DEVELOPMENT AND EVALUATION OF A METHOD TO MEASURE TRACTION ON TURFGRASS SURFACES

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DEVELOPMENT AND EVALUATION OF A METHOD TO MEASURE TRACTION ON TURFGRASS SURFACES

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ABSTRACT

Traction on and hardness of sports turf are surface characteristics that can affect both playability and safety. Traction as it relates to field safety involves the athlete, studded footwear, and the turf. Traction involves two types of forces: those acting in a vertical manner that compress the turf and those that act horizontally and produce a shearing or tearing effect on the turf. The objectives of this research were to develop an apparatus and operating procedure to measure the horizontal forces associated with traction, to determine how species, cutting height, and amount of loading weight influence traction, and to compare this device to others used to quantitatively measure traction.

The apparatus, termed PENNFOOT, consists of a framework that supports a leg and foot assembly that can be used to measure both rotational and linear traction using different footwear under various loading weights. Using a hydraulic system with a hand pump, the force required to cause foot movement is measured at various degrees of rotation or linear distance traveled. Although various methods have been used to measure traction, PENNFOOT is an improvement over existing methods because it allows versatility in the selection of loading weights and footwear type for surface evaluations.

Tractional forces, using PENNFOOT, were found to increase as the sole was rotated or moved in a linear fashion, and peaks occurred at 30° and 3.81 cm, respectively, for rotational and linear traction. At these peaks linear and rotational traction were well correlated (r=0.94). Tall fescue (Festuca arundinacea Schreb.) and Kentucky bluegrass (Poa pratensis L.) provided the highest traction values while creeping red fescue (Festuca rubra L. spp.) provided the least. Intermediate values were obtained with perennial ryegrass (Lolium perenne L.). Rotational traction was unaffected by cutting height; however, higher linear traction values were associated with lower cutting heights. Amount of loading weight also proved to be significant with the heaviest loading weight (102.0 kg) providing the highest traction.

Comparisons of methods obtained with a shear vane and a replica of Canaway and Bell's traction measuring device (Apparatus A) with PENNFOOT on different grass species and cutting heights (3.8, 5.1, and 6.4 cm) provided low correlations. Neither Apparatus A (r=0.07) nor PENNFOOT (r=0.02) correlated well with the shear vane. Apparatus A and PENNFOOT detected different species as providing the highest traction values.

To obtain a greater range of traction values for the three machines, measurements were taken on bare soil, thin turf (50% cover), a compacted turf roadway (75% cover), and tall fescue and Kentucky bluegrass plots each having 100% cover. Greater ranges of values were obtained with the PENNFOOT and shear vane than with Apparatus A. Low correlation values among the three machines indicated that they were detecting different turf/soil characteristics. Differential penetration may play an important part in results obtained.

Although more work is needed on the turf and soil characteristics that influence traction, the PENNFOOT with its versatility seems appropriate for traction evaluation at this time.

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INTRODUCTION

The majority of outdoor sports are played on natural turf athletic fields. The surfaces of these fields should not only enhance player performance, but should also provide a degree of safety for the player. Athletic field safety involving the players and their interaction with the field is largely dependent on the hardness and degree of footing(traction) associated with the field. The design, construction, and general maintenance of the existing field all have an effect on the playability and safety of the field. To ensure safety and playability, a field should consist of a dense, uniform stand of wear tolerant grass grown on a smooth, well-drained growing medium. When these conditions exist, the surface of an athletic field can absorb some of the impact from a falling player and provide adequate traction. The amount of traction should be at a level that benefits the player's actions. Too little or too much traction may be a hindrance to performance or cause injury.

There are three basic causes of injuries that can occur during an athletic event: injuries due to player/player contact, injuries caused by impact on the field surface or other objects, and those resulting from an improper footing or traction condition. Combinations of these causes may also occur. Of these injuries, those associated with traction often may be solely attributed to a field condition, whereas injuries related to hardness are usually initiated by player/player contact.

The player's interaction with the surface with respect to traction involves two types of forces. Those acting in a vertical manner that compress the turf and compact the soil and those that act horizontally and produce a shearing or tearing effect on the turf. The horizontal forces can be further divided into linear and rotational. Linear traction exists when an object or player's foot moves in a straight forward, side to side, or backward motion, whereas rotational traction occurs when the player's foot changes direction and is rotated about an axis.

Various methods have been developed to measure horizontal forces associated with traction. The difference among these methods is the design of the testing surface and it's interaction with the turf. How these apparatuses interact with the turf may or may not affect the magnitude of force measured. The method that can best simulate the interaction of an athlete's foot in contact with the turf will probably provide the most accurate measurement of traction.

Factors that may affect traction on an athletic field are the shoe type, amount of weight applied on the shoe, and existing turf conditions, which are highly associated with cultural practices. The amount of influence that these cultural practices and associated field conditions may or may not have on traction has not been well documented.

All athletic fields provide an area upon which sporting events can be played. Unfortunately, the playability and safety among some fields are not satisfactory. For this reason, research on field hardness and traction is needed so that conditions can be improved. Before traction conditions can be improved, the factors that influence traction have to be characterized. The goal of this research was to develop a testing apparatus and procedure that will reliably measure traction on natural turf, allowing the characterization of traction to take place in the future.

LITERATURE REVIEW

The literature review has been divided into three sections: a section describing traction and its associated properties, a material tests section describing previous traction research, and a section summarizing the results of the material tests.

Traction and Its Associated Properties

The terms used to describe how a foot wearing a studded shoe reacts with natural grass are numerous. Gripability, shear strength, friction, abrasion, and traction have been used interchangeably in the past. Bell et al.(1985) proposed that the term traction should only be used when footwear containing studs, spikes, or cleats are in contact with the turf.

When a body slides on another body, the force tangent to the contact surface that resists the motion of one body relative to another is defined as friction (Higdon and Stiles, 1951). The coefficient of friction is defined as the ratio of the maximum frictional force to the normal force between the two surfaces (Higdon and Stiles, 1951). These terms are generally associated with two smooth, rigid surfaces, e.g. wood on steel. The irregularities associated with studded footwear and the disturbance in the turf surface created by the cleats, negate the application of the properties associated with friction. In order to describe the resistance properties associated with natural turfgrass, variations of friction testing procedures had to be developed.

Traction, like friction, can be subdivided into linear and rotational traction. Linear, or translational, traction occurs when the shoe moves across the turf in a linear manner, while rotational traction exists when the shoe is rotated on the turf surface. In a review on the methods used to describe both types of traction, Nigg (1990) stated that "tractional characteristics on natural turf have been described by using two methods: material tests and subject tests." Material tests provide information on the shoe-surface interaction, whereas the subject tests provide information on the shoe-surface-athlete interaction. The latter interaction is used primarily when studying traction related to injuries, because material tests cannot represent human body movements or reactions. Shoe-surface material tests are adequate only for testing the interaction of the shoe and the turf. Both interactions are important; however, the shoe-surface interaction has received little attention with respect to natural turf surfaces.

Material Tests

The following text provides a summary of the material tests that have been conducted for linear and rotational traction. It should be noted that the primary focus for the some of the work was not on turf but rather on different shoe types and their relationship to possible injury.

Linear Traction

Gramckow (1968) measured linear traction by pulling an aluminum plate across the turf. Four 1.9 cm (0.75 in) football cleats were attached to the bottom of the plate, which contained a 18.2 kg (40 lb) weight. The plate was connected to a lever arm assembly to create a force which was measured by a spring scale between the plate and the lever arm. A constant force was applied to the lever arm and the spring scale reading just before the plate jerked forward was recorded.

Similar translational measurements to study the relationship between type of shoe and knee injuries were reported by Milner (1972). The force required to initiate and maintain linear motion was measured by an Instron tensile test machine. The traction between the shoe and surface was measured in terms of a "gripability" index defined as the ratio of pulling force to load.

ASTM has developed a standard laboratory procedure (ASTM, 1989) for determining static coefficient of friction of shoe sole and heel materials. Shoes are placed on a table where different walking surfaces are mounted. The table is then moved linearly to determine the force exerted at the sole surface interface.

A method currently being considered by an ASTM committee utilizes a size 11 cleated shoe, weighted with a 11.3 kg (25 lb) barbell weight. The amount of force required to initiate movement and the average force required to maintain motion are taken in four directions, each perpendicular to the previous one. Description of the turf and the air, canopy, and subsurface temperatures are recorded to characterize the area upon which measurements were taken.

Rotational Traction

Rotational traction studies have received more attention than linear traction studies. Conventional football shoes containing long cleats were cited by Torg et al.(1973) as the major cause of knee injuries at all levels of football. They tested various types of shoes by measuring the relative amounts of torque necessary to statically release weighted shoes 60° or 90° on both artificial and natural turf. The authors used an apparatus they developed called the Shoe-Turf Tester. This device consisted of a prosthetic foot that was fitted with a shoe and mounted on a stainless steel shaft equipped with weights. Torque was applied and measured with a torque wrench connected at the top of the shaft.

Bonstingl et al. (1975) measured rotational traction on both natural and artificial turf. Their machine consisted of a rigid frame which housed a synthetic leg and foot assembly. They tried to simulate the force created at the shoe-surface interface by applying a force to the lower leg similar to that involved with a tackle. The impact on the leg was initiated by a weighted pendulum, which struck an arm connected to the leg to generate the rotational force. The peak torque at the shoe-surface interface was measured by two polarly mounted strain gauges on the leg.

Canaway (1975) designed a device to measure rotational forces on natural grass. The test equipment consisted of a steel circular disk upon which different sports studs were attached in a manner such that each stud was at an equal degrees apart. Attached to the disk was a shaft that held circular weights (total weight 47.8 kg). The top of the shaft contained a torque wrench that was used to apply and measure the force required to tear the apparatus from the turf (initial force).

Canaway (1978) later adapted this device to study abrasion on different turfgrass species. He tried to simulate the abrasion on fine turf caused by the forces involved with walking. He attached a hiking boot sole to the device and measured the abrasion associated with walking across a golf green, bowling green, etc. He used the term abrasion instead of traction when the sole contained no spikes or cleats.

Canaway and Bell (1986) noted that on their original apparatus that the stud placement prevented the device from rotating about a central axis and that the one-handled torque wrench also contributed to this problem. Winterbottom (1985) corrected some of these problems by replacing the torque wrench with a two-handled device, and he eliminated the weights by using a compression spring. However, the device could only be used on level ground due to changes in spring compression; therefore, it was found to be unsatisfactory for natural turf.

Canaway and Bell(1986) later expanded on Winterbottom's corrections by placing the studs equidistant from the center, using a two-handled torque wrench, and again using circular weights. They also engineered a transport device that allowed a reproducible drop height. This modified version was used to measure traction by Bell et al. (1985), Baker and Bell (1986), Baker (1987, 1989), Bell and Holmes

(1988), and Holmes and Bell (1986) and is currently being used in England for traction evaluation.

Studying the turf's resistance to shear, Zebarth and Sheard (1985) developed a machine that simulated a horse's hoof rotation when in contact with the turf. The resistance to shear was measured as the peak force required to rotate a vane out of the test surface. The 8 cm wide steel vane was connected to the bottom of a rotating arm. The vane penetrated the test surface to a depth of 6 cm. The arm was rotated by a rope attached to a winch. The tension in the rope was then measured by a strain gauge device mounted between the rotating arm and the rope.

Henderson (1986), Rogers and Waddington (1989, 1990), and Rogers et al. (1988) measured traction with a field shear test apparatus, Type 1B, Eijkelkamp Equipment, Giesbeek, The Netherlands. The apparatus measures the shear resistance of the turf by pressing the vanes into the ground to a depth of 1.6 cm and then turning the handle which is equipped with a scale(Nm) to obtain a measurement. There are 12 fins, 1.0 and 2.0 cm long, alternatively welded to a circular disc which is connected to the handle by a straight shaft.

Results of Material Tests

Although there are numerous factors that may influence the degree of traction, the relationship between only some of these factors and traction has been documented. Torg et al. (1973) found that as the load on the shoe was increased from 11.3 kg (25lb) to 68.0 kg (150lb) by 11.3 kg (25lb) increments there was a linear relationship between load and force required to pivot the loaded shoe. Knowing that a coefficient of friction could not be determined on turf, they proposed to describe the constant relationship as r = force ÷ weight, where r = the release coefficient. The release coefficients ranged from 0.55(± 0.06) to 0.28(± 0.03). The variation was attributed to the number, length, and diameter of the cleats as well as the type of surface. Relating these results to their previous injury study, they felt that a release coefficient less than 0.31 was safe.

Significant differences among grass species with respect to traction were shown by Canaway (1975). Kentucky bluegrass (Poa pratensis L.) provided greater grip than common timothy (Phleum pratense L.), perennial ryegrass (Lolium perenne L.) and creeping red fescue (Festuca rubra L.). Common timothy and perennial ryegrass were not significantly different from each other but, both provided more grip than creeping red fescue. Canaway (1975) did not find any significant differences among cultivars of any species. Canaway (1978) found Kentucky bluegrass mowed at 25 mm required 34.8 Nm of torque to slip a climbing boot sole, 24.6 Nm for perennial ryegrass at 25 mm, and 26.8 Nm for red fescue at 8mm. The friction coefficients for Kentucky bluegrass, perennial ryegrass and red fescue were 15.5, 10.9, and 11.9 respectively. Gramckow (1968) and Zebarth and Sheard (1985) concluded that turf on soils had a higher resistance to shear than turf on sand. Zebarth and Sheard (1985) also found that resistance to shear increased with bulk density for soil without turf and that with turf there was no correlation of shear with bulk density. The mean resistance to shear using their machine was 389 Nm for turf and 142 Nm for a sandy loam soil alone. Their explanation for the increase in shear with turf was the root system associated with turf.

