BIOMECHANICAL CHARACTERIZATION OF SLIPPING ON PERVIOUS AND TRADITIONAL CONCRETE WALKING SURFACES

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ABSTRACT

Pervious concrete is a porous material that may provide superior slip resistance due to its ability to exfiltrate melted ice and other slippery surface contaminants. The purpose of this study was to analyze slip-related biomechanical characteristics during gait on pervious and traditional concrete in dry and icy conditions. The hypothesis tested was that pervious concrete, compared to traditional, would exhibit improved frictional characteristics that are less likely to cause slipping events. Both pervious and traditional concrete slabs were manufactured, and misted water was frozen on the surface of the icy slabs. Ten participants completed walking trials across traditional and pervious concrete in both dry and icy conditions. Ground reaction forces were captured by a force platform beneath each concrete surface and used to determine friction usage, which was defined as the ratio of peak utilized shear to normal force normalized to static coefficient of friction. An analyses of variance (ANOVA) was performed on the resulting data. A statistically significant decrease in friction usage was found for pervious concrete compared to traditional. Pervious concrete exhibited significantly smaller levels of friction usage for icy conditions, suggesting its potential utility in reducing slipping events.

The faculty listed below, appointed by the Dean of School of Computing and Engineering, have examined the thesis titled "Biomechanical Characterization of Slipping on Pervious and Traditional Concrete Walking Surfaces," presented by Adam Patrick Bruetsch, candidate for the Master of Science degree, and certify that in their opinion it is worthy of acceptance.

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CHAPTER 1

INTRODUCTION

Slips and falls can be frightening and dangerous experiences and are of significant concern in the areas of public safety, city planning, and personal health. Non-ideal surfaces such as ice or rain covered sidewalks increase the risk of such accidents by reducing the available friction of the surface and thereby increasing the likelihood that a slip or fall will occur [1]. Slippery walking surfaces pose a particular danger to older adults, who often suffer from reduced mobility and high fall risk [2].

The use of pervious concrete, a porous material that allows rain and melted ice to pass through its surface and drain elsewhere, could significantly reduce the risk associated with slips and falls during cold weather conditions [3]. Its porous makeup allows for improved drainage of slippery materials from its surface, and its rough surface texture provides an increase in the friction between the surface and the foot of the pedestrian.

Therefore, the purpose of this study was to analyze slip-related biomechanical characteristics while walking across pervious and traditional concrete surfaces in dry and icy conditions. It was hypothesized that pervious concrete would exhibit improved slip resistance under icy conditions in comparison to traditional concrete. Slip resistance was quantified with ground reaction forces, foot plantarflexor and dorsiflexor muscle activity, and foot motion data captured from human participants walking across prepared concrete surfaces in the UMKC Human Motion Laboratory (HML).

A positive result for this hypothesis would establish the feasibility for future work to evaluate walking surface safety and make recommendations for the use of pervious concrete in any location where slip prevention is desired. Its usage would promote an increase in personal health as well as public safety, and could also reduce medical expenses caused by injuries related to slips and falls.

CHAPTER 2

BACKGROUND

2.1 – Significance of Slips and Falls

Before examining biomechanical characteristics of slips and falls, it is important to understand how these terms are defined and their significance in human health and injury prevention. Slipping has been defined as "a sudden loss of grip, often in the presence of liquid or solid contaminants, resulting in sliding of the foot on a surface due to a lower coefficient of friction than that required for the momentary activity" [4]. While the current study focuses on the surface characteristics of slipping, there are also many other extrinsic and intrinsic risk factors besides surface contamination that can account for slipping incidents, such as insufficient lighting, age, vestibular disease, peripheral neuromuscular dysfunction, diabetes, osteoporosis, alcohol intake, and drug usage [4].

A slip is often followed immediately by a fall if balance cannot be regained after the slip has occurred. Fall-related injuries that are caused by an interaction between the victim's foot and a surface have been defined as an "underfoot accident" [5]. Slips are a leading cause of falls and underfoot accident-related injuries in both home and work environments [6]. However, slips are not the only causes of an underfoot accident. An underfoot accident can also be caused by other unforeseen events such as tripping, stumbling, missed footing, twisted foot or ankle, and collapsed or removed surfaces [5].

Slips and falls can occur on any surface and at any location due to a number of intrinsic or extrinsic factors. They are most likely to occur when the pedestrian is faced with extrinsic environmental factors such as a snow or ice-covered surface [7]. Geographical location and regional weather conditions can also play a large role in the likelihood of slips and falls. For example, the rate of slips and falls are especially high in outdoor occupations such as mining and mail delivery during winter months [8]. Slips and falls suffered by the elderly are of critical concern as the elderly are not only more likely to fall than any other age group, but also face a greater prospect of injury or death. It has been shown that one third of adults over the age of 65 years will suffer an injurious fall each year [2].

The costs associated with falls are also a serious concern both in the home and workplace. In the home, falls account for 44% of all injuries and 36% of all deaths and their resulting medical treatments cost an estimated $90 billion annually [9]. This makes them a source of tremendous financial burden for individuals by saddling them with medical bills. Employers can also be forced to deal with lawsuits or worker's compensation claims filed by an employee who falls while on the job. Falls can be particularly disastrous experiences for a pedestrian. Fallers can experience a variety of medical problems including bone fracture, tissue damage or even permanent disability [10].

2.2 – Muscle Response Characteristics of Slips and Falls

To understand the biomechanical characteristics of slips and falls, the muscle response characteristics of the pedestrian, the surface characteristics of the material on which the slip occurs, and the foot kinematics during the slip must be examined. The muscle response characteristics during slipping will be examined first and are already widely reported from many experiments.

In comparison to non-slippery surfaces, walking on a slippery surface is associated with decreased electromyographic (EMG) amplitude in the tibialis anterior

(TA) muscle during heel contact, and decreased EMG amplitude in the gastrocnemius muscle (GL) during the mid-stance phase [11]. This suggests more cautious step preparation in which slippery surfaces are anticipated prior to heel contact. To prevent a slip, it is ideal to utilize either greater toe grip or a gentler heel strike. This may be achieved by plantarflexing the ankle and metatarsals to give improved flat foot ground contact, especially at heel strike in order to shift the ground reaction force to a more vertical direction [12]. The redirection of the force vector to a vertical direction would prevent excessive amounts of shear force during the step, leading to less potential for slipping. If a slip does occur, postural activity from the bilateral leg and thigh muscles and coordination between the legs allow for an attempt to regain balance within one gait cycle. If balance is not regained within one gait cycle, a fall is more likely. This naturally occurring feedback process occurs due to the central nervous system reacting to the threat of a slip [13]. During an especially severe slip, younger adults demonstrate longer, more powerful responses in muscle activity than older adults. During an unanticipated slip, the potential loss of balance can be made less severe by greater contraction of the ankle muscles. When a potential slip is anticipated due to the presence of a slippery surface, more muscular activity and contraction at the ankle and knee occurs in comparison to baseline conditions, as well as an earlier onset and longer duration in posterior muscle activation [14].

2.3 – Foot Kinematic Characteristics of Slips and Falls

Foot kinematics are another important component when considering the causes of slips and falls. Control of foot trajectory is a critical motor function for safe gait, as it allows achievement of safe ground clearance and gentle heel landing [1]. As was mentioned earlier, the human body's central nervous system is adept at reacting to a slip based on the sensory input provided by the foot. This not only brings about muscular adaptations, but changes in the kinematics of the foot as well. For example, when a slip is anticipated, horizontal heel velocity, horizontal heel acceleration, and vertical heel acceleration all decrease during heel strike [22]. Additionally, during an anticipated slip, step length and peak anterior heel velocity will decrease while step width will increase on slippery surfaces [23]. When a slip is unanticipated, foot velocity during the slip is greater than during an anticipated slip [24].

