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Abstract

Background. The interaction between a shoe and a turf surface is highly complex and difficult to characterize. Over the three decades since artificial turf was introduced, researchers have attempted to understand the traction caused by the interaction. However, some of the methodologies used for traction measurements have not capitalized on advances in currently available technology for testing and most testing conditions have not simulated realistic physiological loads.

Method of Approach. To assess the effect of test condition on traction results, the newly designed TurfBuster testing device was used to collect traction data on FieldTurf™ brand artificial turf under varying conditions. Four cleated athletic shoes were tested under eight different vertical loads ranging from 222-1780 N. The static, dynamic, and peak traction coefficient values were calculated and averaged over three trials for each shoe and condition.

Results. In all but the lowest vertical load condition, the static traction coefficient was less than the dynamic traction coefficient. There was a distinct separation found between 666 N and 888 N loading conditions for all three variables measured. Below the load condition of 666 N only one significant difference was found in all comparisons across and within shoe styles. Above 888 N multiple differences were found across shoe styles, but differences were not found within a shoe style until a load of at least 1554 N.

Conclusions. At loads below 666 N the cleats perform almost identically at all three variables measured, static, dynamic, and peak traction coefficients. At loads above 888 N, shoe traction was different among the cleat styles for all traction variables. However, at loads between 888 N and 1334 N there were no differences found within a shoe style. This implies that each shoe has no performance difference in loads representative of up to one bodyweight. Due to these results the measurement of traction characteristics between cleated shoes and FieldTurf should be conducted at a load of at least 888 N to determine differences across shoe styles and loads ranging from 888 N to at least 1554 N to determine individual shoe characteristics.

Keywords: traction coefficient, turf, static traction, dynamic traction

Introduction

Characterization of the shoe-sports surface interface has becoming an increasingly popular topic among researchers as seen by the proliferation of journal articles published within the past five years [1-6]. Studies of this nature have been ongoing since the advent of artificial turf in the 1970's [7-16]. One of the major focus areas of this research has been on the interaction between American style football cleats and the surface the cleats are used upon [1, 4, 6]. Traction or the forces involved in traction have been the primary parameters studied as it has been hypothesized that an increase in traction increases musculoskeletal loads and concomitantly injuries [14, 16]. Traction has been quantified on both artificial and natural surfaces, in rotational and translational motions, and across varying loading conditions.

The general testing concept derived by researchers has been to take a shoe or shoe form and apply a vertical load to the shoe while either translating or rotating the shoe. Most of the research has dealt with rotational motion as this is assumed to be the primary cause of ankle and knee injuries. To measure torsional loads required to rotate a shoe through a given range of motion researchers have used equipment ranging from a manual application of loads [1, 3, 8, 17] to a computer driven assembly [6, 7, 12, 13] with only one study conducted on a full turf installation [6].

Translational tests have been conducted in the same fashion as rotational with the exception that due to the large forces needed to translate the shoe a pneumatic or hydraulic cylinder applied the forces [3, 4, 12, 13]. The translational tests were conducted within a laboratory setting using a small section of turf attached to the testing apparatus [4, 9, 12] or the tests took place on small plots of turf outside the laboratory [3, 13].

The one consistency among the studies that have dealt with quantifying the shoe-surface interaction is that some form of specialized equipment has been used to collect the necessary data. The equipment has ranged from a simple pulley and cable assembly based within a lab to the PENNFOOT device, which employs hydraulics to achieve desired loads and motions on an actual field installation [9, 13]. The most sophisticated testing system described in the current literature used a 980 N (220 lb) vertical load to measure traction characteristics. However, the system was lab based and could not conduct tests above a 980 N load due to buckling of the small test surface used [4].

Though research has been ongoing since the 1970's, the majority of the early testing methodologies used are not relevant [16] and most are not up to date with technologies currently available for both data acquisition and data analysis. One of the key weaknesses of many existing studies is the use of vertical compressive forces that are lower than those created by an athlete in realistic situations [13]. Vertical loads ranging from as low as 67 N and up to 1055 N have been used, often without much justification [1, 3, 4, 13, 18, 19]. Only one study has reported any data relevant to traction characteristics at multiple load conditions [4].

