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REVIEW

A review of turfgrass sports field variability and its implications on athlete–surface interactions

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Abstract

Natural turfgrass sports fields can be highly variable depending on construction, usage, and management. Research involving athlete–surface interactions often fails to thoroughly account for variability by grouping these fields into the single category of "natural turfgrass." This can obscure results and make it difficult to identify specific field characteristics that most strongly influence athletes, making it almost impossible to implement strategies for improvement. The purpose of this literature review was to highlight the between- and within-field variations of turfgrass sports fields and their influence on athlete–surface interactions. The components of turfgrass sports fields and common methods used to objectively quantify surface characteristics in situ are discussed. Then, current literature is reviewed that involves several athlete–surface interactions under a variety of turfgrass sports field scenarios. It was found that turfgrass surface characteristics generally influence athlete biomechanics, performance and physiology, perceptions, and injury occurrence. To better interpret and compare findings, it is recommended that future studies fully describe field characteristics and management practices. Consistency with field and athlete data collection methods, analysis, and reporting are also important. Athlete–surface interaction research incorporating new technologies; addressing athlete performance, physiology, and psychological aspects; and investigating athletes other than professionals is also needed. These recommendations are more likely to happen with increased collaboration between turfgrass scientists, sports turf managers, sports scientists, and sports medicine clinicians. Ultimately, the goal would be to develop evidence-based guidelines for turfgrass sports field management that improve the overall athlete experience under an assortment of turfgrass sports field scenarios.

1 | INTRODUCTION

Playing surfaces are essential for most athletic competitions. Sports played on a field are usually surfaced with natural turfgrass or artificial turf. Considerable focus has been given to comparisons between the two regarding athlete–surface interactions (Andersson, Ekblom, & Krustrup, 2008; Kent, Forman, Lessley, & Crandall, 2015; Meyers, 2010; Williams, Hume, & Kara, 2011); however, each individual surface has received less attention for its unique contributions. Characteristics of turfgrass fields can be highly variable and dependent on several factors, such as turfgrass species, soil texture, drainage capabilities, usage, and management (Orchard et al., 2013; Stiles, James, Dixon, & Guisasola, 2009; Straw,

Abbreviations: ACL, anterior cruciate ligament; GPS, Global Positioning System; NDVI, normalized difference vegetation index.

Grubbs, Tucker, & Henry, 2016). Many studies fail to thoroughly account for variability, particularly those comparing turfgrass versus artificial turf and large-scale epidemiology studies that include a substantial number of fields (Gabbett, Minbashian, & Finch, 2007; Orchard, 2001; Ramirez, Schaffer, Shen, Kashani, & Kraus, 2006; Twomey, Finch, Lloyd, Elliott, & Doyle, 2012a). Using the term "natural turfgrass" without providing a sufficient description of a field can obscure results by masking between- and within-field variations, making it difficult to identify the specific characteristics that most strongly influence athletes and therefore making it almost impossible to implement strategies for improvement.

The purpose of this literature review is to highlight the between- and within-field variations of turfgrass sports fields and their implications on athlete–surface interactions, excluding those involving head–surface impacts. In doing so, the varying components of turfgrass sports fields and common methods used to objectively quantify surface characteristics in situ (i.e., on actual turfgrass sports fields) are discussed. Then, current literature is reviewed that involves several athlete–surface interactions under a variety of turfgrass sports field scenarios in a laboratory and in situ. We conclude by addressing limitations and offering suggestions to assist future studies evaluating certain athlete–surface interactions on turfgrass sports fields.

Core Ideas

- Turfgrass sports fields are spatially and temporally variable.
- Turfgrass sports field variability is oftentimes overlooked in research.
- Turfgrass sports field variability affects multiple athlete–surface interactions.
- Recommendations are made to better interpret and compare future research findings.
- Research should move toward evidence-based guidelines for turfgrass sports field management.

2 | TURFGRASS SPORTS FIELDS

Turfgrass sports fields have two primary components: turfgrass and soil. The most common turfgrasses used for sports fields are bermudagrass (*Cynodon* spp.), seashore paspalum (*Paspalum vaginatum* L.), Kentucky bluegrass (*Poa pratensis* L.), perennial ryegrass (*Lolium perenne* L.), and tall fescue (*Festuca arundinacea* Schreb.) (Puhalla, Krans, & Goatley, 2010) (Table 1). Each provides specific qualities, such as strong intermediate rhizomes (bermudagrass, seashore paspalum, Kentucky bluegrass, and rhizomatous tall fescue), robust vegetative growth (all except seashore paspalum), and moderate to excellent wear resistance (all except seashore paspalum), that produce successful sports fields. All of these turfgrasses can be maintained at a desirable mowing height for play, contingent upon turfgrass species, climate, season, sport, and competition level (Puhalla et al., 2010) (Table 1).

Climate is the primary factor used for the selection of turfgrass species on sports fields (Turgeon, 2011). Bermudagrass and seashore paspalum are warm-season turfgrasses typically found on fields in warmer climates, whereas Kentucky bluegrass, perennial ryegrass, and tall fescue are cool-season turfgrasses typically found on fields in cooler climates (Christians, Patton, & Law, 2016) (Table 1). Mixtures of cool-season turfgrasses are common, as is overseeding warm-season grasses with perennial ryegrass in regions where bermudagrass goes dormant in winter months (Turgeon, 2011).

Soils used for turfgrass sports fields can vary (James, 2011). The soil provides a medium for turfgrass growth but also influences playing conditions and management strategies. Fine-textured soils, such as clay, have a higher water holding capacity, are more susceptible to soil compaction, and normally have higher strength (i.e., greater resistance for displacement) than course-textured soils like sand (Beard, 1973; Carrow & Petrovic, 1992). This is due to the compactibility of the smaller clay particles (<0.002 mm) compared with the larger sand particles (2.0–0.05 mm), resulting in less soil macropores and more micropores that restrict air and water movement (Carrow & Petrovic, 1992). Fields with high clay content usually require less water and fertility, although they may be more susceptible to harder surfaces under low soil moisture conditions or puddling due to poor water infiltration after rainfall. Conversely, sand sports fields generally require more water and fertility, although they are less prone to soil compaction or standing water at the surface following rainfall (Guisasola, James, Llewellyn, Stiles, & Dixon, 2010b; Guisasola, James, Stiles, & Dixon, 2010a; James, 2011). Because sand sports fields are more prone to divots (i.e., complete removal of the turfgrass plant from the root zone), synthetic reinforcement materials could be incorporated into the root zone to increase divot resistance after roots are reduced from foot traffic (McNitt & Landschoot, 2005; Serensits, McNitt, & Petrunak, 2011).

