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# I) Title Page

# Small Grant: Slip, Trip and Fall Injuries in Construction and Transportation

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# IV) Abstract

The initially proposed work was to evaluate the effects of various soil amendments on the occurrence of slip trip and fall injuries in the construction and transportation industries. These types of injuries represent a total lifetime cost of injuries in the ten's of billions of dollars. It was initially believed that the insight required for the work could be obtained from simple modulus measurements in the vertical and horizontal direction. To this end, initially modeling and testing was performed. It was then determined that the vertical modulus while coupled to the horizontal shear strength measure, needed to be independently evaluated. Vertical modulus was also found to be a secondary factor in the occurrence of slip as noted in the relevant literature. Therefore the emphasis was shifted to developing methods to measure the require shear failure of soil and boot interface. This effort has focussed on the development of test protocol for the measurement of kinetic coefficient of friction for the heel slide gait pattern and the sole slide gait pattern. The two failure modes, slipping and shear failures of the soil are considered using the approach taken in the work. The apparatus while promising does not at this point produce sufficiently repeatable measurements on soil tat soil amendments can be evaluated. It will be necessary therefore to step back and evaluate both the soil preparation system and the test apparatus to determine if measurements of kinetic coefficient of friction can be sufficiently reliable on soil surfaces to make meaningful conclusions based on in-situ measurements of the soil. This is the first effort found in the literature to join the work in terramechanics literature to the ergonomics of waling on unimproved surfaces. While the initial barriers are significant, the long term potential for the effort is great and could greatly impact a very costly type of lost time injury.

## V) Significant Findings

The most significant outcome of this work is the combining of the theoretical framework created in the soil mechanics and terra-mechanics literature with the understanding of the ergonomics literature on slip trip and fall. The resulting framework allows measurements to be made on soils and on work boots to assesses the likelihood of slip trip and fall injuries. The following testing must be performed in order to understand the effective boot deign and soil amendments on the likelihood of slip trip and fall injuries.

1) Soil must be controlled for moisture and type as done in standard soil testing. If an existing surface is being assessed, then the conditions must be consistent across the area to be tested. Moisture content and packing are first order effects, and other factors that impact primarily damping are of less concern
2) The vertical modulus must be assessed for a range of drop heights and velocities to assess the strain rate dependence of the soil and to obtain a reasonable estimate of the modulus change with depth. An accurate assessment of the modulus is required for evaluation of the depth of the effective layer of the soil. A single drop test is insufficient, but the drop weight (estimate of the foot mass) is less critical than the contact area and velocity of impact.
3) Use of a soil test box will allow the testing of new soil amendments to be done in a manner which will allows the depth of influence to be evaluated. This is critical since the depth of influence determined the required soil preparation depth as well as the effective depth of the soil fiber distribution.
4) The testing of slip thus requires that the soil be prepared to the appropriate depth. Soil preparation to the correct depth is required for creating a repeatable surface for testing of boots. Soil preparation depth is also a key variable in the placing of soil amendments to the required depth. Further, the vertical modulus of the soil impacts the shear modulus measurement since the stress with depth is a function of the modulus. In this configuration both the heel-slide gait pattern, $\mu_{k1}$, and the sole-slide gait pattern, $\mu_{k2}$ kinetic coefficient of friction need to be evaluated. During these measurements the following need to be controlled or measured: normal force, sliding velocity and horizontal force.

Based on these measurements an apparatus can be developed that will be able to characterize soils and boots in-situ and to compare surfaces for potential engineering controls. A prototype apparatus required for these measurements has been developed and demonstrates a number of the challenges facing such a system.

## VI) Usefulness of Findings

Reduction of workplace injuries is important to reduce the human cost of injuries, as well as the financial losses that result from insurance claims and lost productivity. It has been clearly recommended that, with respect to eliminating worker exposure to hazards, engineering controls are preferred and should be used as a first line of defense in the efforts to reduce workplace injury (NIOSH 1988 and OTA 1985). However, prior to implementing any type of engineering controls, a sufficient understanding of the problem must exist to facilitate proper technology selection. The process of slip trip and fall injuries is not completely well understand even for the more direct problem of physical interaction of industrial floor surfaces with the sole materials of footwear (Ridd and Manning 1995). For construction and transportation industry workers, the work surface may be either a graded or ungraded soil surface. The complex interaction between the visco-elastic shoe sole and the soil determines the safety of the work surface in these industries. Because of the work environment, the construction and transportation industries have the highest per capita cost of injury due to slip, trip and fall injuries. This effort began the process of measuring in-situ the interaction between work boots and the work surface for these industries. Test of an engineering control approach requires a better understanding of the potential for success of several different approaches. In particular it is likely, depending on the situation, that either custom sole design or walking surface modification may be appropriate as a control of the risk to workers. Thus the system used to test approaches must make it possible to test shoe soles in-situ, along with potential surface modifications.

The effort invested into the research is worthwhile since based on a human capital approach, the total lifetime cost of injuries due to falls in the USA in 1985 was estimated at $37.3 billion (Rice et al, 1989). Falling is the second highest cause of work-related fatalities with the number of fall fatalities exceeding the combined number of workplace deaths associated with poison, electric current, fire, burns, and drowning (National Safety Council, 1993). Slipping and falling may be caused by a variety of factors: slippery or uneven flooring, contaminants, footwear, loss of balance, poor lighting, unexpected change in floor condition, pushing, pulling, carrying objects, stopping, and turning. Due to the large number of factors involved in slip and fall accidents, no single solution exists to this problem.

Falls were the most costly claims for the construction industry and ranked second for trucking companies (motor vehicle accidents were the most costly) (Leaman & Murphy, 1995). Construction and trucking had the highest cost per capita of eight industries investigated for claims from falls with the majority of these falls occurring on the same level, not from an elevation (Leamon & Murphy, 1995). The study into causes and solutions to slip and fall accidents on soil as seen by construction workers and truckers requires that the mechanics be understood. Even though this is a major problem on the work-site, no investigations have been made into slips and falls on soil surfaces. A number of extensive studies have examined solid type surfaces (Gronqvist, 1995; Leclercq et al, 1995a; Leclercq et al, 1995b; Myung & Smith, 1997). However, the mechanisms and solutions for slips and falls on loose, granular surfaces are expected to be significantly different from solid surfaces.

## VII) Scientific Report

### *A) Key Factors in Slip and Trip*

On a soil surface, two factors have been determined to be of primary concern in the development of a model of slipping and tripping. The first, the vertical modulus, is key to understanding the soil mechanics and to determine the depth of the soil layer that will be impacted by the vertical loading of the soil. The other key element is the soil shear strength with load that is analogous to the interaction for slip resistance of floors. Because of the interaction with the shear strength of the soil at depth it is thus necessary to separate out the two measurements. As a result, it is necessary to perform studies which will lead to an understanding of the interaction with soil loading and depth of the surface layer in order to engineer a soil as initially proposed.