The redesigned apparatus by Canaway and Bell (1986) was found to measure 82.6% of the torque experienced by the original Canaway (1975) apparatus. In a characterization of athletic fields for association football (soccer) Bell and Baker (1986) found traction coefficients ranging from 1.02 to 2.17. Baker (1987) on a pitch containing 75% bermudagrass (Cynodon dactylon [L.] Pers.) and 25% perennial ryegrass and tall fescue (Festuca arundinacea Schreb.), measured 35.9 Nm of torque before irrigation and 34.7 Nm after irrigation; however, both numbers fell within a range of acceptable play.

In a comparison of athletic field construction methods Bell and Holmes (1988) using Canaway and Bell's apparatus measured traction on sand carpet (32.3 Nm), ameliorated (sand/soil mix, 30.5 Nm), slit drained (soil, 28.8 Nm), pipe drained (soil, 30.6 Nm), and native soil fields (26.6 Nm), all with a similar turf cover. They also found an acceptable relationship between questionnaire responses of football (soccer) players and the results from the traction tests. They proposed that a reading of 30 Nm was a preferred minimum but a reading of 20 Nm was acceptable, while a maximum value can not be given since higher readings may be unsafe because of the possibility of injuries to knees and ankles induced by torsion.

Rogers et al. (1988) found in their characterization of football fields that greater turf cover led to increased resistance to shear. Rogers and Waddington (1989) found no cutting height effect on shear resistance with tall fescue and that the presence of verdure was associated with higher traction values compared to bare soil and to turf with verdure removed. Rogers (1988) also found that compacted tall fescue plots were associated with higher traction levels while aerated Kentucky bluegrass plots showed lower traction levels than nonaerated plots.

OBJECTIVES

The recent interest in field safety has provided impetus for research in this area. A few researchers have dedicated a lot of their time in trying to determine what factors affect athletic field safety.

Traction as it relates to field safety involves the athlete, studded footwear, and the turf. Previous research has concentrated on studying the athlete and studded footwear in order to understand and improve traction. These parameters have proven to be very important, but the variability among grass species and cultural practices may be so great that the turf surface may provide the largest influence on traction. Therefore, the effect of turf on traction needs to be ascertained before a complete characterization of traction can be made.

In the UK, Canaway and Bell's (1986) device is used extensively for testing traction on athletic fields. Their machine, although thoroughly tested, does not possess the versatility to measure both horizontal forces (rotational and linear) and accommodate external factors such as different player weights and shoe types. To completely understand the turf's relationship with traction and to enable the characterization of traction, a versatile and reliable testing apparatus and procedure needs to be developed.

Objectives of this research were as follows:

1. Develop an apparatus and operating procedure to measure the horizontal forces associated with traction on natural turfgrass.

2. Determine how different cutting heights, different turfgrass species, and amount of loading weight influence traction on athletic field turf.

3. Compare this device to other devices used to quantitatively measure traction.

MATERIALS AND METHODS

The materials and methods have been divided into four sections: one describing the traction measuring apparatus developed for this research and three sections describing the various tests conducted.

Description of Traction Apparatus and Procedure for Operation

This section describes the development and construction of the traction measuring apparatus termed PENNFOOT and the procedure required to operate the device.

Background Information

Traction exists when an athlete equipped with a studded shoe runs or walks across a turfgrass surface. To understand traction, the forces associated with it must be fully understood. To demonstrate the forces involved and how these forces interact, the mechanics of walking can be used as an example. In walking, the foot applies vertical forces acting at right-angles to the ground and horizontal forces which result in friction between the sole and grass. Horizontal forces can be grouped into two categories: linear horizontal forces and rotating horizontal forces or torque. The following text by Canaway (1978) best expresses how these forces act in walking:

> In walking, the horizontal forces applied by the foot are opposed by the frictional forces which provide "grip." When these frictional forces are small the surface is experienced as slippery. While the foot is in contact with the ground, the values of both the horizontal and vertical forces change rapidly due to such factors as vertical movement of the body, the walker propelling him/herself forward, etc. If the horizontal force produced by the body exceeds the maximum frictional force, the foot slips.

The literature review showed that both rotational and linear traction have been studied and tested by numerous devices. Nigg (1990) stated that there is no well-defined correlation between the resistance to translational and rotational movement and that tests using rotational movement might produce results different from tests that use a translational movement. Testing the amount of abrasion caused by walking on flooring materials Harper et. al. (1961) found that torque or rotating horizontal forces caused the most amount of abrasion. Therefore, to properly characterize the traction conditions on sports turf, both translational and rotational traction should be studied.

To study traction, the resistance properties of the grass, when in contact with a studded sole need to be measured. By adapting the properties of friction to turfgrass/studded sole interfaces, certain frictional testing procedures and calculations can be applied.

Friction encompasses two separate entities; static and kinetic friction. Static friction refers to the force that resists any attempt to start a body moving and is expressed as:

$$F_{fr} \leq \mu_s F_N \quad \text{(Giancoli, 1985)}$$

where F_{fr} = static friction

μ_s = coefficient of static friction

F_N = the normal force

Kinetic friction is the force that acts to oppose the sliding of two surfaces past each other and can be expressed as:

$$F_{fr} = \mu_k F_N \quad \text{(Giancoli, 1985)}$$

where μk = coefficient of kinetic friction

Both static and kinetic friction have a coefficient of friction term. For any two surfaces it is difficult to obtain reliable data on either the kinetic frictional force or the maximum static frictional force because any slight variation in the condition of the contact surfaces has an appreciable effect on the resulting frictional force, (Higdon and Stiles, 1951). However, for two similar, plane objects, e.g. steel on steel, a constant has been determined to be the ratio of the frictional force F_{fr} to the normal force F_N and is called the coefficient of friction.

Previous authors have exchanged the term traction for friction because of the dissimilar surface interaction created by the studded footwear and the irregular turf surface. Some researchers (Canaway,1975; Canaway and Bell,1986) have even defined a "coefficient of traction" as the ratio of the tractional force to the normal force. However, Torg et al.(1973) proposed that a coefficient of traction does not exist.

The objectives for designing a new traction measuring device were to build an apparatus that could measure both linear and rotational traction as well as test various factors that may influence traction. The possible factors that may influence traction will be divided into two groups: external and environmental factors. The external group consists of the player's weight(normal force) and shoe type. The environmental category contains numerous factors ranging from grass species and cultural practices to various soil conditions. The interaction between the two types of factors must also be considered.

The PENNFOOT was not designed to simulate actual human foot movements. The reason for the development of this machine was to study the turfgrass with respect to traction. This machine represents an improvement compared to other machines since it simulates human movements. Close approximations of actual foot movements with respect to traction have been accomplished by Lloyd et al.(1990) in artificial turf traction tests by attaching a piece of artificial turf to a piezoelectric load cell and then performing traction tests. This type of system is not feasible for natural turfgrass because the load cell must be directly under the foot and such placement would disrupt the soil and rootzone. Secondly, only one measurement can be taken at a specific spot on natural turfgrass because of the disturbance created by the cleats.

The following text will describe the forces associated with both types of traction movements and how these forces were measured and calculated. The force required to initiate movement (static friction) was measured for both translational and rotational traction, but the focus of this research is the force imparted between the shoe and turf as the foot moves away from the starting position(kinetic friction).

For the translational measurements the tractional property of the turf will be described by the force (N) for a given set of variables (e.g. species and cutting height), at various positions throughout the linear movement.

Rotational traction characteristics were determined by measuring the moment of rotation with respect to the central axis of rotation. The moment of rotation is a result of two forces acting at the same magnitude and distance from the axis but in opposite directions. If a central axis does not exist, the force exerted will not be a true rotational force. Torque ($\tau = rF$) is determined by multiplying the force ($F=ma$) by the perpendicular radius (determined from the central axis to the point where force is applied).

The tractional property of the turf will be described by the amount of torque (Nm) measured for a given set of variables. Canaway and Bell (1986) calculated a coefficient of rotational traction (μ_t) by placing the studs in a circular pattern with a common radius that allowed them to cancel the meter (m) term in torque (Nm), leaving a dimensionless coefficient term when divided by the normal force

$$\mu_t = \frac{\tau(\mathrm{Nm})/(\mathrm{m})}{F_N(\mathrm{N})} = \frac{F(\mathrm{N})}{F_N(\mathrm{N})}$$

Because a common distance among the studs on the sole of PENNFOOT could not be defined, a coefficient of rotational traction was not calculated.

The numbers determined for tractional characteristics for both linear and rotational traction were and will be used for comparative purposes only. Attempts to calculate a coefficient of traction from these data should not be made, because these numbers cannot be placed in a traction equation if other combinations of variables and normal forces are known.

Construction

The testing apparatus (termed PENNFOOT) used in this research was constructed by using the frame and leg assembly from Bonstingl's (1975) device for measuring traction. A photo of the PENNFOOT appears in Fig. 1. Descriptions of the sub-assemblies and measuring instruments are included in the following text.

Frame assembly

The assembly of PENNFOOT contained two frames. The original angle iron frame, was used to construct an internal

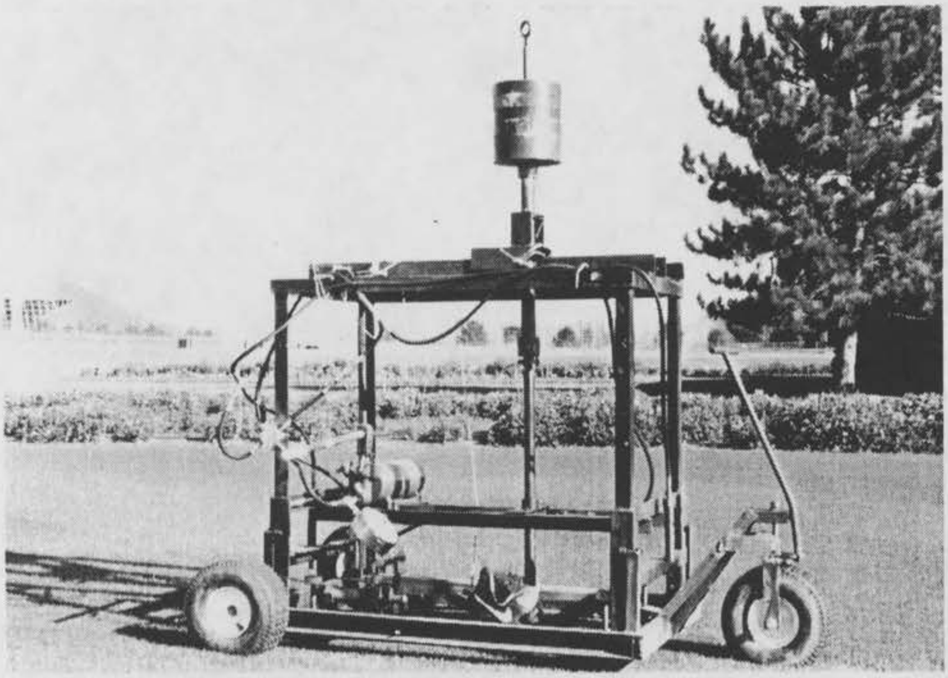

Figure 1. PENNFOOT traction measuring device.

frame. This modification allowed the leg assembly to reach the ground, decreased the overall weight, and made transferring loading weights easier. A second frame, shorter than the internal frame was constructed around the bottom portion of the internal frame. The use of the second frame allowed for ease of lifting the weighted foot between measurements. The uprights located at each corner of the external frame were made out of 3.81 cm wide angle iron to provide support while the internal frame moves up or down inside the external frame. The top of the internal frame contained a centrally located collar through which the leg-shoe assembly slides. A set screw mounted on the collar locks the leg-shoe assembly to the internal frame during lifting or transporting. When the set screw is loosened the weights and the leg-shoe assembly act independently of the internal frame. Two rims and tires were mounted on one end of the external frame and a third rim and tire was mounted on the other end for transporting the machine.

Player leg and foot assembly

The player leg consisted of a solid (3.81 cm diameter) steel rod whose upper end was a ball-and-socket assembly (simulating the human hip joint) and whose lower end was pinned to a cast aluminum foot (simulating a pivoted ankle joint). The extreme top portion of the leg (above the ball-and-socket) was capable of being equipped with circular weights to simulate different player weights. The simulated player weights were obtained by placing weights on top of the 33.7 kg (74.4 lb) leg-shoe assembly.

The simulated foot (Fig. 2) was cast out of aluminum from a size 10 foot mold. Two holes located on top of the foot are used for connection with the leg. The first hole located toward the toe allows the heel to be raised off the ground therefore distributing the weight on the ball of the foot. The second hole is used to place the entire sole in contact with the turf and distribute the weight evenly across the sole. The molded foot can be fitted with different shoes. Two football shoes were used in this research. Shoe I is a hightop with molded sole that contains 18 triangular studs (12 mm long) around the perimeter of the sole and 35 smaller studs (9 mm long) in the center (Nike, Inc., 150 Ocean Dr., Greenland, NH). The second shoe (Shoe II) is a lowcut studded shoe which contains 12 cylindrical studs, each 12 mm long x 11 mm in diameter (Nike, Inc., 150 Ocean Dr., Greenland, NH). Both shoes had been used by the Penn State football team. A third shoe utilized in one test was a smooth leather soled shoe.

Figure 2. Cast aluminum foot, Shoe I, and Shoe II used with PENNFOOT traction measuring device.

Hydraulic system assembly

The horizontal forces associated with traction and the force required to lift or lower the internal frame were generated by a Energy HP-100 hand pump (Energy MFG.CO., Inc. Monticello, IA) with a 20.7 MPa (3000 psi) pressure limit. The rotating horizontal force was created by two model HTB-1R pistons (Air & Hydraulic Power, Inc. Wyckoff, NJ), which were horizontally mounted on angle iron and were 38.1 cm above the ground when the machine was in position to take a measurement (Fig. 3). These pistons have a bore of 2.54 cm and a stroke of 5.08 cm. A strike plate for the pistons to push against was connected to the simulated leg the same distance above the foot by a set screw. The pistons apply equal pressure on opposite sides of the leg in opposite directions, therefore creating a rotational force. A collar containing a protractor scale (as shown in Fig. 3) surrounded the simulated leg to prevent it from tilting while the rotational force was applied. A lubricant was applied around the collar and on the ball-and-socket joint to minimize friction. The scale was used to determine how far the leg had moved from the starting position.