2.4 – Surface Characteristics of Slips and Falls

Walking surface characteristics, including slipperiness, are equally important to muscle response and foot kinematic characteristics in the analysis of slips and falls. Prior research has defined the term slipperiness as "conditions underfoot which may interfere with human beings, causing a foot slide that may result in injury or harmful loading of the body tissues due to a sudden release of energy" [1]. Although there are currently no unambiguous methodologies or generally accepted criteria for measuring slipperiness, available coefficient of friction (aCOF) of the surface is frequently used [15]. The aCOF is a material property that simply measures the static coefficient of friction of a walking surface. This quantity is distinct from the required coefficient of friction (rCOF), which refers to the ratio of the shear and vertical ground reaction forces of the pedestrian's foot. While the rCOF can be measured directly via a force plate, the aCOF is estimated based on the material being tested. One such way of doing this is using a footwear slip resistance tester [16]. A footwear slip resistance tester can either consist of an elaborate laboratory device such as a James machine, which consists of an articulated arm used to push a test pad sitting in contact with a surface, or a simpler device such as a horizontal dynamometer pull-meter, which consists of a weighted block sitting atop a rubberized pad which is then dragged across a surface [17]. While the James machine is large, heavy, and not intended for field operation, the horizontal dynamometer pull-meter can be constructed in any machine shop and is accepted by American courts for testing both roadway and flooring surfaces [17].

The rCOF can be normalized to the aCOF in order to express the proportion of available friction used such that slipping is likely as this normalized quantity approaches a value of 100% [1]. This quantity can be defined as friction usage. A friction usage value of less than one indicates that there is more available friction than required friction and that the surface characteristics are less likely to induce a slip. A friction usage value equal to or greater than one indicates that there is not as much available friction as required friction, and that the surface characteristics are likely to induce a slip. Friction usage is the quantity that will be used throughout this study to examine the likelihood of a slip occurring while walking on a given surface.

Another important variable in slip testing is footwear. Shoes with elevated heels or especially hard soles impair walking stability, especially in older people or on wet floors, and thus are not ideal in minimizing risk of slips and falls. High collar shoes of medium sole hardness are the most stable choice for most common types of walking surfaces including level, dry, irregular, and wet surfaces [18]. When measuring friction usage, it is important to use consistent shoe and floor conditions during each testing session, as a change in either of these variables can cause inconsistencies in the quantities of sliding speed, contact pressure, and normal force [19].

Prior research on slip and fall deterrence by examination of surface characteristics has mostly been limited to preventative measures taken to prevent slips on traditional walking surfaces such as concrete. These studies include examining the effects of different footwear and the application of chemical deicers, salt, or sand to improve traction [20]. However, the chemical methods are not always effective, and are also commonly overused, which can lead to environmental issues if the surrounding areas are environmentally sensitive as these products can cause excessive runoff. [21].

2.5 – Pervious Concrete

Pervious concrete (PC) is a relatively new type of pavement material. While possessing the same material makeup as traditional concrete, it is mixed with modified aggregates, allowing it to be highly permeable [3]. This permeability allows moisture to quickly pass through the concrete, thus reducing surface buildup of liquids. The surface is kept drier because cold weather precipitation such as rain and ice are allowed to seep through the surface. This drier surface, combined with its naturally rougher surface texture, gives pervious concrete a greater amount of surface friction than traditional concrete can provide during non-ideal weather conditions.

Pervious concrete was initially developed to control pollution discharge. It accomplishes this by allowing rainwater to rapidly infiltrate into its open-graded aggregate subbase and then into the ground [3]. Additionally, pervious concrete's porous surface allows for mechanical filtering of larger pieces of biological material for later collection during routine maintenance that would otherwise potentially contaminate nearby runoff collectors [3]. Not only does this decrease biological contamination, but it could potentially save on infrastructure costs that would be otherwise necessary to convey the water away from the concrete surface [25].

Pervious concrete has also been shown to melt ice and snow atop its surface at temperatures below which deicer treatments are effective, which is approximately 12°F [26]. This represents yet another way in which pervious concrete can contribute to the reduction in environmental waste products, as fewer contaminating agents are carried into the water system when the snow later melts.

The benefits of pervious concrete have been noticed by many metropolitan areas. A recent increase in the usage of pervious concrete for both parking areas and streets has occurred in cities such as Chicago, IL, in an attempt to both reduce the costs of wastewater elimination as well as mitigate the risk of flooding [27].

While there are many studies examining the biomechanics of slips and falls on both regular and slippery surfaces, none have yet specifically investigated the slipping characteristics of pervious concrete. Since pervious concrete has been proven to possess superior surface moisture elimination properties and possesses a rougher surface texture than traditional concrete, it is highly likely that it may also provide a reduction in fall risk for pedestrians during non-ideal weather conditions by providing more available friction and thus offering a lower friction usage value than traditional concrete. Further study could prove extremely beneficial as a reduction in slips and falls would be extremely beneficial for both pedestrians and municipalities.

CHAPTER 3

METHODS

3.1 – Hardware and Software Configuration

In conducting the experiment, a variety of hardware, software, and other laboratory devices were employed. The force plate used was an AMTI OR6-6 force platform as shown in Figure 1. The OR6-6 has a 6-component transducer which measures forces acting on its surface. The measured quantities include three dimensional force components F_x, F_y, and F_z, as well as three moment components M_x, M_y, and M_z. These measurements were collected at a sampling frequency of 1,000 Hz. The force platforms were connected to AMTI MSA-6 MiniAmp Strain Gage Amplifiers, with each amplifier corresponding to a respective force platform. These provided high-resolution signal amplification in order to aid in the processing of the resulting data samples.

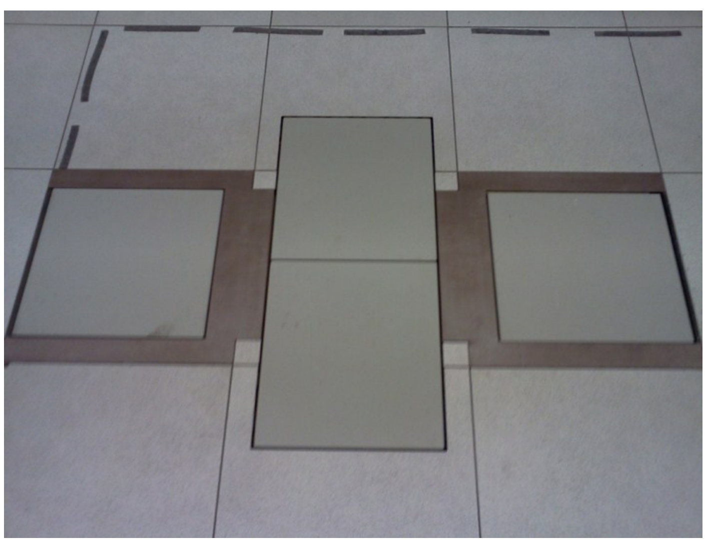

Figure 1: AMTI OR6-6 force platforms

Each trial was also tracked and captured through digital video using six VICON MX-T40 motion capture cameras, shown in Figure 2, running at a frequency of 100 Hz.

Force and motion data was simultaneously collected through a VICON Analog to Digital Interface Unit. For this experiment, only the lower body needed to be tracked. Thus, a portion of the standard marker set specified by the Plug-in Gait model requirements was used, which consisted of markers affixed bilaterally to the knee, tibia, ankle, toe, and heel. An example of the markers used is shown in Figure 3.

Figure 2: VICON MX-T40 motion capture camera

Figure 3: Motion capture marker

The software used to conduct the experiment was VICON Nexus, a motion capture application that reads human biomechanical activity and writes it as numerical data. VICON Nexus also utilizes VICON Plug-in Gait, a gait model that provides real-time results of gait data while the experiment is being performed.

The Delsys EMG system, shown in Figure 4, was used to measure the muscles that exhibit a response when undergoing slipping. These consist of the stance leg tibialis anterior (TA), which indicates dorsiflexion during heel strike and toe off, and the medial gastrocnemius (GL) muscles, which indicate plantarflexion during midstance.

Figure 4: EMG system

3.2 – Materials Preparation

The traditional and pervious concrete slabs were fabricated in the UMKC Material Testing Laboratory. The traditional concrete was manufactured to ASTM standards with a standard broomed finish. The pervious concrete was produced using ASTM D57 granite according to the guidelines found in *The Design of Pervious Concrete Mixtures* [28]. This consisted of a 4.75 mm uniformly graded surface with 20%

porosity. Both types of slabs were cut to dimensions of 45 by 50 cm. An example pervious concrete slab can be seen in Figure 5.