In order to fully understand the mechanisms of slip trip and fall on soil surfaces, a number of theoretical and experimental issues must be resolved. One of the most important is to understand more fully the generation of shear banding in soils. In dense granular soils, homogenous deformation takes place up to a certain peak stress. Beyond the limiting stress, the deformation suddenly localizes into narrow zones called shear bands. In the shear band, large voids are generated and a high gradient of particle rotation occurs in the soil [Iwashita and Oda, 1998].

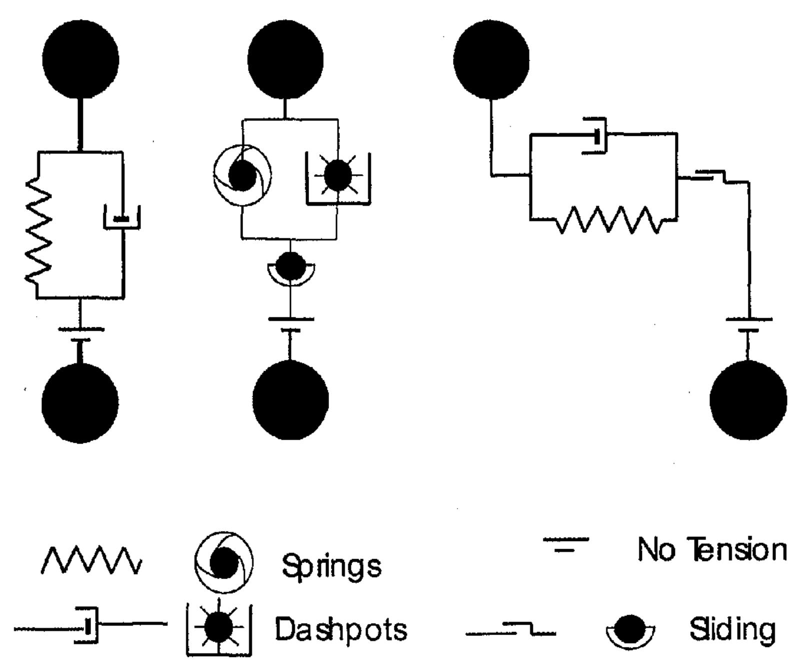



**Figure 1: Models of soil for different gait phases in normal level walking. Toe-off and heel contact are critical to slipping, where the high horizontal forces (more than 15% of vertical force) are present.**

### *B) Vertical Modeling of Ground/Foot Impact*

In order to understand the dynamics of the soil underneath the foot, it is critical to know both the loading rate of the foot as well as the peak loads that will be experienced in the soil. As a result of the visco-elastic response of the soil and the elastomeric response of the shoe sole, the problem is coupled. While it is known that the kinetic coefficient of friction $\mu_k$ is reduced significantly as a result of changing contact pressure on floors [Gronqvist, 1995], this same background knowledge does not exists in for granular surfaces. In such a coupled problem it is necessary to obtain at least an order of magnitude understanding of the modulus of the soil, prior to being able to evaluate either the loading conditions or the effective strain rate of the subsurface layers.

Both when the foot hits the ground and during the time that the foot is in contact with the ground, a force is exerted on the foot by the ground. The components which will be considered are: the vertical component which supports the weight of the person, the fore/aft component which first resists the sliding of the foot and then functions to propel the person on push-off, and medial/lateral components which stabilize the gait.

The magnitude and time varying characteristics of the GRFs are dependent on several factors. These factors include the size and mass of the foot (**m**), the mass of the person (**M**), the velocity of the foot and person at ground contact, the stiffness of the limb (**$k_1$**), the stiffness of the shoe sole and soil (**$k^*_1$**) and shock absorbing qualities of the shoe sole and soil (**$c_1$**) (Alexander et al, 1986). The stiffness of the limb, shoe sole and soil may all be mechanically represented by springs with different spring constants. The shock absorbing qualities of the sole and soil may be mechanically represented by dashpots with appropriate damping coefficients. The springs and dashpots can then be combined into a single spring and dashpot using the standard methods for addition of springs and dashpots (Figure 2(a)). This model has been shown to predict GRFs in the vertical direction with great accuracy for animals with compliant paw pads assumed to be landing on an infinitely stiff surface (Alexander et al, 1986). The equations of motion for this system are:

$$\ddot{Z} = \left(\frac{k_1}{m_1}\right)(Z - z) - g$$

and

$$\ddot{z} = -\left(\frac{k_1^*}{m_1}\right)z - \left(\frac{k_1}{M_1}\right)(z - Z) - \left(\frac{c_1}{m_1}\right)\dot{z} - g$$

if foot is on ground or

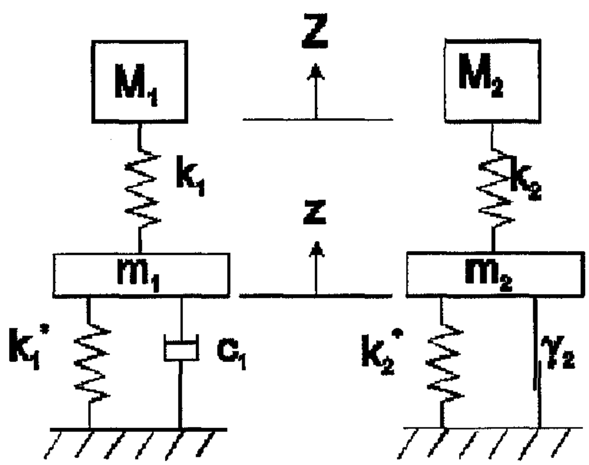
$$\ddot{z} = -\left(\frac{k_1}{m_1}\right)(z - Z) - g$$

if foot is off ground.

In contrast Figure 2(b) shows a model of damping which is much more consistent with the expected behavior of a soil sole interaction model. The differential equation that would describe the sliding and directional friction (or Coulomb damping) shown in the other model is less familiar and would present more of a challenge for the modeling. The additional complexity results since the time dependence of the combined loading would need to be included in the model. The equation of motion for the second model when the foot is in contact with the ground would be of the form:

$$\ddot{z} = -\left(\frac{k_2^*}{m_2}\right)z - \left(\frac{k_2}{M_2}\right)(z - Z) - \left[\frac{(M_2+m_1)\gamma_2}{m_2}\right]\frac{z}{|z|} - g$$

Air or turbulent water type of damping has also been used as an interaction model with granular material. For air type damping a velocity squared term similar replaces the Coulomb damping term with the direction opposite to the direction of propagation. The alternative representation of damping behavior has been used to better represent the behavior of the interface compared to the viscous case if the visco-elastic behavior of the interfaces is determined not to be a secondary effect. Even the more general form of the model cannot be determined without preliminary experimental results from representative surfaces.




(a) (b)

**Figure 2: Models for calculation of ground reaction forces in vertical direction. (a) Separate spring/dashpot models for foot and soil. (b) Alternative spring damping model of foot and soil.**

The variation in loading of the soil will alter the strength of the soil over the period of the stance phase of the step. The susceptibility to slip is in turn dependent on the shear strength of the surface. Knowing these parameters will allow for improved traction on soil surfaces by altering the material of the walkway or custom designing the tread for the surface.

