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Review

The relationship between ground conditions and injury: What level of evidence do we have?

Lauren A. Petrass*, Dara M. Twomey

School of Health Sciences, University of Ballarat, Mt Helen, Ballarat, Victoria, Australia

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ABSTRACT

Objectives: To identify studies which address the relationship between ground conditions and injury, in a sporting context and to evaluate current practice and provide recommendations for future studies that measure ground conditions and injury risk.
Design: Systematic review.
Methods: A comprehensive search of electronic databases from the earliest records available until the end of 2011, and supplemental hand searching was conducted to identify relevant studies. A classification scale was used to rate the methodological quality of studies.
Results: 79 potentially relevant articles were identified, and 27 met all inclusion criteria. They varied in methodological quality, with analytical observational studies the most common design, although four descriptive observational studies, considered to be of lower quality were also identified. Only five studies objectively measured ground conditions, and of studies that used subjective assessment, only one provided descriptors to explain their classifications. It appears that harder/drier grounds are associated with an increased injury risk but the presence of major limitations necessitates cautious interpretation of many key findings.
Conclusions: There is limited high quality evidence of the relationship between injury risk and ground conditions. Further research with high quality designs, and measurement of ground conditions are required to draw more definitive conclusions regarding this relationship.

1. Introduction

In an array of sports including cricket and the different codes of football, characteristics of ground conditions have been identified as a factor associated with injury risk.[1–7] Ground hardness (the effect that the surface has on absorbing impact energy) and traction (the type of footing or grip a playing surface provides) have been cited as the two main surface characteristics related to injury, particularly the lower limb.[8] Hardness is most highly correlated with soil moisture content and traction with grass cover.[8] While studies investigating the relationship between ground conditions and injuries are evident in the sports medicine and international sports science literature,[1,2,4,5,9–11] the range of approaches used to investigate this relationship have not previously been systematically and comprehensively examined. Accordingly, there are no standardised practices for the measurement of ground conditions, and this has resulted in an intuitive relationship, rather than a solid evidence base linking ground conditions and injury.[1,4,12,13]

Orchard[5] identified that there was a need to make use of, and further develop instruments to measure ground conditions, although as an initial step in advancing current practice, it seems appropriate to recognise and evaluate published studies. While two systematic reviews investigating injury and playing surfaces have been published recently, they have addressed the difference in injury rates on natural and artificial playing surfaces,[14] and the incidence, nature and mechanisms of football injuries on natural turf compared to newer generation artificial turfs.[15] This systematic review differs as it aims to identify and compare studies which address the association between ground conditions and injury, in a sporting context. More specifically, it describes the methodologies and assessment of ground conditions, and highlights the strengths and weaknesses of different approaches. Implications for understanding the relationship between ground conditions and injury risk, and considerations for improving the quality of ground measurement in future studies are discussed.

2. Method

Studies were included in this systematic review if they met all of the following criteria: (1) subjectively and/or objectively evaluated

* Corresponding author.
E-mail address: l.petrass@ballarat.edu.au (L.A. Petrass).

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ground conditions; (2) reported on a type of sport; (3) included an outcome measure of injury incidence; and were (4) peer reviewed original research articles.

Studies that measured weather variables (i.e. evaporation, rainfall, temperature) and ACL injury were excluded because ground conditions were not evaluated.[16–19] Similarly, a study that generalised that grounds were hard due to drought but did not evaluate the ground was excluded.[13] Other studies[20,21] that objectively measured ground hardness were also excluded if they used an industry standard predictor of injury (The Gadd Severity Index), but did not measure injury incidence. In addition, studies with insufficient details relating to the ground assessment (i.e. only reported data were collected on the surface during the match or training) were excluded.[22] Studies that investigated differences between surfaces (e.g. between natural and synthetic) were excluded unless the surface condition was explicitly described or measured.

To identify relevant studies, multiple electronic databases were searched from the earliest records available until the end of December 2011. Multiple databases were selected as research indicates that a literature search performed in a single database will lead to, on average, a loss of more than half of the available literature.[23] Further, the importance of searching multiple databases for multidisciplinary fields was adhered to.[24] Searching of electronic databases were supplemented by hand-searching of bibliographies of systematic and non-systematic reviews and the reference lists of all other identified studies.

To ensure that relevant studies were identified, a number of search keywords and synonyms were adopted, and recommended guidelines for electronic searching followed[25] (see supplementary material for details of search strategy and terms). Although English language search terms were implemented, no language restrictions were applied.

Relevant studies were identified by screening titles, abstracts and keywords according to the inclusion criteria defined a priori. Obvious exclusions were removed, and full texts were obtained for articles meriting further review. To determine appropriateness, articles were read and assessed against the inclusion criteria by one author. Uncertainties were resolved through discussion and additional review by the authors. Final classification of all studies was agreed upon by both authors.

To analyse the quality of selected studies, both the study design and method utilised to assess ground conditions were considered. To date, no scale or checklist is universally accepted.[26] Accordingly, for the purpose of this review two scales assessing common study designs in public health and injury prevention were identified,[27,28] and a classification scale for studies measuring ground conditions and injuries was derived from these (Fig. 1). This scale allowed all identified studies to be critically analysed and classified according to capacity to eliminate or minimise bias. A second scale ensured a systematic and explicit approach was implemented for making judgments about the assessment of ground conditions (Fig. 1).