The linear horizontal force was created by using one model HTB-1E pulling piston with a bore of 5.08 cm and a stroke of 5.08 cm. The piston was mounted on the bottom of

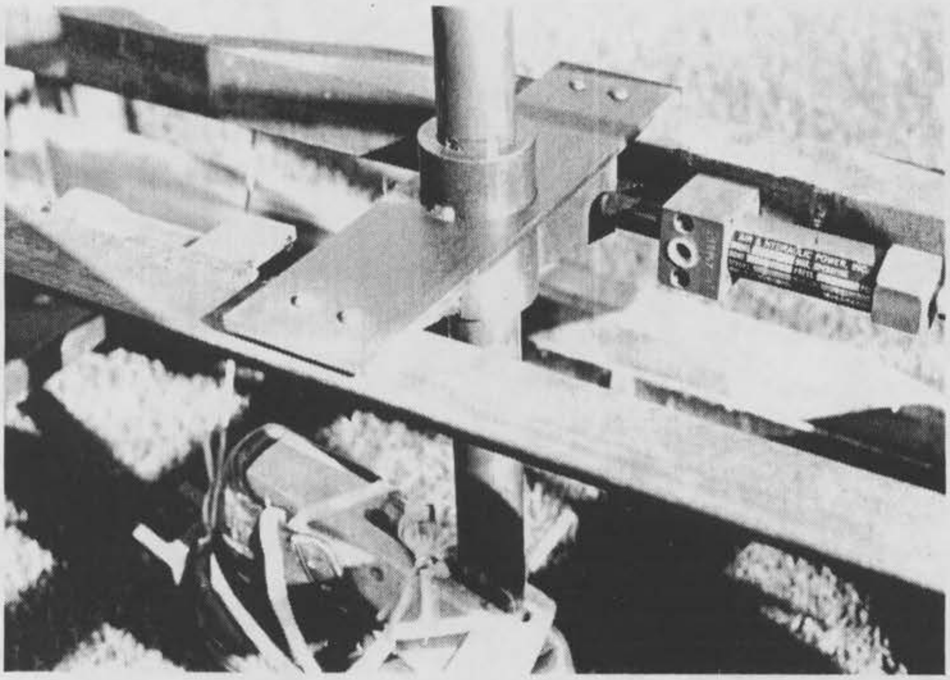

Figure 3. Rotational measurement setup for the PENNFOOT.

the internal frame and the pulling rod was 7.3 cm above the ground when the internal frame rested on the ground (Fig. 4). The end of the rod was pinned to a bracket mounted on the heel of the foot. The distance traveled by the foot was measured by a dial indicator (Jewels) (Fig. 4). The dial indicator was mounted on the piston casing and a plate was attached to the piston rod for the end of the dial indicator to rest against. As the piston is pulled in along with the plate, the distance on the dial indicator increases. The force to rotate or pull the leg/shoe assembly when suspended in the air was 100 kPa (15 psi.) The pistons used to create the tractional forces came equipped with return springs which reset the pistons when pressure was alleviated; however, the return springs were removed to prevent unnecessary opposing forces.

Raising or lowering the machine was accomplished by two model HTB-1R pistons vertically mounted at opposite ends of the internal frame. These pistons have a bore of 2.54 cm and a stroke of 10.16 cm. The ends of the piston rods rest on the external frame; therefore, when pressure was applied, the internal frame would lift up and it could be lowered by releasing the pressure. A 15.2 cm (6 inch) Noshok C-X60SSSB10 6.9 MPa (1000 psi) liquid filled pressure gauge was directly connected to the pump to monitor the pressure being applied to the pistons. A Vickers MRV3-ID-D2-2 selector valve allowed the pressure to be directed to

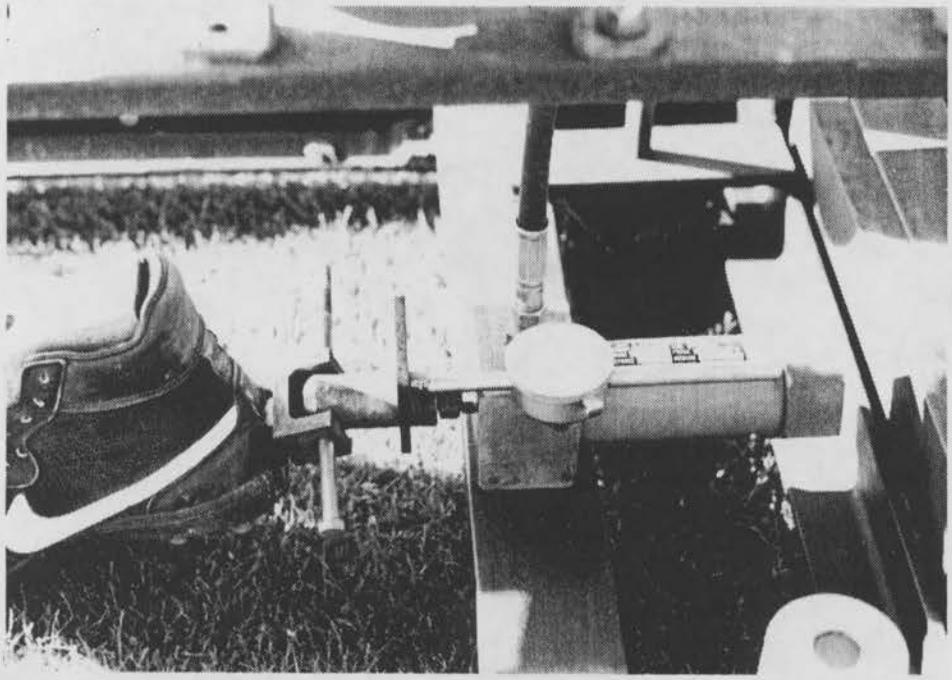

Figure 4. Linear measurement setup for the PENNFOOT.

pistons creating the horizontal forces or to the pistons used for the raising or lowering the internal frame.

Procedure

The procedure for the collection of data using the PENNFOOT was as follows:

1. The leg-shoe assembly was weighted to arrive at a particular loading weight and the selected shoe was secured on the simulated foot.

2. The machine was situated over the desired location and the pistons were reset. The pistons used for the rotational measurements were pushed back into the cylinders and the plate they push against was placed in contact with the end of the pistons. When the pistons and the plate were in this position (zero position) the degree indicator mark on the leg lined up with the 0° mark on the collar scale.

Resetting the linear piston involved pulling out the piston from the pulling cylinder until the dial indicator read zero. When the desired pistons had been reset the internal frame was then lowered slowly while the heel was held up until the toe came in contact with the turf. At this point the set screw, holding the top portion of the leg assembly, was released allowing the leg-shoe assembly and weights to act independently from the internal frame. This procedure allowed placement rather than dropping of the weighted assembly onto the surface.

3. The selector valve was turned to connect either the rotational or linear pistons to the hand pump. For a rotational measurement, one person operated the pump and monitored the pressure gauge. A second person watched the foot and indicated when the shoe first started to move and indicated when the mark on the leg was aligned with certain positions on the collar. When initial movement was achieved and when the mark on the leg reached a position on the collar the pressure at that time was recorded. Five pressure readings were taken: at initial movement, 10°, 20°, 30°, and a final reading when the pistons were fully extended (40°).

The measurement for linear traction also required two people: one to operate the pump and read the pressure gauge and one to watch for initial movement and read the dial indicator. Nine pressure readings were taken for a linear measurement: initial movement and one at every 0.25 inch for 2.0 inches of travel. Quarter inch increments were than converted to cm for tables and figures.

4. The last step in the procedure was the conversion of pressure to N and Nm for linear and rotational measurements respectively. Linear forces (N) were determined by calculating the product of the effective area of the pulling piston (3.14 in^2) and the amount of pressure

(psi) read from the gauge, which converts pressure(psi) to force (lb). The amount of force (lb) was then converted to SI units by the ratio of 1 lb:4.45 N. Condensing these steps, multiplying psi by 13.97 will convert it directly to N.

Rotational forces were determined by calculating the moment of rotation. The moment of rotation is the force multiplied by a lever arm (Giancoli, 1985), which for the PENNFOOT was the strike plate that the pistons pushed against. The effective area of the pistons was 0.785 in^2 and the length of the lever arm, measured from the center of the leg to the point where the piston contacted the strike plate, was 81 mm. Multiplying the force, determined in the same manner as for linear measurements, by the lever arm provides the moment of rotation (Nm). To convert directly from psi to Nm, the pressure reading can be multiplied by 0.283.

Measurements of Species, Cutting Height, and Loading Weight Effects on Rotational and Linear Traction

The objectives of this study were to determine the effects of grass species, cutting height, and loading weight on traction and to compare rotational traction to linear traction by using the PENNFOOT. Traction was measured on plots located at the Joseph Valentine Turfgrass Research Center located at The Pennsylvania State University in September 1991. In further references, these plots will be termed "species plots." Four grass species, 'Aspen' Kentucky bluegrass (Poa pratensis L.), Penn State 222 experimental perennial ryegrass (Lolium perenne L.), 'Pennlawn' creeping red fescue (Festuca rubra L.), and 'Arid' tall fescue (Festuca arundiancea Schreb.), were established in August 1990. The soil was a Hagerstown silt loam (mixed mesic hapludalf). The experimental design was a randomized complete block design with three replications. Each species plot (5.49m by 6.1m) was divided into three cutting height subplots (1.83m by 6.1m) for heights of 3.8, 5.1, and 6.4 cm (1.5, 2.0, and 2.5 inch). Blocks were split for loading weight treatments.

Traction collection followed the procedure mentioned earlier. Four loading weights (59.9, 73.9, 88, and 102 kg) were used in combination with shoe I for linear traction measurements. The lighter loading weight was not used for rotational measurements. For each combination of grass x cutting height x loading weight, four measurements were taken. All measurements, in these and following tests, were taken on dry turf: i.e., free of dew, precipitation, or irrigation water on the turf surface. The data were analyzed using the analysis of variance and the least significant difference (lsd) test at the 0.05 level was used on the means. The lsd was not calculated when the F ratio was not significant at the 0.05 level. Error terms were pooled if the initial F ratio of error mean square was not significant at the 0.25 level. Pooling was used only in 1991 with rotational data analysis. Rotational and linear data were then correlated.

Each species x cutting height plot was characterized by pulling three 81 cm^2 by approximately 5.1 cm deep plugs from each plot. Plugs were then trimmed to obtain a 2 cm soil depth. The procedure described by Lush(1991) was followed for determination of verdure dry weights and tiller density. The below-ground vegetation was determined by first washing the soil from the roots and then determining the percent organic matter by using ASTM's (1990) method for percent organic matter by loss on ignition (LOI). Percent moisture (dry mass basis) was determined on each sampling date by extracting four 2.4 cm^2 by 1.5 cm deep plugs from each species x cutting height plot.

Comparison of Methods

The first comparison was between the PENNFOOT and the Field Shear Test Apparatus, Type 1B, Eijkelkamp Equipment, Giesbeek, The Netherlands. The shear vane was also used to measure traction across all species and cutting heights at the times of both the linear and rotational traction measurements in the previous study in order to compare the results and correlate the two devices.

The shear vane (Fig. 5) consisted of 12 fins welded at right angles to a cutting head (7.0 cm diameter). The fins were 1.0 and 2.0 cm long and alternatively placed around the cutting head and they had a penetration depth of 1.6 cm. The shear vane was pressed into the surface using foot pressure. The foot was removed and torque was applied manually by turning the opposite handles in the same direction and the maximum torque (Nm) was read from the calibrated gauge on top of the apparatus. Averages of four measurements were recorded.

The data were analyzed using the analysis of variance and the least significant difference (lsd) test at the 0.05 level was used on the means. The lsd was not calculated when the F ratio was not significant at the 0.05 level. Rotational and linear data were then compared with shear vane results by calculating correlation coefficients. Both the PENNFOOT and the shear vane data were also compared with tiller density, verdure, and below-ground vegetation.

The objective of the second comparison was to compare the PENNFOOT against the shear vane and the device developed by Canaway and Bell (Apparatus A). Traction values were measured in August 1992 on the species plots to determine how the three machines responded to differences in species

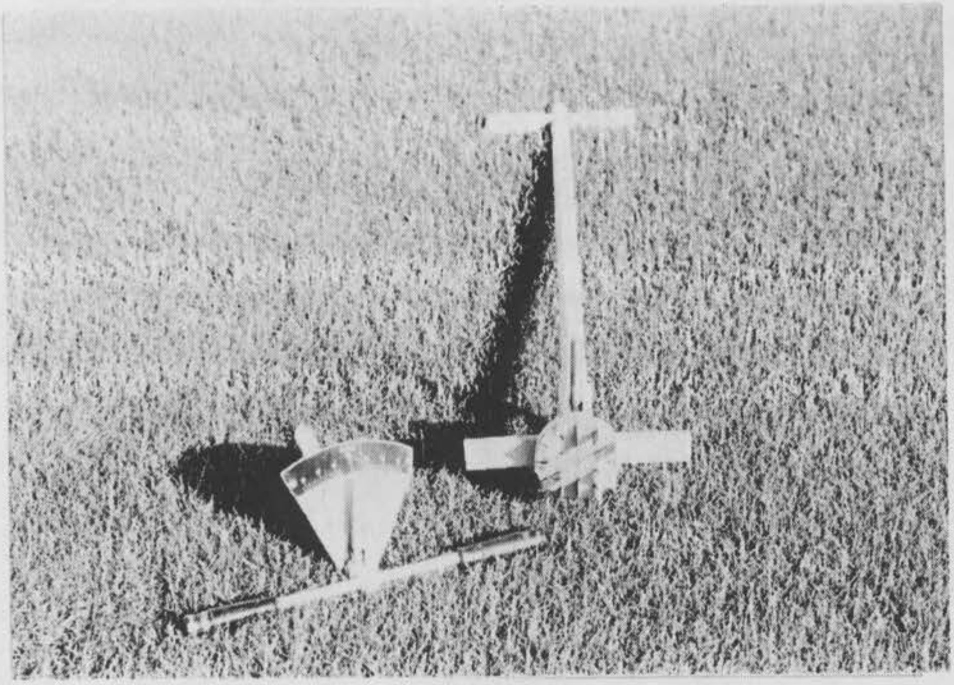

Figure 5. Eijkelkamp type 1B field shear test apparatus.

and cutting height. The plots were again characterized by determining tiller density, verdure, and below-ground vegetation. Four measurements per plot were taken for each method. The PENNFOOT was equipped with shoe II which had studs similar to those on Apparatus A and was tested using a loading weight(47.6 kg) close to the loading weight with Apparatus A.