The vertical impact model was created based on the work of Alexander *et al.* (1986). Alexander's model examined the role of quadrupedal footpads during the stance phase on an incompressible surface. The magnitude and time varying characteristics of the VGRF are dependent on several factors, including: the size and mass of the foot (**m**), the mass of the person (**M**), the mass of displaced soil (**$m_s$**), the velocity of the foot and worker at impact, the stiffness of the limb (**$K_l$**), the stiffness (**$K_h$**) and damping qualities of the foot and work boot (**$C_h$**), and the stiffness (**$K_s$**) and damping qualities of the work surface (**$C_s$**).

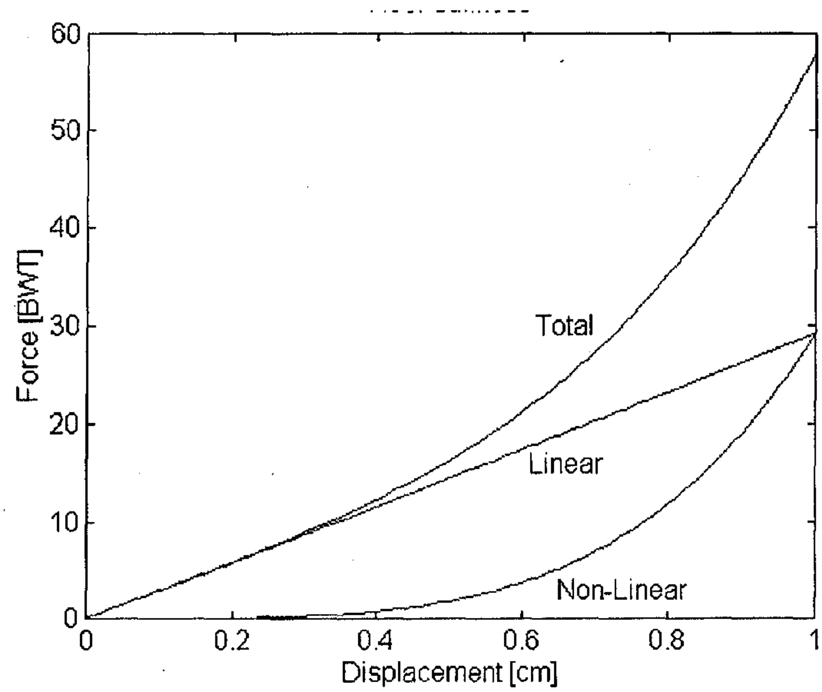



**Figure 3: Spring stiffness used in model for non-linear response.**

The stiffness of the limb, foot, and work surfaces are modeled by springs with appropriate response characteristics and spring constants. The damping qualities of the foot and work surface can be modeled with equivalent viscous dashpots. A linear spring is used to represent the leg and surface while the foot is modeled as a non-linear spring with a stiffness that is proportional to the sum of the distance compressed plus the distance compressed to the fourth power (Alexander et al. 1986). Under this type of non-linear spring stiffness, when displacements are small the exponential term in spring stiffness has little effect, however, as the compression increases the stiffness also increases. The additional exponential term prevents the foot and sole from compressing beyond realistic limits (Fig. 3).

The spring stiffness and damping coefficient of the work surface will vary depending on the granular structure, moisture content, amount of organic material, and density of the soil (Barry et.al., 1991). In addition, the change in these properties with depth must be accounted for when accurately modeling the response characteristics under loads. The soil model also includes consolidation. The soil material is twice as stiff on unloading as it is on loading and does not return to its original height (Vyalov, 1986), effectively leaving a footprint.

Arbitrary values of the constants were used in the initial modeling of the work surface in order to evaluate the sensitivity to different measurements. This step reduces the required data acquisition from the project and allows the effort to be focussed on the portion of the work with the greatest potential for results. The relative levels of force resulting from variation of the soil surface are thus obtained which can lead to a greater understanding of the processes that occur. The model sensitivity to the mass of the boot/foot, mass of displaced soil, and surface area of the sole of the boot was tested. These values were independently altered by plus and minus 50% of the base values and results were computed for one of the intermediate surfaces (medium soil with damping ratio of 15% of critical damping).

The initial vertical velocity of the center of mass was set at -0.1m/s. Soil material parameters were selected based on soil engineering studies (Das, 1983). These studies categorized the soils as: weak (stiffness=20,000[kN/m$^3$]*Area[m$^2$]), medium strength (40,000*Area), or strong soils (75,000*Area), and rocks (100,000*Area). Weak soil includes clay and silty clays with sand in a plastic state; clayey and silty sands; also soils with laminae of organic silts and of peat. Medium strength soils include clays and silty clays with sand close to the plastic limit, and sand. Strong soils include: clays and silty clays with sand of hard consistency, gravels and gravelly sands, and loess and loessial soils. The spring constant for each of these surface categories is obtained by multiply the reported elastic subgrade modulus by the area under impact (Das, 1983). Damping ratios for soils range from approximately 0.1 to just under 0.3 (Hardin and Drnevich 1972). The soil damping ratio ($\xi$) is related to the soil damping coefficient (**$C_s$**) in the following manner:

$$\zeta = \frac{C_s}{\sqrt{4 \cdot m_s \cdot K_s}}$$

When the damping ratio is multiplied by 100 it is referred to as the percent of critical damping.

Results from the preliminary modeling suggest that factors other than soil damping may be most important for the prediction of response to footfall. The subtle impact of damping on the VGRF loading rate, energy dissipation, and stance phase duration all indicate that previous approaches that later soil damping are unlikely to significantly impact the vertical forces or the loading rate. Alterations in surface stiffness or foot contact area appear to be more important in determining the level of these loading factors. It is, however, necessary to verify that the damping ratios of actual construction site materials do not vary over a greater range than that used in this study. The results do suggest that soil amendments that primarily alter surface damping may not be particularly important factors in determining the force versus time characteristics of the walking. As previously mentioned, however, the force versus time character is important in determining the strength and stiffness of the soil in the horizontal direction, and thus the likelihood of slip. What is uncertain as well is how the walker responds to feedback from soil stiffness.

More significant than damping effects are results in which soil surface stiffness is altered. The area in contact with the surface plays a major role in the loading response.

A 50% change in the area has the effect of making the surface respond with a stiffness characteristic of a different soil type. This is a less important issue if the shoe area of a worker is clearly associated with body size. However with different tread designs, it is possible that effective surface area may be dramatically different for different workers. The sensitivity analysis does show that altering the foot area does not change the characteristic pattern of the ground reaction force. Future investigative research should be conducted to quantify these input parameters for the model. Better understanding of these values will make it possible to accurately predict the loading response under different conditions.

While significant potential exists for extensions to the model, prioritization of efforts may be considered based on these results and the data required for shoe or soil design. Extensive kinematic data may be obtained with relative ease to verify the center of mass and foot velocities at impact. However the model indicates that the second order characteristics of the mass of the foot will not result in a large error in the estimated loading using the current approach. One exception would be if gait is significantly altered by the surface characteristics. To determine if gait is altered, kinematic data must be collected on various surfaces to confirm that center of mass and work boot velocities remain relatively consistent on surfaces with different stiffnesses. If the kinematics vary on different surfaces these effects may be accounted for using the current model.

