# Characterization of Athletic Shoe-Surface Mechanics *in situ* at Loads and Rates Relevant to Game Situations

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***Abstract*** One factor related to athletic performance and the risk of certain injuries is the interaction between a player's shoes and the playing surface. The literature is lacking the description of a device and method for simulating and measuring the loads and rates generated in-situ by elite athletes during performance. A transportable device was built to quantify shoe-surface interactions through three tests that reflect generic classes of tasks: 1) a translation test (representing a "start from stop"); 2) a rotation test (representing a "twist"); and 3) a translation/drop test (representing a "cut/stop"). All three tests were performed using the cleated portion of a molded American football shoe on two types of natural grass surfaces. To assess repeatability of tests, multiple trials of each test under the same testing conditions were performed. To assess sensitivity of the device, the type of playing surface was varied. The variation among the results of repeated trials was less than the variation between the results of a given test under differing testing conditions, so the device and method were deemed to have acceptable levels of repeatability and sensitivity in the set of conditions considered.

***Keywords*** Ankle injury, foot injury, footwear, method, sports.

## I. INTRODUCTION

The interaction between a player's foot and the playing surface is of critical importance in sports for both performance and injury risk. A player's grip with the surface dictates how fast he/she can accelerate, stop, and change direction. This same interaction also may be a factor in the risk of injury to the lower extremities. Among lower extremity injuries in American football and soccer, 21%-61% are "non-contact" type injuries – injuries that do not result from direct loading of the affected limb by another player or object [1], [8], [21], [26], [34]. It has been postulated that these types of injuries may be caused by foot "entrapment" that can cause injurious stresses within the lower extremities [18], [23], [29]. Particular attention has been paid to the role of pivoting (rotational) foot entrapment in ACL injury [18], [29], although entrapment during other loading motions (*e.g.*, lateral movement causing inversion of the ankle [5]) also may be detrimental.

Many researchers have studied the interaction between various types of shoes and playing surfaces (natural and artificial) using mechanical testing. Torg et al. [29] performed one of the first of these studies, which analyzed resistance to rotational motion from different combinations of cleated shoes and playing surfaces (both natural grass and early-generation artificial turfs). The study combined observations on the peak torques measured with observations of high school American football injuries to develop recommendations on cleated shoe performance specifications. Subsequent studies have investigated shoe-surface interactions through additional rotation-type testing [3], [6], [10], [15], [19], [30], [33] and through drag-type testing, where a shoe is pulled in a linear fashion across a playing surface [7], [15]. Standards for the testing of shoe-surface interactions have been developed using both rotational and drag-type movement [2], [11].

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***Limitations of Previous Testing Methods***

Previous studies of shoe-surface interaction were limited in a few key areas. First, the vertical forces investigated were too low to represent the forces generated by some elite athletes in performance situations (*e.g.*, collegiate or professional American football players). The horizontal force and torque that can be generated by the interaction between the foot and a playing surface depend on the magnitude of vertical force acting to push the foot into the ground [19], [29]. Several studies have shown that the peak vertical ground reaction force generated by athletes tends to range from 2.5 to 3.5 of their body weight during tasks such as running, stopping, changing direction (cutting), and pivoting [9], [16], [17], [20], [28], [31]. Yet the vertical forces used in previous shoe-surface interaction studies varied from 0.06 kN [7] to 1 kN [33], a range representing a far lesser force than that of three times the body weight of a large elite athlete in a collegiate or professional-level performance situation. In addition, unlike traditional friction, the relationship between the applied vertical force and the horizontal force or torque is not linear at higher levels of force [32]. In other words, it is not possible to extrapolate low-force interaction to predict behavior at higher forces. This limitation in previous studies is particularly important for assessing contemporary playing surfaces, which may be layered and exhibit dramatically different behavior as cleats penetrate the surface at higher levels of vertical force.

Second, previous studies did not control, or considered only limited, loading rates. Natural ground consists of a combination of solid inorganic matter (e.g., sand), solid organic matter (grass and root systems), and fluid matter (water). The presence of organic matter and interstitial fluid suggests that the mechanical behavior of natural grass is loading rate-dependent. Most previous researchers, however, performed tests only at relatively slow loading rates, or did not systematically control for the loading rate (e.g., manual rotation-type tests with the rotation of the foot form applied with a torque wrench [4], [18], [29], [30].

