143	0.18
	Closed	26	46			
	Unsure	16	28			
LOADING LEG	Injured	24	42	30.632	< 0.0001	0.37
	Uninjured	11	19			
	None	3	5			
	Both	2	4			
	Unsure	17	30			
FOOT STRIKE	Fore	6	23	5.385	0.145	0.26
	Mid	8	31			
	Heel	10	38			
	N/A	2	8			
HORIZONTAL SPEED	Very low	4	7	19	< 0.001	0.33
	Low	19	33			

	Moderate	25	44			
	High	9	16			
VERTICAL SPEED	Very low	18	32	47.772	< 0.001	0.53
	Low	34	60			
	Moderate	3	5			
	High	2	4			
PHASE	Acceleration	32	56	0.86	0.354	0.12
	Deceleration	25	44			

Run-type

Run-type HSIs, accounting for 51% of all injuries, were analyzed in detail (Table S2 and S3). Among these, 41% started from a standing position and half while jogging. Curved runs accounted for 52%, while the remainder were linear. Injuries were classified by run phase: acceleration (21%), high-speed (59%), and deceleration (21%). Only seven (24%) occurred in typical running scenarios without ball interaction, opponents, or duels. The majority (72%) occurred while attacking, with strikers most affected (34%). The estimated run distance was 19±12 meters, with a duration of 2.9±1.8 s and 13±7 steps.

Kick-type

Most of the kick-type injuries occurred while passing (43%) and crossing/clearing (43%), and 14% while shooting. Injuries occurred while attacking in 79% of the cases, with midfielders most affected (43%). No injuries were reported during free kicks, corner kicks, or other dead-ball situations; all occurred with the ball in motion. One case involved a goalkeeper's punt kick. Kick-type injuries were evenly split between the loading (43%) and the kicking leg (57%) (See table S4).

Duel-type

Forty-three percent of these injuries occurred during ball interceptions, 29% while pressing, and 14% while protecting possession. This pattern showed a high incidence of duels (83%), with 58% involving indirect contact. Strikers were most affected (58%). Injuries involved the dominant leg in 83% of cases and occurred in a closed kinetic chain (CKC) scenario in 75%. Most injuries (83%) occurred while decelerating rather than accelerating (See details in table S5).

Joint and Trunk Kinematics

Biomechanical analysis was available for 39 videos (excluding 14 run-type, two kick-type, and the two wall jump cases; see Table S6). For knee joint movement, a specific injury pattern was observed in most cases, involving knee extension (59%) at an angle of less than 30° at the IF. The hip joint was frequently (39%) involved in flexion. For inter-limb angle detection (n=26), the range was typically between 60° and 90°. Trunk position was recorded as flexion in 16 cases, neutral in 18 cases, and extension in 5 cases. Hip extension (0-30°) was primarily observed in run-type injuries (7/8), while other patterns mostly involved hip flexion. The trunk was mostly neutral but showed extension and flexion roles in kicking injuries.

Table S6 – Sagittal plane kinematics of total HSIs (n=39) categorized by situational pattern.

Variable	**Category**	**Run**		**Kick**		**Duel**		**Total**	
	flex/ext	**n**	**%**	**n**	**n**	**%**	**%**	**n**	**%**
Hip range	(0-30)	2	5	3	11	28	8	6	15
	(30-60)	4	10	4	10	26	10	2	5
	(60-90)	0	0	3	5	13	8	2	5
	ext (0-30)	7	18	0	8	21	0	1	3
	N/A	2	5	2	5	13	5	1	3
Knee range	(0-30)	8	21	6	23	59	15	9	23
	(30-60)	2	5	1	4	10	3	1	3
	(60-90)	3	8	3	7	18	8	1	3
	N/A	2	5	2	5	13	5	1	3
Inter-limb angle	(0-30)	0	0	0	2	5	0	2	5
	(30-60)	2	5	4	6	15	10	0	0
	(60-90)	6	15	2	12	31	5	4	10
	(90-120)	3	8	1	6	15	3	2	5
	N/A	4	10	5	13	33	13	4	10
Trunk flexion	Extended	0	0	3	5	13	8	2	5

Neutral	8	21	2	18	46	5	8	21
Flexed	7	18	7	16	41	18	2	5

Seasonal Match and Pitch Injury Distribution

March had the highest injury incidence (25%). Injuries were most common during the second (16′-30′, 28%) and fifth (61′-75′, 21%) match periods (Figure S1 and S2). Nearly half of the injuries occurred in the offensive third of the pitch (goal area and left corridor), one-third in the midfield zone, and the remainder in the defensive third (Figure 4).

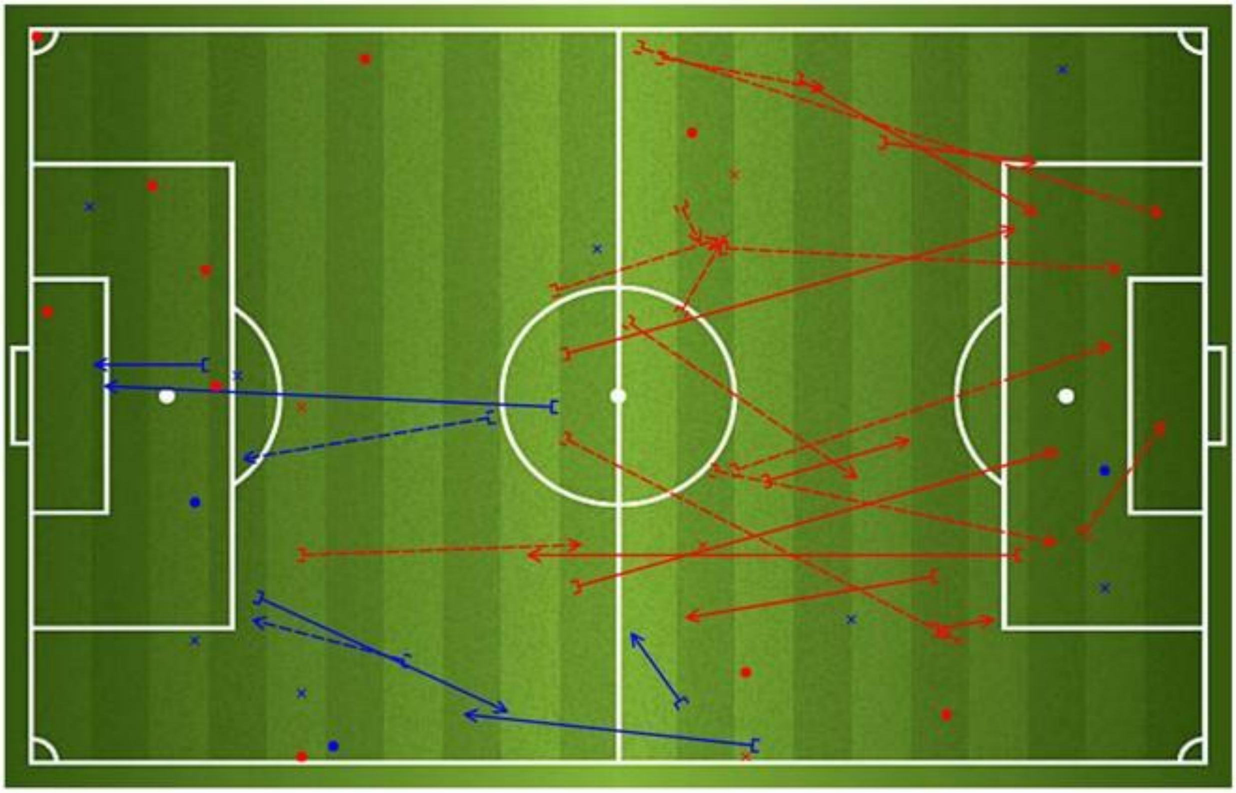

Figure 4: Injury pitch distribution. Red: offensive phase injury. Blue: defensive phase injury. The continuous line indicates the linear sprints and the dashed line the curved sprints. Circles represent the kick-type, crosses the duel-type, and triangles the other-type injuries.

Discussion

The key finding of this study was that hamstring injuries in elite women's football primarily followed run-type and stretch-type situational patterns [73,261,263]. These patterns often involve rapid movements with high eccentric demands on the posterior thigh along with hip flexion and knee extension. Both injury types are strains, with stretch-type occurring at long muscle lengths, while run-type occurs within the muscle's normal working range [268]. In addition to situational patterns, external factors such as ball interaction, opponent pressure, physical contact, and space constraints, force players to rapidly adapt movements increasing injury risk.

Injury context

Only 52% of the injury videos were eligible for analysis, meaning this study represents a sub-section of HSIs in women’s football match play. The player substitution criterion likely skewed the sample toward more acute onset and severe injuries, potentially underrepresenting less severe cases, as reflected in the high injury severity observed. While this represents an inherent limitation of observational studies, it warrants consideration when interpreting the findings. It is important to note that video analysis studies aim to describe injury mechanisms and situational patterns, rather than providing a complete epidemiological overview. This focus is especially relevant for HSIs, where players can often complete the game despite the injury, unlike ligament or tendon injuries which typically force players to stop immediately. Additionally, the limited media coverage of women’s football may result in more attention being paid to severe injuries, which are more likely to be reported, potentially contributing to a selection bias that affects the representation of injury severity. HSIs were more common in offensive situations (72%), whereas the opposite trend was observed for ACL ruptures [467,553]. Most injuries in this study occurred during the middle quarter of both halves. The timing of ACL injuries is often linked to higher-intensity demands or early onset of fatigue, which can impair neuromuscular control and decision-making [473]. Similarly, HSIs are suggested to be preceded by a short period of higher running demands in professional football players [451]. This suggests that the mechanisms underlying injuries are often more complex than a single triggering event, indicating non-linear causality. Injuries may result from the dynamic interaction of multiple factors that evolve across different timescales [8]. This complexity arises from the interplay between intrinsic factors, such as fatigue and pre-existing conditions, and extrinsic factors, including environmental and contextual conditions (see Table S1), which may increase the probability that a movement typically considered safe becomes more likely to result in injury. Future video analysis studies should include a control group with comparable situations and/or biomechanics not resulting in injury (item 10 of the QA-SIVAS scale) to better establish causal relationships and mitigate misinterpretation of findings.

Injury mechanisms

All injuries were classified as either non-contact (74%) or indirect contact (26%). These results align with Gronwald *et al.* findings on professional male soccer [73], but the proportion of indirect contact injuries doubled that reported by Della Villa *et al* [261]. Indirect contact injuries, primarily associated with upper body perturbations, were twice as likely to involve stretch-type compared to run-type injuries. These contacts were categorized into hold/pull and hit/push types, as players must manage distinct perturbations that challenge their biomechanical strategies. In hold/pull contacts, sudden deceleration potentially increases the eccentric load on lower limbs, as they counteract the force and maintain balance [554]. This effect is further intensified by trunk tilt, which puts additional stress on the posterior muscle chain [555]. In hit/push situations, an acceleration force increases the injured player's velocity, shifting the center-of-mass forward and likely reducing the time to stabilize joints before ground contact [556]. Hold/pull-type contacts seemed to be associated with greater injury severity (122±104 days) compared to hit/push-type contacts (73±71 days), suggesting that different types of perturbation may influence not only injury risk but also its nature and in turn recovery time. Further research is warranted to better understand the relationship between perturbation type and injury severity. Contact in football can involve multiple areas (upper and lower body), multiple players, can be prolonged (e.g., shirt pulling) and vary in intensity. Our analysis suggests that midfielders, especially when interacting with the ball, are at higher risk of indirect contacts and should receive targeted training. Given that most indirect contacts (60%) occur at the upper body level, these interactions likely increased trunk perturbations and, consequently, influenced pelvic stability. The biarticular nature of hamstring muscles and its myofascial connection to the erector spinae via the sacrotuberous ligament emphasize the pelvis's role in hamstring strain regulation [222]. For instance, increased anterior pelvic tilt has been shown to lead to a significant, non-uniform increase in tissue elongation across all regions of the hamstrings, with greater elongation in the proximal region [557]. Athletes with a history of HSI often show reduced neuromuscular coordination of the lumbopelvic muscles when responding to unanticipated trunk movements [412]. Perturbation training has been shown to improve neuromuscular control and reduce the risk of ACL injuries, particularly in female athletes with quadriceps dominance deficits, by enhancing hamstring activation and knee flexion angles [558]. Given the importance of neuromuscular coordination in injury prevention, video analysis could serve as a valuable feedback tool for enhancing movement efficiency and technique refinement. Commonly used in football for tactical preparation, video analysis could similarly help athletes identify and correct technique flaws and behaviors, potentially reducing injury risk while optimizing performance [499].

Situational pattern

HSIs were equally distributed between run and stretch-types (see Figure 3). All stretch-type injuries (excluding two landings from a wall jump) involved an interaction with the ball. Stretch-type injuries often occurred with excessive hamstring lengthening, with the hip flexed and the knee extended. Most kick-type injuries occurred during passing and crossing rather than shooting. Nearly half of the cases (43%) involved the loading leg, suggesting that rotational forces, extreme ROM in unusual positions, and anticipation movements influence HSIs more than peak force alone [270]. However, 2D video analysis, due to its intrinsic limitations, does not allow for such detailed analysis. There is ongoing debate about whether run-type injuries occur during the early stance or swing phase of running [275]. Based on our visual inspection of joint kinematics on the sagittal plane, the rapid transition from knee flexion to extension in the middle swing phase could also be critical, particularly when combined with overstriding. Most run-type injuries occurred at high speeds, but about 40% during acceleration or deceleration. The distance covered during these runs was 19±12 m. This highlights the need to incorporate match demands into sprint training, such as linear and curved progressions, varied run lengths, ball interactions, opponent engagement, and cognitive demands (e.g., decision-making). Moreover, skilled footballers often manipulate their opponents' perceptions by, for example, hiding their true intentions (e.g., feints) through motor inhibition [559]. These training features should be tailored to individual players' positions, characteristics, and team tactics.

An important aspect of designing effective injury prevention programs is the identification, analysis, and replication of influential risk factors and sport-specific movements, beyond just sprinting, recognized as high-risk situations. Without this comprehensive approach, prevention efforts may remain incomplete, leaving players more vulnerable. In addition to improving hamstring flexibility and strength, training strategies should emphasize technique, coordination, balance, and control—key skills for efficient movement execution that ensure both movement quantity and quality. This is particularly relevant in football, where the lower limbs play a dual role in both locomotion and ball-handling demands [560], a distinction that sets this sport apart from all others. This unique characteristic may partly explain why football is the sport with the highest incidence of HSIs.

Clinical implications

Understanding the situational patterns and biomechanical characteristics of HSIs provides evidence-based information for developing targeted injury risk reduction strategies [23]. Injury prevention programs may improve by targeting sport-specific injury patterns including running, kicking, and dueling. Incorporating varied exercises and real on-field scenarios into training can better prepare the hamstring muscles for game demands, potentially reducing the risk of injury. While there is growing evidence supporting the role of targeted training in injury prevention, the causal relationship between targeting specific injury mechanisms and reducing injury incidence remains an area of ongoing investigation, and further studies are required to definitively establish this link.

Limitations

Limited footage in women's football due to reduced media coverage made tracking injuries challenging. To collect enough cases, the study covered seven seasons across six different championships, which hinders findings generalization. Differences in playing style, fitness level, match frequency, climate, together with other factors may influence injury patterns and mechanisms. An official injury video database would enhance research in this field by overcoming limitations such as small sample sizes and time-consuming searches, providing more reliable results and supporting future data-driven applications. A major limitation in video-based analysis of hamstring strain injuries (HSIs) is the challenge in identifying the precise injury frame (IF), which is less clear than in ACL ruptures or tendon injuries. This is especially problematic in "run" and "open kinetic chain stretch" patterns, where injury mechanisms involve rapid, complex movements that make it difficult to isolate the exact moment of injury onset. To enhance the accuracy of identifying the IF, incorporating athletes' own narratives of their injury experiences could provide valuable insights. For instance, using questionnaires or interviews to gather players' accounts of their movements, symptoms, and perceptions at the time of injury could help corroborate or refine video-based observations. The injured location was often recorded generically as 'hamstring,' with only 23% specifying the exact muscle involved. Further details on injury level and type were usually unavailable and no MRI imaging was collected. Enhanced diagnostic precision in future studies could support analysis of potential associations between situational patterns and injury types as existing evidence suggests that biceps femoris long head is frequently linked to run-type HSI, while semitendinosus and semimembranosus are more common in stretch-type patterns [150,561]. The absence of match play and exposure data further limited the study. Addressing these limitations in future research may contribute to a deeper understanding of the situational and biomechanical factors underlying distinct hamstring injury types.

Conclusion

This study analyzed 57 HSIs in elite women's football, revealing that HSIs primarily followed run-type and stretch-type patterns, with non-contact mechanisms being the most common. However, a subset of injuries involved indirect contact mechanisms, such as push or pull perturbations from an opponent, which may have contributed to the loss of balance or altered movement execution preceding injury, particularly in the duel-type subcategory. HSIs often took place during offensive play, particularly while sprinting or engaging in ball-related actions, with additional factors such as opponent pressure and cognitive demand influencing the injury risk. Our findings highlight the importance of replicating match conditions in injury prevention programs, incorporating varied sprint distances, ball interactions, and opponents' influence to prepare players for the dynamic and changing circumstances identified in HSI scenarios.

Competing interests: None declared.

Contributorship: Contributors AP and MZ conceived and designed the study. AR and FE assisted with video collection, injury data retrieval, and video editing. AP, FDV, and MB analyzed and rated the video footage for injury mechanisms, situational patterns, and biomechanical characteristics. All authors participated in the consensus discussions. AP performed data analysis and interpretation. All authors provided intellectual contributions to the writing and drafting of the manuscript. MZ and AP assume responsibility for the overall content as guarantors.

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Ethical approval: All accessed videos were publicly available, and no personal player information was used, hence ethical approval was not required.

Data sharing statement: Data are available upon reasonable request. Key data are presented in the paper or in the supplementary material. General personal information about participants are available through public, open-access repositories like *www.fbref.com* and *www.soccerdonna.de*. Video footages were sourced from public platforms like Youtube or via Wyscout.

Patient involvement: Not applicable. Patients and/or the public were not involved in any stage of this research.

Supplemental Material

Table S1 - Match Condition and Characteristics.

Variable	**Category**	**n**	**%**	$\chi 2$	**p-value**	φ_c
Competition	National	40	66	9.281	0.002	0.40
	International	17	34			
Surface	Grass	39	68	32	<0.001	0.53
	Hybrid	11	19			
	Artificial	7	12			
Weather	Clear/Sunny	44	77	51.47	<0.001	0.67
	Cloudy	11	19			
	Rainy	2	4			
Kick-Off	Lunch-time	15	26			
	Evening	14	25	6.421	0.040	0.24
	Night-time	28	49			
Game State	Win	24	42			
	Draw	20	35	3.263	0.195	0.17
	Lose	13	23			
Ground	Home	17	30	13.05	0.001	0.34
	Neutral	9	16			
	Away	31	54			

Table S2 - Run-type situational pattern description.

Variable	**Category**	**n**	**%**	$\chi 2$	**p-value**	**φc**
Start	standing	12	41	9.586	0.008	0.41
	jogging	15	52			
	N/A	2	7			
Direction	linear	14	48	0.034	0.853	0.03
	curved	15	52			
Range	(0-10m)	6	21	9.759	0.021	0.33
	(10-20m)	12	41			
	>20m	10	34			
	N/A	1	3			
Running phase at IF	Acceleration	6	21	8.345	0.015	0.38
	HSR/sprint	17	59			
	Deceleration	6	21			
Mechanism	Indirect	5	17	12.448	<0.001	0.66
	non-contact	24	83			
Ball interaction	yes	13	45	0.31	0.577	0.10
	no	16	55			
Duel	yes	13	45	0.31	0.577	0.10
	no	16	55			
Playing phase	attack	21	72	5.828	0.016	0.45
	defend	8	28			
Kinetic chain	open	6	21	3.379	0.185	0.24
	closed	9	31			
	unsure	14	48			

Table S3 – Run-type duration, distance, and number of steps.

Variable	mean	SD
Duration (s)	2.9	1.8
Distance (m)	19	12
Steps (n)	13	7

Table S4 - Kick-type (Stretch-type subcategory) situational pattern description.

Variable	Category	n	%	$\chi 2$	p-value	φc
Type	pass	6	43	2.286	0.319	0.29
	cross	6	43			
	shot	2	14			
Injured limb	kicking	8	57	0.286	0.593	0.14
	loading	6	43			
Ball	moving	14	100	14	< 0.001	1.00
	standing	0	0			
Mechanism	indirect	1	7	10.286	0.001	0.86
	non-contact	13	93			
Duel	yes	5	36	1.143	0.285	0.29
	no	9	64			
Playing phase	attack	11	79	4.571	0.033	0.57
	defend	3	21			
Kinetic chain	open	6	43	2.286	0.319	0.29
	closed	6	43			
	unsure	2	14			

Table S5 – Duel-type (Stretch-type subcategory) situational pattern description.

Variable	Category	n	%	$\chi2$	p-value	φc
Type	protect	2	17	2.000	0.368	0.29
	press	4	33			
	intercept	6	50			
Mechanism	indirect	7	58	0.167	0.683	0.12
	non-contact	5	42			
Duel	yes	10	83	5.333	0.021	0.67
	no	2	17			
Playing phase	attack	8	67	1.333	0.248	0.33
	defend	4	33			
Dominance	yes	10	83	5.333	0.021	0.67
	no	2	17			
Kinetic chain	open	3	25	3.000	0.083	0.50
	closed	9	75			
Phase	acceleration	2	17	5.333	0.021	0.67
	deceleration	10	83			

Table S6 – Sagittal plane kinematics of total HSIs (n=39) categorized by situational pattern.

Variable	**Category**	**Run**		**Kick**		**Duel**		**Total**	
	flex/ext	**n**	**%**	**n**	**n**	**%**	**%**	**n**	**%**
Hip range	(0-30)	2	5	3	11	28	8	6	15
	(30-60)	4	10	4	10	26	10	2	5
	(60-90)	0	0	3	5	13	8	2	5
	ext (0-30)	7	18	0	8	21	0	1	3
	N/A	2	5	2	5	13	5	1	3
Knee range	(0-30)	8	21	6	23	59	15	9	23
	(30-60)	2	5	1	4	10	3	1	3
	(60-90)	3	8	3	7	18	8	1	3
	N/A	2	5	2	5	13	5	1	3
Inter-limb angle	(0-30)	0	0	0	2	5	0	2	5
	(30-60)	2	5	4	6	15	10	0	0
	(60-90)	6	15	2	12	31	5	4	10
	(90-120)	3	8	1	6	15	3	2	5
	N/A	4	10	5	13	33	13	4	10
Trunk flexion	Extended	0	0	3	5	13	8	2	5
	Neutral	8	21	2	18	46	5	8	21
	Flexed	7	18	7	16	41	18	2	5

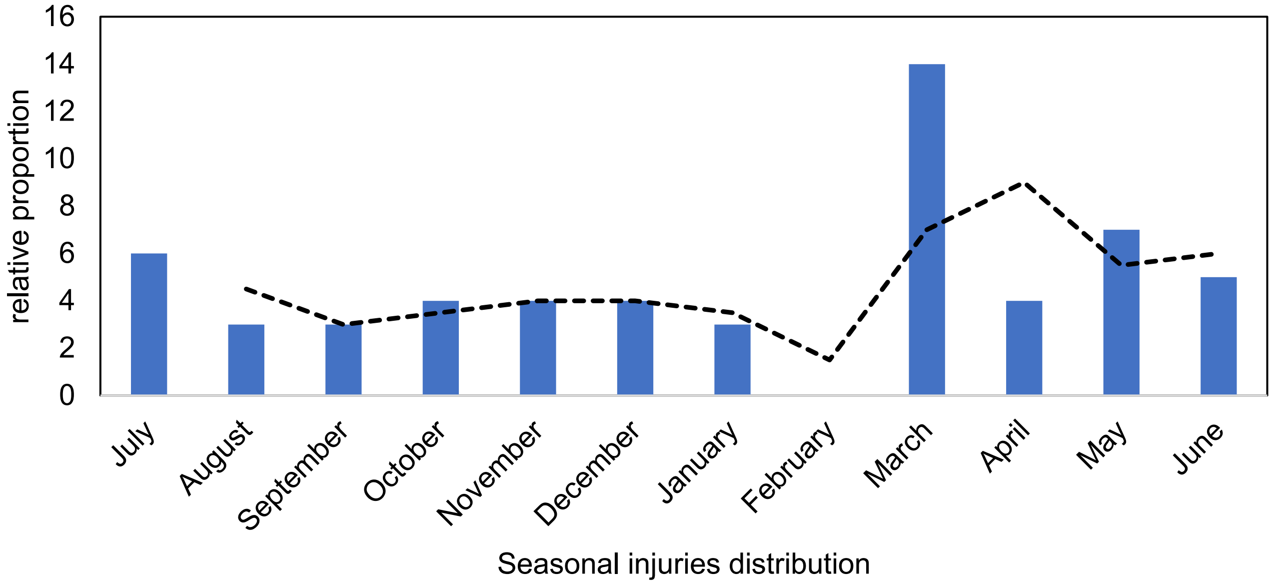

Figure S1: monthly injury distribution across seven seasons.

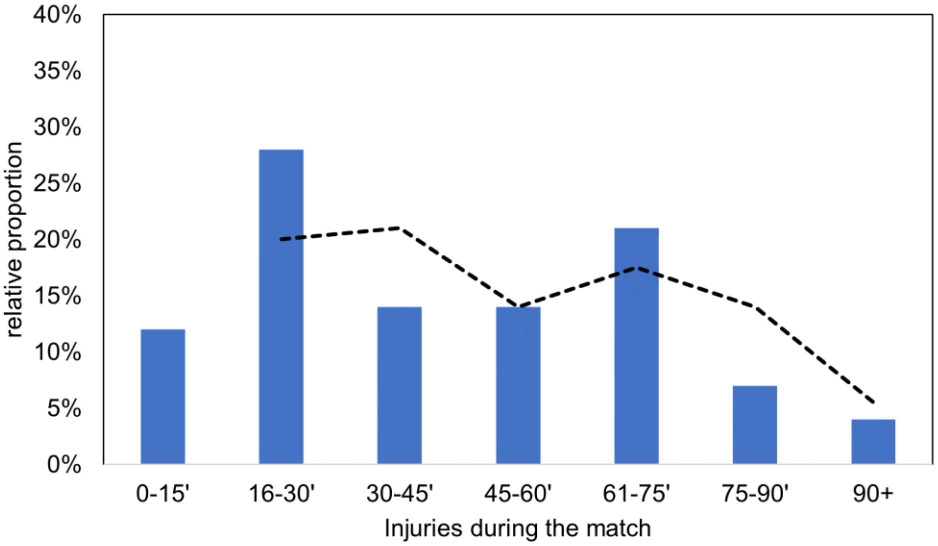

Figure S2: injury time distribution during the match. The dashed line indicates the moving average of HSIs throughout the game.

Paper 2

Three-Dimensional Reconstruction of Run- and Stretch-Type Hamstring Injury Patterns in Professional Football Using Model-Based Image Matching

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Abstract

Purpose: Hamstring injuries (HSIs) are common in football and are often associated with high-speed running. However, non-sprinting actions, such as stretch-type movements, also contribute substantially to overall injury burden. Detailed biomechanical insights into these distinct situational patterns remain limited. The aim of this case report was to reconstruct the three-dimensional (3D) joint kinematics of one run-type and one stretch-type HSI in professional football using the model-based image matching (MBIM) technique.