The purpose of this paper is to quantify the effect of varying vertical load on the shoe-turf traction characteristics on an actual artificial turf installation and describe the equipment and technology required to consistently and accurately make these types of measurements.

Materials and Methods

Test Apparatus

The testing apparatus, known as the Boise State TurfBuster, was developed to provide a testing system that utilized the latest data acquisition technology and removed any foreseeable operator error from the testing procedures (Figure 1). The TurfBuster design includes a fully automated testing system that controls translational and rotational motion as well as loading conditions with minimal input from the operator.

The TurfBuster consists of three main assemblies: 1) the outer frame, 2) the inner frame, and 3) the dynamic motion assembly. The outer frame is the support structure for both the inner frame and dynamic motion assembly and the housing for the compressed gas tanks. The outer frame also has wheel attachments for easy movement of the TurfBuster on the field surface. Within the outer frame are the inner frame assembly and the dynamic motion assembly, along with the sensors and pneumatic cylinders that provide for, and control, any predefined motion of the shoe relative to the surface. The inner frame allows for vertical motion of the shoe and the application of the vertical load to the dynamic motion assembly. The dynamic motion assembly maintains all predefined shoe and ankle positions and guides the linear and rotational motion of the shoe throughout any series of tests. The shoe orientation can be adjusted in 15° increments from 90° of external rotation to 90° of internal rotation to mimic motions such as a side cut. The ankle angle can also be adjusted from 90° of plantarflexion to 20° of dorsiflexion and from 30° of inversion to 30° of eversion. These angles have continuous adjustment throughout their ranges.

Horizontal motion of the footform is created by a single pneumatic cylinder controlled programmatically through an automated pressure regulator and flow controller. To control the horizontal velocity, the pneumatic cylinder is fitted with a linear transducer that gives position feedback. The shoe velocity is then calculated by a point-to-point numerical differentiation algorithm. The horizontal force resisting motion of the shoe is measured by a load cell connected in-line with the pneumatic cylinder and dynamic slide assembly. The horizontal cylinder can provide motion to either pull (athlete accelerating) or push (athlete decelerating) a shoe. For example, by pulling the shoe the frictional force is recreated so that it mimics the frictional force caused by an athlete accelerating, shown in Figure 10.

Vertical motion and loading is also created through a single pneumatic cylinder. Unlike the horizontal cylinder, the vertical cylinder is controlled solely by a pressure regulator. Since the vertical velocity is not a variable of concern there is no linear transducer. To measure the vertical load applied to the shoe, the dynamic slide assembly houses a

load cell which is connected directly to the ankle shaft. The load cell is also used as a feedback sensor to control the user defined vertical load.

For rotational motion a single removable pneumatic cylinder is connected to the ankle via a moment arm to provide the necessary torque for motion. The rotational cylinder is controlled with the same system as the horizontal cylinder. A selector valve routes the compressed gas to either the rotational or horizontal cylinders. The rotational cylinder is designed to provide either 45° of internal or external rotation of the shoe. A torque cell is mounted directly to the ankle shaft to measure the rotational loads applied to the shoe.

Control System

The control system on any automated system is of extreme importance in creating predefined and repeatable motion. The specifics of the control system can also become important when attempting to compare study results between different research groups. The TurfBuster uses a commercially available software package for data acquisition and system control (LabVIEW software, National Instruments, Austin, TX). Through the software several Proportional-Integral-Derivative (PID) controllers were used to control the user-defined motion or load condition. Few controllers can match the simplicity, functionality, and ease of use as the PID control [20]. However, the major problem associated with the PID control is tuning. Slight adjustment in one of the three gains, proportional, integral, or derivative, can result in either an improvement in stability of the system or a major degradation (Figure 11). If these changes occur while attempting to control either the vertical load or horizontal velocity differences in traction will be manifested [20].

Working in conjunction with, and as part of, the control system, the data acquisition (DAQ) system is responsible for accurately collecting and converting the raw analog signals of the sensors into a digital signal to be processed. The TurfBuster uses a 16-bit DAQ card capable of up to 200,000 samples/second (National Instruments DAQPad 6025e).

