LEADING ARTICLE

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Is There a Relationship Between Ground and Climatic Conditions and Injuries in Football?

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Abstract

Most soccer, rugby union, rugby league, American football, Australian football and Gaelic football competitions over the world are played on natural grass over seasons that commence in the early autumn (fall) and extend through winter. Injury surveillance in these competitions has usually reported high rates of injury to the lower limb and an increased incidence of injuries early in the season. This 'early-season' bias has not usually been reported in summer football competitions, or in sports played indoors, such as basketball. Although easily compared rates have not often been published there has also been a reported trend towards a greater injury incidence in football played in warmer and/or drier conditions. Injury incidence in American football played on artificial turf has often been reported to be higher than in games played on natural grass. This review concludes that the most plausible explanation for all of these reported findings involves variations in playing surface characteristics. Shoe-surface traction for the average player is the specific relevant variable that is most likely to correlate with injury incidence in a given game of football. Shoe-surface traction will usually have a positive correlation with ground hardness, dryness, grass cover and root density, length of cleats on player boots and relative speed of the game. It is possible that measures to reduce shoe-surface traction, such as, ground watering and softening, play during the winter months, use of natural grasses such as perennial ryegrass (*Lolium perenne* L.) and player use of boots with shorter cleats, would all reduce the risk of football injuries. The most pronounced protective effect is likely to be on injuries to the lower limb of a noncontact nature, including anterior cruciate ligament injuries. Intervention studies should be performed, both using randomised and historical controls.

1. Assessing Risk Factors for Football Injuries

1.1 The Van Mechelen Paradigm for Injury Prevention

Sports injury research and prevention has been recommended to follow a model of four stages (table I).[1,2] Although this paradigm has gained widespread acceptance within the sports medicine community, progress in the area of injury prevention has been slow. This is best illustrated with the example of anterior cruciate ligament (ACL) injuries of the knee, which are amongst the most costly of

Table I. Van Mechelen's recommendations for injury prevention[1]

Stages of injury prevention	
1.	Identify frequency of common and serious injuries
2.	Identify risk factors (both intrinsic and extrinsic) for the most common and serious injuries
3.	Institute preventative programmes based on modification of reversible risk factors
4.	Monitor success of intervention with ongoing surveillance

all sports injuries, particularly in the football codes (soccer, rugby union, rugby league, American football, Australian football and Gaelic football).[1] The risk factors for ACL injuries that have been well-established are generally intrinsic variables that are nonreversible, such as female gender, family and personal history, and variations in knee anatomy.[3,4] Factors that are nonreversible are relevant to consider as confounders in analysis, but they cannot form the basis of intervention studies as per stage 3 of Van Mechelen's paradigm (table I).

1.2 The Confounding Relationship Between Potentially Reversible Risk Factors and Performance

The most widely researched potentially reversible risk factor for knee injuries in football, dating back 30 years, has been the configuration of the cleats on the sole of the football boot.[5-12] The original studies from the 1970s hypothesised an increase in shoe-surface traction with longer cleats on the football boot, with various reductions of injury reported from changing to boots with either shorter cleats[5-7,12,13] or swivel design[8] to minimise traction. Shoe-surface traction has been shown to have a linear association with the effective bottom cleat surface area.[14] Lambson et al.[11] looked specifically at ACL injuries and found that wearing of shoes with longer and more peripheral cleats was associated with both an increase in shoe-surface traction (torque) and ACL injuries. Despite agreement amongst 30 years' worth of similar studies that shorter cleats produce less traction and less knee injuries, a well documented randomised control intervention trial has not been published. This is probably because it would be difficult to get players to agree to be randomly assigned to a high or low traction boot, as for performance reasons players will prefer to increase traction rather than risk slipping over during the game.[4,15]

Performance considerations make it unlikely that football players will voluntarily choose low-traction boots when their opponents are free to choose higher-traction boots. It would be difficult to pass a law against certain types of football boot based on greater propensity for shoe-surface traction in professional games, as much of the attraction of watching professional sport is in the elite skill level on show. This would not be a suggestion without merit at an amateur or junior level, but it would be arduous to check every player's boots before each game to see whether they conformed to a maximum standard.