Figure 5: Pervious concrete slab covered with layer of ice atop force platform

A variety of tests were performed on the pervious concrete to quantify its material properties. These included tests for voids, infiltration, permeability, and compressive strength. The tests were performed using cylindrical samples measuring 100 mm by 150 mm. Examples of cylinders used for these tests can be seen in Figure 6. The percentage of voids was calculated using a procedure developed by Montes et al. This consisted of utilizing Archimedes' principle, or the concept that any floating object displaces its own weight in fluid. The procedure consisted of inserting the slab samples into a tank and measuring the amount of water displaced [29].

Infiltration was calculated using ASTM C-1701 standards. This consisted of affixing a plastic rim to the pervious concrete. The rim was secured with putty around the base forming a watertight seal. A designated amount of water was then poured atop the concrete and the rate of infiltration through its surface was recorded [30].

Permeability was calculated using the ACI falling head procedure shown in Figure 7. This consisted of wrapping plastic wrap tightly around the cylinders, then securing the edges with thick pieces of rubber. The wrapped cylinder was then mounted in an apparatus containing an adjustable valve and two pipe fasteners which were tightened around the bottom and top edges of the cylinder. A designated amount of water was then poured into a cylinder attached to the top fastener, and the valve was opened. The rate of permeability through the surface of the concrete was recorded [31].

Compressive strength was calculated using ASTM C39 standards and was tested at 28 days on sulfur-capped samples cured according to ASTM C192 standards. This test consisted of utilizing a compression testing machine on the sulfur-capped concrete cylinders to determine their compressive strength. The cylinders were placed in the machine and a constant compression load was applied until failure was reached. The compressive strength was then calculated based on the amount of load withstood [32].

The results from the material testing are shown in Table 1.

Table 1: Pervious concrete material testing results

Voids (%)	Infiltration (cm/s)	Permeability (cm/s)	28-day Comp. Str. (MPa)
30.5	1.0	2.8	27.4

These results indicated high relative values for both permeability and compressive strength when compared against other concretes used for pedestrian applications [33]. This suggests that the pervious concrete used in this experiment would be adequately durable in real usage. It also confirms that pervious concrete represents a superior surface for preventing standing water from developing atop its surface due to its high permeability.

Figure 6: PC cylinders being prepared for permeability testing

Figure 7: Permeability test

The pervious concrete was also characterized by the amount of surface contact area it offered. The rough surface texture the material provides means that only a portion of its surface area will come in contact with a pedestrian's shoe during walking. This reduction in shoe contact is also dependent on the sole of the shoe. An incompressible sole will contact only the portions of the material on the surface, while a compressible sole will depress slightly into the material, coming into contact with some additional amount of material.

In order to determine the percentage of surface area that would come into contact with a shoe surface, a test was conducted in accordance with ASTM C-457 standards [34]. A ¼ inch paint roller was dipped in black paint and applied to the surface of a slab of pervious concrete. This provided a stark visual contrast between portions of the surface above ¼ inch depth, which became black, and those below, which appeared white. Graphical processing software was then used to estimate the amount of black surface in the image. This software estimated the image to be approximately 45% black. This means that approximately 45% of the top portion of the pervious concrete is within ¼ inch from the surface. An example of the concrete used can be seen in Figure 8.

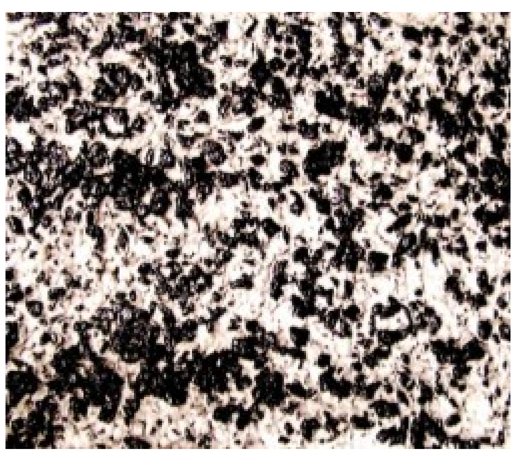

Figure 8: Pervious concrete contact area

Paint tests were also used to determine the amount of surface contact area for an athletic shoe contacting each type of concrete. An approximation of the underside of the shoe's surface area was measured with a ruler and is represented as Shoe Surface in Table 2. The shoe's underside was then rolled with the same ¼" paint roller dipped in black paint. The same image processing procedure was performed and the portion of the shoe covered in black paint is represented as Shoe Potential in Table 2. Finally, the paint-covered shoe was pressed against a slab of traditional concrete and the resulting amount of black paint transferred to the slab is represented as Shoe Actual in Table 2.

Pressure was then calculated as a ratio of normal force divided by contact area. The normal force was measured by a force platform and taken for an 82 kg (180 lb) man. The pressure was calculated during the heel strike, mid stance, and toe off phases. The results shown in Table 2 indicate that for all conditions, greater pressure is exerted on the pervious concrete slab than the traditional concrete slab.

Table 2: Shoe contact characteristics

	Shoe Surface	**Shoe Potential**	**Shoe Actual**
Contact Area (cm^2)	250	200	117
TC Heel Strike (kPa)	136.1	170.2	290.9
TC Mid Stance (kPa)	16.4	20.5	35.0
TC Toe Off (kPa)	102.1	127.6	218.2
PC Heel Strike (kPa)	300.1	376.1	642.9
PC Mid Stance (kPa)	36.2	45.3	77.3
PC Toe Off (kPa)	225.4	282.0	482.2

In addition to testing the contact area of the pervious concrete, the static and dynamic coefficient of friction was also graphically compared between the two types of concrete surface. This was accomplished by cutting out a small piece of the athletic shoe sole and affixing it to a 10 kg mass and string. This apparatus, shown in Figure 9, was then slowly dragged in a straight line across both types of concrete and force measurements were taken using the force platforms. COF was then calculated by comparing the ratio of shear to vertical force. The results can be seen in Figure 10.

Figure 9: Material coefficient of friction test

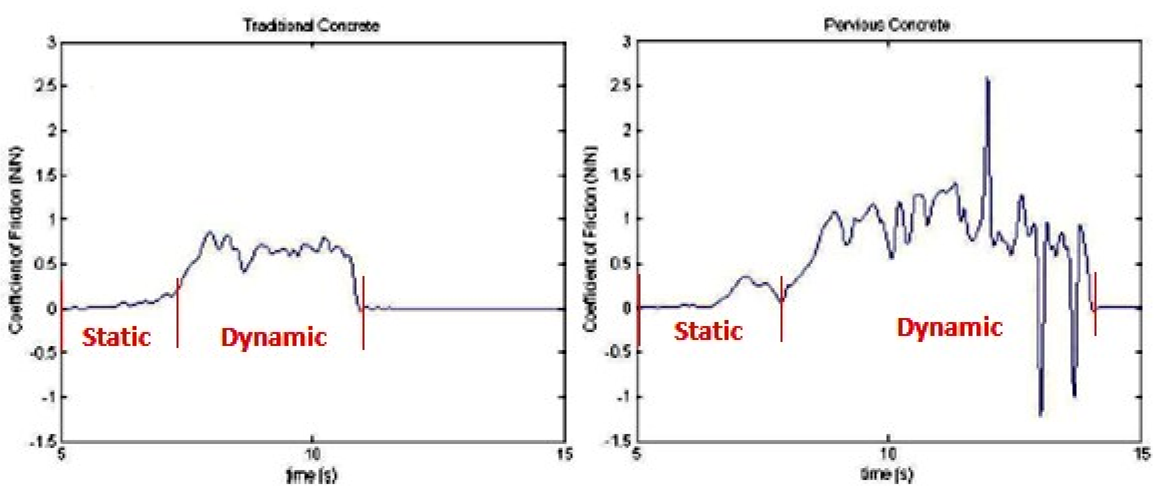

Figure 10: Static and dynamic COF results for TC and PC

The COF testing results were filtered at 5 Hz to reduce noise. While there is still some noise present, it can still clearly be seen that pervious concrete reaches higher values of COF than traditional concrete once slipping occurs. The traditional concrete reaches an average COF value of approximately 0.70 while the pervious concrete reaches an average COF value of 1.0.

This procedure was also used to calculate the material COF for later use in determining the friction usage values for each surface. However instead of using the shoe piece, the actual shoes used in the experiment, as seen in Figure 11, were mounted onto the weight apparatus. The apparatus was pulled as slowly as possible atop each surface until the static friction gave way and the shoe began moving. This procedure was repeated three times and an average was taken for each condition. These values shown in Table 3 represent the material static COF.