A replica of Canaway and Bell's device for measuring traction was constructed for use in this research. The apparatus shown in Fig. 6 consists of a steel disc (15 cm diameter) containing six football cleats (14 mm long by 12 mm diameter) arranged equidistant (46 mm) from the center of the disc. The disc is center drilled and threaded to take a 78 cm long shaft. The top of the shaft is connected to a 40 Nm torque wrench, which was modified with another handle. Circular weights were placed on top of the disc to produce and overall loading weight of 47.8 kg. A cart to carry the apparatus and provide a standardized drop height (60 mm) was also made to simulate the original.

To obtain measurements the apparatus is held so that the support bars are the same height as the cross bars on the cart. The apparatus is then released and allowed to fall a standard height of 60 mm. The two handled torque wrench with a 40 Nm capacity is then turned to obtain a measurement. The torque applied can be converted to a traction coefficient by:

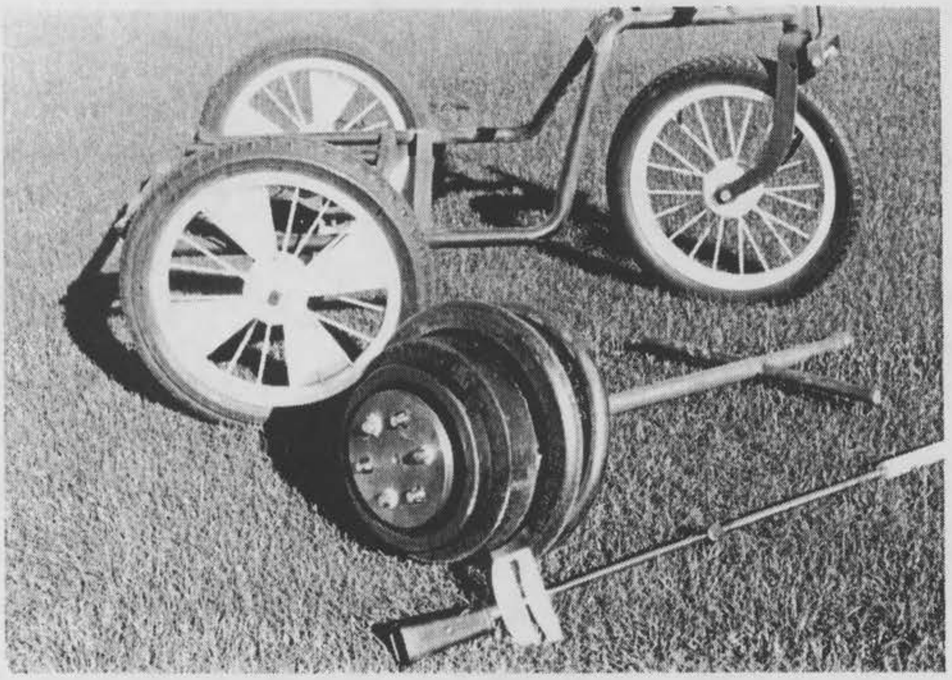

Figure 6. Replica of Canaway and Bell's device - Apparatus A.

$$\mu = \frac{3T}{2WR}$$

where: μ = traction coefficient

T = applied torque (Nm)

W = applied load (N)

R = radius to cleats (m)

In this study the torque values were used to characterize traction. The data were analyzed using the analysis of variance and the least significant difference (lsd) test at the 0.05 level was used on the means. The lsd was not calculated when the F ratio was not significant at the 0.05 level. All methods were then correlated against one another and vs. tiller density, verdure, and below-ground vegetation.

In a third comparison of these methods, areas were selected to provide a greater range of traction values than were obtained on the previous site. Traction measurements were taken on bare soil (firm but not compacted), a thinned turf stand (60% turf cover), compacted turf roadway (75% turf cover), and noncompacted Kentucky bluegrass and tall fescue plots (100% turf cover). The PENNFOOT was equipped with shoe II and tested using two loading weights: one (47.6 kg) which was similar to that of Apparatus A (47.8 kg), and one of 102 kg. Apparatus A was tested by using the standard procedure of a 60 mm drop height and by placing the apparatus on the turf without dropping it. The second method was incorporated to create an initial contact similar to that of the PENNFOOT, and to see if placing Apparatus A on the surface provided different results from the standard procedure. Detailed characterizations and soil moisture contents of the different areas were not determined because the primary purpose of this test was simply to determine the degree of correlation among the five methods.

Characterization of Species Using Smooth Sole Footwear

It seemed apparent that athletic footwear, Apparatus A, and the shear vane negated the often observed slipperiness differences among species. In an attempt to determine species differences in slip, rotational measurements were made by equipping the PENNFOOT with footwear having a smooth, leather sole.

Four traction/friction values for the leather soled shoe were measured on the 5.1 cm cutting heights for each species on the "species plots" in August 1992. The data were analyzed using the analysis of variance and the least significant difference (lsd) test at the 0.05 level was used on the means. The lsd was not calculated when the F ratio was not significant at the 0.05 level.

RESULTS AND DISCUSSION

Effects of Species, Cutting Height, and Loading on Rotational and Linear Traction

The objective of this study was to determine what effect grass species, cutting height, and amount of loading weight had on traction. This was accomplished by using the PENNFOOT to measure both rotational and linear traction.

The tractional forces associated with natural turf were found to increase as the sole was rotated or moved in a linear fashion for the species, cutting height, and loading weight variables. Linear traction forces were found to increase sharply for the main effects of grass species, cutting height, and loading weight from initial movement to 2.5 cm of travel, increase slightly less to 3.8 cm, and then decrease slightly to 5.1 cm (Fig. 7, 8, 9). Rotational forces responded similarly and the peak occurred around 40° (Fig. 10, 11, 12).

Significant differences (at each degree or linear increment) due to treatments are shown in Tables 1 and 2. Traction values for all main effects are shown in Tables 3 and 4. A significant cutting height x loading weight interaction occurred at 3.2 and 3.8 cm for the linear measurements. Interaction means for each degree and linear

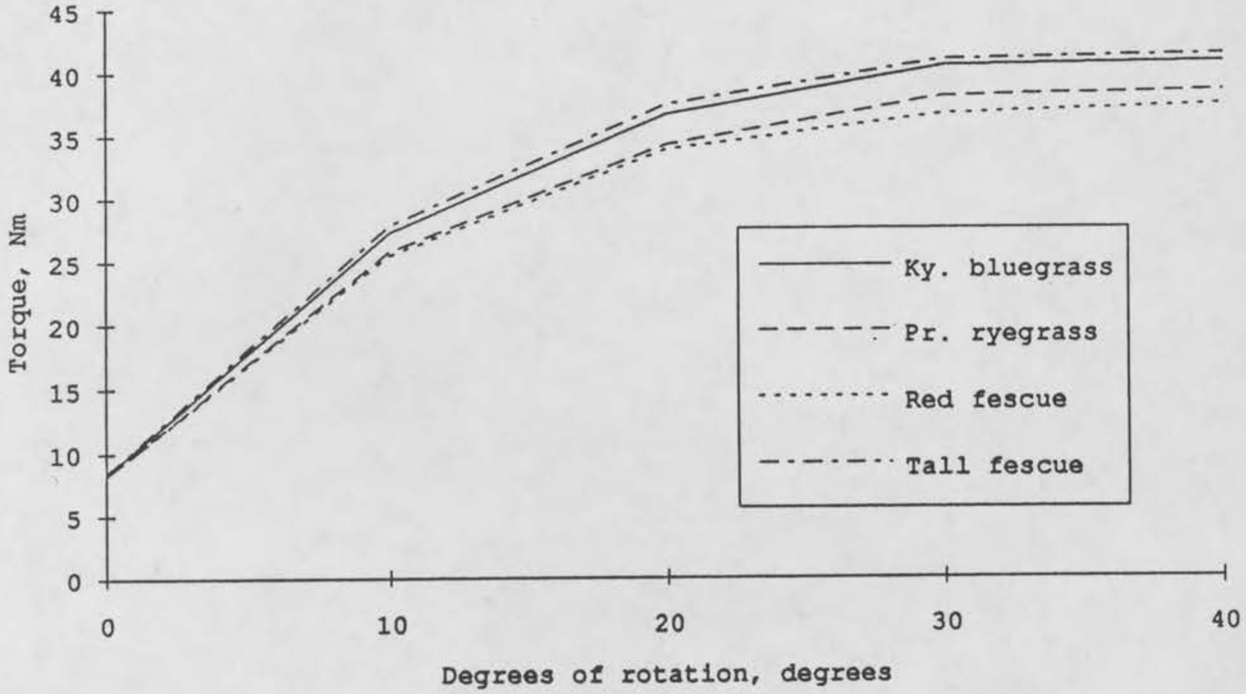

Figure 7. Mean rotational forces for grass species across all cutting heights and loading weights for measurements taken in September 1991.

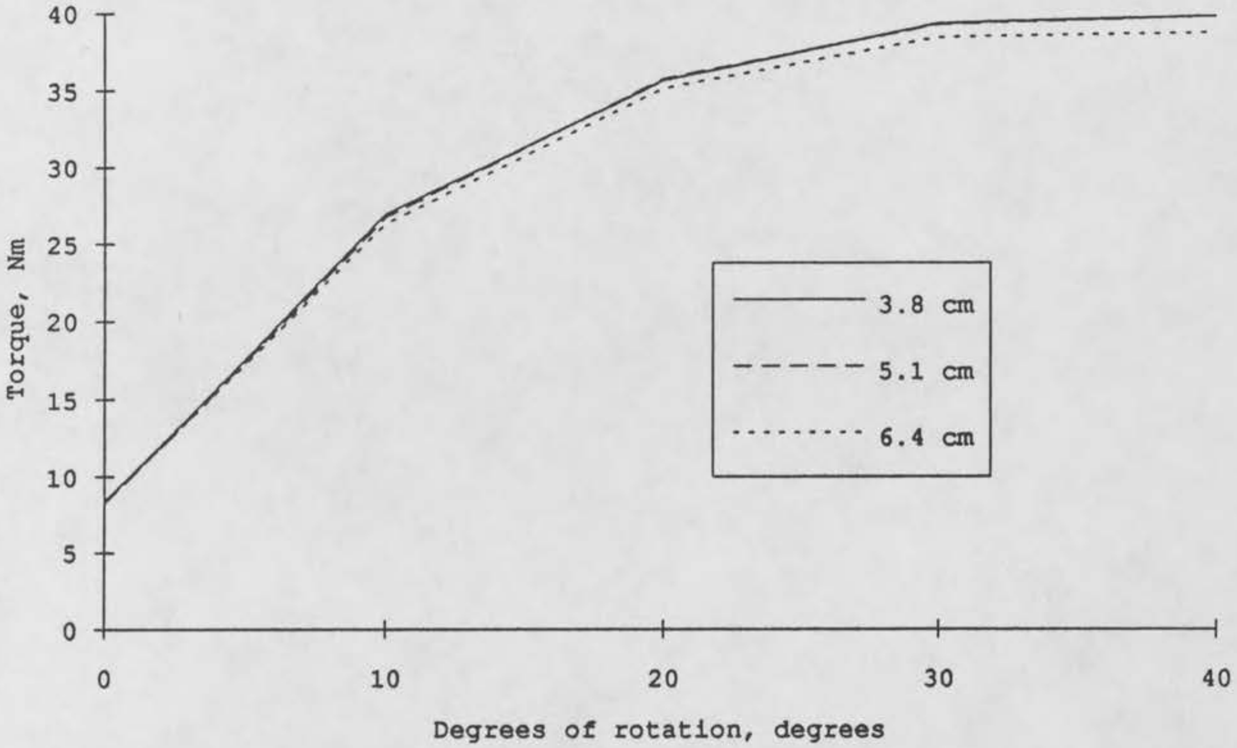

Figure 8. Mean rotational forces for cutting height across all grass species and loading weights for measurements taken in September 1991.