Variable Definitions

In determining the performance characteristics of turf surfaces, researchers have generally reported static and dynamic traction forces or coefficients based upon the model of Coulomb friction, even though many of the assumptions of Coulomb friction are violated in the case of turf-shoe interactions. The following definitions were used to determine the dynamic, static and peak traction variables (Figure 12).

1. Static Traction Coefficient- the ratio of the horizontal force resisting motion of an object and the normal force created by the object's weight and applied load at the instant before motion occurs.
2. Dynamic Traction Coefficient- the ratio of the horizontal force resisting motion of an object and the normal force created by the object's weight and applied load while the object is moving at a constant velocity. In this study, the dynamic traction coefficient was computed as the average of the traction coefficient over a 2 cm distance while sliding at a constant velocity of 10 cm/s.
3. Peak Traction Coefficient- The peak value of the ratio of the horizontal force resisting motion of an object and the normal force created by the object's weight and applied load.

Test Protocol

Variations in traction characteristics due to changes in the vertical load applied were quantified using four different sport shoes on a single artificial turf surface. FieldTurf (FieldTurf Inc., Montreal, Quebec, Canada) was chosen as the testing surface because it accounts for approximately 75% of the artificial surfaces used in National Football League stadiums. Four representative shoe types were selected to encompass the range of different styles currently available to football players. The specific shoes tested were (Figure 13)

- Adidas Scorch 7 Fly Low – Molded conical cleat
- Nike Air Zoom Super Bad – Molded conical cleat on forefoot with blade cleats on the hindfoot
- Reebok 4 NFL Speed III – Detachable conical cleats with fin style molded cleats on the forefoot
- Nike Air Zoom Super Speed – Detachable conical shape cleat

All shoes tested were men's size 12 and were kept complete and in original sale condition for testing. Previous studies have used a rigid artificial foot model that required alterations to be made to the shoe [12, 13]. Alterations in one study went as far as removing all but the forefoot portion of the shoe [1]. Each shoe was fitted with a rigid steel foot and ankle shaft with the remaining void in the shoe filled with an acrylic resin fortified grout. The ankle shaft, foot mold, and shoe were aligned to create a neutral ankle joint position. The foot position was chosen to engage all the shoe cleats as would occur under the condition of a hard stop by an athlete.

All testing was done in the Boise State University Caven-Williams indoor practice facility. Each shoe was tested in 8 different loading conditions ranging from 222 N to 1780 N in 222 N (50-400 lbs, by 50 lb increments) increments. The shoes were tested three times at each load. After each trial the TurfBuster was moved to a new location on the field. All shoes were tested at a horizontal velocity of 10 cm/second over a 20 cm displacement. All measurements were collected at a rate of 250 Hz and post-processed using Matlab software.

After determining the individual magnitudes of static, dynamic, and peak traction coefficients for each trial, the results were averaged together. A one-way ANOVA was performed to determine any differences across the shoes with a Tukey post-hoc analysis. For comparison within each shoe across the load conditions a repeated measures ANOVA was performed with a pair-wise T-Test post-hoc using a Bonferroni sliding scale adjustment for multiple comparisons.

Results

Traction coefficients varied with both load and test configuration. Mean static, dynamic, and peak traction coefficients for each loading condition are summarized in Figure 14. For all four shoes tested, the static traction coefficient was smaller in magnitude than the dynamic traction coefficient in all except the lowest load condition (222 N). This is a contradiction to the classical theory of Coulomb friction in which static frictional coefficients are always greater than dynamic frictional coefficients. Another interesting feature of the data shown in Figure 6 is a distinct change in the slope of the traction vs. load curve between 666 N and 888 N. The change in slope of the traction curve was seen in all shoes tested.

The effect of the load condition seen in the data in Figure 14 is also demonstrated in the shape of the traction coefficient vs. shoe displacement curves (Figure 15). The test data collected at 222 N demonstrates the performance of a shoe that was below the 666 N cutoff, while the other curve was collected from a cleat above the 888 N cutoff with a compressive force of 1780 N. The major difference between the two is at the instant the static traction coefficient was recorded. The static coefficient for the below 666 N load is emphasized by a distinct peak followed by a drop-off after which the shoe quickly loads to the peak traction coefficient. For the loads above 888 N the static coefficient is not followed by any drop-off and the curve climbs more gradually to the peak traction coefficient value.