Turfgrass species and soil combinations can differ significantly between sports fields. The soil texture of fields constructed on native soil change between regions (Beard, 1973). Some facilities construct their fields on man-made soil mixtures, such as the United States Golf Association specification (Hummel, 1993), which has an ~30-cm layer of medium-textured sand placed on top of a ~5.1- to 10.2-cm layer of very coarse sand and fine gravel over the top of an ~10.2-cm layer of pea gravel with drainage pipes beneath

TABLE 1 Common turfgrasses used to surface sports fields [a]

Turfgrass species [b]	Description[c]	General maintenance	Positive attributes	Negative attributes	Notes
Bermudagrass (*Cynodon* spp.)	Warm-season turfgrass that spreads by rhizomes and stolons	Mowing height 1.9–5.1 cm; fertilization 2–4 kg N annually per 100 m^2; irrigation required to achieve highest quality; regular vertical mowing and topdressing	Robust growth and ability to recover; excellent wear resistance; excellent sod	Poor cold and shade tolerance; thatch accumulation	Can be overseeded with perennial ryegrass; hybrid bermudagrass cultivars are most common but must be vegetatively propagated by sod, sprigs, or plugs
Seashore paspalum (*Paspalum vaginatum* L.)	Warm-season turfgrass that spreads by rhizomes	Mowing height 1.9–5.1 cm; fertilization 1–2 kg N annually per 100 m^2; minimal irrigation requirement compared with most warm-season turfgrasses; regular vertical mowing and topdressing	Excellent salt tolerance; more shade tolerant than bermudagrass; good visual mowing quality	Limited to very warm regions; slow recuperative ability; can be sensitive to certain pesticides; thatch accumulation	Used in areas where water quality is strongly effected by salt or irrigation is supplied using a reclaimed water source
Kentucky bluegrass (*Poa pratensis* L.)	Cool-season turfgrass that spreads by rhizomes	Mowing height 1.9–7.6 cm; fertilization 1–3 kg N annually per 100 m^2; irrigation required to achieve highest quality; vertical mowing	Robust growth and ability to recover; moderate wear resistance; excellent sod strength	Poor heat and shade tolerance; slow establishment from seed	Typically a mono-stand or mixed with tall fescue and/or perennial ryegrass
Perennial ryegrass (*Lolium perenne* L.)	Cool-season, bunch-type turfgrass	Mowing height 1.9–7.6 cm; fertilization 1–3 kg N annually per 100 m^2; irrigation required to achieve highest quality	Robust growth; excellent wear resistance; quick establishment from seed; excellent visual mowing quality	Intolerant to extreme heat, cold, and drought; more susceptible to environmental and pest damage	Can be a monostand, used as a mixture with other cool-season turfgrasses, or overseeded with a warm-season turfgrass to promote green color and wear resistance during cooler temperatures
Tall fescue (*Festuca arundinacea* Schreb.)	Cool-season, bunch-type or rhizomatous turfgrass	Mowing height 3.8–7.6 cm; fertilization 1–2 kg N annually per 100 m^2; irrigation required to achieve highest quality	Robust growth; excellent wear resistance; good heat and drought tolerance for a cool-season turfgrass	Poor cold tolerance	Typically a mono-stand or mixed with Kentucky bluegrass; newer cultivars, referred to as "turf-type" tall fescues, are common and produce rhizomes

[a]Sources: Puhalla et al. (2010) and Turgeon (2011).
[b]Cultivars within turfgrass species may differ substantially regarding desirable attributes, such as color, texture, density, management input requirements (e.g., fertility, irrigation), mowing height, and/or adaptation to pest and environmental stresses (e.g., heat, cold, drought, disease, insects, shade).
[c]Favorable temperatures for warm-season turfgrass growth are generally between 27 and 35 °C, whereas favorable temperatures for cool-season turfgrass growth are between 16 and 24 °C. Rhizomes and stolons are elongated stems that grow underground and aboveground, respectively, from which the turfgrass may spread. Bunch-type turfgrasses produce new tillers from the plant crown.

(Puhalla et al., 2010). Native soil fields are commonly recreational-level fields, whereas fields constructed on man-made soil mixtures are more common at higher-end community level, collegiate, semi-professional, and professional level fields (James, 2011). As previously mentioned, the turfgrass species is much less variable and is primarily selected based on climate (Puhalla et al., 2010). Nonetheless, cultivars within species may be different and selected based on specific traits (e.g., wear tolerance, drought tolerance, and/or disease resistance) that are advantageous for particular scenarios (Baldwin & McCarty, 2008; Bonos, Clarke, & Meyer, 2006).

Furthermore, the overall quality of a field varies by sport, competition level, usage, drainage capabilities, management, and management budget (Canaway & Baker, 1993; James, 2011). Sports that involve athletes digging and pressing into the surface with their footwear, such as rugby or American football, may be more detrimental to the turfgrass field than sports where athletes are primarily running, such as soccer (aside from goal mouth areas) (Carrow & Petrovic, 1992). Fields designated for lower levels of competition typically have smaller-sized athletes who cause less negative impact to the turfgrass and soil, but these fields may receive excessive turfgrass wear and soil compaction due to native soil construction and increased usage (Adams & Gibbs, 1994). Conversely, fields designated for higher levels of competition typically have larger-sized athletes who can cause more negative impact to the turfgrass and soil, but these fields are often better constructed, receive less usage, and have an increased management budget to maintain a higher standard of quality (Adams & Gibbs, 1994; James, 2011).

3 | PERFORMANCE TESTING

Several studies have used subjective classifications to assess turfgrass sports fields, for instance, "good," "satisfactory," or "poor" (Andresen, Hoffman, & Barton, 1989; Gabbett et al., 2007; Hagel, Fick, & Meeuwisse, 2003). Although convenient, this method is not reliable because the majority of these studies do not report specific definitions that describe subjective classifications, measurements cannot be replicated, and people conducting field assessments are not always consistent (Petrass & Twomey, 2013; Rennie, Vanrenterghem, Littlewood, & Drust, 2016; Twomey, Otago, Ullah, & Finch, 2011). Although qualitative descriptors and perceptions are informative, they have limited ability to provide quantitative data for designing interventions (e.g., thresholds to guide field management or proper equipment selection). "Performance testing" is a term used in the turfgrass industry and refers to in situ quantification of field characteristics using objective measurements (Bartlett, James, Ford, & Jennings-Temple, 2009; McAuliffe, 2008). Several sampling devices have been used in situ to objectively describe turfgrass sports fields, yet only the most common are discussed in this section.

Surface hardness, or ground hardness, is the most frequently quantified field characteristic on turfgrass sports fields (Sleat, O'Donoghue, Hughes, & Bezodis, 2016; Takemura, Schneiders, Bell, & Milburn, 2007; Twomey et al., 2012a). The term "hardness" indicates the firmness of the playing surface, which includes stiffness (i.e., the ratio of force applied and its deflection) and resilience (i.e., the ratio of energy returned to an athlete after contact and energy applied before contact) (Aldahir & McElroy, 2014). The handheld Clegg Impact Tester is widely used to measure surface hardness on sports fields (Clegg, 1976) (Table 2). Other researchers have used a penetrometer as an indicator of surface hardness (Orchard, 2001; Straw et al., 2016; Takemura et al., 2007) (Table 2). Although the penetrometer and Clegg do not measure the same thing, their data are, in general, positively correlated (Caple, James, & Bartlett, 2012a; Petrass & Twomey, 2013). There are several types of penetrometers; most are handheld and have a cylindrical cone at the end of a shaft. Penetrometer measurements have also been referred to as "penetration resistance" (Straw et al., 2016) (Table 2).