Methods: Two video-confirmed HSIs sustained during official football matches were analyzed. MBIM was applied to reconstruct 3D full-body kinematics from broadcast footage, focusing on joint angles and movement patterns in the time window preceding and including the injury frame. Injury-inciting activities and contextual circumstances were also described.

Results: The stretch-type injury occurred during a multiplanar, lunge-like action involving trunk tilt and rotation toward the non-injured side, combined with rapid hip abduction and internal rotation. The run-type injury occurred during high-speed running, characterized by predominantly sagittal-plane motion and higher linear velocity. Although similar joint configurations were observed at the injury frame (hip flexion, knee extension, trunk flexion), the kinematic patterns leading to injury differed substantially between cases.

Conclusions: The MBIM technique enabled detailed 3D reconstruction of movement patterns preceding HSIs in real-game scenarios. These findings highlight the potential of integrating video analysis with 3D biomechanical reconstruction to better capture the diversity of injury-inciting activities underlying HSIs in football.

Keywords: video analysis; hamstring injury; injury prevention; football (soccer); biomechanics

Introduction

Video analysis of broadcast footage has become an established method for investigating injury events in sport, with recognized value in both clinical and scientific contexts [69,463,485]. In football, two-dimensional (2D) video analysis has been widely used to examine a range of injuries, including HSIs, enabling the description of injury-inciting activities and their surrounding circumstances in real-game [72,73,261–266,290]. This approach has contributed to a more ecologically valid understanding of how injuries occur and has supported the development of context-specific prevention strategies [2,64,70].

HSIs predominantly occur via a non-contact mechanism during rapid, high-intensity movements, when the hamstrings activate to decelerate the swinging leg and resist excessive knee extension and hip flexion, exposing the muscle–tendon unit (MTU) to a combination of eccentric loading, high velocity, and moderate-to-long length that may exceed tissue tolerance [268–271]. Traditionally, running-based actions have been considered the predominant situational pattern of HSIs and have received the greatest attention in both research and practice [275,399,426,562].

However, recent video analysis studies have highlighted that HSIs also frequently occur during non-sprinting actions, such as stretch-type movements, which may account for a substantial proportion of cases [73,261]. These findings suggest that HSIs can arise from different sport-specific tasks characterized by distinct movement demands. Such variability reflects the anatomical and functional complexity of the biarticular hamstring muscle group, which operates across multiple joints and planes of motion during dynamic football-specific actions [151,196,563].

In addition to movement-related factors, contextual elements such as ball interaction, opponent pressure, and task constraints can further influence injury risk by disrupting movement coordination and stability [564–566]. Football performance unfolds in a dynamic and interactive environment in which players continuously adapt their actions to evolving spatial and temporal constraints. This highlights the importance of adopting a comprehensive perspective when analyzing injury events, accounting for the interaction between multiple influencing factors. While 2D video analysis provides valuable qualitative insights into these real-world scenarios, its ability to quantify joint kinematics remains limited by factors such as parallax distortion, subjective interpretation, and reliance on visual estimation [464,481].

A more advanced, yet seldom adopted, method for quantitative kinematic estimation is the Model-Based Image-Matching (MBIM) technique, which enables 3D reconstruction of the injured player’s movement from uncalibrated video footage, providing a time-based analysis of joint angles [482,484]. However, despite its successful application in the study of other sports injuries, its use in the investigation of HSIs in football remains unexplored.

The aim of this case report was to reconstruct the 3D joint kinematics of one run-type and one stretch-type HSI in professional male football using the MBIM technique. In addition, injury-inciting activities, contextual circumstances, and relevant player information were described to provide a more comprehensive understanding of injury occurrence, informing future research on injury prevention strategies.

Methods

Two cases of biceps femoris strain injuries sustained during official Serie A matches in the 2023/24 season were analyzed. Both injuries occurred within the same team, at their home stadium (natural grass), under similar weather conditions and with the same match result (draw: 0 – 0).

Player A, a 26-year-old right full-back (height 1.90 m; body mass 82 kg), sustained a type 3b biceps femoris injury at the musculotendinous junction in the proximal middle third of his dominant right thigh, resulting in a 34-day layoff, with no prior reported history of HSI according to the Transfermarkt database. Player B, a 23-year-old right winger (height 1.84 m, body mass 76 kg), sustained a type 3b biceps femoris injury in the proximal middle third of his dominant right thigh, leading to a 50-day layoff, also without a previous HSI history. All clinical information was obtained from the club's medical staff, and the diagnosis of Player B was confirmed by magnetic resonance imaging (MRI) examination (Figure 1), while MRI for Player A was not available.

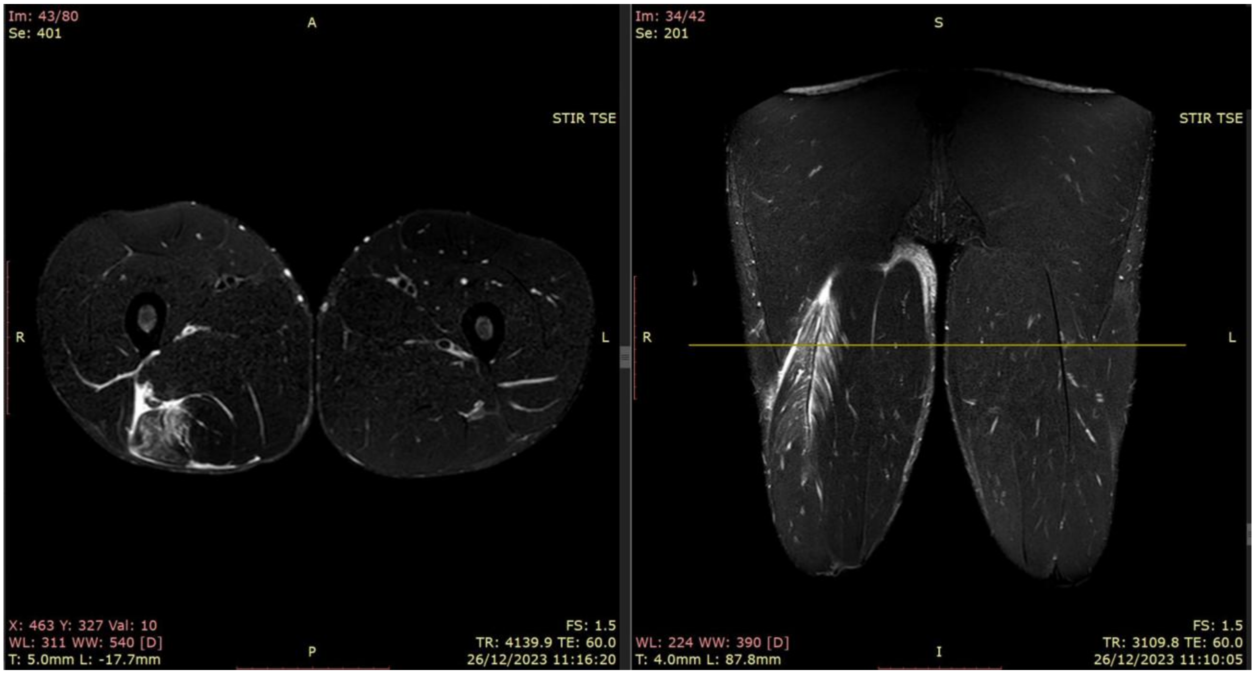


Fig. 1 *Biceps femoris injury confirmation through MRI scans in axial (left) and coronal (right) views at Short Tau Inversion Recovery sequence (Player B)*

A set of predefined variables was used to characterize each injury, following an established methodological approach [265]. Each video was independently reviewed by two analysts to reduce intra- and inter-operator variability [464].

Both videos had a resolution of 1920 × 1080 pixels and a sampling frequency of 25 frames per second. Player A's video included two camera views: a wide, elevated semi-sagittal left view from the main camera and a replay showing a semi-frontal anterior perspective. Player B's video included three camera views: a wide, elevated semi-sagittal left view from the main camera, along with two replay angles showing semi-sagittal right and semi-frontal anterior perspectives.

As described by Zago et al. [484], the MBIM technique was applied following these steps: (i) multi-view, non-coaxial video images were inspected using Kinovea (v. 0.9.5, KinoveaInk) to identify the "injury frame" (IF); (ii) camera views were captured at approximately 100 ms intervals from 400 ms before IF to 110 ms after IF; (iii) a size-matched pitch was created in Blender (v. 3.3, Blender Foundation) and used for camera calibration by matching reference points in the images; (iv) a 3D skeletal model consisting of 39 skeletal segments connected by 30 rotational joints was fitted to the player's pose in each frame from each view; (v) intermediate poses were interpolated; and (vi) Euler joint angles of the trunk and lower limbs (injured and contralateral) were extracted.

The video footage analyzed in this study was publicly available broadcast material. All data were anonymized and handled confidentially, in line with previous similar investigations.

Results

Injury-inciting activities and contextual features

The injury to Player A occurred in the sixth minute of the match during a duel in the lateral defensive half of the pitch. After receiving the ball, the player performed an initial controlled touch, followed by a technical error during the subsequent touch while advancing with the ball, covering approximately 8 m from the first contact to the IF. The player's gaze was directed at the ball. The injury was classified as an indirect contact mechanism within a stretch-type situational pattern. Three distinct contacts were identified within 240 ms before and at the IF: lateral upper-body contact, contact at the ankle of the uninjured leg, and contact to the upper-body back. These were classified as hold-type for the first two and push-type for the latter. The football-specific pattern was categorized as duel-type, involving a shielding movement with a lunge to protect ball possession, performed with the injured leg in a closed kinetic chain and a heel-strike ground contact.

The injury to Player B occurred in the 42nd minute of the first half during an offensive play in the right lateral corridor of the attacking half, near the sideline. The injury was also classified as an indirect contact mechanism, occurring within a run-type situational pattern. A single but prolonged push-type contact to the lateral upper body on the uninjured side was observed within 241 ms preceding and up to the IF. The sport-specific injury pattern involved high-speed running following an approximately 37 m curved run with ball conduction, initiated from a steady start position over 5.6 seconds. At ground contact, the injured leg was in a closed kinetic chain with a forefoot-strike pattern, and the gaze was directed at the ball. The foot position relative to the center of mass suggested an overstride pattern at ground contact.

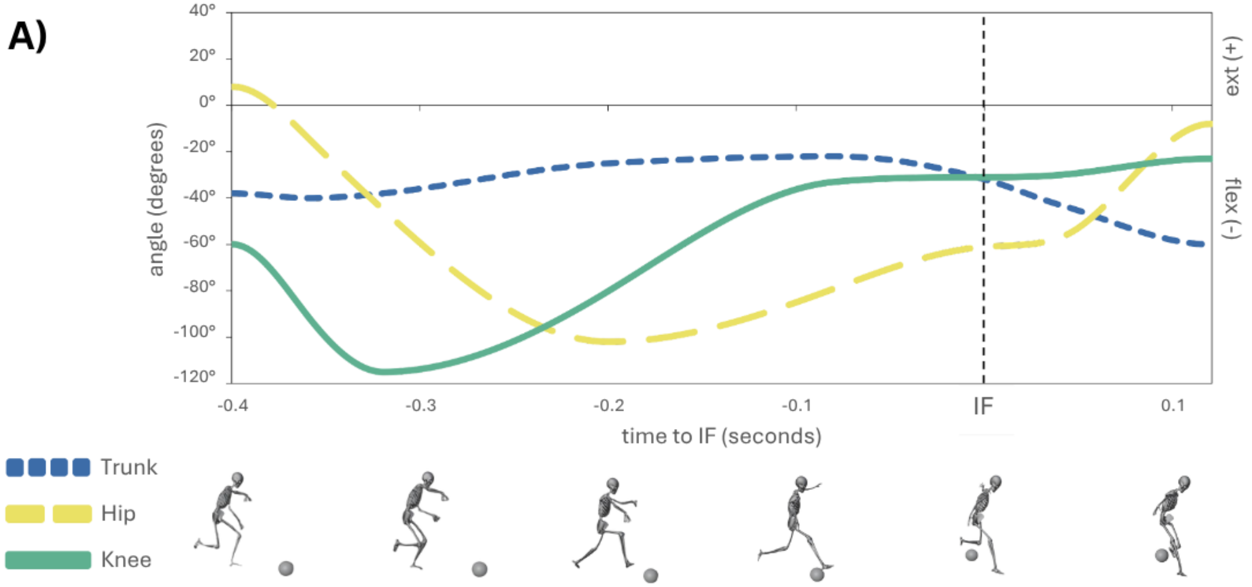
Kinematic analysis – Player A (stretch-type)

Kinematic analysis of Player A (Figures 2 and 3) revealed a coordinated lunge-like movement involving combined trunk and lower limb adjustments. In the sagittal plane, the hip transitioned from extension to peak flexion approximately 300 ms before IF, followed by a progressive decrease in flexion as ground contact approached. This was accompanied by knee extension from a flexed position, reaching approximately 32° at IF, and ankle plantarflexion of approximately 21°. The trunk showed a rapid increase in flexion prior to IF, consistent with the push-type contact on the upper-body back. In the frontal plane, an initial trunk tilt toward the injured side was followed by a rapid shift toward the uninjured side. The hip simultaneously transitioned from approximately 30° of adduction to an abducted position within less than 100 ms. In the transverse plane, the hip moved rapidly from 35° external rotation to 9° internal rotation, while the trunk rotated from 10° toward the uninjured side to −12° toward the injured side. These changes reflected a rapid reorientation of the body in response to the duel and contact conditions.

Kinematic analysis – Player B (run-type)

The movement pattern of Player B (Figures 2 and 3) reflected a running strategy characterized by relatively continuous motion and smaller angular variations despite the prolonged push-type contact. In the sagittal plane, the hip extended and then flexed to approximately 25° at IF, while the knee transitioned from approximately 75° of flexion 160 ms before IF to around 50° at IF. The trunk maintained a relatively stable flexion posture (approximately −20°), with minor adjustments before IF and a slight increase afterward. In the frontal plane, the hip moved from an abducted to a more neutral position approximately 200 ms before IF, while the knee showed a brief adduction peak of approximately 14° before stabilizing. The trunk initially tilted toward the uninjured side, peaked at approximately 12°, and then gradually shifted toward the injured side around 50 ms before IF. In the transverse plane, the hip rotated from approximately 10° internal rotation to 16° external rotation before returning toward internal rotation near IF. The trunk showed a similar pattern, rotating first toward the uninjured side, then toward the injured side, and finally reversing again. The knee showed small oscillations between internal and external rotation, reaching approximately 3° internal rotation at IF.

The kinematic profiles and joint configurations at the IF are summarized in Figures 2 and 3.


A)
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0°
-20°
-40°
-60°
-80°
-100°
-120°
angle (degrees)
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IF
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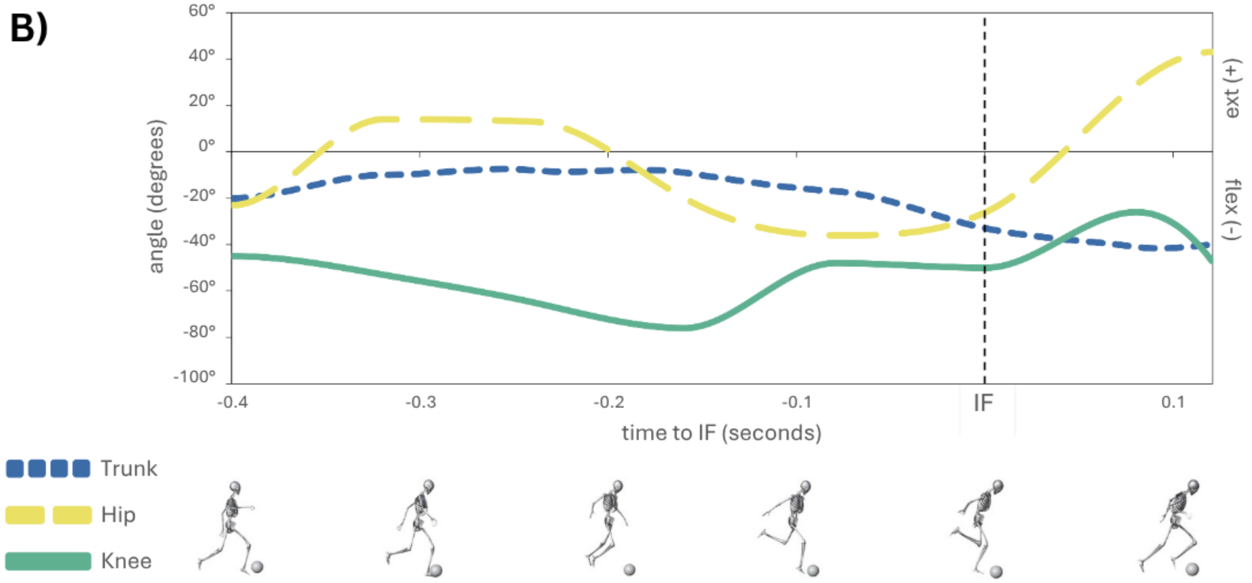
time to IF (seconds)
Trunk
Hip
Knee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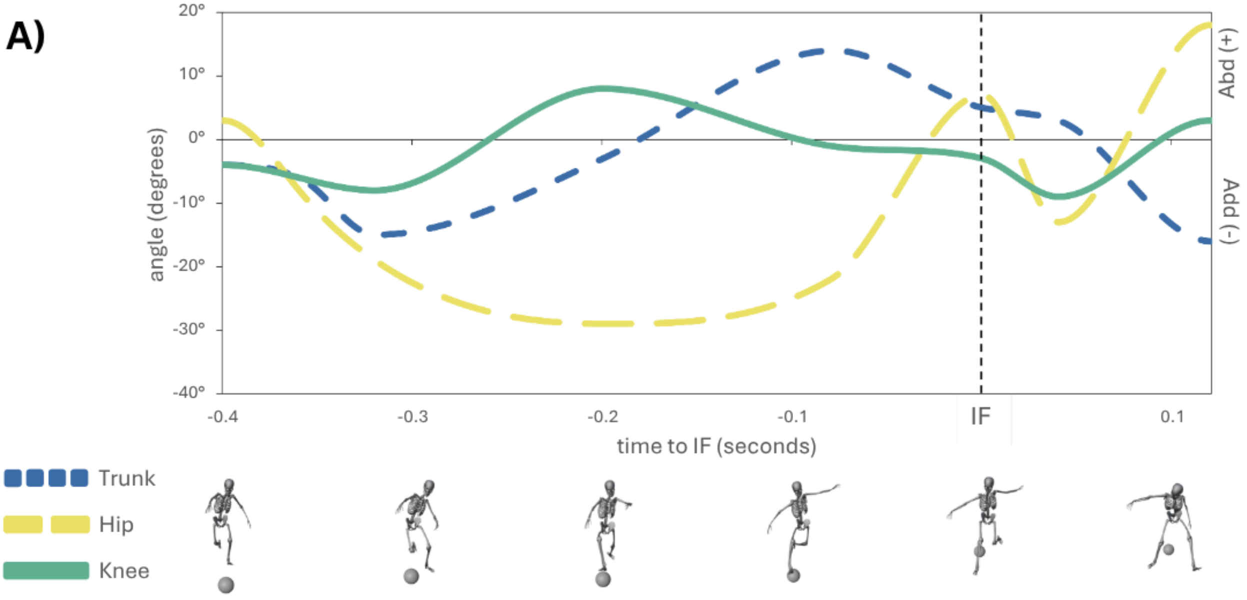
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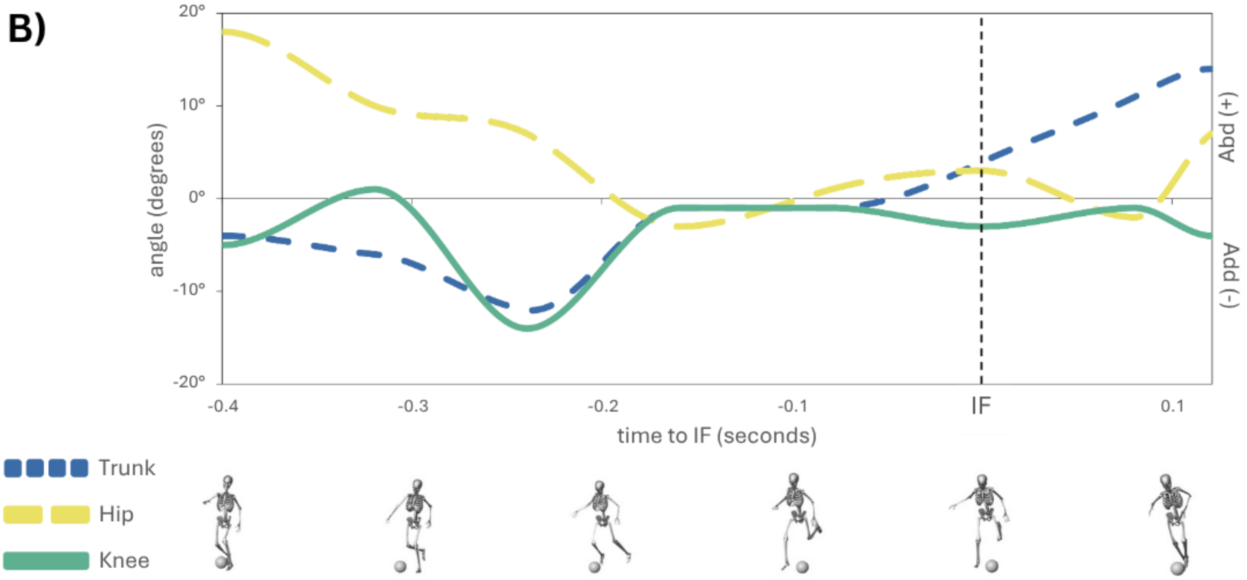
Knee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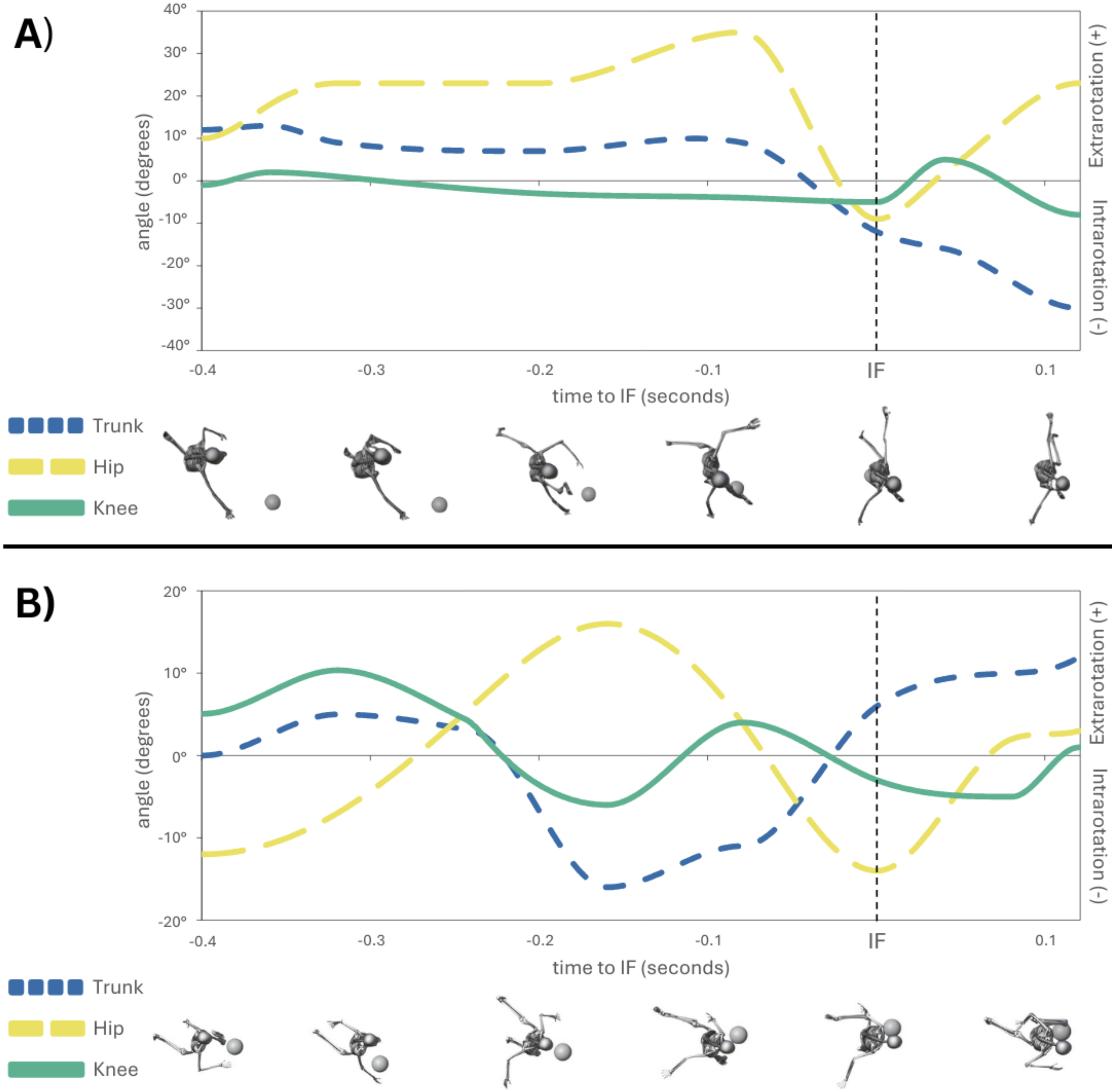
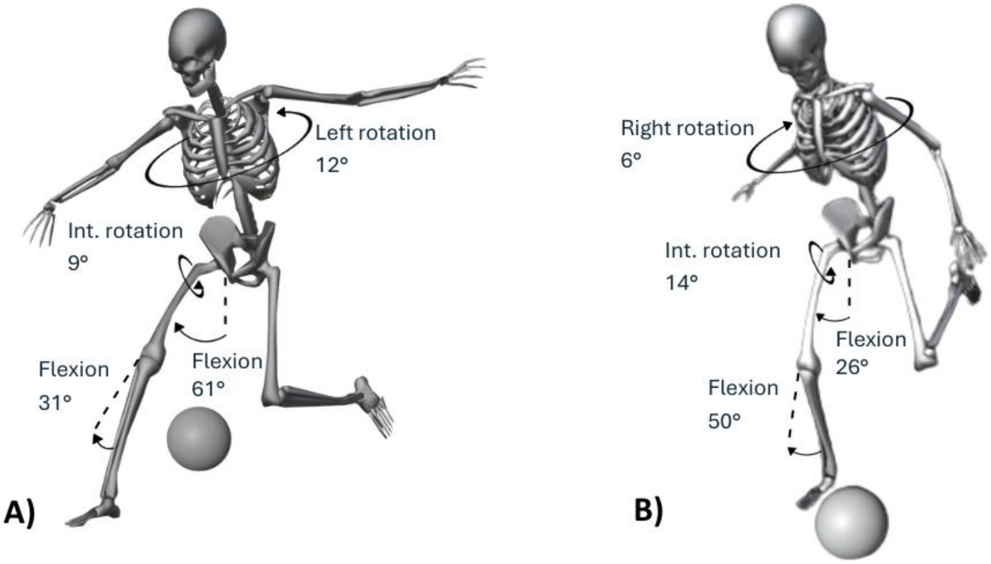


Fig. 2 *Time-series kinematic profiles in the sagittal (top panel), frontal (middle panel), and transverse (bottom panel) planes for Player A (upper row) and Player B (lower row). Joint angles of the trunk (blue short-dashed line), hip (yellow long-dashed line), and knee (green solid line) of the injured (right) limb are plotted from −0.4 to +0.1 seconds relative to the estimated injury frame (IF; vertical dashed line).*



Joint	Sagittal		Frontal		Transverse	
Trunk	- 32°	- 33°	5°	4°	- 12°	6°
Right Hip	- 61°	- 26°	7°	3°	- 9°	- 14°
Right Knee	- 31°	- 50°	- 3°	- 3°	- 5°	- 3°

Fig. 3 *Summary of the main kinematic findings at the injury frame (IF). Top: 3D skeletal models illustrating joint positions, with arrows indicating movement directions. Bottom: table reporting joint angles across the three planes. Sagittal plane (z): extension (+) / flexion (−); frontal plane (x): abduction (+) / adduction (−); transverse plane (y): external rotation (+) / internal rotation (−)*

Discussion

This study represents the first application of MBIM to HSI in football, enabling a more comprehensive examination of movement patterns associated with injury events. We analyzed two representative HSI cases: one stretch-type and one run-type, to capture the diversity of inciting activities typically observed in football [73,467].

