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A Study of Walkway Safety and Evaluation of Tribological Test Equipment

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A Study of Walkway Safety and Evaluation of Tribological Test Equipment

by

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A thesis submitted to the School of Engineering in partial fulfilment of the requirements for the degree of Master of Science in Mechanical Engineering

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LIST OF SYMBOLS AND ABBREVIATIONS

ADA – Americans with Dissabilities Act

ADAAG – Americans with Dissabilities Act Accessibilities Guidelines

ANOVA – Analysis of Variance

ANSI – American National Standards Institute

ASSE – American Society of Safety Engineers

ASTM – American Society of Testing and Materials

CABO – Council of American Building Officials

CDC – Centers for Disease Control and Prevention

CO_2 – Carbon Dioxide

COF – Coefficient of Friction

COG – Center of Gravity

DCOF – Dynamic Coefficient of Friction

EDTA – Ethylenediaminetetraacetic (acid)

EVA – Ethylene Vinyl Acetate

F_N – Normal Force

F_T – Tangential Force

F_F – Frictional Force

FBC – Florida Building Code / Florida Building Commission

ft/s – feet per second

fps – frames per second

FTM – Floor Treatment Material (UL410)

IAPMO - International Association of Plumbing and Mechanical Officials

IBC – International Building Code

IC – Initial Contact Phase of Gait

ICBO – International Conference of Building Officials

in/s – Inches per Second

ISw – Intitial Swing Phase

HS – Heel Strike

LED – Light emitting diodes

LR – Loading Response Phase of Gait

MS – Mid Stance Phase of Gait

m/s – meters per second

MSw – Mid Swing Phase of Gait

n - number of samples or tests conducted

NICB – National Insurace Crime Bureau

NFPA – National Fire Protection Association

NFSI – National Floor and Safety Institute

NSC – National Safety Council

OSHA – Occupational Safety and Health Administration

PIAST – Portable Inclinable Articulated Strut Tester

psi – Pounds per square inch of pressure

PSw – Pre Swing Phase of Gait

rpm – Revolutions per minute

SBC – Standard Building Code

SBCCI – Southern Building Code Congress International

SBR – Styrene Butadiene Rubber

SCOF – Static Coefficient of Friction

SD or sd – Standard Deviation

SLS - Sodium Lauryl Sulfate

TCNA – Tile Council of North America

TS – Terminal Stance Phase of Gait

UBC – Uniform Building Code

UL – Underwriter's Laboratory

US – United States of America

VIT - Variable Incident Tribometer

μ = Coefficient of Friction

μ_s = Static Coefficient of Friction

μ_k = Dynamic or Kinetic Coefficient of Friction

WCM – Walkway Construction Material (UL410)

ABSTRACT

A walkway tribometer measures the coefficient of friction between flooring material and a test foot. The value of the coefficient of friction is an indicator as to whether the flooring surface is slippery and has a propensity to cause slip and falls. This study determined that one style of tribometer, an XL Tribometer, mimics the heel-to-floor interaction of the human heel strike. High speed video footage revealed that the test foot strikes the surface and rotates so that full engagement occurs before sliding thus mimicking the affect of a human ankle. The test foot accelerates forward as would be expected during a human slip event. The manufacturer's reported impact speed of 11 in/s, when set to the operating pressure of 25psi, was found to be much lower than measured speeds of three calibrated tribometers. Three XL tribometers were tested and provided a range of impact speeds from 17.4 to 22.7 in/s (n=540) when set to the operating pressure of 25 psi. The pressure setting was found to have a significant effect on the impact speed while the mast angle had an insignificant affect. A review of human walking studies revealed a range of pedestrian heel impact speeds on the order of 19.4 to 45.3 in/s during normal human ambulation activities. These tribometers fell on the low side of this speed range. A sensitivity study showed that the measured value of the coefficient of friction tends to decrease with a higher impact speed. This COF decrease was on the order of 0.02 and below the machine resolution and considered inconsequential within the walkway safety community.