Table 3: Material COF values for utilized friction

	Mean	St. Dev.
PC Dry	0.812	0.323
PC Icy	0.299	0.039
TC Dry	0.924	0.079
TC Icy	0.129	0.017

3.3 – Subject Preparation

Ten healthy young adult subjects, five male and five female, were recruited for the experiment. Ages were reported and heights and weights were measured in the laboratory. Ages ranged from 19 to 25 years with a mean of 21.6 years and a median of 21 years. Subject height ranged from 160 cm to 190 cm with a mean of 173.7 cm and a median of 174 cm. Subject mass ranged from 49.1 kg to 125.9 kg with a mean of 77.8 kg and a median of 73.2 kg. All subjects were required to complete a questionnaire detailing any history of musculoskeletal, neurological or cardiovascular conditions. None of the subjects reported any such conditions. A summary of the subject demographics can be seen in Table 4.

Table 4: Subject demographics

	Height (cm)	Mass (kg)	Age (yr)
Mean	173.7	77.8	21.6
Median	174.0	73.2	21.0
Min	160.0	49.1	19.0
Max	190.0	125.9	25.0

In order to standardize the footwear used during the experiment, soft-soled XBok athletic shoes were used for each subject in their appropriate size. These shoes, shown in Figure 11, were ordered in bulk quantity in a large range of sizes that were able to accommodate the shoe size of every subject. This prevented any inconsistencies in the testing environment, as footwear can strongly affect the likelihood of a slip or fall occurring as described in Chapter 2 Section 4.

Figure 11: Standardized soft-soled athletic shoes

3.4 – Experimental Procedure

Approximately 48 hours before the beginning of subject testing, the wet slabs used from the prior experiment were allowed to drain in room temperature overnight.

After 24 hours, the dry slabs were placed in an upright freezer. The freezer was set to a temperature of -12°C (10° F). Ice was formed atop the slabs by uniformly spraying them with an 8 oz misting water bottle. This process was repeated once per hour until the entire 8 oz of water had been used, which produced a layer of ice of 1 mm thickness. The thickness was measured using a pair of calipers around four perimeter points on the slab to ensure even coverage.

Six additional slabs were arranged in a straight line to form a simulated walkway comprised of seven total slabs. This was accomplished by placing the slabs in a line alternating between traditional and pervious slabs. This walkway was arranged such that the fifth slab in the walkway was placed atop one of the force platforms. This would represent the testing slab on which the force data would be taken from the subject.

In order to prevent subject injury and comply with IRB safety standards, a protective safety harness was used during all trials. The harness was attached around the subject's underarms and groin and affixed to the ceiling along a sliding runner. To ensure that gait was not altered by the influence of the harness, an assistant accompanied the subject during each trial, pushing the runner along the track at the same speed as the subject walked.

Once the subject was oriented, was read a script of instructions, and completed the health questionnaire in accordance with IRB standard protocol, the motion capture markers and EMG electrodes were affixed to their body. A static trial was then performed with the subject remaining motionless atop the force plate. This was necessary to capture baseline measurements and calibrate the motion capture analysis results.

At this time, the slabs were then removed from the freezer and exposed to room temperature conditions until they warmed to a temperature of -4°C (25°F). This temperature was chosen because it had been identified during pilot testing as the most likely temperature for slips to occur [33]. The temperature was measured using an Extech infared thermometer. After the slabs reached their desired temperature, the subject completed a number of trial gait cycles to familiarize themselves with the procedure. A small piece of masking tape was placed along the first slab of the walkway to ensure that the subject began walking from the same location throughout each trial. Subjects were instructed to walk at a normal pace such that their right foot came into contact with the test slab.

Once the formal testing began, three trials were performed consecutively for each type and condition of concrete. The first type of concrete used was alternated with each new subject. Thus, a total of twelve trials were performed: three for dry traditional concrete, three for dry pervious concrete, three for icy traditional concrete, and three for icy pervious concrete.

Upon completion of the twelve trials the electrodes, motion capture markers, and shoes were removed from the subject and sterilized.

3.5 – Data Preparation

Before any statistical analysis could be performed, the utilized friction needed to be calculated from the raw force data. First, the required coefficient of friction was calculated based on the extracted values from the force platform. This value is shown in Equation 1.

$$COF_{Required} = \frac{F_y}{F_z}$$

Equation 1: Coefficient of friction calculation

Next, the coefficient of friction calculated from the force platform was normalized to the appropriate material coefficient of friction as shown in Table 3. This value represents the friction usage. It is shown in Equation 2. The full table of friction usage values for each trial can be found in the Appendix.

$$FU = \frac{COF_{Required}}{COF_{Material}}$$

Equation 2: Friction usage calculation

At this time it is also important to explain that the statistical analysis did not include any motion capture or EMG data, although this data was successfully collected. This was due to technical issues and will be explained in detail later in Chapter 5.

3.6 – Statistical Analysis Preparation

The main requirement of the experiment was to determine whether the concrete type (pervious/traditional) or the concrete condition (icy/dry) affected the utilized friction. Minitab software was used in order to determine which factors and which interactions between factors were significant at a 95% confidence level.

As an additional consideration, the demographic data was analyzed. This was done in order to ensure that none of the demographic factors were skewing the results. Prior to testing, each subject's body weight, age, gender, and height were collected. Each of these may be potential nuisance factors that could provide an influence on the outcome of the statistical analysis. If it is found that any of these factors are significant in explaining the friction utilization, then blocking on the nuisance factor must be performed in order to systematically eliminate its effect.

The demographic data was categorized using coded variables of value 1 and -1. In order to implement this, a cutoff value was set and a subject was assigned either a 1 or -1 depending on whether their value was greater than or less than the cutoff value. Table 5 shows how the cutoff values were implemented. Note that for gender, it was not necessary to utilize a cutoff value.

Table 5: Coded demographic factors

Factor	Value	Coded Number
Body weight (A)	< 161 lbs.	-1
	> 161 lbs.	1
Height (B)	< 174.1 cm	-1
	> 174.1 cm	1
Age (C)	< 21 years	-1
	> 21 years	1
Gender (D)	Female	-1
	Male	1

The demographic data was analyzed by performing a multiple regression analysis. This was used in order to identify demographic factors that were significant at predicting the friction utilization. The concrete type, concrete condition, and the interaction between these factors were included in the model.

A 2x2 factorial design (two factors at two levels) was used in order to perform the analysis of the concrete type and condition. The data was coded in the same fashion as the demographic data. A “1” is used in order to indicate a high level of the factor, and a “-1” is used in order to indicate a low level of the factor. The coded data for the concrete type and condition is shown in Table 6.

Table 6: Coded factors for factorial design

Factor	Value	Coded Number
Concrete Type (E)	Pervious	-1
	Traditional	1
Concrete Condition (F)	Icy	-1
	Dry	1

To analyze the factorial design, an analysis of variance (ANOVA) was performed. If a demographic nuisance factor was identified in the regression analysis, then it would be necessary to analyze the factorial design in blocks. This would ensure that the effect of the undesirable nuisance factor was removed from the analysis, and thus would isolate the two factors of interest: concrete type and concrete condition.

CHAPTER 4

RESULTS

4.1 – Friction Usage Results

The friction usage values for each concrete type and condition were calculated using the methods explained in Chapter 3 Section 5. Mean values were calculated for each combination of type and condition in order for a graphical comparison to be made.