3. Results

Searching identified 79 potentially relevant citations, although after screening against the inclusion criteria 27 studies were selected. Studies that did not meet inclusion criteria were eliminated principally because no measures of ground conditions were reported or injury incidence was not considered. Of the eligible studies, the majority ($n = 23$) were analytic observational study designs and case–control and cohort studies were the most common. The remaining studies were descriptive observational designs and these were considered to provide lower evidence.[1,29–31] Only five studies objectively measured ground conditions,[2,5,9–11] and all measured ground hardness. Only one study[4] that subjectively measured ground conditions provided detailed descriptions to explain the categorisation implemented. All other studies ($n = 17$) utilised subjective assessment with broad terms and no additional details, thus demonstrating that there is a paucity of high quality evidence examining the role of ground conditions as a risk factor for injury.

The assessment of ground conditions and injuries has been explored primarily within the different football codes including American football,[4,32–39] Australian Rules football,[5,9,10,40,41] rugby union and rugby league,[6,7,11,12,29–31,42,43] soccer,[3,44,45] and Gaelic football.[1] Recently, the first study examining the relationship between ground hardness and injuries in junior cricket has also emerged.[2] The following sections describe studies that have examined the relationship between ground conditions and injuries within each sporting context.

Many studies[4,32–36,38,39] have explored the relationship between ground conditions and injury in American football, although a major limitation to date is that all studies subjectively assess ground conditions (Table 1).

Andresen et al.[4] was the only study to provide descriptors to explain their subjective classifications of 'good', 'wet/slippery', 'hard', and 'muddy' in their attempt to determine associations between injuries and both environmental and playing conditions. All data were obtained by direct observation and recorded on a standardised form by the medical support staff at each game but it is unclear exactly where or how the observations were undertaken.

Findings demonstrated a significant difference in injuries (defined as "an insult that prevented the player from continuing play or for which medical attention was requested", p. 28) under different pitch conditions.[4] 'Good' conditions were associated with the highest injury frequency (3.3 injuries per game) and 'wet/slippery' conditions the lowest (1.7 injuries per game). Comparable injury rates were observed for 'hard' and 'muddy' conditions (2.3 and 2.1 injuries per game, respectively).

Overall, the relationship between ground conditions and injury risk in American football appears inconclusive. There is some evidence to suggest that more minor injuries are sustained on drier grounds but objective measurements or detailed descriptions of both the classification and methods of subject assessment are warranted.

Two cohort studies have investigated ground hardness and anterior cruciate ligament injuries in the Australian Football League (AFL).[5,10] The earlier study objectively measured ground hardness at 571 elite level AFL matches using a penetrometer.[5] While the study failed to provide specific details of the instrument, typically a penetrometer consists of a shaft [metal rod with a conical tip] and a hammer [specified weight that falls onto the strike plate/anvil around the rod], with the hammer lifted to a predetermined height and dropped.[46] This action pushes the shaft into the soil and the resultant depth of penetration is the measurement taken.[46] As the penetrometer was an established and reliable measure for determining track hardness in horse racing,[47] a pilot study was conducted in the first year to develop a method to measure football ground hardness.[5] To achieve consistency with horse racing values, ground hardness was measured at 20 sites, with the average of three consecutive drops at each site taken as the final reading. The 20 sites corresponded to the 18 player positions on an AFL field and two additional readings were taken in the centre square. The penetrometer was not moved between the three drops and as a result, the third drop provided the highest reading in all instances.[5] The protocols for testing ground hardness over the following seasons were the same, with two exceptions in the instructions. First, for grounds with a cricket pitch, no more than four readings were to be conducted on the cricket surface. Second, ground staff were encouraged to prepare grounds with "a degree of give in the surface" (p. 221) with extra

Table 1
Summary of American football studies that utilise subjective assessment to measure ground conditions.

