

A Systematic Review of Effects on ACL Injury of Soccer Shoe Outsoles, Soccer Playing Field Surfaces, and Outsole–Surface Interface

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Abstract: Soccer is a sport with a high incidence of injuries. The most common injury occurs when the anterior cruciate ligament of the knee has undergone a sprain, strain, or partial or total rupture. Besides fitness factors (e.g., proprioception, balance and strength capabilities), a principal cause of ACL injuries is sport shoes and playing surfaces. Especially with the emergence of artificial surfaces (rubbers, turfs, concrete, asphalt, red turf), the ACL injuries dramatically increase. The cost of ACL injuries is high both in terms of career termination and in social and economic costs. Thus, it is necessary to understand the impact of sport shoes and playing surfaces on the ACL and how it can be mitigated. The present literature review followed the PRISMA methodology to identify the major biomechanical factors influencing the behavior of surfaces and shoes in relation to the ACL damage. Fifty-eight papers were identified. After reviewing the mechanism of injuries, we identified several distinct factors: type of outsole and mechanical arrangement of the outsoles; shear forces; characteristics of artificial turf surfaces; effect of weather on artificial surface aging and change in mechanical characteristics; outsole/ground interface; and the frictional, tractional and rotational forces in the pathogenesis of ACL injuries in soccer.

Keywords: soccer; ACL; injuries; shoes; surfaces; biomechanics



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1. Introduction

As one of the most popular sports in the world, soccer has an enormous number of participants and quite a high injury risk. Hammer et al. [1], in a cohort study of contact and noncontact injuries in sports among high school students during the 2002–2009 and 2012–2013 school years, found that the injury risk for soccer (RR—relative risk, 4.03; 95% CI—confidence interval, 3.70–4.39) was higher than the mean risk of practice overall (RR, 4.01; 95% CI, 3.90–4.12), behind only American football (RR, 5.74; 95% CI, 5.55–5.93) and field hockey (RR, 3.48; 95% CI, 3.10–3.92); its risk of serious injury (RR, 5.97; 95% CI, 4.82–7.39) was also high, just behind ice hockey (RR, 16.0; 95% CI, 9.51–26.9) and American football (RR, 6.48; 95% CI, 6.02–6.98). Marar et al. [2] also concluded that most concussions resulted from participation in American football (47.1%, $n = 912$), followed by girls' soccer (8.2%, $n = 159$). Based on this, it is important to study soccer injuries in terms of both commercial and societal benefits. Our study reviews the relevant literature, which met the inclusion criteria, about the etiology of ACL injuries in soccer in relation to sport shoes and playing surfaces. In professionals, knee injuries represent 13% of all injuries observed as well as 26% of all severe injuries, and of those, 34% were ligament injuries [3]. An ACL injury is highly disabling for soccer players, causing a mean of 183 days of absence in professional (UEFA) players [4]. The mean ligament injury rate for all UEFA teams in the 2020 season was 1.1 injuries for every 1000 h. The mechanics of ACL and knee injuries have been extensively studied. It was measured that 88% of knee injuries in soccer happen as a result of indirect contact with the opponent, but under the pressure of a match-playing situation [5]. Knee valgus loading is the dominant injury mechanism. Sagittal plane

biomechanical factors, such as small knee flexion angle, great posterior ground reaction force and great quadriceps muscle force, are the major ACL loading mechanisms [6]. The primary determining factors of injury are intrinsic (bone and muscular biomechanics under load) and extrinsic. Extrinsic non-contact ACL injury risk factors include dry weather and surfaces, and artificial surfaces instead of natural grass [7]. The aim of this review is to provide the state of the art on the influence of sport shoes and playing surface on the mechanics of ACL injuries in soccer.

2. Methods

A comprehensive computerized search was performed in the following databases: PubMed, Scopus, Web of Science, and Sport Discus.

The following search terms were used in all databases: “ACL injur*” OR “soccer female injur*” AND “soccer shoe outsole” AND “soccer playing surface” OR “shoe surface interface” OR “artificial turf” OR “synthetic turf” OR “natural turf” OR “turf wear”. The same search was performed substituting soccer with “soccer”, and different combinations of the terms were used. Search terms were adjusted for each of the databases.