Third, researchers performed previous studies in laboratory settings with isolated test samples of playing surfaces [3], [6], [7], [15], [18], [29], [32]. Results of such tests can be affected by the boundary conditions imposed on the test samples [22]. In addition, the properties of playing surfaces can be affected by weather conditions (such as temperature) [22], [30], moisture content [22]-[24], and maintenance practices. To account for these potentially confounding factors, it is important to study shoe-surface interactions on a playing surface installed in the environment of its actual and intended use.

Fourth, all of the previous studies listed above employed one (or both) of two specific types of testing – either a planted foot rotating on the surface, or a planted foot dragging across the surface. Neither testing method represents a maneuver commonly associated with both performance and injury – landing on one foot either following a running jump or during a running cut. Such maneuvers involve velocity components of the foot in both the horizontal and vertical directions. As a result, the interaction with the playing surface depends on both the vertical stiffness of the surface and the horizontal forces generated by the interaction between the cleated portion of the shoe and the playing surface.

Finally, interpretation of previous findings is limited by the historical use of a “traction coefficient” to describe the mechanical interaction between the shoe and playing surface. This traction coefficient is a ratio of either the horizontal force or torque on the shoe and the vertical ground reaction force. The use of a traction coefficient presents two significant limitations. First, the traction coefficient does not reflect any information about the magnitude of the loading. The absolute magnitudes of the force components are of interest in understanding the mechanics of the interaction and the consequences for athletic performance and injury risk. Second, the use of a single coefficient implies a friction-like linear relationship between the numerator (i.e., horizontal force or torque on the shoe) and the denominator (i.e., vertical ground reaction force). A shoe interacting with a playing surface under realistic loads does not exhibit such a linear relationship.

***Goal of this Study***

The goal of this study was to develop a repeatable and sensitive device and method to test the forces generated by shoe-surface interactions of elite athletes under realistic performance conditions on the collegiate and professional levels, and to assess the device and method with the cleated portion of a shoe mounted onto a

rigid foot form interacting with two natural grass playing surfaces. The specifications for this device were as follows:

1) Must be able to perform three types of tests: pre-loaded translation, pre-loaded rotation, and combined translation/drop;
2) Must be able to generate vertical forces up to 3 times the body weight of a 95 kg elite athlete (nom. 2.8 kN) in all pre-loaded testing conditions;
3) Must be portable and thus able to test playing surfaces as installed *in situ*;
4) Must perform all tests at dynamic loading rates; and
5) Must measure all components of force and motion of the foot form with acceptable levels of repeatability.

## II. METHODS

The test device (the BioCore Elite Athlete Shoe-Surface Tester, or BEAST) is shown in Figure 1. The device consists of a foot form connected to a shaft that can move horizontally and vertically along an inner support frame. For the experiments reported here, the foot form was rigid and only the cleated portion (bottom) of the shoe was tested (although other foot forms could be used if an intact shoe is to be tested). The inner support frame can move vertically on a heavy outer frame (shown schematically in Figure 2). The various degrees-of-freedom (d.o.f.) of the shaft (rotation, vertical and horizontal motion) and of the inner support frame (vertical motion) can be constrained or freed to perform each of the three tests. In all cases, motion of the foot form is powered by a high-speed pneumatic actuator connected to the shaft by a steel cable. Wheels attached to the outer frame can be lowered to lift the device for transport, and raised to allow the device to rest on the playing surface for testing. The functions of the device are explained below in the context of each of the three tests.

### *Pre-loaded Translation Test*

This test was designed to displace the foot form horizontally across the playing surface while under vertical load. To perform the pre-loaded translation test, the horizontal d.o.f. of the shaft is unconstrained, and the rotational d.o.f. is constrained. The vertical d.o.f. of the shaft relative to the inner support frame is constrained by a roller attached to the shaft, which rides in a horizontal rail system attached to the inner frame. The vertical d.o.f. of the inner frame relative to the outer frame is freed so that the entire weight of the inner frame, shaft, etc., is supported by the cleated foot form resting on the surface. The desired vertical force is achieved by attaching weights to the top of the inner frame. The cleats are pulled across the surface by venting compressed gas into the pneumatic actuator via a high-speed solenoid valve. The device inputs are the vertical pre-load and the firing pressure, and the outputs are the motions and loads on the foot form.