Author (date)	Surface	Details of subjective ground assessment	Injury definition	Major findings related to ground conditions and injury
Adkison et al. (1974)[32]	Natural and artificial turf	Soaked, wet, or dry.	Same definition as published in Bramwell et al.[33]	No statistically significant differences were found between injury rates on wet and dry fields.
Andresen et al. (1989)[4]	Natural turf	Good = normal grass cover without recent or ongoing rain; wet/slippery = addition of rain to normal grass cover; hard = dry, packed-down areas of bare dirt; muddy = addition of rain to dirt surfaces.	"An insult that prevented the player from continuing play or for which medical attention was requested" (p. 28)	Injury rates differed significantly during different ground conditions. Rates were highest during 'good' field conditions (3.3 injuries per game) and lowest during 'wet/slippery' conditions (1.7 injuries per game). During 'hard' or 'muddy' conditions rates per game were 2.3 and 2.1, respectively.
Bramwell et al. (1972)[33]	Natural and artificial turf	Wet or dry.	"Traumatic medical conditions resulting from participation in a football game that resulted in the player not finishing the game and/or missing two or more subsequent practices and/or any subsequent game/games" (p. 167) Severe injury – "inability to participate in two or more subsequent games" (p. 167)	No statistically significant differences were found between injury rates on wet and dry grass, or between dry synthetic turf and wet or dry grass. Dry artificial turf had a significantly higher injury rate than all other surface/condition combinations ($p < 0.01$).
Hagel et al. (2003)[34]	Natural and artificial turf	Wet or dry.	Acute injuries were defined as "any injury resulting in one or more complete or partial sessions of time loss; and any concussion or transient neck neurologic injury" (p. 826)	During dry field conditions, head and neck injuries were 1.59 times higher on artificial turf than natural grass (95% confidence interval [CI] 1.04, 2.42). Under both wet (rate ratio [RR] = 2.31, 95%CI 1.18, 4.25) and dry (RR = 1.83, 95%CI 1.35, 2.48) conditions, lower extremity injury rates were higher on artificial turf compared to natural grass.
Meyers (2010)[35]	Natural and artificial turf	No precipitation/dry field, rain, snow, sleet, no precipitation/wet field.	"Any game related football trauma that resulted in (1) an athlete missing all or part of a game, (2) time away from competition, (3) any injury reported or treated by the athletic trainer or physician, and (4) all cranial/cervical trauma reported" (p. 689)	Compared to natural grass, a significantly lower incidence of injuries was reported on FieldTurf during no precipitation-dry field conditions, as well as during no participation-wet field conditions.
Meyers and Barnhill (2004)[36]	Natural and artificial turf	No precipitation/dry field, rain, snow, sleet, no precipitation/wet field.	"Any game related football trauma that resulted in (1) an athlete missing all or part of a game, (2) time away from competition, (3) any injury reported or treated by the athletic trainer or physician, and (4) all cranial/cervical trauma reported" (p. 1628)	The majority of injuries occurred during dry conditions. Conditions of no precipitation-dry field were associated with 88.3% of injuries on FieldTurf, and 84.8% on natural turf. Wet field or rain conditions were associated with 11.7% on FieldTurf and 15.6% on natural turf.
Mueller and Blyth (1974)[37]	Natural turf	Comparison between grounds that were completely resurfaced and maintained in good condition and regular fields.	"One in which the participant restricted his regular activity for one day after the injury occurred or for which professional medical treatment was received" (p. 2)	Significant decrease in the rate of injuries (knee and ankle) when playing on well maintained fields and wearing football cleats, compared to participants playing on regular fields ($p < 0.01$).
Ramirez et al. (2006)[38]	Natural and artificial turf	Normal, wet or muddy, irregular or other.	"Physical trauma to a player resulting in the player either leaving a game or practice session or missing the next subsequent game or practice session; or a concussion, fracture, or dislocation sustained by a player, regardless of time lost" (p. 1148)	Injury rates were 1.2 times more common on wet or muddy surfaces compared to normal surfaces (95%CI 1.0, 1.5). Injuries were less likely on surfaces classified as irregular (RR = 0.7, 95%CI 0.6, 0.9) or other (RR = 0.9, 95%CI 0.6,1.4) compared to normal surfaces.
Stevenson and Anderson (1981)[39]	Natural and artificial turf	Dry, damp, wet, very wet or poor (i.e. rough, uneven).	"Classified as major or minor according to the American Medical Association, Standard Nomenclature of Athletic Injuries 1966" (p. 60)	Very wet conditions were associated with the highest risk ratio for minor injuries, while wet conditions were associated with the highest risk ratio for major injuries on artificial turf. On natural grass, dry field conditions were associated with the highest risk ratio for minor injuries, although very wet conditions were associated with the highest risk ratio for major injuries.

Type of Methodological Approach	Strength of Evidence	Measurement of Ground conditions
Meta-analyses	MOST ROBUST	Objective
Randomised controlled trials		
Analytic observational study designs (including cross-sectional, case-control, nested case-control and cohort studies)		Subjective with detailed descriptions that enable replication.
Descriptive observational study designs (case series, case report, cross sectional)		
Anecdotalor expert opinion	LEAST ROBUST	Subjective

Fig. 1. Classification scale for assessing the strength of evidence used in studies measuring ground conditions and injuries (adapted from Harbour and Miller[27] and Finch and Kelsall[28]) and for evaluating the types of evidence available for measuring ground conditions.

watering recommended when rainfall was low, and evaporation high.[5]

Orchard[5] found no significant relationship between ACL injury (defined as requiring a knee reconstruction) and penetrometer readings, although a trend was evident towards an increased risk when ground conditions were classified as harder and this was strongest when the first drop average penetrometer measurement was used. Accordingly, in the later study ground hardness was measured using the first drop penetrometer technique.[10] Findings were comparable to the earlier study, with ground hardness not identified as a significant predictor of ACL injury.[10]

Recently, a study in community level Australian Rules footballers has considered the relationship between prospectively measured injury data and objectively measured ground hardness.[9] Ground hardness was measured (using a 2.25 kg Clegg hammer dropped from 45 cm, with the first drop measure recorded) at nine locations on a subset of grounds over the 2007 and 2008 football seasons. A total of 352 injuries were able to be matched to ground hardness measures. Findings indicated that there was significantly higher risk of injury on grounds categorised as 'low/normal' hardness (30–69 g) and 'unacceptably high' hardness (>120 g) compared to grounds categorised in the preferred hardness range (70–89 g). While the reported number of injuries were low, similar to Grimmer et al.[41] injuries were most frequently associated with grounds in the low/normal or preferred range, few injuries were associated with grounds considered unacceptably high.