The reference lists of the studies retrieved were manually searched to identify potentially eligible studies not captured by the electronic searches. Finally, an external expert (PhD, Associate Professor, with 20 years of publishing experience in the topic) was contacted to verify the final list of references included and check if any study was not detected. As suggested by Cochrane’s guidelines, the inclusion and non-inclusion criteria were provided to the external expert; however, no information was provided on which databases to consult or the type of search strategies, so as not create a bias stemming from the expert. This process (a double-check from an external expert) is recommended by PRISMA guidelines to confirm the accuracy of the initial search. Only papers in scholarly journals indexed in SCI were considered.

2.1. Eligibility Criteria

The inclusion criteria were as follows: (i) studies that investigated soccer shoe outsoles and playing surfaces; (ii) studies that included the mechanics of ACL injuries; (iii) studies that focused on the sport sciences area; (iv) articles and review articles; (v) studies that were published in English; (vi) studies that were published after 2000, though some very relevant papers published before were included. All the studies should be peer-reviewed and written in English and provide the full text. Studies were excluded if they were involved in other areas except sport sciences; were narrative reviews, brief reviews, or methodological proposals; did not include relevant data; were not fully written in English; or consisted of abstracts only, without the accompanying full texts.

The title, abstract, and reference list of each study were screened to locate potentially relevant studies. The screening was independently performed by two authors (Jierui He and Antonio Cicchella). Additionally, they reviewed the full version of the included papers in detail to identify articles that met the selection criteria.

2.2. Data Extraction

A data extraction sheet was prepared in Microsoft Excel (v. 18.0. Microsoft Corporation, Readmon, WA, USA) in accordance with the Cochrane Consumers and Communication Review Group’s data extraction template. The Excel sheet was used to assess the inclusion requirements and was tested for all selected studies. The process was independently conducted by the two authors. Full-text articles were excluded, and the reasons were recorded. All the records were stored in the sheet. The data were retrieved and checked by the two authors.

2.3. Data Items

The following information was extracted from the included studies: author, topic, title, year published, and type of original articles included. Articles should be experimental (with

an intervention or measurement of an effect), observational analytic (with descriptions of the outcomes and no intervention), or reviews.

The methodological quality of the included studies was evaluated using the AXIS Tool for the Critical Appraisal of Cross-sectional Studies. This tool contains 20 questions and was used to assess study design quality and risk of biases. Each question can be answered as “Yes”, “No”, or ‘Unsure/comment’. The assessment was performed independently by the two reviewers. When consensus was not reached through discussion, a third reviewer was consulted.

2.4. Study Identification and Selection

The search produced 252 papers. The articles were screened for their relevance by reading the titles and the abstracts. This process resulted in the removal of 168 studies. Following the screening procedure, 84 articles were selected for in-depth reading and analysis. After reading the full texts, 26 studies were excluded because they focused on American soccer and were performed with subjects < 14. All fifty-eight papers included in the review were considered the outcomes. The PRISMA flowchart is presented in Figure 1.