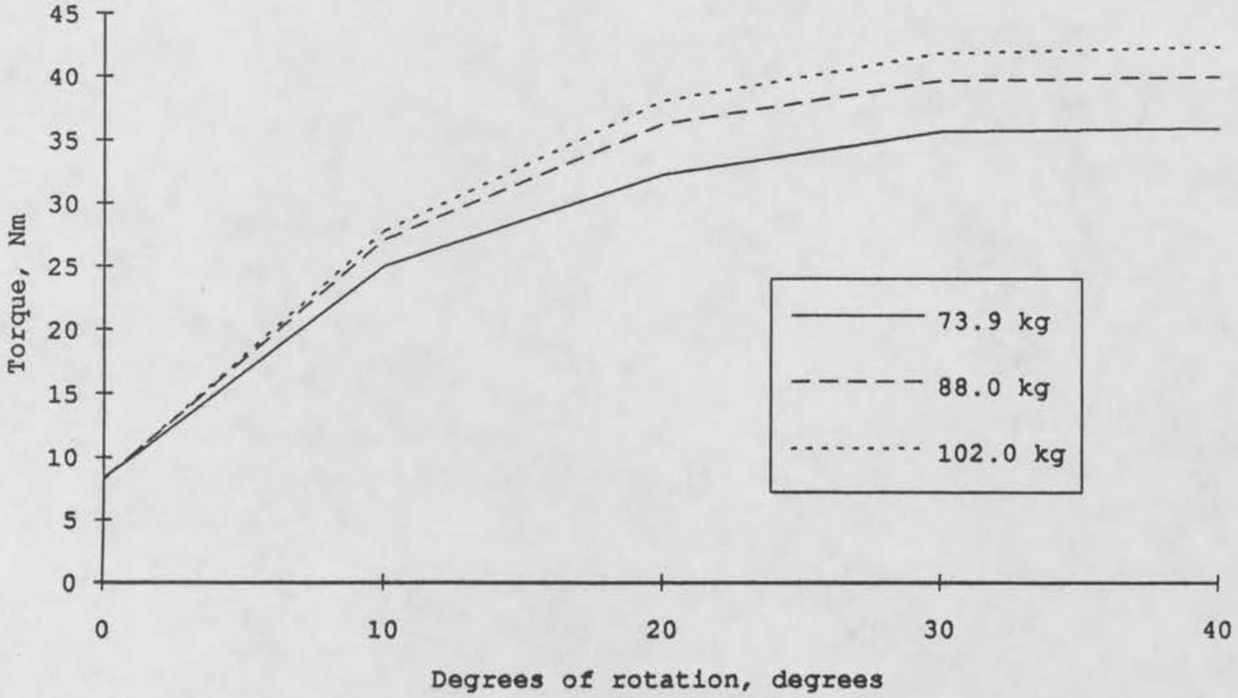

Figure 9. Mean rotational forces for loading weights across all grass species and cutting heights for measurements taken in September 1991.

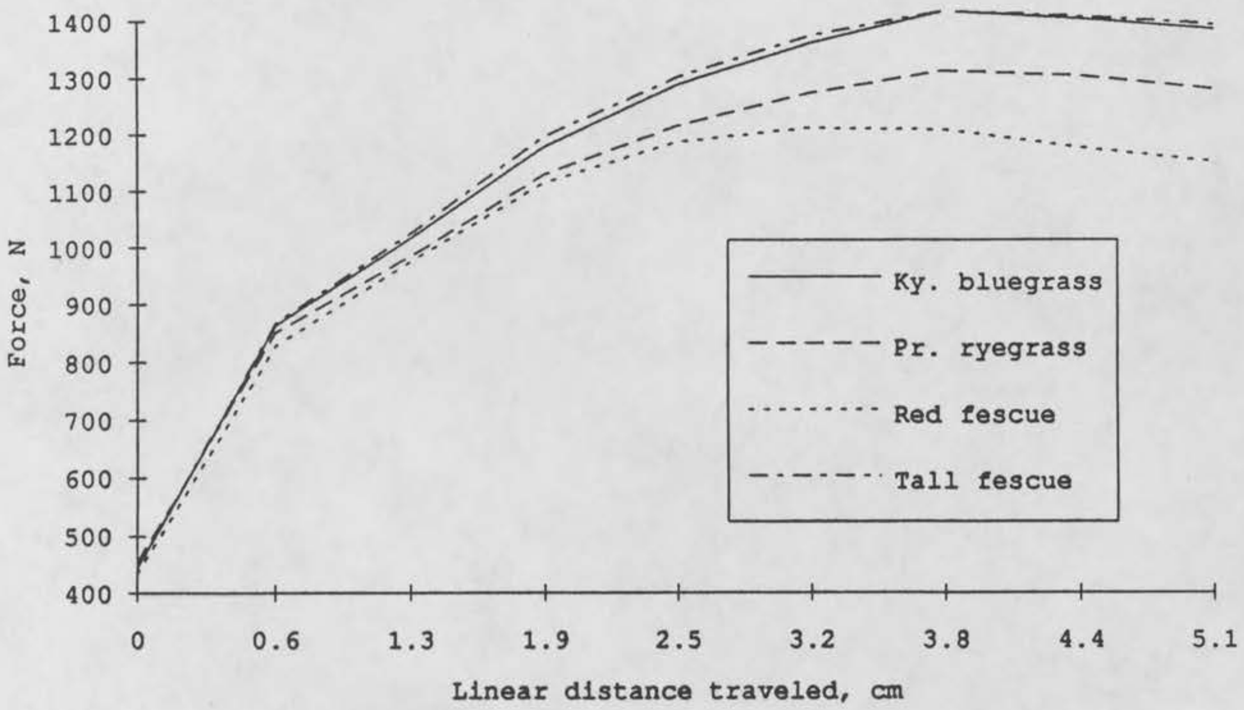

Figure 10. Mean linear forces for grass species across all cutting heights and loading weights for measurements taken in September 1991.

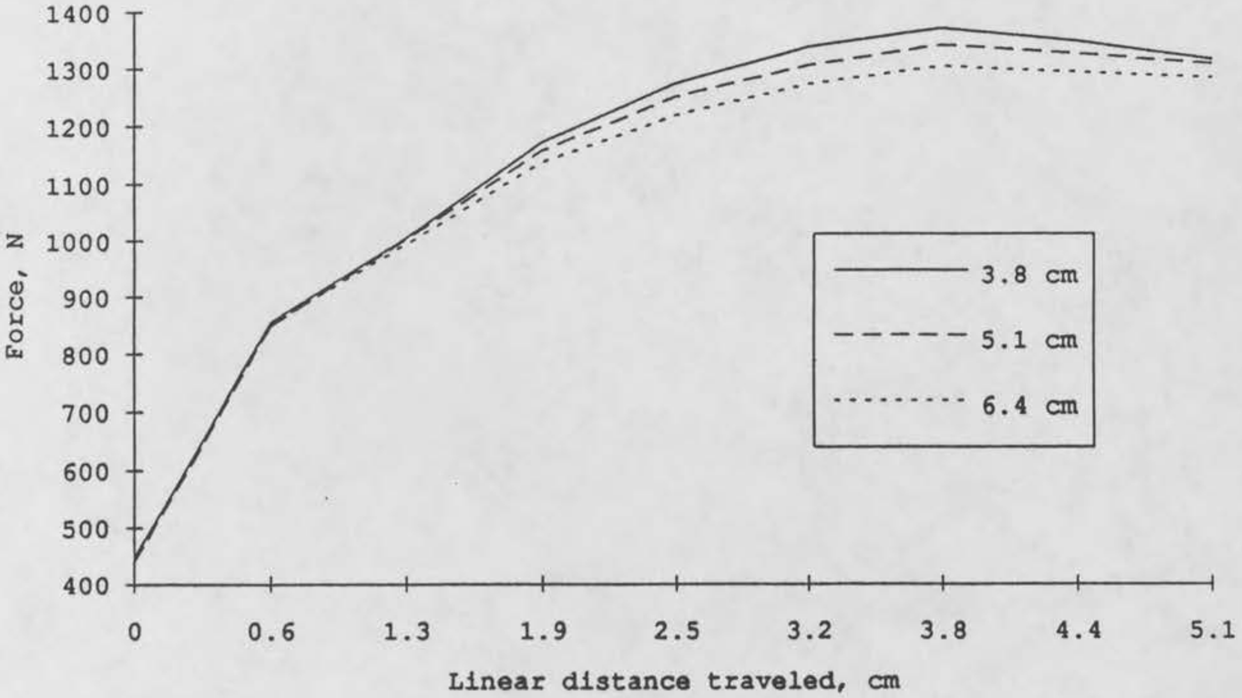

Figure 11. Mean linear forces for cutting heights across all grass species and loading weights for measurements taken in September 1991.

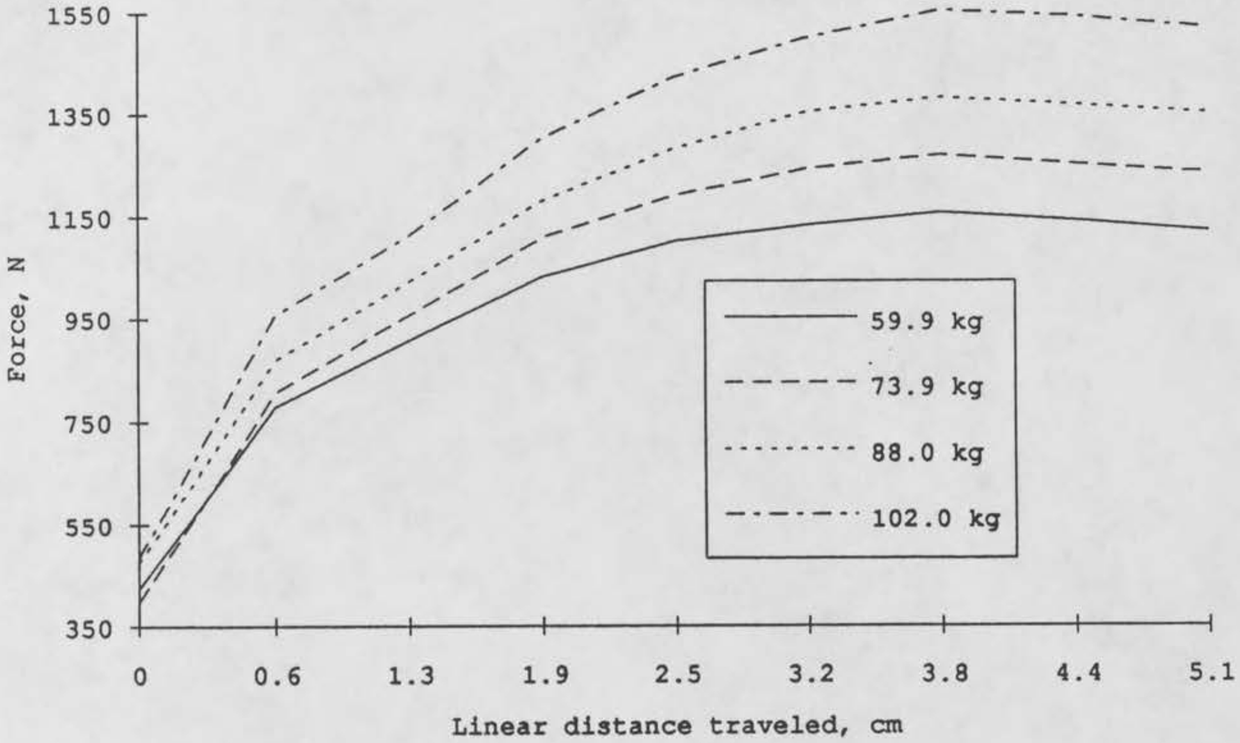

Figure 12. Mean linear forces for loading weights across all grass species and cutting heights for measurements taken in September 1991.

Table 1. Significant differences for main effects and interactions for rotational traction measurements in September 1991.

Source	Degrees of freedom	initial	-------- degrees of rotation ---------			
			10	20	30	40
Blocks, R	2	**	**	**	*	*
Species, S	3	NS	**	**	**	**
Error (a), RS	6					
Cutting Height, C	2	NS	NS	NS	NS	NS
SC	6	NS	NS	NS	NS	NS
Error (b), RSC	16					
Loading Weight, L	2	*	*	*	*	*
Error (c), RL	4					
SL	6	NS	NS	NS	NS	NS
Error (d), RSL	12					
CL	4	NS	NS	NS	NS	NS
SCL	12	NS	NS	NS	NS	NS
Error (e), RSCL	32					

NS = not significant
** = significant at 0.01 level
* = significant at 0.05 level

Table 2. Significant differences for main effects and interactions for linear traction measurements in September 1991.

Source	Degrees of freedom	cm of travel								
		initial	0.6	1.3	1.9	2.5	3.2	3.8	4.4	5.1
Blocks, R	2	**	*	*	NS	NS	NS	NS	NS	NS
Species, S	3	NS	NS	NS	NS	*	**	**	**	**
Error (a), RS	6									
Cutting Height, C	2	NS	NS	NS	**	**	**	**	*	NS
SC	6	NS	NS	NS	NS	NS	NS	NS	NS	NS
Error (b), RSC	16									
Loading Weight, L	2	NS	**	**	**	**	**	**	**	**
Error (c), RL	4									
SL	6	NS	NS	NS	NS	NS	NS	NS	NS	NS
Error (d), RSL	12									
CL	4	NS	NS	NS	NS	NS	*	*	NS	NS
SCL	12	NS	NS	NS	NS	NS	NS	NS	NS	NS
Error (e), RSCL	32									

NS = not significant
** = significant at 0.01 level
* = significant at 0.05 level

Table 3. Mean traction values for the designated variables obtained from rotational measurements in September 1991.

Variable	degrees of rotation				
	Initial	10	20	30	40
Species					
			Nm		
Tall fescue	8.3	27.9	37.4	40.9	41.3
Ky. bluegrass	8.3	27.3	36.6	40.4	40.7
Pr. ryegrass	8.2	25.8	34.2	38.0	38.4
Red fescue	8.2	25.5	33.8	36.6	37.3
lsd (0.05)	NS	0.8	1.0	1.4	1.2
Cutting Height(cm)					
			Nm		
3.8	8.3	26.9	35.6	39.3	39.8
5.1	8.2	26.7	35.7	39.2	39.8
6.4	8.3	26.3	35.1	38.4	38.7
lsd(0.05)	NS	NS	NS	NS	NS
Loading weight(kg)					
			Nm		
73.9	8.3	25.0	32.2	35.6	35.9
88.0	8.3	27.1	36.2	39.6	40.0
102.0	8.2	27.8	38.0	41.8	42.4
lsd (0.05)	NS	1.41	3	3.05	2.97

Table 4. Mean traction values for the designated variable obtained from linear measurements in September 1991.

