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Anterior Cruciate Ligament (ACL) Injuries in Soccer: A Comparative Study of Natural Grass and Artificial Turf Playing Surfaces

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Abstract

Purpose of research: This study considers biomechanical, mechanical, and epidemiological factors that differentiate natural grass (NG) from artificial turf (AT) in relation to anterior cruciate ligament (ACL) injury risk in soccer, with particular emphasis on shoe-surface interactions plus knee kinematics.

Research materials and methods: A comprehensive literature review was conducted, incorporating biomechanical studies, epidemiological reports, and meta-analyses published between 2022 and 2025. The analysis used data from large-scale databases, including the NCAA and NEISS, to compare injury incidence across several demographics, playing levels, and exposure types.

Basic results: Modern artificial turf exhibits 15% to 22% greater rotational resistance than natural grass, resulting in a hazardous "cleat lock" effect during pivoting maneuvers. Epidemiological data indicate that female players experience up to an 18% higher ACL injury risk on artificial turf, while male cohorts show no significant overall difference during match play. In contrast, injury risks on natural grass primarily result from surface irregularities, such as divots.

Conclusions: Artificial turf offers a considerable mechanical risk to the ACL due to increased rotational traction and surface stiffness. Effective risk mitigation calls for a diverse approach, including the enforcement of appropriate footwear (conical studs), consistent surface upkeep to prevent compaction, and the implementation of daily neuromuscular injury prevention programs such as FIFA 11+.

Keywords: Anterior Cruciate Ligament (ACL), soccer, biomechanics, artificial turf, natural grass, shoe-surface interaction, rotational traction, injury epidemiology, sports medicine.

1. Introduction

Soccer (Association Football) is characterized by high-intensity, intermittent actions including rapid decelerations, sudden changes of direction (cutting), and pivoting maneuvers [7]. These active movements place immense multi-planar stress on the knee joint, frequently pushing the biological limits of the anterior cruciate ligament (ACL) [13]. An ACL rupture is a catastrophic event for a soccer player, commonly requiring surgical reconstruction, 6 to 12 months of intensive rehabilitation, and carrying an increased long-term risk of early-onset post-traumatic osteoarthritis [3].

In the study of orthopedic biomechanics and sports medicine, the continuing debate over the playing surface—specifically, the comparative safety of natural grass (NG) versus artificial turf (AT)—continues as an important, highly polarized area of focus [14]. With the widespread use of third-generation (3G) and emerging fourth-generation (4G) artificial turf in community, collegiate, and elite soccer, owing to their durability, cost-effectiveness over time, and weather resistance, understanding the precise interaction among the athlete, the footwear, and the surface is critical [15]. While early artificial surfaces were widely condemned for their high injury rates, modern synthetic pitches are designed specifically to mimic the shock absorption and energy return of pristine natural grass [1]. However, the human body interacts with these synthetic materials differently at a microscopic and biomechanical level [2]. This paper thoroughly evaluates biomechanical mechanisms, mechanical surface properties, and the most recent epidemiological incidence rates of ACL

injuries on natural grass versus artificial turf, using the latest data to provide a state-of-the-art overview of this significant issue in sports science.

2. Background and Literature Review

The evolution of artificial playing surfaces has significantly modified the field of soccer injury research. First-generation artificial turf (Astroturf), introduced in the 1960s, consisted of short nylon fibers upon an asphalt or concrete base [14]. This surface was notorious for severely low shock absorption and excessively high translational friction, leading to a drastic increase in lower extremity joint injuries and epidermal abrasions ("turf burn").

The modern era of soccer is dominated by 3G artificial turf. A standard 3G pitch features longer synthetic grass fibers (typically polyethylene), a polyurethane backing material, and an infill mixture—usually composed of styrene-butadiene rubber (SBR) crumb and silica sand—designed to provide cleat penetration and mimic the yielding nature of natural soil [2]. In spite of these massive engineering advancements, the medical and biomechanical literature continues to be divided.

An early landmark study by Ekstrand et al. (2006) for the UEFA Elite Club Injury Study found no significant difference in overall injury rates between 3G turf and natural grass among professional male cohorts [1]. However, the literature has evolved rapidly as new surface generations and data gathering techniques have emerged. A recent 20-year nationwide analysis using the National Electronic Injury Surveillance System (NEISS) database evaluated 21,868 sports-related orthopedic injuries and found that 76.3% occurred on grass and 23.7% on turf [11]. While soccer injuries overall were more frequent on grass (due to higher overall exposure rates), the analysis indicated considerable variations in injury patterns, with specific ligamentous sprains being more common on turf [11].