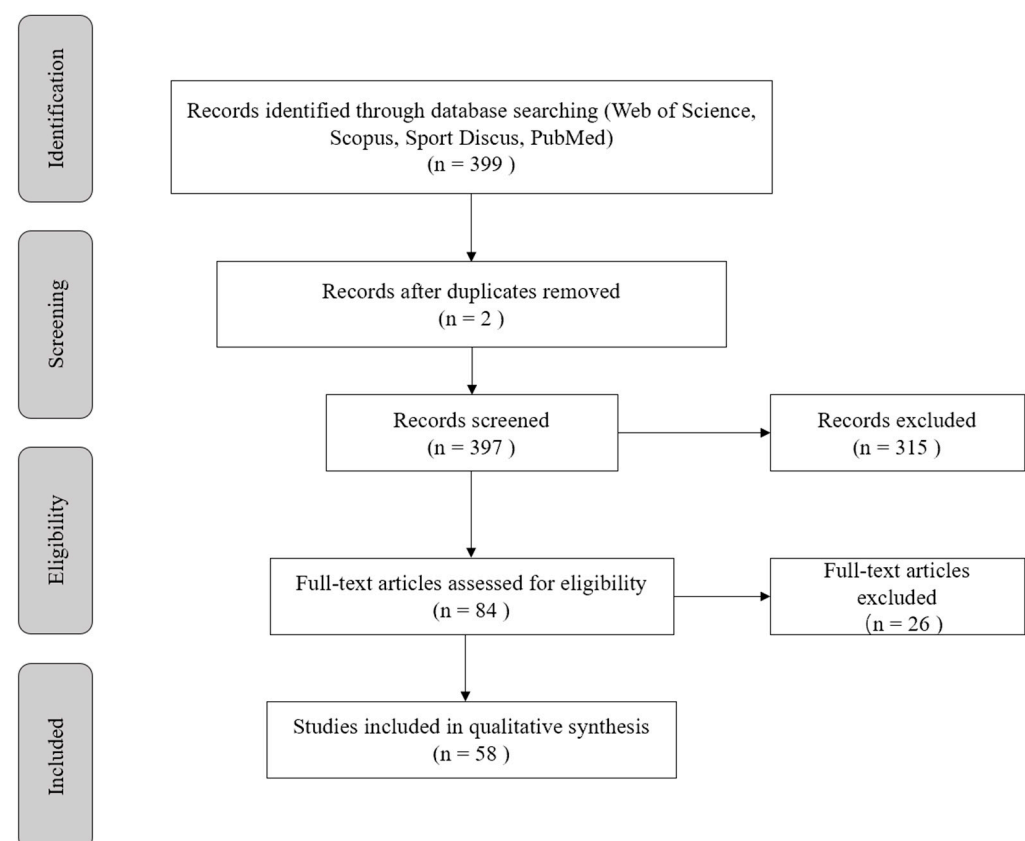


Figure 1. PRISMA flow chart.

3. Results

3.1. Injuries in Soccer

Injuries in soccer can be categorized into contact and noncontact injuries, and in general, the prevalence of injuries in youth soccer players is lower than in adult athletes [8], while lower extremity injuries are the most common type of injury in both youth and adults [9,10]. Gender is an influential factor in lower extremity injuries, and an available epidemiologic study found that ACL injuries account for 3.1% of total athletic injuries in females, compared to 1.9% in males [11]. Agel et al. [12] also noted that the prevalence of ACL injuries in soccer was higher in both male and female college students compared to basketball. Although it has been suggested that females have the highest risk of injury in

late adolescence or in the year following puberty [13], females have a higher incidence of knee and ankle injuries than males in both youth and adult soccer players [14,15].

Regarding parts of the body injured, Chandran et al. [16], found knee (16.7%) and ankle (14.8%) injuries to be the highest percentage of all reported injuries in a survey of injuries among athletes on NCAA women's soccer teams from the 2014–2015 to 2018–2019 seasons. A survey of the Women's Bundesliga also found that the highest prevalence of injuries among female soccer players were in the knee (31%), ankle (22.1%), thigh (12.9%), and head (7.1%) [17]. And among knee injuries, Chandran et al.'s [18] study of NCAA women's soccer team athletes published in 2023 further found the injury with the highest prevalence in female athletes to be ACL injuries (IR = 2.60 per 10,000 AE).

Several studies point to the efficacy of appropriate warm-up activities and muscle training to reduce the risk of ACL injury [19,20]. However, the level of evidence that warm-up brings about a reduction in the risk of ACL injury in female soccer players is low [21]. So, it is still relevant to conduct research in the direction of kinematics and kinetics and to seek other risk factors that have a stronger correlation.

3.2. Anatomical Mechanism of ACL Injuries

Approximately 70% of ACL injuries occur when there is no physical contact between athletes, such as during a side-cutting or a rotation, with the remaining 30% being injuries caused by physical contact [22,23]. In particular, the highest incidence of ACL injuries occurs in athletes aged 15–25 years practicing rotational sports with non-contact [24]. There are several risk factors for ACL injuries, which were broadly categorized into extrinsic and intrinsic factors by Sutton et al. [25] Extrinsic factors include climate, shoe-surface interface properties, etc.; intrinsic factors are mainly anatomical characteristics, such as quadriceps angle (Q angle), intercondylar notch, ACL size, posterior tibial inclination, etc. Other risk factors include biomechanical and neuromuscular factors, hormones, etc.