CHAPTER 1: Introduction

Walking is the successive loss and recovery of balance and is one of the most unsafe modes of natural motion [1, 2]. Walking has also been described as a series of falls and catches with each step taken establishing a support base to catch the fall of the upper body [3]. As humans walk in our built environment the interaction between the foot and the surface requires a certain amount of resistant force in order to continue the forward motion. This surface-foot interaction is complex given the variety of shoe materials, floor materials, contaminants, gait patterns, and walking speeds. The coefficient of friction of the shoe-contaminant-floor interface is believed to be a direct indicator as to the propensity for a pedestrian to slip and fall. Building codes and industry standards demand that walking surfaces be slip resistant but there is silence within the codes and standards regarding the quantitative measurement of slip resistance. Machines called tribometers are used to measure coefficient of friction or the slip resistance between two surfaces; namely the subject flooring material, possibly a contaminant, and a test foot. There are many forms of tribometers and some were developed to similuate the human foot's interaction with the walking surface.

Environmental characteristics are largely the responsibility of the property owner while shoe material, gait patterns and walking speeds are characteristics of the pedestrian. There are legal responsibilities placed on property owners to ensure they provide a reasonably safe place when people use their property. However, the definition of 'reasonably safe' is open to interpretation and usually settled within the judicial system. These legal aspects can result in years of litigation and cost that places a burden on the property owner, the legal system, and the person that was hurt. The pedestrian is responsible for the style of shoes being worn along with how fast they walk on a given surface. Ultimately, the pedestrian is expected to watch where they are walking and avoid any noticeable hazards.

The structure of this thesis is divided into four portions. The statistics surrounding slip and fall events in the United States and the associated economic and human costs are first discussed. The second portion outlines the laws, codes, standards and regulations associated with the prevention of slippery walking surfaces. The third portion gives a detailed description of the XL Tribometer and how it is used to determine whether a walking surface is slippery or not. The fourth and final portion is the experimental setup and results of XL Tribometer testing.

CHAPTER 2: Literature Review

2.1 Scope of Slip and Falls in the US

An average person takes 8000 steps per day [4]. In 2011 the Occupational Health and Safety Administration (OSHA) recorded 681 workplace fatalities due to falls, slips, and trips [5]. In 2012 that number was 668 fatalities. In 2011, there were 225,550 reported slip and fall injuries that resulted in lost days away from work [6]. According to the claims data from Liberty Mutual, one of the largest workers' compensation insurance companies in the U.S., the second most costly category of disabling workplace injuries are falls on the same level. Falls on the same level means the person did not fall from a height. Falls on the same level account for $8.61 billion of direct cost to employers during 2010, the most recent year for which data are available [7]. The cost increase appears to be a growing trend. From 1998 to 2010 the cost of injuries categorized as injuries due to falls on the same level has risen by 42.3%. These numbers only represent people that were working at the time of their injury.

People slipping or tripping in retail locations, government buildings, educational and healthcare facilities or at home are not included in the above work-environment numbers. According to the National Safety Council (NSC), there were 8.9 million injuries due to falls in 2011 [8, 9]. Falls are the leading cause of emergency room visits and lead to over 20,000 deaths each year in the U.S. [4]. Falls are only second to automobile accidents as the leading cause of unintentional deaths with 25,000 fatalities in 2009. With the US population aging, this can become an even bigger issue in years to come. According to the Center for Disease Control (CDC) 26,009 fall deaths occurred in 2010 and 94% (21,649) of those deaths were people over the age of 65 [10, 11]. Among older persons, slips have been identified as a primary cause of falls in the workplace and home accounting for 57% of all falls [12].

2.2 Human Ambulation

The term ambulation means to walk around or travel by foot from place to place. The scientific principles used to explain movement is kinematics [13]. Kinematics is only concerned with the motion itself such as linear and angular displacement, velocity and acceleration and not the forces that cause the movement. The tribometer testing described later in this thesis focuses on one particular kinematic aspect of human ambulation, the heel strike, and not any forces that created that movement.