Turfgrass quality (i.e., color, coverage, and density) has been primarily rated visually in turfgrass research (Morris & Shearman, 1998; Trenholm, Carrow, & Duncan, 1999). Spectral reflectance techniques were introduced in the 1980s to differentiate green canopies from soil (Haggar, Stent, & Isaac, 1983), where various combinations of red and near-infrared spectra reflected from the surface are measured to calculate vegetation indices (Table 2). Normalized difference vegetation index (NDVI) is among the most common vegetation indices in turfgrass, and higher NDVI values indicate green, dense turfgrass canopies (Bremer, Lee, Su, & Keeley, 2011; Carrow, Krum, Flitcroft, & Cline, 2010). Handheld NDVI sensors are currently the most abundant spectral reflectance devices in turfgrass research to measure turfgrass quality (Bell & Xiong, 2008; Trenholm et al., 1999); however, their use in situ on sports fields has been minimal (Straw, Henry, Shannon, & Thompson, 2019; Straw, Samson, Henry, & Brown, 2018).

Soil moisture is the relative amount of water in a soil (Turgeon, 2011). Traditional methods use the "wet" and "dry" weight of a soil core in an equation to determine percent soil moisture (Beard, 1973). This direct methodology of measuring soil moisture is still used, but it is a time-consuming process for in situ research with large sample sizes. A quicker method becoming more common among turfgrass managers and researchers involves time domain reflectometry or capacitance sensors (Krum, Carrow, & Karnok, 2010; Leib, Jabro, & Matthews, 2003; Straw et al., 2016) (Table 2). Handheld versions allow for a rapid and indirect method of measuring soil moisture, which is reported as percent volumetric water content (Table 2).

The Toro Precision Sense 6000 (a mobile data acquisition unit) has recently been introduced in turfgrass sports field research (Straw & Henry, 2018; Straw et al., 2016, 2018, 2019). This device can simultaneously measure hundreds of penetration resistance, NDVI, and soil moisture data points while traversing a field. One advantage of mobile devices over handheld devices, other than time needed for intense sampling, is the consistency a measurement is obtained, as opposed to the various user errors that could occur with handheld devices (e.g., inconsistent height of Clegg missile drops or force of a penetrometer entering the soil between sampling locations) (Straw et al., 2016; Twomey et al., 2011).

Traction indicates frictional forces applied to a playing surface, which are typically reported as translational (i.e.,

TABLE 2 Common performance testing devices used on turfgrass sports fields

Device	Field characteristic	Sampling technique	Measurement	Notes
Clegg Impact Tester	Surface hardness (or ground hardness)	A missile of a known mass with an accelerometer on the end is dropped through a guide tube from a standard height (Clegg, 1976)	Peak deceleration on impact at the surface reported as Gmax or gravities	Number of missile drops at measurement locations vary in the literature and can influence values (Twomey, Ullah, & Petrass, 2014)
Penetrometer	Penetration resistance	A cylindrical cone at the end of a shaft penetrates the surface to a certain depth by dropping a weight from a standard height down the shaft or pushing down on the shaft manually (Orchard, 2001; Straw et al., 2016)	Depth of soil penetration (e.g., cm) or force required to penetrate a soil to a certain depth (e.g., MPa; measured by a load cell)	User can influence sampling technique that involves pushing down on the shaft manually (Straw et al., 2016; Twomey et al., 2011)
Spectral reflectance sensors	Turfgrass quality (i.e., color, coverage, density)	The sensor is pointed toward the surface, and a button is pushed on a user interface, or a trigger is pulled on The device, to take a measurement (Straw et al., 2016)	Red (R) and near-infrared (NIR) spectra are determined and a vegetation index is calculated (e.g., normalized difference vegetation index [NIR-R/NIR+R]; 0–1 scale)	
Time domain reflectometry (TDR) and capacitance sensors	Soil moisture	Metal probes at the end of a shaft are inserted into the surface to a certain depth, and a button is pushed on a user interface to initiate a high frequency pulse along the probes to take a measurement (Straw et al., 2016)	TDR sensors measure the permittivity and the velocity of the pulse and capacitance sensors measure the charge time of a capacitor (Dean, Bell, & Baty, 1987; Plauborg, Iversen, & Lærke, 2005); both determine changes in the soil dielectric constant (ε) as water fluctuates and report soil moisture as volumetric water content (%) (Leib et al., 2003)	
Studded disc and shear vanes	Turfgrass shear strength	Studs or vanes are inserted into the surface by dropping a weight or pushing down on a shaft with a torque wrench handle manually; the handle is then turned steadily until the turfgrass begins to tear (Canaway et al., 1990; Straw et al., 2018)	Force applied to cause the turfgrass to tear (e.g., Nm); typically rotational and used as indication of rotational traction	User likely influences measurements; error can be eliminated and other types of traction can be measured (e.g., linear, horizontal, vertical) with more sophisticated, uncommon devices that use hydraulic pressure (Kent et al., 2012; McNitt et al., 1997, 2004; Thoms et al., 2013)
Straight edge or profile gauge	Surface evenness	A straight edge or profile gauge of a certain length is placed along the surface (Baker, 1999; Bartlett et al., 2009; McClements & Baker, 1994); a set of rods are free to move vertically along the profile gauge and become displaced by surface undulations	The greatest deviation from the surface along a straight edge or the mean of the SD of rod displacement on the profile gauge (e.g., mm)	

linear) or rotational (Aldahir & McElroy, 2014). Handheld devices for turfgrass usually measure shear strength in relation to traction because traction gives an indication of the force needed to cause the turfgrass to fail (i.e., divot). The most common devices measure rotational shear strength, which have a two-handled torque wrench attached to a shaft with either a studded disc or shear vane foot (Canaway & Bell, 1986; Straw et al., 2018) (Table 2). Linear shear strength has been measured with less common handheld devices that pull a shaft through the turfgrass surface in an arching motion (Caple, James, & Bartlett, 2012b; Caple et al., 2012a). The Pennfoot (McNitt, Landschoot, & Waddington, 2004; McNitt, Waddington, & Middour, 1997), the Tennessee Athletic Field Tester (Thoms, Brosnan, Paquette, Zhang, & Sorochan, 2013), and the BioCORE Elite Athlete Shoe-Surface Tester (Kent et al., 2012) are examples of more sophisticated shoe–surface interaction measuring devices that can quantify various forces (e.g., linear and rotational traction, vertical impact) using hydraulic pressure (Table 2).

Surface evenness is an indication of the levelness of a playing field. It has been quantified one of two ways: by a straight edge or by a profile gauge (Table 2). The straight edge is laid along the surface and is used to record localized changes in evenness from the turfgrass surface (Bartlett et al., 2009; McClements & Baker, 1994). The profile gauge is also laid along the surface, but evenness is measured using several independently moving rods in a frame that become displaced by surface undulations (Baker, 1999; Bell & Holmes, 1988) (Table 2).