Two observational studies conducted in junior Australian Rules footballers were also identified.[40,41] Over the 1992 football season, the incidence, nature and mechanisms of injuries in 1253 children was evaluated.[40] Ground conditions were subjectively recorded by a club volunteer when a child was injured (defined as "any trauma that caused some disability or pain", p. 302). While on most occasions the categories were self-evident (i.e. muddy, soft etc.), for categorisations such as hard, firm, coordinators were trained using visually presented standards. Unfortunately, no further details relating to training or the standards were provided. Findings indicated that most injuries occurred on firm or soft grounds (42% and 30%, respectively). While only 11% of injuries occurred on hard grounds, these conditions were associated with a high proportion of fractures (21%).[40]

Grimmer et al.[41] also considered injuries (defined as "anything that significantly interfered with enjoyment of, or participation in, the sport", p. 330) sustained by Australian Rules footballers aged seven to 17 years. Ground conditions were subjectively measured, although limited details were provided with the authors only stating that the surface on which the injury occurred was recorded for approximately 80% of the injuries. Ground conditions were not significantly associated with injury risk and injuries were most frequently associated with grounds considered OK (40.2%), followed by soft (29.5%) and hard (11.5%) grounds.

Overall, studies in Australian Rules football have demonstrated a non significant relationship between ground conditions and injuries.[5,10,40,41] Interestingly studies with elite AFL players (that objectively measured ground conditions) identified an increased risk when ground conditions were classified as harder, which is in contrast to junior level where injuries were most frequently associated with firm, OK or soft grounds. Further research using consistent and high quality methods to determine ground conditions are required in both elite and community level Australian Rules football.

Only one relevant study that investigated the association between injury risk and objectively measured ground hardness in junior community level cricket was identified.[2] This study prospectively monitored 323 junior players over one playing season and measured ground hardness using a Clegg hammer (consisting of a 2.25 kg hammer fitted with an accelerometer, and released from 45 cm through a guide tube) on a purposively selected sample of fields where matches were played. On each of the selected fields, ground hardness was measured at 13 sites which corresponded to cricket fielding positions, with four single drops conducted within a one metre square at each site for consistency. The average from all sites was reported as the ground hardness for the field. Hardness measures were subsequently linked to injury and exposure data, where injury was defined as "an event which requires the provision of medical attention, either on or off the field, and/or results in missed participation during the match".[2(p2)]

Results indicated that 82% of fields were considered to have 'unacceptably high' levels of hardness when categorised according to the Australian football scale, while the remaining 12% were of 'high/normal' hardness.[2] There were 31 injuries sustained during the season, with less than one quarter associated with ground conditions. However, the ability to determine a definitive link between ground hardness and injury in cricket was limited as only one injury occurred on a field that had been objectively tested.

Injuries from six elite Gaelic football teams over a six month period (January–June 1997) were examined to determine the nature, site, outcome and possible risk factors contributing to injuries.[1] An injury was defined as "one sustained during training or competition resulting in restricted performance or time lost from play".[1(p106)] Information was collected via a specifically designed

questionnaire, although the authors did not indicate whether their questionnaire had good reliability or validity. This is of concern as invalid measures may not measure what they claim to measure, and it is not possible to determine the consistency of responses obtained.[48]

In total, 95 injuries were reported, with most injuries sustained to the lower limb (69%).[1] Almost one-third (29%) of participants reported that they felt the condition of the pitch contributed to their injury, reporting the conditions as dry/hard (43%), wet/soft (39%) or uneven (18%). A major limitation of this study is that ground conditions were subjectively and retrospectively reported, and accordingly further empirical research is needed in Gaelic football.

A number of studies have considered the relationship between ground conditions and injuries in rugby, although with one exception,[11] all studies utilised subjective measurement for the assessment of grounds.[6,7,12,29–31,42,43] Although there is over three decades between the earliest[42] and most recent study[6] the subjective assessment of ground conditions remain analogous (Table 2). The ground conditions are generally based on two to four broad categorisations (for example hard, muddy, soft) with no detail provided on the location of where the subjective judgments occurred or the number of locations considered on the ground. This lack of detail regarding assessment of ground conditions makes it difficult to compare across studies, and when looking at the major findings it is evident that there is a lack of homogeneity in results (Table 2).

A prospective epidemiological study investigating the contribution of ground hardness, rainfall and evapotranspiration to injury incidence in 271 elite rugby union players[11] remains the only rugby-related injury study to objectively measure ground conditions. Ground hardness was objectively measured an average of two hours before each game using a penetrometer (Eijkelkamp model 06.01), with 15 standardised sites measured on each playing field. Three adjacent measures were performed at a constant speed (~2 cm/s) at the 15 sites, and the maximum ground penetration force was recorded in kilonewtons and converted to megapascals. For the purpose of the study, an injury was defined as "any physical event that required medical attention, or subsequently caused a player to miss at least one scheduled game or team training session" (p. 582), and either a sports medical practitioner or physiotherapist associated with each team recorded these.[11] Consistent with Orchard,[5] ground hardness decreased significantly throughout the rugby season, however, there was no significant relationship between ground hardness and community-level rugby union injuries.

While an association between ground conditions and rugby injuries were identified in most of the studies that assessed ground conditions subjectively,[7,12,29,30,42] findings from this study using an objective measure of ground hardness demonstrated a non-significant association between these two factors.[11] The validity of a penetrometer to determine ground hardness on natural turf playing fields is questionable due to the depth of penetration of the device, therefore, a greater evidence-base using valid and objective measures is required to relate ground conditions to injury risk in rugby.