Walking or ambulation has been described as eight continuous phases [14, 16, 17]. These phases are repeated over and over again resulting in the individual moving in a forward direction. A gait cycle starts when a foot (in the following description the right foot strikes first) contacts the ground and ends when that foot again hits the ground. The first phase is called Initial Contact (IC) where the heel strike (HS) occurs and the right foot comes to a stop on the ground. This contact surface will now act as a pivot point for the rest of the body. The second phase is called the Loading Response (LR). The LR is where the right foot starts to accept the body weight. Up to this point in the gait the body has support from both feet (double support). The third phase is Mid Stance (MS). This phase is where the left foot propels or lifts the body so that it is directly over the right foot which is supporting all of the weight. The left foot swings forward and the ankles of both feet are adjacent at the end of the MS phase. The fourth phase is called Terminal Stance (TS). TS is the period of time from the MS just prior to the heel contact of the swinging left foot. During the MS and TS phases the body is supported by only one foot (single support). The fifth phase is called Pre Swing (PSw). PSw is the time interval from when the heel contact of the left foot just prior to the right foot leaving the ground and propelling the body forward. The sixth phase is called the Initial Swing (ISw) and this is the time period when the right foot leaves the ground after toe-off and attains maximum knee flexion as it passes by the left leg. The seventh phase is called Mid Swing (MSw) and it happens between the ISw and when the right leg's tibia is vertical to the ground. The tibia is the large bone between the knee and the foot [14]. The eighth and final phase is called the Terminal Swing (TSw) and this is the period between the MSw and just prior to the right heel striking the ground. Figure 1 shows visually how these eight phases relate to one another in sequential order.

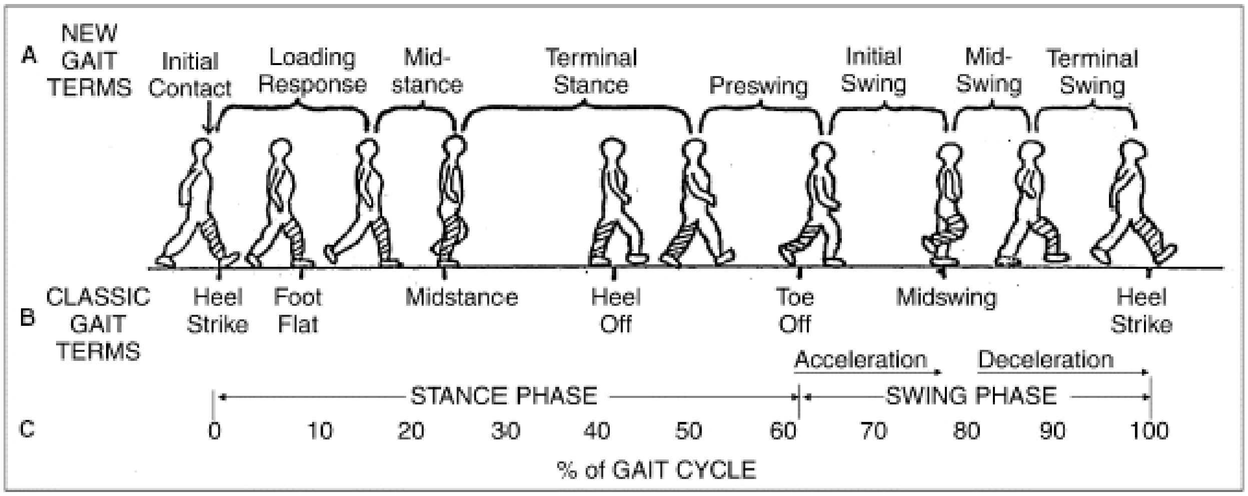

Figure 1: Gait cycle phases and events[1]

The above gait description is of a healthy adult walking normally with typical footwear. The mechanics and biophysics of the human musculoskeletal system is a complex topic and outside the scope of this paper. The topic becomes even more complex with the addition of