4 | ATHLETE–SURFACE INTERACTION RESEARCH

The majority of current research involving athlete–surface interactions on turfgrass has compared turfgrass and artificial turf surfaces (Galbusera et al., 2013; Kent et al., 2015; Ronkainen, Osei-Owusu, Webster, Harland, & Roberts, 2012; Sassi, Stefanescu, Bosio, Riggio, & Rampinini, 2011; Villwock, Meyer, Powell, Fouty, & Haut, 2009). The primary focus of this review is on between- and within-field variability of turfgrass sports fields; therefore, this section emphasizes results from research comparing athlete–surface interactions among, at minimum, two different turfgrass species or soil characteristics as well as findings from recent research evaluating the influence of within-field variability (e.g., changes across a single field comprised of one turfgrass species and soil type) on athlete–surface interactions. It is divided into four categories: athlete biomechanics, performance, perceptions, and injury occurrence. Studies conducted in a laboratory and in situ are discussed.

4.1 | Athlete biomechanics

Guisasola et al. (2009) combined biomechanical and soil mechanical testing to investigate the relationship between human vertical loading forces (i.e., forces that humans load, or push, onto the surface that come back up on them) and soil dynamic stiffness during running (Table 3). Nine male soccer or rugby athletes wearing standardized metal studded soccer boots ran on ryegrass grown on two soil types in a laboratory (Table 3). Although peak vertical loads were not significantly different among soils, peak vertical loading rate on the sand soil was significantly greater than on the clay loam soil. This indicates that, even when athletes experience the same vertical load on different soil types, the rate of vertical loading may be different, which could influence athlete running speed and energy use and consumption. The researchers also observed dynamic stiffness of a soil was dependent on loading rate (i.e., as a soil is loaded more quickly it becomes more stiff); sand had greater dynamic stiffness than clay, and dynamic stiffness increased when the clay loam soil was dried (Guisasola et al., 2009). Thus, vertical loading experienced by athletes can be influenced by soil stiffness, which could change over time based on soil moisture conditions.

A laboratory study involving nine male soccer or rugby participants, conducted by Stiles, Guisasola, James, and Dixon (2011), collected ground reaction forces and kinematic data (Table 3). These measures were compared during running and turning tasks (180° cutting maneuver) among ryegrass grown on three soil types (Table 3). Surface hardness and turfgrass shear strength were measured before and after participant testing on each surface (Table 3). Differences in surface hardness and turfgrass shear measurements were observed between soil types before and after running and turning tasks, indicating that these characteristics changed, even with limited use. During running, the peak vertical loading rate was greater on the sand soil, which was found to be the softest surface, compared with the clay. During turning, fifth metatarsal phalangeal impact velocity was significantly greater on the medium soil compared with the harder clay soil. No other significant differences were observed with kinematics between surfaces on either the running or turning maneuvers (Stiles et al., 2011). The loading rate and impact velocity findings were unexpected considering the biomechanical results did not support the surface hardness findings, meaning the surface with the least impact attenuation (i.e., the hardest surface) should have theoretically yielded the highest levels of loading on the human body. It was suggested that more sophisticated dynamic and whole leg stiffness measurements may offer an explanation (Stiles et al., 2011).

The influence of footwear type (soccer boots with traditional studs, boots with molded studs, and boots designed for artificial turf) and soil density on loading within the shoe

TABLE 3 Methods used in research comparing athlete–surface interactions to between- and within-variations of natural turfgrass sports field characteristics[a]

Study	Location	Turfgrass species and/or soil type(s)[b]	Athlete measurements[c]	Surface measurements
Biomechanics				
Guisasola et al. (2009)	Laboratory	Ryegrass grown in plastic trays comprised of sand or clay loam soil and maintained at 3 cm height of cut	Peak vertical force and peak vertical loading rate of nine male soccer or rugby athletes during running using a force plate	Dry bulk density; volumetric moisture content; degree of saturation; dynamic stiffness using a modified dynamic triaxial soil testing apparatus
Stiles et al. (2011)	Laboratory	Ryegrass grown in plastic trays comprised of clay, medium, or sand soil and maintained at 2.9 cm height of cut	Ground reaction forces (e.g., peak impact force, peak vertical loading rate, peak horizontal braking force using a force plate) and kinematic data (e.g., several foot, ankle, and knee angles and/or angular velocities using a three-dimensional motion measurement system) of nine male soccer or rugby athletes during running and turning	Surface hardness using a 0.5-kg Clegg; turfgrass shear strength using a cruciform shear vane; soil water content; saturation ratio
Dixon et al. (2008)	Laboratory	Sandy loam soils representing “hard” and “soft” soil surfaces based on dry bulk densities	In-shoe loading data (e.g., peak vertical force, peak vertical loading rate, peak heel vertical force) of five male subjects during running using an insole system	Dry bulk density; moisture content; surface hardness using a 0.5 kg Clegg; peak penetration resistance using a cone penetrometer; vertical component of soil stress using pressure transducers
Villwock et al. (2009)	2 outdoor football fields	Kentucky bluegrass with a small percentage of perennial ryegrass grown on a native Michigan soil and a custom engineered soil consisting of 90% sand and 10% silt and clay	N/A	Peak torque and rotational stiffness at the shoe–surface interface using a custom portable testing apparatus
Thomson et al. (2019)	1 football pitch	Sand rootzone with seashore paspalum during the summer months and seashore paspalum overseeded with perennial ryegrass in the winter months maintained at 2.5 cm height of cut	N/A	Surface hardness using a 2.25 kg and soil moisture using a ThetaProbe from five measurement locations in the field; rotational and translational traction using a portable traction testing device from twelve and six measurement locations in the field, respectively
Performance and physiology				
Sleat et al. (2016)	In situ (number of fields not clear)	N/A	Several locomotive (e.g., running), path changes (e.g., turns, v-cuts), and game events (e.g., passes, shots) of one male soccer athlete using match analysis software and manual observations from video footage	Surface hardness using a 2.25-kg Clegg from six measurement locations in a field

(Continues)

TABLE 3 (Continued)