An alternative method to try to reduce injury by reducing shoe-surface traction is to make changes to the quality of the playing surface that would lead to all players having a universal decrease in shoe-surface traction. The objective of this review is to examine the relationship between playing conditions (weather and ground conditions) and football injury, to determine the extent to which injury may be potentially reduced by making changes to the playing surface. Because few studies have made direct assessments of playing surface and correlated these with injury, this review will commence with an analysis of the reported variations of injury incidence as playing surfaces change over the course of a football season.

2. The Early-Season Bias for Football Injuries

2.1 The Early-Season Bias for Injuries in Rugby Union

Rugby union is a winter sport played in many countries throughout the world in a variety of cli-

1 The term football will be used in this article to indicate any or all of the sports listed. If a statement refers to a specific type of football, the full name of the sport will be used, except for Association Football, which will be called 'soccer'.

mates. Multiple studies from various countries have reported that the total injury incidence is higher earlier in the playing season in rugby union.[16-30] The studies of Lee and Garraway[24] and Alsop et al.[27] have both examined this issue in great detail and have a large number of factors in common, in addition to addressing the same sport. Both of these studies were conducted in competitions that commenced in autumn and ran through winter in temperate climates with cold winters (Scotland and New Zealand). Both studies also considered multiple factors in their analyses and found that the early-season bias was most marked for lower limb injuries. The Alsop et al.[27] study examined the slope of the trend towards a decrease in injury and found a significant decrease for lower leg and foot injuries of –0.0464 ($\chi^2 = 4.18$, $p = 0.041$). For other body parts there was no significant relationship between month of season and risk of injury, except that trunk injuries increased significantly throughout the season ($\chi^2 = 7.60$, $p = 0.006$). This study also found that the phase of the game responsible for the decrease in injuries was back play ($\chi^2 = 5.81$, $p = 0.016$), whereas there was no significant difference between time of season and risk of injuries in tackles, scrums, rucks and mauls. The Lee and Garraway[24] study examined both month of the year and state of the pitch and found that earlier month of the year and firmer pitch were both risks for injury, although month of the year was more significant using a multivariate analysis. Compared with the early-season months of August and September, risk of injury in December [relative risk (RR) = 0.25, 95% confidence interval (CI) = 0.10 to 0.59] and February (RR = 0.20, 95% CI = 0.08 to 0.49) were significantly lower. When injury was subdivided into specific types, only lower limb fractures had a notable difference between pitch conditions (0.94 compared with 0.18 injuries per 1000 player hours, 95% CI for difference = 0.08 to 1.44).[24] Neither the Lee and Garraway[24] nor Alsop et al.[27] study were committed regarding the underlying reasons for their findings, but both studies strongly suggested that the early-season bias existed for rugby injuries in their cohorts.

Studies that have examined the incidence of catastrophic spinal injury in rugby union have also generally found that the incidence is higher early in the rugby season,[16,22,31,32] although no definite explanation for this phenomenon has been proposed.

There is one significant long-term study of rugby union injuries that has not reported a trend towards more injuries at the start of the season.[33-35] This study of schoolboy rugby union injuries attended to at a single school in Sydney, Australia, by a single practitioner over a 28-year period (1969 to 1996), involving 2169 injuries occurring in 115 937 player hours. The school rugby season was consistently played over 9 weeks in winter and there was a trend towards increased injuries over the latter part of the season, with the 5th, 6th and 8th weeks showing the highest rates of injury (RM Davidson, personal communication). Sydney is a Southern Hemisphere city with a coastal temperate climate with mild winters. Mean daily temperatures do not vary substantially throughout winter. However, rainfall is higher in late autumn and early winter than late winter.[36] The Davidson study also noted an increase in the number of fractured clavicles during the 1986 season, which was reported to be a very dry winter in Sydney, associated with a harder playing field than usual. The mechanism of this injury was generally reported to be a collision of the player with the ground. A harder playing field in Sydney than in the UK was cited by the author for a larger overall rate of fractured clavicles than a similar schoolboy survey in the UK.[30,34]

Rugby union, particularly when played as a winter competition in the countries of the UK, South Africa and New Zealand, exhibits a definite early-season injury bias. This bias is greatest for lower leg injuries and cervical spine injuries. An exception to this finding has been reported in a long-term schoolboy study conducted in the city of Sydney.[33-35] An explanation for this exception may be that the rugby season in this study was

short, but was generally associated with wetter weather conditions at the start of the season and drier weather conditions towards the end.