Furthermore, a 2024 analysis by Ngatuvai using high school reporting systems found that ACL injuries were substantially more likely to occur on artificial turf than on natural grass in girls' soccer, with an Injury Proportion Ratio (IPR) of 1.53; the association in boys' soccer was less statistically significant [5]. This epidemiological discrepancy is heavily supported by contemporary biomechanical studies by Kent et al. (2021) and subsequent updates, which have demonstrated that modern artificial turf systems exhibit 15% to 22% higher rotational resistance than natural grass, creating a fundamentally different and potentially hazardous shoe-surface interaction profile [2].

3. Biomechanics of ACL Injuries in Soccer

To accurately assess how a surface contributes to injury, it is necessary to establish the biomechanical etiology of ACL ruptures in soccer. The vast majority—approximately 70% to 80%—of ACL injuries in soccer are non-contact or indirect contact, such as a slight perturbation from an opponent leading to an awkward, unbalanced landing [7], [13].

The classical mechanism of a non-contact ACL injury involves a devastating combination of multi-planar joint loading occurring within milliseconds of foot strike [8]. When a player performs a sudden cutting maneuver or deceleration, the lower extremity experiences a cascade of dangerous kinesiological events:

Shallow Knee Flexion: During the critical moment of foot plant, the knee is typically at 0° to 30° of flexion. In this extended, relatively stiff position, the patellar tendon angle is maximized relative to the tibia. The massive contraction of the quadriceps mechanism

exerts an intense anterior shear force on the proximal tibia, translating it forward relative to the femur and directly straining the ACL [13].

Dynamic Valgus Collapse: This is characterized by a medial collapse of the knee joint. It is driven proximally by hip adduction and internal rotation, and distally by tibial external rotation and foot pronation. This posture places immense tensile stress on the medial collateral ligament (MCL) and subsequently the ACL [15].

Transverse Plane Rotation: The most essential factor relating to the playing surface is internal or external tibial rotation while the foot is securely planted [8].

A recent study evaluating the specific mechanism of ACL injury in female soccer players via video analysis found that, among non-contact injuries, 55% occurred during cutting maneuvers and 44% during pressing or defending actions [13]. The researchers concluded that ACL injuries often occur as non-contact events during defensive pressing, regardless of the specific area of the pitch, pointing to the danger of uncoordinated deceleration [13]. From a mechanical physics perspective, if the foot remains fixed to the surface (high rotational traction) while the femur and upper body rotate internally over the fixed tibia, an extreme torque is generated at the knee joint [2]. Torque is defined by the cross product of the moment arm and the applied force.

$$\tau = r \times F$$

In the context of the shoe-surface interface, rotational stiffness (T_z) can also be modeled as torque relative to the angle of rotation (θ):

$$T_z = k_\theta \cdot \theta$$

When the rotational traction of the surface exceeds the failure threshold of the biological matter, the resulting torque overcomes the ultimate tensile strength of the ligament—which biomechanical cadaveric studies place at approximately 2000 N to 2200 N in healthy young adults—resulting in a catastrophic rupture [8].

4. Differences Between Natural Grass and Artificial Turf Surfaces

The interaction between a player's boot and the pitch is determined by both the physical structure and the physical composition of the surface. Modern soccer fields incorporate multiple engineered layers, including a synthetic fiber or natural grass playing layer, a stabilizing infill (such as rubber crumb and sand for artificial turf), a shock-absorbing base, and specific sub-base constructions designed to modulate surface hardness, rotational traction, and energy return. These carefully integrated elements directly influence how studs penetrate, release, and transmit forces, all of which are fundamental in forming the shoe-surface interface and, consequently, biomechanical injury risk.