Study	Location	Turfgrass species and/or soil type(s)[b]	Athlete measurements[c]	Surface measurements
Hales and Johnson (2019)	2 outdoor fields	N/A	Several muscle activity (e.g., vastus medialis, bicep femoris, tibialis anterior), cardiopulmonary factors (e.g., maximal oxygen consumption, heart rate, energy expenditure), and sprint and agility course times of eleven male athletes from four different sports using electromyography electrodes attached to lower extremity areas, a worn facemask gas exchange system, and digital cameras	Force reduction, vertical deformation, and energy restitution in each quadrant of the test areas using an Advanced Artificial Athlete
Perceptions				
Bell and Holmes (1988); Canaway et al. (1990);	20 football pitches	Five different soil construction types: sand, sand/soil ameliorated, slit drained, pipe drained, and native soil with no drainage	Hundreds of athlete questionnaire responses regarding opinions concerning the playing surface from a variety of Associated Football competition levels	Football rebound height and roll distance, surface hardness using a 0.5-kg Clegg, traction using a studded disc, surface evenness using a profile gauge, percent green vegetation using a Reflectance Ratio Meter, and moisture content using "wet" and "dry" weights of soil cores from six measurement locations in a field
McClements and Baker (1994)	21 rugby pitches	N/A	Hundreds of athlete questionnaire responses regarding opinions concerning the playing surface from a variety of rugby competition levels	Football rebound height, surface hardness using a 0.5 and 2.25-kg Clegg, traction using a studded disc, surface evenness using a profile gauge and straight edge, ground cover using a Reflectance Ratio Meter, grass height using a rising disc apparatus, and moisture content using "wet" and "dry" weights of soil cores from five measurement locations in a field
Aldous et al. (2005)	8 grounds	N/A	Nearly 2000 survey responses regarding opinions concerning the playing surface from 44 Australian Football League (AFL) players	Surface hardness using a Clegg, traction using a studded boot, turfgrass shear strength using a Clegg Shear Tester, moisture content, botanical composition, and thatch depth from five measurement locations in a field
Straw et al. (2019)	1 recreational field	Hybrid bermudagrass grown on native soil maintained at 2.5 cm height of cut	Walking interview responses concerning the playing surface from 25 collegiate club rugby and ultimate frisbee athletes	Turfgrass quality using the Precision Sense 6000 (PS6000), surface hardness using a 2.25-kg Clegg, and turfgrass shear strength using a Turf-Tec Shear Strength Tester from ~255 measurement locations in the field

(Continues)

TABLE 3 (Continued)

Study	Location	Turfgrass species and/or soil type(s)[b]	Athlete measurements[c]	Surface measurements
Injuries				
Orchard (2001)	10 grounds	Bermudagrass, bermudagrass overseeded with ryegrass, or ryegrass grown on a variety of soils	Anterior cruciate ligament (ACL) injuries in 571 AFL matches	Ground hardness using a penetrometer from 20 measurement locations in a field
Orchard et al. (2005)	8 grounds	Monostands of bermudagrass, kikuyugrass, and ryegrass, as well as polystands with various combinations of bermudagrass, ryegrass, and annual bluegrass	ACL injuries over 13 AFL seasons	Ground hardness using a penetrometer from 20 measurement locations in a field
Takemura et al. (2007)	13 fields	N/A	All injuries of 271 players in New Zealand premier grade rugby	Ground hardness using a penetrometer from 15 measurement locations in a field
Twomey et al. (2012a)	20 grounds	N/A	All injuries of players from 40 community Australian football teams	Ground hardness using a 2.25 kg Clegg from nine measurement locations in a field
Twomey et al. (2012b)	38 grounds	N/A	All injuries of 323 players during 434 matches in junior cricket	Ground hardness using a 2.25 kg Clegg from 13 measurement locations in a field
Straw et al. (2018)	2 recreational fields	Hybrid bermudagrass grown on native soil and hybrid bermudagrass overseeded with perennial ryegrass grown on a 25-cm sand cap with clay beneath both maintained at 2.5 cm height of cut	Ground-derived injuries of collegiate club lacrosse, rugby, and ultimate frisbee athletes	Soil moisture using the PS6000 from ∼765 to 1,295 measurement locations in the field, as well as turfgrass quality using the PS6000, surface hardness using a 2.25-kg Clegg, and turfgrass shear strength using a Turf-Tec Shear Strength Tester from ∼255 to 324 measurement locations in the field

[a]Excluding athlete–surface interactions involving head-surface impacts.

[b]Turfgrass species and/or soil type(s), athlete measurements, and surface measurements that are not included or explained in detail within the table were not reported or made clear from the cited study. The terminology used in each study are used in the table.

[c]It was not always a study's objective to compare athlete measurements and surface measurements. For example, in the biomechanics studies, surface hardness and soil moisture were sometimes used to demonstrate similarities or differences between two or more of the surfaces being investigated.

during running was tested under controlled conditions by Dixon, James, Blackburn, Pettican, and Low (2008) (Table 3). In-shoe pressure data from five male participants were collected on "hard" and "soft" soil surfaces (dry bulk density of 1460 and 1590 kg m^{-3}, respectively) (Table 3). No significant differences were observed in peak vertical force or loading rate between the hard and soft surfaces; however, the authors reported a significantly higher peak heel vertical force for the hard compared with the soft surface. Moreover, a lower peak rate of vertical loading was revealed for the molded boot compared with the studded boot, but only on the hard surface. It was concluded that specific phases (e.g., contact, midstance, propulsive) and modes (e.g., running, sprinting, cutting) of athlete loading should be considered when comparing shoe–surface interactions and that care should be taken in selecting the most appropriate shoe for the athlete and surface due to these potential interactions (Dixon et al., 2008).

Villwock et al. (2009) investigated simulated rotational traction of five football cleat patterns (10 total cleat models) on two different turfgrass playing surfaces (Table 3). The sand-based surface produced higher peak torques than the native soil, but the differences were not statistically significant. The rotational stiffness was found to be similar between surfaces. The authors noted that most peak torque values reported exceeded recommended values reported by Hirsch and Lewis (1965) and Torg, Quedenfeld, and Landau (1974). They also stated that other research had implied that lower torque values could allow more time for neuromuscular control mechanisms to commence and prevent injury (Livesay, Reda, & Nauman, 2006). Additionally, Villwock et al. (2009) observed that rotational stiffness and peak torque varied among the individual shoes and surfaces, but statistical tests were not performed comparing individual shoe interactions with either turfgrass surface.

Shoe–surface traction and grass species variation were evaluated throughout a full playing season on one soccer field in Qatar by Thomson, Whiteley, Wilson, and Bleakley (2019) (Table 3). Surface hardness and soil moisture were also measured (Table 3). Peak rotational traction was significantly different throughout the season across shoe models, shoe outsole groups, and grass species. Translational traction was not significantly different throughout the season across shoe models but was significantly different by grass species. The overseeded perennial ryegrass had the lowest rotational and translational traction values, whereas the paspalum had the highest. Statistical tests were incorporated to assess the influence of surface hardness and soil moisture on traction measurements, but no significant associations were found. Because high rotational traction has been associated with anterior cruciate ligament (ACL) injuries (Orchard, 2001; Orchard, Chivers, Aldous, Bennell, & Seward, 2005), Thomson et al. (2019) recommended choosing a shoe type with lower rotational traction that does not affect performance (i.e., high translational traction). With seasonal variations among turfgrass sports field characteristics and differences in shoe types, objective data, coupled with player perception, are important when deciding which shoe to use (Thomson et al., 2019).

4.2 | Athlete performance and physiology

Sleat et al. (2016) conducted a case study in which one male soccer athlete's sport-specific movements were recorded over 11 matches for comparison to surface hardness (Table 3). Hardness measurements obtained from a field were averaged and grouped into two categories: "harder" (68–93 g) or "softer" (41–58 g). The authors reported that high-intensity shuffling frequency was significantly greater on softer surfaces than on harder surfaces. A large effect size (Cohen's d >0.8) was recognized on softer surfaces for running, low- and high-intensity activities, headed clearances, aerial challenges, moderate intensity turns, sharp right turns, and v-cuts, which occurred more frequently than on harder surfaces. There was a greater frequency of headed shots and dribbling on harder surfaces compared with softer surfaces, and these effect sizes were large. The authors speculate that playing on a softer field is more physically demanding and requires greater muscular force, energy expenditure, and physiologic workload over the course of a match (Sleat et al., 2016). Although theses findings are preliminary, they indicate that fatigue and training load may need to be considered with different levels of field hardness.