The stretch-type injury occurred during a multiplanar, less sagittal-dominant movement, whereas the run-type injury involved higher linear velocity. Despite differences in movement patterns, both injuries occurred during active play situations that required simultaneous management of multiple task demands, including decision-making, ball interaction, and dueling with an opponent under time constraints. These shared contextual features suggest that the emergence of HSIs may not be solely explained by biomechanical factors but also involves perceptual-cognitive demands inherent to football performance [567,568].

Injury prevention strategies may benefit from incorporating more representative, task-specific scenarios that reflect the complexity of real-game situations. Training approaches that extend beyond isolated drills, integrating technical, tactical, and perceptual demands alongside physical loading may better prepare players for high-risk situations. Additionally, considering contextual factors such as playing position, tactical role, and phase of play (e.g., offense, defense, transition) may contribute to more individualized and ecologically valid preventive interventions.

Indirect contacts

In both cases, the players experienced indirect contact through side-by-side duels with opponents. These contacts differed in terms of location, type (push vs hold), intensity, and timing relative to the IF. In such situations, players are required to rapidly adapt to external perturbations, which may challenge coordination, stabilization, and reaction time, potentially increasing injury susceptibility. From a practical perspective, players who are frequently exposed to duels may benefit from additional perturbation training (e.g., reaction to contacts) aimed at improving neuromuscular control under different unanticipated external forces [558,569]. Special emphasis should be placed on pelvic and trunk stability, given their proposed association with hamstring strain risk [396,412,413,557].

Kinematic analysis

Although both players exhibited similar joint configurations at the injury frame—characterized by hip flexion, knee extension, and trunk flexion, consistent with previous literature—the movement patterns preceding the injury differed substantially.

Player A, injured during a lunge-like action, exhibited greater hip (~100°) and knee (~120°) flexion prior to the injury, reflecting deeper loading of the lower limb. In contrast, Player B displayed a more linear, forward-oriented strategy typical of sprinting, with a rapid transition from hip extension to flexion and a lower peak knee flexion (~80°). In the frontal plane, Player A showed a marked hip excursion from adduction to abduction shortly before the IF, whereas Player B exhibited more controlled frontal-plane motion. In the transverse plane, both players demonstrated trunk rotation, although in different directions, possibly reflecting adjustments to maintain balance following upper-body contact.

Player A was characterized by rapid, large-amplitude changes in hip rotation (from external to internal rotation), combined with trunk rotation toward the injured side, suggesting a highly dynamic and coordinated response to a perturbation. Conversely, Player B exhibited a more continuous movement pattern with smoother kinematic transitions and smaller angular variations, consistent with high-speed running demands without sudden acceleration / deceleration or change of direction.

Overall, these observations suggest that different movement strategies may expose the hamstring MTU to distinct mechanical demands. Despite these differences, both cases resulted in injury to the biceps femoris, suggesting that multiple interacting pathways may converge toward a similar injury outcome.

Clinical implications

Each injury-inciting activity may impose distinct biomechanical and neuromuscular demands, supporting the concept that HSIs are multifactorial and heterogeneous in nature [297]. Research evidence indicates that mechanical loads and muscle activation profiles vary depending on the specific movement performed, potentially affecting distinct regions and components of the hamstring MTU [285,570–572].

This variability suggests that HSIs may not be adequately addressed by a one-size-fits-all approach. Instead, rehabilitation and return-to-play strategies may benefit from being tailored to the specific movement demands and contextual characteristics associated with reported injury events. For example, interventions targeting long muscle-length loading, multiplanar control, and perturbation management may be particularly relevant for stretch-type patterns, while high-speed running mechanics may be more relevant for sprint-related injuries. Importantly, the presence of different injury patterns should not be interpreted as contradictory, but rather as consistent with the complex functional role of the hamstrings across diverse sport-specific tasks [293].

To advance rehabilitation and return-to-play strategies, interventions should be individualized, targeting the specific demands and vulnerabilities including previous injury history, rather than being generalized or limited to restoring sprinting performance alone. Monitoring players over time may further support this approach by capturing fluctuations in injury susceptibility.

Future directions

Although the combination of video analysis and MBIM provides detailed biomechanical insights, it remains time-consuming and limited to small sample sizes. Future developments in automated motion analysis and computer vision may facilitate larger-scale applications of this approach. Integrating 3D kinematic data with additional information sources, such as MRI findings, external load monitoring, and contextual variables, may further enhance the understanding of underlying injury etiology. Future research should also explore muscle activation patterns and inter-muscular coordination during football-specific tasks that replicate common HSI scenarios. Such approaches may help identify modifiable risk factors, ultimately supporting the development of more representative screening tools and return-to-play assessments in football.

Limitations

This study has some limitations that should be acknowledged. First, the analysis is based on two cases only, which limits the generalizability of the findings. Second, although the MBIM technique allows detailed 3D reconstruction, it relies on manual fitting procedures and assumptions related to camera calibration, which may introduce estimation errors. Third, MRI confirmation was available for only one of the two cases, limiting the integration between biomechanical and clinical data. Finally, the approach is time-consuming and currently not feasible for large-scale analyses, restricting its application to selected cases rather than broader epidemiological investigations.

Perspective

Recent video analysis studies in football have shown that HSIs occur across a range of sport-specific actions, extending beyond high-speed running to include stretch-type situational patterns, often in combination with external perturbations and ball-related actions. While these studies have improved the ecological understanding of injury-inciting activities, they remain largely descriptive and limited in their ability to quantify joint-level biomechanics.

The present study extends this line of research by integrating video analysis with 3D biomechanical reconstruction using the MBIM technique. This approach enables a more detailed and time-resolved characterization of movement patterns preceding injury, providing complementary insights to existing video-based frameworks.

From a broader sports medicine perspective, these findings contribute to bridging the gap between qualitative descriptions of injury events and quantitative biomechanical analysis. This integration may support the development of more comprehensive models of injury occurrence that account for the interaction between contextual, task-related, and mechanical factors. As such, the combined use of video analysis and 3D reconstruction represents a promising direction for advancing injury research in football and other team sports.

Paper 3

Methodological Approaches in Video Analysis Studies of Hamstring Injuries in Football: A Systematic Review

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Abstract

This systematic review examined how video analysis has been applied to study hamstring injuries (HSIs) in football, with a focus on methodological procedures, reporting practices, and classification systems. A comprehensive search was conducted in PubMed, Scopus, Web of Science, and Google Scholar (last search: 12 December 2024). Observational studies of professional players of either sex that used video footage to analyze HSIs were eligible. Two reviewers independently screened records and extracted data. Risk of bias was assessed using the JBI Critical Appraisal Checklist for Analytical Cross-Sectional Studies and the QA-SIVAS tool. Data were synthesized narratively according to methodological domains and descriptive variables.

Out of 215 records, 11 studies met inclusion criteria, encompassing 399 HSIs in total. All studies involved professional players, with only one including female athletes. Six studies investigated HSIs exclusively, while five included multiple injury types. Methodological quality varied, with frequent limitations in observer training, coding procedures, inter/intra-rater reliability, diagnostic confirmation, and study design clarity. Statistical analyses were mostly descriptive. Injury mechanism (non-contact or indirect contact) was most consistently reported, whereas injury-inciting activities were heterogeneously defined, particularly at the situational pattern level (run- and stretch-type) and their football-specific subcategories. Biomechanics and contextual factors were inconsistently addressed.

The lack of standardized procedures limits comparability and generalizability across studies and may restrict the ability to derive clinically meaningful conclusions. This review highlights the need for more rigorous and uniform practice in video-based research on HSIs in football and proposes a structured methodological guide for future research. PROSPERO registration: CRD42025629162.

Keywords

hamstrings; football; athletic injuries; video analysis; biomechanics; risk factors

Introduction

Football (soccer) has the highest incidence of hamstring strain injuries (HSIs) among team sports [242], and HSIs represent the most common injury in football [48,104]. Despite generally resulting in short lay-off periods [123], their high recurrence rate leads to significant long-term performance and economic burdens [101], ultimately affecting team success and career longevity [271]. While the rise in high-intensity demands of modern football likely contributes to this trend, a prior HSI remains the strongest predictor of future re-injury [296]. Despite extensive research, HSI incidence continues to rise [49], suggesting that current strategies may not adequately address their multifactorial nature or translate into effective prevention [268,573].

Injuries arise from complex and dynamic interactions among biomechanical, physiological, and behavioral factors, rather than isolated events. In such systems, injuries do not result from a single point of failure but from evolving interactions and feedback loops among multiple components [8,21]. Identifying and describing the specific activities and circumstances surrounding injuries is therefore a critical component for prevention models [24,68]. This broader perspective, extending beyond the injured player to include situational and environmental features, can help uncover underlying mechanisms and modifiable risk factors, ultimately informing targeted and testable prevention strategies.

Video analysis of sports injuries has become an increasingly adopted method in the football medicine community, with growing recognition of its scientific and clinical value. Over the past decades, it has been applied to various injury types, including anterior cruciate ligament (ACL) tears, Achilles tendon ruptures, and adductor strains [77,468,470]. While video analysis provides valuable insights into real-world injury scenarios, it remains limited by factors such as video quality, reviewer(s) experience, subjective interpretation, and the lack of standardized procedures. In the absence of an ideal method for evaluating on-field injuries, efforts should focus on standardizing the video analysis process to mitigate biases and improve the reliability and validity of findings. Despite the growing body of video analysis research, heterogeneity in classification systems has led to inconsistencies in reporting HSIs injury-inciting activities, particularly at the situational pattern and football-specific action levels. Such inconsistencies risk oversimplifying diverse injury scenarios (run vs. stretch-type) and may lead to prevention strategies that fail to appropriately target the underlying causes [64]. Accurate and consistent reporting of how injuries occur is key to comparing, combining, and generalizing results across studies and improving knowledge translation to practitioners [16,574].

Although football-specific guidelines for injury reporting [31] and injury-inciting circumstances [70] exist, and the QA-SIVAS tool provides quality assessment of video analysis studies [464], practical methodological guidance remains limited for conducting and reporting video analysis studies tailored to a specific injury type within a given sport. Given that video analysis study design, coding priorities, and relevant variables vary by injury type and sport context, a key aim of this systematic review was to provide a football- and HSI-specific synthesis of commonly reported methods and variables, while highlighting gaps and inconsistencies in the literature.

Methods

This systematic review adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 statement [575]. The protocol was registered with PROSPERO (CRD42025629162).

Eligibility criteria

Studies were included if focused on professional male and/or female football players who sustained a HSI confirmed directly by diagnostic methods (e.g., MRI, clinical examination) or reported by media or official databases. We use the term hamstring injury (HSI) to describe any injury affecting the hamstring muscle-tendon unit, regardless of the specific mechanism or structural involvement. This term is more inclusive and anatomically accurate, as it covers muscle tears, tendon injuries, and avulsions. The phenomenon of interest was the description of injury-inciting activities, defined as the action performed in the moments leading to and at the time of injury, and injury-inciting circumstances, referring to the environmental and contextual factors surrounding the injury [70]. Only observational studies using video analysis were included. Studies lacking an explicitly stated design were classified based on their methods. Eligible studies had to report at least one of the following: methodological approaches, classification systems, or key biomechanical and situational variables. Only peer-reviewed articles in English were considered; conference abstracts and unpublished manuscripts were excluded. Studies were also excluded if they did not use video analysis, did not analyze HSIs in football, or lacked sufficient methodological details.

Information sources

Searches were conducted across PubMed (via NCBI), Scopus (via Elsevier), and Web of Science (via Clarivate). Additional sources were identified through Google Scholar and PROSPERO register. In addition to database search, backward and forward citation tracking and manual reference list screening were performed to identify further eligible studies. There were no restrictions on publication year. The last search was performed on 12/12/2024.

Search strategy

The search strategy was developed using the SPIDER framework [576] (Table S1 and S2), combining free-text keywords and controlled vocabulary (e.g., MeSH, Emtree) related to HSIs, video analysis, and football. The search strategy was iteratively refined and peer reviewed to ensure comprehensive coverage. The search syntax was tailored to each database utilizing Boolean operators (AND/OR), adjacency operators, and truncation where appropriate. Complete search strategies and query strings are provided in supplementary materials (Table S3).

Selection process

Two reviewers (AP, MZ) independently screened titles and abstracts, with disagreements resolved by a third reviewer (FDV). Reasons for exclusion at the full-text stage are documented (Table S4). The same two reviewers then independently screened the full text. No automation tools or machine-learning classifiers were used. The selection process is illustrated in the PRISMA flowchart (Figure 1).

Data collection process

Data were extracted independently and in duplicate by two reviewers (AP, MZ) using a custom-designed Microsoft Excel spreadsheet. Discrepancies were resolved through discussion or consultation with a third reviewer (FDV). When relevant information was missing or unclear, authors were contacted for clarification. No automation tools were used.

Data items

The primary outcomes included methodological and classification approaches. These included how video analysis was applied to describe injury mechanisms, injury-inciting activities, biomechanical characteristics, and injury-inciting circumstances of HSIs. Injury mechanisms were categorized as non-contact, indirect contact, or direct contact based on the presence or absence of contact at the suspected injury frame (IF) [30]. Injury-inciting activities were coded as the overall action performed in the moments leading to and at the suspected IF and were extracted at multiple levels of detail: (i) the situational pattern (general, sport-agnostic classification as run-type or stretch-type), (ii) football-specific category (sport-specific activity category within the situational pattern), (iii) player action (more detailed description of the football-specific categories), and (iv) additional information (descriptors providing further detail extracted from video analysis). Injury-inciting circumstances encompassed contextual and environmental elements surrounding the injury event, and biomechanical characteristics included joint angles and qualitative movement features at and around the IF.

All relevant data within these domains were extracted, regardless of the number of measures, time points, or analytical methods used. Additional variables were recorded to contextualize the methods used: study characteristics (publication year and study design), participant demographics (age, sex, and competition level), injury verification methods (imaging confirmation, clinical diagnosis, or media reports), video analysis details (source of video footage, type of analysis, and coding procedures), observer training and reliability, any reported risk factors, and information on injury distribution (e.g., game minute, pitch location). In cases of missing or unclear information, no assumptions were made, and only data explicitly reported in the original studies were considered.

Risk of bias assessment

Risk of bias was assessed using the JBI Critical Appraisal Checklist for Analytical Cross-Sectional Studies [577], evaluating domains such as sample representativeness, exposure and outcome measurement, statistical analysis, and the management of confounding factors. Additionally, the QA-SIVAS scale [464] was used to assess video-specific methodological rigor, including footage quality, consistency and transparency of coding procedures, observer reliability, and injury classification accuracy. Two reviewers independently assessed the risk of bias, with discrepancies resolved with a third reviewer. Assessment tools were used as published, without modification or automation.

Effect measures

Descriptive statistics were reported using frequencies and percentages for categorical variables and mean ± standard deviation (SD) for continuous variables. No formal meta-analysis or effect size calculations were performed due to heterogeneity in study designs and data reporting. Data were reported in their original form, and no transformation of effect measures was applied.

Synthesis methods

A narrative synthesis was performed due to methodological heterogeneity. Variables reported using different terminology were grouped into common categories for comparability. Findings were synthesized using structured tables and graphical formats, organizing studies by population and competition characteristics, study design and statistical approaches, injury information and risk factors, injury-inciting activity and circumstances, and biomechanical data. No sensitivity or subgroup analyses were conducted; however, methodological variability was considered when interpreting findings, ensuring transparency in the review process.

Results

Study selection

Database searches identified 213 records: 59 from PubMed, 68 from Scopus, 86 from Web of Science, and two from PROSPERO register. After removing 104 duplicates, 111 studies were screened by title and abstract. Of these, 13 underwent full-text review, and eight [72,73,261–264,266,578] were included. A separate Google Scholar search identified 30 studies, of which 16 were retrieved and three met eligibility criteria [443,451,579]. In total 11 studies were included (Figure 1).

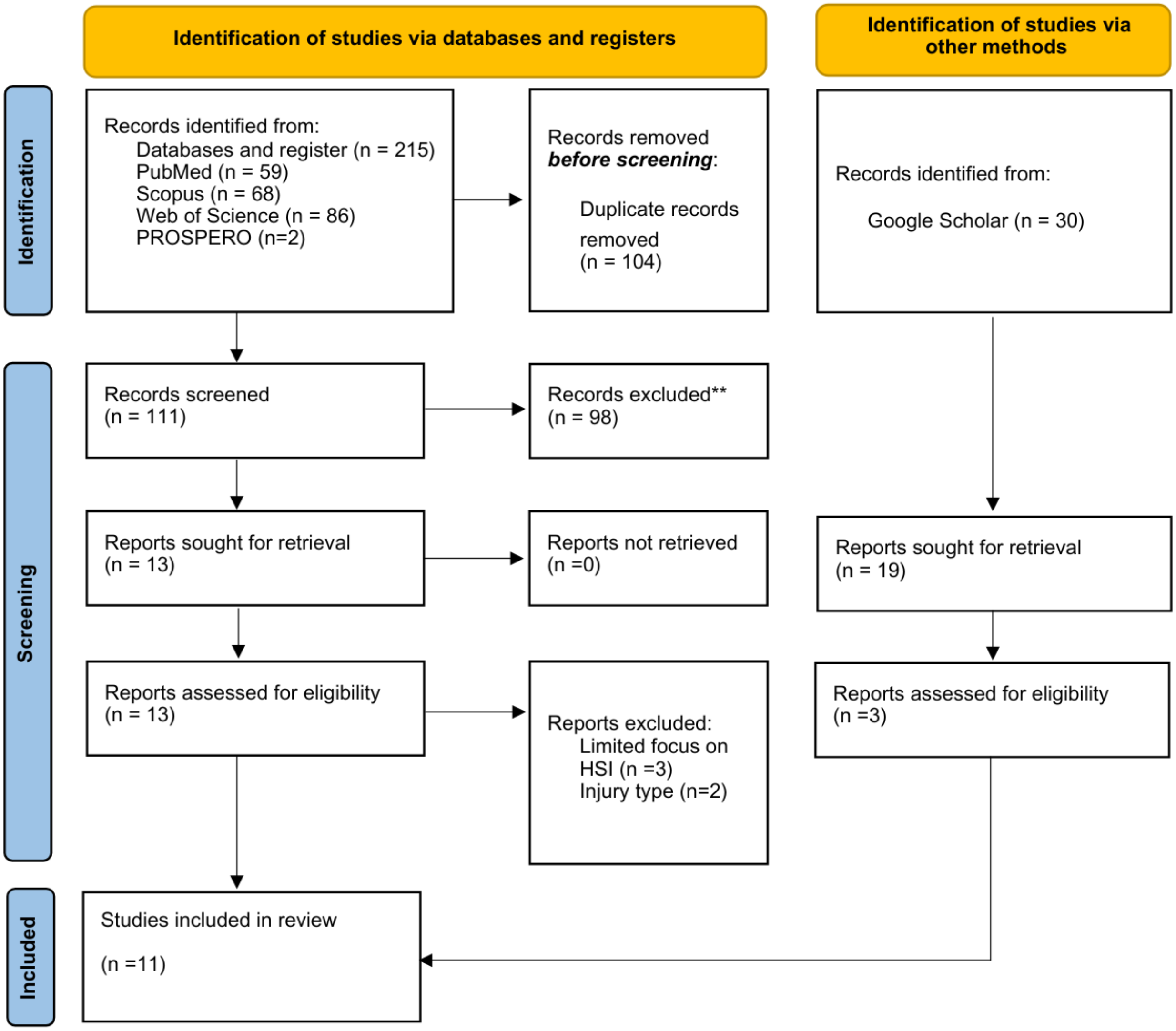


Figure 1 *PRISMA 2020 flow diagram illustrating the process of study identification, screening, eligibility assessment, and inclusion in the review*

Study characteristics

The included studies, published between 2021 and 2024 (with no restriction on publication year), involved professional football players. Six focused exclusively on HSIs [73,262,263,266,451,578], while five investigated broader injury types [72,261,264,443,579]. Only one study included female footballers [262], and one comprised multiple sports [578]. The number of HSIs analyzed through videos ranged from 8 to 61, but only five studies [73,261,262,264,266] reported the total number of HSIs occurred during the study period.

Risk of Bias in studies

The JBI Critical Appraisal Checklist for Analytical Cross-Sectional Studies revealed varying bias levels (Table S6), with critical weaknesses in inter- and intra-rater reliability (item 3) assessed in only two studies [72,578]. Diagnostic imaging (MRI) confirmed injuries in three studies [73,263,451] and clinical examination in one [266]. The rest relied on medical records, online databases, or reports. Only two studies [443,579] explicitly addressed confounding factors, mainly in the context of subgroup comparisons; however, most studies were primarily descriptive and did not aim to estimate exposure effects. Statistical analysis was mainly descriptive, often limited to absolute and percentage distributions. The QA-SIVAS scale ratings ranged from 9 to 14 out of 18 (Table S7), with key concerns in video quality, as no study met all requirements. Injury details were often incomplete, and only one study [451] included a non-injured control group (item 10). While three studies [73,263,578] provided quantitative biomechanics, none used a validated methodology (item 11).

Population characteristics and injury distribution

Demographic data were reported inconsistently (Table S8). Age was reported in eight studies [262–264,266,443,451,578,579], as mean ± SD or categorized into age groups. Only three studies provided anthropometrics [264,266,451], and four assessed player laterality [261,262,443,579]. Playing position was reported in eight studies [72,261–263,266,443,451,579], generally grouped as goalkeepers, defenders, midfielders, and forwards. Seven studies did not specify the source of player information; the others relied on official databases (e.g., Lega Serie A) and publicly available sources (e.g., kicker.de, transfermarkt.de, Fbref.com).

Most studies focused on official matches, with three also considering friendlies and training [262–264]. Four studies covered domestic leagues [266,443,451,579], while others included national cups and/or international tournaments [72,73,261,262,264], or did not specify. The number of seasons covered ranged from 1 to 7, between 2013 and 2023. Match result was reported in two studies [264,451], venue in three [264,451,579] (Table S9).

Six studies reported injury distribution based on field location, using seven [266] to 14 distinct areas [72]. Five assessed injury time distribution: two reported the season and month [261,262], three the match number of the season (e.g., 4 out of 34) [443,451,579]. Eight studies documented injury timing within the match, using quarters [73,264], halves and quarters [261,262], or halves, quarters and extra time [266,443,451,579]. Only two specified the exact minutes played before injury [262,264] (Table S10).

Study design and statistical approach

Six studies explicitly stated their design as cross-sectional observational [73,261], retrospective descriptive [264], single-centre observational cohort [266], or nomothetic follow-up observational [443,579]; five did not. Regarding injury severity, four studies included moderate-to-severe HSIs [72,73,264,451], two severe-only [261,262], while the remaining did not define inclusion based on lay-off criteria. Two studies [443,579] used the inability to continue the match and being forced to leave the pitch as inclusion criteria. Seven studies systematically registered injuries [72,73,261,264,266,443,579]. Data collection methods included observation sheets and checklists based on previous research [30,72,463,467,470,580–583], the FIICCS [70], software LINCE v.1.4 [584], and OI-INJURIES-FOOTBALL observational instrument [585].

Statistical analysis tool included Microsoft Excel (2016 and 2018 versions) [73,261,263], IBM SPSS (versions 23-27) [72,266,443,451,578,579], Stata V.12 [261], Python statistical libraries [262], while one study [264] did not report any statistical software. Statistical approaches ranged from descriptive (absolute numbers, percentages, means, medians, interquartile ranges) [73,263,264,266] to inferential analyses, including chi-square (x^2) tests, Fisher's exact test [72], Student's t-tests [262], Pearson's correlation coefficients [443], and pattern analysis techniques such as T-patterns and polar coordinates [443,579]. Reliability was assessed using Fleiss' κ [72,578] and Cohen's κ [72] for inter- and intra-rater agreement, while the intraclass correlation coefficient (ICC) evaluated observer consistency [578]. Full details are in Table S11.

Diagnosis and injury characteristics

Five studies reported injury side (left/right) but only two specified whether it was the dominant leg. The specific hamstring muscle involved was reported in only two studies [73,263]. Injury severity was reported in four studies, with data presentation varying across studies; some used mean ± SD, while others reported median and range. MRI was used as direct diagnostic method in three studies, clinical examination in one; others relied on secondary sources (e.g., official medical records, insurance databases, online platforms) (see Table S12). One study explicitly defined injury, referring to Aspetar Injury and Illness Surveillance Programme [266]. Most studies cited Fuller et al. [33] for injury recording and classification, while two studies cited Bahr et al. [30] and two referred to the UEFA model [46]. Seven studies involved team physicians and/or players in injury assessment [72,73,261,263,264,266,451], one provided a narrative description [263]. Data on subsequent injury (recurrence) were reported in one study [451]. One study [263] reported injury level (proximal/central/distal), and another [264] the mode of onset (sudden/gradual/mixed). Injury incidence was available in just one study [451]. Two studies included external workload data before injury, using GPS [264] and Mediacoach [451].

Video analysis assessment

The methodological approach to video analysis assessment varied across the included studies (Table S13). Rater training or experience in video analysis was mentioned in three studies [72,261,266], and five detailed backgrounds [261–263,266,578]. Ten studies explicitly stated the number of raters involved, which ranged from two to nine, but only two studies assessed inter/intra-rater reliability [72,578]. Video sources included broadcasting platforms (e.g., Sky, InStat, Wyscout), social media platforms, and personal/team archives. Most studies used software tools for video processing. Four studies [72,73,263,451] reported the number of camera views and video resolution (pixel quality), and only one [451] reported the sampling frequency (fps/Hz). One study [263] included video examples in supplementary material alongside screenshots/video frames of the injury in the main text, as required by item 15 of the QA-SIVAS scale.

Injury mechanisms and injury-inciting activities

Eight studies categorized injury mechanisms as contact (direct/indirect) or non-contact (Table 1). Four studies classified contact by the body area involved (e.g., upper body, pelvis, injured leg); four specified contact type (e.g., tackles, collisions). Regarding injury-inciting activities, seven studies identified distinct situational patterns, with sprint- and stretch-related injuries most common, although some also reported “other” or “mixed” pattern.

Table 1 - Summary of injury mechanisms and injury-inciting activities reported across included studies.