The statistical analysis of the shoes further demonstrates the difference in loading patterns above and below the above mentioned cutoffs. At 666 N and below there were only 2 significant differences out of 9 (22%) comparisons made across shoes and loading conditions. The difference occurred at a load of 222 N between the SuperBad and SuperSpeed shoes for dynamic and peak traction coefficients ($p < 0.05$). At 888 N and above there were multiple differences found among the comparisons, 12 out of 15 (80%). Most of the differences incorporated either the SuperBad or SuperSpeed shoes.

Statistical results within each shoe were conducted for the load conditions at 888 N and above. For all four shoes there were no statistical difference in any of the load conditions or any of the traction variables between 888 N and 1332 N. The only statistical differences were found between high and low loads. For example, some of the shoes displayed a difference between the 1779 N and 888 N loads in all three traction variables.

A final interesting result from the data is in regards to the shoe velocity-traction relationship. Between the instants that the static and peak traction coefficients were recorded, the traction coefficient increased rapidly to the peak magnitude while the velocity oscillated around 8 cm/s (Figure 16). The oscillations are due to the PID controller attempting to maintain the setpoint velocity of 10 cm/s and are not a response to turf conditions. Later, as the traction coefficient decreased from its peak magnitude the shoe underwent acceleration due to the large horizontal

force applied to move the shoe through the point of peak traction causing the velocity to increase from the 8m/s to 60 cm/s. Once the control system recovers from the quick change in horizontal forces, the shoe again reaches a point of constant velocity where the dynamic traction coefficient is calculated.

Discussion

Of all the literature that has been written regarding the interaction between a shoe and turf surface, only a few have reported an actual static traction value [12, 13]. The majority of the other studies report only the horizontal force required to displace the shoe and in some cases do not define the point in time the data is reported for [4, 9]. However, for the studies that do report a static traction coefficient the value is comparable to the average value found in this study. For example, in the study conducted by McNitt et al the testing was conducted at a load of 529 N and the static coefficient ranged from approximately 0.8 to 1.3 depending on the shoe and surface combination [13]. As seen in Figure 14 these values correspond closely with the static traction values measure in this study even though different shoe and surface combinations were tested.

In classical Coulomb friction the static friction coefficient is always greater than the dynamic friction coefficient. In our results, all load conditions except one produced a static traction coefficient that was less than the dynamic traction coefficient, further proving that the shoe-surface interface does not follow the traditional idea of static and dynamic friction. However, the one test that resulted in static traction being greater than dynamic traction was conducted at 222 N, the lightest load condition tested. This result corresponds to Bowers who reported the dynamic friction coefficient to be at least 90% of the static friction for a loading condition below 62 N [9].

A second interesting finding was the decrease in the traction coefficient as the vertical load applied increased. Since the traction coefficient is defined as the ratio of the horizontal force over the vertical force, this means that as the vertical force increased there was a relatively small increase in the force resisting the motion of the shoe. The decrease in traction coefficient occurs both below 666 N and above 888 N for all shoes. However, there is a difference in the rate of decrease of the traction coefficient for the two conditions. The change in rate may represent the difference between a partially and fully engaged cleat which occurs below 666 N and above 888 N.

Further evidence for measuring traction characteristics at loads of 888 N and above is demonstrated by the statistical results of the comparisons across the four cleat styles. At loads below 666 N the cleats perform almost identically at all three variables measured, static, dynamic, and peak traction coefficients. The only difference seen at the lower load conditions was at 222 N where the shoes' performance is most like classical friction. While there were performance differences seen across the shoes at all loads of 888 N and above, there were only statistical differences within each shoe at loads of 1554 N and 1779 N. This implies that each shoe has no performance difference in traction characteristics in loads representing one bodyweight (up to 300 lbs). Above the one bodyweight range the shoes themselves begin to react differently to the turf surface.