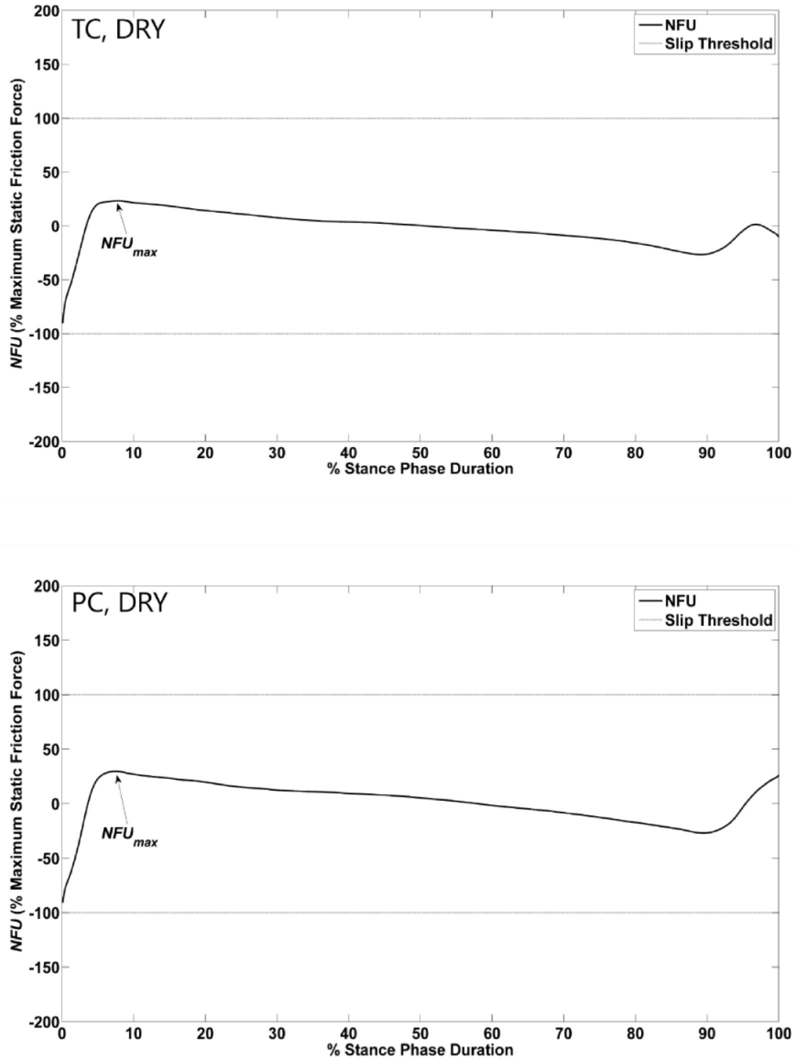

Figure 12: Normalized friction usage mean values for dry condition

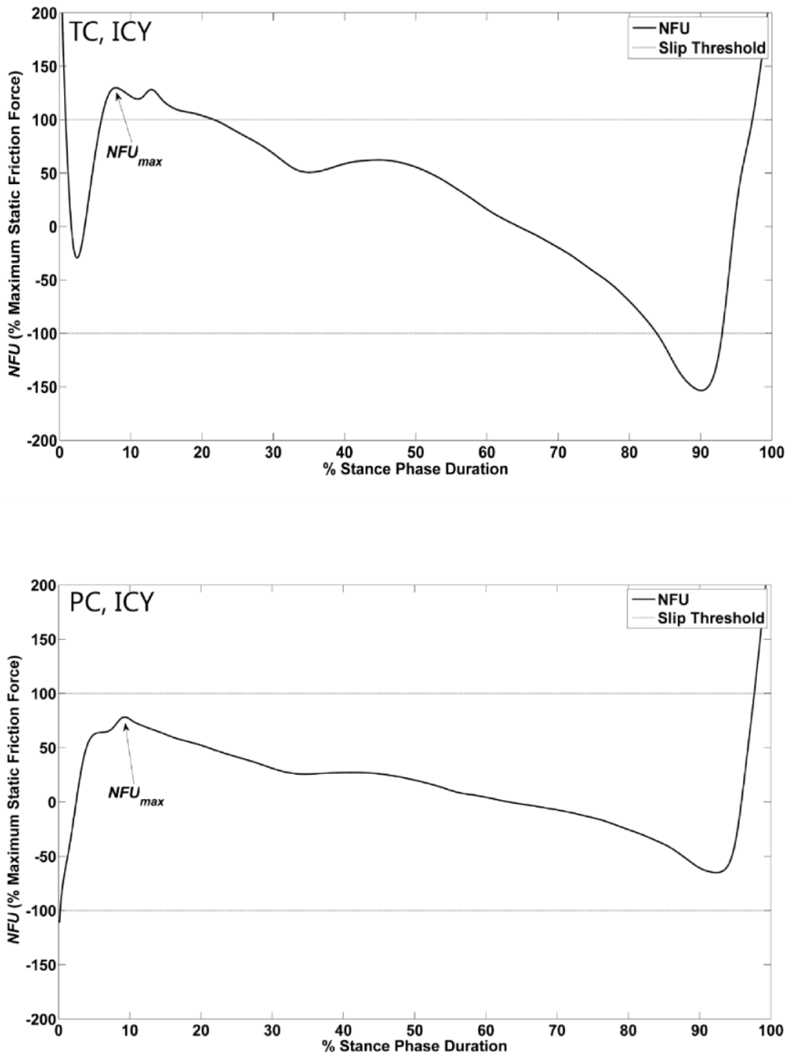

Figure 13: Normalized friction usage mean values for icy condition

As can be seen in Figure 12, there is minimal difference between the normalized friction usage for pervious and traditional concrete. However, in Figure 13, it can be seen that traditional concrete reaches both a significantly higher value of normalized friction usage upon heel strike and a significantly lower value during the toe off phase than pervious concrete. Both of these mean values exceed values of 100% and -100%, respectively. A value of greater than 100% or less than -100% indicates likely conditions for a slip to occur. This is denoted in the figures with gray lines labeled “Slip Threshold.”

4.2 – Statistical Analysis Theory & Verification

The demographic factors were first analyzed using multiple linear regression. This was performed in order to determine whether any nuisance factors were present. The concrete type and condition were also included in the regression model.

Three different hypotheses were tested in the factorial experiment. The first hypothesis that was tested was to determine if differences were present between the various levels of the row factor (concrete type). The null hypothesis is shown in Equation 3.

$$H_0: \tau_{PC} = \tau_{TC} = 0$$

Equation 3: Null hypothesis

The alternative hypothesis is shown in Equation 4.

$$H_1: at\ least\ one\ \tau_i \neq 0$$

Equation 4: Alternative hypothesis

The second hypothesis that was tested was to determine if differences were present between the various levels of the column factor (concrete condition). The null hypothesis is shown in Equation 5.

$$H_0: \beta_{ICY} = \beta_{DRY} = 0$$

Equation 5: Second null hypothesis

The alternative hypothesis is given Equation 6.

$$H_1: at\ least\ one\ \beta_i \neq 0$$

Equation 6: Second alternative hypothesis

The third hypothesis that was tested was used to determine whether row and column treatments interact. This is shown in Equation 7.

$$H_0: (\tau\beta)_{ij} = 0 \quad for\ all\ i, j$$

$$H_1: at\ least\ one\ (\tau\beta)_{ij} \neq 0$$

Equation 7: Third hypothesis

In order to ensure that the conclusions obtained by using ANOVA were valid, the assumptions of the analysis had to be verified. This was accomplished by performing an analysis of residuals. An initial analysis of the residuals revealed that the fitted value versus residual plot shows that the variance is not constant at each level of the factor.

In order to overcome the issue of a non-constant variance, a transformation was applied to the utilized friction data. Based upon the results of a Box-Cox transformation, it was necessary to apply a variance stabilizing transformation. The friction utilization data was transformed by being raised to the power of -0.268216. The transformed data is shown in Figure 14.

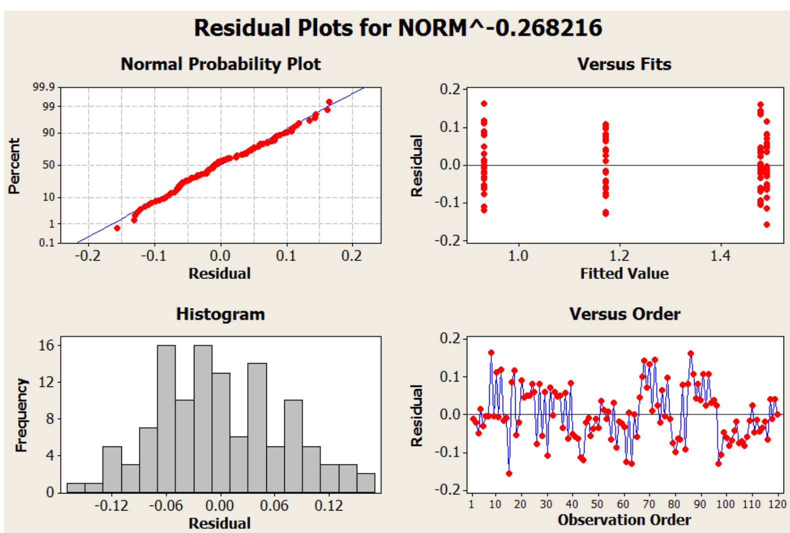

Figure 14: Residual analysis of transformed data

The fitted value versus residual plot shows the variance to be approximately constant. The assumption of normality appears to be valid; inspection of the normal probability plot shows the residuals are normally distributed with a mean value of zero.