Mechanical Property	Natural Grass (NG)	3G Artificial Turf (AT)	Biomechanical Implication
Surface Stiffness	Variable; highly dependent on soil moisture, root zone depth, and grass species (e.g., Perennial Rye vs. Bermuda).	Highly uniform; determined by the underlying shock pad (if present) and infill density. Often ranges from 60 to 85 Shore A hardness.	Affects energy return and shock attenuation during landing. Higher stiffness on AT increases vertical ground reaction forces.
Rotational Traction	Generally lower. The thatch layer and topsoil yield or tear (creating a divot) under extreme shear stress, releasing the boot.	Significantly higher (15% to 22% higher than NG). Synthetic polyethylene fibers and rubber infill resist yielding, locking the cleats in place.	High rotational traction increases torque on the knee joint during pivoting, leading to the "cleat lock" phenomenon.
Translational Friction	Moderate to low, heavily dependent on wetness.	High, though infill splash (displacement of rubber pellets) can slightly mitigate this during linear sliding.	Affects the ability to slide, potentially increasing deceleration forces and altering how quickly a player can stop.
Compliance Variability	High. NG exhibits 10 mm to 15 mm of surface deformation, which can change drastically within a single game due to wear.	Low. Reduces compliance variability, offering a highly predictable but consistently stiff surface.	NG risk fluctuates with weather and field degradation; AT presents a constant, unyielding biomechanical environment.

Note: The emergence of "hybrid" pitches—natural grass reinforced with synthetic fibers interlaced within the root zone (e.g., Desso GrassMaster)—attempts to close this gap. Recent mechanical testing (2022) indicates that hybrid pitches have rotational traction profiles closer to pure natural grass than 3G turf, provided they are maintained correctly [14].

5. Mechanisms Increasing ACL Injury Risk on Each Surface

Artificial Turf: The "Cheat Lock" Phenomenon

The primary biomechanical and orthopedic concern with AT is the presence of excessive rotational traction [7]. When a soccer player plants their foot to execute a sharp, high-velocity cut, the studs of the boot penetrate the rubber infill and sit among the synthetic fibers [8]. Unlike a natural soil matrix, the synthetic backing and high-tensile polyethylene fibers do not easily tear, deform, or yield [2].

This creates the well-documented "cheat lock" effect [7]. When the player's momentum carries their center of mass over and around the planted foot, the kinetic energy must be dissipated. Because the surface refuses to yield (as it would in the formation of a divot on a grass pitch), the failure point shifts proximally up the kinetic chain—away from the ground and directly into the organic tissues of the ankle and knee [8]. The extreme rotational torque is absorbed almost entirely by the ACL, the menisci, and surrounding capsular structures, frequently leading to failure [15].

Natural Grass: Surface Irregularities and Thatch Tearing

Conversely, natural grass is not immune to causing injuries; the mechanisms simply differ. While the yielding nature of soil protects against excessive rotational torque, NG is highly prone to surface irregularities [1]. Divots, uneven root growth, and varying moisture levels create an unpredictable biomechanical environment [14]. An unexpected perturbation—such as stepping on a hidden divot or slipping slightly on wet thatch during a high-speed deceleration—can cause a sudden, uncoordinated neuromuscular response [7]. This unanticipated shift in the center of gravity often forces the knee into a rapid dynamic valgus collapse before the hamstring muscles can fire to stabilize the joint, resulting in an ACL rupture [13].

6. Epidemiology and Injury Incidence Rates

Epidemiological studies comparing NG and AT have historically yielded complex and occasionally contradictory results. Large-scale prospective cohort studies generally conclude that the overall incidence of lower extremity injuries is statistically similar between 3G turf and natural grass, with soft tissue injuries (muscle strains and contusions) dominating both surfaces equally [1], [3].

Severe Knee Injuries and the Female Athlete: When isolating for ACL ruptures, the data diverges considerably based on the demographic [3]. Female soccer players inherently exhibit an ACL injury incidence rate 2 to 6 times higher than their male counterparts owing to bodily traits (e.g., wider Q-angle, narrower intercondylar notch) and hormone variations [9]. Crucially, recent systematic reviews and meta-analyses indicate that this risk is exacerbated by the surface. A

2022 meta-analysis by Xiao et al. demonstrated that female soccer players had an 18% higher ACL injury risk (Incidence Rate Ratio = 1.18) on artificial turf compared to natural grass during games, whereas male players showed no statistically significant difference [9]. Furthermore, the NEISS database indicated an Injury Proportion Ratio of 1.53 for high school girls' soccer on AT versus NG, signifying a clearly elevated risk [5].