2.2 The Early-Season Bias for Injuries in Other Football Codes

Codes of football other than rugby union have generally also reported an early-season bias for injuries, albeit with smaller numbers of studies and less agreement amongst studies. Some soccer studies from the UK and northern Europe have reported a definite trend towards higher rates of injury at the start of the season with a gradual decline over the course of the season.[37-42] The Hawkins and Fuller study[39] found a steady decline in both match and training injuries over the course of the soccer year (August to May) in professional players. However, for match injuries in youth players they reported a 'U' shaped curve (injury frequency rate of 40 injuries per 1000 player hours in August falling to 20 from October to January and then rising to a peak at the end of the season in April). It was not determined whether this may reflect a different tendency in youth players (such as excessive rate of playing matches over the course of the season) or possibly whether by April (spring) ground conditions in the UK had started to become harder relative to the winter months.

A recent report[43] of Major League Soccer (MLS) in the US showed a late-season rather than early-season injury bias, although MLS is a summer competition played with a regular season from April to September. In some major studies[44,45] of soccer injuries, no seasonal variation in injury was mentioned. One study[46] of female soccer players reported neither an early-season bias nor any relationship of injuries to weather, playing surface or temperature, but only 41 players were surveyed over one season and no power analysis was presented. A study[47] of soccer injuries in Finland reported an early-season bias with an outdoor soccer season that is played in reverse seasonal order (early spring to early autumn). Luthje et al.[47] stated in this study that the soccer season in Finland differed remarkably from other countries because of 'partly Arctic' weather conditions, and perhaps frozen grounds at the start of the season were a confounding environmental factor.

Various studies[48-51] in American football, which is played over a season from fall (autumn) to winter, have also reported an early-season injury bias. Bramwell et al.[49] found a higher rate of injury on artificial turf than grass over the season, with the difference between the two surfaces only occurring later in the season, when the grass surfaces (in Seattle, WA, USA) presumably became softer because of climatic conditions. Andresen et al.[51] examined weather conditions and found that injuries on muddy or wet natural grass surfaces were less frequent than on good or hard surfaces in Wisconsin, concluding that the early-season bias was accounted for by changing ground conditions. Scranton et al.[52] found that the surface was described as good or dry for the vast majority of non-contact ACL injuries in the National Football League (NFL), although no estimate of exposure on differing surfaces was made. The rate of ACL injury in the NFL showed an early-season bias in matches played on natural grass or artificial turf in the open air, but not during matches played on artificial turf indoors.[53]

ACL injuries in the Australian Football League (AFL) have been shown to exhibit a strong early-season bias, from a rate of over 40 injuries per 1000 matches in February to March (late summer) to under 20 injuries per 1000 matches from May to September (winter) (t-test value = 3.1, $p = 0.002$).[15,54] Injuries in total exhibited an early-season bias in professional[55] and amateur adult[56] and junior Australian football.[57] McMahon et al.[57] attributed the highest rate of injuries in the first month of their study to harder grounds, and found that injuries on harder grounds were more likely to be fractures associated with ground contact.

Rugby league is a similar sport to rugby union, although it is primarily played in two locations of the world with very different climates – north-eastern Australia (warm temperate to tropical hu-

mid) and the north of England (cool temperate humid). Although the two forms of football are very similar, rugby league has not shown the consistent early-season injury bias that is present in rugby union.[58-60] One study[55] of rugby league injuries in a Sydney-based competition showed an early-season injury bias, but a study[58] of amateur rugby league players in the Gold Coast (subtropical humid climate) demonstrated a significant late-season bias. The Gold Coast is an even hotter climate than Sydney, but also has a wet early winter and drier late winter.[36]

A study[61] of elite Gaelic football injuries has reported a late-season injury bias. This observation must be treated with caution as the methodology was retrospective, so a significant recall bias may have been responsible.[62] However, it is interesting to note that the Gaelic football season was played from the months of January (winter) to June (early summer), with the highest rate of injury occurring in June.[61]

A study[63] of the games of touch football, which is an indoor noncontact version of rugby, did not report any early-season injury bias.