The assumption of independence of residuals is valid since there is no correlation between the residual and the observation order. Based on the residual analysis that has been performed, all of the assumptions of the analysis have been found to be valid, thus conclusions drawn from the ANOVA will be valid.

4.3 – Regression Analysis Results

The results of the regression analysis are shown in Table 7.

Table 7: Regression analysis results

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Regression	7	4.1174	4.1174	0.5882	207.86	< 0.001
A	1	0.00329	0.00049	0.00049	0.17	0.677417
B	1	0.00003	0.00021	0.00021	0.08	0.783423
C	1	0.00063	0.00005	0.00005	0.02	0.89337
D	1	0.04083	0.04083	0.04083	14.43	< 0.001
E	1	0.25982	0.25982	0.25982	91.82	< 0.001
F	1	3.49899	3.49899	3.49899	1236.47	< 0.001
E*F	1	0.3138	0.3138	0.3138	110.89	< 0.001
Error	112	0.31694	0.31694	0.00283		
Lack-of-Fit	28	0.17467	0.17467	0.00624	3.68	< 0.001
Pure Error	84	0.14226	0.14226	0.00169		
Total	119	4.43434				

An R^2 value of 92.41% was obtained for the model that was developed. The regression equation that was developed as a result of the analysis is shown in Equation 8.

$$Max\ Norm\ COF^{-0.219602}$$
$$= -1.21123 + 0.002255465A - 0.00168759B - 0.00067785C$$
$$+ 0.0191658D - 0.0465314E - 0.170758F + 0.0511374\ E * F$$

Equation 8: Regression equation

The p-value for D is less than 0.05; therefore it is significant in explaining the friction usage. Demographic factor D corresponds to the subject’s gender. Since gender is an undesirable nuisance factor, a block design was used for the 2x2 factorial experiment that was performed. Two blocks were used; one for each gender.

4.4 – ANOVA Results

An ANOVA was conducted for the 2x2 factorial design. The results of the ANOVA are shown in Table 8.

Table 8: ANOVA results

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Blocks	1	0.392	0.392	0.39203	78.07	<0.001
Main Effects	2	6.1169	6.1169	3.05845	609.03	<0.001
Concrete Type	1	5.6381	5.6381	5.63809	1122.72	<0.001
Concrete Condition	1	0.4788	0.4788	0.4788	95.34	<0.001
Residual Error	116	0.5825	0.5825	0.00502		
Pure Error	116	0.5825	0.5825	0.00502		
Total	119	7.0915				

An R2 value of 91.57% was obtained for the model that was developed. The main effects plot is shown in Figure 15.

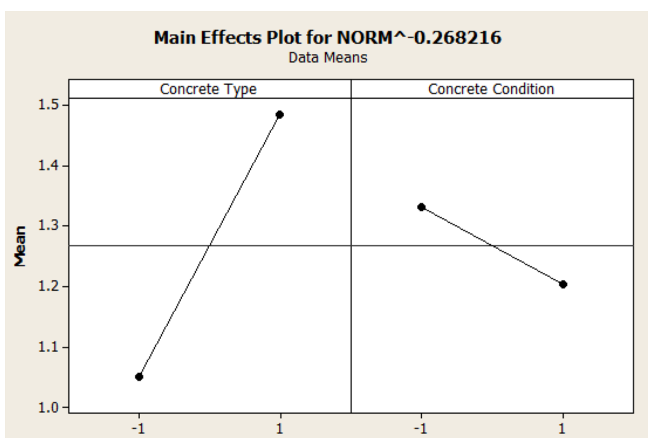

Figure 15: Main effects plot

The interaction plot is shown in Figure 16.

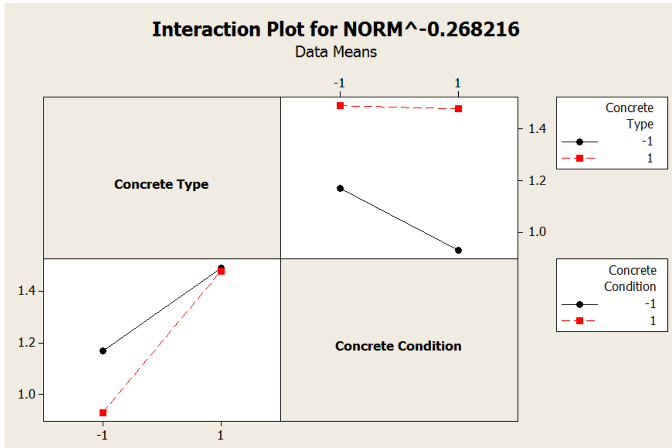

Figure 16: Interaction plot

Table 6 shows the coded factors and should be referenced in order to comprehend the significance of Figure 15 and Figure 16. Examination of the ANOVA for the regression analysis reveals that only factors D, E, F and EF are significant (indicated by a p-value of less than 0.05). Factors E and F are the concrete type and condition respectively. Factors E, F and EF were of primary interest in the experiment. Factor D was also found to be significant in explaining the friction utilization. Factor D is the gender of the subject. The regression equation that was developed allows for analysis of the effect each factor has on the utilized friction. The coded numbers can be substituted into the regression equation in order to determine whether the factors positively or negatively affect the utilized friction. Factor D, gender, has a positive friction usage. Thus, upon performing substitution into the regression equation, it can be determined that the male gender increases the regression equation while female gender decreases the regression equation. This corresponds to higher mean values of friction utilization for the male gender and lower mean values of friction utilization for the female gender, indicating that males may be more likely to slip. Since gender has been shown to be an unwanted nuisance factor it was necessary to utilize blocking for the factorial design analysis that was performed.

The 2x2 factorial design was analyzed by using two blocks. This had the desirable effect of removing the effect of the unwanted nuisance factor D (gender). The results of the ANOVA show that concrete type and concrete condition have a p-value of less than 0.05, indicating that they both present statistical significance in explaining the resulting utilized friction in the experiment. An R^2 value of 91.57% was obtained for the model that was developed, thus 91.57% of the variability can be explained by the model.

The main effects plot shown in Figure 15 contains two graphical representations of the means of the transformed data. The first compares by concrete type. It is clear that traditional concrete possesses a higher mean value of utilized friction when compared to pervious concrete. This indicates that traditional concrete on average has a greater likelihood for a slip to initiate while walking on than pervious concrete. The second plot compares the two concrete conditions. In this instance, the icy condition has a much higher mean value when compared to the dry condition. This indicates that the icy condition on average has a greater likelihood for a slip to initiate while walking on than the dry condition.

There are two separate interaction plots of the means of the transformed data, both of which are shown in Figure 16. This allows for simultaneous examination of the effects type has on condition and the effects condition has on type. In the first plot, concrete condition is plotted along a line while concrete type is marked on the x-axis. It can be seen that for the icy condition, the means of transformed utilized friction is greater for traditional concrete than for pervious concrete. This means that for the icy condition, traditional is slipperier than pervious concrete. It can also be seen that for the dry condition, there is little to no variation between the slipperiness of traditional versus pervious concrete.

In the second plot, concrete type is plotted along a line while concrete condition is marked on the x-axis. It can be seen that for traditional concrete, the means of the transformed utilized friction is greater for the icy condition than for the dry condition. This means that for traditional concrete, the icy condition is slipperier than the dry condition. It can also be seen that for pervious concrete, the icy condition is slipperier than the dry condition.

4.5 – Preliminary EMG and Motion Results

While the EMG and motion data was not statistically analyzed, it is still worth making note of the resulting data acquired from the pilot testing for the study. This data could potentially prove useful for further studies and also provides some insight as to whether these methods are viable means to quantify slip likelihood. Note that the data displayed in these plots were acquired from pilot participants, not the group of ten participants from which all other data in this study was collected.