Analysis of our data also suggests that any device used to measure traction must have a sensor capable of measuring displacement of the shoe for two reasons. First, the static traction coefficient should be recorded at the instant before relative motion between the shoe and the surface occurs. Without a sensor measuring movement or displacement this instant cannot be identified. Recording time instead of displacement does not give an adequate identifier for static traction because a change in the loading rate of the horizontal force used to move the shoe or the amount of force resisting motion can yield differences in the time history of the trial. Second, the dynamic traction coefficient is defined by a period of constant velocity motion. Without a displacement time history, the velocity of the shoe cannot be calculated and thus the dynamic traction coefficient cannot be reliably determined. In addition, the properties of the shoe-surface interface may be velocity dependent and therefore without velocity control of the shoe there can be differences in traction coefficients if the shoe velocity is not kept consistent between different shoes and surfaces. The rationale for a displacement sensor can be extended to rotational traction measurement as well.

These results are currently limited to a single installation of FieldTurf. Based on previous research not included in this article there can be large differences in traction characteristics at different FieldTurf sites due to maintenance, age, and infill mixture. To fully define future load conditions for the measurement of traction characteristics the current study will be expanded to include multiple FieldTurf installations as well as other artificial and natural turf surfaces.

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Figure 1: Boise State University TurfBuster

Figure 2: Depiction of the TurfBuster recreating the required friction force during a specified motion

Figure 3: Block diagram of a generic PID controller

Figure 4: Static, Peak, and Dynamic traction variables defined

Figure 5: The four shoe models tested: A) Adidas Scorch 7 Fly Low, B) Nike Air Zoom Super Bad, C) Reebok 4 NFL Speed III Low, D) Nike Air Zoom Super Speed

Figure 6: Average traction coefficient vs. vertical load condition across all loading conditions for the Static, Peak, and Dynamic traction variables

Figure 7: Representative Traction curves below 666 N and above 888 N

Figure 8: Traction coefficient and shoe velocity for a representative trial



Figure 9: Boise State University TurfBuster

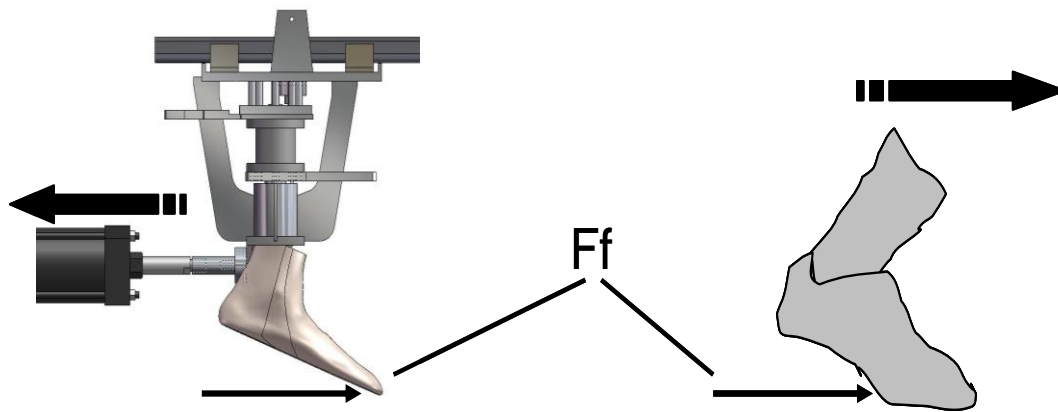


Figure 10: Depiction of the TurfBuster recreating the horizontal friction/traction force that enables an athlete to accelerate