Authors	Mechanisms	Area of contact	Type of contact	Situational Patterns
Gronwald et al. 2022	non-contact indirect	no	collision with ball, collision with opponent, kick of opponent, hit/push of opponent, other interaction with opponent, pull/hold of opponent	1) Sprint-related 2) Stretch-related 3) Other
Della Villa et al. 2023	non-contact indirect	upper body, pelvis, injured leg, un-injured leg	no	1) Running 2) Stretching 3) Kicking 4) Others
Jokela et al. 2023	non-contact indirect	*Yes*: direct contact to injured leg, indirect contact to trunk/ shoulder/ uninjured leg *No*: opponent close <2m / >2m away	*Who*: tackling other player, tackled by other player, both players tackling *Movement*: sliding (one foot/both feet), upright (foot/shoulder) *Direction*: from side/ front/ back	1) Sprint-related 2) Stretch-related 3) Mixed-type
Aiello et al. 2023	non-contact	no	no	1) Running 2) Jumping
Klein et al. 2021	non-contact indirect	head, neck, shoulder, upper arm, elbow, lower arm, wrist, hand/finger, trunk (chest, abdomen, back), hip, thigh, knee, lower leg, ankle, foot	*a)* Collision with opponent, teammate, ball, other collision, hit/push of opponent, pull/hold of opponent, kick of opponent, other interaction with opponent *b)* Fall, ankle twist, knee twist, slip, overuse, other	1) Running 2) Lunging
Della Villa et al. 2024	non-contact indirect	upper body, pelvis, injured leg	no	1) Running, 2) Stretching 3) Kicking 4) Others
Vermeulen et al. 2024	non-contact indirect	no	*Indirect contact:* intentional contact by injured player, intentional contact by opponent, unintentional contact *Type of contact:* sliding tackle, shoulder tackle, collision, push (with arms), other, unclear	1) Running 2) Stretching 3) Others

Prieto-Lage et al. 2021	no	no	no	no
Moreno-Perez et al. 2024	non-contact	no	no	no
Argibay-González et al. 2022	no	no	no	no
Yüce et al. 2022	non-contact indirect	no	no	no
Total (Out of 11)	**8**	**4**	**4**	**7**

HSIs situational patterns and football-specific actions

Table 2 summarizes situational patterns identified across studies. Seven studies analyzed running-related HSIs, considering linear or curved runs, changes of direction (COD), acceleration, deceleration, high-speed running [72,73,261–264,266]. Two studies categorized CODs by angle (0–45°, 45–90°, >90°), type (e.g., side-step, crossover), and movement direction relative to the injured leg (toward/away) [263,266].

Stretch-related HSIs have been reported in seven studies, involving both open kinetic chain (OKC) and closed kinetic chain (CKC) movements such as kicking, lunging, braking, reaching and shielding [72,73,261–264,266]. Four studies specifically examined kicking, noting the injured leg's role (kicking/supporting), type of kick (e.g., pass, cross, shot), and ball impact zone [72,263,266]. Other less frequent actions included jumping, goalkeeping, heading, heel-kicking, and rabona.

Two studies estimated pre-injury distance (m) covered in running-type pattern: one via video analysis [266], the other via GPS, which also provided acceleration, peak speed, and % max speed [264]. Studies covering broader injury types reported more general, rather than HSI-specific patterns.

Table 2 Classification of football-specific actions linked to hamstring injuries across the included studies.

Authors	Running pattern	Stretching pattern	Kicking injury	Other
Gronwald et al. 2022	acceleration, high-speed running, deceleration, curved high-speed running, exclusion with reason	open chain: kicking, other closed chain: braking, stopping (landing); braking, stopping (lunging); other	included in stretching pattern	no
Della Villa et al. 2023	acceleration and high-speed running	open kinetic chain, closed kinetic chain	only when the injured lower limb was the kicking one	reaching, jumping, heel kicking, twisting, rabona and while kicking without the ball
Jokela et al. 2023	acceleration, in speed, deceleration, change of direction	shielding, reaching for ball (with injured leg), jumping (landing)	kicking with injured/ uninjured leg, *type*: pass (short/ long), cross, shot on goal, clearing *direction*: forwards, backwards, to the side *ball impact*: side-foot, outside-foot, instep, toe kick, heel, volley, half volley	tackling, heading, dribbling, controlling ball, receiving pass (standing/running), screening, blocking, pressing (intention to tackle/no intention to tackle), goal keeping, collision, reaching for ball (with uninjured leg), jumping (taking-off/being mid-air), sliding, stretching
Aiello et al. 2023	linear and curved run; accelerating, steady speed, decelerating	controlling the ball in the air after a jump	no	no
Klein et al. 2021	starting, running up (to ball or opponent) or sprinting, stopping, change of direction	lunging	receiving, dribbling, passing, clearing, shooting,	heading, tackling, sliding tackle, shielding (ball/opponent), blocking (shot)
Della Villa et al. 2024	linear and change of direction, constant speed, acceleration and decelerating	open kinetic chain, closed kinetic chain	only when the injured lower limb was the kicking one	jumping, heel kicking and rabona kick

Vermeulen et al. 2024	linear and curved; acceleration, at speed, deceleration, and unclear; turning from injured leg, turning towards injured leg, and unclear; *speed:* fast, moderate, slow, and unclear	change of direction, kicking, jumping, receiving the ball, reaching, heading screening, blocking and pressing	*leg:* kicking, supporting, unclear *type of kick*: pass, long pass, cross, shot on goal, clearing, unclear *direction*: forwards, backwards, to the side (side of the injured leg), to the side (side of the uninjured leg), diagonal, unclear *ball impact*: side-foot, instep, toe kick, heel kick, volley, half-volley, unclear	receiving the ball, reaching, heading, screening, blocking, pressing
Prieto-Lage et al. 2021	no	no	no	*how the injury took place*: ALONE (sprint, turn, shooting, ball control) RIVAL (jump, collision, received tackle, performed tackle, hit by ball, goalkeeper's save)
Moreno-Perez et al. 2024	no	no	no	no
Argibay-González et al. 2022	no	no	no	*causative agent of the injury*: alone, opponent, partner *how the injury is caused*: sprint, dribbling, sliding, turning, tackled by other, shooting, falling, hit by ball, tackling other player, stretching, collision, kicked by other, unknown
Yüce et al. 2022	no	no	no	stopping/turning, descent from jump, jump, collision, sprint (fast running), fall
Total (out of 11)	**7**	**7**	**4**	**7**

HSIs mechanisms and situational patterns distribution

Six studies clearly reported injury mechanisms and situational patterns, enabling comparisons (Figure 2). Only the female cohort from Della Villa et al. (2024) was included, as the male cohort overlapped with Della Villa et al. (2023). One case in Vermeulen et al. (2024) was classified as unclear. Aiello et al. (2023) included only non-contact injuries. For consistency, similar terms were grouped into shared categories (Table S14).

Figure 2A shows total number of HSIs per study (range: 14-63) by injury mechanism. Non-contact was predominant, but indirect contact accounted for 27–35% in some studies [73,262,266]. Figure 2B shows distribution according to the situational pattern, categorized as run- and stretch-type or other situations. Run-type ranged from 21% to 94%, being most frequent in three studies. Conversely, stretch-type together accounted for over half of the cases in Gronwald et al. (2022) and Della Villa et al. (2023), highlighting non-running patterns' relevance. "Other" patterns were uncommon, peaking 43% in Jokela et al. (2023), reflecting classification differences.

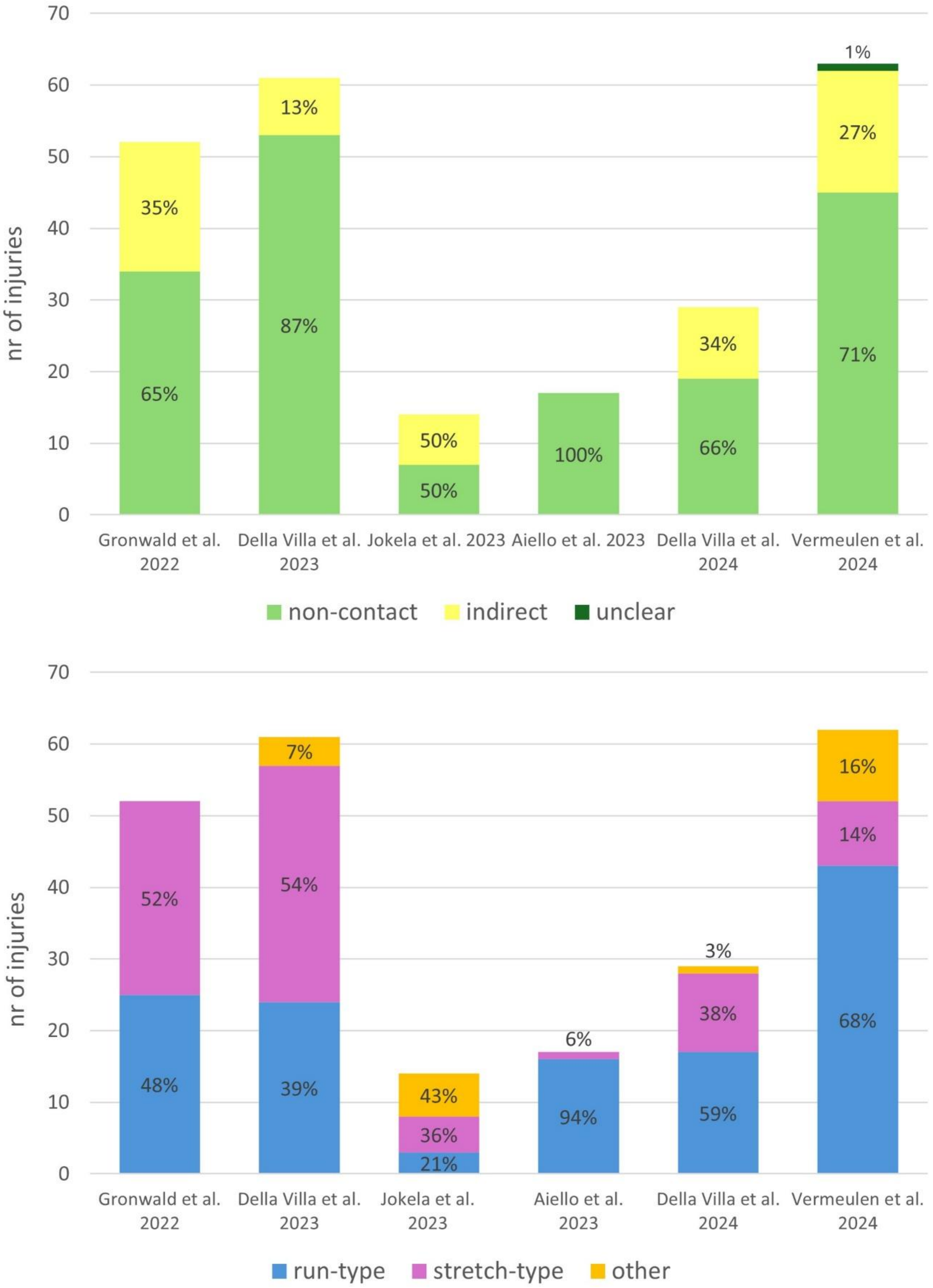


Figure 2 *Bar chart showing the total number of HSIs reported in six studies and their distribution by (a) injury mechanism: non-contact (light green), indirect contact (yellow), and unclear (dark green); and (b) situational pattern: run-type (blue), stretch-type (plum), and other (orange). The total number of injuries per*

study is indicated by the height of each bar, with proportional percentages of each injury mechanism displayed within the colored segments.

Injury-Inciting Circumstances

Table S15 summarizes injury contextual factors. Three studies examined concurrent movements (e.g., standing, jogging, sprinting, jumping) alongside the primary action during injury onset [72,263,266]. Ball possession (injured player, teammate, opponent, or loose ball) was analyzed in three studies [72,264,266], and interactions or duels with other players in four [72,263,443,579]. Additionally, five studies classified the playing phase preceding the injury, identifying offensive, defensive, and set-play situations (e.g., throw-ins, free kicks, corners, penalties, and goal kicks) [72,261,262,264,266].

Biomechanics

A subset of studies analyzed biomechanics (Table 3). Three studies reported sagittal hip and knee angles (in ranges of 45°), with one also assessing trunk tilt and rotation. Two studies classified movement direction (forward, lateral, backward, non-horizontal). Player velocity at IF was reported in five studies: three estimated intensity levels via video analysis (zero, low, moderate, or high), while two used direct measurements. Finally, three studies classified HSIs based on injured limb involvement in either open or closed kinetic chain (OKC or CKC), or unclear cases (e.g., run-type patterns occurring at the transition between late swing and early stance phase) due to the difficulty in determining ground contact from video footage.

Table 3 - Overview of biomechanical variables assessed in each study.

Authors	Kinematics	Movement direction	Movement velocity	Kinetic Chain
Gronwald et al. 2022	injured hip and knee, trunk (45° range)	no	no	no
Della Villa et al. 2023	no	no	horizontal and vertical (zero, low, moderate and high)	open, closed, unsure
Jokela et al. 2023	injured and uninjured hip and knee, trunk (45° range)	forward, lateral, non-horizontal	horizontal and vertical (zero, low, moderate and high)	open, closed, unsure
Aiello et al. 2023	no	no	directly measured with GPS	no
Klein et al. 2021	no	forward, lateral, backward, not horizontal	no	no
Della Villa et al. 2024	no	no	horizontal and vertical (zero, low, moderate and high)	open, closed, unsure
Vermeulen et al. 2024	no	no	no	no
Prieto-Lage et al. 2021	no	no		
Moreno-Perez et al. 2024	no	no	directly measured with Mediacoach	no
Argibay-González et al. 2022	no	no	no	no
Yüce et al. 2022	injured thigh, knee, foot ankle and trunk (flexion, extension, neutral) trunk tilt and rotation (ipsilateral, contralateral, neutral)	no	no	no
Total (out of 11)	**3**	**2**	**5**	**3**

Discussion

This systematic review provides a comprehensive overview of the methodologies used in 11 video analysis studies investigating HSIs in football (2021 – 2024), identifying consistent patterns, key strengths and limitations, and research gaps. While video analysis is a valuable tool, its application to HSI research in football appears relatively recent, as reflected by the publication years of eligible studies, and currently lacks standardized guidance specific to this context, limiting reliability and comparability. To advance the field, robust quality assessment tools, methodological standards, and consensus on terminology are needed. Future sports injury research would also benefit from integrating video analysis assessments with complementary quantitative data for a more comprehensive understanding of injury occurrence [547] [586]. In this context, we propose a methodological guide for HSI video-analysis research in football. Although extensive, this guide is intended as a structure synthesis and reporting aid rather than a validated framework; future work may refine and expand it according to specific research aims and emerging advancements in the field.

Study characteristics and methodological approaches

Most studies included in this review focused on male professional football players; only one study involved female players, and none examined youth or amateur populations, highlighting a significant gap in the current literature. The number of hamstring injuries analyzed per study ranged from 8 to 61, indicating considerable variability in sample sizes. Creating an official video injury database would substantially strengthen future research by reducing current limitations (e.g., small samples and time-consuming data collection) and enabling data-driven applications. However, implementation would require addressing practical and ethical barriers, including privacy and informed consent, proprietary ownership and access restrictions on match/training footage, and constraints on data sharing and long-term storage. According to item 2 of the QA-SIVAS checklist, video analysis studies should report both (i) the total number of injuries recorded during the study period and (ii) the number of cases for which video footage was available and analyzed. However, only five studies met this criterion. The lack of this information limits the ability to assess whether the analyzed sample is representative of the overall injury count, potentially introducing selection bias. Separately, from an epidemiological reporting perspective, athletes may sustain more than one health problem during the surveillance period; therefore, descriptive data should distinguish between the number of health problems (events) and the number of athletes affected [43].

It is also important to distinguish between video analysis studies and epidemiological studies. Video analysis is particularly suited to exploring the context and circumstances surrounding injuries, whereas epidemiological studies are more effective in systematically tracking injury incidence and trends over time. This distinction is especially relevant for muscle injuries such as hamstring injuries, which may not always be observable or documented in video footage. This is crucial given the limitations of video-based methods, which may miss injuries that occur off-camera, are obscured by other players, or do not immediately result in visible impairment or player substitution. In the case of hamstring injuries, players often complete the match and only report symptoms or receive a diagnosis in the days following the game, making it difficult to precisely identify the IF in video footage.

The type and depth of analysis achievable in observational video analysis studies largely depend on the study design. Single-club studies, such as Aiello et al. (2023), enabled more detailed injury reconstruction using direct data. In contrast, multiple team or league studies relied on public sources, which may offer less detail but better generalizability to a broader football population. Both approaches are valid and should be selected according to research aims and available resources.

Risk of bias was high for some studies, requiring cautious interpretation. Only two assessed inter- and intra-rater reliability [72,578]. Best practice recommends at least two experienced/trained raters, blinded to each other, reporting agreement for each variable [481]. Achieving an acceptable level of reliability initially can be challenging, but it should be considered an iterative process, where discrepancies are resolved through discussion and consensus-building [467,582,587]. Although study designs varied, all used retrospective observational methods. Future research should implement prospective video tracking to monitor players over time, enabling better identification of predisposing risk factors and providing a more dynamic and longitudinal perspective on injury development.

Statistical analyses

The statistical approaches used were predominantly descriptive and univariate, with only a few studies applying inferential analyses (e.g., x^2/Fisher's exact tests, Student's t-tests, ANOVA, odds ratios) and correlation analyses (e.g., Pearson's correlation), and occasional pattern-analysis techniques (e.g., T-patterns and polar coordinates) (Table S11). Although these approaches may identify basic associations, they are generally inadequate for capturing the complex and multifactorial nature of sports injuries, which often involve nonlinear interactions and dynamic feedback loops, leading to oversimplified interpretation [2,19,20]. There is growing recognition of the need for interdisciplinary collaborations to develop innovative statistical and computational methods for studying sports injuries, particularly in the context of team sports [588]. To advance the field, future research may benefit from exploring computational and system-oriented approaches to better capture the contextual and dynamic nature of injuries [26].

In practical terms, computational modelling approaches may support data-driven identification of recurring mechanism-circumstance profiles across injuries and, where appropriate, systems-oriented methods such as agent-based modelling could be used to explore “what-if” scenarios by simulating how changes in constraints (player-opponent interactions, task demands, match context) may influence the distribution of injury situations. Machine learning-assisted video processing may also support more scalable and standardized extraction of key events and kinematic surrogates (e.g., injury frame, foot strike, joint/segment orientation), reducing operator dependence and supporting replicable biomechanical procedures.

Player, injury, and competition characteristics

Sample characteristics reporting was inconsistent. While age was often included, variables like anthropometrics, dominant foot, and playing position were often missing. Seven studies did not specify player data sources, raising concerns about accuracy and reliability. Injuries were mostly from matches, with a minimal focus on training, potentially overlooking mechanisms that occur outside competitive play. While many studies classified injuries by season, month, or game segments, only two reported exact match timing, limiting insights into player status (starter/substitute) or minutes played before injury. Furthermore, contextual data such as competition type, venue, result, weather, and pitch surface were often underreported. Including such information would enrich risk factor analysis [589].

Injury verification and contextual injury/player profiling

Injury verification methods varied. Only a few studies confirmed diagnoses directly; most relied on secondary sources whose reliability is unclear, risking misclassification. Ideally, confirmation should involve direct communication with medical staff or injured players.

The term "hamstring injury", while commonly used, is overly generic, and only two studies have specified the muscle involved. Other clinically relevant details, such as dominance, severity, recurrence, onset mode, injury level (proximal/central/distal), and type (myofascial/musculo-tendinous/intratendinous) were largely missing, limiting the depth and precision of analysis. No study included prior injury history, despite being a well-established risk factor [590,591]. Pairing video observations with key clinical and player-level descriptors is important to contextualize the event and enable stratified analyses across clinically meaningful subtypes. These descriptors do not necessarily explain the visual injury mechanism per se, but they can improve interpretability for prevention and rehabilitation. To improve standardization, we recommend frameworks such as: FIICCS [70], STROBE-SIIS [30] and its football-specific extension [31], QA-SIVAS [464], and the London International Consensus and Delphi study on hamstring injuries part 1: classification [156]. Additional data collection tools (e.g., custom observation sheet or checklist) should be explicitly defined and shared. Finally, player load and exposure data were rarely integrated with video-based descriptions, despite the potential relevance of fatigue-related mechanisms in HSIs [592]. In line with a complex-systems view, injury determinants may emerge from interactions among constraints across short- (match) and long-term (weeks/season) timescales. Where tracking systems were used (GPS or Mediacoach), they were primarily leveraged to estimate running speed at (or immediately before) the injury event rather than to quantify broader match load. Where feasible, future studies should report basic contextual exposure descriptors from video footage (e.g., minute of injury, minutes played before injury) and acute match-load indicators from additional data sources (e.g., meters covered at high-speed, sprint counts, number of high-intensity accelerations/decelerations), and link these to longer-term exposure metrics (e.g., recent match congestion, seasonal exposure). Importantly, the achievable depth of such information, as well as the inclusion of other established risk-related measures, will necessarily depend on the aim, data availability, and setting of the study.

Injury mechanisms and injury-inciting activities

Studies generally agreed on injury mechanism classification. Non-contact injuries predominated, with fewer indirect contact and no direct contact cases. However, within injury-inciting activities, greater heterogeneity emerged at the situational pattern level (e.g. run-type, sprint-type, stretch-type, mixed, other patterns) and at its football-specific action level (e.g., running, kicking, dueling, other). While running is a generally recognizable pattern, stretching-related injuries exhibit greater variability, leading to inconsistent classification. They often involve rapid hip flexion and knee extension movements with high eccentric loading of the hamstrings, typically at longer muscle lengths and during less sagittal-dominant movement than run-type injuries [63,64]. Some studies differentiated between OKC and CKC movements, emphasizing actions like braking, stopping, lunging, reaching, and shielding. Kicking was either grouped with stretch-type injuries or analyzed separately, providing valuable insights into whether the injured limb functions as the kicking or supporting leg, as well as the type of kick executed. To enhance consistency in future research, we propose a multi-level reporting structure for injury-inciting activities consistent with our data extraction (Methods 2.6) and summarized in Figure 3E.

As shown in Figure 2B, non-running activities together accounted for most HSIs in three of six studies, indicating that prevention efforts overly focused on sprinting may overlook stretch-type patterns. Although progress has been made in analyzing running mechanics for performance and injury prevention [399,416,425,514,593], stretch-type patterns deserve equal attention in football. Even within the run-type pattern, recent findings indicate that HSIs are more frequently associated with acceleration rather than peak sprint speed [266], challenging traditional beliefs. Although running in all its variations (acceleration, change of direction, high-speed running, sprinting, deceleration) is indispensable for success in football and should receive significant attention, the lower limbs, particularly the hamstring muscle complex, are often required to reach extreme ranges of motion during less predictable, sagittal-dominant movements when interacting with the ball and/or opponent. Further MRI-based studies are needed to clarify associations between situational patterns and specific injury diagnoses.

Injury-inciting circumstances

Reporting of injury-inciting circumstances was limited and heterogeneous across the included studies. Only three studies reported ball possession status at injury onset, four evaluated player–opponent interactions/duels, and five classified the phase of play preceding the injury (e.g., offensive/defensive/set-play situations). In addition, only three studies described concurrent tasks performed alongside the primary action. Collectively, these findings suggest that contextual descriptors beyond the injury-inciting activity are inconsistently captured, despite their potential relevance for interpreting injury situations within the match environment. From a complex-systems perspective, HSIs likely emerge from interactions among multiple constraints (e.g., ball interaction, opponent pressure, concurrent tasks) that shape player behavior and susceptibility in the moments leading to injury [573]. In the studies that reported contextual factors, injuries were reported during active play, that often involve multitasking demands (neuromuscular and cognitive load), tactical constraints, and decision-making under pressure, which could collectively contribute to injury risk [594]. These findings support context-driven prevention programs that replicate real-game high-risk situations. While research has focused largely on biomechanical and neuromuscular factors, emerging studies link cognitive functions to football performance and injury susceptibility [567,568,595]. For example, impairments in working memory and inhibitory control have been linked to ACL injury risk [473]. In a recent cognitive framework for football performance [596], video analysis has emerged as a valuable tool for assessing on-field cognitive functions, such as scanning and decision-making. Further research should investigate whether stronger cognitive skills can mitigate injury risk by allowing players to better anticipate and adapt to unfolding game situations.

Video analysis quality and biomechanics

Broadcast footage remains the most used source for video-based injury analyses even though it may lack the technical specifications for accurate kinematic evaluation. Frame rate determines the temporal precision for identifying the suspected injury frame and rapid joint events; spatial resolution/zoom and the availability of multiple camera views affect landmark visibility, occlusion, and the feasibility of multi-planar assessment. However, many studies did not report these key features (frame rate, resolution, number and type of camera views as per the QA-SIVAS item 4), limiting appraisal of measurement uncertainty and comparability across studies.

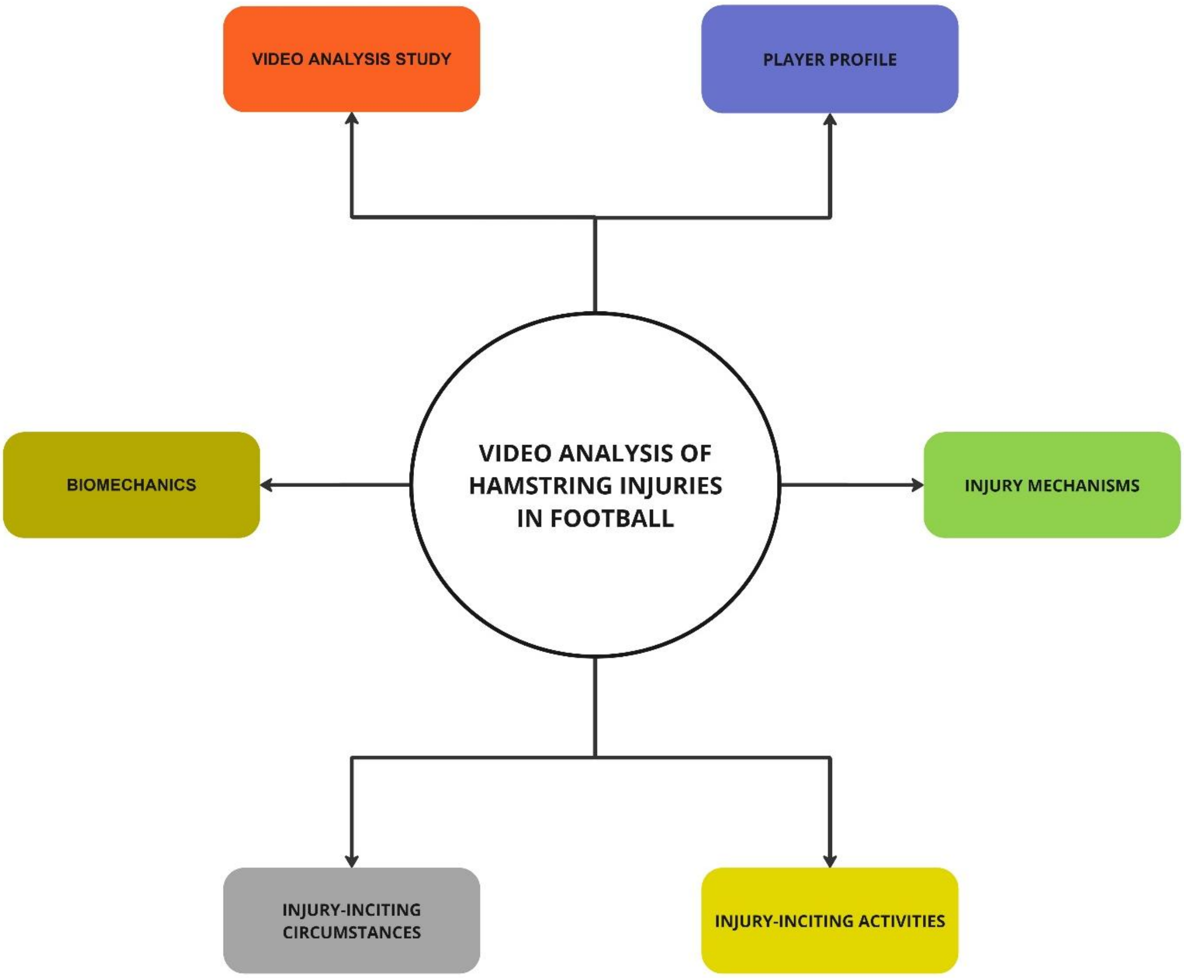
Since injury events unfold within milliseconds and involve a brief latency between the athlete’s reaction and the actual injury [597], determining the IF with absolute accuracy remains a key challenge, especially for muscle injuries, which are less visually distinct than ligament tears. This uncertainty can propagate to downstream classifications and to kinematic surrogates extracted at the IF. To mitigate this limitation, future studies should use independent, blinded multi-rater IF identification with a predefined tolerance (e.g., ±1–2 frames, depending on frame rate) and report inter-/intra-rater agreement. Minor discrepancies within tolerance may be resolved through collegial consensus, whereas larger discrepancies should be flagged as uncertain and, where appropriate, excluded from video analysis. Where feasible, IF identification may be supported through triangulation with complementary sources (e.g., player and/or medical staff narratives) [68].