Addition of the horizontal motion of the center of mass of the subject would result in the foot leaving the surface at the end of stance. The horizontal motion of the center of mass will reduce the contact time of the foot on the surface, since one component of the inertia will pull the leg in the direction of motion after the center of mass passes over the foot. The addition of the horizontal component will also alter the direction of the resulting loading force in the soil, the sum of the vertical and horizontal components. Soil failure is likely to be dependent both on the direction and the magnitude of the soil loading force. This motion will make the stance duration times more realistic for all surfaces. This change would be expected to significantly alter the vertical loads during the latter portion of the stance phase. Reductions of the vertical component will in turn reduce the shear strength of the soil and increase the likelihood of breaking the foot out of traction.

Most importantly, in addition to the vertical displacements and forces of the foot, the foot has horizontal displacements, velocities, accelerations, and forces that are non-zero. The foot has initial horizontal motion that first causes braking forces (to resist sliding) at initial impact and then propulsive forces. These horizontal motions and ground reaction forces are expected to be significantly affected by the surface material properties and, therefore, may contribute to the safety of the worker. Additional horizontal motion occurs during lateral movements which subjects the leg to additional forces. The resulting stress field in the soil under the boot will control the shear strength of the soil.. The reduced shear strength at the beginning and end of the contact with the ground is expected to be a controlling factor in slip.

### *C) Experimental Approach*

The experimental approach has four segments: the vertical soil loading, the shear tests of the soil, kinematic data and sensitivity to engineering controls based on soil amendments. The initial effort included small-scale efforts in all of these areas to evaluate the potential for future application of the controls. Due to errors in the models of the initial mechanisms associated with slip trip and fall, the experimental portion of the work was not completed as proposed. Instead, an emphasis was placed on developing procedures that extends measurement methods such as those used by Gronqvist et. al. to soil surfaces [1989].

### i) Vertical work-site soil loading characteristics

The testing procedures used for the assessment of the cushioning properties of a surface can be assigned to one of the following groups: drop tests in which a dropping mass falls onto a test foot containing force sensors that lies on the surface of interest, drop tests in which the dropping mass which is outfitted with impact sensors falls directly onto the surface of interest, drop tests in which the dropping mass falls directly onto the surface of interest which has force sensors underneath the surface, test procedures to determine the stress-strain characteristics of a surface sample, test procedures in which subjects perform typical movements on the surface of interest and the forces are quantified, and test procedures in which subjects perform typical movements on the surface of interest and in which the deformation of the surface is quantified.

Each of these methods has its shortcomings (Nigg, 1990). The drop tests have the advantage of being easily replicated from surface to surface. However, they generally are limited by the assumption that there is a well-defined correlation between the impact forces measured by the test and the impact forces acting on a subject's body. Nigg & Yeadon (1987) showed that this speculation is not correct. This does not completely rule out the use of drop tests for quantifying vertical loading characteristics of a work-site surface. It does, however, require modifications to the drop tests so that the soil is not just tested using a single mass dropped from one height. Multiple masses dropped from a variety of heights are required to quantify the loading characteristics of the soil. This will provide data for accurate calculation of ground reaction forces on a construction worker's foot during walking on the work-site, since as the foot strikes the ground the soil response is due to the mass of the foot alone (Alexander et al, 1986). The initial mass then slowly increases as the person puts more weight on the foot. Subsequently, the mass decreases to zero as the foot leaves the ground. Hence, the mass applied to the ground and the soil reaction are functions of time during the stance phase of gait. It is also important to note that nearly all constitutive models of granular surfaces have been observed to be rate dependent. Thus, the loading rate must be consistent with that seen in the actual loading of the foot on the soil. This is particularly challenging for a situation such as walking where the subject has control feedback that can be used to limit the peak loads. Thus, loading rate can be reduced by a change in gait as a result of variation in surface modulus.

Drop tests are most appropriately used with a mass has similar size and shape of a person's foot to quantify the vertical loading characteristics of the soil. The mass and drop height will be varied starting with a mass that is similar to the mass of a human foot and work boot , dropped from a height that will produce a velocity similar to the entrance velocity of the foot at impact. The mass and drop height of the simulated foot/boot is then increased until no further changes in the response of the soil is measured. This will allow the subsurface soil characteristics to be monitored to the depth required. The maximum load on the foot will determine the depth of the peak stress. The horizontal region and vertical zone that serves as a cushion for footfall will also be impacted by the peak load. More importantly, the location of the peak stress in the soil will, depending on soil compaction, determine the portion of the soil that will serve as the limiting factor in the soil shear strength.

### ii) Horizontal testing of work-site surface loading characteristics

The testing procedures used for the assessment of the frictional properties of a surface can be assigned to one of the following groups: sliding or rotational tests using a test foot with a standard material or with various shoes and sliding or rotational tests with subjects performing typical movements. As with the vertical testing procedures, the horizontal tests also have their limitations (Nigg, 1990). The main issues to keep in mind are: frictional resistance depends on the characteristics of both the foot and the surface, absence of a well-defined correlation between resistance to translational and rotational movement, and the drastic impact of the normal force on the results of the tests. In addition, the loading rate will influence both the depth of the soil that is impacted by the loading of the foot, and the normal force is under the control of the subject. Therefore, the horizontal loading problem becomes coupled with vertical loading results. The loading rate and the resulting normal force also determine issues such as the depth of soil preparation required for the tests.

It was initially proposed that the same simulated foot be used in the horizontal loading response tests that was used in the vertical loading response tests. It was proposed that the mass of the simulated foot will begin at the mass of a typical foot and work boot and be systematically increased similarly to how the vertical response tests were conducted. A modal hammer from the rear (Figure 4) would have then been used to strike the simulated foot. A force transducer attached to the rear of the simulated foot to measure the impact force and accelerations would be measured.

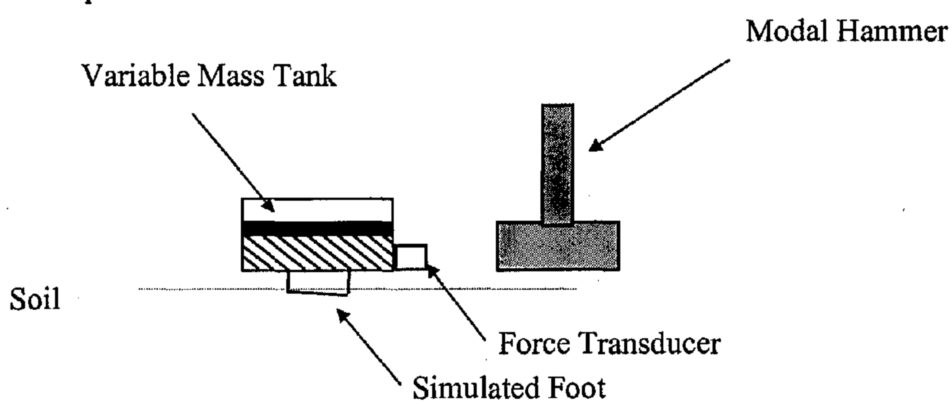



**Figure 4: Initially horizontal soil testing device. Changing the volume of the water will vary the mass in the tank. A plate will cover the water to prevent water movement from affecting the response of the system.**