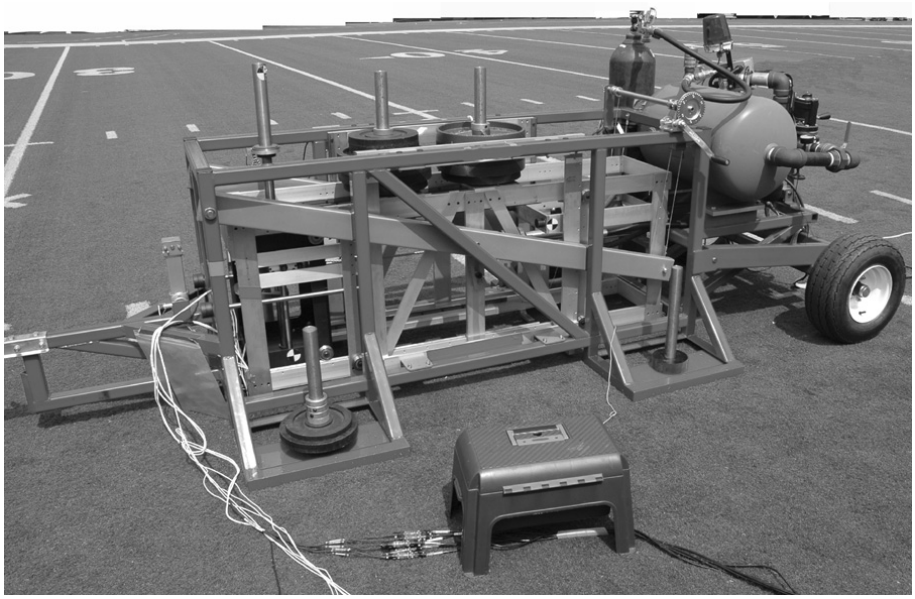

Fig. 1. Photograph of the BEAST test device configured for a translation test.