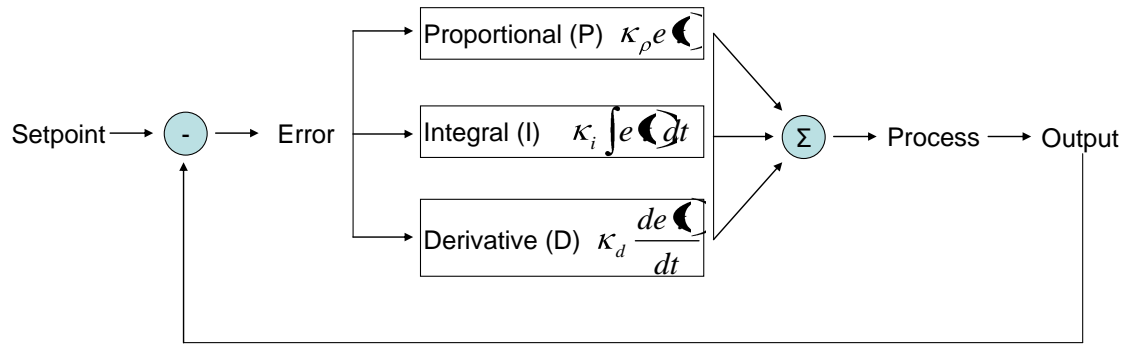


Figure 11: Block diagram of a generic PID controller

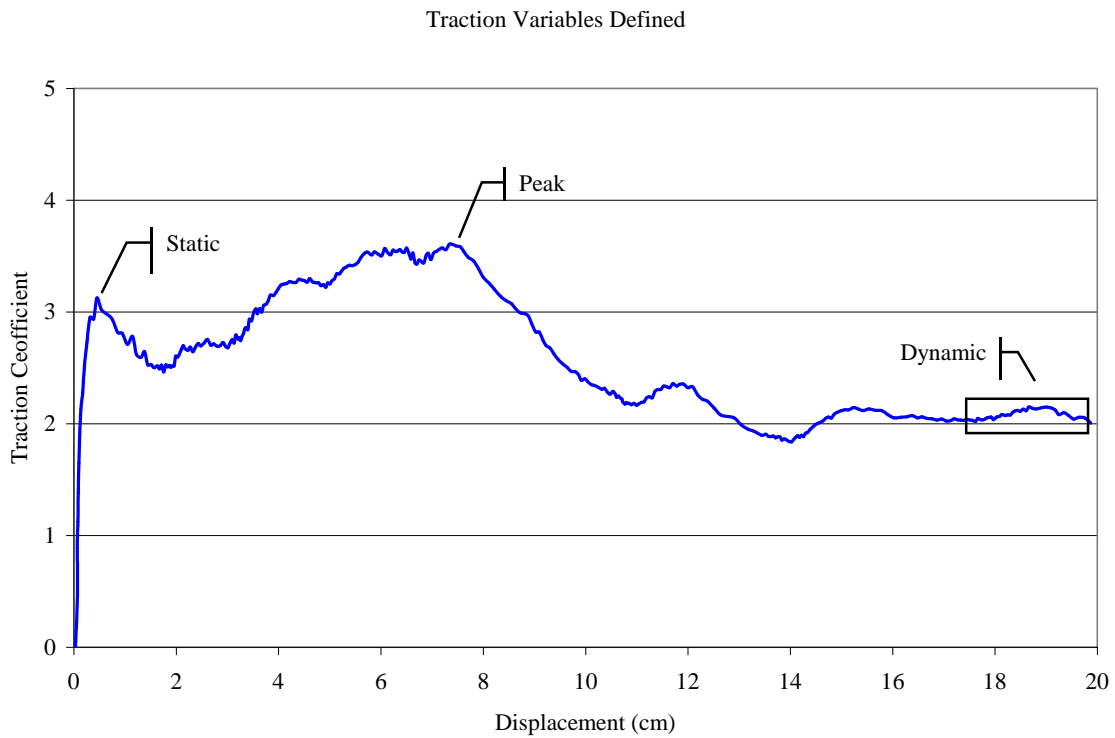


Figure 12: Static, Peak, and Dynamic traction variables defined



Figure 13: The four shoe models tested: A) Adidas Scorch 7 Fly Low, B) Nike Air Zoom Super Bad, C) Reebok 4 NFL Speed III Low, D) Nike Air Zoom Super Speed