The effect of playing surface conditions and injuries in soccer has only been considered in few studies to date.[3,44,45] A prospective study of 1272 youth soccer players over a two year period, showed an injury rate of 2.6 injuries per 100 participants (a total of 34 injuries).[44] Of these, 24% were associated with a poor pitch condition (either a wet surface or potholes), however limited details were provided to determine who made the subjective judgments related to ground quality. Ekstrand and Gillquist[45] also found that 24% of injuries were associated with poor playing surfaces. It was further identified that sprains, strains and contusions were generally caused by slipperiness as a result of rain, snow or ice, or by a rough playing surface. Similar to the earlier study[44] this study also lacked detail regarding assessment of ground conditions.

More recently, Chomiak[3] investigated players of different skill levels (youth to professional teams) and ages (14–42 years) over one year to determine intrinsic and extrinsic factors contributing to major or severe injuries defined as "those caused by football, regardless of the consequences with respect to participation in training or games. Such injuries were further defined as being accompanied by complaints lasting more than 4 weeks, absence from the sport for 4 or more weeks, or association with serious damage to the musculoskeletal system".[3(ps59)] All players who sustained a severe injury were asked to visit the orthopaedic surgeon, who completed a standard examination and analysis of medical history. Players also completed a specific questionnaire relating to the circumstances of injury and retrospectively reported pitch quality. In contrast to Cromwell et al.,[1] 45.2% of severely injured players reported 'good' pitch quality, while 21% felt the ground condition contributed to their injury reporting 'poor' pitch quality.[3] Akin to the Gaelic football study, no details were provided relating to reliability nor validity, and details of what constitutes 'good' or 'poor' pitch quality were not considered. The lack of detail regarding assessment of ground conditions in all soccer studies highlights the need for further work to determine the association between ground conditions and injury risk in soccer.

4. Discussion

This systematic review has highlighted that analytical observational studies and descriptive observational studies are the most commonly used designs to examine the relationship between injuries and ground surfaces. Very few objectively measured ground conditions and within the subjectively measured studies only one provided descriptors to explain their subjective classifications. Interestingly, all the studies reviewed reported ground hardness and, with the exception of four subjective studies[3,4,7,43] that used "slippery" as a classification of ground condition, no study to date has investigated the relationship between injuries and observed traction measures. Accordingly, it is evident that there is a dearth of high quality evidence of the extent to which injury risk is associated with quality of the sports playing surface.

Only four descriptive studies were identified that examined the relationship between ground conditions and injury risk. While descriptive designs are useful for providing preliminary information regarding possible associations between exposure and outcome, a major limitation of this design is that causal relationships cannot be established.[49] Analytic observational studies typically involve more thorough data collection and analyses, thus enabling researchers to control for confounding factors and accordingly, these designs can enable better associations between exposure and outcome and identification of possible preventive measures.[49] Cohort designs are considered to be one of the most powerful observational studies,[50] and within this systematic review cohort and case–control studies were the most common. Although RCTs and meta-analyses are considered to provide the highest levels of evidence, none of these were identified.

Meta-analyses, the best level of evidence, provide a synthesis and evaluation of the relationship among results from many individual studies, and consequently stronger conclusions can be drawn.[51] In order for this to occur constructs that are the same or similar need to be examined, consistent definitions implemented (i.e. injury), and findings need to be configured in a comparable statistical form.[51] While this is frequently challenging in new research areas, the lack of consistency in injury definitions has been identified as a major limitation in injury surveillance literature for many

Table 2
Summary of rugby studies that utilise subjective assessment to measure ground conditions.

Author (date)	Surface	Details of subjective ground assessment	Injury definition	Major findings related to ground conditions and injury
Alsop et al. (2005)[12]	Natural turf	Very hard/hard, or soft/very soft.	"Required medical attention or missed at least one game or team practice" (p. 173)	Playing on a hard/very hard ground was associated with a significantly higher risk of injury (odds ratio [OR] 1.52, 95%CI 1.15, 2.02, $p = 0.003$).
Chalmers et al. (2012)[6]	Natural turf	Firm, muddy or very hard.	"Any event that resulted in an injury requiring medical attention or causing a player to miss at least one scheduled game or team practice" (p. 96)	Compared to firm grounds, muddy grounds were associated with a 10% higher injury risk and very firm grounds a 50% higher injury risk.
Dallalana et al. (2007)[31]	Natural turf	Firm-hard or slippery-heavy.	"Any injury that prevents a player from taking a full part in all training and match play activities typically planned for that day for a period of greater than 24 hours from midnight at the end of the day the injury was sustained" (p. 819)	Firm-hard grounds were associated with a slightly higher proportion of injuries compared to slippery-hard surfaces. The differences observed for all types of injuries did not however reach statistical significance.
Davies and Gibson (1978)[42]	Natural turf	Normally soft, very muddy, hard and dry, or hard and frosty.	"Severe enough to cause at least a temporary interruption to a player's contribution to a game or impaired his subsequent ability to train or play" (p. 1759)	A total of 151 injuries were reported, and surface conditions were recorded for 91% ($n = 138$). Of these, 80% occurred when the pitch was either very muddy or normally soft. Hard and dry pitches and hard and frosty pitches were associated with 33% and 7% of injuries, respectively.
Gabbett et al. (2007)[7]	Natural turf	Heavy, slippery, firm or hard.	"Any pain or disability suffered by a player during a match or training session, and subsequently assess by the head trainer during, or immediately following the match or training session" (p. 213)	Harder grounds were associated with a higher injury rate for matches, but injury rates remained constant across the ground condition categories for training.
Inglis and Stewart (1981)[29]	Natural turf	Hard or soft.	"Injuries were classified as to their nature (bruise, laceration, fracture etc.) and requirement for follow up (inpatient, outpatient, none)" (p. 349)	Of the 1085 players with rugby injuries, half occurred when the playing field was soft. Hard grounds had no affect on injury trends i.e. concussion did not increase on hard grounds.
Lee and Garraway (2000)[43]	Natural	Hard, firm, yielding, slippery, or heavy.	"Sustained on the field during a competitive match on a Saturday that prevented the player from playing rugby football from the time of the injury or from the end of the match in which the injury was sustained" (p. 92)	No significant difference in types of injuries, or the duration of time a player missed between injuries based on the state of the pitch.
Ryan and McQuillan (1992)[30]	Natural turf	Hard or soft.	No definition provided	In total, 242 patients visited the accident and emergency department. Of the reported injuries, the majority (91.3%) occurred while playing on a soft pitch, while only 8.7% occurred on a hard pitch.