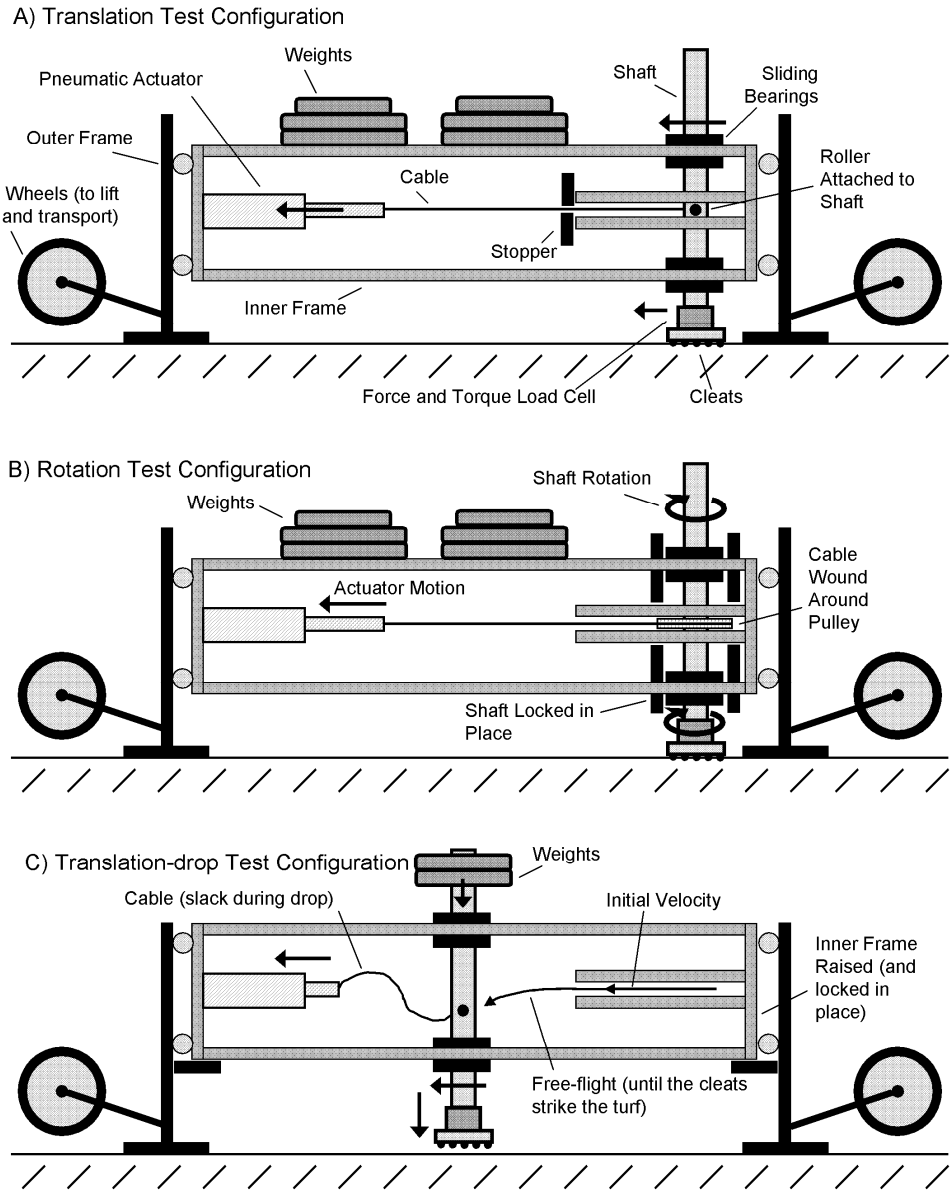


Fig. 2. Schematic depictions of the BEAST test device configured for the three tests.

In conducting the translation test, the initial vertical force on the foot form was 2.8 kN, as measured by the load cell shown in Figures 2 and 3B, and the maximum pulling force (which could be adjusted based on the pressure introduced into the actuator) was set to be the highest that the device could produce safely (approximately 4.2 kN, based on the specifications of the pneumatic system).

***Pre-loaded Rotation Test***

This test was designed to rotate the foot form on the playing surface while under vertical load. To perform the pre-loaded rotation test, the horizontal d.o.f. of the shaft is locked and the rotational d.o.f. of the shaft is unconstrained. The vertical d.o.f. of the shaft relative to the inner frame is constrained, the vertical d.o.f. of the inner frame relative to the outer frame is freed such that the entire weight is supported by the foot form, and the desired vertical force is generated by applying weights to the inner frame. The loading cable is wound around a pulley fixed to the shaft. When the pneumatic cylinder is fired (pulling on the cable), the shaft and foot form rotate. The device inputs are the vertical pre-load and the firing pressure, and the outputs are the motions and loads on the foot form.

In conducting the rotation test, the initial vertical force on the foot form was 2.8 kN, and the pulling force of the actuator was adjusted to produce a peak torque on the foot form (approximately 190 Nm) just above the

threshold needed for cleats to tear natural grass when subjected to this vertical force (approximately 150 Nm torque, based on initial trials with this device).

***Combined Translation/Drop Test***

This test was designed to launch the foot form into the playing surface with velocity components in both vertical and horizontal directions. To accomplish the combined translation/drop test, the inner support frame is raised and locked in place such that the foot form is off of the playing surface by a controlled height at its initial position. The rotational d.o.f. of the shaft is locked, the horizontal d.o.f. of the shaft is freed, and the stoppers are removed so that the shaft roller can fall off the rails during the test. The shaft is initially placed at the end of the machine (furthest from the actuator), supported above the playing surface by the inner rail. Then the pneumatic actuator is fired, pulling the shaft along the inner rail (with the foot form still above the playing surface). When the shaft arrives at the end of the inner rail, the shaft roller falls off of the rail, allowing the shaft to fall vertically until the cleats impact the surface. The lengths of the rail and the loading cable are designed such that the loading cable goes slack when the shaft falls off of the rail, allowing the foot form to continue in a state of free-flight until it impacts the playing surface. Thus, at the point of playing surface impact, the foot form has programmable velocity components in both the horizontal and vertical directions, and the foot form motion is arrested only by the interaction of the cleats with the surface. The device inputs are the mass, the drop height, and the firing pressure (which dictates the horizontal speed), and the outputs are the foot form motion and the loads on the foot form after the point of surface contact.

In conducting the combined translation/drop test, a mass of 42 kg, horizontal speed of 1.5 m/s, and drop height of 67 mm were used. These values were selected to generate a nominal vertical ground reaction force peaking at 3 kN with a duration of 100 ms when the cleated portion of the shoe is tested on natural grass.

***Cleated Foot Form***

In previous studies, there was variation in the manner in which cleats of a shoe were attached to test machines. Many studies have used whole shoes, attached to the test machines by fitting them around an artificial foot [3], [6], [14], [15], [29], [30], [32], [33]. Such a method can be affected, however, by the fit of the shoe on the artificial foot and the deformation in the shoe upper and sole. For example, Villwock et al. [33] used whole shoes in rotation tests and found that deformation in the shoe upper caused the soles to rotate under the artificial foot, thereby confounding the test results. To isolate the interaction of cleat patterns with the playing surface, other researchers have chosen to rigidly attach shoe bottoms directly to the test machine [19]. The BEAST device described in this study can accommodate either method.