3.3. Kinematics of ACL Injuries

Paolo et al. [26], performing 3D and 2D motion scans of the kinematics of the lower extremities of four ACL-injured and twelve non-ACL-injured female athletes participating in competitive soccer with a Change of Direction (COD) task, found that the ACL-injured individuals performing the sidestep cut task showed greater knee valgus, greater internal rotation and lower knee flexion ($p = 0.017$ – 0.029). They also showed lower hip flexion with greater external rotation ($p = 0.003$ – 0.042), and ankle eversion and contralateral pelvis drop ($p < 0.001$). The COD task consisted of a 6 m frontal sprint followed by a 90° sidestep cut with a foot strike on a force platform, and a further 3 m sprint. A pre-season jump–landing kinematic study of 205 female players by Hewett et al. [27] found that the knee abduction angle of those who sustained ACL injuries during the season was on average 8.4° greater at the initial contact with ground and 7.6° greater at maximum displacement than the non-injured knees. Overall, the knee sustained 2.5 times the momentum, 20% more reaction force from the ground, and a 16% shorter stance time than those with non-ACL injuries. Sutton et al.'s [28] study notes that knee valgus also appears to be a risk factor for ACL injuries, especially since females' knees are laxer relative to males', and thus females' knee valgus angle may be greater relative to males'. Villa et al.'s [29] study investigated the main movements that lead to indirect contact or non-contact ACL injuries in men's soccer games, including pressing and tackling, being tackled, regaining balance after kicking, and landing after a jump. Knee valgus appeared in 86%, 86%, 67% and 50% of these four movements, respectively. A similar investigation in women's soccer games showed that the three main actions leading to ACL injuries were pressing and tackling, regaining balance after kicking, and being tackled, with knee valgus occurring in 88% of the cases [30].

3.4. Strain Forces on the ACL

Berns et al. [31] measured strain forces on the ACL when the knees were subjected to different loads in a cadaveric experiment. The results showed that a single anterior shear

force on the proximal tibia was the determining factor for ACL tearing. In contrast, the combination of tibial external rotation and knee valgus was the determining factor for ACL tearing as well, and even had a greater effect than the former factor. Markolf et al. [32] further investigated the effects of the combined factor in a cadaveric experiment. They found that the combination of an anterior shear force on the proximal tibia and knee valgus and tibial external rotation produced significantly greater ACL tearing forces than those produced by the action of the above single conditions. It is evident that anterior shear force on the proximal tibia, knee valgus, and tibial external rotation may be correlated with ACL injury. Indeed, from an anatomical point of view, one of the functions of the ACL is primarily to limit the angle of the axial rotation of the tibia. From this perspective, reducing the risk of ACL injury needs to be considered as avoiding excessive knee valgus, tibial external rotation and anterior force on the proximal tibia.

4. Soccer Shoes and ACL Injuries

4.1. Types of Outsoles

According to the Laws of the Game 2022/2023 from the International Soccer Association Board (IFAB) Laws of the Game [33], the surface of the field of play must be wholly natural or, if competition rules permit, wholly artificial, or an integrated combination of artificial and natural materials (hybrid system). To obtain a good grip on the playing field, the outsole of soccer boots is often designed with some studs. According to the criteria of soccer shoe outsoles by manufacturers, the types of outsoles with studs can be commonly categorized into four types: Soft Ground (SG), Firm Ground (FG), Artificial Ground (AG), and Turf (TF). The first three types of outsole materials are usually TPU, nylon, or a mixture of the two. The studs on the SG outsole are partly made of metal. The TF outsoles are usually of rubber. The number of studs on the outsoles of SG, FG, and AG is, commonly, 6 to 11, 11, 14, or more, respectively. The studs of TF are several short, dense soft rubber studs. The length of the studs varies. Some SG outsole cleats can be partly replaced with metal cleats ranging from 7 mm to 15 mm in length according to the need, based on the nylon or TPU pedestal of studs, with a total length of more than 1 cm. FG studs are mostly a length of more than 1 cm. AG stud lengths are about 1 cm. TF studs are about 3 mm dense rubber protrusions and generally can be regarded as a flat outsole. The shapes of soccer cleats are also different. Traditionally, studs are conical. Some brands have rounded triangular prism studs. Some studs are designed as blade-like. There is also a kind of outsole for soccer boots, which is without cleats and only for indoor playing on hard surfaces like floorboard or PVC floor and will not be considered below.