Variable	cm of travel								
	Initial	0.6	1.3	1.9	2.5	3.2	3.8	4.4	5.1
Species									
	N								
Tall fescue	443	868	1,025	1,197	1,301	1,375	1,418	1,408	1,396
Ky. bluegrass	442	863	1,017	1,178	1,288	1,362	1,417	1,404	1,387
Pr. ryegrass	453	851	984	1,129	1,215	1,274	1,312	1,303	1,282
Red fescue	432	828	975	1,115	1,186	1,211	1,208	1,176	1,151
lsd (0.05)	NS	NS	NS	NS	68	66	72	82	91
Cutting Height (cm)									
	N								
3.8	445	856	1,004	1,171	1,274	1,338	1,371	1,348	1,317
5.1	438	849	1,002	1,157	1,250	1,306	1,341	1,326	1,309
6.4	446	852	993	1,137	1,218	1,273	1,305	1,294	1,285
lsd (0.05)	NS	NS	NS	17	20	26	33	36	NS
Loading Weight (kg)									
	N								
59.9	422	778	907	1,302	1,101	1,132	1,155	1,139	1,119
73.9	395	806	956	1,179	1,189	1,241	1,267	1,249	1,232
88	472	869	1,023	1,108	1,281	1,352	1,379	1,365	1,348
102	482	957	1,113	1,031	1,421	1,498	1,551	1,538	1,517
lsd (0.05)	NS	51	31	30	35	34	37	36	46

increment are shown in the appendix (Tables 15, 16, 17, 18, 19, and 20).

Significant block differences appeared to be related to soil water content rather than vegetative characteristics. Soil water contents varied across blocks on dates when traction values were determined. For rotational measurements, block soil water contents of 14.7, 20.2, and 23.0% (dry mass basis) were associated with average tractional values (averaged over all degrees) of 27.4, 29.9, and 29.3 Nm respectively. Block soil water contents for linear measurements were 4.9, 8.7, and 17.4% (dry mass basis) and were associated with linear traction values of 792, 754, and 749 N (averages of points where block significance occurred). Traction values were not significantly different for initial movement for both rotational and linear traction for the grass species, cutting height, and loading weight variables (Tables 3 & 4).

Significant differences among grass species and cutting height were not detected with linear traction until travel distances of 1.9 and 2.5 cm, respectively, were achieved. With rotational traction, a species effect was noted within each increment (10°) of travel; however, cutting height never significantly influenced rotational traction.

Although the turf differentially affected rotational and linear traction, the traction values at 30° and 3.8 cm of travel over all grass species, cutting heights, and loading weights were highly correlated (r = 0.94). Traction values for tall fescue and Kentucky bluegrass were not significantly different from each other but were significantly greater than perennial ryegrass and red fescue at 2.54 to 5.08 cm of travel and at 10° to 40° for linear and rotational measurements, respectively (Tables 3 and 4). Perennial ryegrass traction values were only significantly greater than red fescue at 30° for rotational measurements (Table 3) and between 3.81 to 5.08 cm of travel for linear measurements (Table 4).

Differences due to cutting height were obtained only for linear measurements. The 3.8 and 5.1 cm cutting heights had significantly greater traction values than the 6.4 cm cutting height from 1.90 to 3.81 cm of travel and the 3.8 cm cutting height also had significantly greater traction values than the 5.1 cm cutting height at 2.5 to 3.2 cm of travel(Table 4).

All loading weights were significantly different from each other and loading weight 102.0 kg provided the highest traction values (Tables 3 and 4) for both rotational and linear measurements. Only linear measurements on grass species x cutting height plots provided significant correlations among individual loading weights. Values obtained with each loading weight were not significantly correlated with shear vane data (Tables 5 and 6). Correlation between rotational and linear measurements for individual loading weights across species and cutting height were significant at p = 0.01 except for the 88.0 kg loading weight which was only significant at p = 0.05 (Table 7).

The tractional forces observed for both linear(N) and rotational(Nm) measurements can not be compared because of the different units. To convert rotational forces to N the radius of the sole that is in contact with the turf must be measured; however, because of the presence of the irregular cleat pattern this distance can not be defined or measured. As Nigg (1990) and Harper (1961) stated, linear and rotational forces should not be of the same magnitude; however, in this study although the units of measurement for rotational and linear forces could not be directly compared, they were highly correlated when grass species x cutting height x loading weight means at 30° and 3.8 cm of travel were compared.

The trends for both linear and rotational measurements were very consistent across all variables tested, and indicate that maximum tractional forces will occur at 3.2 cm for linear traction and 40° for rotational traction. It should be noted that even though 40° provided the highest traction values, separation among grass species, cutting height, and loading weight occurred at 30° for rotational measurements.

Table. 5 Correlation coefficients (df = 10) for rotational forces at 40° among PENNFOOT loading weights and between weights and shear vane values across all species x cutting height plots for measurements taken in September 1991.

PENNFOOT loading wt.	PENNFOOT 88.0 kg	PENNFOOT 102.0 kg	shear vane
73.9 kg	0.75 **	0.50 NS	0.14 NS
88.0 kg		0.61 *	0.32 NS
102.0 kg			0.32 NS

NS = not significant
** = significant at 0.01 level
* = significant at 0.05 level

Table 6. Correlation coefficients (df = 10)for linear force at 3.81 cm among PENNFOOT loading weights and between weights and shear vane values across all species x cutting height plots for measurements taken in September 1991.

PENNFOOT loading wt.	PENNFOOT 73.9 kg	PENNFOOT 88.0 kg	PENNFOOT 102.0 kg	Shear vane
59.9 kg	0.90 **	0.94 **	0.86 **	-0.14 NS
73.9 kg		0.88 **	0.88 **	-0.17 NS
88.0 kg			0.85 **	0.08 NS
102.0 kg				-0.21 NS

NS = not significant
** = significant at 0.01 level
* = significant at 0.05 level

Table 7. Correlation coefficients (df = 10) for linear force at 3.81 cm vs. rotational force at 40° for loading weights and between two sets of shear vane data across all species x cutting height plots for measurements taken in September 1991.

	-------- PENNFOOT linear --------			
PENNFOOT rotational	73.9 kg	88.0 kg	102.0 kg	Shear vane†
73.9 kg	0.84 **			
88.0 kg		0.70 *		
102.0 kg			0.75 **	
Shear vane‡				0.95 **

† = values obtained during period of linear force measurements
‡ = values obtained during period of rotational force measurements
NS = not significant
** = significant at 0.01 level
* = significant at 0.05 level

Comparison of Methods

Comparison of Rotational and Linear Traction with Shear Resistance

The shear resistance on the plots mentioned in the previous study (1991) was determined along with tractional forces by using the shear vane. Shear resistance was not significantly correlated with rotational and linear traction. The correlation coefficients for rotational and linear traction vs. the shear vane were r=0.30 and r=0.18, (both nonsignificant) respectively, when using means across all loading weights for the species x cutting height data. Rotational, linear and shear resistance measurements were compared with tiller density, verdure, and below-ground vegetation in an attempt to find a basis for these differences (Table 8). Significant differences for turf and soil characteristics are shown in Table 9.

The correlation between the shear vane and linear or rotational traction measured by the PENNFOOT provided weak correlation. The shear vane seems to be measuring primarily the shear resistance of the soil and below-ground vegetation because the fins on the apparatus are pushed through the turf and into the soil before a measurement is made. The PENNFOOT however, rests on the turf surface, with depth of penetration being a function of soil moisture, turf density,

Table 8. Correlation coefficients (df = 10) for PENNFOOT traction across all loading weights, grass species, and cutting heights vs. the shear vane and for the machines vs. below ground vegetation, verdure, and tiller density for measurements taken September 1991.

Treatments	PENNFOOT rotational at 3.81 cm	Shear vane	Below ground vegetation	Verdure	Tiller density
PENNFOOT linear at 40°	0.94^{**}	0.18^{NS}	0.55^{NS}	0.21^{NS}	-0.48^{NS}
PENNFOOT rotational at 3.81 cm		0.30^{NS}	0.57^{NS}	0.41^{NS}	0.30^{NS}
Shear vane			0.77^{**}	0.50^{NS}	-0.26^{NS}
Below ground vegetation				0.22^{NS}	-0.24^{NS}
Verdure					-0.84^{**}

NS = not significant
** = significant at 0.01 level
* = significant at 0.05 level

Table 9. Significant differences for the turf and soil characteristics of the plots used in September 1991 measurements.

Source	Degrees of freedom	Verdure	Below ground Vegetation	Tillers	% H_2O Rotation	% H_2O Linear
Block, R	2	NS	NS	NS	**	**
Species, S	3	**	**	**	NS	NS
Error (a), RS	6					
Cutting height, C	2	NS	NS	NS	NS	NS
SC	6	NS	NS	NS	NS	NS
Error (b), RC, RSC	16					

NS = not significant
** = significant at 0.01 level
* = significant at 0.05 level

shoe sole properties, and loading weight. Penetration often increases as traction measurements are made. It is speculated the correlation coefficient between the two machines may increase if tested on very moist turf environments. In comparisons of linear forces at 3.8 cm, rotational forces at 40°, and shear vane values with tiller density, verdure, and below-ground vegetation (Table 8), the shear vane had higher correlation values with below ground vegetation and verdure compared to PENNFOOT. Of plant characteristics measured, below-ground vegetation had the highest correlation with traction measurements.

The data from this study and the previous one indicate that initial movement for both linear and rotational measurements was not significantly affected by treatments. It appears that in order to find significant differences and the highest traction values among variables, measurements should be taken from 2.54 to 5.08 cm for linear traction and at 30° and 40° for rotational traction. If only the highest traction value is desired only one person would be required to obtain measurements. Pressure can be applied and the highest amount of pressure can be observed by one person before the pistons are fully extended or retracted.

Comparison of Three Machines Tested on Four Grass Species and Three Cutting Heights

In 1992 the species plots were tested again by using the PENNFOOT (rotational, 47.6 kg), Apparatus A, and the shear vane. PENNFOOT used in the determination of the effects of grass species, cutting height, and loading weight showed an increase in force as the shoe was rotated. These results indicate that the amount of force required to initiate foot movement was not the force that resulted in the greatest differences in traction among the treatments. Therefore, the procedure for Apparatus A was changed from measuring the force required to tear the turf(initial force) to the greatest force measured.

PENNFOOT showed little separation among grass species and no separation among cutting heights using shoe II (Table 10). Tall fescue provided the highest traction values at all positions measured. At 10, 20, and, 40° significant differences were not apparent among tall fescue, Kentucky bluegrass, and perennial ryegrass; however, values for tall fescue and Kentucky bluegrass were significantly higher than those for red fescue. At 30°, traction on tall fescue was significantly greater than on perennial ryegrass and red fescue.

The shear vane provided separation among all species with Kentucky bluegrass providing the most traction, but no separation was found among cutting heights (Table 10). With

Apparatus A, traction on red fescue was significantly higher than on tall fescue, Kentucky bluegrass, and perennial ryegrass. Tall fescue, Kentucky bluegrass, and perennial ryegrass were not significantly different from each other (Table 10). Using Apparatus A, cutting height 3.8 cm had significantly higher traction values than cutting height 6.4 cm (Table 10). Although differences among species measured by an individual machine were small, all three machines detected a different species as providing the highest traction. A negative correlation existed between Apparatus A and PENNFOOT (r=-0.81) for grass species x cutting height means. The results indicate that these machines were differentially affected by turf under the conditions of this experiment. Neither Apparatus A (r=0.07) nor PENNFOOT (r=0.02) correlated well with the shear vane.

In this study the separation among species with rotational traction was less pronounced than in 1991. The possible factors contributing to this difference are different shoe type, characteristics of the stand (root, tiller density, and verdure), and soil water content. Significant differences for turf characteristics and soil water content are shown in Table 11. Below-ground vegetation as found in 1991 had the highest correlation with traction measurements (Table 12). Apparatus A, however, had low correlation values with all plant characteristics. PENNFOOT's r values for below-ground vegetation and verdure

Table 10. Mean traction values for grass species across all cutting heights, and mean traction values for cutting height across all species for measurements taken in August 1992.

Variable	Apparatus A	Shear vane	PENNFOOT(47.6kg) at 40° degrees
Species			
		Nm	
Red fescue	25.3	18.1	14.5
Tall fescue	23.1	15.8	16.4
Pr. ryegrass	22.2	11.5	15.8
Ky. bluegrass	22.1	22.1	16.3
lsd (0.05)	1.4	1.3	0.9
Cutting Height(cm)			
		Nm	
3.8	23.8	17.0	15.7
5.1	23.1	16.8	15.6
6.4	22.6	16.8	15.9
lsd (0.05)	1.0	NS	NS

Table 11. Significant differences for the turf and soil characteristics of the plots used in August 1992 measurements.

Source	Degrees of freedom	Verdure	Below ground Vegetation	Tillers	Rotation % H_2O
Block, R	2	NS	NS	NS	NS
Species, S	3	NS	**	**	NS
Error (a), RS	6				
Cutting height, C	2	NS	NS	NS	NS
SC	6	NS	NS	NS	NS
Error (b), RC, RSC	16				

NS = not significant
** = significant at 0.01 level
* = significant at 0.05 level

Table 12. Correlation coefficients (df = 10) between the three machines across grass species x cutting heights and for the machines vs. below-ground vegetation, verdure, and tiller density for measurements taken in August 1992.

	Apparatus A	Shear vane	Below ground vegetation	Verdure	Tiller density
PENNFOOT rotational at 40°	-0.81 **	0.02 NS	0.29NS	0.10	-0.66
Apparatus A		0.07	-0.17	-0.32	0.29
Shear vane			0.93	0.33	-0.10
Below ground vegetation				0.36	-0.29
Verdure					-0.33

decreased from 1991 to 1992 while tiller density r values increased (Tables 8 and 12). The shear vane had a higher correlation coefficient (r=0.93) for below-ground vegetation in 1992 compared to r=0.77 in 1991.