These initial tests were performed on the reference soil before identifying the essential error in the procedure. What is being measured this test is the horizontal shear modulus of the soil at a range of loading. This will impact the loading time on the sole, and may be a factor in a more complete modeling of the shoe sole ground interaction. However, this test is flawed in that it does not measure the shear strength of the soil. Other more traditional soil shear strength tests are also flawed however because they do not simultaneously measure the shear strength of the soil while increasing the vertical load on the soil. Because of compaction of the soil and the dynamic response effects of the granular media, it is not realistic to expect the soil strength to be well represented by a generic vane type soil test. Such vane tests are sufficient for comparing the relative response of soils (much like a single drop test) if factors such as moisture content are controlled; however, they are inadequate for determining the likelihood of slip on a particular surface. The horizontal spring constants (**k**) and dashpot coefficients (**c**) can be determined from the test that was initially proposed, as well as the type of spring and dashpot (linear, exponential, or infinite). However, the strength of the soil cannot be tested and thus the effect of the fibers on slipping will not be appropriately considered. Therefore an approach was required which would provide information that was directly applicable to the characterization of slip trip and fall on soil and also that would allow soil surfaces to be compared.

### iii) Modification of the Horizontal testing of work-site surface

Because of the lack of published information in the ergonomics literature on slip, trip and fall on soil surfaces, it was necessary to look at other related fields in which similar sort of measurements are required. Over the course of several decades, a large effort has gone into reducing the impact on vegetation and soil surface by the passage of wheeled vehicles. Chiefly because of needs in the agricultural area, models and testing techniques have developed for similar configuration to those that are needed for testing of boots on soil surfaces. These range from test configurations that provide the resistance to the interactions of a lug with a soil surface [Hermawan et. al, 2000] to the determination of soil deformation patterns below the surface [Shikanai et. al., 2000].

The modified approach extends work in terra-mechanics to footfall measurements while somewhat simplifying the most accurate systems used for measurement of slip resistance on floors. For example, Gronqvist and co-workers [1989] developed a planar system with a full three degrees of freedom for the measurement of slip resistance in footwear and floors. As noted by Gronqvist et. al., the key points in the gait phases are heel contact and toe-off peaks, where the horizontal force may be as high as 25% of the vertical force. Thus, as a simplification of the Gronqvist apparatus, the rotational degree of freedom was designed to be fixed, with the angle of the work boot being adjustable within a small range to represent the heel-slide gait pattern for measurement of $\mu_{k1}$. In this case, the first critical gait phase was of particular focus because the weight of the body is maintained on the forward foot due to the momentum of the walker. Suggestive depth of influence information was obtained from the terramechanics literature [Shikanai et. al, 2000]. However, due to the newness of the approach, it was determined that the apparatus should follow the design of systems used for verification of numerical models of soil interaction. In this way, both the depth of influence can be evaluated, and the potential for deep burial of the fibers can be evaluated.

When walking on a soil surface, three principal mechanisms contribute to the frictional force generated between the shoe sole and the surface.

$$F_\mu = \begin{cases} F_a + F_h \text{ if } F_\mu \le \sigma_f \\ \sigma_f \text{ if } F_\mu > \sigma_f \end{cases}$$

The mechanisms for the first case are the same as that encountered on solid surfaces. The frictional force is a function of adhesion and hysteresis (Moore 1972, p. 249). However the area of contact and the role of the contact area is significantly different on a soil surface where there is both macroscopic and microscopic interpenetrating of the surfaces. Soil surfaces also present some additional challenges with respect to the less well-characterized visco-elastic material properties that in turn impact the maximum frictional force that it is possible to generate. However, unlike normal dry walling surfaces, the potential also exists in soil interfaces for failure to occur in the shear of the soil beneath the surface prior to slipping on the surface of the soil. In this second case, the granular media of the soil will slip relative to itself and case the same effect as slipping of the shoe on the interface. Thus any apparatus that was developed needed to consider both of the failure modes and the fact that the two failures may not be independent. By changing the modulus of the soil, the effective area of loading is altered and thus the visco-elastic properties of the soil that control the frictional forces are in turn changed. Like any situation where the factors that control multiple failure modes are interrelated, improvements in one measured parameter will not necessarily improve the performance of the system.

The approach that was determined to be necessary was that an apparatus modeled on Gronqvist et. al. (1989) that was modified to simplify the system as noted above. The apparatus was then combined with a soil testing box similar to that used by [Shikanai et. al., 2000]. This apparatus allows the resistance to slip to be measured for a typical work boot, while at the same time enabling the soil deformation to be envisioned below the surface when used with the soil box. It is also possible to remove the apparatus from the legs and the soil box. Using just the loading frame, an air supply and 110V power, it is then possible to test soils in-situ. The apparatus is more fully described in a paper that is currently in preparation (Peterson, in prep.)

### iv) High speed videography of footfall on soil

It was not intended that a significant quantitative data gathering would occur regarding kinematics in this initial small grant effort. In future efforts, high-speed videography can be used to supplement the testing of the impact stiffness and shear strength of the soil. It is of particular interest to determine if walkers adapt to soil conditions by altering gait characteristics. While extensive kinematic data may be obtained with a reasonable amount of effort, the mass of the foot is sufficiently low that effect on the calculated value of the vertical loading component would be expected to be minimal. However, the adaptation of gait to the surface stiffness would be expected to have a significant impact on the horizontal and vertical components of the acceleration. As a result, understanding of the gait variation with surface characteristics is key to the development of a general model of work boot soil interaction. The use of the soil box for the test apparatus developed for this work, will allow in-situ measurements of gait to be compared to the measurements made in the clear soil box. These measurements will then allow the soil models to be expanded to include an appropriate depth characterization for the soil.

### v) Comparison to engineered soils

An important alternative to shoe tread design is the use of engineered soil surfaces when an unpaved path will be used for considerable foot traffic. This technology has the potential to be a low cost solution for applications where temporary surfacing is impractical or undesirable but where significant foot traffic is expected. This approach is important once the primary issues related to slipping on soil and sand are understood. Not only is it possible to alter the stiffness of the soil using continuous fiber reinforcement, but the ultimate strength of the soil can also be adjusted based on the stiffness of the fiber (Michalowski 1996). Stiffness of the soil would be, for example, increased with the use of steel fiber reinforcement and would be reduced with the addition of polyamide fibers. The expense in either of these cases would be minimal since the fibers are not costly and they can be added using a roto-tiller. This is accepted technology for the use of temporary airfields in rapid deployment applications (Michalowski 1998). Engineered soils provide the potential to adjust the breakout force of the soil as well as the stiffness with which the initial footfall occurs. In situations where vision may be partially obstructed due to carrying or pushing equipment, an *increased* soil stiffness may even be desirable to provide additional feedback for walking.