2.3 The Early-Season Bias for Injuries in Other Sports

It is notable that rugby union has had so many studies that have consistently reported an early-season bias for injuries, compared with soccer and American football, which are also played extensively. It is possible that there is a form of publication bias, in that studies of rugby union will all note the early-season bias in their literature review and then report the presence or absence of seasonal variation for injuries in their results. Therefore, the lack of reporting of a seasonal bias in a sport suggests, but does not prove, that it does not exist. In general, there has been very little published about seasonal variance in injuries for indoor sports, such as basketball. Studies of basketball injuries using good methodology that involve large numbers of exposures and injuries have not mentioned any seasonal variation in injuries.[44,45,64-66] A study[67] of basketball injuries that reported injury incidence by month of the season showed a fairly even distribution of injuries across the course of the season.

Ice hockey is generally an indoor sport where an early-season bias has been reported.[68,69] However, unlike basketball, it is not a good sport to use as a 'control' because it is possible that the quality of ice varies across the course of the season.

One study[56,70] compared the month-by-month injury incidence of four different sports in Perth, Australia, using the same methodology for each. A significant early-season bias was present for all four sports studied in the first year of study, but varied in its intensity.[56] The sport with the highest early-season bias was Australian football, with basketball having a much smaller early-season bias that just reached statistical significance. Netball and field hockey had an early-season bias that was less marked than Australian football but greater than basketball. In the second year of the study, only football showed a significant early-season injury bias.[70] Unfortunately, no information about the playing surfaces was presented in this study. However, the surface types for Australian football (natural grass) and basketball (hard court) would have been constant, as these sports are only played on one type of surface. Netball is played in Australia on both natural grass and hard courts, and field hockey is played on both artificial and natural grass. A conclusion from the first year of the study was that all four sports exhibited an early-season bias, but the sport that was played on natural grass (Australian football) showed a greater early-season bias than the sport that was played on a consistent surface (basketball).[56]

2.4 Is the Early-Season Bias Attributable to Extrinsic or Intrinsic Factors?

Both intrinsic factors, such as variations in player fitness,[19-21,29,39,40] and extrinsic factors, particularly the variation in weather and ground conditions[20,51,54,57] have been cited as possible explanations for the early-season bias. Unfortunately, there have been no studies that have per-

formed serial fitness measures over the course of a season to correlate these with injury risk. Alsop et al.[27] found that the rate of decline of injury incidence over the course of the rugby season was not influenced by player fitness at the start of the season. A few studies[24,51] have attempted to monitor ground conditions, although in general this has been using subjective methods of assessment. One study[15] has measured the hardness of grounds in the AFL using a penetrometer as an objective measure. This study found a significant trend towards softer grounds as the season progressed, a significant decline in the risk of ACL injury as the season progressed, and a nonsignificant trend towards increased risk of ACL injury when the ground was harder (RR = 2.60, 95% CI = 0.94 to 7.20). It concluded that the early-season bias was almost certainly related to ground conditions, but that it was difficult to assess whether ground hardness, or another confounder such as grass type or shoe-surface traction, was responsible.[15]

It is unlikely that a systematic reporting bias is responsible for the early-season bias for injuries. Poor methodology (e.g. retrospective reporting of injuries) would tend to favour a late-season recall bias, if anything.[62] A relevant factor that should be considered more often by studies reporting an early- or late-season bias is the definition of an injury recurrence. Recurrent injuries are more likely to occur later in the season, as there is a greater accumulation of players who have returned to play from a previous minor injury. Pooling of new and recurrent injuries, which is done in most studies, would tend to produce a late-season injury bias. A method to account for this bias is to split injury rates up into incidence (considering new injuries only) and period prevalence (considering both new and recurrent injuries over the same time period).[26] Another method is to simultaneously assess intrinsic and extrinsic risk factors for all injuries using multivariate analysis, with the unit of exposure being a 'player match' rather than a 'match'. Using this method, recent injury of the same type is assessed as a risk factor for injury, and other variables are adjusted to account for this in the multivariate analysis.[3,71] Early-season biases noted for severe injuries that cause the player to miss the entire season, such as spinal injuries and ACL injuries, are not influenced by the definition of an injury recurrence. Because such severe injuries are uncommon, it is also unlikely that removal of susceptible players from the cohort at an early stage of the season is likely to create a substantial early-season bias.