However, this data is not broadly relevant across all competition levels. A comprehensive five-season study published in 2025 evaluating Finnish elite-level female footballers (involving 517 league matches) found an overall injury incidence rate of 19.6 per 1000 match hours on artificial turf and 19.3 on natural grass [10]. The researchers concluded there was no statistical difference observed for the risk of sudden-onset knee injuries between the two surfaces at the absolute elite professional level, suggesting that superior physical conditioning and neuromuscular control at the elite tier may mitigate surface-related risks [10].

The Practice vs. Match Anomaly: A massive NCAA study revealed an unanticipated finding: collegiate soccer players who practiced on natural grass had an increased risk of ACL injury compared to those practicing on artificial surfaces (0.52 vs 0.06 per 10,000 Athletic Exposures) [4]. However, no difference was detected during actual matches [4]. Researchers hypothesize that this may be due to the uneven, poorly maintained nature of practice grass fields versus pristine game-day grass fields, whereas artificial turf stays consistently uniform regardless of whether it is used for practice or a match [4], [14].

7. Risk Factors

The etiology of ACL injuries is inherently multifactorial. The playing surface interacts constantly with a variety of modifiable and non-modifiable variables:

Shoe–Surface Interaction (Cleat Design): The coefficient of friction is determined not just by the pitch, but by the footwear [8]. Wearing Firm Ground (FG) boots with long, bladed studs on a 3G artificial surface drastically increases rotational traction [15]. Bladed studs act like anchors in the synthetic infill, maximizing the "cleat lock" effect and increasing plantar pressure on the lateral border of the foot [8]. Stratified biomechanical analyses have indicated that for circular cleats, material and stud diameter are the primary determinants of torque, while for pyramid-shaped or bladed cleats, the total number of studs has the greatest impact [12], [15]. Utilizing Artificial Grass (AG) boots—which feature shorter, conical, and more heavily distributed studs—allows for safer rotational release on synthetic surfaces, significantly mitigating injury risk [8].

Weather Conditions and Thermal Risks: Natural grass is highly weather-dependent; wet grass significantly lowers traction, which decreases the risk of ACL injuries (as the foot easily slips, releasing torque), though it increases the risk of adductor strains [14]. Conversely, artificial turf yields unique thermal risks [16]. On a 90-degree Fahrenheit day, while a grass field may remain around 98 degrees, artificial turf can reach surface heat levels up to 166 degrees Fahrenheit [16]. This extreme heat can put athletes at a higher risk of heat-related illness, accelerate central and peripheral neuromuscular fatigue, and potentially

alter the stiffness and yielding properties of the synthetic materials (such as SBR rubber), indirectly causing injury risk [16].

8. Neuromuscular and Biomechanical Factors

From a kinesiological perspective, the human body acts as a highly advanced sensory system, attempting to alter its motor control strategies based on somatosensory feedback from the surface [7]. On artificial turf, players subconsciously alter their kinematics because of the perception of higher surface stiffness and friction [2]. Biomechanical studies adopting 3D motion capture and force plates have demonstrated that athletes tend to land with slightly less knee flexion (a stiffer leg) and greater peak vertical ground reaction forces on AT compared to NG [8].

This stiffer landing strategy reduces the shock-absorbing capacity of the lower limb musculature (quadriceps, hamstrings, and gastrocnemius), effectively bypassing the muscles and transferring kinetic energy directly into the passive ligamentous structures [15]. The hamstring muscles act as an essential ACL agonist; by pulling the tibia posteriorly, they protect the ACL from anterior shear [13]. Any delay in hamstring activation—whether due to heat-induced fatigue, physical exhaustion in the latter stages of a match, or the sudden unyielding grip of a synthetic surface—leaves the ACL entirely exposed to the mechanical forces of deceleration [7]. This risk is severely compounded by existing muscular imbalances, especially when athletes display weak hamstrings in relation to their quadriceps [17]. When this disproportion is combined with generalized ligamentous laxity and the high-friction environment of an artificial pitch, the risk of a non-contact rupture increases exponentially [17].