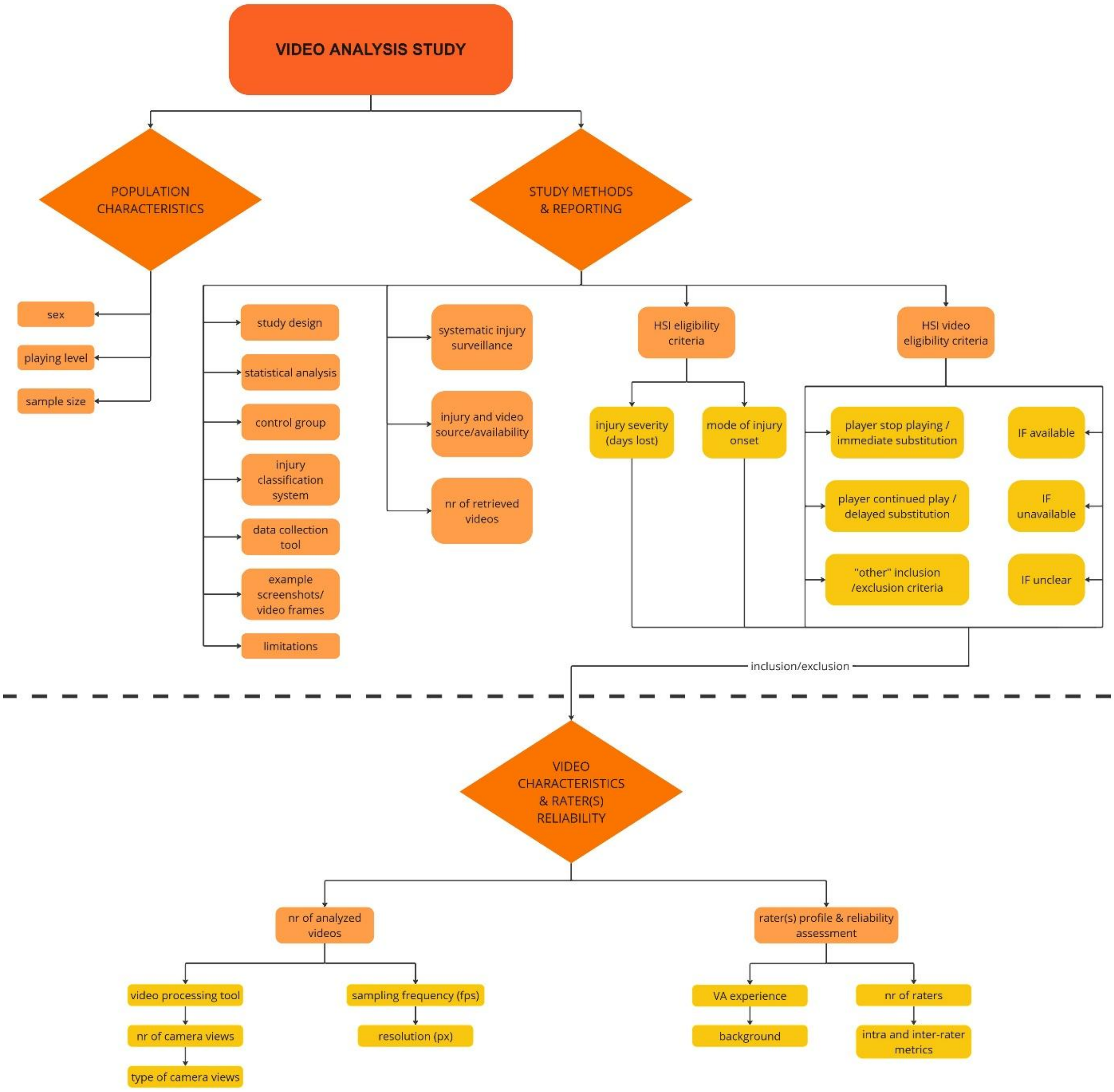
Although few studies performed biomechanical analysis, some described common kinematic features such as hip flexion and knee extension at IF. Trunk tilt and rotation have also been analyzed, reinforcing the role of whole-body coordination in injury occurrence [412]. Velocity, with distinctions between horizontal and vertical components, as well as movement direction (forward, backward, lateral) and phase (acceleration/deceleration) were described, as both directional force and movement speed may influence injury risk. However, these insights remain constrained by the subjective nature of visual interpretation rather than objective quantification, leading to inter-rater variability. Indeed, none of the included studies satisfied QA-SIVAS item 11, reflecting the lack of validated, standardized methods to address issues such as parallax errors and motion quantification. Future integration of automated motion analysis tools may help improve objectivity and accuracy [495] [598] [496]. Finally, the absence of control groups (i.e., similar movements performed without injury) limits the ability to draw causal relationships and may lead to misinterpretation of the findings.

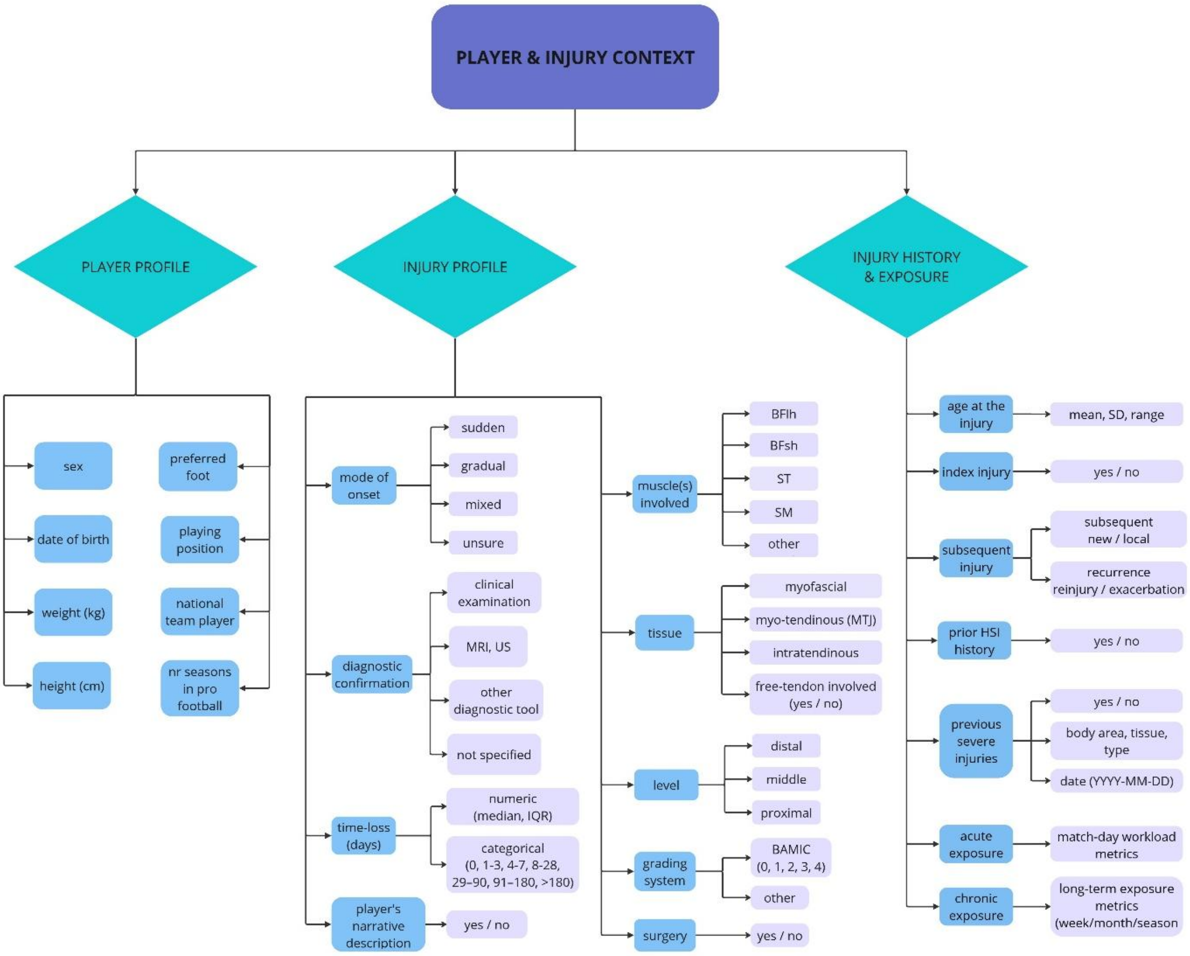
A methodological guide for video analysis studies of HSI in football

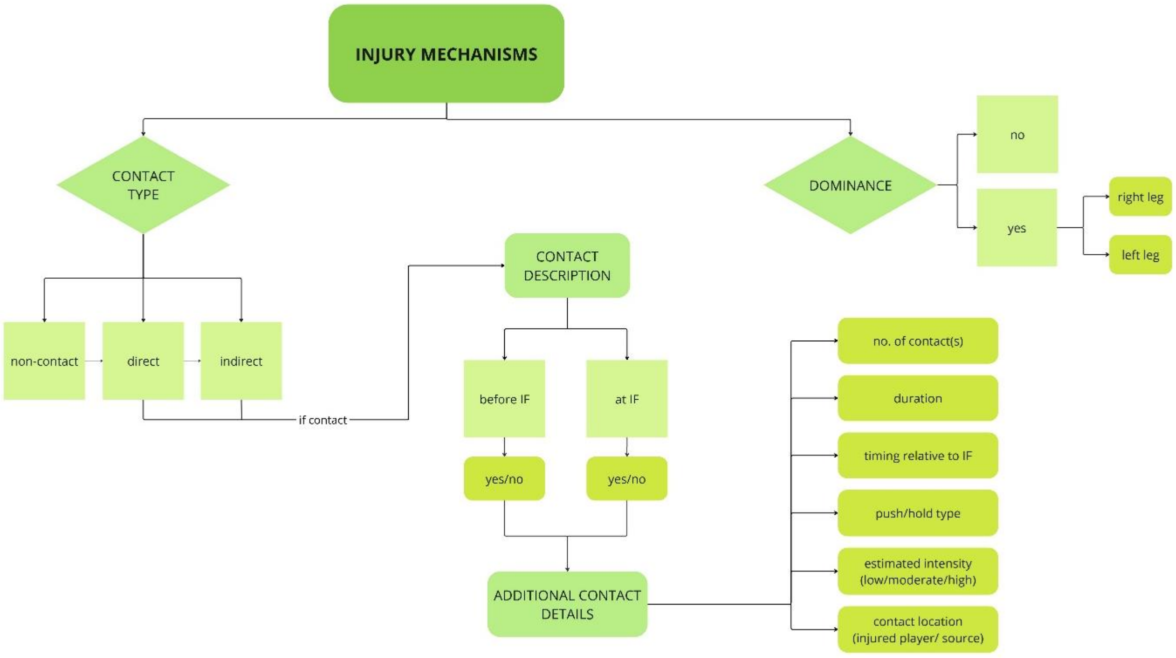
Video analysis is uniquely positioned to capture ecologically valid information about the injury event in its natural competitive context and represents an important step within the injury prevention cycle [24]. However, the present review identified substantial methodological, taxonomic, and operational heterogeneity across studies, which limits reproducibility, comparability, and interpretation of findings. To address these gaps, we developed a practical methodological guide to support more consistent data extraction and reporting in future video-analysis studies of HSIs in football (Figure 3A–G). A detailed user manual with operational definitions for each item is provided in the Supplementary Material to support consistent interpretation and application of Figure 3.

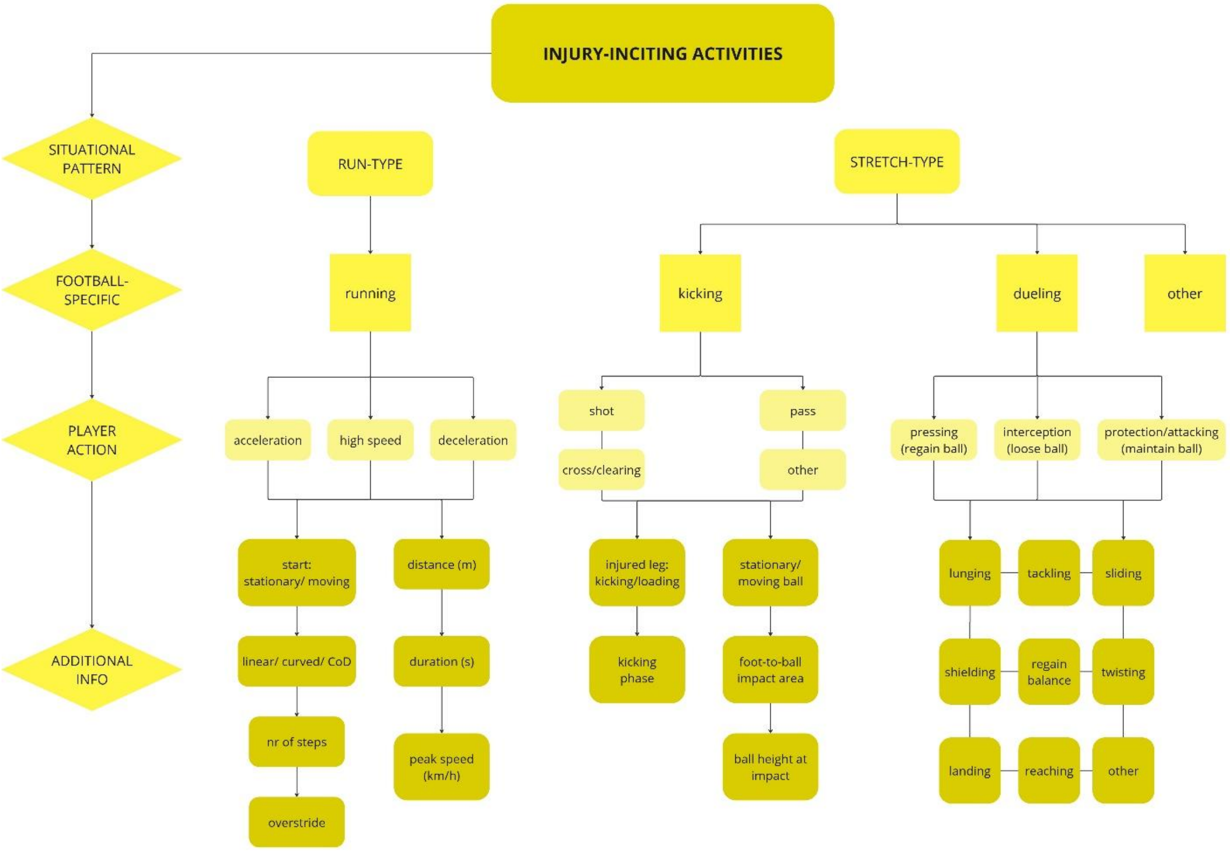
Development of the guide followed three steps: (i) extracting the methodological procedures and variables reported in the included HSI football video-analysis studies (as summarized in the manuscript and supplementary tables), (ii) mapping these elements onto established reporting and quality guidance for injury surveillance and video-analysis methodology [30,31,70,464], and (iii) incorporating HSI-specific consensus terminology and imaging-based descriptors [156,131]. The guide is intended as a structured synthesis and reporting aid rather than a decision algorithm. Importantly, it is not presented as a validated framework or classification system and has not undergone formal consensus development or validation testing. Future work should evaluate feasibility and reproducibility (e.g., inter-/intra-rater agreement for key coded items) and may refine the guide through formal expert consensus methods. Conceptually, the guide aligns with constraints-led and complex-systems principles [8,21]: video-derived descriptors operationalize task demands and situational/environmental conditions through injury mechanism, injury-inciting activities, and injury-inciting circumstances, while biomechanics represents the organism-level movement output. In addition, player history and exposure indicators reflect multi-timescale dynamics and individualized susceptibility. Researchers may report a minimal set of core items or extend reporting to additional subdomains when available. Core items should be prioritized, unavailable items should be reported as limitations, and relevant additional contextual data integrated.

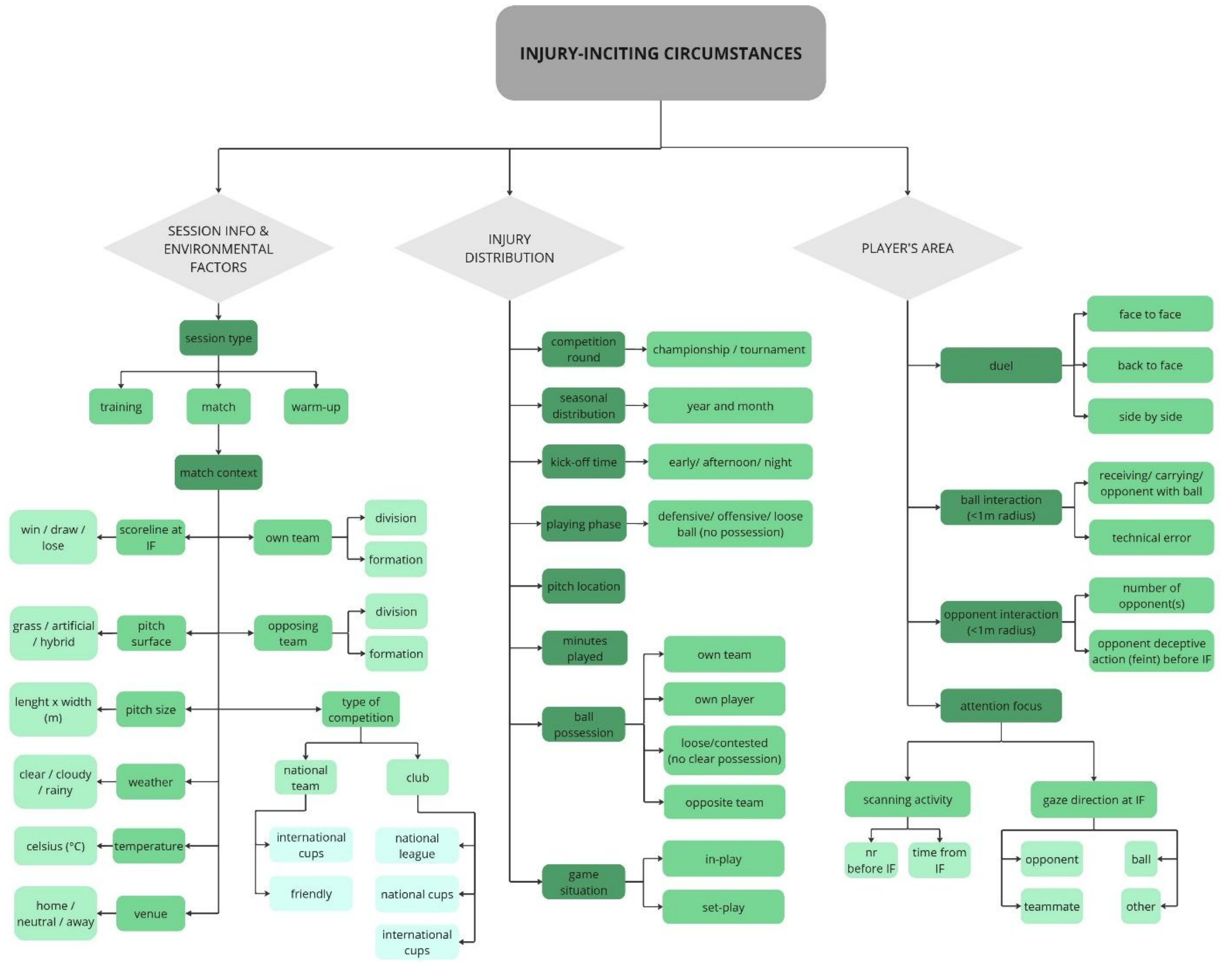



VIDEO ANALYSIS STUDY
POPULATION CHARACTERISTICS
STUDY METHODS & REPORTING
sex
playing level
sample size
study design
statistical analysis
control group
injury classification system
data collection tool
example screenshots/ video frames
limitations
systematic injury surveillance
injury and video source/availability
nr of retrieved videos
HSI eligibility criteria
injury severity (days lost)
mode of injury onset
HSI video eligibility criteria
player stop playing / immediate substitution
IF available
player continued play / delayed substitution
IF unavailable
"other" inclusion /exclusion criteria
IF unclear
inclusion/exclusion
VIDEO CHARACTERISTICS & RATER(S) RELIABILITY
nr of analyzed videos
video processing tool
nr of camera views
type of camera views
sampling frequency (fps)
resolution (px)
rater(s) profile & reliability assessment
VA experience
background
nr of raters
intra and inter-rater metrics


PLAYER & INJURY CONTEXT
PLAYER PROFILE
INJURY PROFILE
INJURY HISTORY & EXPOSURE
sex
date of birth
weight (kg)
height (cm)
preferred foot
playing position
national team player
nr seasons in pro football
mode of onset
sudden
gradual
mixed
unsure
diagnostic confirmation
clinical examination
MRI, US
other diagnostic tool
not specified
time-loss (days)
numeric (median, IQR)
categorical (0, 1-3, 4-7, 8-28, 29–90, 91–180, >180)
player's narrative description
yes / no
muscle(s) involved
BFlh
BFsh
ST
SM
other
tissue
myofascial
myo-tendinous (MTJ)
intratendinous
free-tendon involved (yes / no)
level
distal
middle
proximal
grading system
BAMIC (0, 1, 2, 3, 4)
other
surgery
yes / no
age at the injury
mean, SD, range
index injury
yes / no
subsequent injury
subsequent new / local
recurrence reinjury / exacerbation
prior HSI history
yes / no
previous severe injuries
yes / no
body area, tissue, type
date (YYYY-MM-DD)
acute exposure
match-day workload metrics
chronic exposure
long-term exposure metrics (week/month/season


INJURY MECHANISMS
CONTACT TYPE
non-contact
direct
indirect
if contact
CONTACT DESCRIPTION
before IF
at IF
yes/no
yes/no
ADDITIONAL CONTACT DETAILS
no. of contact(s)
duration
timing relative to IF
push/hold type
estimated intensity (low/moderate/high)
contact location (injured player/ source)
DOMINANCE
no
yes
right leg
left leg


INJURY-INCITING ACTIVITIES
SITUATIONAL PATTERN
FOOTBALL-SPECIFIC
PLAYER ACTION
ADDITIONAL INFO
RUN-TYPE
running
acceleration
high speed
deceleration
start: stationary/ moving
linear/ curved/ CoD
nr of steps
overstride
distance (m)
duration (s)
peak speed (km/h)
STRETCH-TYPE
kicking
shot
pass
cross/clearing
other
injured leg: kicking/loading
kicking phase
stationary/ moving ball
foot-to-ball impact area
ball height at impact
dueling
pressing (regain ball)
interception (loose ball)
protection/attacking (maintain ball)
lunging
tackling
sliding
shielding
regain balance
twisting
landing
reaching
other
other


INJURY-INCITING CIRCUMSTANCES
SESSION INFO & ENVIRONMENTAL FACTORS
INJURY DISTRIBUTION
PLAYER'S AREA
session type
training
match
warm-up
match context
win / draw / lose
scoreline at IF
own team
division
formation
grass / artificial / hybrid
pitch surface
opposing team
division
formation
lenght x width (m)
pitch size
type of competition
clear / cloudy / rainy
weather
national team
club
celsius (°C)
temperature
international cups
national league
friendly
national cups
home / neutral / away
venue
international cups
competition round
championship / tournament
seasonal distribution
year and month
kick-off time
early/ afternoon/ night
playing phase
defensive/ offensive/ loose ball (no possession)
pitch location
minutes played
own team
own player
ball possession
loose/contested (no clear possession)
opposite team
game situation
in-play
set-play
face to face
duel
back to face
side by side
receiving/ carrying/ opponent with ball
ball interaction (<1m radius)
technical error
number of opponent(s)
opponent interaction (<1m radius)
opponent deceptive action (feint) before IF
attention focus
scanning activity
gaze direction at IF
nr before IF
time from IF
opponent
ball
teammate
other

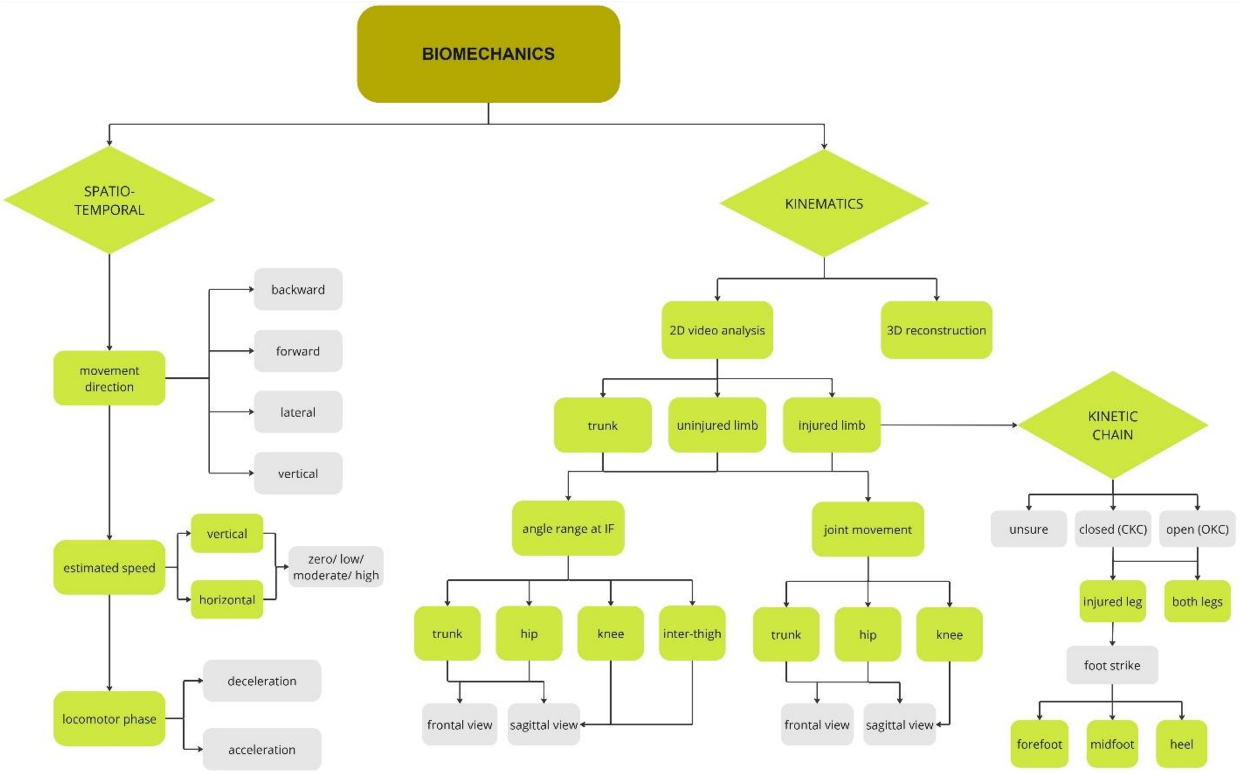

BIOMECHANICS
SPATIO-TEMPORAL
KINEMATICS
backward
forward
movement direction
lateral
vertical
vertical
estimated speed
zero/ low/ moderate/ high
horizontal
deceleration
locomotor phase
acceleration
2D video analysis
3D reconstruction
trunk
uninjured limb
injured limb
KINETIC CHAIN
angle range at IF
joint movement
unsure
closed (CKC)
open (OKC)
trunk
hip
knee
inter-thigh
trunk
hip
knee
injured leg
both legs
foot strike
frontal view
sagittal view
frontal view
sagittal view
forefoot
midfoot
heel

***Figure 3**. Methodological guide for video analysis studies of HSIs in football. Panel (A) provides an overview of the main domains. Panels (B–G) provide domain-specific detail to support consistent reporting and coding of HSI events in football: (B) Video analysis study (planning and case selection; video characteristics; rater profile and reliability considerations). (C) Player & injury context summarizes non-video contextual descriptors (player profile, injury profile, and injury history/exposure) that can complement video-derived variables. (D) Injury mechanisms describes event-level descriptors including contact classification and other injury-mechanism coding elements. (E) Injury-inciting activities outlines a multi-level structure for describing the action during which HSIs occur, including the situational-pattern level and football-specific subcategories. (F) Injury-inciting circumstances summarizes contextual and environmental descriptors surrounding the injury event. (G) Biomechanics summarizes movement and kinematic descriptors obtained from video at/around the IF.*

Limitations

This review followed PRISMA 2020 guidelines and was registered in PROSPERO, yet limitations in the review process should be acknowledged. Although the search strategy was comprehensive, restricting inclusion to English-language studies may have introduced language bias and excluded relevant work. The reliance on academic databases and publicly accessible sources may also have limited access to grey literature. Most studies involved only male professional players, with limited representation of their female counterparts. As the review focused on professional football, findings may not generalize to youth and non-professional settings. Race, socioeconomic status, or other equity-related variables were not reported. Some included studies addressed HSIs or used video analysis only as secondary aims. While relevant, these studies often lacked detailed reporting, which may have affected the strength of extracted data. Heterogeneity in study design, terminology, and analytical methods further limited comparability and precluded formal meta-analysis. Similar inconsistencies affected our effort to group comparable injury-inciting activities, introducing a degree of subjectivity into the classification process. Finally, the last search was performed on 12/12/2024; therefore, studies published after this date may not have been captured. While this is unlikely to alter the overall methodological conclusions, it may provide additional examples of reporting practice and should be addressed in future updates.