4.2. Mechanical Arrangement of the Outsole and Effect on the ACL

The correlation between cleat length, numbers and shapes, and ACL injuries is reflected in the performance of the outsoles, i.e., the translational traction forces generated during contact with the field surface and the rotational forces in the horizontal plane. As previously mentioned, the kinematic and kinetic risk factors of ACL injuries include greater proximal tibial anterior shear force, knee valgus moment, and tibial external rotation moment. The horizontal traction force and tibial rotation torque will act on the lower limb, and different outsoles have different effects with these factors, and consequently, there is a difference in the risk of ACL injuries. Grund et al. [34] measured the axial rotation torque exerted on the tibia by different cleats (conical and blade-like) with the combination of the four ACL risk factors in different values, namely, the knee valgus angle, the knee flexion angle, the knee axial load, and the tibial axial rotation angle, on a natural grass playing surface. The results showed no significant effect of different cleats on the magnitude of tibial axial torque. Müller et al. [35] tested the translational traction and reacting force from the surface of four pairs of shoes with different outsole types (SG, AG, HG (hard ground), and prototype shoes), while performing acceleration and side-cutting on the same artificial playing surface with 0°, 45°, and 180° side-cutting, respectively. The results showed that, except for SG, the differences in stud length and alignment of the other outsole types had

no significant effect on the traction force. The reason for this may be that the SG studs are too long to be fully inserted into the infill layer of the artificial surface, resulting in ineffective traction provided by the cleats.

4.3. Importance of Shear Forces

In comparison, the FG boots showed a stronger horizontal shear force in side-cutting and acceleration. Combined with the poorer traction performance shown by SG shoes on artificial surfaces and the fact that the vertical component of the force did not change when the shear force brought about by different movements changed, the authors concluded that shear force is the primary criterion for evaluating the traction of boots [35]. Subsequently, the performance of horizontal shear force was further explored, and the traction force was mainly categorized into two aspects, namely rotational torque and translational traction, from the practice of the sport [36,37]. Thomson et al. [38] measured the translational traction and rotational traction in 2019 for the same brand of six pairs of different outsole soccer shoes used by elite soccer players (including one AG, one SG, and four FG) on the same piece of natural grass surface. They found that there was a significant main effect of different outsole types on rotational traction, with the AG boots producing the lowest rotational traction in the winter when using cool-season grass, with an average moment of 28.1 Nm. In contrast, the SG boots had the highest rotational traction during the entire experiment period (January, March, April, May, and November), and the average of the five times test was 52.2 ± 6.2 Nm [38]. Villwock et al. [36] determined rotational stiffness (Nm/deg) and peak torque (Nm) by determining the rotational traction produced by different outsole boots, and found that there was no significant difference in rotational stiffness and peak torque produced by other types of boots including AG and FG, except for the TF outsole in the experiment. It is worth noting that when it comes to rotational stiffness measurements, several experiments [36,39] mentioned that the degree of upper bendability may affect the stiffness of soccer boots during rotation. Boots with less pliable uppers made it more difficult to transfer rotational moments from the foot to the sole, and harder to generate an earlier rotation of the boots, and therefore had a greater rotational stiffness.

In summary, it can be seen that, except for the SG outsole, which is only used on wet natural grass playing surfaces, and the TF outsole, which is significantly different in appearance from the other cleated soccer shoes, there is essentially no difference in translational traction and rotational stiffness between the other outsole types, neither in terms of cleat length nor on the same soccer playing surface. The SG outsole, on the other hand, generally provides significantly higher traction and rotational torque, while the TF outsole does the opposite.

