Participation in field sports is an important part of American culture, and overall levels of participation have increased dramatically in the past 20 years, as have the number of injuries to the lower extremities, especially the knees. There are an estimated 80,000 ACL tears each year in the United States alone, and approximately 50,000 ACL reconstructions are performed annually, leading to a total cost of these injuries of almost $1 billion per year. Although many ACL injuries are caused by collisions between players, the vast majority of these injuries—approximately 70%—occur in noncontact situations, including falls, sudden stops while running, or rapid changes of direction. From an injury prevention perspective, there are numerous possible causes for these noncontact ACL injuries, but a primary factor implicated in many of them is the interaction between the player’s shoe and the playing surface.

Torg and Quedenfeld were among the first researchers to document the important role that the interaction between a shoe and the playing surface has in understanding and preventing noncontact injuries. They observed that the number and size of cleats on a shoe were correlated with the occurrence of knee and ankle injuries in (American) football; less aggressive cleats produced fewer injuries. In a follow-up study, Torg et al defined a “release coefficient” based on the peak torque developed at the shoe-surface interface, to quantify the injury potential of specific shoe-surface combinations.
It was later demonstrated that the torque developed at the shoe-surface interface is further dependent on the physical distribution of material at the heel and toe of the shoe, the type of playing surface, and the weight and stance of the player. For “traditional” artificial turfs, the effective cleat engagement has also been shown to control peak torque because the playing surface can deform like a membrane and not all cleats may be fully engaged. Interestingly, there is little effect of the relative velocity between the shoe and the surface on the friction occurring at the shoe-surface interface over the range of 1 to 5 m/s.

In a landmark study, Lambson et al examined shoes with 4 different cleat designs and tracked the relative incidence of ACL tears with each design in a group of 3119 high school football players between 1989 and 1991. They concluded that the cleat design most likely to be associated with a major knee injury on natural grass used long, irregular cleats placed at the peripheral margin of the sole, with a number of smaller, pointed cleats positioned interiorly. Because the shoe-surface interface involves both the cleat pattern on the shoe and the playing surface, it can be dangerous to make generalizations as to what constitutes an “unsafe” cleat, as the performance of a given cleat may change on different playing surfaces. At the present time, the majority of field sports are played on either natural grass or a synthetic surface such as Astroturf, Astroplay, or FieldTurf (Figure 1). Astroturf, the first synthetic playing surface to be developed and widely used, is composed of coarse, monofilament knitted nylon fibers. More recently, synthetic turfs such as Astroplay and FieldTurf have been developed to more closely mimic natural grass. These playing surfaces are based on an in-fill system consisting of a mat of polyethylene fibers within a bed of sand and/or rubber particles.

Although it is clear that certain shoe-surface combinations may increase the likelihood of knee injuries, a complete understanding of the complex interaction at the shoe-surface interface remains elusive. There are limited data available on the torques produced at the shoe-surface interface for newer artificial surfaces, such as Astroplay and FieldTurf, relative to those generated on natural grass or a more traditional artificial surface, Astroturf. Moreover, little work has been conducted to
characterize the rate at which the peak torque is developed for different shoe-surface combinations, despite the acknowledged role of neuromuscular control in many types of human injury. For these reasons, the objective of the present work was to measure the torque developed at the shoe-surface interface as a function of rotation angle for 2 shoe types (a traditional soccer-style grass shoe and a turf cleat) on 5 different playing surfaces: natural grass, Astroturf, an outdoor installation of Astroplay, an indoor installation of Astroplay, and an indoor installation of FieldTurf.