One characteristic cleat pattern was studied in the tests discussed herein. Shoe bottoms were taken from size 12 shoes (right foot) designed for professional American football players. The cleat pattern was regarded as an "all purpose" pattern, intended for use either on natural grass or artificial infill turf (Figure 3A). The pattern consists of eight round molded cleats around the periphery of the forefoot (11-mm diameter at base, 8-mm diameter at tip, 13-mm length), with four smaller, shorter triangular cleats located interiorly (7-mm length), two small cleats on the anterior edge of the periphery (8-mm length), and 15 very small plastic cleats positioned laterally, medially, and down the mid-line (2-mm length).

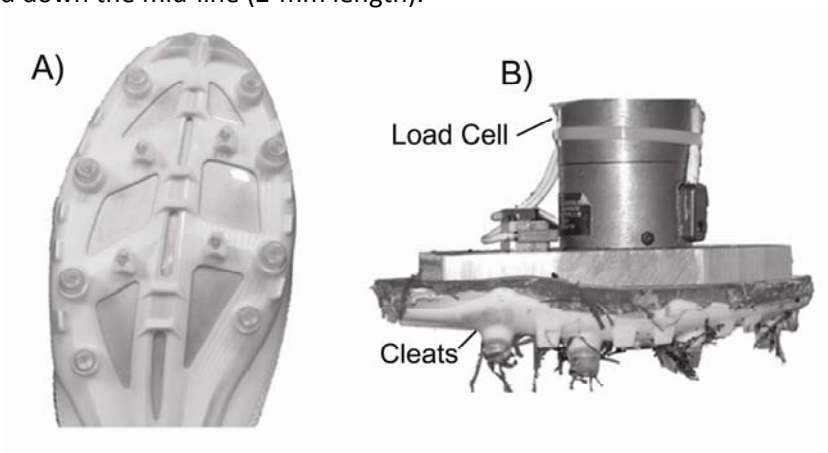


Fig. 3. Photographs of the forefoot of the molded cleat (A) and of the cleat mounted to the footform (B).

To simulate a player pushing, pivoting, or landing with a raised hindfoot [2], [25], only the forefoot sections of the cleat patterns were used. First, the forefoot portion of the shoe bottom was isolated off of new shoes. Automobile body filler then was applied to the upper surface of the samples to create a rigid, reinforced, flat surface that could be bolted to the flat plate foot form of the test device (Figure 3B). In the translation test, the cleated portion of the shoe was oriented such that the cleats dragged in a posterior direction across the surface, simulating a player pushing on the surface to move forward. In the combined translation/drop test, the cleats were rotated 90º such that the horizontal velocity vector was orthogonal to the long-axis of the shoe, simulating the leading foot of a player moving laterally across the surface (e.g., during a cut or landing from a laterally-moving jump).

***Instrumentation***

The forces and torques generated by the interaction of the cleated foot form and the playing surface were measured by a strain-gage load cell (model 1914, R.A. Denton, Rochester Hills, Michigan) mounted between the foot form and the shaft of the machine (Figures 2 and 3B). This load cell is capable of measuring the forces and torques generated in each of the three principle directions, but only the vertical force, horizontal force (in the direction of motion), and torque about the vertical axis (in the rotation test) are reported here. A linear displacement transducer (TLM series, Novotechnik, Southborough, Massachusetts) measured the horizontal motion of the foot form relative to the playing surface, a string potentiometer (161 series, Firstmark Controls, Creedmoor, North Carolina) measured the vertical motion (in the combined translation/drop test), and a rotary potentiometer (model SP22GS, ETI Systems, Carlsbad, California) measured the rotation of the foot form. All signals were recorded at a rate of 10 kHz with a National Instruments (Austin, Texas) Compact DAQ data acquisition system. All signals were filtered according to the Society of Automotive Engineers (SAE) Recommended Practice for Instrumentation for Impact Tests [27].

***Testing Surfaces and Conditions***

Two different natural grass playing surfaces, separated by approximately 1100 kilometers, were used as the testing surfaces in the study. The first (S1) was an outdoor field of new (*i.e.*, less than 1 year old) Kentucky Bluegrass. The second (S2) was an outdoor field of 13-year-old Bermuda grass. Professional, full-time maintenance staffs maintain both fields, which are used as practice fields by professional American football teams. The test device and mechanical and data acquisition equipment were transported to each of these sites by covered trailer.