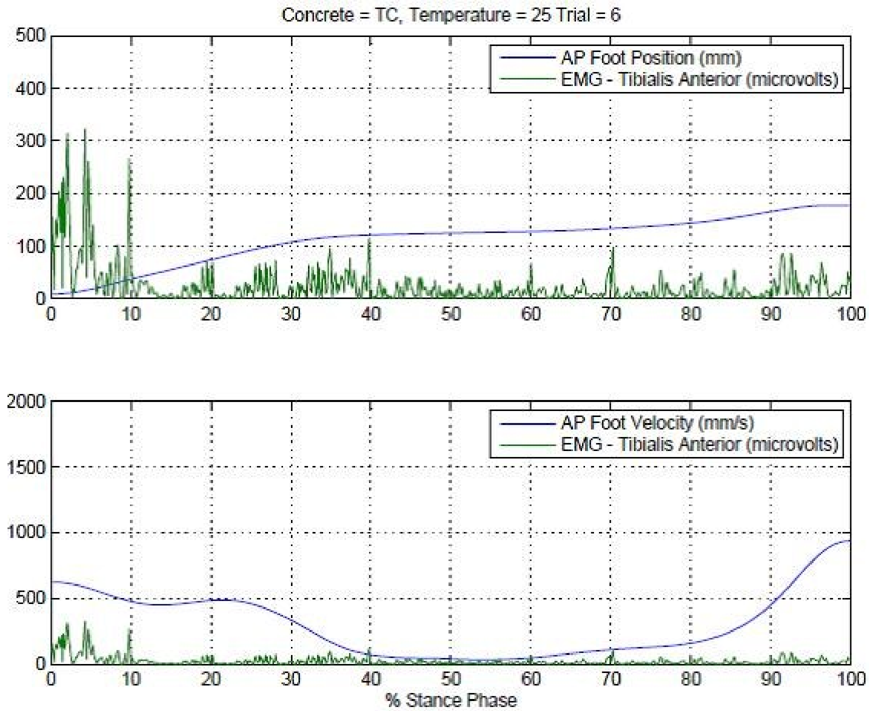

Figure 17: TC AP foot position/velocity and TA EMG

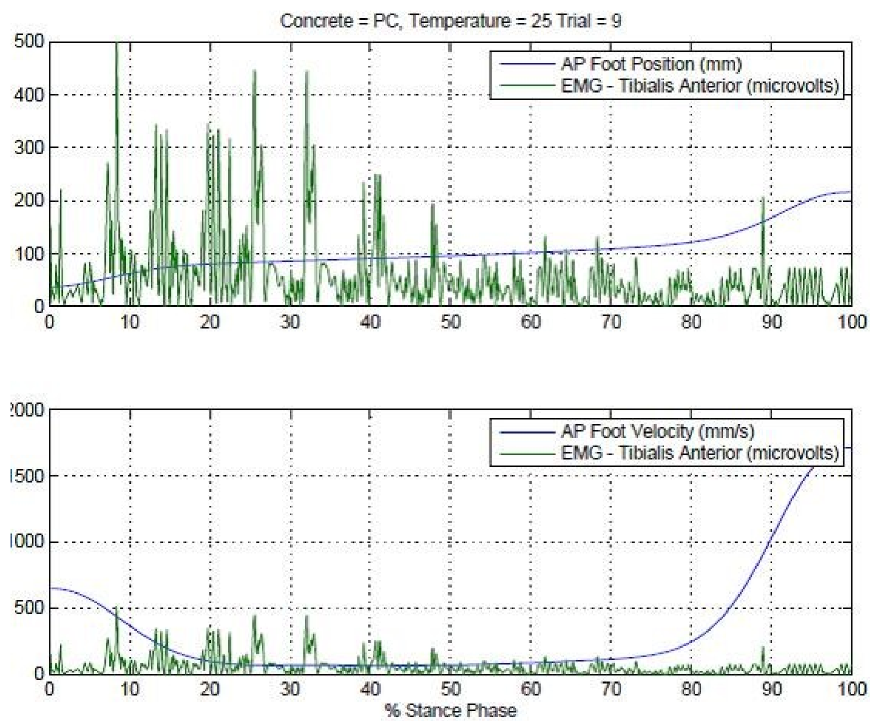

Figure 18: PC AP foot position/velocity and TA EMG

Table 9: Mean and standard deviation of EMG and motion data

		Mean	Std. Deviation
EMG Amplitude (mV)	TC	0.052929	0.0317789
	PC	0.096450	0.0637486
Heel Velocity (mm/s)	TC	287.299711	89.3143247
	PC	235.147925	57.9425174

No significant differences were found between pervious and traditional concrete for foot velocity or TA amplitude. However, EMG results revealed marginal significance, with trends toward reduced ankle dorsiflexion during traditional concrete trials. This is consistent with studies reporting reduced ankle dorsiflexion during slipping [11]. This trend may suggest marginal improvement of slip performance when walking on pervious concrete.

CHAPTER 5

DISCUSSION

5.1 – Interpretation of Results

As Figure 15 and Figure 16 clearly show, the results support the hypothesis that pervious concrete exhibits improved slip resistance under icy conditions in comparison to traditional concrete. As explained in Chapter 3.5, friction usage represents a ratio of the required coefficient of friction against the material coefficient of friction. Higher levels of this measure indicate a reduced margin between friction available and friction used, thus increasing slip likelihood. Thus, the results clearly indicate that pervious concrete possesses a smaller chance of inducing a slip as well as a greater margin of safety than traditional concrete. The reasoning for these results is explained in Chapters 2.5 and 3.2. Pervious concrete possesses a rougher surface texture that provides a superior ability for the foot to remain in contact with the surface than traditional concrete, and it also prevents ice from accumulating on its surface as easily as this occurs on traditional concrete.

Additionally, the material testing detailed in Chapter 3 Section 2 revealed increased levels of contact pressure on pervious concrete, providing further evidence that it may lead to fewer instances of slipping. It should be noted that no statistical analysis was performed on the results of the material testing aside from a simple direct comparison. The reasoning behind this is due to the fact that the primary focus of this experiment was on the biomechanical analysis of the gait results. The material testing results are included as additional supportive material to further enhance the results of the study.

5.2 – Comparison to Previous Studies

Many other studies have examined slips and falls in the context of gait, and other research has been conducted to study pervious concrete in different capacities. However, to our knowledge, no other research has combined the study of slips and falls while walking on pervious concrete. Despite this, it is still important to attempt to quantify the results of this experiment in comparison to current research.

Previous studies have examined the effects of slips and falls on ice and snow. Such incidents were determined to be detrimental to the wellbeing of pedestrians, however little was found to remedy the problem except increasing the regularity of snow plowing, spreading additional salt and sand, and improving shoe traction technology [20]. While these are all important measures to take in the prevention of winter accidents, the results of this study suggest that the usage of pervious concrete might offer a better solution than any current measures.

There are other studies that have been conducted that have somewhat similar intents. A study was conducted that extracted the rCOF for a walking trial in order to obtain the amount of contribution of transverse shear force [35]. However, this study did not involve slippery surfaces or traditional or pervious concrete. Another study was conducted that extracted ground reaction forces (GRF) from animals walking across slippery surfaces [36]. However, this study did not involve pervious or traditional concrete either and also did not involve human subjects. As such, the current research is inadequate in describing the likelihood of slips and falls when walking across pervious and traditional concrete.

5.3 – Implications of Results

As mentioned above, no such research examining both the effects of slips and falls and pervious concrete has been conducted as of yet. The finding that there is a significantly larger level of friction usage while walking on traditional concrete under hazardous conditions suggests that traditional concrete may be associated with increased slip likelihood in comparison to pervious concrete. Thus, it would be beneficial to conduct further study of these results and also begin propagating this information to those who work with pervious concrete or city planning. An ideal outcome of this study and subsequent research in this area would be for more municipalities, universities and organizations to realize the safety benefits of pervious concrete and begin incorporating it into use for paving their surfaces.

5.4 – Limitations of the Experiment & Future Work

Due to technical issues, the data recorded for the EMG and motion capture analysis was lost before the completion of the experiment. While this was an unfortunate turn of events, it had already been determined from pilot testing that the force plate analysis was the most important means of testing in terms of proving a statistically significant difference between the likelihood of falling on pervious and traditional concrete. Preliminary analysis had shown no significant difference between foot velocity for traditional and pervious concrete, although there was a slight difference in EMG results with traditional concrete showing a small reduction in ankle dorsiflexion.