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[1] Reprinted from the public domain National Institute of Health Website

abnormalities, disabilities, and walking-assist devices. The gait pattern can be significantly altered due to neuromuscular abnormalities such as arthritis, obesity, joint replacement, malformed bone structure, flat-footedness, amputation or stroke [17-19]. Normal aging processes can also affect gait patterns. As we age, stride lengths become shorter, double-support periods increase, push-off power decreases, and heel strikes reduce to a more flat-footed landing [20, 21]. Moreover, elderly people walk slower with an increase in heel strike velocity [22]. This increase in heel strike velocity as we get older may play a role in the ability to recover from the initiation of a slip and fall event given the decrease in reaction time of the elderly versus the young. Understanding the heel strike speeds of normal human ambulation in comparison to the speeds of tribological test equipment that supposedly mimics human heel strikes is important. This thesis attempts to make that comparison.

2.3 Coefficient of Friction

During human ambulation a typical point of slipping and falling is when the heel strikes the walking surface and there is insufficient friction to resist the forward motion of the foot in relationship to the floor [2, 23, 24]. Prior to the heel strike, the pedestrian’s center of gravity (COG) is forward of the support base [20, 25] which is the planted foot. This unbalanced position occurs because the trailing leg is behind the COG and the leading leg has yet to make contact with the ground and provides no support as seen in the MS and TS phases. At this point during the gait the heel will strike the surface at a variable angle and speed depending upon the characteristics of the pedestrian, their activity, and their traveling speed [9, 20, 26, 27]. If there is insufficient friction available between the floor and the shoe-heel material then the foot will slip forward causing the pedestrian to become unbalanced. Once the pedestrian becomes unstable they may or may not be able to recover their balance. If s/he cannot recover and becomes too unbalanced then gravitational forces will take over and the walker falls to the ground with the potential to cause bodily injury.

Friction force (F_F) develops as a result of two bodies of material moving against one another [28, 29]. F_F is a vector force thus having direction and magnitude and develops on the interface of two materials. The direction of F_F is in the opposite direction of the relative motion of the two materials. The classic example is a block of wood sitting on a table. As a horizontal force is applied to the block a resistive force develops between the block-table interface that tends to prevent the wood from sliding in the direction of the applied force. This resistive frictional force is equal to the applied force until the moment just before the block begins to move and slide along the table. Once the block starts to move the resistive frictional force is generally less than the resistive force when the block was stationary. The amount of F_F that develops under the static and dynamic scenarios are proportional to the normal force applied to the block i.e. the weight of the block. This proportional variable is generally referred to as the Coefficient of Friction (COF) and has the symbol μ. The COF is a dimensionless number and is the ratio of the horizontal component of force (parallel to the walking surface and passing through the COG) required to overcome the friction to the normal component of the vertical force (weight) of the object [29-32]. The relationship between the static friction force and the applied force is:

$$F_f \leq \mu_s N \qquad \textbf{Equation 1}$$

Where μ_s = Static Coefficient of Friction, N = Normal force, and F_f = Frictional force.

The relationship between the dynamic friction force and the applied force is:

$$F_f = \mu_k N \qquad \textbf{Equation 2}$$

Where μ_k = Kinetic (sometimes referred to as Dynamic) Coefficient of Friction.

The values of μ_k and μ_s depend on the nature of the surfaces but μ_k is generally less than μ_s [28, 33].

The concept of F_f is actually much more complicated than presented here and the interaction between two surfaces not only deals with the general roughness but also electrostatic forces between atoms and molecules at the surface's interface. Also, the μ_k is known to vary with speed and applied normal loads [2, 27, 28, 34, 35]. Two materials sliding against one another can have different μ_k's depending upon how fast they are moving relative to each other. Figures 2 and 3 are charts showing how μ_k changes with speed for two dry metals [36, 37]. The charts are interesting in the fact that for stainless steel on aluminum the μ_k decreases with an increase in sliding speed. However, the μ_k increases with sliding velocity when 202 stainless steel slides across 304 stainless steel.