The first series of experiments involved repeated trials of all three tests on S1 in late August 2009 on a warm, sunny day between 11:36 AM and 5:44 PM (ambient temperature 29.8 ± 6.7 °C, ground temperature 23.8 ± 0.8 °C, ambient humidity 36.4 ± 10.8%). A second series of repeated trials of the three tests took place on S2 in late September 2009 on a warm, sunny day between 10:39 AM and 3:27 PM (ambient temperature 25.2 ± 3.1 °C, ground temperature 20.5 ± 2.8 °C, ambient humidity 37.3 ± 7.2%).

The cleat samples were inspected between tests for damage, although no significant damage was observed. After each test, the device was lifted and moved approximately 0.7 m to a new spot on the field for the repeated trial. Care was taken to avoid testing on seams or painted areas of the natural grass playing surfaces.

## III. RESULTS

The test matrix is shown in Table 1. Thirteen tests were performed in total, including repeated trials of all three tests on both surfaces. The device performed all three tests with acceptable levels of repeatability and was sensitive to the type of natural grass playing surface (Figure 4). In the translation test, S1 allowed the foot form to displace more rapidly over the range of motion than S2 (134-138 ms vs. 148-154 ms), and resulted in horizontal force opposing the motion that was both lower in peak (2.9-3.0 kN vs. 3.1-3.2 kN) and of a shorter duration (Figure 4a). The rotation test indicated a similar mechanical difference between surfaces, with S1 allowing the foot form to rotate more quickly over its range of angular motion (96-97 ms vs. 107-116 ms) and generating an axial torque lower in peak magnitude (131-135 Nm vs. 152-158 Nm) and of shorter duration (Figure 4b). In the combined translation/drop test, S1 generated greater peak force in both the horizontal (2.4-2.6 kN vs. 2.2-2.4 kN) and vertical (4.2-4.3 kN vs. 3.3-3.4 kN) directions.

TABLE I

TEST MATRIX

| Test Identifier | Surface | Test Type | Trial |
|---|---|---|---|
| 43 | S1 | Translation/Drop | 1 |
| 44 | S1 | Translation/Drop | 2 |
| 45 | S1 | Translation | 1 |
| 46 | S1 | Translation | 2 |
| 51 | S1 | Rotation | 1 |
| 52 | S1 | Rotation | 2 |
| 53 | S1 | Translation/Drop | 3 |
| 84 | S2 | Translation/Drop | 1 |
| 85 | S2 | Translation/Drop | 2 |
| 90 | S2 | Translation | 1 |
| 91 | S2 | Translation | 2 |
| 92 | S2 | Rotation | 1 |
| 93 | S2 | Rotation | 2 |

The findings show that the variation between the results of repeated trials on a given surface was less than the variation between the results of a given test on different surfaces. This indicates that the device and method were repeatable and sensitive to the conditions considered.

## IV. DISCUSSION

### *Overall Performance*

Overall, the BEAST performed as intended. The device executed the three tests specified (translation, rotation, combined translation/drop), produced the desired vertical pre-loads (3 times the body weight of a 95 kg elite athlete), measured all components of force and motion of the foot form, and performed the tests dynamically (with speeds up to 2.4 m/s and 2400 rotational degrees/s). The device was portable and used to test natural grass playing surfaces installed at two different sites. The device produced repeatable test results when moved to a different (undisturbed) location of the natural grass playing surface during trials. The device also demonstrated sensitivity to the type of natural grass playing surface. Further, although not a primary goal of this study, this test device proved to be compatible with the ASTM F2333-04 "[s]tandard test method for traction characteristics of the athletic shoe-sports surface interface" [2].

### *Shoe-Surface Interaction (Mechanism and Description of Release)*

In previous studies, the interaction between the cleated portion of shoes and playing surfaces has been described using a single ratio of vertical force to horizontal force (or torque), commonly termed the "traction coefficient". This traction coefficient derives from the friction coefficient used when studying the forces generated when two relatively flat surfaces slide across each other, and implies that the horizontal force (or torque) needed to cause relative motion (breakaway) is linearly related to the applied vertical force.

The interaction of the cleated foot form and a deformable, grass-like surface is not governed, however, by the conventional linear concept of friction [12], [32]. The complexity of the interaction is highlighted by the fact that the combined translation/drop test exhibited different mechanisms of interaction than either of the tests that started with the foot form and surface in contact. The translation test described herein may represent the case closest to that of classic friction, but the highly transient horizontal force measured in these translation tests (see, e.g., Figure 4a) illustrates the lack of a constant, or even linear, relationship between horizontal and vertical force. Instead, as illustrated by the translation and rotation tests, the cleats dug into the small area of grass in which they were engaged. Rather than sliding across the surface, the foot form tore the patch of grass below the cleats away from the surrounding grass – reducing the resisting force and allowing the foot form to move over its entire range of motion.