years.[52] It is encouraging that the definition of injury has been included in all reviewed studies. However, the variety of definitions requires careful consideration when both interpreting and comparing study findings. Further, for meta-analyses to be conducted, a consistent definition of injury should be considered for future studies. The published consensus statement injury definitions for soccer ("any physical complaint sustained by a player that results from a football match or football training, irrespective of the need for medical attention or time loss from football activities"[53(p193)]) and rugby union ("any physical complaint, which was caused by a transfer of energy that exceeds the body's ability to maintain its structural and/or functional integrity, that was sustained by a player during a rugby match or rugby training, irrespective of the need for medical attention or time-loss from rugby activities"[54(p329)]) provide a consistent injury definition for future injury studies in these sports. Further, these definitions provide a sound starting point for injury studies in other team sports.

The use of equipment to directly measure ground conditions in injury-related studies has been relatively limited, with only five studies found across all sports. The penetrometer which measures soil strength by depth of penetration (below the surface) and the Clegg hammer which measures deceleration on impact (at the superficial layer of the surface) are the two devices that were used to measure ground hardness. While both devices appear to give an indication of ground hardness, the differences in the exact point measured on the ground make it difficult to compare results. A notable consideration for future work using these devices is the inter-rater reliability. Recently poor reliability between experienced and novice testers was identified, particularly for the penetrometer.[55] It is recommended that future studies report reliability of the equipment used in order to facilitate an accurate interpretation of the findings. Furthermore despite the practicality and portability of the devices, their ability to validly replicate human surface interactions has been questioned[56] and undoubtedly requires continued efforts to increase the understanding of the contribution of ground conditions to injury risk.

A large number of subjectively based studies identified across the different sports produced somewhat conflicting findings. In many American football and rugby studies, a higher risk of minor

injuries appeared to be associated with harder/drier grounds, whereas in soccer, players attributed more injuries to 'good' pitch quality. A major limitation of the subjective ground classifications used was the lack of detailed descriptions of the terms used. For example, the word 'heavy' is highly subjective and may fail to provide the reader with an accurate representation of the condition of the ground. Moreover, subjective terms such as hard, soft or muddy, were used as overall ground measures and it was assumed that the area in which the injury occurred matched this description. As mentioned by Naunheim et al.[21] the condition of all outdoor surfaces will vary according to environmental and maintenance conditions. On natural surfaces, variability can be vast, largely dependent on areas of higher traffic, prolonged training, or time in the season, therefore, associating injury risk with an overall ground condition may be erroneous.

In addition to a description of the condition of the surface, other factors that have been postulated to affect injury risk include grass cover, grass type, soil type and evenness.[8,57] Inclusion of these details in future research will add immense value to the quality and repeatability of the work and provide invaluable information for future injury prevention strategies. Furthermore, the condition of the ground is only one element of a player–surface interaction. As the foot is the interface with the ground, the footwear a player is wearing plays a key role in the interaction. While there is lots of research on traction on various surfaces and with different footwear,[58–60] no study linking injuries with ground conditions reported details on footwear. In future injury surveillance studies, identification of the type of footwear, with ample details of the sole design, will help to address this fundamental omission.

Another limitation apparent in the subjective studies is the lack of reported reliability or level of training undertaken by assessors, and few studies considered the problems associated with unknown reliability or validity. This is of concern because invalid measures may not measure what they claim to measure, and it is not possible to determine the consistency of results obtained from such measures.[48] In many instances, the grounds were subjectively assessed by the medical support staff across multiple venues prior to the games. It is possible that training in the identification of ground characteristics was undertaken to ensure consistency between assessors but it was not reported in any study. It is advocated that future studies, which are limited to subjective assessments of the condition of the playing surface, report reliability, number of locations observed for the overall assessment, and include detailed descriptors of the subjective classifications.

5. Conclusion

In conclusion, this review has highlighted the need for high quality studies to determine the relationship between ground conditions and injury risk across a variety of sports. It provides insight into quality research designs and identifies essential issues for consideration in future studies. Adoption of its recommendations will advance our understanding of the relationship between ground conditions and injury.