In the initial effort several fibers were considered. Because of environmental concerns that fibers could become airborne and a lack of data in this area, the tests were limited to evaluation the effect on water uptake of the soil and breakdown over time. Further work is needed with the risk assessment of fibers in soil, both for this new application and for existing applications in sporting fields. Fibers that would not break down in the soil were not considered because of potential long-term environmental risks. Polyamide fibers were found that would be suitable but represent a number of concerns including cost, availability and other issues.

## *D) Experimental design*

The proposed effort is intended to frame the parameters of an investigation into development of an engineered soil/work boot interface. Given the magnitude of variation expected between and locations within regions, a simplified experimental design was proposed to determine the feasibility of the approach. A single site was used to obtain soil for the testing. This site consisted of clay/loam that is representative of much of the soil in the Orono Maine area. If this work is found in the future to represent significant engineering controls for slips and falls in construction and transportation, then extensive additional site testing will be required. The steps that must be performed at each site are as follows:

1. Documentation of work boot and boot tread design in use
2. Drop hammer test in test area
3. Shear failure test in test area

4. Soil sampling in test area
5. Test of soil with additive fiber

### E) Results

#### i) Apparatus Design and Construction

The principal result from this effort has not been characterization of two soil samples as originally proposed, but the development o of an apparatus that joins concepts from soil mechanics and terra-mechanics with ideas from the ergonomics literature. The apparatus consists of a rectangular framework with two horizontal guide bars ( . Attached to the horizontal guides is a carriage that has a travel of approximately 8 feet. Mounted in the middle the carriage (which has a clear span of approximately 4 feet) is a vertical air cylinder. The air cylinder has in turn mounted on it a last on which a shoe or work boot can be mounted. The entire carriage is able to move on the horizontal guides with a dead weight loading platform and an in-line rodless air cylinder. This configuration has a load ell in the configuration which will in turn measure the base load (from the dead weights) and the applied load from the rodless air cylinder.

The frame sits in turn on a set of legs that allows a box with soil to be positioned under the last mounted foot. The last mounted foot presses on the top of the soil box, which is 8 inches by 8 feet. The soil box is made out of acrylic and the soil is placed within the box with markers in the soil [Shikanai 2000]. From the markers depth of penetration of the force and the influence of fibers can be evaluated. The absolute values of the soil strength are not accurate using this system however. For that reason the frame is configured to be used in-situ with the legs removed. Placed on a level test area it is possible to eliminate the boundary effects caused by the sides of the soil tank and to obtain actual measures of the soil strength when loaded by a boot. The ability to test in-situ drove the modification of the approach of Gronqvist et. al. [1989], from hydraulics to pneumatics based both on weight and the availability of air compressors on most work sites.

Data acquisition and control makes use of two electro-pneumatic control valves and load and position sensors on the carriage. The data acquisition system is a universal serial bus system (National Instruments DAQPAD-6020E, Austin TX) with 16 analog outputs and 2 analog inputs. The applied horizontal load is measured by an in-line S type load cell (Omega Engineering LC703-300, Stamford CT) which is excited by a panel meter to give visual feedback to the operator and to provide a 0-10 V output for the data acquisition system (Omega Engineering DP-25-S, Stamford CT). Loading of the footing the vertical direction will be controlled by the air pressure from the electro-pneumatic valve (Proportion-Air QB-1, McCordsville, IN) attached to the vertical cylinder. Based on knowledge of the expected maximum load, deadweights will be applied to the loading stage. The deadweights are loaded to within 20 lbs. of the anticipated failure loading of the foot interface. The air cylinder then applies the final 20 lbs. of load by control of the second electro-pneumatic valve (Festo MPPE-3-1/4-6-010-B, Hauppauge NY).

Soil that is prepared to a standard moisture content by taking a sample of the soil and weighing the sample before and after drying in an oven. Using a concrete mixer, the soil is then mixed with water until it meets the target moisture content for the test. The soil is then added to the soil box in layers. Each layer is approximately 5 cm thick, and is packed into the box using a platform and a drop weight. After a minimum of 4 layers of soil is added to the box the soil box is rolled into position under the loading carriage.

A boot is then loaded onto the last that is attached to the vertical air cylinder. The preload is then applied with the air cylinder using a boot that is positioned at either 5 degree from horizontal for the heel slide gait pattern or flat for the sole slide gait pattern measurement. The electronic control system then is used to maintain the pressure in the vertical direction and load the horizontal loading system. While loading in the horizontal direction the position is monitored using the inputs from the two linear position transducers (Celesco) and the load is monitored with the load cell. Peak load is acquired from the meter that reads both peak and continuous so immediate feedback is obtained from the system.