DECLARATIONS

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Conflicts of interest: The authors have no conflicts of interest that are relevant to the content of this review.

Availability of data and material: Data are available upon reasonable request. Key data are presented in the manuscript or in the supplementary material.

Ethical approval: All accessed information was publicly available, no identifiable personal data were used; therefore, ethical approval was not required.

Patient involvement: Not applicable. Patients and/or the public were not involved in any stage of this research.

Author Contributions: AP and MZ conceived and designed the study. They also conducted the literature search, study selection, and data extraction. FDV acted as a third reviewer to resolve disagreements. AP performed data analysis and interpretation. All authors contributed to methodological categorization and synthesis. AP drafted the manuscript, and all authors critically revised it for important intellectual content.

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Supplementary Information

Table S1 - The SPIDER tool applied to the review question

SPIDER	Justification
S – Sample	Male and female professional football players who sustained a hamstring injury, as confirmed by diagnostic methods (e.g., MRI, clinical diagnosis) or reported by reliable sources, such as media or official databases.
PI – Phenomenon of Interest	The sport-specific activity during which injuries occur (injury-inciting activity) and the environmental or contextual factors surrounding the injury (injury-inciting circumstance). This includes mechanisms, situational patterns, player actions, and game scenarios leading up to the injury.
D – Design	Observational study designs, including cross-sectional, retrospective descriptive, and cohort studies that utilized video analysis to investigate hamstring injuries. Studies with unclear designs will be categorized based on their methodological details.
E – Evaluation	Identification and assessment of methodological procedures used in video analysis. This includes analysis of variables such as injury mechanisms, situational patterns, biomechanical features, and contextual factors contributing to injury.
R – Research	Qualitative and mixed methods

Table S2 – Boolean search string

SPIDER	Search Terms
S – Sample	“elite” OR “professional” OR “high-level” “football” OR “soccer” “player*” OR “athlete*” OR “footballer*” “hamstring injur*” OR “hamstring strain*” OR “HSI”
PI – Phenomenon of Interest	“injur*” “mechanism*” OR “situational pattern*” OR “inciting activit*” OR “inciting circumstance*” OR “movement pattern*” OR “action*”
D – Design	“video analys*” OR “video-based” OR “video review”
E – Evaluation	“biomechanic*” OR “kinematic*” “contact” OR “duel” OR “stretch-type” OR “run-type”
R – Research	“qualitative study” OR “qualitative analysis” “mixed methods” OR “mixed-method analysis”

Table S3 - Search strategy for each database

Database	Search Strategy	search	Date	Results (n)
PubMed	("elite" OR "professional" OR "high-level") AND ("football" OR "soccer") AND ("player*" OR "athlete*" OR "footballer*") AND ("hamstring injur*" OR "hamstring strain*" OR "HSI" OR "injur*") AND ("injur*" AND ("mechanism*" OR "situational pattern*" OR "inciting activit*" OR "inciting circumstance*" OR "movement pattern*" OR "action*")) AND ("video" OR "video analys*" OR "video-based" OR "video review") AND ("biomechanic*" OR "kinematic*" OR "contact" OR "duel" OR "stretch-type" OR "run-type")	all fields	06/12/2024	59
Scopus	("elite" OR "professional" OR "high-level") AND ("football" OR "soccer") AND ("player*" OR "athlete*" OR "footballer*") AND ("hamstring injur*" OR "hamstring strain*" OR "HSI" OR "injur*") AND ("injur*" AND ("mechanism*" OR "situational pattern*" OR "inciting activit*" OR "inciting circumstance*" OR "movement pattern*" OR "action*") AND ("video" OR "video analys*" OR "video-based" OR "video review") AND ("biomechanic*" OR "kinematic*" OR "contact" OR "duel" OR "stretch-type" OR "run-type")	title-abs-key	09/12/2024	68
Web of Science	("elite" OR "professional" OR "high-level") AND ("football" OR "soccer") AND ("player*" OR "athlete*" OR "footballer*") AND ("hamstring injur*" OR "hamstring strain*" OR "HSI" OR "injur*") AND ("injur*" AND ("mechanism*" OR "situational pattern*" OR "inciting activit*" OR "inciting circumstance*" OR "movement pattern*" OR "action*")) AND ("video" OR "video analys*" OR "video-based" OR "video review") AND ("biomechanic*" OR "kinematic*" OR "contact" OR "duel" OR "stretch-type" OR "run-type")	topic	10/12/2024	86
Google Scholar	("hamstring injury" OR "hamstring strain" OR "HSI") AND ("professional football" OR "elite football" OR "soccer") AND ("player*" OR "athlete*") AND ("video analysis" OR "video review" OR "video-based")	no filters	10/12/2024	30
PROSPERO	("elite" OR "professional" OR "high-level") AND ("football" OR "soccer") AND ("player*" OR "athlete*" OR "footballer*") AND ("hamstring injur*" OR "hamstring strain*" OR "HSI" OR "injur*") AND ("injur*" AND ("mechanism*" OR "situational pattern*" OR "inciting activit*" OR "inciting circumstance*" OR "movement pattern*" OR "action*")) AND ("video" OR "video analys*" OR "video-based" OR "video review") AND ("biomechanic*" OR "kinematic*" OR "contact" OR "duel" OR "stretch-type" OR "run-type")	No filters	12/12/2024	2

Table S4 - List of excluded records with reason

Title	Authors	Year	Reason of exclusion
Systematic video analysis of ACL injuries in professional male football (soccer): injury mechanisms, situational patterns and biomechanics study on 134 consecutive cases.	Della Villa F, Buckthorpe M, Grassi A, Nabiuzzi A, Tosarelli F, Zaffagnini S, Della Villa S.	2020	Injury type
Systematic Video Analysis of Anterior Cruciate Ligament Injuries in Professional Female Soccer Players.	Lucarno S, Zago M, Buckthorpe M, Grassi A, Tosarelli F, Smith R, Della Villa F.	2021	Injury type
Three distinct mechanisms predominate in non-contact anterior cruciate ligament injuries in male professional football players: a systematic video analysis of 39 cases.	Waldén M, Krosshaug T, Bjørneboe J, Andersen TE, Faul O, Hägglund M.	2015	Injury type
The Landing Error Scoring System as a Screening Tool for an Anterior Cruciate Ligament Injury-Prevention Program in Elite-Youth Soccer Athletes.	Padua DA, DiStefano LJ, Beutler AI, de la Motte SJ, DiStefano MJ, Marshall SW.	2015	Injury type
Mechanisms and situations of anterior cruciate ligament injuries in professional male soccer players: a YouTube-based video analysis.	Grassi A, Smiley SP, Roberti di Sarsina T, Signorelli C, Marcheggiani Muccioli GM, Bondi A, Romagnoli M, Agostini A, Zaffagnini S.	2017	Injury type
Video Analysis of Pectoralis Major Injuries in Professional Australian Football Players. Orthop J Sports Med.	Schwab L, Warby S, Davis K, Campbell P, Hoy S, Zbeda R, Hoy G.	2022	Injury type
Indirect Rectus Femoris Injury Mechanisms in Professional Soccer Players: Video Analysis and Magnetic Resonance Imaging Findings.	Jokela A, Mechó S, Pasta G, Pleshkov P, García-Romero-Pérez A, Mazzoni S, Kosola J, Vittadini F, Yanguas J, Pruna R, Valle X, Lempainen L.	2023	Injury type
Anterior cruciate ligament injury in elite football players: video analysis of 128 cases.	DE Carli A, Koverech G, Gaj E, Marzilli F, Fantoni F, Liberati Petrucci G, Lorenzon F, Ferretti A.	2022	Injury type
Video Analysis of Anterior Cruciate Ligament Tears in Professional American Football Athletes.	Johnston JT, Mandelbaum BR, Schub D, Rodeo SA, Matava MJ, Silvers-Granelli HJ, Cole BJ, ElAttrache NS, McAdams TR, Brophy RH.	2018	Injury type & Sport
Shoulder injuries in elite rugby union football matches: Epidemiology and mechanisms.	Usman J, McIntosh AS, Quarrie K, Targett S.	2015	Injury type & Sport
The Injury Mechanism of Knee Extensor Mechanism Rupture in Professional Athletes: A Video Analysis Study.	Yüce A, Yerli M, Mısır A.	2022	Injury type & Sport
Etiology and Biomechanics of Tarsometatarsal Injuries in Professional Football Players: A Video Analysis.	Kent RW, Lievers WB, Riley PO, Frimenko RE, Crandall JR.	2014	Injury type
A Review of On-Field Investigations into the Biomechanics of Concussion in Football and Translation to Head Injury Mitigation Strategies.	Rowson B, Duma SM.	2020	Injury type
Its not all about sprinting: mechanisms of acute hamstring strain injuries in professional male rugby union-a systematic visual video analysis.	Kerin F, Farrell G, Tierney P, McCarthy Persson U, De Vito G, Delahunt E.	2022	Sport

Factors Associated With the Mechanism of ACL Tears in the National Football League: A Video-Based Analysis.	Brophy RH, Wojtys EM, Mack CD, Hawaldar K, Herzog MM, Owens BD.	2021	Injury type & Sport
Video Analysis of Anterior Cruciate Ligament Injuries in Male Professional Basketball Players: Injury Mechanisms, Situational Patterns, and Biomechanics.	Tosarelli F, Buckthorpe M, Di Paolo S, Grassi A, Rodas G, Zaffagnini S, Nanni G, Della Villa F.	2024	Injury type & Sport
Match Situations Leading to Head Injuries in Professional Male Football (Soccer)-A Video-Based Analysis Over 12 Years.	Beaudouin F, Aus der Fünten K, Tröß T, Reinsberger C, Meyer T.	2020	Injury type
Video analysis of Achilles tendon rupture in male professional football (soccer) players: injury mechanisms, patterns and biomechanics.	Della Villa F, Buckthorpe M, Tosarelli F, Zago M, Zaffagnini S, Grassi A.	2020	Injury type
Concussion incidence and mechanisms differ between elite females and males in Australian Football.	Sunderland PJ, Davis GA, Hearps SJC, Anderson HH, Gastin TJ, Green BD, Makdissi M.	2023	Injury type & Sport
The Mechanism of Anterior Cruciate Ligament Injuries in the National Football League: A Systematic Video Review.	Schick S, Cantrell CK, Young B, Mosher Z, Ewing M, Elphingstone JW, Brabston E, Ponce BA, Momaya AM.	2023	Injury type & Sport
Four distinct patterns of anterior cruciate ligament injury in women's professional football (soccer): a systematic video analysis of 37 match injuries.	Achenbach L, Bloch H, Klein C, Damm T, Obinger M, Rudert M, Krutsch W, Szymski D.	2024	Injury type
Three Main Mechanisms Characterize Medial Collateral Ligament Injuries in Professional Male Soccer-Blow to the Knee, Contact to the Leg or Foot, and Sliding: Video Analysis of 37 Consecutive Injuries.	Buckthorpe M, Pisoni D, Tosarelli F, Danelon F, Grassi A, Della Villa F.	2021	Injury type
The injury mechanism correlation between MRI and video-analysis in professional football players with an acute ACL knee injury reveals consistent bone bruise patterns.	D'Hooghe P, Grassi A, Villa FD, Alkhelaifi K, Papakostas E, Rekik R, Marin T, Tosarelli F, Zaffagnini S.	2023	Injury type
Most Anterior Cruciate Ligament Injuries in Professional Athletes Occur Without Contact to the Injured Knee: A Systematic Review of Video Analysis Studies.	Gopinatth V, Smith MV, Matava MJ, Brophy RH, Knapik DM.	2024	Injury type
Tackle mechanisms and match characteristics in women's elite football tournaments.	Tscholl P, O'Riordan D, Fuller CW, Dvorak J, Junge A.	2007	Injury type
Head injuries in professional male football (soccer) over 13 years: 29% lower incidence rates after a rule change (red card).	Beaudouin F, Aus der Fünten K, Tröß T, Reinsberger C, Meyer T.	2019	Injury type
Video analysis of Achilles tendon ruptures in professional male football (soccer) reveals underlying injury patterns and provides strategies for injury prevention.	Hoenig T, Gronwald T, Hollander K, Klein C, Frosch KH, Ueblacker P, Rolvien T.	2023	Injury type
Video Analysis of Shoulder Dislocations in Rugby: Insights Into the Dislocating Mechanisms.	Montgomery C, O'Briain DE, Hurley ET, Pauzenberger L, Mullett H, Moran CJ.	2019	Injury type & Sport
Republication of "High-Speed Video Analysis of Syndesmosis Injuries in Soccer-Can It Predict Injury Mechanism and Return to Play? A Pilot Study".	Jain N, Murray D, Kemp S, Calder J.	2023	Injury type
Mechanisms of ACL injuries in men's football: A systematic video analysis over six seasons in the Qatari professional league.	Rekik RN, Bahr R, Cruz F, Read P, Whiteley R, D'hooghe P, Tabben M, Chamari K.	2023	Injury type

The Safe Landing warm up technique modification programme: An effective anterior cruciate ligament injury mitigation strategy to improve cutting and jump-movement quality in soccer players.	Olivares-Jabalera J, Fílter A, Dos Santos T, Ortega-Domínguez J, Soto Hermoso VM, Requena B.	2022	Injury type
Tackle injuries in professional Rugby Union.	Quarrie KL, Hopkins WG.	2008	Injury type & Sport
MRI Findings Associated With Anterior Cruciate Ligament Tears in National Football League Athletes.	Brophy RH, Baker JC, Crain JM, Herzog MM, Stollberg B, Wojtys EM, Mack CD.	2023	Injury type & Sport
Video analysis of the mechanisms of shoulder dislocation in four elite rugby players.	Longo UG, Huijsmans PE, Maffulli N, Denaro V, De Beer JF.	2011	Injury type & Sport
Instrumented Mouthguards in Elite-Level Men's and Women's Rugby Union: The Incidence and Propensity of Head Acceleration Events in Matches.	Tooby J, Woodward J, Tucker R, Jones B, Falvey É, Salmon D, Bussey MD, Starling L, Tierney G.	2024	Injury type & Sport
Video analysis of the mechanisms for ankle injuries in football.	Andersen TE, Floerenes TW, Arnason A, Bahr R.	2024	Injury type
Mechanisms of ACL injury in professional rugby union: a systematic video analysis of 36 cases.	Montgomery C, Blackburn J, Withers D, Tierney G, Moran C, Simms C.	2018	Injury type & Sport
Reliability of the Tuck Jump Injury Risk Screening Assessment in Elite Male Youth Soccer Players.	Read PJ, Oliver JL, de Ste Croix MB, Myer GD, Lloyd RS.	2016	Injury type
Mechanisms of head injuries in elite football.	Andersen TE, Arnason A, Engebretsen L, Bahr R.	2004	Injury type
Characteristics of potential head injury situations at the FIFA World Cup Qatar 2022TM.	Peek K, Aiello F, Avery L, Gardner T, Rutherford H, Massey A, Georgieva J, Andersen TE, Dahlén S, Serner A.	2024	Injury type
Rapid Posterior Tibial Reduction After Noncontact Anterior Cruciate Ligament Rupture: Mechanism Description From a Video Analysis.	Grassi A, Tosarelli F, Agostinone P, Macchiarola L, Zaffagnini S, Della Villa F.	2020	Injury type
3-Dimensional Biomechanics of Noncontact Anterior Cruciate Ligament Injuries in Male Professional Soccer Players.	Zago M, Esposito F, Stillavato S, Zaffagnini S, Frigo CA, Della Villa F.	2024	Injury type
The relationship of the kicking action in soccer and anterior ankle impingement syndrome. A biomechanical analysis.	Tol JL, Slim E, van Soest AJ, van Dijk CN.	2002	Injury type
Mechanisms of acute adductor longus injuries in male football players: a systematic visual video analysis.	Serner A, Mosler AB, Tol JL, Bahr R, Weir A.	2019	Injury type
Mechanisms of traumatic injury to the shoulder girdle in the Australian Football League.	Schwab LM, McGrath T, Franettovich Smith MM, Mendis MD, McGhee D, Hides J.	2019	Injury type & Sport
When to Pull the Trigger: Conceptual Considerations for Approximating Head Acceleration Events Using Instrumented Mouthguards.	Tooby J, Till K, Gardner A, Stokes K, Tierney G, Weaving D, Rowson S, Ghajari M, Emery C, Bussey MD, Jones B.	2024	Injury type & Sport
Video analysis of potential concussions in elite male Hurling: are players being assessed according to league guidelines?	Sokol-Randell D, Rotundo MP, Tierney G, Cusimano MD, Deasy C.	2022	Injury type & Sport
Dismissing the idea that basketball is a "contactless" sport: quantifying contacts during professional gameplay.	Wellm D, Jäger J, Zentgraf K.	2024	Injury type & Sport

Mechanisms of acute ankle syndesmosis ligament injuries in professional male rugby union players: a systematic visual video analysis.	Delahunt E, Farrell G, Boylan A, Kerin F, Tierney P, Hogan H, Boreham C.	2021	Injury type & Sport
Studying Contact Replays: Investigating Mechanisms, Management and Game Exposures (SCRIMMAGE) for brain health in the Australasian National Rugby League: a protocol for a database design.	Gardner AJ, Iverson GL, Bloomfield P, Flahive S, Brown J, Edwards S, Fuller GW, Ghajari M, Jhala P, Jones B, Levi CR, McDonald W, McLeod S, Owen C, Page G, Quarrie KL, Smith O, Stanwell P, Tadmor D, Tahu T, Terry DP, Thomson C, Tucker R, Fortington LV.	2024	Injury type & Sport
A video analysis of head injuries satisfying the criteria for a head injury assessment in professional Rugby Union: a prospective cohort study.	Tucker R, Raftery M, Fuller GW, Hester B, Kemp S, Cross MJ.	2017	Injury type & Sport
Systematic video analysis of ACL injuries in professional Spanish male football (soccer): Injury mechanisms, situational patterns, biomechanics and neurocognitive errors - A study on 115 consecutive cases	Buckthorpe M., Pirli Capitani L., Olivares-Jabalera J., Olmo J., Della Villa F.	2024	Injury type
Video Analysis of 26 Cases of Second ACL Injury Events in Collegiate and Professional Athletes	Vargas M., Chaney G.K., Jaramillo M.C.M., Cummings P., McPherson A., Bates N.A.	2023	Injury type
Systematic Video Analysis of Anterior Cruciate Ligament Injuries in Professional Male Rugby Players: Pattern, Injury Mechanism, and Biomechanics in 57 Consecutive Cases	Della Villa F., Tosarelli F., Ferrari R., Grassi A., Ciampone L., Nanni G., Zaffagnini S., Buckthorpe M.	2021	Injury type & Sport
Mechanisms and situations of anterior cruciate ligament injuries in professional male soccer players: a YouTube-based video analysis	Grassi A., Smiley S.P., Roberti di Sarsina T., Signorelli C., Marcheggiani Muccioli G.M., Bondi A., Romagnoli M., Agostini A., Zaffagnini S.	2017	Injury type
Motor imagery and rehabilitation of a professional soccer player after anterior cruciate ligament injury: A case report	Mangone M., Bernetti A., Paoloni M., Canonico R., Tognolo L., Attanasi C., Cruciani A., Alviti F., Santilli V., De Nicola A.	2017	Injury type
Defending Puts the Anterior Cruciate Ligament at Risk During Soccer: A Gender-Based Analysis	Brophy R.H., Stepan J.G., Silvers H.J., Mandelbaum B.R.	2015	Injury type
Estimating anterior tibial translation from model-based image-matching of a noncontact anterior cruciate ligament injury in professional football: A case report	Koga H., Bahr R., Myklebust G., Engebretsen L., Grund T., Krosshaug T.	2011	Injury type
Tackle characteristics and injury in a cross section of rugby union football	McIntosh A.S., Savage T.N., McCrory P., FréchÈde B.O., Wolfe R.	2010	Injury type & Sport
Characteristics of anterior cruciate ligament injuries in Australian football	Cochrane J.L., Lloyd D.G., Buttfield A., Seward H., McGivern J.	2007	Injury type & Sport
An assessment of the relationship between behaviour and injury in the workplace: A case study in professional football	Fuller C.W.	2005	Injury type
Risk assessment in professional football: An examination of accidents and incidents in the 1994 World Cup finals	Hawkins R.D.	1996	Injury type
Video analysis of anterior cruciate ligament (acl) injuries a Systematic Review	Carlson VR, Sheehan FT, Boden BP.	2016	Injury type

Decision-making to stop or continue playing after football injuries-a systematic video analysis of 711 injury situations in amateur football	Volker K, Julia O, Werner K, Oliver L, Johannes W, Maximilian K, Siegmund L, Matthias K, Volker A, Michael W.	2022	Injury type
Stiff Landings, Core Stability, and Dynamic Knee Valgus: A Systematic Review on Documented Anterior Cruciate Ligament Ruptures in Male and Female Athletes	Larwa J, Stoy C, Chafetz RS, Boniello M, Franklin C.	2021	Injury type
Head Trauma in Mixed Martial Arts	Hutchison MG, Lawrence DW, Cusimano MD, Schweizer TA	2014	Injury type & Sport
Event-specific impact test protocol for ice hockey goaltender masks.	Clark JM, Hoshizaki TB, Gilchrist MD.	2020	Injury type & Sport
Lower incidence of arm-to-head contact incidents with stricter interpretation of the Laws of the Game in Norwegian male professional football	Bjorneboe J, Bahr R, Dvorak J, Andersen TE.	2013	Injury type
Characteristics of potential concussive events in three elite football tournaments	Armstrong N, Rotundo M, Aubrey J, Tarzi C, Cusimano MD	2020	Injury type
Collision with opponents-but not foul play-dominates injury mechanism in professional men's basketball	Achenbach L, Klein C, Luig P, Bloch H, Schneider D, Fehske K.	2021	Sport
Protective capacity of an ice hockey goaltender helmet for three events associated with concussion	Clark JM, Hoshizaki TB, Gilchrist MD.	2017	Injury type & Sport
Video analysis of the mechanisms of shoulder dislocation in four elite rugby players	Longo UG, Huijsmans PE, Maffulli N, Denaro V, De Beer JF.	2011	Injury type & Sport
Effect of Cognitive Loading on Single-Leg Jump Landing Biomechanics of Elite Male Volleyball Players	Amoli SM, Ataabadi PA, Letafatkar A, Wilkerson GB, Mansouri MB.	2021	Injury type & Sport
An Investigation of Factors Associated With Head Impact Exposure in Professional Male and Female Australian Football Players	Reyes J, Mitra B, McIntosh A, Clifton P, Makdissi M, Nguyen JVK, Harcourt P, Howard TS, Cameron PA, Rosenfeld JV, Willmott C.	2020	Injury type & Sport
Hip and Ankle Kinematics in Noncontact Anterior Cruciate Ligament Injury Situations Video Analysis Using Model-Based Image Matching	Koga H, Nakamae A, Shima Y, Bahr R, Krosshaug T.	2018	Injury type & Sport
Different visual stimuli affect body reorientation strategies during sidestepping	Lee MJC, Lloyd DG, Lay BS, Bourke PD, Alderson JA.	2017	Injury type & Sport
Kiss goodbye to the 'kissing knees': no association between frontal plane inward knee motion and risk of future non-contact ACL injury in elite female athletes	Nilstad A, Petushek E, Mok KM, Bahr R, Krosshaug T.	2021	Injury type & Sport
ACL biomechanical risk factors on single-leg drop-jump: a cohort study comparing football players with and without history of lower limb injury	Daoukas S, Malliaropoulos N, Maffulli N.	2019	Injury type
Emergence of Contact Injuries in Invasion Team Sports: An Ecological Dynamics Rationale	Leventer L, Dicks M, Duarte R, Davids K, Araújo D.	2015	Injury type