Practical implications

- There is a dearth of high quality evidence of the extent to which injury risk is associated with quality of the playing surface, and therefore efforts should be made to improve the quality of ground assessment in future studies.
- Objective ground assessment measures are critical for accurate interpretation of the relationship between ground conditions and injury risk. For studies that are limited to subjective assessment, descriptions of subjective ground categorisations and number of locations observed for the overall assessment should be noted.
- Inclusion of other factors that have been postulated to affect injury risk will add immense value to the quality and repeatability of work in this area and provide invaluable information for future injury prevention strategies.

Conflict of interest

None.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.jsams.2012.07.005.

References

1. Cromwell F, Walsh J, Gormley J. A pilot study examining injuries in elite Gaelic footballers. *Br J Sports Med* 2000; 34(2):104–108.
2. Twomey DM, White PE, Finch CF. Injury risk associated with ground hardness in junior cricket. *JSAMS* 2012; 15(2):110–115.
3. Chomiak J, Junge A, Peterson L et al. Severe injuries in football players. Influencing factors. *Am J Sports Med* 2000; 28(5):s58–s68.
4. Andresen BL, Hoffman MD, Barton LW. High school football injuries: field conditions and other factors. *Wis Med J* 1989; 88(10):28–31.
5. Orchard J. The AFL penetrometer study: work in progress. *JSAMS* 2001; 4(2):220–232.
6. Chalmers DJ, Samaranayaka A, Gulliver P et al. Risk factors for injury in rugby union football in New Zealand: a cohort study. *Br J Sports Med* 2012; 46(2):95–102.
7. Gabbett T, Minbashian A, Finch CF. Influence of environmental and ground conditions on injury risk in rugby league. *JSAMS* 2007; 10(4):211–218.
8. Orchard J. Is there a relationship between ground and climatic conditions and injuries in football? *Sports Med* 2002; 32(7):419–432.
9. Twomey DM, Finch CF, Lloyd DG et al. Ground hardness and injury in community level Australian football. *JSAMS* 2012; 15(4):305–310.
10. Orchard JW, Chivers I, Aldous D et al. Rye grass is associated with fewer non-contact anterior cruciate ligament injuries than bermuda grass. *Br J Sports Med* 2005; 39(10):704–709.
11. Takemura M, Schneiders AG, Bell ML et al. Association of ground hardness with injuries in rugby union. *Br J Sports Med* 2007; 41(9):582–587.
12. Alsop JC, Morrison L, Williams SM et al. Playing conditions, player preparation and rugby injury: a case–control study. *J Sci Med Sport* 2005; 8(2):171–180.
13. Durie RM, Munroe AD. A prospective survey of injuries in a New Zealand schoolboy rugby population. *NZ J Sports Med* 2000; 28(4):84–90.
14. Dragoo JL, Braun HJ. The effect of playing surface on injury rate. A review of the current literature. *Sports Med* 2010; 40(11):981–990.
15. Williams S, Hume PA, Kara S. A review of football injuries on third and fourth generation artificial turfs compared with natural turf. *Sports Med* 2011; 41(11):903–923.
16. Orchard JW, Powell JW. Risk of knee and ankle sprains under various weather conditions in American football. *Med Sci Sports Exerc* 2003; 35(7):1118–1123.
17. Orchard J, Seward H, McGivern J et al. Rainfall, evaporation and the risk of non-contact anterior cruciate ligament injury in the Australian Football League. *Med J Aust* 1999; 170(7):304–306.
18. Orchard J, Seward H, McGivern J et al. Intrinsic and extrinsic risk factors for anterior cruciate ligament injury in Australian footballers. *Am J Sports Med* 2001; 29(2):196–200.
19. Orchard JW. Intrinsic and extrinsic risk factors for muscle strains in Australian football. *Am J Sports Med* 2001; 29(3):300–303.
20. Naunheim R, Parrott H, Standeven J. A comparison of artificial turf. *J Trauma* 2004; 57(6):1311–1314.
21. Naunheim R, McGurren M, Standeven J et al. Does the use of artificial turf contribute to head injuries? *J Trauma* 2002; 53(4):691–694.
22. Bjørneboe J, Bahr R, Andersen TE. Risk of injury on third-generation artificial turf in Norwegian professional football. *Br J Sports Med* 2010; 44(11):794–798.
23. Lawrence DW. What is lost when searching only one database for articles relevant to injury prevention and safety promotion? *Inj Prev* 2008; 14(6):401–404.
24. Walters WH, Wilder EI. Bibliographic index coverage of a multidisciplinary field. *J Am Soc Inf Sci Technol* 2003; 54(14):1305–1312.
25. Blackhall K, Ker K. Searching for studies for inclusion in Cochrane Systematic Reviews on injury prevention. *Inj Prev* 2008; 14(2):137–138.
26. Patsopoulos NA, Analatos AA, Ioannidis JPA. Relative citation impact of various study designs in the health sciences. *JAMA* 2005; 293(19):2362–2366.
27. Harbour R, Miller J. A new system for grading recommendations in evidence based guidelines. *BMJ* 2001; 323(7308):334–336.