Although an insufficient number of studies have directly measured ground conditions to eliminate all confounders, circumstantial evidence suggests that it is highly likely that variation in ground conditions is at least partially responsible for the widely reported early-season bias for football injuries. The most impressive association is that the early-season bias is most often reported in football competitions that are played on natural grass surfaces in temperate climates over an autumn-to-winter season.[15,21,24,27-29,49,51,54,55,57] The early-season bias is generally either absent, not reported, or even reversed in football competitions not played over an autumn-to-winter season,[43,60,61,72] in subtropical climates,[58] and in the sport of basketball,[44,45,64-66] conditions that would not exhibit the standard winter late-season changes in natural grass playing field conditions.

3. The Dry-Season Bias for Football Injuries

3.1 The Dry-Season Bias for Lower-Limb Injuries in Australian Football

Australia is the sixth largest country in the world in geographical size. Although much of the country is dry and hot throughout the year, there are coastal cities in cool (Melbourne) and humid (Brisbane and Sydney) climates. The AFL competition was originally based in the southeastern coastal city of Melbourne, but now contains teams from six cities around Australia. A consistent method of injury surveillance has been used in the AFL competition since 1992.[73] This injury surveillance, along with player injury payments that have been recorded by the league administration, has found that for every

year over the last decade, the teams based in northern (warmer) cities have had a greater injury incidence and prevalence than the teams based in Melbourne.[74] This northern bias is greatest for ACL injuries occurring with a noncontact mechanism ($p < 0.001$),[54] but is also present for ankle sprains, quadriceps, calf and groin strains and knee cartilage injuries.[74] All of these injury types usually involve a noncontact mechanism. The northern bias compared with Melbourne relates both to cities in relatively humid (Brisbane and Sydney) and dry (Adelaide and Perth) climates. In addition, in the city of Melbourne, where most teams are based, there is also a relationship between the amount of rainfall for the year and the rate of lower limb injuries, particularly noncontact ACL injuries.[3,54]

In an international context, it is confusing to use the term 'northern bias' because most of the world associates northern venues with cooler weather. It is preferable to state that there is a 'dry-season' bias for injuries in the AFL, with the explanation that warmer temperatures will generally lead to drier conditions through the process of water evaporation.[54] This dry-season bias in the AFL relates to both warmer location, and the amount of rainfall in a season.

In conclusion, observation of AFL injuries over a long duration has consistently shown that lower limb noncontact injuries, particularly noncontact ACL injuries, are less likely in the winter months in Melbourne than both the summer months in Melbourne and the more northern (warmer) parts of Australia.[3,15,54,74] It is therefore worth detailing the climatic patterns of the city of Melbourne during winter. This is a temperate humid climate where the overnight temperature rarely freezes in winter but where temperatures are almost always cool to mild (average daily minimum 6°C and maximum 13°C in July).[36] During the winter months Melbourne rainfall averages ~50 mm/month, which exceeds water evaporation.[36] The resultant football grounds during Melbourne winters tend to be soft and moist but not frozen. This climate would not be dissimilar to the autumn-winter climates of many countries and cities where an early-season injury bias has been reported, such as New Zealand, England and Scotland, coastal areas in South Africa, and coastal cities in the northern US, such as Seattle.

The major cool-season grass species used on Melbourne AFL grounds is perennial ryegrass (*Lolium perenne* L.) which tends to predominate in winter over warm-season grasses such as couchgrass (bermudagrass) [*Cynodon dactylon* L.] which may be part of the grass profile.[15] McNitt et al.[75] have reported that perennial ryegrass is associated with lower shoe-surface traction than Kentucky bluegrass (smooth-stalked meadow grass, *Poa pratensis* L.), the most widely-used cool-season turfgrass used in the US. Ryegrass is probably also associated with lower shoe-surface traction than couchgrass,[15,76] because of lower shoot density.[77] Ryegrass has been hypothesised as being a safer surface than couchgrass because of lower shoe-surface traction,[15] and better cushioning due to higher mowing height.[78] Matches played on couchgrass surfaces in recent seasons of the AFL have shown a trend towards more ACL injuries than matches played on ryegrass surfaces (RR = 2.37, 95% CI = 0.89 to 6.36).[15]