Water polo throwing velocity and kinematics: differences between competitive levels in male players	Melchiorri G, Viero V, Triossi T, De Sanctis D, Padua E, Salvati A, Galvani C, Bonifazi M, Del Bianco R, Tancredi V.	2015	Injury type & Sport
A systematic video analysis of National Hockey League (NHL) concussions, part I: who, when, where and what?	Hutchison MG, Comper P, Meeuwisse WH, Echemendia RJ.	2015	Injury type & Sport
Tackle technique and tackle-related injuries in high-level South African Rugby Union under-18 players: real-match video analysis	Burger N, Lambert MI, Viljoen W, Brown JC, Readhead C, Hendricks S.	2016	Injury type & Sport
Physiotherapists Can Identify-Female Football Players With High Knee Valgus Angles During Vertical Drop Jumps Using Real-Time Observational Screening	Nilstad A, Andersen TE, Kristianslund E, Bahr R, Myklebust G, Steffen K, Krosshaug I.	2014	Injury type & Sport
First-time anterior cruciate ligament injury in adolescent female elite athletes: a prospective cohort study to identify modifiable risk factors	Zebis MK, Aagaard P, Andersen LL, Hölmich P, Clausen MB, Brandt M, Husted RS, Lauridsen HB, Curtis DJ, Bencke J.	2022	Injury type & Sport
Knee joint kinematics during the sidestep maneuver in professional futsal athletes: Effect of sport-specific sidestep cutting	Bedo BLS, Cesar GM, Vieira AM, Vieira LHP, Catelli DS, Andrade VL, Santiago PRP.	2022	Injury type
I spy with my little eye ... a knee about to go 'pop'? Can coaches and sports medicine professionals predict who is at greater risk of ACL rupture?	Mortvedt AI, Krosshaug T, Bahr R, Petushek E.	2020	Injury type & Sport
Anterior cruciate ligament injuries in female athletes: is it time for a new approach?	Mancino F, Gabr A, Plastow R, Haddad FS.	2023	Injury type & Sport
The Vertical Drop Jump Is a Poor Screening Test for ACL Injuries in Female Elite Soccer and Handball Players: A Prospective Cohort Study of 710 Athletes	Krosshaug T, Steffen K, Kristianslund E, Nilstad A, Mok KM, Myklebust G, Andersen TE, Holme I, Engebretsen L, Bahr R.	2016	Injury type
Maximal hip and knee muscle strength are not related to neuromuscular pre-activity during sidecutting maneuver: a cross-sectional study	Husted RS, Bencke J, Hölmich P, Andersen LL, Thorborg K, Bandholm T, Gliese B, Lauridsen HB, Myklebust G, Aagaard P, Zebis MK.	2018	Injury type
Effects of Game-Specific Demands on Accelerations during Change of Direction Movements: Analysis of Youth Female Soccer	Alanen AM, Benson LC, Jordan MJ, Ferber R, Pasanen K.	2023	Injury type
Contact - but not foul play - dominates injury mechanisms in men's professional handball: a video match analysis of 580 injuries	Luig P, Krutsch W, Henke T, Klein C, Bloch H, Platen P, Achenbach L.	2020	Injury type & Sport
Head Impact Magnitude in American High School Football	Schmidt JD, Guskiewicz KM, Mihalik JP, Blackburn JT, Siegmund GP, Marshall SW.	2016	Injury type & Sport
Effect of Impact Mechanism on Head Accelerations in Men's Lacrosse Athletes	Vollavanh LR, O'Day KM, Koehling EM, May JM, Breedlove KM, Breedlove EL, Nauman EA, Bradney DA, Goff JE, Bowman TG.	2018	Injury type & Sport
On-field Characteristics and Head Impact Magnitude in Youth Tackle Football	Le RK, Anderson MN, Johnson RS, Lempke LB, Schmidt JD, Lynall RC.	2021	Injury type

Descriptive Characteristics of Concussions in National Football League Games, 2010-2011 to 2013-2014	Clark MD, Asken BM, Marshall SW, Guskiewicz KM.	2017	Injury type & Sport
Effects of a proprioceptive focal stimulation (Equistasi®) on reducing the biomechanical risk factors associated with ACL injury in female footballers	Spolaor F, Guiotto A, Ciniglio A, Cibin F, Sawacha Z.	2023	Injury type
How are athletes trained to move? A systematic review exploring the effects of implicit and explicit learning on biomechanics of sport-specific tasks	Nijmeijer E, Brals F, Kempe M, Elferink-Gemser M, Benjaminse A.	Ongoing	Irrelevant focus
A systematic review of the predictive value of biomechanical factors and functional motion patterns for non-contact ankle sprain injuries.	Lamote L, Brenard L.	Ongoing	different injury type
The reliability and validity of a video-based method for assessing hamstring strength in football players	Justin W.Y. Lee, Cheng Li, Patrick S.H. Yung, Kai-Ming Chan.	2017	Study design
Economic impact of muscle injury rate and hamstring strain injuries in professional football clubs. Evidence from LaLiga	Nieto Torrejón L, Martínez-Serrano A, Villalón JM, Alcaraz PE.	2024	Study design
Reliability and validity of 2D-video analysis to objectively assess hamstring performance during the H-test.	Prince C, Latella S, Gachon B, Picot B.	2023	Study design
Acute Changes in Hamstring Injury Risk Factors After a Session of High-Volume Maximal Sprinting Speed Efforts in Soccer Players.	Carmona G, Moreno-Simonet L, Cosio PL, Astrella A, Fernández D, Padullés X, Cadefau JA, Padullés JM, Mendiguchia J.	2024	Study design
Risk factors for hamstring muscle injury in male elite football: medical expert experience and conclusions from 15 European Champions League clubs	Ekstrand J, Ueblacker P, Van Zoest W, Verheijen R, Vanhecke B, van Wijk M, Bengtsson H.	2022	Study design
Recurrent hamstring muscle injury: applying the limited evidence in the professional football setting with a seven-point programme	Ekstrand J, Ueblacker P, Van Zoest W, Verheijen R, Vanhecke B, van Wijk M, Bengtsson H.	2014	Study design
Video Analysis of Acute Hamstring Injury Mechanisms During Deadlifts	Dao A, Trifoi F, Qu T, Nedaie S, MacDonald G, Elmaraghy A.	2023	Sport
Match High-Speed Running Distances Are Often Suppressed After Return From Hamstring Strain Injury in Professional Footballers.	Whiteley R, Massey A, Gabbett T, Blanch P, Cameron M, Conlan G, Ford M, Williams M.	2021	Study design
Quantifying volume and high-speed technical actions of professional soccer players using foot-mounted inertial measurement units.	Lewis G, Towlson C, Roversi P, Domogalla C, Herrington L, Barrett S.	2022	Study design
Strength Imbalances and Prevention of Hamstring Injury in Professional Soccer Players: A Prospective Study.	Croisier J-L, Ganteaume S, Binet J, Genty M, Ferret J-M.	2008	Study design

Table S5 - List of full text records excluded with reason

Title	Authors	Year	Reason of exclusion
Causation of injuries in female football players in top-level tournaments.	Tscholl P, O'Riordan D, Fuller CW, Dvorak J, Gutzwiller F, Junge A.	2007	Injury type
Broadening our understanding of injury mechanisms to include at-risk situations: an overview of potential injuries at the FIFA men’s World Cup Qatar 2022TM	Aiello F., Avery L., Gardner T., Rutherford H., McCall A., Impellizzeri F.M., Peek K., Della Villa F., Massey A., Serner A.	2024	Limited focus on HSIs
A prospective video-based analysis of injury situations in elite male football: Football incident analysis	Arnason A., Tenga A., Engebretsen L., Bahr R.	2004	Limited focus on HSIs
Football incident analysis: A new video based method to describe injury mechanisms in professional football	Andersen T.E., Larsen O., Tenga A., Engebretsen L., Bahr R.	2003	Limited focus on HSIs
Research approaches to describe the mechanisms of injuries in sport: limitations and possibilities	Krosshaug T, Andersen TE, Olsen OEO, Myklebust G, Bahr R.	2005	Injury type
Range of Motion and Injury Occurrence in Elite Spanish Soccer Academies. Not Only a Hamstring Shortening—Related Problem.	Lahti J, Mendiguchia J, Edouard P, Morin JB.	2020	Study design
Risk factors for hamstring muscle injury in male elite football: medical expert experience and conclusions from 15 European Champions League clubs	Sanz A, Carlos P, Ballester R, Jose Vicente SA, Huertas F.	2023	Study design
Video analysis of injuries and incidents in Norwegian professional football	Andersen TE, Tenga A, Engebretsen L, Bahr R	2004	Limited focus on HSIs
Video analysis of situations with a high-risk for injury in Norwegian male professional football; a comparison between 2000 and 2010	Bjørneboe J, Bahr R, Einar Andersen T.	2014	Limited focus on HSIs
Soccer video analysis by ball, player and referee tracking	Naidoo WC, Tapamo JR.	2006	Study design
A review of vision-based systems for soccer video analysis	T. D’Orazio, M. Leo	2010	Study design

Table S6 - JBI Critical Appraisal Checklist for Analytical Cross-Sectional Studies to assess Risk of Bias

Study ID	1: Criteria for Inclusion Defined	2: Subjects and Setting Described	3: Exposure Measured in a Valid and Reliable Way	4: Objective Standard Criteria Used for Measurement of the Condition	5: Confounding Factors Identified	6: Strategies for Confounding Factors Stated	7: Outcomes Measured in a Valid and Reliable Way	8: Appropriate Statistical Analysis Used	Overall appraisal
Gronwald et al. 2022	Yes	Yes	No	Yes	Unclear	No	Yes	Unclear	Include
Della Villa et al. 2023	Yes	Yes	No	Unclear	Unclear	No	Yes	Unclear	Include
Jokela et al. 2023	Yes	No	No	Yes	Unclear	No	Yes	Unclear	Include
Aiello et al. 2023	Yes	Yes	No	Unclear	Unclear	No	Yes	Unclear	Include
Klein et al. 2021	Yes	Yes	Yes	Unclear	Unclear	No	Yes	Unclear	Include
Della Villa et al. 2024	Yes	Yes	No	Unclear	Unclear	No	Yes	Unclear	Include
Vermeulen et al. 2024	Yes	Yes	No	Unclear	Unclear	No	Yes	Unclear	Include
Prieto-Lage et al. 2021	Yes	Yes	No	Unclear	Yes	Yes	Yes	Yes	Include
Moreno-Perez et al. 2024	Yes	Yes	No	Yes	Unclear	Unclear	Yes	Unclear	Include
Argibay-González et al. 2022	Yes	Yes	No	Unclear	Yes	Yes	Yes	Yes	Include
Yuce et al. 2022	Yes	No	Yes	Unclear	No	No	No	Unclear	Include

Table S7 - QA-SIVAS scale rating

Study ID	1. Objective stated	2. Representative sample	3. Information about sample	4. Video source & quality	5. Applied methods	6. Systematic approach	7. Medical report info	8. Background/ expertise of raters
Gronwald et al. 2022	Yes	Yes	No	No	Yes	Yes	Yes	Yes
Della Villa et al. 2023	Yes	Yes	No	No	Yes	Yes	No	Yes
Jokela et al. 2023	Yes	No	Yes	No	Yes	Yes	Yes	Yes
Aiello et al. 2023	Yes	Yes	Yes	No	Yes	Yes	No	No
Klein et al. 2021	Yes	No	No	No	Yes	Yes	No	Yes
Della Villa et al. 2024	Yes	No	Yes	No	Yes	Yes	No	Yes
Vermeulen et al. 2024	Yes	Yes	Yes	No	Yes	Yes	No	Yes
Prieto-Lage et al. 2021	Yes	No	Yes	No	No	Yes	No	No
Moreno-Perez et al. 2024	Yes	Yes	Yes	No	No	Yes	No	No
Argibay-González et al. 2022	Yes	No	Yes	No	No	Yes	No	No
Yuce et al. 2022	Yes	No	Yes	No	Yes	No	No	Yes

continued

9. Findings by more than one rater	10. Control group	11. Quantitative biomechanical analysis	12. Main results described	13. Injury case numbers	14. Injury context details	15. Example screenshots/ frames	16. Findings in context of evidence	17. Clinical/practical implications	18. Limitations addressed	Final Rate
Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	**14**
Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	**13**
Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	**14**
Yes	No	No	Yes	Yes	Yes	No	Yes	Yes	Yes	**12**
Yes	No	No	Yes	Yes	Yes	No	Yes	Yes	Yes	**11**
Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	**13**
Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	**14**
Yes	No	No	Yes	Yes	Yes	No	Yes	Yes	No	**9**
No	Yes	No	Yes	Yes	Yes	No	Yes	Yes	Yes	**11**

Yes	No	No	Yes	Yes	Yes	No	Yes	Yes	Yes	**10**
Yes	No	No	Yes	Yes	Yes	No	Yes	No	Yes	**10**

Table S8 - Characteristics of the study population

Author	Total nr. HSI	Nr. Videos available	Age	Anthropometric Data	Player Laterality	Playing Position	Player Information Source
Gronwald et al. 2022	63	51	No	No	No	No	German Football League (DFL), kicker.de, transfermarkt.de
Della Villa et al. 2023	65	61	No	No	right and left	goalkeepers, defenders, midfielders, forwards	No
Jokela et al. 2023	Not reported	14	mean ± SD	No	No	goalkeepers, defenders, midfielders, forwards	No
Aiello et al. 2023	28	17	Yes	height and body mass	No	No	No
Klein et al. 2021	Not reported	40	No	No	No	goalkeepers, defenders, midfielders, forwards	German Football League (DFL), kicker.de, transfermarkt.de
Della Villa et al. 2024	65 (male) & 64 (female)	61 & 21	mean ± SD	No	right and left	goalkeepers, defenders, midfielders, forwards	legaseriea.it, teams' website, Fbref.com
Vermeulen et al. 2024	295	63	mean ± SD	height and body mass	No	goalkeepers, defenders, midfielders, forwards	No
Prieto-Lage et al. 2021	Not reported	31	range (<21, 21-25, 26-30, >30)	No	right, left, and ambidextrous	goalkeepers, defenders, midfielders, forwards	No
Moreno-Perez et al. 2024	Unclear	44	mean ± SD	height and body mass	No	ext midfielders, ext defenders, forwards,	No

						central midfielders, central defenders	
Argibay-González et al. 2022	Not reported	49	range (<21, 21-25, 26-30, >30)	No	right, left, and ambidextrous	goalkeepers, defenders, midfielders, forwards	No
Yüce et al. 2022	Not reported	8	mean ± SD	No	No	No	Public databases and transfermarkt.com.tr
Total (out of 11)	**5**	**11**	**8**	**3**	**4**	**8**	**4**

Table S9 - Competition's characteristics

Author	Activity	Type	Competition	Nr. Seasons	Period	Match result	Venue
Gronwald et al. 2022	official matches	domestic league and national cup	Bundesliga 1 and 2	4	2014/15 to 2018/19	no	no
Della Villa et al. 2023	official matches	domestic league, european and international cup	Serie A	3	2018/19 to 2020/21	no	no
Jokela et al. 2023	official matches and training sessions (n=1)	not specified	not specified	not specified	Sept 2017 to Jan 2022	no	no
Aiello et al. 2023	official and friendly matches, training sessions (n=6)	domestic league and international cup	a Serie A club	3	2019/20 to 2021/22	win, lose, draw	home/ away
Klein et al. 2021	official matches	domestic league and national cup	Bundesliga 1 and 2	3	2014/15 to 2016/17	no	no

Della Villa et al. 2024	official and friendly matches	domestic league, european and international cup	Serie A (male), and Serie A, Bundesliga, La liga, Ligue 1, Premier League and Women Super league (female)	3 (male) and 7 (female)	2018/19 to 2020/21 (male) 2017/18 to 2022/23 (female)	no	no
Vermeulen et al. 2024	official matches	domestic league	Qatar Stars League	7	2013/14 to 2019/20	no	no
Prieto-Lage et al. 2021	official matches	domestic league	La Liga	1	2016/17	no	local/ visitor
Moreno-Perez et al. 2024	official matches	domestic league	7 clubs from La Liga	3	2016/17 to 2018/19	win, lose, draw	home/ away
Argibay-González et al. 2022	official matches	domestic league	La Liga and Premier league	1	2018/19	no	no
Yüce et al. 2022	not specified	not specified	not specified	not specified	1989 to 2021	no	no
Total (out of 11)	**10**	**9**	**9**	**9**	**11**	**2**	**3**

Table S10 - Injury pitch and time distribution

Author	Field location	Time distribution	Match distribution	Minute of injury
Gronwald et al. 2022	no	no	quarters	no
Della Villa et al. 2023	11 zones	season, month	halves and quarters	no
Jokela et al. 2023	no	no	no	no
Aiello et al. 2023	no	no	quarters	yes
Klein et al. 2021	14 areas	no	no	no
Della Villa et al. 2024	11 zones	season, month	halves and quarters	yes
Vermeulen et al. 2024	7 areas	no	halves and quarters + extratime	no
Prieto-Lage et al. 2021	8 zones	match nr of the league, month	halves and quarters + extratime	no
Moreno-Perez et al. 2024	no	match nr of the league	halves and quarters + extratime	no
Argibay-González et al. 2022	8 zones	match nr of the league, month	halves and quarters + extratime	no
Yüce et al. 2022	no	no	no	no
Total (out of 11)	**6**	**5**	**8**	**2**

Table S11 - Study design and statistical approaches

Author	Study design	Lay-off criteria	Systematic registration	Data collection	Statistical tool	Statistical Analysis
Gronwald et al. 2022	cross-sectional observational study	moderate and severe	yes	a standardised observation sheet based on previous research (*Klein et al. 2021*)	Microsoft Excel 2016	absolute numbers and percentages
Della Villa et al. 2023	cross-sectional observational study	severe	yes	a predetermined checklist based on previous research (*Buckthorpe et al. 2021 and Della Villa F et al. 2020*)	Microsoft Excel 2016 and Stata V.12	absolute numbers and percentages; mean (±SD) or median (range); proportion test ($\alpha < 0.05$)
Jokela et al. 2023	not declared	not declared	no	a specific questionnaire based on previous research (*Andersen et al. 2004, Della Villa et al. 2020, Waldén et al. 2015, Klein et al. 2020, Serner et al. 2019*)	Microsoft Excel 2018	absolute numbers and percentages
Aiello et al. 2023	retrospective descriptive study	moderate and severe	yes	Football Injury Inciting Circumstances Classification System (FIICCS)	not reported	absolute numbers and percentages; median and interquartile range (IQR)
Klein et al. 2021	not declared	moderate and severe	yes	an observation form based on previous research (*Waldén et al. 2015, Andersen et al. 2004, Olsen et al. 2004, Hutchison et al. 2014, Luig 2016*)	IBM SPSS Statistics (V.25.0)	absolute numbers and percentages; x2 test and Fisher's exact test ($p < 0.05$); Fleiss' κ (novice); Cohen's κ (expert, intra-rater)
Della Villa et al. 2024	not declared	severe	no	a predetermined checklist	Python library	absolute numbers and percentages; mean (±SD) or median (range); x2 tests for proportion; unpaired Students' t test for sex-related differences; statistical power ($\pi > 0.8$); $\alpha < 0.05$.

Vermeulen et al. 2024	single-centre observational cohort study	not declared	yes	a standardised scoring form based on previous research (*Serner et al. 2019, Hendricks et al. 2020*)	IBM SPSS Statistics (V.26.0)	absolute numbers and percentages
Prieto-Lage et al. 2021	nomothetic, follow-up and unidimensional observational design	not declared	yes	LINCE v.1.4 software + OI-INJURIES-FOOTBALL observational instrument	IBM SPSS Statistics (V.25.0)	absolute numbers and percentages; x2 test; T-patterns and polar coordinates analysis (Theme v.5.0, GSEQ5, HOISAN); $p < 0.05$
Moreno-Perez et al. 2024	not declared	moderate and severe	yes	an electronic document based on STROBE-SIIS (*Bahr et al. 2020*)	IBM SPSS Statistics (V.27.0)	absolute numbers and percentages; mean (±SD) or median (range); x2 test; two-way ANOVA (ηp^2 effect size); paired t-tests; Cohen's d (effect size with 95% CI); odds ratio (OR, 95% CI); $\alpha < 0.05$.
Argibay-González et al. 2022	nomothetic, follow-up and unidimensional observational design	not declared	yes	LINCE v.1.4 software + OI-INJURIES-FOOTBALL observational instrument	IBM SPSS Statistics (V.25.0)	absolute numbers and percentages; x2 test; Pearson's correlation coefficient; T-patterns and polar coordinates analysis (Theme v.5.0, HOISAN); $p < 0.05$.
Yüce et al. 2022	not declared	not declared	no	not declared	IBM SPSS Statistics (V.23.0)	absolute numbers and percentages; mean (±SD) or median (range); Shapiro-Wilk test (normality); Fleiss' kappa and ICC for reliability (interpretation thresholds specified); $\alpha < 0.05$.
Total (out of 11)	**6**	**6**	**8**	**10**	**10**	**11**

Table S12 - Overview of injury diagnosis and related factors reported in the included studies.

Author	Injured side	Dominance	Severity (days lost)	Muscle involved	Diagnostic method	Injury sources
Gronwald et al. 2022	no	no	median and range	yes	MRI	German statutory accident insurance for professional athletes VBG
Della Villa et al. 2023	yes	yes	mean ± SD	no	no	Transfermarkt.De + national and local media
Jokela et al. 2023	no	no	no	yes	MRI	private departments at specialized sports medicine hospitals in Finland and Spain
Aiello et al. 2023	no	no	no	no	no	medical data were routinely collected by the sports medicine department
Klein et al. 2021	no	no	no	no	no	German statutory accident insurance for professional athletes VBG
Della Villa et al. 2024	yes	yes	mean ± SD	no	no	transfermarkt.de + local media AND FBref.com + Google search
Vermeulen et al. 2024	no	no	no	no	clinical examination	medical staff from each club
Prieto-Lage et al. 2021	yes	no	no	no	no	official medical records of the clubs and TransferMarkt
Moreno-Perez et al. 2024	no	no	mean ± SD and range	no	MRI	medical staff of the teams
Argibay-González et al. 2022	yes	no	no	no	no	official medical records of the clubs and TransferMarkt
Yüce et al. 2022	yes	no	no	no	no	Google search
Total (out of 11)	**5**	**2**	**4**	**2**	**4**	**11**

Table S13 - Summary of video analysis procedures across included studies.

Author	Video Analysis experience/ training	Raters background	Nr. of raters	Intra and Inter-rater reliability	Video acquisition	Video processing	Nr. camera views	Resolution (pixel)
Gronwald et al. 2022	no	no	5	no	Sportcast Mediaportal	Kinovea	yes	yes
Della Villa et al. 2023	yes	yes	3	no	InStat	Kinovea	no	no
Jokela et al. 2023	no	yes	4	no	personal and teams' archiving system + Sky Italia	QuickTime player V.10.4.	yes	yes
Aiello et al. 2023	no	no	2	no	a fixed-camera system + TV broadcasting services	no	no	no
Klein et al. 2021	yes	no	2	yes	Sportcast Mediaportal	no	yes	yes
Della Villa et al. 2024	no	yes	3	no	InStat + Youtube + Wyscout	Kinovea	no	no
Vermeulen et al. 2024	yes	yes	9	no	Wyscout + Stats Perform	VLC media player	no	yes
Prieto-Lage et al. 2021	no	no	2	no	Wyscout	LINCE v.1.4	no	no
Moreno-Perez et al. 2024	no	no	not declared	no	Mediacoach	Mediacoach	yes	no
Argibay-González et al. 2022	no	no	2	no	Wyscout	LINCE v.1.4	no	no
Yüce et al. 2022	no	yes	3	yes	YouTube, Twitter, Facebook	IC Measure (2.0.0.286)	no	no
Total (out of 11)	**3**	**5**	**10**	**2**	**11**	**9**	**4**	**4**

Table S14 - HSIs mechanisms and situational patterns distribution

Author	Mechanism	n	%	Situational Pattern	n	%	Inciting-Activities	n	%
Gronwald et al. 2022	Non-contact	34	65	Sprint pattern	25	48	Acceleration	14	27
							High-speed running	10	19
							Kicking	8	15
	Indirect contact	18	35	Stretch pattern	27	52	Braking, stopping: landing	2	4
							Braking, stopping: lunging	16	31
							Other	1	2
Della Villa et al. 2023	Non-contact	53	87	Running	24	39			
				OKC stretching	15	26			
				CKC stretching	12	19			
	Indirect contact	8	13	Kicking	6	9			
				Others	4	7			
Jokela et al. 2023							Running (acceleration)	1	7
				Sprint-type	3	21	Running (in speed)	2	14
	Non-contact	7	50				Change of direction	4	29
							Jumping (landing)	1	7
				Stretch-type	5	36	Reaching for ball	1	7
							Shielding	1	7
							Kicking with uninjured leg	1	7
	Indirect contact	7	50	Mixed-type	6	43	Kicking with injured leg	2	14
							Kicking (approach to kick)	1	7
Aiello et al. 2023	Non-contact	17	100	Linear run	15	88	Accelerating	3	18
							Decelerating	4	24
				Curved run	1	6	Running at steady speed	9	53
				Jumping - in air	1	6	Jumping - in air	1	6
	Non-contact	19	66	Running	17	59			

Della Villa et al. 2024				OKC stretching	4	14			
				CKC stretching	2	7			
	Indirect contact	10	34	Kicking	5	17			
				Others	1	3			
Vermeulen et al. 2024	Non-contact	45	71	Running type	43	68	Acceleration	19	30
							At speed	11	17
	Indirect contact	17	27	Stretching type	9	14	Deceleration	2	3
	Unclear	1	2	Other	10	16	Unclear	3	5

Table S15 - Injury-inciting circumstances

Authors	Concurrent movements	Ball situation summary	Duel/ Interactions with other players	Playing phase before injury
Gronwald et al. 2022	no	no	no	no
Della Villa et al. 2023	no	no	no	offensive/defensive
Jokela et al. 2023	standing, walking, jogging, running, maximal sprinting, not horizontal	no	running duel, heading, other	no
Aiello et al. 2023	no	injured player with/ without ball, loose ball, running with ball, dribbling, direct opponent with ball	no	offensive/defensive
Klein et al. 2021	standing/lying, starting, running, sprinting, stopping, change of direction, lunging, taking-off, being mid-air, landing, sliding	ball possession: injured player, own team, opponent team, unclear/nobody	no other player, teammate, opponent, both	regular game play, counter-attack, counter pressing, set-play defence/ offence. If set-play: throw-in, free kick, corner kick, penalty, goal kick
Della Villa et al. 2024	no	no	no	offensive/defensive
Vermeulen et al. 2024	‘single-player action’ and ‘multiple-player actions’	ball possession: injured player running with ball, injured player running without ball	no	in play, set play, unclear team action: defensive, offensive, free ball (no possession), unclear
Prieto-Lage et al. 2021	no	no	alone and rival	no
Moreno-Perez et al. 2024	no	no	no	no
Argibay-González et al. 2022	no	no	alone and rival	no
Yüce et al. 2022	no	no	no	no
Total (out of 11)	**3**	**3**	**4**	**4**

Table S16 PRISMA 2020 Checklist

Section and Topic	Item #	Checklist item	Location where item is reported
TITLE			
Title	1	Identify the report as a systematic review.	Title
ABSTRACT			
Abstract	2	See the PRISMA 2020 for Abstracts checklist.	Abstract
INTRODUCTION			
Rationale	3	Describe the rationale for the review in the context of existing knowledge.	Page 3
Objectives	4	Provide an explicit statement of the objective(s) or question(s) the review addresses.	Page 3
METHODS			
Eligibility criteria	5	Specify the inclusion and exclusion criteria for the review and how studies were grouped for the syntheses.	Page 4
Information sources	6	Specify all databases, registers, websites, organisations, reference lists and other sources searched or consulted to identify studies. Specify the date when each source was last searched or consulted.	Page 4
Search strategy	7	Present the full search strategies for all databases, registers and websites, including any filters and limits used.	Page 4 and Table S1, S2
Selection process	8	Specify the methods used to decide whether a study met the inclusion criteria of the review, including how many reviewers screened each record and each report retrieved, whether they worked independently, and if applicable, details of automation tools used in the process.	Page 4-5
Data collection process	9	Specify the methods used to collect data from reports, including how many reviewers collected data from each report, whether they worked independently, any processes for obtaining or confirming data from study investigators, and if applicable, details of automation tools used in the process.	Page 5
Data items	10a	List and define all outcomes for which data were sought. Specify whether all results that were compatible with each outcome domain in each study were sought (e.g. for all measures, time points, analyses), and if not, the methods used to decide which results to collect.	Page 5
	10b	List and define all other variables for which data were sought (e.g. participant and intervention characteristics, funding sources). Describe any assumptions made about any missing or unclear information.	Page 5
Study risk of bias assessment	11	Specify the methods used to assess risk of bias in the included studies, including details of the tool(s) used, how many reviewers assessed each study and whether they worked independently, and if applicable, details of automation tools used in the process.	Page 5
Effect measures	12	Specify for each outcome the effect measure(s) (e.g. risk ratio, mean difference) used in the synthesis or presentation of results.	Page 6