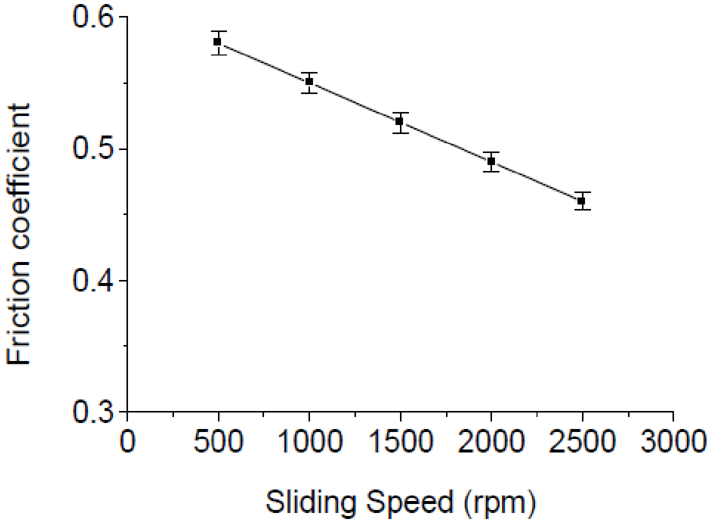

Figure 2: Variation of μ$_k$ with sliding speed between aluminum and steel[2]

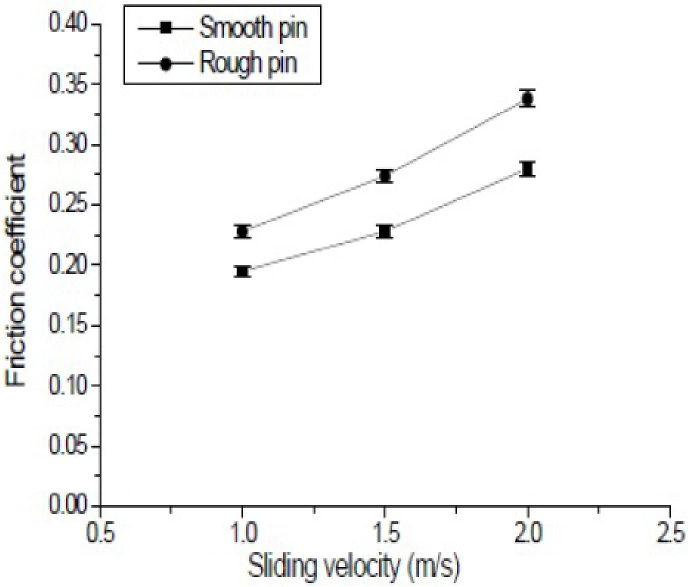

Figure 3: Variation of μ$_k$ with sliding speed between two grades of stainless steel[3]

Keep in mind that most slip and falls occur on wet floors where the first surface is the floor the second surface is the shoe bottom and the contaminate separates these two surfaces thus creating

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[2] Reprinted by permision of author M.A. Chowdury, Dhaka University, Bangladesh India

[3] Reprinted by permission of author M.A. Chowdury, Dhaka University, Bangladesh India

two interfaces rather than one [4]. The issue of varying μ_k with speed becomes more complex when a third substance such as water or some form of lubrication is introduced between the two surfaces. Consideration must be given to fluid dynamics such as the viscosity, hydrodynamic fluid pressure and film thickness of the lubricant. The body of research into the science of tribology (the science of friction, lubrication and wear) is much more focused on the reduction of friction for the purpose of controlling wear in bearings and moving joints rather than an increase in friction for the purposes of walking. When a lubricant is present between two moving surfaces the μ_k is better described using a Stribek-Hersey curve as shown in Figure 4 [38].