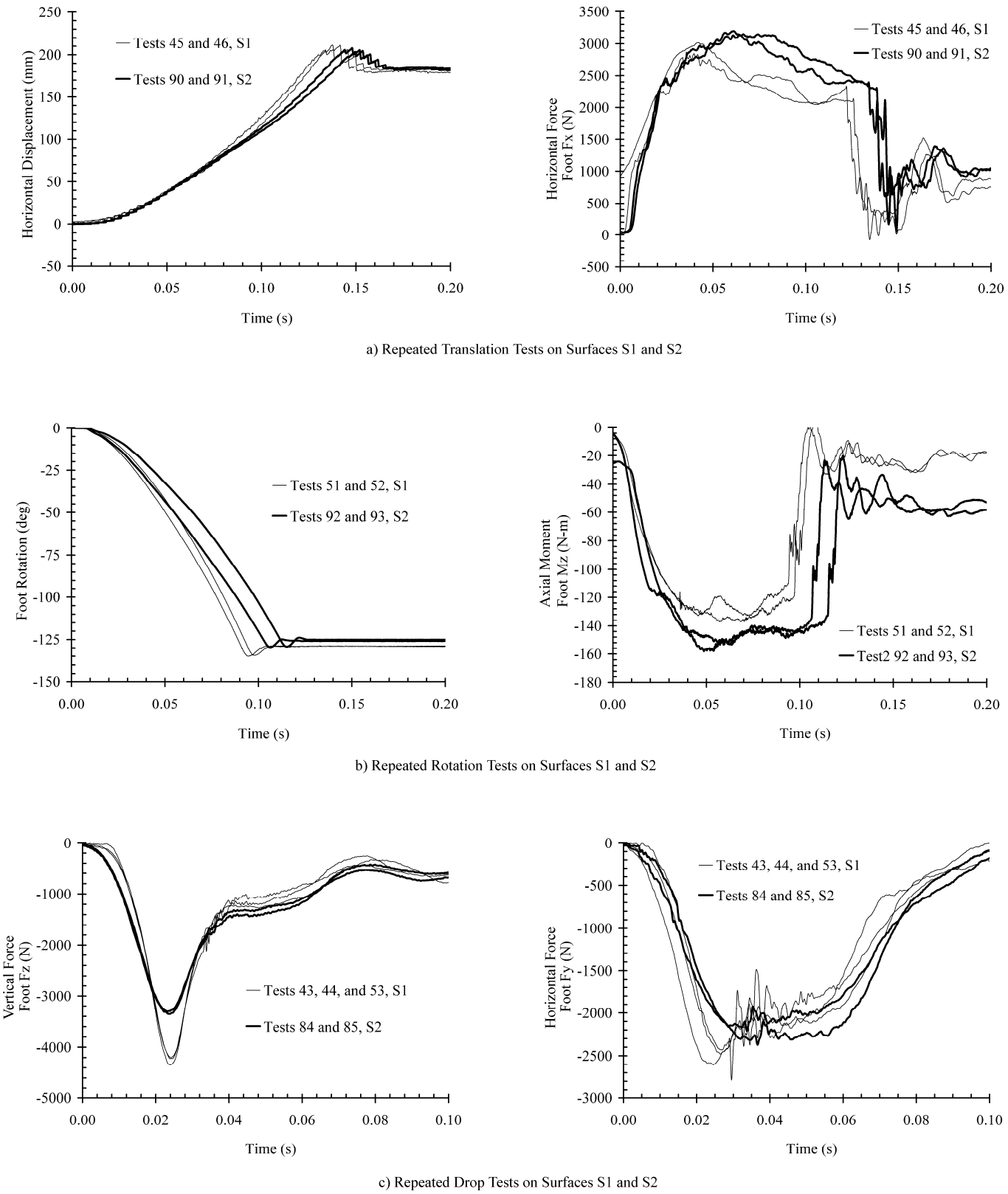


Fig. 4. Assessment of repeatability (intra-surface repeated trials) relative to sensitivity (inter-surface trials) on two natural grass surfaces (S1: 1-year-old Kentucky bluegrass; S2: 13-year-old Bermuda).