Section and Topic	Item #	Checklist item	Location where item is reported
Synthesis methods	13a	Describe the processes used to decide which studies were eligible for each synthesis (e.g. tabulating the study intervention characteristics and comparing against the planned groups for each synthesis (item #5)).	NA
	13b	Describe any methods required to prepare the data for presentation or synthesis, such as handling of missing summary statistics, or data conversions.	Page 6
	13c	Describe any methods used to tabulate or visually display results of individual studies and syntheses.	Page 6
	13d	Describe any methods used to synthesize results and provide a rationale for the choice(s). If meta-analysis was performed, describe the model(s), method(s) to identify the presence and extent of statistical heterogeneity, and software package(s) used.	Page 6
	13e	Describe any methods used to explore possible causes of heterogeneity among study results (e.g. subgroup analysis, meta-regression).	NA
	13f	Describe any sensitivity analyses conducted to assess robustness of the synthesized results.	NA
Reporting bias assessment	14	Describe any methods used to assess risk of bias due to missing results in a synthesis (arising from reporting biases).	NA
Certainty assessment	15	Describe any methods used to assess certainty (or confidence) in the body of evidence for an outcome.	NA
RESULTS			
Study selection	16a	Describe the results of the search and selection process, from the number of records identified in the search to the number of studies included in the review, ideally using a flow diagram.	Page 7 and Figure 1
	16b	Cite studies that might appear to meet the inclusion criteria, but which were excluded, and explain why they were excluded.	Page 7 and Table S4-5
Study characteristics	17	Cite each included study and present its characteristics.	Page 7 and Table S8
Risk of bias in studies	18	Present assessments of risk of bias for each included study.	Table S6-7
Results of individual studies	19	For all outcomes, present, for each study: (a) summary statistics for each group (where appropriate) and (b) an effect estimate and its precision (e.g. confidence/credible interval), ideally using structured tables or plots.	NA
Results of syntheses	20a	For each synthesis, briefly summarise the characteristics and risk of bias among contributing studies.	Page 7-16, Fig. 2, Table 1,2,3
	20b	Present results of all statistical syntheses conducted. If meta-analysis was done, present for each the summary estimate and its precision (e.g. confidence/credible interval) and measures of statistical heterogeneity. If comparing groups, describe the direction of the effect.	NA
	20c	Present results of all investigations of possible causes of heterogeneity among study results.	NA
	20d	Present results of all sensitivity analyses conducted to assess the robustness of the synthesized results.	NA

Section and Topic	Item #	Checklist item	Location where item is reported
Reporting biases	21	Present assessments of risk of bias due to missing results (arising from reporting biases) for each synthesis assessed.	NA
Certainty of evidence	22	Present assessments of certainty (or confidence) in the body of evidence for each outcome assessed.	NA
DISCUSSION			
Discussion	23a	Provide a general interpretation of the results in the context of other evidence.	Page 17-20
	23b	Discuss any limitations of the evidence included in the review.	Page 21
	23c	Discuss any limitations of the review processes used.	Page 21
	23d	Discuss implications of the results for practice, policy, and future research.	Page 22
OTHER INFORMATION			
Registration and protocol	24a	Provide registration information for the review, including register name and registration number, or state that the review was not registered.	Abstract and page 4
	24b	Indicate where the review protocol can be accessed, or state that a protocol was not prepared.	Page 4
	24c	Describe and explain any amendments to information provided at registration or in the protocol.	Page 4
Support	25	Describe sources of financial or non-financial support for the review, and the role of the funders or sponsors in the review.	Declarations
Competing interests	26	Declare any competing interests of review authors.	Declarations
Availability of data, code and other materials	27	Report which of the following are publicly available and where they can be found: template data collection forms; data extracted from included studies; data used for all analyses; analytic code; any other materials used in the review.	Declarations

From: Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372:n71. doi: 10.1136/bmj.n71. For more information, visit: http://www.prisma-statement.org/

Table S17 PRISMA 2020 for Abstract Checklist

Section and Topic	Item #	Checklist item	Reported (Yes/No)
TITLE			
Title	1	Identify the report as a systematic review.	Yes
BACKGROUND			
Objectives	2	Provide an explicit statement of the main objective(s) or question(s) the review addresses.	Yes
METHODS			
Eligibility criteria	3	Specify the inclusion and exclusion criteria for the review.	Yes
Information sources	4	Specify the information sources (e.g. databases, registers) used to identify studies and the date when each was last searched.	Yes
Risk of bias	5	Specify the methods used to assess risk of bias in the included studies.	Yes
Synthesis of results	6	Specify the methods used to present and synthesise results.	Yes
RESULTS			
Included studies	7	Give the total number of included studies and participants and summarise relevant characteristics of studies.	Yes
Synthesis of results	8	Present results for main outcomes, preferably indicating the number of included studies and participants for each. If meta-analysis was done, report the summary estimate and confidence/credible interval. If comparing groups, indicate the direction of the effect (i.e. which group is favoured).	Yes
DISCUSSION			
Limitations of evidence	9	Provide a brief summary of the limitations of the evidence included in the review (e.g. study risk of bias, inconsistency and imprecision).	Yes
Interpretation	10	Provide a general interpretation of the results and important implications.	Yes
OTHER			
Funding	11	Specify the primary source of funding for the review.	Yes
Registration	12	Provide the register name and registration number.	Yes

From: Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372:n71. doi: 10.1136/bmj.n71. This work is licensed under CC BY 4.0. To view a copy of this license, visit https://creativecommons.org/licenses/by/4.0/

Paper 4 (ongoing)

Analysis of Football-Specific Movements Associated with Hamstring Injury Stretch-Type Patterns Using On-field Markerless Motion Capture and Musculoskeletal Modeling

Background

Hamstring injuries (HIs) remain among the most prevalent and costly injuries in football, often resulting in substantial time-loss and high recurrence rates [49,253,259,271,599]. These injuries typically occur when the muscle–tendon unit (MTU) is exposed to a combination of high forces, lengthening contractions, high velocity, and moderate-to-long muscle length conditions [270,272,424,600]. Traditionally, research has focused on sprint-related HIs, which typically occur during repetitive high-speed running primarily constrained to the sagittal plane. The terminal swing phase is considered the critical moment for injury occurrence, as the hamstrings lengthen eccentrically to decelerate the leg before ground contact [406,411,446,521,601].

However, a growing body of video analysis evidence indicates that a substantial proportion of HIs in football arise from stretch-type situational patterns, movements characterized by greater variability and multidirectional demand. These actions include lunging, sliding, reaching for the ball, twisting, or kicking, which require extensive muscle lengthening at high velocity [73,261,263]. These movements frequently occur during active-play actions involving duels for ball possession, where the hamstrings must manage high loads to react under unpredictable and changing environmental conditions. While sprint-type injuries have been well characterized biomechanically, stretch-type underlying mechanisms remain poorly understood. This gap may partly explain the limited effectiveness of current prevention and rehabilitation programs in reducing their incidence and recurrence.

Anatomical and imaging studies suggest that the specific hamstring muscle affected depends on the type of task performed. The biceps femoris long head (BFlh) is most vulnerable during high-speed running due to its role in eccentric deceleration, whereas the semimembranosus (SM) and semitendinosus (ST) are more affected during movements requiring extreme hip flexion and knee extension [176]. Stretch-type injuries, frequently involving the proximal free tendon and ischial region, are associated with longer recovery times and higher reinjury risk [256]. Despite these differences, most rehabilitation and prevention programs still adopt a one-size-fits-all approach centered on sprint-type mechanisms. Therefore, a deeper understanding of hamstring function during football-specific overstretching tasks is essential to refine mechanism-specific prevention, screening, and rehabilitation strategies.

According to Heiderscheit et al. (2010) , functional assessments should reproduce sport-specific, high-intensity movements. Screening tools such as the Sprint Mechanics Assessment Score (S-MAS) have demonstrated the value of technique-based evaluation for sprinting; similarly, new movement-specific protocols are needed to assess the biomechanical and neuromuscular demands of stretch-type actions.

Aim

This ongoing study aims to simulate and analyze football-specific movements associated with stretch-type HI mechanisms using a markerless motion capture system (OpenCap) integrated with musculoskeletal modeling (OpenSim). The objective is to estimate musculotendon strain, lengthening velocity, and joint kinematics of the hamstrings during these tasks, and to compare loading patterns across individual muscles (SM, ST, BFlh, and BFsh) under varying task conditions. It is hypothesized that stretch-type movements will elicit high muscle lengthening and strain velocity, particularly in the medial hamstrings, with distinct biomechanical patterns depending on the movement performed.

Participants

The study included 11 male competitive football players (aged 19–28 years), all right-foot dominant, recruited from the School of Exercise and Sport Sciences, University of Milan. All participants were active players and free of acute musculoskeletal injuries. Past medical history included three anterior cruciate ligament (ACL) ruptures (2022–2023), one rectus femoris strain (2022), one right meniscus tear (2024), and one biceps femoris injury (2015). Testing sessions were conducted outdoors on a synthetic turf field under mild weather conditions (15–25 °C, overcast, no wind or rain) and players used standard playing equipment (boots, socks, shorts, and jersey).

Experimental Design and Setup

Two football-specific overstretching tasks were designed to reproduce high-risk scenarios typically associated with stretch-type hamstring injuries. The closed kinetic chain interception (CKCI) task involved a forward lunge to intercept a ground ball following a short 5-meter approach run. The open kinetic chain interception (OKCI) task simulated an aerial interception, replicating a reaching motion toward a suspended ball. Both tasks were executed at maximal intensity, replicating realistic in-game situations in which a player attempts to intercept a pass between opponents, either on the ground or in the air. Each task was then repeated in a reduced step-length and range-of-motion version (CKCIH and OKCIH), allowing comparison between maximal and submaximal executions performed under equivalent intensity conditions (Figure 1). Each participant completed three valid trials per condition, following a standardized 15-minute warm-up and task familiarization session. The familiarization phase was used to determine the ball position for each player based on individual reach and movement capacity while maintaining consistency across trials. The ball was placed slightly beyond each player's maximum reach, preventing direct contact and avoiding ball–foot obstruction in the recorded footage, while still serving as a visual and spatial reference to preserve ecological validity. In OKC tasks, the ball was suspended from the goal crossbar with a net and rope, at heights between 157–205 cm, and positioned 90–180 cm forward and 60–115 cm lateral to the 5-meter end marker (figure 2).

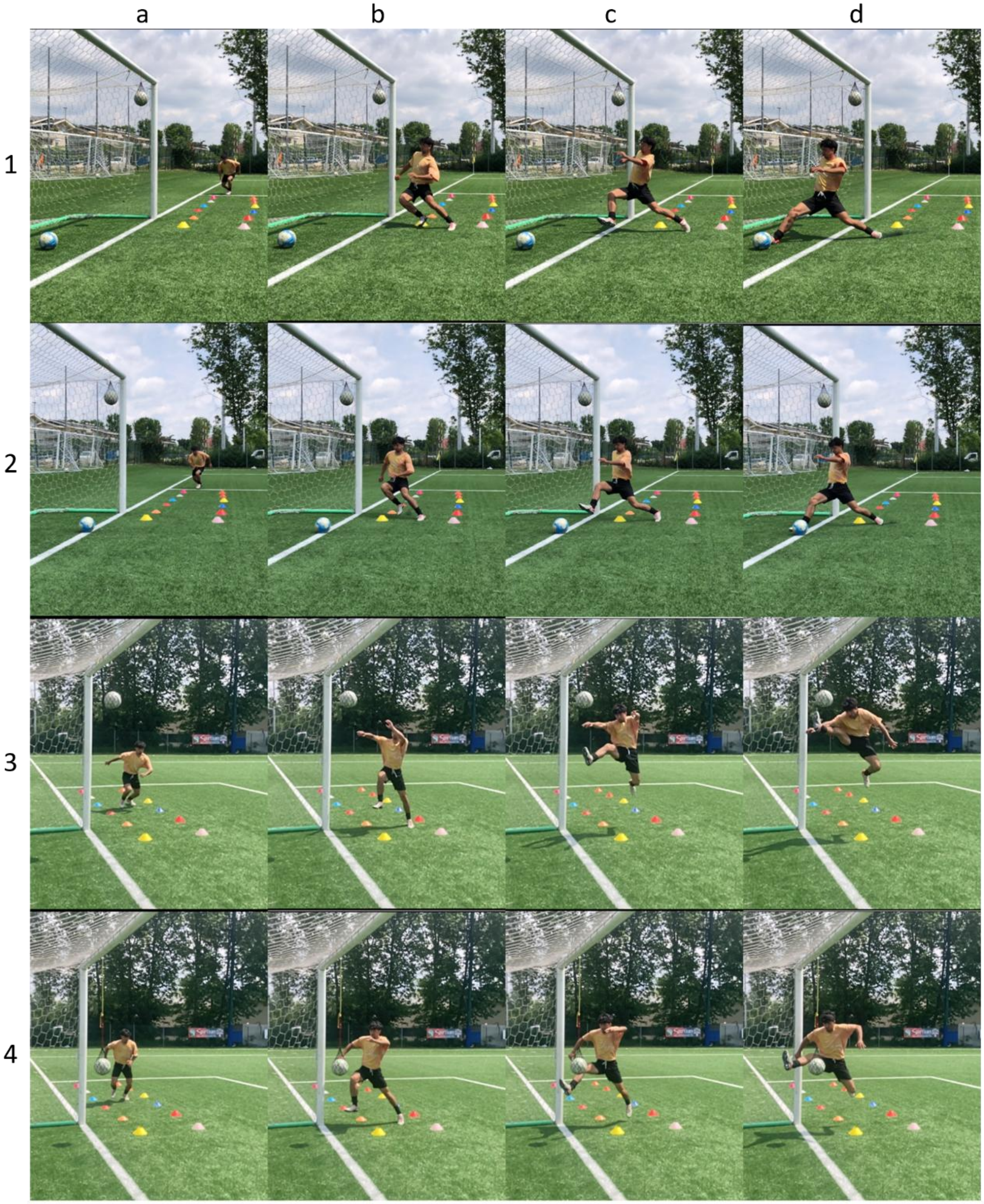

Figure 1: Sequence of football-specific movements simulating stretch-type hamstring injury mechanisms. Panel 1 illustrates the closed kinetic chain interception (CKC-I) task, consisting of a forward lunge to intercept a ground ball after a 5 meters approach run. Panel 3 depicts the open kinetic chain interception (OKC-I) task, simulating an aerial ball interception. Each movement was performed at maximal intensity and half

intensity (CKCIH, OKCIH), respectively panel 2 and 4, achieved by proportionally reducing step length and movement amplitude.

Instrumentation and Data Collection

Motion capture was performed using OpenCap, a smartphone-based markerless motion capture system that reconstructs 3D kinematics from 2D video data. Three iPhones (SE 2020, 11, 12 Pro) recording at 120 fps were mounted on tripods at 130–150 cm height (Figure 2). Distances from the ball were 5.30 m for cameras a and c, and 6.30 m for camera b. Captured motion data were uploaded to the OpenCap cloud platform, where 3D joint kinematics and body segment trajectories were automatically computed. These data will then be exported to OpenSim for musculoskeletal modeling and estimation of muscle forces, tendon strain, and lengthening velocities for each hamstring muscle.

A key methodological challenge encountered during data collection was limb occlusion, particularly in OKC interceptions where the arms partially obscured the reaching leg. To address this issue, the video data are currently being reprocessed using OpenPose's high-accuracy settings, which have been shown to yield more precise 2D joint tracking at higher computational cost [494]. This ongoing step aims to improve the accuracy of lower-limb kinematics before subsequent modeling in OpenSim.

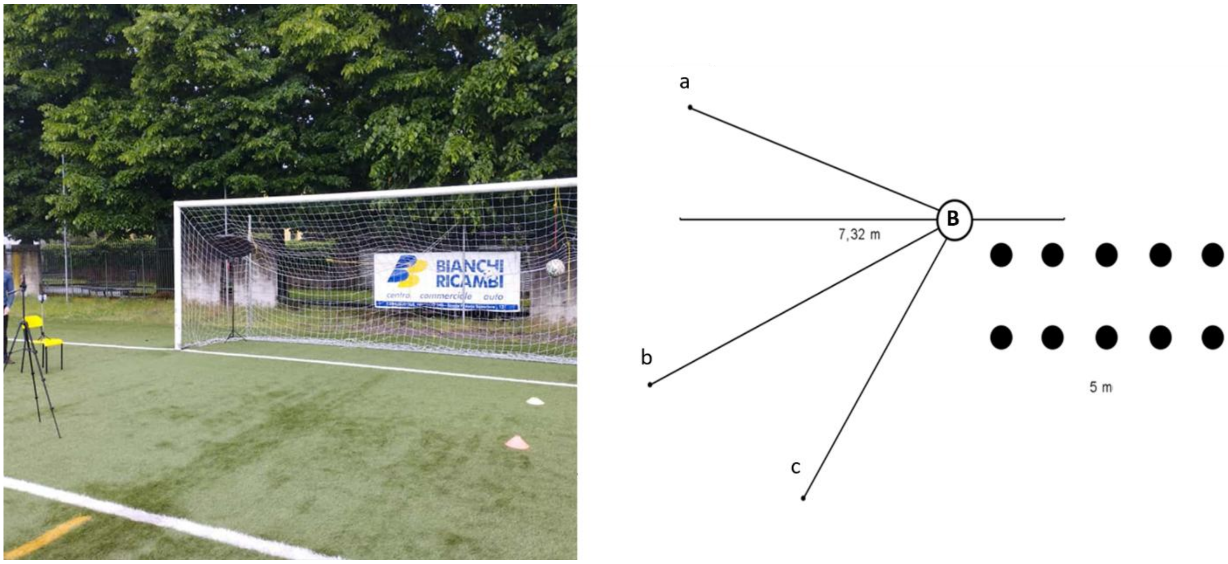

Figure 2: Experimental setup and camera configuration for CKC and OKC trials. The left panel shows the on-field setup, while the right panel provides a schematic top view illustrating the spatial arrangement of the three cameras (a, b, c) relative to the ball (B). Distances from the ball were 5.30 m for cameras a and c, and 6.30 m for camera b. The black dots represent the cones delimiting a 5-meter corridor within which players performed the approach run before executing the corresponding CKC

movement. For both OKC and CKC trials the final step was required to occur before the end line of the corridor for the trial to be considered valid.

For data analysis, specific kinematic and kinetic events will be extracted to characterize each movement phase. The analysis will begin with the last push-off of the analyzed leg, corresponding to the last step at the end of the 5-meter line. This frame will serve as the reference for both the CKC and OKC movements. In CKC tasks, which are preceded by a 5-meter approach run, the push-off phase marks the transition from sprinting to the lunge action. In OKC tasks, no specific starting point is imposed, but the analyzed leg must not cross the final 5-meter line during ground contact and push-off. Subsequent analyses will focus on the ground contact frame for CKC movements and the peak vertical displacement for OKC tasks. Thigh angular velocity will be calculated between push-off and ground contact for CKC tasks, and between push-off and peak vertical displacement for OKC movements. Peak hamstring lengthening and lengthening velocity will be quantified to characterize the mechanical demands associated with each task.

In addition to hip–knee joint angles, lumbopelvic control will be examined by quantifying anterior pelvic tilt, trunk flexion–extension, and lateral tilt angles, providing insight into compensatory or potentially hazardous movement strategies. Performance outcomes will also be assessed based on the horizontal distance achieved during the lunge in CKC tasks and the maximum reach height in OKC tasks, reflecting each player’s ability to execute the movement effectively while managing hamstring load. Both distance and height measures will be normalized to each participant’s body height to allow for inter-individual comparisons and account for anthropometric variability. This integrated approach will enable a detailed biomechanical and functional characterization of stretch-type hamstring injury mechanisms, combining ecological field-based motion capture with musculoskeletal modeling to identify movement strategies associated with elevated strain and lengthening velocity in the hamstring muscle–tendon unit.

Current Status and Perspectives

At present, the video data are undergoing reprocessing and model validation, and results are not yet available. Once finalized, the dataset will provide an unprecedented description of football-specific overstretching mechanics using ecological, field-based acquisition. This study is expected to clarify the relationship between task-specific biomechanics, hamstring strain, and neuromuscular control, and to contribute to the development of mechanism-based rehabilitation and prevention strategies tailored to stretch-type injuries.

List of Additional Publications

Della Villa, F., Buckthorpe, M., **Pellegrini, A.**, Ranzini, A., Esposito, F., Crescenzo, C., Nanni, G., & Zago, M. (2024). A comparative video analysis of hamstring injuries mechanism and situational pattern in men's and women's football (soccer). Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA, 32(10), 2610–2621. https://doi.org/10.1002/ksa.12313

Pulici, L., Randelli, P., **Pellegrini, A.**, Zago, M., Bellistri, G., Niccolai, R., Galli, M., Dellasette, E., Tosi, L., & Volpi, P. (2024). Injuries in elite football (soccer) academy: A 4-year observational cohort study of five categories and 515 players. International Journal of Sports Science & Coaching, 19(5), 2090-2102. https://doi.org/10.1177/17479541241232765

Ranzini, A., Alessandro, C., Nitri, M., **Pellegrini, A.**, Esposito, F., Della Villa, F., & Zago, M. (2025). 3D kinematics of noncontact and indirect contact ACL injuries in elite male football players. Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA, 10.1002/ksa.12612. https://doi.org/10.1002/ksa.12612

3. CONCLUSION AND PERSPECTIVES

Hamstring injuries (HIs) remain the most frequent injuries in football, characterized by high recurrence rates and substantial consequences for player performance, career longevity, and club finances. Despite decades of research and the identification of numerous risk factors, their incidence continues to rise, confirming the multifactorial and complex nature of their etiology.

The primary aim of this PhD thesis was to analyze HIs in football through a complex systems approach using VA, integrating contextual, cognitive, and biomechanical dimensions. By examining the injury-inciting event, this work contributes to the second step of the “sequence of prevention” model by providing injury-contextual and situational information that traditional epidemiological tools cannot capture. Because football is a dynamic, interactive environment where players must continuously adapt to rapidly changing spatial and temporal constraints, their motor actions result from intricate perceptual–cognitive processes. Accordingly, this thesis integrated variables such as attentional focus, visual scanning behavior preceding the injury, gaze direction at the time of injury, and potential shifts in visual attention immediately before the event. This approach marked a conceptual shift from analyzing the injured player in isolation to considering the interactional environment in which the injury occurs, and from focusing on a single injury frame to reconstructing the action sequence that precedes it. Likewise, it moved beyond isolated risk factors toward a multifactorial model, and from focusing on the individual muscle injured to assessing the entire kinetic chains implicated in the movement. The findings of this thesis confirm that VA is an ecological and multidimensional tool, capable of investigating injury mechanisms from both biomechanical and contextual perspectives.

2D VA was first applied to analyze HIs in women’s football, addressing the lack of sex-specific injury research (Paper 1). Subsequently, Model-Based Image Matching was used for the first time in football to reconstruct, in three dimensions and over time, the full-body kinematics of the two classical HI patterns, run-type and stretch-type, from uncalibrated video footage (Paper 2). Finally, markerless 3D motion capture (OpenCap) enabled field-based analysis of stretch-type football-specific movements, such as lateral lunging in CKC and reaching for the ball in OKC. The aim is to estimate muscle lengthening and lengthening velocity across the individual hamstrings, testing the hypothesis that medial hamstrings (ST, SM) undergo greater stretch than BFlh (Paper 4).

The main conceptual contribution of this work was the development of a comprehensive methodological framework to guide future research on football-related HIs using VA (Paper 3). The framework integrates the most up-to-date consensus statements and guidelines on injury classification, diagnosis, and risk factors [30,31,134,156] with methodological standards for VA [464]. It was designed to promote high-quality, reproducible data collection and facilitate integration with complementary data sources such as MRI findings, GPS data, questionnaires, and advanced analytical approaches, including improved statistical modeling and mixed-methods designs. The framework also highlights the need for transdisciplinary collaboration, connecting biomechanics, neuroscience, clinical science, and performance analysis to evolve as new evidence emerges. Within this framework, a new football-specific classification system for HIs was proposed, extending beyond the traditional dichotomy of run-type and stretch-type injuries. It introduces two additional subcategories, kick-type and duel-type, to more accurately describe underrepresented stretch-type injuries, and offers an expanded description of indirect contact events, which account for nearly one-third of all cases. These findings underscore the importance of perturbation-based training and lumbo-pelvic stabilization as core elements of modern preventive strategies.

Collectively, the results of the presented studies challenged the long-standing notion that HIs occur predominantly during maximal sprinting. Many injuries instead occur during football-specific movements other than high-speed running. Approximately half of all cases involved stretch-type mechanisms, and even within the run-type category, a considerable proportion occurred during acceleration or deceleration phases rather than at top speed (paper 1). In the 2D VA study (Kinovea, calibrated to pitch dimensions), the average running distance before injury was 19 ± 12 m, indicating that injuries often occurred after brief, submaximal runs. Interestingly, most kick-type injuries in women's football occurred during passing rather than shooting. Together, these findings underscore the importance of developing screening and preventive strategies that accurately reflect the injury profiles observed in football, including short, submaximal runs, lunging, shielding, reaching, and passing actions, rather than focusing solely on maximal sprinting activities. Paper 4 represents, to our knowledge, the first attempt to analyze football-specific movements associated with stretch-type injury patterns under field conditions, thereby addressing this critical research gap and emphasizing the need to move beyond sprint-only analyses and laboratory-based testing.

The MBIM case study (Paper 2) further revealed that different movement patterns can result in the same injury type. Although hip flexion and knee extension were common to both, stretch-type case exhibited greater motion in the transverse and frontal planes than the run-type one, which occurred largely within a normal ROM on the sagittal plane. These observations suggest that preventive exercises should target hamstring loading at long muscle lengths while simultaneously challenging multiplanar stability. MRI data were used to ensure diagnostic accuracy, and future research should systematically link movement patterns to lesion type and anatomical location to identify potential correspondences between mechanical and structural injury features.

The contextual dimension of injury was also found to be crucial. Most HIs occurred during active phases of play, involving ball handling or duels, with or without contact, consistent with other findings showing that nearly all football-related HIs involve ball-related actions [406]. These complex, multitasking situations require rapid decision-making under several spatiotemporal constraints, emphasizing the interdependence between cognitive and motor demands inherent of injury occurrence. Injury distributions also varied by playing position, reflecting differences in task-specific mechanical and perceptual demands of each role.

Future preventive strategies should therefore aim to reproduce the variability and unpredictability of real-game contexts. Training should target muscle chain motor reprograming of feedforward control patterns and enhance the integration of visual, vestibular, and somatosensory systems to prepare players for unexpected perturbations. Screening tests should incorporate cognitive and perceptual components, reflecting the interactive and anticipatory nature of football performance. In summary, this thesis demonstrated that VA, combined with advanced motion reconstruction techniques and contextual interpretation, offers a powerful framework for investigating the mechanisms of HI in football.

By bridging biomechanics, neurocognition, and environmental interaction, it promotes a more dynamic and ecological understanding of injury. Future research should continue to foster transdisciplinary collaboration between data science, neuroscience, and applied coaching practice to translate laboratory findings into effective, on-field injury prevention strategies.

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