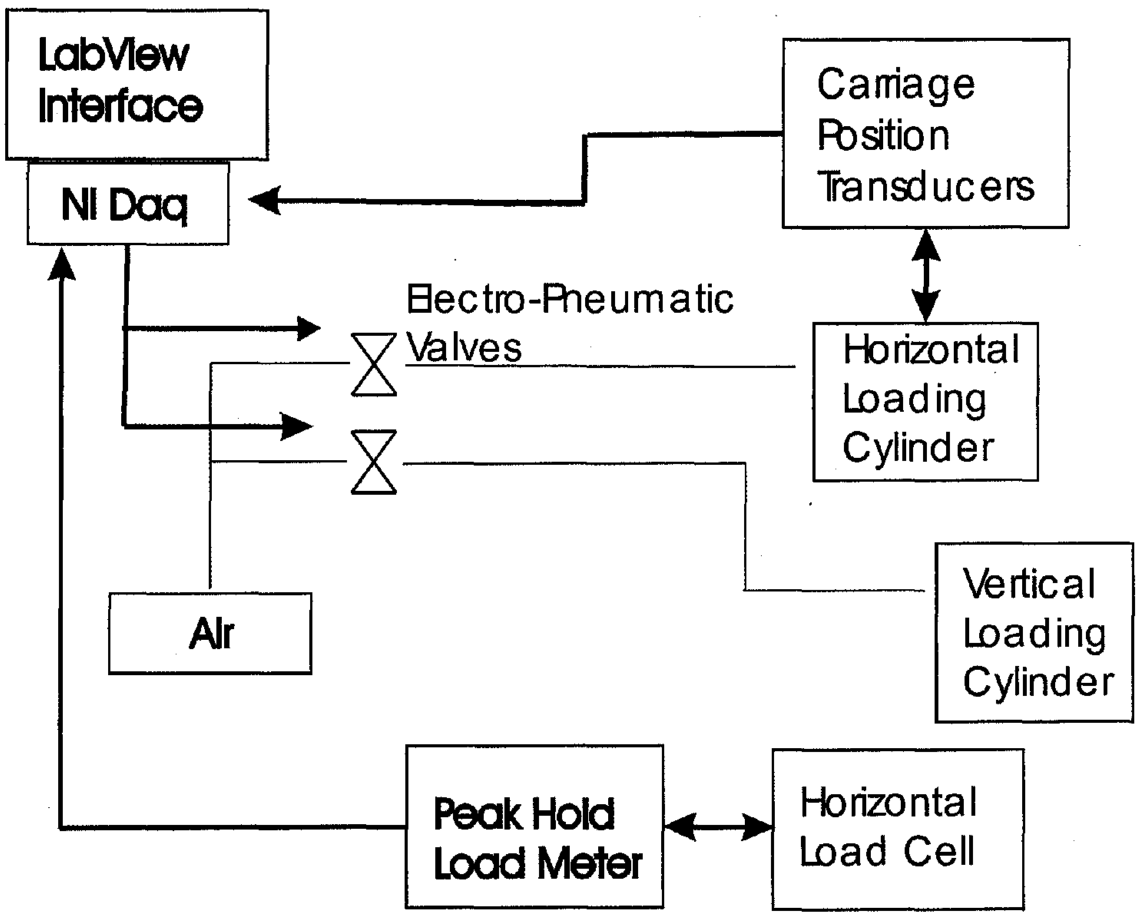



**Figure 5: Overall schematic of system for measurement of slip on soil.**

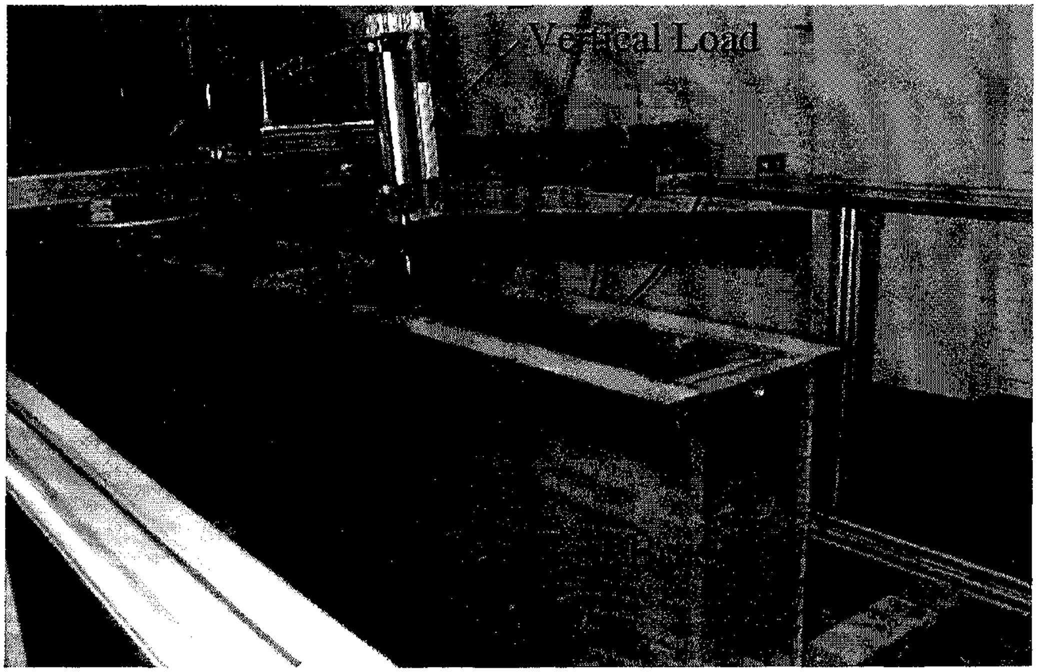



**Figure 6: Vertical-loading system showing boot mounted on last and positioned on carriage**

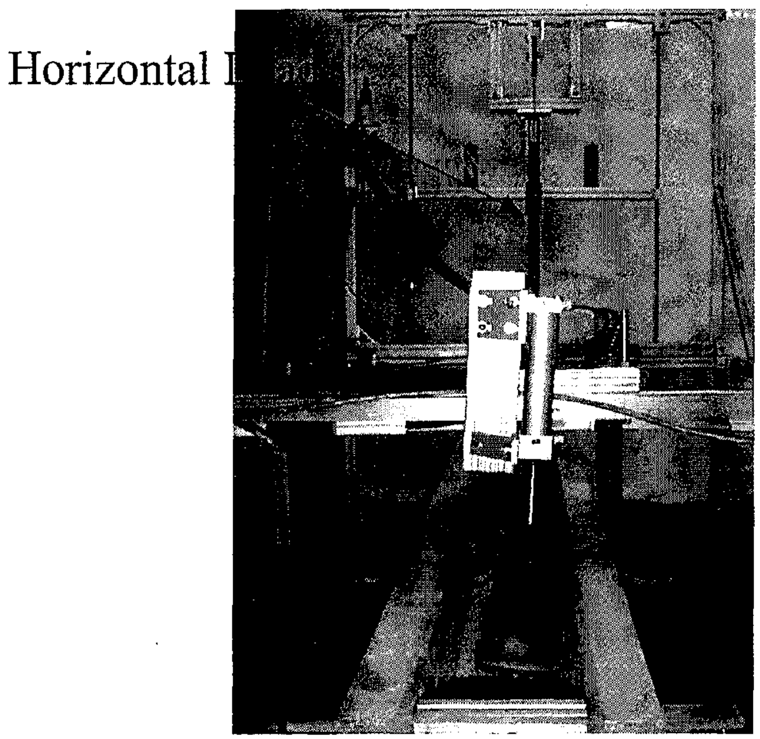



**Figure 7: Deadweight loading system with in-line air cylinder. Weights are mounted on pins on end of frame cylinder provides additional loading**

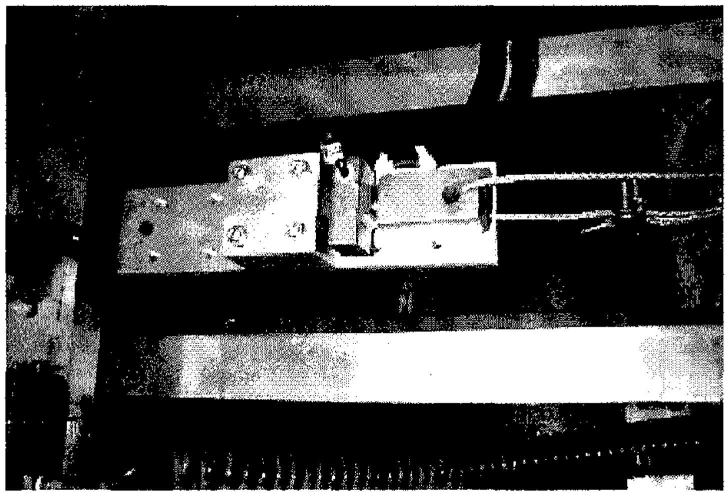


**Figure 8: Load cell mounted in-line nd right before loading carriage for boot. Load cell is mounted on linear rail to eliminate lateral forces.**