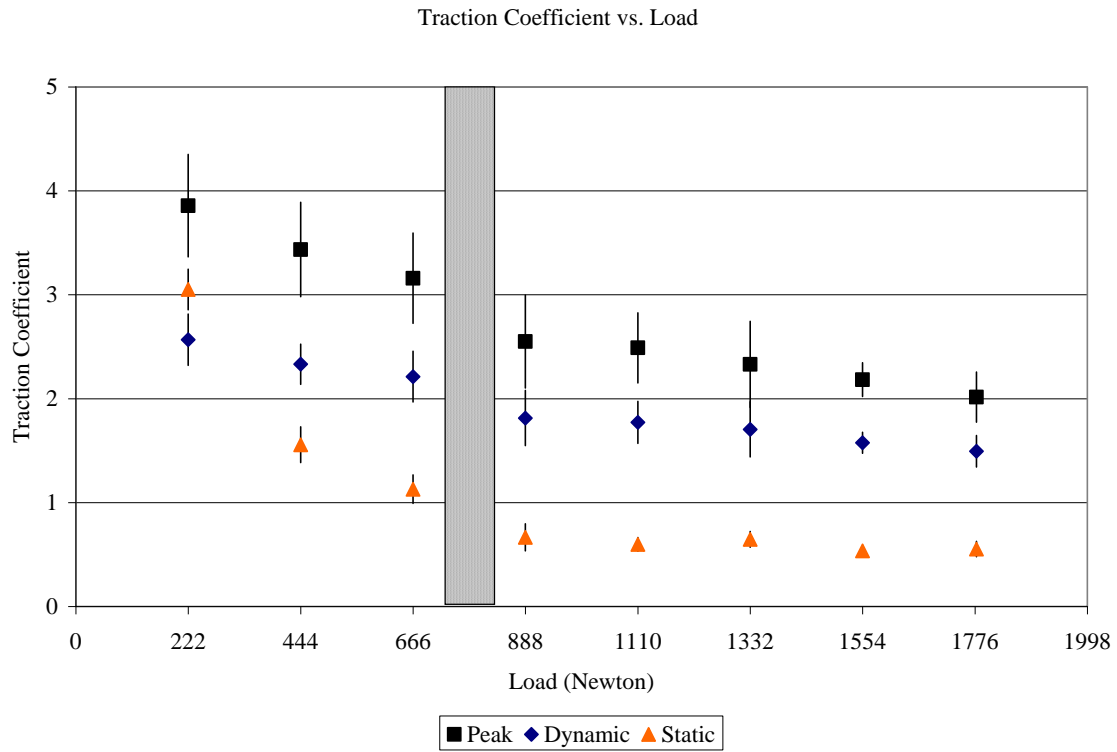


Figure 14: Average traction coefficient vs. vertical load condition across all loading conditions for the Static, Peak, and Dynamic traction variables