Performance factors of 11 male athletes from four different sports were examined by Hales and Johnson (2019) on two turfgrass fields with different mechanical characteristics (Table 3). At each field, participants completed a series of agility circuits and sprints, to fatigue, a week apart. Several muscle activity and cardiopulmonary factors were evaluated (Table 3). The agility course was completed 5.2% faster on the field with greater energy return (i.e., harder surface), and the sum of muscle activity was 13% greater on the field with less energy return (i.e., softer surface). However, metabolic components were found to be not significantly different between the fields, possibly due to duration of the agility test. It was concluded that practicing and competing on surfaces with unfamiliar mechanical characteristics could predispose athletes to overuse injuries due to atypical movements and changes in neuromuscular function (Hales & Johnson, 2019).

4.3 | Athlete perceptions

Several studies have gathered athletes' perceptions of turfgrass sports field conditions, all of which used a similar approach of comparing questionnaire responses to objectively measured field data to develop playing standards in certain sporting leagues (Aldous, Chivers, & Kerr, 2005; Bell & Holmes, 1988; Canaway, Bell, Holmes, & Baker, 1990; McClements & Baker, 1994) (Table 3). Field data were arbitrarily categorized into classes (e.g., for surface hardness: 40–59.9 g, 60–79.9 g, etc.), and then each class was grouped with the number of respective questionnaire responses (e.g., "good," "satisfactory," or "poor" perception of playing quality) to develop contingency tables for comparison using chi-square analysis. In all studies, the field tests corresponded well with player's perceptions in relation to athlete–surface interactions; for example, the test for traction corresponded well with the player's opinion about the amount of footwear grip that could be obtained on the pitch. Overall, the center of the field and/or goal mouths had the majority of poor responses, whereas wings had more satisfactory and good responses. Athlete responses were most strongly influenced by turfgrass coverage (Aldous et al., 2005; Bell & Holmes, 1988; Canaway et al., 1990; McClements & Baker, 1994).

Straw et al. (2019) used a qualitative geographic information system approach to investigate if variability within a recreational-level turfgrass sports field influenced athletes' perceptions. Georeferenced NDVI, surface hardness, and turfgrass shear strength data were obtained using a sampling grid to create hot spot maps that identified statistically significant high- and low-valued areas within the field of each measured field characteristic (Table 3). Hot spot maps were combined with information gathered from on-field interviews, where questions about perceptions of within-field variability were asked of male and female collegiate club sports athletes. Areas of significantly high NDVI and low surface hardness were identified by 76% of athletes as the "best" locations in the field, and areas of significantly low NDVI and low turfgrass shear strength were identified by 84% of athletes as the "worst." They perceived within-field variations of turfgrass coverage and surface evenness (not measured) to be most important, and a majority expressed awareness of potential influences that these variations could have on their in-game behavior and strategy (Straw et al., 2019).

4.4 | Athlete injuries

Orchard (2001) conducted a penetrometer study monitoring ACL injuries from 1997 to 2000 in the Australian Football League. Ground hardness was measured from several fields before hundreds of matches (Table 3). A nonsignificant trend toward a higher risk of ACL injury on harder playing surfaces and on surfaces comprised of bermudagrass, as opposed to ryegrass, was reported. Later, Orchard et al. (2005) investigated the contribution of ground hardness, grass type, and weather variables on ACL injury in the Australian Football League from 1992 to 2004 (Table 3). Ground hardness was again not significant, but high evaporation and low rainfall prior to matches were associated with increased ACL injury. Higher injury rates occurred in bermudagrass compared with ryegrass. It was hypothesized that higher thatch levels (a layer of living and dead organic matter between the soil surface and turfgrass leaves) of bermudagrass caused football shoes of athletes to become "trapped" in the surface. This prevents the caught foot from freely rotating, which places more stress on knee ligaments (Orchard et al., 2005).

Takemura et al. (2007) used a penetrometer to measure ground hardness before New Zealand premier-grade rugby matches (Table 3). They found a nonsignificant relationship between any kind of injury incidence and ground hardness and determined no association between injury incidence and the combination of ground hardness, rainfall, and evapotranspiration on the day of a match or cumulative rainfall and evapotranspiration prior to a match. An early-season injury bias resulted, where nearly twice as many injuries occurred in the first half of the season compared with the second half. Although ground hardness decreased over the course of the season, the contribution of ground hardness to injury occurrence was not significant, indicating it was not a sole cause of the early-season injury bias in this study (Takemura et al., 2007).

Twomey et al. (2012a) monitored injury incidence of any kind in community level Australian football and linked them with ground hardness (Table 3). Ground hardness data were placed into five categories according to recommendations for Australian football grounds (Chivers & Aldous, 2004): unacceptably high (>120 g), high/normal (90–120 g), preferred range (70–89 g), low/normal (30–69 g), and unacceptably low (<30 g). Only a small percentage of injuries occurred in the unacceptable high and low hardness categories (3.7 and 0.3%, respectively). Relative to the preferred hardness range, the highest risk of injury was associated with low/normal (relative risk, 1.31; 95% CI, 1.06–1.62) and unacceptable high hardness (relative risk, 1.82; 95% CI, 1.17–2.85), with the more severe injuries occurring with low/normal hardness. Twomey, White, and Finch (2012b) monitored injury incidence of any kind over the 2007–2008 playing season in junior cricket. Thirty-eight test sessions of ground hardness measured with a Clegg took place on match eve over the season on 19 fields at 13 locations in a field that corresponded with athlete positions. Ground hardness data were categorized similar to Twomey et al. (2012a). Only one injury (out of 38 reported) occurred on a field that had ground hardness objectively measured; therefore, no statistical test could be made.

Straw et al. (2018) conducted a preliminary study introducing a methodology to evaluate the potential relationship between within-field variations of turfgrass sports field characteristics and ground-derived athlete injuries. Soil moisture, NDVI, surface hardness, and turfgrass shear strength were measured from two fields (Table 3). Hot spot maps, similar to Straw et al. (2019), were evaluated in relation to ground-derived injury locations that were self-reported by the participating collegiate club rugby, ultimate frisbee, and lacrosse athletes over 2 yr. Twenty-three ground-derived injuries were reported, and injury occurrence was significantly higher in areas of low turfgrass quality and high soil moisture (Straw et al., 2018).