3.2 Dry-Season Bias for Other Sports

The major rugby league competition in the northern hemisphere is played mainly in the north of England. A significant change to the structure of this competition occurred in 1996, when it was moved from a winter to a summer season. Two separate studies[60,72] reported a substantial increase in injuries after this move. In the study by Phillips et al.,[60] when injuries were analysed by stage of the season and month of the year, it was found that summer months had a much greater correlation with risk of injury than stage of the season. That is, the 'warm-season' or 'dry-season' bias had a far greater influence on the rate of injuries than the stage of the season. The Gissane et al.[72] study found that the 'dry-season' (summer) bias was proportionally greater in backs, who tend to sustain non-

contact injuries, than forwards, who tend to sustain contact-mechanism injuries. Both of these groups of investigators attributed the dry-season (summer) injury bias to differences in the playing surface, particularly hardness.[60,72]

Backx et al.[79] reported injury rates of 1818 school children playing in 18 different sports in Holland over winter and spring seasons. They found that the children sustained more injuries, and that these were of a greater severity, in spring than winter, but noted that bad weather in winter led to reduced exposure. Soccer was the most popular sport, played on natural grass, but there were other sports played indoors and, unfortunately, they did not compare seasonal injury differences by sport.[79]

It is difficult to compare injury rates from studies conducted in different countries, because of variations in methodology. Notwithstanding this caveat, injury incidence in rugby league has generally been reported to be greater in north-eastern Australia (with drier and harder playing surfaces) than the UK, particularly when the UK competition was played in winter.[55,60,72,80-82] An editorial by Webb[83] has also noted an anecdotal trend for visiting southern hemisphere rugby union squads (from warmer climates) to have a greater prevalence of players who sustained ACL injuries than northern hemisphere teams.

A strong relationship has also been shown between the risk of musculoskeletal injury in racehorses and rating of the track, on natural grass surfaces. Two separate studies[84,85] from Australia and the UK have shown a strong and linear decrease in injury risk, as the track became softer, through each stage of track hardness. Similar patterns are seen in greyhound racing.[86]

3.3 Are Dry-Season and Early-Season Bias in Football Related?

Although there are multiple potential confounders involved, Ockham's razor suggests that the early-season bias for injuries may be wholly or partially accounted for by whatever mechanisms are responsible for the dry-season bias for injuries. Based on an appraisal of the studies listed above, there is overwhelming evidence that there is an early-season bias in rugby union, and in other winter football competitions played in similar climates to rugby union. There is strong evidence that there is a dry-season injury bias in rugby league and Australian football. It is most probable that all of these phenomena are explained by extrinsic surface-related conditions, although to date the exact mechanisms of these are not fully established.

4. Comparison Between Sports Played on Different Surfaces

4.1 Injury Rates on Artificial Turf and Natural Grass in American Football

Many studies have compared the injury rates between artificial surfaces, such as AstroTurf®[2] (Southwest Recreation Industries, Leander, TX), and natural grass. Some studies[52,87-90] have found that artificial turf and grass have a similar overall injury rate. Injuries to the foot and ankle have been reported as being more common on AstroTurf® than natural grass.[10,89-93] Injuries to the knee have been reported as either not related to the playing surface or slightly more common on artificial turf.[10,89-93] Of the two major review articles comparing artificial turf to natural grass, Skovron et al.[92] concluded that there was a 30 to 50% increase in lower-limb injury risk on artificial turf, whereas Nigg and Segesser[94] concluded that there was a definite increase in less serious injuries on artificial turf, a possible increase in severe knee and ankle injuries on artificial turf, but no difference between severe injuries of all types on artificial turf (compared with natural grass).

The studies least affected by confounders have been from the official injury surveillance system of the NFL, where knee sprains (RR = 1.13, 95% CI = 1.00 to 1.27),[90] and ankle sprains (RR = 1.34, 95% CI = 1.17 to 1.53)[91] have been found to be

2 Use of tradenames is for product identification only and does not imply endorsement.

slightly but significantly more common on artificial turf than natural grass.