Furthermore, the psychological dimension of neuromuscular control has acquired considerable traction in recent sports pedagogy and clinical research. Following a previous injury, a near-miss, or even chronic exposure to a surface perceived as 'hazardous' (such as an overly compacted 3G pitch), athletes frequently develop "kinesiophobia"—a severe fear of pain, movement, and reinjury [18]. Clinical evaluations establish that kinesiophobia is strongly associated with limited joint movement, increased pain intensity, and altered limits of physical stability along the course of dynamic tasks [18]. Such a psychological barrier physically presents as maladaptive neural behavior. When an athlete lacks psychological readiness or mindfulness during sport performance, the central nervous system defaults to excessively stiff, deterministic patterning during landing and cutting phases [18]. This anxiety-driven stiffness drastically reduces the neuromuscular system's ability to transition between functional, task-specific networks, consequently leading to uncoordinated decelerations and an increased risk of dynamic valgus collapse [18].

9. Preventive Approaches and Injury Prevention Programs

Given that replacing existing artificial turf with natural grass is economically impractical for many amateur clubs, universities, and municipalities, injury prevention must focus aggressively on modifiable factors:

Footwear Optimization: Athletes must be strictly educated to match their boot stud configuration to the playing surface [8]. The use of FG-bladed cleats on AT should be

strongly discouraged. Conical studs (AG or TF shoes) should be mandatory for 3G turf to allow for rotational release and prevent cleat lock [15].

Rigorous Surface Maintenance: An artificial pitch requires frequent, meticulous grooming, including scrubbing the synthetic fibers and decompaction of the rubber infill [12]. Biomechanical testing indicates that maintaining exposed fiber lengths below 18–20 mm and guaranteeing adequate, even infill depth is necessary for keeping rotational traction within safe parameters [12]. A compacted, neglected 3G pitch acts like concrete, drastically raising surface hardness and rotational friction in hazardous territories [2].

Neuromuscular Training Programs: The implementation of evidence-based warm-up routines, most notably the FIFA 11+ program, is critical [3]. These routines replace traditional static stretching with dynamic plyometrics, core stability exercises, and movement mechanic drills (e.g., teaching athletes to land softly with flexed knees and consciously avoiding dynamic valgus). Enhanced neuromuscular control can effectively override the sudden mechanical perturbations caused by surface interactions [13].

10. Discussion

The debate regarding natural grass versus artificial turf is complex, involving clinical biomechanics, epidemiological statistics, and the commercial realities of sports infrastructure [3]. Although aggregate injury data do not conclusively implicate 3G artificial turf, the biomechanical evidence of high rotational traction is a major concern for sports medicine professionals [2]. The "cleat lock" mechanism constitutes a clear, quantifiable mechanical threat to the ACL, especially when combined with improper footwear, high-velocity deceleration maneuvers, and the anatomical predispositions of female athletes [8], [9].

The conflicting findings in the literature probably arise from broad and imprecise definitions of playing surfaces. "Artificial turf" covers a range of systems with variations in fiber length, fiber wear, infill type (such as SBR rubber, cork, or EPDM), and maintenance schedules, all of which greatly affect the mechanical properties of the field [12], [15]. Similarly, "natural grass" includes both meticulously maintained hybrid pitches at elite levels and poorly maintained community fields [14]. Therefore, determining whether one surface is universally "safer" than the other calls for careful contextualization of pitch conditions and athlete demographics.

11. Limitations of Present Research

Despite the recent influx of high-quality data, the current body of literature suffers from several notable methodological drawbacks that obscure the precise relationship between playing surfaces and ACL injuries.

Validity of Performance and Agility Measures: A major limitation lies in the validity of the performance measures used to assess athletes' biomechanics during change of direction (COD) and agility testing. In both applied practice and research, the use of 'total time' as the primary measure of COD performance has been widely considered valid [20]. However, recent research suggests that relying purely on speed masks the actual COD ability and does not capture the specific rotational torques and joint loads applied to the knee [20]. The misidentification or incorrect assessment of this physical quality means current research may not completely capture the true biomechanical stress occurring at the shoe-surface interface during high-demand matches [20].

Heterogeneity and Seasonal Variation of Surfaces: Grouping all synthetic surfaces into a single "artificial turf" category, or all biological surfaces into "natural grass," ignores the vast biomechanical differences within those categories [12]. Furthermore, the within-field and between-field variations of turfgrass sports fields are rarely accounted for in longitudinal studies. The mechanical features of natural turf pitches vary drastically across a 10-month season due to changes in volumetric water content, penetration resistance, and weather conditions [19]. Existing research typically treats natural grass as a static, constant variable, ignoring the fact that sand-based rootzones demonstrate low shear stability and rely heavily on grass presence, which fluctuates heavily depending on maintenance and climate [19].