Data from this study do not support the feasibility of calculation of a coefficient of traction as defined by Canaway and Bell (1986). As mentioned in the development section, one reason is the irregularities associated with the cleated sole and the irregular surface created in the turf/soil from the cleats. A second reason for not calculating a coefficient of traction relates to the properties governing static and kinetic friction. For any given pair of surfaces with the same normal force, the kinetic friction will be less than the maximum static friction (Higdon and Stiles, 1951). To relate this friction relationship to this research, the force required to initiate movement of the foot should have been the largest force measured; however, as the data show for both linear and rotational measurements the initial measurement was by far the smallest force measured. This occurrence may be explained by the cleats plowing deeper into the turf and soil as the sole is moved linearly or rotated, and deeper positioning would increase below ground vegetation encountered and would also increase the amount of compacted matter in front of the cleats.

The degree of rotation for Apparatus A where the maximum tractional force occurred was not documented, but usually occurred between 30 to 50° of rotation. In order to determine what each machine was actually measuring a much more detailed study utilizing a greater range of traction values is suggested for future research in which the relative effect of various factors affecting each machine can be ascertained.

Traction values using the shear vane (11-22 Nm) and traction coefficients (1.54-1.76) if calculated for Apparatus A are similar to values obtained by other researchers. Rogers et al. (1988) measuring traction on athletic fields using the shear vane found traction values ranging from 13 to 19 Nm. Baker and Bell (1986) using Canaway's device calculated traction coefficients ranging from 1.02 to 2.17 for natural turf pitches (athletic fields).

Comparison of the Five Methods to Measure Traction on Soil and Different Turf Densities

This comparison was set up in order to obtain a greater range of traction values for the various machines than was obtained in the previous study. The mean traction values for the different methods tested on the various plots are shown in Table 13. On these areas, greater ranges of values were obtained with the PENNFOOT and shear vane than with Apparatus A. With each method, traction was greater with tall fescue, Kentucky bluegrass, and thinned turf than on bare soil; however, full turf of tall fescue and Kentucky bluegrass gave greater traction than thinned turf only with the PENNFOOT and shear vane. Both the light and heavy weighted PENNFOOT showed least traction on the compacted turfgrass roadway. The differences among methods on this compacted area appeared to be a result of differential penetration. Correlation between different machines was low, although high correlation occurred between the light and heavy weighted PENNFOOT and between both procedures used with Apparatus A(Table 14). Correlation improved between PENNFOOT and Apparatus A when the Apparatus A was not dropped, and the shear vane correlated better with Apparatus A when the drop procedure was used.

Ideally, all the methods should correlate over all conditions that might exist on athletic field surfaces. In the previous study where turf conditions were optimum across all the species, the three methods did not show much difference among species except the one that provided the highest traction values. In this study however, the three machines varied from one another, indicating that they are

Table 13. Mean traction values for the three machines and their procedures for measurements taken on bare soil and different turf densities in August 1992.

Traction plot	PENNFOOT 102.0 kg	PENNFOOT 59.9 kg	Apparatus A dropped	Apparatus A not dropped	Shear vane
			Nm		
Tall fescue	27.7	15.8	20.0	17.0	17.0
Ky. bluegrass	22.9	14.2	19.0	16.0	23.0
Thinned turf stand	21.2	13.3	20.0	17.0	15.0
Bare soil	18.7	11.0	17.0	13.0	10.0
Compacted turf roadway	17.5	10.2	21.0	16.0	22.0

Table 14. Correlation coefficients (df = 10) between machines and their methods for measruements taken on bare soil and different turf densities in August 1992.

Treatment	PENNFOOT(40°) 59.9 kg	Apparatus A dropped	Apparatus A not dropped	Shear vane
PENNFOOT (40°) 102.0 kg	0.97^{**}	0.14^{NS}	0.55^{NS}	0.10^{NS}
PENNFOOT (40°) 59.9 kg		0.11^{NS}	0.59^{*}	0.12^{NS}
Apparatus A dropped			0.84^{**}	0.66^{*}
Apparatus A not dropped				0.55^{NS}

NS = not significant
** = significant at 0.01 level
* = significant at 0.05 level

probably measuring something different; that is, soil and turf differentially affect the force required to rotate these devices. As mentioned in the results of the second study in 1991, the shear vane was thought to measure the shear resistance of the soil and below-ground vegetation rather than traction. Rogers(1988) found with the shear vane that shear resistance increased with increasing bulk density. Apparatus A, using the standard drop procedure, had the highest correlation with the shear vane (r=0.66). Both the shear vane and Apparatus A depicted the compacted turf roadway as providing relatively high traction. This result would indicate that Apparatus A is also measuring the shear resistance of the soil, because the apparatus is dropped initially allowing the studs to penetrate through the turf and into the soil.

Another possibility for the differences between Apparatus A and the PENNFOOT is the design of the machines. Apparatus A has 6 studs arranged equidistant from the center of the machine whereas the PENNFOOT uses a studded shoe with twelve studs mounted in an irregular geometric pattern, with only the front seven being in contact with the turf during these measurements. Another design problem associated with Apparatus A, is measuring the moment of torque. In order to measure a moment, the forces acting on an object must be rotated about a central axis. It was noted that Apparatus A had a tendency to pivot during a measurement causing the center of the apparatus to be displaced about 2.5 cm from the original starting position. It appeared that the pivoting occurred around one stud that remained stationary, while the others shifted.

Characterization of Grass Species, Using Smooth Sole Footwear

The PENNFOOT, when set up for rotational measurements and equipped with leather sole footwear, detected the often observed differences in slipperiness among grass species. The mean rotational forces for grass species across the 5.1 cm cutting height and both the high (102.0 kg) and low (59.9 kg) loading weights were 17.4, 15.8, 15.1, and 12.2 Nm for perennial ryegrass, Kentucky bluegrass, tall fescue and red fescue respectively. The lsd (0.05 level) was 1.3 Nm. Thus the data show that perennial ryegrass provided more "grip" than Kentucky bluegrass, tall fescue, and red fescue. The amount of loading weight was also significant as in previous studies. A loading weight of 102.0 kg induced an average traction/frictional force of 18.9 Nm while the 59.9 kg loading weight had an average force of 11.3 Nm. The species x loading weight interaction was not significant. Although this study confirmed the slipperiness of grass species, this type of testing procedure is not adequate for athletic field characterization due to studded footwear worn by athletes.

SUMMARY AND CONCLUSIONS

This thesis includes a review of previous methods of traction evaluation and descriptions of the development, construction, and operating procedure for the traction measuring apparatus (termed PENNFOOT), which was used in the reported research.

Player safety on athletic fields has become a very important issue. Traction as it relates to field safety involves the athlete, studded footwear, and the turf. The variability among grass species and cultural practices associated with athletic fields may provide the largest influence on traction; however, these conditions have not been well documented.

Objectives of this research were:

1. Develop an apparatus and operating procedure to measure the horizontal forces associated with traction on natural turfgrass.

2. Determine how different cutting heights, different turfgrass species, and amount of loading weight influence traction on athletic field turf.

3. Compare this device to other devices used to quantitatively measure traction.

The PENNFOOT traction measuring apparatus consisted of a frame assembly, leg and shoe assembly, and a hydraulic system to create forces to horizontally move the cleated shoe. This apparatus allows the flexibility for measuring both linear and rotational traction, changing the amount of loading weight on the foot, and changing the footwear that is in contact with the turf.

The hydraulic system used to create tractional forces and the leg and shoe assembly are essential components of this apparatus. The frames, however, could be more compact and lighter as long as there is sufficient amount of weight to prevent the apparatus from moving when a measurement is taken.

The development and testing stages of the PENNFOOT provided useful information concerning traction and the procedure used for the PENNFOOT. Traction values for rotational and linear traction were found to increase as degrees of rotation (0, 10, 20, 30, and 40o) or linear increment (eight equal increments over 5.1 cm) increased and that traction values for initial movement were not significant. From these results and the properties of static and kinetic friction, it was concluded that a coefficient of traction as proposed by researchers in the past does not exist and should not be calculated.

Grass species, cutting height, and loading weight had an effect on traction, although the effects were not always the same for rotational and linear traction. Traction values for tall fescue and Kentucky bluegrass were not significantly different from each other but were significantly greater than perennial ryegrass and red fescue at 2.5 to 5.1 cm of travel and at 10° to 40° for linear and rotational measurements, respectively. Differences in cutting height were obtained only for linear measurements, with cutting heights of 3.8 and 5.1 cm providing significantly greater traction than 6.4 cm. All loading weights were significantly different from each other and loading weight 102.0 kg provided the highest traction values. Maximum tractional forces for all variables test were found to occur at 40° and 3.2 cm for rotational and linear traction, respectively.

Comparing the PENNFOOT to other traction testing machines on different species, cutting heights, and different turf densities, resulted in low correlations. It was proposed that the other traction measuring apparatuses were not measuring the same variables as the PENNFOOT; however, it is believed that the PENNFOOT, more than the other devices, is measuring characteristics of the turf that relate to traction as experienced by a player.

More work is needed on turf and soil characteristics that influence traction and on the geometry of traction testing machines. When this information is obtained, the appropriateness of the different machines can be determined. At present, it seems important to make traction measurements using methods that approximate the type of traction (linear or rotational), loading weight, footwear, and contact with the turf surface that are similar to real conditions.

Ideally, results with instrumentation will correlate with players' assessments of traction. Such comparisons need to be made in future research. The results of this research are based on the conditions used in the various experiments and different environments such as soil water content in the soil and on the vegetation, thatch, other vegetative characteristics, and shoe design may have a strong influence on future results.

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APPENDIX

ADDITIONAL MATERIALS

Definition of terms

Below-ground vegetation - the vegetative matter consisting of the crowns, thatch, rhizomes, and roots at and below the soil surface.

Coefficient of kinetic friction - the ratio of the kinetic frictional to the normal force.

Coefficient of static friction - the ratio of the static frictional force to the normal force.

Crown - a highly compressed stem with a succession of nodes separated by short internodes, located at the base of the leaves.

Force - an action capable of accelerating an object, the product of mass x acceleration, usually presented in N (newton).

Lever arm - the distance which is perpendicular to both the axis of rotation and to an imaginary line drawn along the direction of the force.

Linear traction - the resistance properties of natural turf when a studded shoe moves in a translational, or linear, motion; e.g., a front to back or side to side motion.

Newton(N) - the SI unit of force, $1N = 1kg(m/s^2)$.

Newton-meter(Nm) - the SI unit of rotational force,
$1\ Nm = 1\ kgm^2/s^2$.

Moment of force - the product of force times the lever arm.

Rotational traction - the resistance properties of natural turf when a studded shoe is rotated about a central axis.

Tiller - a lateral shoot, usually erect, that develops intravaginally from axillary buds.

Torque - rotational force, the product of force x lever arm (moment of force), usually presented in Nm (newton meter).

Turf - a covering of mowed vegetation, usually a turfgrass, growing intimately within an upper soil stratum of intermingled roots and stems.

Turfgrass - a species or cultivar of grass, usually of spreading habit, which is maintained as a mowed turf.

Verdure - the layer of green living plant tissue remaining above the soil surface following mowing.

Table 15. Mean rotational traction values for grass species x cutting height across all loading weights for measurements taken in September 1991.

	Cuttting	-------- degrees of rotation --------				
Species	height	Initial	10	20	30	40
	cm	------------------ Nm -------------				
Tall fescue	3.8	8.5	28.2	37.3	41.0	41.5
Tall fescue	5.1	8.2	28.0	37.4	41.3	41.6
Tall fescue	6.4	8.4	27.6	37.3	40.5	40.7
Ky. bluegrass	3.8	8.4	28.2	37.5	40.6	40.8
Ky. bluegrass	5.1	8.3	27.2	36.8	41.3	41.7
Ky. bluegrass	6.4	8.4	26.6	35.3	39.2	39.4
Pr. ryegrass	3.8	8.2	26.3	34.5	38.5	39.0
Pr. ryegrass	5.1	8.2	25.8	34.5	38.4	38.7
Pr. ryegrass	6.4	8.2	25.4	33.7	37.2	37.7
Red fescue	3.8	8.2	24.9	33.3	37.0	37.7
Red fescue	5.1	8.1	25.9	34.0	35.9	37.2
Red fescue	6.4	8.3	25.6	33.9	36.7	37.1
lsd (0.05)		NS	NS	NS	NS	NS

Table 16. Mean rotational traction values for loading weight x grass species across all cutting heights for measurements taken in September 1991.

Loading Weight	Species	degrees of rotation				
		Initial	10	20	30	40
kg		Nm				
73.9	Tall fescue	8.4	26.5	33.9	37.5	37.8
73.9	Ky. bluegrass	8.3	25.4	33.0	36.7	37.1
73.9	Pr. ryegrass	8.3	24.7	31.6	35.3	35.7
73.9	Red fescue	8.2	23.6	30.3	32.8	33.0
88.0	Tall fescue	8.5	28.2	37.7	41.2	41.5
88.0	Ky. bluegrass	8.4	27.7	37.4	40.3	40.4
88.0	Pr. ryegrass	8.2	26.0	34.6	38.5	39.1
88.0	Red fescue	8.3	26.4	35.1	38.3	38.9
102.0	Tall fescue	8.2	29.1	40.5	44.2	44.6
102.0	Ky. bluegrass	8.4	29.0	39.3	44.1	44.5
102.0	Pr. ryegrass	8.2	26.9	36.5	40.2	40.6
102.0	Red fescue	8.1	26.4	35.8	38.6	40.0
lsd (0.05)		NS	NS	NS	NS	NS

Table 17. Mean rotational traction values for loading weight x cutting height across all grass species for measurements taken in September 1991.