Because the mechanism of breakaway was the grass tearing away, there is likely an upper limit to the horizontal force that can be generated during the shoe-surface interaction that is dependent solely on the strength of the surrounding grass. By definition, this represents a non-linear relationship between the applied vertical force and the resulting breakaway force (or torque) that cannot be described by a single traction

coefficient. This is illustrated in Figure 5, which plots the ratio of horizontal to vertical force as a function of time in the combined translation/drop test on S1 and S2. The first important aspect of this ratio is that it is highly transient, ranging non-linearly and non-monotonically from zero to approximately 2.5. Furthermore, the characteristics of the ratio are more strongly dependent on the test condition (translation vs. drop) than on the surface being characterized.

This has important consequences in the interpretation of a particular shoe-surface interaction. In the cases illustrated in Figure 5, the ratio based on the translation tests may be interpreted to mean that surface S2 has less "traction" (see Test 90 compared to Test 45) than S1, despite the fact that S2 required a longer time for the foot form to move through its range of motion and maintained a greater horizontal force for a longer duration than S1.

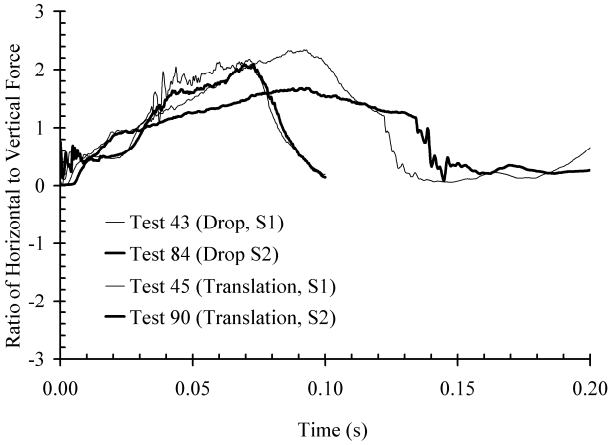


Fig. 5. Ratio of horizontal to vertical force over time for the translation test and the combined translation/drop test on S1 and S2, illustrating the limitations of a "traction coefficient" for describing shoe-surface interactions.

Reporting data in terms of normalized breakaway forces (whether in the form of traction coefficients or otherwise) masks the underlying mechanics of the interaction. It is more appropriate to report the individual components of the force vector as a function of time and to compare shoe-surface combinations based on breakaway forces at specified vertical force levels. This preserves the conveyance of both the vertical forces and breakaway forces (or torques), which are unique pieces of information that are both needed in order to understand testing conditions and compare results. This reporting practice also removes the implicit assumption of linearity inherent to the comparison of results by normalized data, and facilitates both the comparison of the observed breakaway forces to published values on the performance requirements for various tasks and the injury tolerance of the lower extremity [13].

***Future Work***

The study reported here is insufficient to assess absolute injury risk or quantitative performance metrics for the shoe-surface interactions studied. Future research should assess different shoe-surface interactions within the context of performance and injury risk, such that footwear recommendations for specific classes or conditions of playing surfaces can be made. Further study also is needed to investigate fully shoe-surface interactions under the various conditions that can occur during play. Furthermore, by showing that the mechanics in translation and drop conditions are substantially different, this study highlights the fact that observations made with a single applied vertical force should not be extrapolated to predict the mechanics that occur under other levels of vertical force. Further study should be done on the breakaway forces under the range of vertical forces expected to occur during play. The device developed here provides a means to do so. Finally, this study is limited by its use of only the forefoot portion of the cleated shoe bottom mounted to a rigid foot form. This study neglected the complexity of the entire shoe on a deformable foot in order to isolate the particular research questions of interest, but the complexity of the entire shoe is undoubtedly important for understanding both performance and injury risk.

## V. CONCLUSIONS

A portable device and method were developed to test shoe-surface interaction under the loads and rates generated by elite athletes during collegiate or professional-level performance situations. Tests were performed with one cleat pattern on two different types of natural grass playing surfaces. Repeatability was assessed and found through multiple trials of a test on different sections of the same playing surface, and sensitivity was assessed and found by comparing test results across surfaces. The device provides a means to test different cleat and playing surface combinations under various conditions. In addition, the device allows for the measurement of the vector components of all loads acting on the foot during shoe-surface interaction, and of the kinematics that result from those loads, which are required for a comprehensive understanding of the mechanical interactions that dictate performance and injury risk.

## VI. ACKNOWLEDGEMENT

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