Lack of Standardization in Reporting and Positional Isolation: Many epidemiological databases (like the NCAA ISS or NEISS) rely on medical staff or self-reporting, resulting in differences in how exposure hours (AEs) and specific injury mechanisms (contact vs. non-contact) are classified [4], [11]. Finally, many large-scale cohort studies fail to isolate player positions. For instance, strikers and offensive players experience a disproportionately high prevalence of ACL injuries—documented at 57.4% in specific offensive cohorts—because of their unique tactical demands of rapid pivoting and pressing, yet broad epidemiological studies frequently dilute this critical data by averaging it with less active positions [17].

In Vitro vs. In Vivo Translation: Much of our knowledge of rotational traction comes from mechanical testing devices (e.g., the Penn State shoe-surface testing device) [2]. Translating torque measurements from a robotic, mechanical arm to a biological,

neuromuscularly active human leg that is simultaneously adjusting joint stiffness is still a significant biomechanical challenge [8].

12. Future Research Directions

Upcoming research in sports science has to focus on closing the gap between isolated mechanical testing in laboratory settings and actual, on-field epidemiological studies.

Neuropsychological Integration: Upcoming research must move beyond purely mechanical factors and integrate psychological readiness and neuropsychological changes into return-to-sport (RTS) and injury prevention paradigms [18]. Recognizing how peripheral nociceptive input alters pain-related brain structures will be vital [18]. Researchers must develop interventions that target central neural mechanisms, mindfulness, and kinesiophobia alongside traditional physical rehabilitation procedures to fully protect athletes returning to high-traction surfaces [18].

Evaluation of Hybrid Pitch Systems: Future studies must focus on the continued biomechanical and epidemiological evaluation of modern "hybrid" reinforced turf systems. Preliminary laboratory testing indicates that integrated systems (carpet-based or injected synthetic constructions) are less affected by water content and density than purely natural systems, providing more consistent shear stability [19]. However, robust *in vivo* epidemiological data directly comparing their ACL injury rates with those on 3G artificial turf remains sparse and requires long-term investigation [14], [19].

Longitudinal Kinematic Cohort Studies: Tracking athletes using 3D motion capture over multiple seasons is needed to assess not only acute injury rates, along with the chronic effects of surface exposure. Researchers should specifically investigate patellofemoral joint loading and overall hamstring muscle coordination post-reconstruction or post-exposure to artificial turf [21]. Tracking how altered hamstring coordination affects lower limb biomechanics during active, unanticipated movements over multiple seasons will be vital to estimating and preventing ACL reinjury and effectively returning athletes to match rhythm [21].

Wearable Biomechanical Technology: Utilizing high-frequency Inertial Measurement Units (IMUs) and micro-force plates embedded directly into player boots will allow researchers to measure real-time ground reaction forces, acceleration, and rotational velocities during live match play on varying surfaces, providing true *in vivo* data to replace current robotic testing paradigms [15].

13. Summary

The anterior cruciate ligament remains highly susceptible to injury during the dynamic, high-speed, multi-planar movements characteristic of soccer. Although epidemiological data on overall injury rates between natural grass and modern third-generation artificial turf are subtle—varying by sex, level of play, and type of exposure—the biomechanical evidence is unequivocal [1], [5], [9]. Increased rotational traction and surface stiffness on artificial surfaces present a distinct mechanical threat to the knee joint [2]. The inability of synthetic surfaces to yield or tear under extreme shear stress transmits hazardous torques directly to the ACL, facilitating the "cleat lock" phenomenon [7], [8].

Mitigating this risk necessitates more than incremental infrastructure alterations. An active, multilayered strategy is essential: enforcing appropriate footwear selection (specifically, conical AG studs on turf), preserving rigorous synthetic surface grooming to control fiber height and prevent compaction, and implementing daily neuromuscular injury prevention programs such as FIFA 11+ [12], [15]. As soccer remains evolving in speed and physicality, data-driven approaches to managing playing environments must advance accordingly to protect athlete health and longevity.

Disclosure

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