5 | LIMITATIONS OF PREVIOUS RESEARCH

Research comparing objectively measured ground conditions to athlete performance and physiology, perceptions, and injury occurrence has been in situ (Hales & Johnson, 2019;

Orchard et al., 2005; Straw et al., 2018, 2019), and comparison to athlete biomechanics has primarily been laboratory based (Dixon et al., 2008; Guisasola et al., 2009; Stiles et al., 2011). Therefore, there have been minimal associations made between laboratory findings and field research. Athlete biomechanical testing is difficult in either setting due to variations between human subjects (Rennie et al., 2016; Stiles et al., 2009) yet can become increasingly challenging when attempting to incorporate a variety of turfgrass sports field scenarios. Manipulating these scenarios in a laboratory setting complicates research due to the potential differences between the laboratory and the actual field, such as ambient conditions, turfgrass density, soil moisture, and athlete intensity (Rennie et al., 2016; Stiles et al., 2009).

In situ athlete–surface interaction studies often fail to report the simplest identifiable field characteristics: turfgrass species and soil type, especially those studies that include several fields (Table 3). Even when turfgrass species and soil type are provided, two other important management practices rarely mentioned are mowing height and irrigation. Mowing height within turfgrass species could influence ground hardness and turfgrass shear strength levels (Caple, James, & Bartlett, 2011; Grossi, Volterrani, Magni, & Miele, 2004), and soil moisture strongly affects these characteristics as well (Clarke & Carré, 2017; Dickson et al., 2018). Rainfall, temperature, and/or evapotranspiration have been accounted for (Orchard, 2002; Orchard et al., 2005; Takemura et al., 2007), but supplemental irrigation has not. If only climatic conditions are reported, the reader is left speculating soil moisture conditions during periods of no rainfall, which may be extremely low in nonirrigated situations or moderate when irrigation practices are implemented. Both irrigation situations influence soil moisture and could have a strong influence on other field characteristics (Baker, 1991; Straw, Bowling, & Henry, 2017a). The failure to report mowing height and irrigation practices can perhaps be attributed to the lack of collaboration between turfgrass and sports science researchers.

Studies using objective measurements to quantify field characteristics in relation to athlete injuries have been primarily limited to ground hardness measured with a Clegg or penetrometer (Orchard et al., 2005; Takemura et al., 2007; Twomey et al., 2012a, 2012b). A significant relationship between ground hardness and athlete injury was not evident in any of these studies. Furthermore, researchers examining whether there was a relationship between Clegg readings and ground reaction forces generated by a human during a drop landing test found no significant correlation, which questions the ability of data generated by the device to relate surface hardness to "athlete safety" (Saunders, Twomey, & Otago, 2011). These results, along with the aforementioned findings by Straw et al. (2018, 2019), suggest that additional options of objectively measured ground conditions, such as turfgrass quality, soil moisture, turfgrass shear strength/traction, and possibly others, should also be explored for comparison to athlete injury, as well as other athlete–surface interactions.

Incorporation of Global Positioning System (GPS)-equipped sampling devices for spatial map creation of turfgrass sports field characteristics provides an opportunity to explore the influence of within-field spatial and temporal variability on athlete surface–interactions (Straw et al., 2018, 2019). Scientific literature describes that considerable spatiotemporal variations of surface hardness, penetration resistance, NDVI, soil moisture, and turfgrass shear strength can exist on fields of different turfgrass species and soil textures used for a number of sports at various competition levels (Caple et al., 2012b; Freeland, Sorochan, Goddard, & McElroy, 2008; Miller, 2004; Straw et al., 2016), where the degree of variability is likely dependent on field usage, construction, and management (Figure 1). Assuming that turfgrass sports field characteristics are spatially and temporally homogenous within fields is inaccurate and has not been sufficiently addressed in athlete–surface interaction studies.

Other limitations should be noted that make comparisons between studies difficult. First, only six have used objective measurements of ground conditions for comparison to injury incidence (Orchard, 2001; Orchard et al., 2005; Straw et al., 2018; Takemura et al., 2007; Twomey et al., 2012a, 2012b); therefore, comparison of results from these studies to the abundance of studies that used subjective measurements cannot be made. Second, injury definitions, type (e.g., contusion, fracture, strain), and classification (e.g., acute, overuse) as well as methods of reporting (e.g., retrospective versus as the injury occurs) have varied, obscuring comparison of results because certain injuries may be included in one study and not considered in another, or the validity of reported injuries may be questionable (Petrass & Twomey, 2013). Next, differences in data collection methods (e.g., location and number of samples) and analysis can influence interpretation of field data, potentially affecting results once comparisons to athlete data are made (Straw, Henry, Love, Carrow, & Cline, 2017b; Straw et al., 2018). Last, ample research has focused on professional level athletes that generally compete on higher-standard fields (Orchard, 2001; Orchard et al., 2005; Takemura et al., 2007), whereas minimal studies have attempted to connect ground conditions to lower level athletic competition and field quality (Straw et al., 2018; Twomey et al., 2012a, 2012b).

6 | FUTURE SUGGESTIONS

Athlete–surface interactions on turfgrass sports fields under a variety of between- and within-field scenarios are not well understood. Knowledge can be advanced with laboratory and in situ studies. Nonetheless, increased focus should be geared toward engineering and improving methodologies suitable for athlete evaluations in the field, considering these