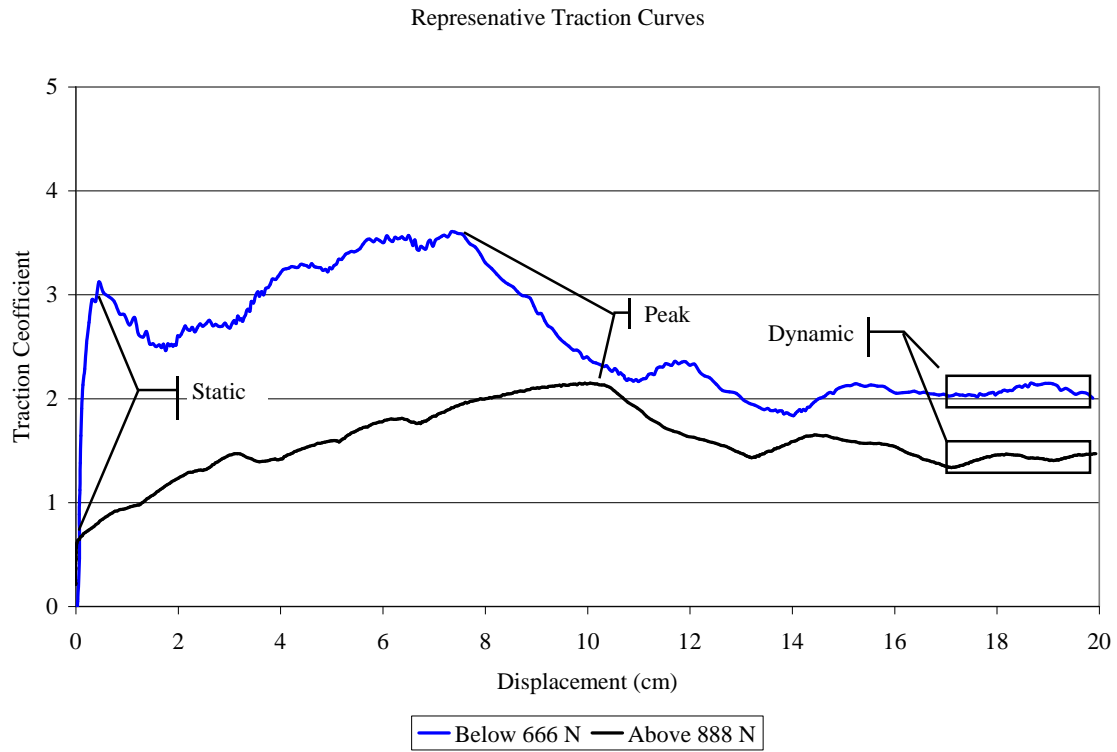


Figure 15: Representative Traction curves below 666 N and above 888 N

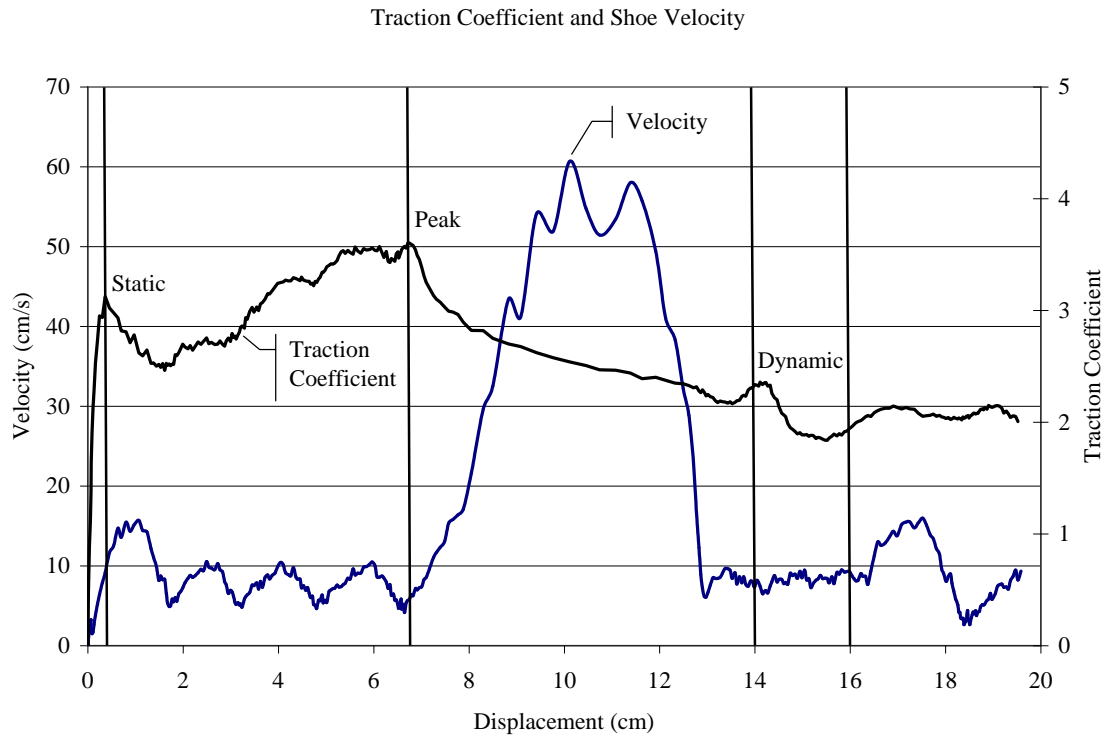


Figure 16: Traction coefficient and shoe velocity for a representative trial