There were also some concerns as to the feasibility of using these methods to quantify the likelihood of slips. While Chapter 2 explains in detail the kinematic and muscle response characteristics that occur during a fall, due to the nature of this particular experiment it proved difficult to apply those techniques. For example, while it was known from prior research that horizontal heel velocity increases during a slip, visible slips did not occur in the majority of trials [22]. Thus, any increase witnessed in heel velocity may have only been caused by actual slips. Additionally, several previous studies only reported slip-related differences in muscle activation when subjects anticipated a slippery surface [14]. In this experiment, subjects were made to be unaware of the surface conditions on which they were walking as much as possible. Thus, these methods may not have been ideal to test the hypothesis of this experiment, but should be considered for future work.

One of the most notable limitations of the experiment is that it attempted to simulate an outdoor phenomenon in an indoor laboratory environment. While great care was taken to recreate as accurate of a simulation as possible, it would still be highly desirable to recreate this experiment in a true outdoor environment under real hazardous weather conditions. This was not considered due to the lack of available equipment; such an endeavor would require mobile force platforms and motion capture cameras which are highly specialized and expensive pieces of equipment.

Another opportunity for future work would be to examine whether or not the results held up for different age groups. The age bracket was intentionally kept narrow for this experiment so as to not contaminate the results with potential age-related differences in slipping behavior. However, it could prove interesting to examine whether the results are the same as, for example, a group of elderly participants. The experiment could be repeated with a sampling of elderly participants, as they are both more likely to fall and suffer more bodily harm from the effects of falling than the younger sample group tested in this experiment [2]. Then, the average utilized friction values of the elderly subjects could be compared against the young subjects to see if a statistically significant difference exists between the two groups.

Finally, one of the unexpected results of the experiment was the discovery that gender proved to be a significant factor in the likelihood of slips. While it was successfully accounted for in the statistical analysis of the remainder of the data, this was not anticipated prior to testing and could make for another interesting study in itself. Similar to a study examining differences between elderly and young subjects, a study could be performed in which male and female participants' friction usages were compared against each other. While this experiment proved that gender acted as a nuisance factor during statistical comparisons of concrete type and condition, an experiment could be conducted in which gender was considered as the main factor and concrete type and condition were not.

5.5 – Conclusion

The objective of the experiment was to analyze slip-related biomechanical characteristics while walking across pervious and traditional concrete surfaces in dry and icy conditions. We hypothesized that pervious concrete would exhibit improved slip resistance under icy conditions in comparison to traditional concrete. This hypothesis was confirmed through a variety of different tests.

Prior to subject testing, the material testing performed on the pervious concrete suggested it to have superior permeability, better allowing it to drain water buildup from its surface thus preventing ice from forming. Pervious concrete was also associated with pedestrian-applied contact pressures that were over twice as much as those associated with traditional concrete in all three phases of a step.

Upon analyzing the data acquired from subject testing, concrete type and condition both proved to be significant factors in the likelihood of a slip occurring. Both the traditional concrete type and the icy condition indicated higher utilized friction values than the pervious concrete type and the dry condition, thus indicating they are more likely to induce a slip during walking.

An interesting development in the experiment was that while age, height and weight had no significant effect on the likelihood of a slip, gender did have a significant effect with males being more likely to slip than females. This may be due to a number of reasons and may indicate that men in general walk on hazardous surfaces more aggressively than women. The gender effect was successfully accommodated for in the study by treating it as a nuisance factor and blocking on the gender factor. This allowed for the contributions of concrete type and condition to be analyzed without bias from a third significant factor.

With the results found from this experiment, it is the hope of the author that this work can be used to improve the safety of pedestrians as well as improve the efficiency of wintertime maintenance for municipalities. It would also be greatly beneficial should other researchers wish to expand upon this work and conduct further studies analyzing the gender effects of slips on icy surfaces or the muscle and motion effects that were not able to be fully analyzed.

APPENDIX

SUB	GENDER	CONCRETE	CONDITION	TRIAL	FU
1	1	1	1	1	0.2728
1	1	1	1	2	0.1657
1	1	1	1	3	0.3125
1	1	1	2	1	1.2979
1	1	1	2	2	1.2326
1	1	1	2	3	1.2455
1	1	2	1	1	0.2269
1	1	2	1	2	0.218
1	1	2	1	3	0.2014
1	1	2	2	1	0.7378
1	1	2	2	2	0.784
1	1	2	2	3	0.6391
2	2	1	1	1	0.2228
2	2	1	1	2	0.1531
2	2	1	1	3	0.1534
2	2	1	2	1	0.7031
2	2	1	2	2	0.8454
2	2	1	2	3	0.8271
2	2	2	1	1	0.2473
2	2	2	1	2	0.1676
2	2	2	1	3	0.1616
2	2	2	2	1	0.3884
2	2	2	2	2	0.4312
2	2	2	2	3	0.529
3	2	1	1	1	0.0683
3	2	1	1	2	0.1093
3	2	1	1	3	0.061
3	2	1	2	1	0.456
3	2	1	2	2	0.6162
3	2	1	2	3	1.1174
3	2	2	1	1	0.1508
3	2	2	1	2	0.1449
3	2	2	1	3	0.144
3	2	2	2	1	0.5038
3	2	2	2	2	0.4453
3	2	2	2	3	0.4081
4	2	1	1	1	0.2329
4	2	1	1	2	0.1977
4	2	1	1	3	0.1851
4	2	1	2	1	0.9118

4	2	1	2	2	0.9806
4	2	1	2	3	0.8491
4	2	2	1	1	0.2977
4	2	2	1	2	0.2725
4	2	2	1	3	0.292
4	2	2	2	1	0.6894
4	2	2	2	2	0.6709
4	2	2	2	3	0.428
5	1	1	1	1	0.1339
5	1	1	1	2	0.129
5	1	1	1	3	0.1179
5	1	1	2	1	1.0997
5	1	1	2	2	0.7427
5	1	1	2	3	0.7652
5	1	2	1	1	0.1541
5	1	2	1	2	0.1313
5	1	2	1	3	0.1423
5	1	2	2	1	0.4031
5	1	2	2	2	0.3605
5	1	2	2	3	0.4103
6	2	1	1	1	0.1817
6	2	1	1	2	0.0991
6	2	1	1	3	0.1934
6	2	1	2	1	0.9841
6	2	1	2	2	1.067
6	2	1	2	3	1.4249
6	2	2	1	1	0.2045
6	2	2	1	2	0.1802
6	2	2	1	3	0.206
6	2	2	2	1	0.3684
6	2	2	2	2	0.3682
6	2	2	2	3	0.4614
7	1	1	1	1	0.1956
7	1	1	1	2	0.1843
7	1	1	1	3	0.2626
7	1	1	2	1	1.5905
7	1	1	2	2	0.9739
7	1	1	2	3	1.1309
7	1	2	1	1	0.2943
7	1	2	1	2	0.272
7	1	2	1	3	0.2762
7	1	2	2	1	0.7749
7	1	2	2	2	0.6426

7	1	2	2	3	0.7133
8	1	1	1	1	0.2433
8	1	1	1	2	0.1904
8	1	1	1	3	0.2225
8	1	1	2	1	1.6784
8	1	1	2	2	1.2013
8	1	1	2	3	1.0944
8	1	2	1	1	0.2206
8	1	2	1	2	0.2243
8	1	2	1	3	0.2375
8	1	2	2	1	0.6256
8	1	2	2	2	0.645
8	1	2	2	3	0.6686
9	2	1	1	1	0.231
9	2	1	1	2	0.1994
9	2	1	1	3	0.2279
9	2	1	2	1	1.4688
9	2	1	2	2	1.2436
9	2	1	2	3	1.2388
9	2	2	1	1	0.2129
9	2	2	1	2	0.2334
9	2	2	1	3	0.2508
9	2	2	2	1	0.5793
9	2	2	2	2	0.631
9	2	2	2	3	0.6164
10	1	1	1	1	0.2575
10	1	1	1	2	0.274
10	1	1	1	3	0.2301
10	1	1	2	1	1.1333
10	1	1	2	2	1.3891
10	1	1	2	3	1.4662
10	1	2	1	1	0.2705
10	1	2	1	2	0.2299
10	1	2	1	3	0.2274
10	1	2	2	1	0.545
10	1	2	2	2	0.472
10	1	2	2	3	0.4854

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