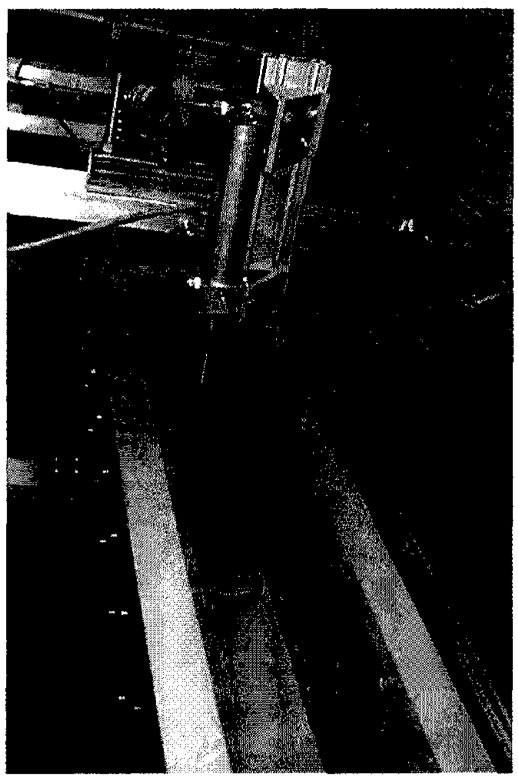


**Figure 9: Close up view of foot on last mounted on air cylinder. Air cylinder will load soil and boot.**

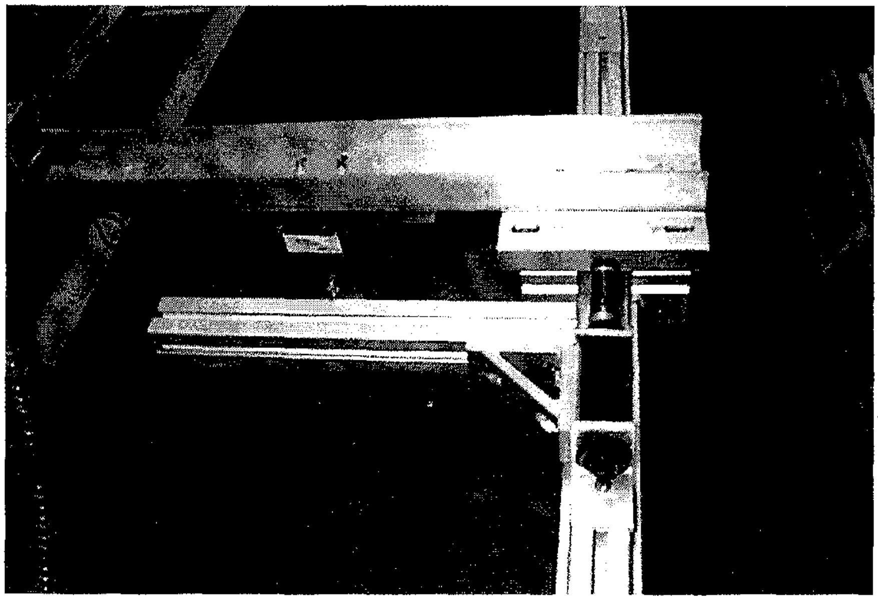


**Figure 10: Close up view of linear potion transducers and snubber used to reduce loading on the system when foot breaks away from soil under loading.**

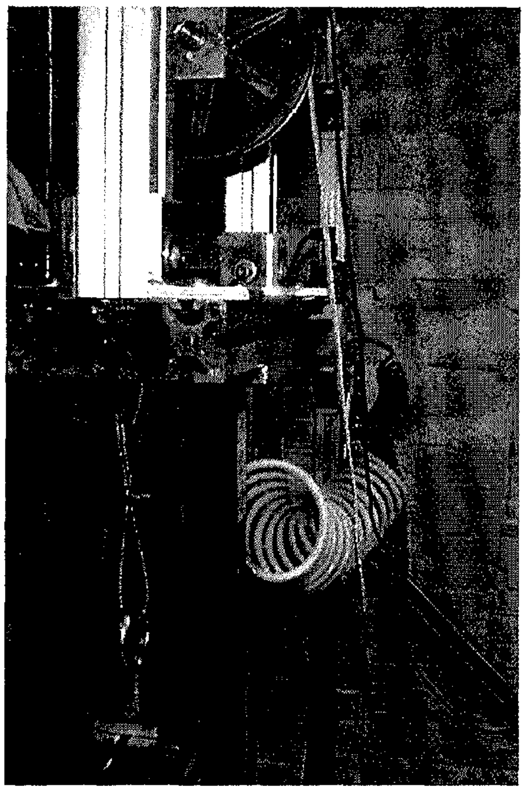


**Figure 11: Detail view of electro-pneumatic control valve and vertical loading system.**

### ii) Vertical Modulus Results

Initial drop tests were performed with a simple system to determine the appropriate systematic increases in mass and drop height. However, without a clear understanding of the soil depth that needed to be fully characterized, it was found that the measurements were not sufficiently consistent for comparative measurements to be made between soils. For example, if a soil area was prepared to a depth of 4 inches, and the drop height increased to 8 inches, the total difference between that soil sample and one prepared to a depth of 2 inches was greater than the effect of the fibers on the measured modulus. Additionally, the simulated foot was instrumented to measure impact force. However, the deformation of the soil was found to be insufficient for the instrumentation currently available. The simulated foot was dropped in such a manner so that it impacted the soil with the same angle that a person's foot impacts the soil during the critical phase of the gait, the heel-slide gait pattern for measurement of $\mu_{k1}$.

Work in this area is ongoing in an attempt to characterize the loading that is required to maintain consistence between the depth of penetration and the measured modulus (on impact and rebound). Additional instrumentation is also being evaluated that would allow these measurements to be cross-checked with the depth of penetration. It may also be determined that this measurement is not possible with the apparatus as currently designed, since additional degrees of freedom may be required.

### iii) Horizontal Loading Results

Horizontal loading results have only begun to be obtained from the apparatus described in this report. At this time it appears that the loads required for shear of the soil using a standard lugged sole will vary from $\mu_k > 0.25$ on a loose soil to $\mu_k \leq 0.12$ on damp packed soil with the same boot. Using the current loading system without a method to overcome cylinder stiction, the variation in the measurements has been greater than 0.05. While Gronqvist et. al. [1989] reports sole-slide gait pattern results, his variation is less than 10% of the mean. Repeatability if not available for any conditions for the apparatus used in the terramechanics papers, however this error needs to be added to the expected error from previous ergonomics research. One approach that is possible is to set up the existing apparatus on a reference surface (such as the glycerin-covered stainless steel used by Gronqvist et. al, to quantify the error of the apparatus. The results form the soil ca then be evaluated with an assurance that the apparatus is consistent and thus the variation can then be traced to soil preparation.

## VIII) Acknowledgements

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## X) Publications, present and anticipated

Oyetunji, Ramat, Expected Fall 2003, M.S. Thesis, "A portable apparatus for assessing the characteristics of soil for slip and trip prevention"

Peterson, M. L., and Reiser, R. ,in preparation, "An apparatus for determining the shear strength of soil under loading due to walking or running"

Peterson, M. L., "The effect of polyamide fibers on the vertical modulus of clay soils for use in reducing walking and slipping injuries"

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