5. Soccer Playing Surfaces

Since the birth of modern soccer, the playing surface has been stipulated as green natural grass. Artificial grass turf was used in soccer initially in the 1960s. With the development of technology artificial turf could be promoted and recognized by FIFA, and further, artificial grass turf combined with traditional natural grass formed the hybrid system, whose artificial grass provides a wet surface as the anchor point for the natural lawn roots and reinforced the stability of the whole surface. The currently widely used surfaces can be divided into natural grass, third-generation artificial grass turf, and hybrid systems. The third-generation artificial grass turf needs to meet the following key indicators: a synthetic material grass filament length of 40–65 mm; and the filaments need to have fine sand as a base layer and be filled with rubber particles [35]. The effects of the three different materials on ACL injuries are also reflected in the knee valgus moment and the tibial external rotation angle [40]. The performance properties of a playing surface, measured when simulating the contact of soccer boots with the surface, can intuitively respond to the effects of the differences in the surface materials on the kinematics of the athletes' lower limb performance [40].

5.1. Artificial Turf and ACL Injuries

Numerous epidemiologic research studies have found that artificial and natural grass turfs exhibit similar injury rates overall [41–43]. Nigg et al. [44] concluded that artificial turf caused significantly more mild lower extremity injuries and potentially more severe knee and ankle injuries than natural grass turfs and that there was no significant difference in the possibility of severe injuries between different artificial turf surfaces. Skovron et al. [45] concluded that artificial turfs exhibit a 30–50% higher rate of lower extremity injuries compared to natural grass surfaces, and several other studies also supported that artificial turfs exhibit higher rates of foot and ankle injuries compared to natural grass turf [46,47]. As can be seen, epidemiological studies have limitations in revealing the correlation between the soccer-playing surface conditions and ACL, and even on lower extremity injuries due to other factors that are difficult to control such as weather, grass conditions, and the monitoring of players' playing time. Therefore, it is necessary to study the correlation between ACL injuries and soccer field surface conditions from a biomechanical perspective.

A further exploration of the kinematic mechanisms of turfs on ACL injuries revealed that the current indicators of surface properties sensitive to ACL injury focus on the translational traction, rotational stiffness and torque of the soccer boots generated by the surface. Zanetti et al.'s [48] experiments compared the property differences between artificial turf filled with thermoplastic rubber, styrene-butadiene rubber (SBR), and natural grass. They found that the natural grass provided significantly lower mean and maximum values of translational traction compared to artificial turf. Both the mean and maximum values were significantly lower for natural turf compared to artificial turf. Rick et al. [49] in 1996 found that artificial turf provided greater rotational traction than natural turf when rotating a shoe by 90° horizontally with a given vertical press force, regardless of cleat type. Villwock et al.'s [39] experiment on the rotational traction properties of soccer shoes and field surfaces in 2009 found that the rotational traction (including rotational stiffness and peak rotational torque moment) generated by artificial turf surfaces was significantly greater. And there was no significant difference in rotational traction between artificial turf surfaces. Livesay et al.'s [37] study also found that natural turf produced the lowest peak rotational torque compared to artificial grass surfaces. The tendency of artificial grass turf to warm up by absorbing heat from direct sunlight is also a factor that makes its property variable.

5.2. Environmental Effect on the Mechanical Properties of Turfs

A study conducted in the National Football League (NFL) found that the incidence of ACL injuries in athletes playing in indoor stadiums was lower than in athletes playing in open-air stadiums, which may be attributed to changes in traction caused by the temperature of the artificial turf [50], and a study confirmed that the higher the temperature of the artificial turf, the higher the traction [51]. A study by Thomson et al. [38] found a significant correlation between the amount of rotational traction and the surface conditions of the soccer field. The rotational traction of boots on natural grass fields in different periods (January, March, April, May, and November) was tested using an instrument, and it was found that the smallest rotational traction was measured during the cool-season grass in January, with an average moment of 36.3 ± 6.0 Nm; in the same way, the largest rotational traction was produced on the warm season grass lawn measured in the two warmest periods (November and May, respectively) with an average moment of 48.0 ± 6.8 Nm and 49.5 ± 6.1 Nm, and further analysis revealed that low soil moisture and high air temperatures were significantly correlated with higher rotational traction [38].