Surface characteristics of artificial turf and particularly natural grass are quite variable.[95] A recent study[53] has compared knee and ankle sprain rates in the NFL under different weather conditions. Although this study examined data for knee and ankle sprain injuries from the decade subsequent to previous NFL studies, the overall relative risks between natural grass and artificial turf for knee and ankle sprains were almost identical to the previous published incidence density ratios.[53,90,91] When analysed by weather condition, it was found that the risk of injury did not vary significantly with weather or stage of season in indoor games on artificial turf. However, cool and wet conditions on natural grass, and cool and dry conditions on AstroTurf® in outdoor stadiums (both of which occurred more frequently late in the season) were associated with lower injury rates for ankle and knee injuries.[53]

4.2 Injuries and Differing Surface Types in Other Sports

American football is the only football code that is commonly played on artificial turf. Soccer and rugby both have indoor versions, but there are usually too many confounders, in differences in rules and size of playing surface, to make valid comparisons of injury rates. One study[96] of ACL injuries in soccer in Norway compared the incidence rate in different divisions. The higher divisions, which played on natural grass, had a far greater incidence of ACL injury than the lower divisions, which played on gravel ($p < 0.0001$), although the methodology of the study makes it impossible to determine whether the standard of play or surface was responsible for the observed difference.[96]

Volleyball injuries have been reported to be more common on hard court surfaces than sand.[13] Sand would be both softer and have lower foot-surface traction than hard courts. Tennis injuries are more common on grass than hard courts, and on hard courts compared with clay.[94,97] These findings in tennis highlight the potential for confounding variables when considering the impact of surface on injury risk. It is possible that grass courts lead to higher 'shoe-surface' traction than either hard court or clay and hence pose a greater injury risk. On the other hand, it is equally plausible that ball speed and bounce are confounding factors, and that ball movement characteristics on grass courts lead to a different style of tennis ('serve-volley' play) and that this style is responsible for the increased injury risk, rather than shoe-surface traction.

5. Possible Explanations for Observed Patterns of Injury

5.1 Ground Hardness and Shoe-Surface Traction

The two main surface characteristics that may relate to injury in football are hardness (the effect that the surface has on absorbing impact energy) and traction (the type of footing or 'grip' a playing surface provides).[42,94,98,99] Traction and hardness of natural grass football surfaces have been shown to correlate significantly ($r = 0.26$ to 0.79, $p < 0.001$).[100,101] Traction is most highly correlated with amount of grass cover,[100-102] whereas hardness is most highly correlated (inversely) with soil moisture content.[100,102] Rootzone materials with a higher sand content (as opposed to soil) maintain greater grass cover, have higher traction and have less variation in hardness caused by recent rainfall.[102]

Penetrometer readings reveal, on average, a slight softening of grounds over the progression of a winter season.[15] Ground hardness measurements vary significantly with the amount of recent rainfall.[102,103] On the other hand, traction shows a constant slow decline over the course of a winter football season with little week-to-week variation depending on rainfall.[102] Figure 1 shows the potential confounding factors that may affect both hardness and traction on natural grass football fields.

Nigg and Segesser[94] have argued that injury incidence is more likely to be related to increasing

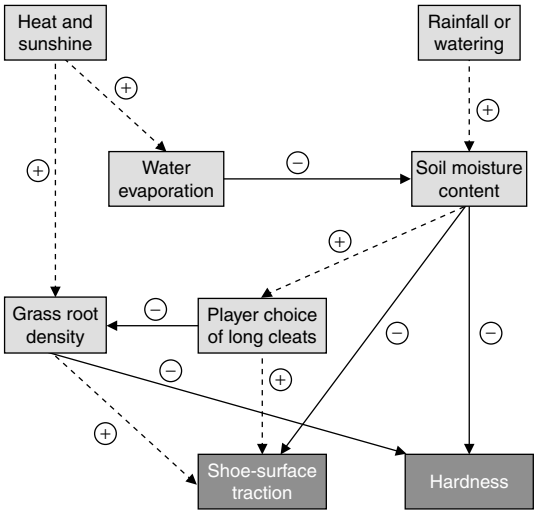

Fig. 1. Potential confounding relationships between some of the variables associated with ground hardness and shoe-surface traction (reproduced from Orchard,[15] with permission).

shoe-surface traction than increased hardness of the surface. Although no study has directly measured traction values and compared these to injury rates, some epidemiological observations support this argument. The relationship between ACL injury in the AFL and weather relates to long-term weather variables rather than daily or weekly rainfall.[54] One study has shown higher ACL injury rates on natural grass than gravel, which could be potentially explained by higher shoe-surface traction but not by greater hardness,[96] although it should be noted that this study did not control for level of play.