MATERIALS AND METHODS

Five surfaces were analyzed for the purposes of this study: natural grass, Astroturf, 2 types of Astroplay, and FieldTurf. The natural grass field was part of an outdoor football stadium with a full-time groundskeeper, and the Astroturf field was the playing surface used in an indoor professional sports stadium with a full-time maintenance staff. The first Astroplay surface was installed outdoors, is normally used for collegiate soccer and football, and had been in place for approximately 2 years when tested. The synthetic grass of this turf is composed of tufted polyethylene fibers and contains an in-fill of 100% rubber particles (Figure 1). The second Astroplay installation consisted of 1 tray of turf (2.44 × 2.44 m) designed to be part of a removable surface for an indoor football stadium. Although the synthetic grass of this turf was identical to that of the outdoor Astroplay field, the in-fill for the Astroplay tray system contained 70% rubber and 30% sand particles. The FieldTurf surface was also 1 tray of turf (2.44 × 2.44 m) designed to be installed in the same type of tray system. This surface also had synthetic grass fibers but possessed an in-fill composed of 50% rounded silica sand and 50% rubber granules.

Each playing surface was tested using 2 different types of shoes, yielding a total of 10 shoe-surface combinations. The front portion of the sole of each shoe (the forefoot) was tested under rotation on the playing surface to mimic a change-of-direction maneuver. The first shoe was a standard soccer-style grass shoe with 12 large cleats (14.25-mm base diameter, 12.7-mm height) and 2 smaller cleats (9.5-mm base diameter, 9-mm height) (Figure 2A). The thickness of the sole was approximately 3.2 mm, and the forefoot possessed 8 large cleats and 2 smaller ones. The second shoe was a turf shoe intended for use on artificial surfaces with a cleat pattern consisting of the sole being entirely covered with numerous small rubber mounds (each with a base diameter of 9.5 mm and a height of 9.5 mm) (Figure 2B). The sole of the turf shoe was thicker than that of the grass shoe (approximately 19 mm) and possessed a larger sole area, despite the fact that both shoes were size 9.5 US and left shoes.

A custom device was fabricated to evaluate the torque developed at the shoe-surface interface and consisted of a T-shaped shaft attached to the forefoot of the shoe and was used to generate a relative rotation between the shoe and the playing surface. Compressive load and torque at the shoe surface were measured using an in-line torque-thrust sensor, and rotation was measured using a rotary potentiometer. Compressive load was applied by hanging weights on the crossbar at the top of the vertical shaft.
IBM-compatible computer. During testing, the forefoot of the shoe was placed on the bottom of the shaft such that the cleats could be pressed into the playing surface with a known compressive (thrust) load. Compressive load was applied by hanging weights on the crossbar at the top of the vertical shaft. The forefoot of the shoe was then rotated through a minimum of 75° relative to the surface (by rotating the vertical shaft) while rotation, torque, and compressive load were recorded. A minimum of 5 trials were conducted for each shoe-surface combination, and the testing device was moved between trials to ensure a “fresh” region of the playing surface was examined during each test.

Before testing of all playing surfaces, the effect of compressive load on the torque generated at the shoe-surface interface was assessed by performing 5 trials at each of 5 different compressive loads (67, 111, 200, 333, and 511 N) using both shoe types on the outdoor Astroplay field. This surface was used for preliminary testing, as it was considered the best representative of an average playing surface, between the extremes of natural grass and Astroturf. Based on these preliminary data, which demonstrated that peak torques and rotational stiffness scaled linearly with the applied compressive load, a load of 333 N was selected for all subsequent testing. This was done to minimize the number of variables affecting the mechanical response across the shoe-surface interface and to enable relative performance to be examined for the remaining 4 surfaces—natural grass, the indoor Astroplay tray, the FieldTurf tray, and Astroturf—for both shoe types.