Loading Weight	Cutting Height	------- degrees of rotation ------- Initial	10	20	30	40
kg	cm	---------------	---------------	Nm	---------------	---------------
73.9	3.8	8.3	25.5	32.9	36.6	37.0
73.9	5.1	8.2	24.9	32.2	35.4	35.8
73.9	6.4	8.4	24.7	31.5	34.7	35.0
88.0	3.8	8.4	27.5	36.6	39.8	40.4
88.0	5.1	8.2	27.5	36.6	40.2	40.5
88.0	6.4	8.4	26.2	35.4	38.8	39.1
102.0	3.8	8.2	27.7	37.4	41.5	42.0
102.0	5.1	8.2	27.8	38.3	42.0	43.2
102.0	6.4	8.2	28.0	38.2	41.7	42.0
lsd (0.05)		NS	NS	NS	NS	NS

Table 18. Mean linear traction values for grass species x cutting height across all loading weights for measurements taken in September 1991.

Species	Cutting Height	Initial	cm of travel							
			0.6	1.3	1.9	2.5	3.2	3.8	4.4	5.1
	(cm)	Newtons								
Tall fescue	3.8	450	877	1,031	1,217	1,336	1,408	1,446	1,426	1,403
Tall fescue	5.1	428	863	1,034	1,197	1,303	1,380	1,429	1,425	1,414
Tall fescue	6.4	453	862	1,011	1,178	1,263	1,334	1,377	1,372	1,368
Ky. bluegrass	3.8	437	862	1,021	1,192	1,313	1,391	1,450	1,426	1,400
Ky. bluegrass	5.1	440	863	1,014	1,185	1,292	1,366	1,419	1,405	1,389
Ky. bluegrass	6.4	450	865	1,014	1,157	1,262	1,330	1,380	1,380	1,372
Pr. ryegrass	3.8	448	855	985	1,146	1,243	1,315	1,347	1,338	1,296
Pr. ryegrass	5.1	461	837	978	1,122	1,210	1,262	1,301	1,291	1,277
Pr. ryegrass	6.4	451	861	988	1,120	1,193	1,248	1,288	1,281	1,277
Red fescue	3.8	444	831	981	1,132	1,207	1,241	1,238	1,201	1,171
Red fescue	5.1	422	834	981	1,120	1,196	1,215	1,215	1,182	1,158
Red fescue	6.4	431	821	963	1,092	1,153	1,178	1,171	1,144	1,126
lsd (0.05)		NS	NS	NS	NS	NS	NS	NS	NS	NS

Table 19. Mean linear traction values for loading weights x grass species across all cutting heights for measurements taken in September 1991.

Loading Weight	Species	cm of travel								
		Initial	0.6	1.3	1.9	2.5	3.2	3.8	4.4	5.1
kg		Newtons								
59.9	Tall fescue	425	792	939	1,081	1,147	1,183	1,213	1,201	1,187
59.9	Ky. bluegrass	425	780	923	1,052	1,151	1,196	1,228	1,208	1,176
59.9	Pr. ryegrass	425	778	877	992	1,062	1,101	1,129	1,127	1,113
59.9	Red fescue	413	763	889	999	1,042	1,046	1,049	1,017	997
73.9	Tall fescue	398	821	984	1,151	1,252	1,319	1,344	1,326	1,312
73.9	Ky. bluegrass	400	809	972	1,129	1,214	1,287	1,337	1,312	1,298
73.9	Pr. ryegrass	406	817	939	1,087	1,154	1,208	1,252	1,246	1,228
73.9	Red fescue	376	778	929	1,063	1,133	1,151	1,144	1,113	1,088
88.0	Tall fescue	475	883	1,034	1,204	1,327	1,414	1,463	1,468	1,456
88.0	Ky. bluegrass	466	894	1,053	1,217	1,338	1,431	1,488	1,481	1,461
88.0	Pr. ryegrass	489	847	997	1,143	1,224	1,291	1,313	1,308	1,298
88.0	Red fescue	458	849	1,007	1,153	1,232	1,134	1,252	1,204	1,179
102.0	Tall fescue	476	974	1,143	1,352	1,478	1,579	1,651	1,636	1,626
102.0	Ky. bluegrass	477	968	1,118	1,313	1,452	1,538	1,611	1,615	1,612
102.0	Pr. ryegrass	495	963	1,122	1,296	1,421	1,498	1,554	1,533	1,492
102.0	Red fescue	481	923	1,073	1,246	1,336	1,372	1,387	1,368	1,341
lsd (0.05)		40.9	NS	NS	NS	NS	NS	NS	NS	NS

Table 20. Mean linear traction values for loading weight x cutting height across all grass species for measurements taken in September 1991.

Loading Weight	Cutting Height	---------- cm of travel ----------								
		Initial	0.6	1.3	1.9	2.5	3.2	3.8	4.4	5.1
kg	cm	---------- Newtons ----------								
59.9	3.8	425	782	908	1,044	1,112	1,150	1,175	1,151	1,111
59.9	5.1	416	784	919	1,044	1,118	1,150	1,179	1,161	1,143
59.9	6.4	425	767	894	1,006	1,072	1,094	1,112	1,104	1,104
73.9	3.8	389	813	965	1,118	1,207	1,255	1,277	1,248	1,222
73.9	5.1	394	805	961	1,115	1,200	1,259	1,285	1,262	1,245
73.9	6.4	402	801	942	1,090	1,157	1,211	1,248	1,238	1,228
88.0	3.8	483	879	1,028	1,207	1,319	1,400	1,422	1,401	1,375
88.0	5.1	466	858	1,016	1,168	1,267	1,327	1,362	1,359	1,347
88.0	6.4	467	869	1,024	1,162	1,256	1,330	1,354	1,336	1,323
102.0	3.8	482	950	1,116	1,319	1,461	1,549	1,609	1,594	1,561
102.0	5.1	474	950	1,109	1,298	1,417	1,486	1,538	1,521	1,503
102.0	6.4	490	971	1,116	1,289	1,387	1,454	1,505	1,499	1,489
lsd (0.05)		NS	NS	NS	NS	NS	39	43	NS	NS

Table 21. Mean weight of below ground vegetation per sample plug (81 cm^2 by 2 cm depth) for each species x cutting height plot measured in 1991.

Species	Cutting Height	----- Replications -----			
		I	II	III	average
	cm	------------- g/plug	-------------		
Red fescue	3.8	5.4	5.0	5.3	5.2
Red fescue	5.1	4.8	5.2	4.2	4.8
Red fescue	6.4	5.2	4.9	5.5	5.2
Ky. bluegrass	3.8	5.9	6.7	6.9	6.5
Ky. bluegrass	5.1	7.6	6.2	6.2	6.6
Ky. bluegrass	6.4	6.3	6.8	5.5	6.2
Pr. ryegrass	3.8	4.2	4.6	4.6	4.5
Pr. ryegrass	5.1	4.0	3.5	3.9	3.8
Pr. ryegrass	6.4	4.5	5.2	4.0	4.6
Tall fescue	3.8	5.5	5.4	5.7	5.6
Tall fescue	5.1	5.7	5.7	5.3	5.6
Tall fescue	6.4	4.5	5.9	4.1	4.8

Table 22. Mean weight of verdure per sample plug (81 cm^2) for each species x cutting height plot measured in September 1991.

Species	Cutting Height	---- Replications -----			Average
		I	II	III	
	cm	------------- g/plug	--------------		
Red fescue	3.8	2.4	3.3	2.8	2.8
Red fescue	5.1	3.9	4.2	4.0	4.0
Red fescue	6.4	4.6	4.9	4.2	4.6
Ky. bluegrass	3.8	3.6	3.2	3.5	3.4
Ky. bluegrass	5.1	4.2	3.5	3.1	3.6
Ky. bluegrass	6.4	3.9	3.5	3.8	3.7
Pr. ryegrass	3.8	2.1	2.5	2.9	2.5
Pr. ryegrass	5.1	2.8	2.8	2.6	2.7
Pr. ryegrass	6.4	2.6	2.5	2.9	2.7
Tall fescue	3.8	4.1	4.6	4.5	4.4
Tall fescue	5.1	4.8	4.9	5.4	5.0
Tall fescue	6.4	5.9	5.7	5.6	5.7

Table 23. Mean number of tillers per plug (81 cm^2) for each species x cutting height plot measured in September, 1991.

Species	Cutting Height	----- Replications ----			
		I	II	III	Average
	cm	------------	no./plug	------------	
Red fescue	3.81	152	175	176	168
Red fescue	5.08	198	201	147	182
Red fescue	6.35	127	132	186	148
Ky. bluegrass	3.81	200	136	164	167
Ky. bluegrass	5.08	170	164	145	160
Ky. bluegrass	6.35	163	106	145	138
Pr. ryegrass	3.81	141	184	228	184
Pr. ryegrass	5.08	175	161	192	176
Pr.ryegrass	6.35	178	168	145	164
Tall fescue	3.81	94	113	112	106
Tall fescue	5.08	104	86	119	103
Tall fescue	6.35	85	107	91	94

Table 24. Mean shear vane values for each species x cutting height plot measured in September 1991.

Species	Cutting Height	---- Replications ----- I	II	III	Average
	cm	----------------	Nm	----------------	
Red fescue	3.8	12.8	18.2	15.8	15.6
Red fescue	5.1	15.2	17.2	16.8	16.4
Red fescue	6.4	16.8	19.2	16.5	17.5
Ky. bluegrass	3.8	20.0	18.2	17.5	18.6
Ky. bluegrass	5.1	19.2	16.5	16.5	17.4
Ky. bluegrass	6.4	16.0	20.0	16.5	17.5
Pr. ryegrass	3.8	12.0	12.2	10.8	11.7
Pr. ryegrass	5.1	11.0	13.0	10.8	11.6
Pr. ryegrass	6.4	8.8	9.5	11.2	9.8
Tall fescue	3.8	16.5	16.5	13.8	15.6
Tall fescue	5.1	15.2	14.2	16.0	15.2
Tall fescue	6.4	16.5	14.5	16.2	15.8

Table 25. Mean weight of below-ground vegetation per sample plug ($81\ cm^2$ by 2 cm depth) for each species x cutting height plot measured in September 1992.

Species	Cutting Height	----- Replications ----- I	II	III	average
	cm	--------------	g/plug	-------------	
Red fescue	3.8	5.0	5.4	5.2	5.2
Red fescue	5.1	5.2	5.3	5.3	5.3
Red fescue	6.4	5.2	5.7	5.0	5.3
Ky. bluegrass	3.8	7.5	8.3	8.9	8.2
Ky. bluegrass	5.1	8.0	7.9	7.8	7.9
Ky. bluegrass	6.4	7.3	8.5	8.5	8.1
Pr. ryegrass	3.8	3.7	3.1	3.8	3.5
Pr. ryegrass	5.1	4.3	2.8	3.7	3.6
Pr. ryegrass	6.4	3.5	3.8	3.3	3.5
Tall fescue	3.8	4.9	5.4	4.6	5.0
Tall fescue	5.1	5.7	5.3	4.8	5.3
Tall fescue	6.4	6.2	7.0	5.4	6.2

Table 26. Mean weight of verdure per sample plug (81 cm^2) for each species x cutting height plot measured in September 1992.

Species	Cutting Height	---- Replications -----			Average
		I	II	III	
	cm	-------------	g/plug	-------------	
Red fescue	3.8	2.6	2.4	2.3	2.4
Red fescue	5.1	3.7	3.2	2.9	3.2
Red fescue	6.4	4.4	3.4	3.3	3.7
Ky. bluegrass	3.8	2.9	2.9	2.6	2.8
Ky. bluegrass	5.1	3.3	3.5	3.2	3.3
Ky. bluegrass	6.4	4.0	3.8	3.8	3.9
Pr. ryegrass	3.8	2.7	2.5	3.0	2.7
Pr. ryegrass	5.1	3.4	2.5	3.0	2.9
Pr. ryegrass	6.4	3.6	3.0	3.2	3.3
Tall fescue	3.8	2.8	3.0	2.7	2.8
Tall fescue	5.1	3.4	2.9	2.9	3.1
Tall fescue	6.4	3.6	3.7	3.0	3.4

Table 27. Mean number of tillers per plug (81 cm^2) for each species x cutting height plot measured in September 1992.

Species	Cutting Height	----- Replications ----			Average
		I	II	III	
	cm	------------ no./plug ------------			
Red fescue	3.8	217	153	226	199
Red fescue	5.1	257	217	213	229
Red fescue	6.4	183	205	186	191
Ky. bluegrass	3.8	193	183	189	188
Ky. bluegrass	5.1	178	162	175	171
Ky. bluegrass	6.4	144	149	145	146
Pr. ryegrass	3.8	235	243	229	236
Pr. ryegrass	5.1	248	187	198	211
Pr.ryegrass	6.4	165	164	163	164
Tall fescue	3.8	111	148	123	127
Tall fescue	5.1	120	99	103	107
Tall fescue	6.4	92	100	91	94

Table 28. Mean shear vane values for each species x cutting height plot measured in August 1992.

Species	Cutting Height	---- Replications -----			
		I	II	III	Average
	cm	Nm			
Red fescue	3.8	18.5	15.8	16.8	17.0
Red fescue	5.1	18.5	16.8	18.8	18.0
Red fescue	6.4	23.2	18.0	16.8	19.3
Ky. bluegrass	3.8	16.2	23.8	23.2	21.1
Ky. bluegrass	5.1	17.2	20.5	20.2	19.3
Ky. bluegrass	6.4	18.2	21.5	21.2	20.3
Pr. ryegrass	3.8	11.5	11.0	11.2	11.2
Pr. ryegrass	5.1	13.0	12.2	10.5	11.9
Pr. ryegrass	6.4	12.8	11.5	10.0	11.4
Tall fescue	3.8	16.2	16.5	13.8	15.5
Tall fescue	5.1	17.2	16.8	13.8	15.9
Tall fescue	6.4	18.2	17.2	12.2	15.9