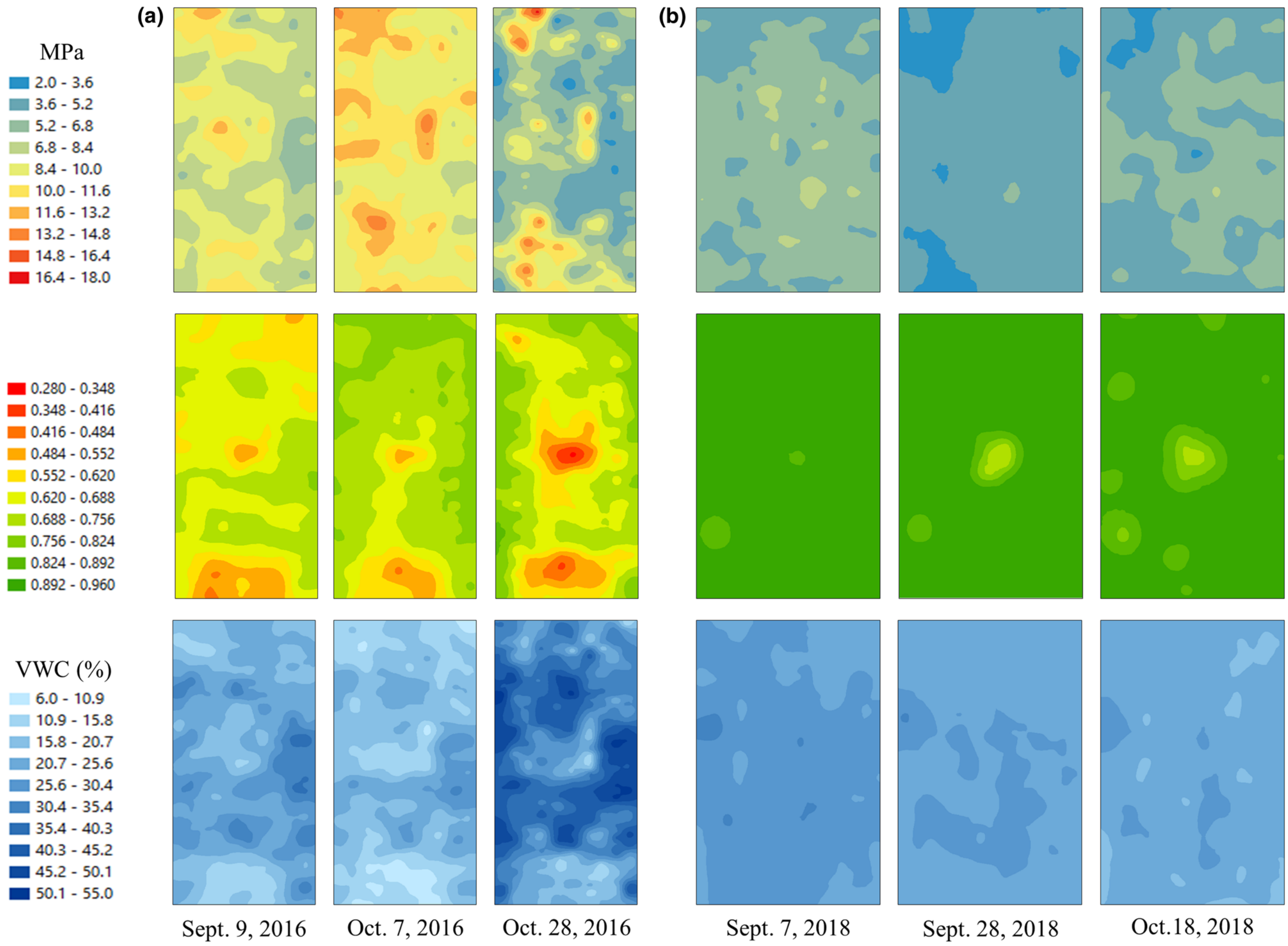

FIGURE 1 Spatial maps exemplifying between- and within-field spatial and temporal variability of penetration resistance (top row; MPa), turfgrass quality (middle row; normalized difference vegetation index), and soil moisture (bottom row; % volumetric water content [VWC]) at three dates during a playing season on fields in (a) Athens, GA, and (b) St. Paul, MN. The Athens field (49 m by 110 m) is hybrid bermudagrass constructed on a sandy loam soil (72% sand, 16% silt, and 12% clay) maintained at a 2.5 cm height of cut. It is a high school–level field used for soccer in the spring, football in the fall, physical education classes throughout the academic year, and summer sports camps. The St. Paul field (69 m by 110 m) is a 90% Kentucky bluegrass and 10% perennial ryegrass blend constructed on a sandy loam soil (76% sand, 6% silt, and 18% clay) maintained at a 1.9 cm height of cut. It is a collegiate-level field used only in the summer for soccer camps and in the fall for varsity soccer. Both fields have irrigation systems to supplement rainfall

are the actual surfaces where they compete (Stiles et al., 2009). Progress is being made with the incorporation of pressure insoles in footwear and GPS athlete tracking devices in equipment to measure loads at the foot plantar surface and athlete performance and physiology (e.g., movement patterns, distance traveled, intensity), respectively (Cummins, Orr, O'Connor, & West, 2013; Hales & Johnson, 2019; Tillman, Fiolkowski, Bauer, & Reisinger, 2002). Data from these technologies should be analyzed in relation to objectively measured field characteristics.

Recent incorporation of GPS technology into field data acquisitions entices a relatively unexplored area of athlete–surface interaction research (Straw et al., 2018, 2019) (i.e., to determine the influence turfgrass sports field variability has on athletes by combining GPS field data with GPS athlete data). Although technical limitations with GPS technologies do currently exist (e.g., measurement accuracy, quality and amount of data) (Coutts & Duffield, 2010; Cummins et al., 2013), future studies should still work toward developing consistent field sampling and data analysis strategies to better understand this phenomenon. One advantage of consistent sampling procedures and data analysis is the ability to compare findings between similar types of studies. For injury studies, adhering to generally accepted guidelines regarding injury classification and reporting is also important for study comparisons.

It is essential that studies evaluating athlete–surface interactions with turfgrass sports fields address field characteristics and management strategies in addition to their interactions, particularly, turfgrass species, soil texture and moisture, and mowing height. Several objectively measured field characteristics should also be obtained, and their impact on athlete–surface interactions should be evaluated. Perhaps data modeling approaches would be best to incorporate this information into larger-scale studies with several fields. Current challenges of including field property data are availability and cost of field data acquisition devices and their validity and reliability (Colino et al., 2017; Straw et al., 2016; Twomey et al., 2011) in addition to sampling labor. Mobile, multisensor sampling devices can be beneficial (Carrow et al., 2010; Straw & Henry, 2018), as would handheld devices that measure multiple field characteristics simultaneously (Caple et al., 2012a, 2012b); however, these are currently not abundant or readily available. Improved field data acquisition devices are also needed that better represent and correlate to human biomechanics (Saunders et al., 2011; Stiles et al., 2009). Additionally, athletes' footwear must be reported because numerous studies have confirmed that their choice of shoe or cleat can influence interactions with the turfgrass playing surface (Galbusera et al., 2013; Kent et al., 2015; Smith, Dyson, & Janaway, 2004).

Research addressing psychological aspects of athlete–surface interactions on turfgrass sports fields is needed. The unpredictability of highly variable natural turfgrass fields influence athletes' perceptions between field types and within individual fields (Mears, Osei-Owusu, Harland, Owen, & Roberts, 2018; Straw et al., 2019). As a result, perceived risk of injury and behavioral factors, such as aggressiveness or tentativeness, may be affected, which likely contributes negatively to overall athlete performance and injury occurrence (Gnacinski, Arvinen-Barrow, Brewer, & Meyer, 2017; Mears et al., 2018; Straw et al., 2019; Wiese-Bjornstal, Smith, Shaffer, & Morrey, 1998). Including field conditions into psychological assessments of individual athletes, such as Wiese-Bjornstal's (2010) biopsychosocial sport injury risk profile, could be useful for creating practical intervention strategies to improve athletes' perceptions and confidence with certain turfgrass sports field conditions.

More collaboration is needed between turfgrass and sports scientists, sports turf managers, and sports medicine clinicians. Intervention strategies and research trials should be conducted to identify surface characteristics, or combinations of surface characteristics, that most strongly influence athletes. The complexity of such studies would be extremely difficult for one discipline to attempt alone. The end goal is to develop evidence-based guidelines for turfgrass sports field management that improve the overall athlete experience under a variety of turfgrass sports field scenarios.

7 | CONCLUSIONS

This review highlights the current challenge of assessing athlete–surface interactions on turfgrass sports fields due to their between- and within-field variability. To attempt comparisons, it is crucial for future studies to fully describe key field characteristics, such as turfgrass species and soil texture. Moreover, several field characteristics and their interactions should be assessed, and standard sampling procedures are needed for in situ research. Improved technologies and procedures that assist with in situ evaluations could lead to a more robust and accurate assessment of athlete–surface interactions under a variety of turfgrass sports field scenarios. In spite of many current limitations, increased collaboration between disciplines is needed to continue moving toward the development and implementation of better research strategies that construct and manage turfgrass sports fields in a manner that improves overall athlete–surface interactions.

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