Concerning translational traction, the Consumer Product Safety Committee has concluded that playing surfaces with a friction G-value greater than 200 are considered unsuitable for sports [52]. For natural grass turfs, surface hardness and horizontal traction have been shown to correlate with injury [53–55], and there was also a significant correlation between the two [56,57]. Traction could be related to the amount of grass cover, while hardness could be related to the soil's ability to retain water [56–58]. Within a certain

range, the higher the amount of grass filament cover, the higher the traction force; the higher the sand content of the soil, the lower the rainfall-induced change in soil wetness, resulting in a relatively small change in hardness [58]. The surface hardness of natural turf varied significantly with seasonal precipitation. The traction appeared to decrease consistently over the winter season (presumably because of a decrease in natural grass filament cover) [58].

Nigg et al. [44] concluded that the incidence of injuries on natural turf is more related to the outsole–surface interface and has relatively little to do with field surface hardness. A study conducted in the AFL also showed that ACL injuries correlate more with rainfall changes on a long-time scale than they do with rainfall changes on a day or week scale. In other words, the correlation between changes in site surface traction due to seasonal temperature changes and ACL injuries was higher than the correlation between changes in site surface hardness due to short-term precipitation changes and ACL injuries [54]. The experiments conducted by Thomson et al. [38] also support this point. They found significant interactions between different types of natural grasses (cool-season grasses and warm-season grasses) and different types of outsole types (AG, FG, SG). The translational traction produced by the combination of SG outsole and warm-season grasses was much greater than that produced by the combination of AG outsole and cool-season grasses [38].

5.3. *Playing Surface Aging and Injuries*

There is very little literature on the aging of soccer field surfaces and their properties. The study by Sánchez et al. [59] in 2018 used FIFA standards to test the performance of artificial turf under different environmental influences. The results showed that there was a significant negative correlation between the increase in density of the artificial surface infill and the increase in rotational traction. Moreover, the degree of increase in the rotational traction of the surface after artificial wear was related to the weight of the pile, the density of the pile, and the pile yarn dtex in the experimental conditions, since the vertical and horizontal forces responsible for the wear and the rotational traction on the shoes are practically of the same origin [59]. While some studies [60] have suggested that increased humidity reduces rotational traction, Sánchez et al.'s [59] study concluded that there was no significant correlation.

6. **Outsole–Surface Interface**

Dowling et al. [61] hypothesized in their 2010 experiment that environments with a high coefficient of friction may bring about a higher incidence of ACL injuries based on previous studies, which included: higher air temperatures, dry surfaces, artificial turf or rubberized surfaces, and boots with high coefficient of friction outsole, etc., and investigated how the knee joint kinematics, knee valgus moments and the center of mass change with side-cutting movements in high coefficient of friction environments, relative to those in low coefficient of friction environments. The results showed that the knee flexion moment of the side-cutting movements on the high friction coefficient field was significantly lower compared to the low friction coefficient field, with an average of $3.39 \pm 1.6\% \text{ BW} \times \text{xHt}$ (% body weight \times height), and the knee valgus angle brought about by the high friction coefficient field was significantly larger compared to the low friction coefficient field, with an average of $0.10 \pm 1.8\% \text{ BW} \times \text{Ht}$ (% body weight \times height) in relative absolute value [61]. A higher traction at the outsole–surface interface may bring about movement changes in athletes with lower knee flexion angles and greater valgus moments, which have been suggested as explanatory factors for ACL injuries [62].

Rotational Friction/Traction and ACL Injuries

From a kinematic point of view, the force of rotating the leg when the foot is fixed may lead to ACL injuries. Accordingly, when Livesay et al. [37] tested the rotational traction of different types of soccer cleat outsoles and different types of soccer field surfaces in 2006, they determined the peak moments during rotation, in addition to the determination of