Data from all trials were analyzed to determine the peak torque (mean and SD) developed at the shoe-surface interface for all shoe-surface combinations. The rotational stiffness for each shoe-surface combination was determined by plotting the torque versus rotation data and determining the slope over the ranges of 0° to 2° (initial region) and 2° to 10° (linear region). Within each shoe type, a 1-factor analysis of variance with post hoc Bonferroni tests was conducted within StatView (SAS Institute, Cary, NC) to assess the effect of playing surface on the peak torque and rotational stiffness (initial and linear region) developed at the shoe-surface interface. To examine differences in rotational stiffness between the shoes on the same surface, differences for each shoe-surface combination were determined by plotting the torque versus rotation data and determining the slope over the ranges of 0° to 10° (initial region) and 2° to 10° (linear region). Within each shoe type, a 1-factor analysis of variance with post hoc Bonferroni tests was conducted within StatView (SAS Institute, Cary, NC) to assess the effect of playing surface on the peak torque and rotational stiffness (initial and linear region) developed at the shoe-surface interface. To examine differences in rotational stiffness between the shoes on the same surface,
of each shoe-surface combination was determined as the maximum torque developed across the shoe-surface interface at any angle of rotation. The rate at which the torque across the shoe-surface interface increased as a function of applied rotation—representing the slope of the torque versus rotation curve—denoted the rotational stiffness of the shoe-surface combination. Based on the general response observed for all shoe-surface combinations (Figure 4), rotational stiffness was determined for 2 regions: rotational stiffness in the initial region (between 0° and 2° of rotation) and the rotational stiffness in the linear region (between 2° and 10° of rotation).

Preliminary testing revealed a strong linear relationship between the peak torque and the applied compressive load (r² values > .99) on the outdoor Astroplay field for both the grass and turf shoes (Figure 5A). The increases in peak torque with increasing compressive load were similar for both shoes types (approximately 0.3 N-m/N). The initial rotational stiffness (slope between 0° and 2° rotation) for both shoe types on the outdoor Astroplay field was also linearly related to the applied compressive load (Figure 5B), as was the rotational stiffness for both shoe types in the linear region of the torque versus rotation curve (between 2° and 10° rotation). Although the peak torques on the outdoor Astroplay field were higher for the grass shoe, the rotational stiffness for the turf shoe on the outdoor Astroplay field was consistently higher than that for the grass shoe at all compressive loads, in both the initial region (0°-2° rotation) and the linear region (2°-10° rotation) of the torque versus rotation curves. Because the data for peak torque, initial rotational stiffness, and linear region rotational stiffness all scaled linearly with increasing compressive load across the shoe-surface interface, all tests conducted for all other shoe-surface combinations were performed using a midrange value of 333 N of compressive load.

Within each shoe type, there was a significant effect of playing surface (P < .0001) on the peak torques developed across the shoe-surface interface, under a compressive load of 333 N. For the grass shoe across 5 different playing surfaces, the highest mean peak torque was found to be 38.8 N-m for the grass shoe–FieldTurf tray combination,
DISCUSSION

Across all combinations of playing surface and shoe type, the highest peak torques were developed by the grass shoe–FieldTurf tray and turf shoe–Astroturf combinations, whereas the lowest peak torques were developed on the grass surface. Early work in this area by Bonstingl et al. found peak torques in the range of 9.5 to 44.7 N·m for a toe stance (similar to the method used here) and 44.7 to 73.2 N·m for a foot stance. Their study considered multiple shoe types and surfaces, the passive action of the relevant ligaments and joint capsule, and the neuromotor control of muscles acting across the ankle, knee, and hip joints. Joint stability during sports activity is controlled by several factors, including the geometry of the articulating surfaces, the passive action of the relevant ligaments and joint capsule, and the neuromotor control of muscles acting across the joint. Because peak torques were developed after considerable rotation (and therefore time) for all shoe-surface combinations evaluated in the present work, all of these factors could be expected to serve a role in stabilizing the joint to withstand the peak torque loading. Consequently, shoe-surface combinations that develop high peak torques may put athletes at increased risk of injury, as has been reported previously. At the same time, this does not necessarily mean that every athlete or trainer will necessarily want to switch to a shoe-surface combination with lower peak torques; there is a trade-off involved. Lower peak torques may be safer, but they may also compromise performance.