28. Finch CF, Kelsall HL. The effectiveness of ski bindings and their professional adjustment for preventing alpine skiing injuries. *Sports Med* 1998; 25(6):407–416.
29. Inglis GS, Stewart ID. Rugby union survey 1979. *NZ Med J* 1981; 94:349–350.
30. Ryan JM, McQuillan R. A survey of rugby injuries attending an accident & emergency department. *Ir Med J* 1992; 85(2):72–73.
31. Dallalana RJ, Brooks JHM, Kemp SPT et al. The epidemiology of knee injuries in English professional rugby union. *Am J Sports Med* 2007; 35(5):818–830.
32. Adkison JW, Requa RK, Garrick JG. Injury rates in high school football. A comparison of synthetic and grass fields. *Clin Orthop Relat Res* 1974; 99:131–136.
33. Bramwell ST, Requa RK, Garrick JG. High school football injuries: a pilot comparison of playing surfaces. *Med Sci Sports Exerc* 1972; 4(3):166–169.
34. Hagel BE, Fick GH, Meeuwisse WH. Injury risk in men's Canada west university football. *Am J Epidemiol* 2003; 157(9):825–833.
35. Meyers MC. Incidence, mechanisms, and severity of game-related college football injuries on fieldturf versus natural grass. A 3-year prospective study. *Am J Sports Med* 2010; 38(4):687–697.
36. Meyers MC, Barnhill BS. Incidence, causes, and severity of high school football injuries on fieldturf versus natural grass. A 5-year prospective study. *Am J Sports Med* 2004; 32(7):1626–1638.
37. Mueller FO, Blyth CS. North Carolina high school football injury study: equipment and prevention. *Am J Sports Med* 1974; 2(1):1–10.
38. Ramirez M, Schaffer KB, Shen H et al. Injuries to high school football athletes in California. *Am J Sports Med* 2006; 34(7):1147–1158.
39. Stevenson MJ, Anderson BD. The effects of playing surfaces on injuries in college intramural touch football. *J Nat Intramural-Recreational Sports Assoc* 1981; 5:59–64.
40. McMahon KA, Nolan T, Bennett CM et al. Australian Rules football injuries in children and adolescents. *Med J Aust* 1993; 159:301–306.
41. Grimmer KA, Jones D, Williams J. Prevalence of adolescent injury from recreational exercise: an Australian perspective. *J Adolesc Health* 2000; 27(4):266–272.
42. Davies JE, Gibson T. Injuries in rugby union football. *BMJ* 1978; 2:1759–1761.
43. Lee AJ, Garraway WM. The influence of environmental factors on rugby football injuries. *J Sports Sci* 2000; 18(2):91–95.
44. Sullivan JA, Gross RH, Grana WA et al. Evaluation of injuries in youth soccer. *Am J Sports Med* 1980; 8(5):325–327.
45. Ekstrand J, Gillquist J. The avoidability of soccer injuries. *Int J Sports Med* 1983; 4(2):124–128.
46. Vanags C, Minasny B, McBratney AB. The dynamic penetrometer for assessment of soil mechanical resistance, *SuperSpoil 2004: 3rd Australian New Zealand Soils Conference*, 2004.
47. Murphy JW, Fielf TRO, Thomas VJ. Racetrack traction assessment by penetrometer. Part II. Application of the model. *J Turfgrass Manage* 1996; 1(4):51–62.
48. Jackson SL. *Research Methods and Statistics: A Critical Thinking Approach*, 2nd ed. USA, Thomson Wadsworth, 2006. p. 55–65.
49. DiPietro NA. Methods in epidemiology: observational study designs. *Pharmacotherapy* 2010; 30(10):973–984.
50. Friis RH, Sellers TA. Study designs: cohort studies, Chapter 7, In: *Epidemiology for Public Health Practice.* 4th ed. Sudbury, MA, Jones and Bartlett, 2009. p. 284–326.
51. Shaughnessy JJ, Zechmeister EB, Zechmeister JS. *Research Methods in Psychology*, 7th ed. New York, McGraw-Hill, 2006.
52. Finch CF. An overview of some definitional issues for sports injury surveillance. *Sports Med* 1997; 24(3):157–163.
53. Fuller CW, Ekstrand J, Junge A et al. Consensus statement on injury definitions and data collection procedures in studies of football (soccer) injuries. *Br J Sports Med* 2006; 40(3):193–201.
54. Fuller CW, Molloy MG, Bagate C et al. Consensus statement on injury definitions and data collection procedures for studies of injuries in rugby union. *Br J Sports Med* 2007; 41(5):328–331.
55. Twomey DM, Otago L, Ullah S et al. Reliability of equipment for measuring the ground hardness and traction. *J Sports Eng Technol* 2011; 225(3):131–137.
56. Saunders N, Twomey DM, Otago L. Clegg hammer measures and human external landing forces: is there a relationship? *Int J Sports Sci Eng* 2011; 5(4):231–236.
57. Canaway PM, Baker SW. Soil and turf properties governing playing quality. *J Sports Turf Res Inst* 1993; 7:192–200.
58. Villwock MR, Meyer EG, Powell JW et al. Football playing surface and shoe design affect rotational traction. *Am J Sports Med* 2009; 37(3):518–525.
59. Kirk RF, Noble ISG, Mitchelle T et al. High-speed observations of football-boot-surface interactions of players in their natural environment. *Sports Eng* 2007; 10(3):129–144.
60. Kuhlman S, Sabick M, Pfeiffer R et al. Effect of loading condition on the traction coefficient between shoes and artificial turf surfaces. *J Sports Eng Technol* 2010; 224(2):155–165.