rotational stiffness, i.e., the value of the magnitude of the moment required for each degree of rotation of the soccer cleat. The authors also categorized the rotational stiffness into an initial stiffness, where the shoe rotates between 0° and 2° , where the value of rotational stiffness increases rapidly in a non-linear way, and a linear stiffness, where the shoe rotates between 2° and 10° , where the value of rotational stiffness increases in an approximately linear fashion. According to their study, natural grass created the lowest peak rotational moment; however, the linear phase of rotational stiffness in terms of the combination of shoe outsole–surface interface type showed no significant difference between the different outsole–surface combinations [37]. Continuing to explore the relationship between rotational stiffness and the outsole type, and the soccer field surfaces based on Livesay's study, it was further proposed that the change in a rotational moment with the angle of rotation can be divided into four phases, i.e., initial breakaway, buildup, and slipping and unloading phases. Different combinations of outsole and field surface will produce different proportions of the four phases, and the value of the moments in each phase may be different, for example, sometimes the sliding phase disappears [39]. Experiments by Drakos et al. [63] used cadaveric lower limbs directly to determine the strain force exerted on the ACL during rotation, and the results similarly showed that the average strain force on the ACL produced by the natural turf-cleated soccer shoes was the smallest in the experiments, followed by the recreational turf-cleated soccer shoes, followed by recreational turf-TF outsole boots, while the professional artificial turf-TF outsole boots produced the largest average ACL strain force. The prospective study by Forrester et al. [64] suggests that the study of friction at an interface can be approached from three perspectives: friction between the outsole of the cleat and the surface of the field, the shear force provided by the field infill to the outsole, and the translational compression of the field infill to the cleat. These three aspects are considered by the authors to be the main factors in exploring the interaction of friction between artificial turf and the outsole of the boots. Of course, few experiments have been conducted to verify this due to the difficulty of experimentally observing the motion of artificial turf infill [64].

7. Conclusions

Soccer is widely played all over the world, and its resulting lower limb injuries are more common among both adult and youth participants. ACL, an important ligament in the knee joint, has a high injury rate in soccer, and in particular, the ACL injury rate in females is significantly higher than that in males. Factors involved in ACL injuries include anatomical factors, biomechanical factors, kinetic factors, environmental, and psychological factors. The friction between the outsole of the boots and the surface of the soccer field has been investigated as a factor affecting ACL injuries, and friction has been commonly categorized into translational traction for parallel movement, and rotational traction for axial rotation. According to the previous section, there was no significant difference in friction between the different types of outsoles on the same soccer field surface, except for SG and TF. The bendability of the upper shoe may be a factor influencing the axial rotational traction of the soccer shoe. The field surfaces were then categorized according to artificial and natural turf and hybrid systems, with artificial turf producing significantly greater friction than natural grass turf, while no comparative studies were found for hybrid systems. According to Forrester's study, most of the friction on the surface of an artificial turf field comes from the resistance of its infill to compression and movement, and this paper speculates that the friction study of hybrid systems can probably be categorized as a natural turf soccer field, because the infill under the grass filaments of a hybrid system is no different from that of a natural grass field, except that the grass filaments and the soil are reinforced by a net of synthetic materials that is buried deeper than the studs can access. The surface of a soccer field is also subject to aging. The degree of deterioration of the surface of a soccer field is also a factor affecting its friction, and this factor is still understudied, with existing studies showing a negative correlation between infill density and the amount of rotational resistance, and the degree of increase in rotational resistance

is related to the wear process of the grass filaments. For natural turf, the surface friction is related to the average wetness of the soil and the density of the seeded grass filaments. The drier the soil, the higher the rotational traction; the denser the grass filaments, the higher the rotational traction. The outsole–surface interface is also an influencing factor. Because there are many irrelevant factors for the determination of friction at the outsole–surface interface, it is difficult to reach a consistent conclusion, but according to Forrester et al. [64], it is known that the calculation of the horizontal movement force of studs in the surface infill can mainly account for the friction situation at the outsole–surface interface.

The influencing factors of ACL injury and their interactions are complex in soccer practice, and are difficult to identify. Due to the rapid updating and variety of soccer cleat designs, there is no universal index or method to determine the performance of soccer cleats regarding the ACL injury influencing factors. Soccer field performance currently has FIFA standards to refer to, but soccer field performance after years of use is not consistent with FIFA rules. The possibility of ACL injury from worn soccer fields and newer shoe outsole designs need to be further investigated using more precise estimation metrics.

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