shoes on hardwood floors, which suggests that the peak forces exerted on the soft tissues in the ankle and knee may be similar across many different sporting activities. Joint stability during sports activity is controlled by several factors, including the geometry of the articulating surfaces, the passive action of the relevant ligaments and joint capsule, and the neuromotor control of muscles acting across the joint. Because peak torques were developed after considerable rotation (and therefore time) for all shoe-surface combinations evaluated in the present work, all of these factors could be expected to serve a role in stabilizing the joint to withstand the peak torque loading. Consequently, shoe-surface combinations that develop high peak torques may put athletes at increased risk of injury, as has been reported previously. At the same time, this does not necessarily mean that every athlete or trainer will necessarily want to switch to a shoe-surface combination with lower peak torques; there is a trade-off involved. Lower peak torques may be safer, but they may also compromise performance.

and the lowest mean peak torque was found to be 21.0 N·m for the grass shoe–grass surface combination (Figure 6A). The peak torque developed for the grass shoe–grass surface combination was significantly lower (P < .0001) than that for all other playing surfaces. The highest peak torque observed for the turf shoe on any playing surface was 33.2 N·m for the turf shoe–Astroturf combination, and the lowest peak torque was found to be 22.0 N·m for the turf shoe–grass combination (Figure 7B). Within each shoe type, there was a significant effect of playing surface (P < .0027) on the initial rotational stiffness (between 0° and 2° applied rotation) of the torque versus rotation curve determined for the shoe-surface interface. For the grass shoe across 5 different playing surfaces, the highest initial rotational stiffness was found to be 3.35 N·m/deg for the grass shoe–Astroturf combination, and the lowest initial rotational stiffness was found to be 1.21 N·m/deg for the grass shoe–Astroplay tray combination (Figure 7A). For the turf shoe, the highest initial rotational stiffness was found to be 4.34 N·m/deg for the turf shoe–Astroturf combination, and the lowest was found to be 1.03 N·m/deg for the turf shoe–grass combination (Figure 7B). The initial rotational stiffness of the turf shoe–Astroturf combination was significantly higher than those of the turf shoe–grass (P = .003), the turf shoe–FieldTurf tray (P = .0031), and the turf shoe–Astroplay tray (P = .0041) combinations.

Within each shoe type, there was also a significant effect of playing surface (P < .0001) on the rotational stiffness of the linear region (between 2° and 10° applied rotation) of the torque versus rotation curve determined for the shoe-surface interface. For the grass shoe across 5 different playing surfaces, the highest linear rotational stiffness was found to be 1.44 N·m/deg for the grass shoe–FieldTurf tray combination, and the lowest linear rotational stiffness was found to be 0.44 N·m/deg for the grass shoe–Astroturf combination (Figure 7A). For the turf shoe, the highest linear rotational stiffness was found to be 2.37 N·m/deg for the turf shoe–Astroturf combination, and the lowest was found to be 0.33 N·m/deg for the turf shoe–grass combination (Figure 7B).
However, as neuromotor control requires a finite time to provide feedback to the musculature surrounding a joint, the peak torque developed at the shoe-surface interface may not be the only criterion by which to evaluate and compare shoe-surface interactions. Specifically, the stabilizing contribution of muscular co-contraction at a joint is also important but is limited by the reaction time of the player. For this reason, the rate at which the torque increases with applied rotation at the shoe-surface interface (the rotational stiffness) may play an important role, particularly at shorter times after initiating a pivot maneuver. Although the rotational stiffness of the shoe-surface interface has not been well explored in previous studies, in the present work the variation of rotational stiffness across all 10 shoe-surface combinations was greater than the variation observed for peak torques. In essence, the rotational stiffness of the shoe-surface interface—both initial (0°-2° rotation) and in the linear region (2°-10° rotation)—may provide a more sensitive indicator of the mechanical interaction between different shoe-surface combinations than would the peak torque developed across the interface.