AstroTurf® has been consistently shown to be harder than grass.[95,104,105] The greater hardness on AstroTurf® results in faster running speeds for players, which has been hypothesised as a mechanism for higher injury rates.[104] The exception to this is when natural grass becomes frozen, where the surface is at least as hard as AstroTurf®.[95] By contrast, the results with respect to traction have varied considerably.[6,14,104,106] One recent study has shown that traction on AstroTurf® is greater when the temperature is warmer.[107] ACL injuries in the NFL in open AstroTurf® stadiums show an early-season bias, whereas ACL injuries in indoor AstroTurf® stadiums do not, which could be explained by temperature-induced changes in traction.[53]

5.2 Other Factors

Figure 1 shows that many factors are potential confounders of ground characteristics. The major confounder is the nonrandom relationship between surface and weather characteristics and shoe selection. For example, on softer and wetter surfaces which may be associated with a decrease in ACL injury risk, players are more likely to choose boots with longer cleats, which may be associated with increased ACL injury risk.

Norton et al.[108] have recently published a study that positively correlated hardness of the playing surface with overall speed of the game. This may be a mechanism by which games played earlier in the season and in warmer climates have higher injury rates. Speed of player movement has also been cited as an explanation for higher rates of injury on artificial turf compared with natural grass.[104]

Weather is a variable for which intervention is not possible, other than the construction of indoor or closed stadiums. Ground conditions in outdoor stadiums are somewhat passively changed by the weather, but can be manipulated with interventions such as changes in soil type (and texture), grass types (and composition), cutting (mowing) height and watering or covering practices as the weather changes. The surface-related factors responsible for playing quality have been previously reviewed,[109,110] although these reviews have been focussed on aesthetic presentation and player satisfaction, which may not necessarily correlate with injury risk.

Very few intervention studies have been performed. In the AFL competition, ACL injury incidence has fallen in recent years, in association with nonrandomised changes to grass types and softening of the playing surfaces.[15,74] Because these

changes have been assessed using historical controls only, it is impossible to adjust for other possible coexisting changes in the competition.

Mueller and Blyth[12] reported a decrease in knee and ankle injuries in a cohort of high school American football teams that were randomly chosen to have their fields resurfaced. Unfortunately, they published very little detail about the specifics of the resurfacing, such as soil type, drainage, grass type etc. Although the reduction of injuries in the Mueller and Blyth study[12] was very impressive, it does not appear to have been replicated by any other study.

6. Conclusion

Weather and other environmental factors can affect ground hardness and/or shoe-surface traction on natural grass football fields, leading to possible changes in the risk of injury. This review has found many studies suggesting that increased surface hardness, and particularly increased shoe-surface traction, may be risk factors for noncontact lower-limb injuries in football. However, very few studies have focussed specifically on this issue and controlled adequately for confounding factors.

Shoe-surface traction on natural grass surfaces will usually be higher on harder and drier grounds and when grass cover and root density are greatest. Perennial ryegrass is probably associated with less shoe-surface traction than other popular grasses such as Kentucky bluegrass and particularly couchgrass (bermudagrass). Play on artificial turf is generally associated with higher shoe-surface traction than natural grass. Football boots with longer cleats will also provide greater shoe-surface traction on natural grass. Football games played on harder surfaces and where traction is greater are probably played at faster speeds, which may partially explain the increased risks of injury.

It is possible that measures to reduce shoe-surface traction can reduce the risk of injury. Marked reductions of shoe-surface traction will lead to a decrease in field and player performance. Preparation of football grounds needs to balance these twin requirements of allowing enough shoe-surface traction for players to reasonably utilise their skills, while avoiding excessive shoe-surface traction which may be associated with increased injuries.

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