If rotational stiffness is considered for the newer synthetic turfs, it can be seen that although the grass shoe—FieldTurf tray, grass shoe—outdoor Astroplay, and grass shoe—Astroplay tray combinations displayed peak torques significantly higher than that of the grass shoe–grass combination, they were not significantly different from the grass shoe–grass combination in terms of initial rotational stiffness of the shoe-surface interface. Moreover, the grass shoe–outdoor Astroplay combination was not significantly different from the grass shoe–grass field combination in terms of rotational stiffness in the linear region. When the performance of these newer synthetic turfs is compared relative to a more traditional synthetic turf (Astroturf), all of the in-fill systems (the FieldTurf tray, the outdoor Astroplay, and the Astroplay tray) combined with a grass shoe produce mean peak torques that were larger than that for the grass shoe–Astroturf combination. At the same time, these in-fill systems (the FieldTurf tray, the outdoor Astroplay, and the Astroplay tray) combined with a grass shoe produce mean initial rotational stiffness lower than that of the grass shoe–Astroturf combination. This finding indicates that the criterion used to evaluate different shoe-surface combinations may drastically alter how newer synthetic turfs are perceived in comparison with both natural grass and a traditional synthetic surface. To enable a direct comparison between shoe types across different playing surfaces—because the shoe type may be the only aspect of a shoe-surface combination that a player can control—the data on rotational stiffness are replotted in Figure 8.

A particular strength of the present work is that the portability of the testing device allowed evaluation of all playing surfaces in situ, without requiring the development of a simulated field section. In addition, both a standard grass playing surface and a traditional synthetic turf (Astroturf) were characterized, in addition to newer synthetic turfs that are experiencing more widespread use. Conversely, a notable limitation of the current study is that testing was limited to a maximum compressive load of 511 N, much less than the weight of a typical professional football or soccer player. However, the preliminary data indicate that peak torque and rotational stiffness (both initial and linear) are linearly correlated with compressive load, at least on the outdoor Astroplay surface (Figure 5). Therefore, the data presented in this work could theoretically be scaled up to reach a desired compressive load, although further experimentation would need to be performed to determine the validity of this scaling. An additional limitation is the fact that previous research indicates a potential effect of both surface temperature and surface dryness on shoe-surface interactions. Although it is a strength of the current work that all surfaces were tested in situ, the 2 outdoor surfaces (the grass and outdoor Astroplay) were tested at a somewhat higher temperature (82°F and 85°F, respectively) than those tested in the indoor football stadium (the Astroturf, FieldTurf tray, and Astroplay tray surfaces, indoor environment 73°F).

One question that remains is, What is the gold standard that shoe-surface combinations should be designed to match, and by what criteria should these combinations be compared (peak torque or initial and/or linear rotational stiffness)? If the peak torque developed at the shoe-surface interface is used to evaluate shoe-surface combinations, and the previously reported viewpoint that more torque is “bad,” then the turf shoe–Astroturf combination would be the worst and the grass shoe–grass combination would be the best. In terms of rotational stiffness, both types of shoes on the FieldTurf tray and Astroplay tray surfaces produced initial rotational stiffness that was significantly lower than when used on Astroturf surface and not significantly different than on the grass surface. However, if the overall behavior of the grass shoe–grass combination is considered ideal, the closest synthetic turf combination might be the grass shoe–outdoor Astroplay, as it had a similar peak torque and almost identical initial and linear region rotational stiffness behavior. In truth, the ideal shoe-surface combination will probably vary by sport, the age of the players, the level of play (eg, amateur vs elite), and several other factors.

It is important to note that the goal of this study was not to determine an optimal shoe-surface combination but to provide baseline characterization of these 5 different playing surfaces interacting with 2 types of shoes. It is not possible to establish safe thresholds for peak torque or rotational stiffness based on shoe-surface interface testing alone, and additional experimental, theoretical, and epidemiological efforts will be required to determine the key factors at the shoe-surface interface that may produce the safest shoe-surface system for a given activity and athlete.

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