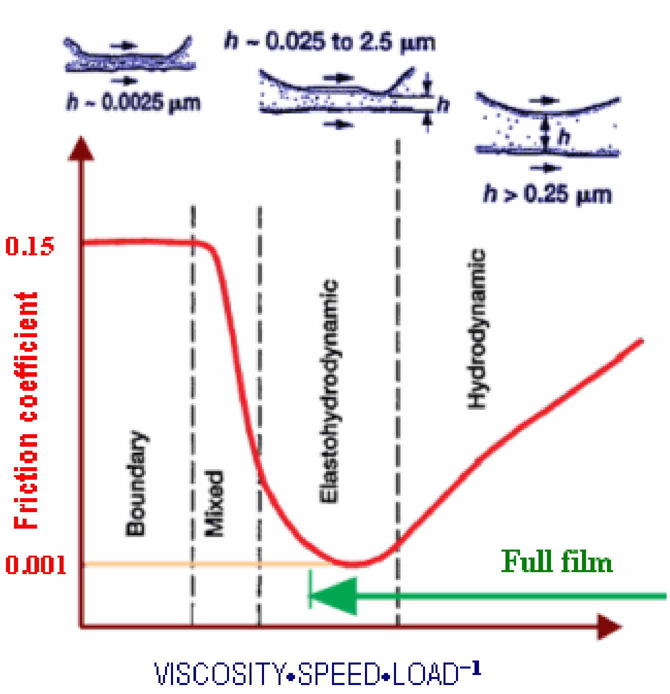

Figure 4: Example of a Stribeck-Hersey curve where μ_k changes with viscosity, speed and applied load

When lubrication is present between two moving surfaces the μ_k is influenced by not only the relative speed between the surfaces but the film thickness of the lubricant. The film thickness can be affected by the wetting capability or surface tension of the lubricant-floor interface. Another variable affecting μ_k is the viscosity or thickness of the lubricant. A less viscous lubricant would tend to disperse faster when the load is applied than a higher viscosity lubricant. The Stribeck-Hersey curve also shows that the μ_k is inversely proportional to the load applied. This relationship means that a lighter loaded moving surface will have a higher μ_k given the other variables remain the same. The science behind fluid dynamics is vast and outside the scope of this work. The concept that μ_k is affected by the speed of the two objects moving past one another is the primary takeaway from the introduction of the fluid dynamics topic.

For clarity purposes, the use of the symbols μ_k and μ_s are typically used in equations and physics analysis but in the general safety community they are referred to as DCOF and SCOF respectively [29].

2.4 Problem Definition

Identifying a walkway as slippery is a subjective assessment just like saying an item is hot, warm or cold. To one person a sidewalk may be slippery and difficult to navigate but to another person that same walkway is easily traversed. Unlike temperature which can be measured using multiple techniques and the result universally accepted, the COF of a walking surface has no universally accepted measurement tools or interpretation of the results [24, 39]. Therefore, if someone falls down and becomes injured a question arises as to whether the individual was being careful or was the walking surface to slippery to safely navigate. If the individual’s carelessness is at fault, blame is placed on that person. If the walking surface is too slippery then blame can be placed on the property owner and compensation for injuries can be sought.

The laws, codes, regulations, and industry standards that seek to prevent slippery walking surfaces are plentiful and, at best, confusing, at worst, contradictory. There are a variety of test methods and machines that reportedly measure the COF of a walking surface but none of them are universally accepted. Most of these techniques use equipment that slides a weighted test foot along the floor surface and calculates a COF. Some techniques attempt to simulate the heel strike portion of the gait cycle while measuring the COF. One of the most popular heel-strike simulation machines is the XL Tribometer. It reportedly has a functional ankle and the test foot hits the ground at a velocity similar to the human heel strike. The manufacturer of this tribometer, Excel Tribometers, has the following statement in their sales literature.

> *The XL VIT instrument mimics significant biomechanical parameters of the human walking gait. The machine is used stationary at the test location and does not walk, but the angle and velocity of the leg operating mechanism, and the size and shape of the test foot, were developed to replicate the heel strike of a human walking; the machine has a functional ankle. The leg of the XL VIT is free to accelerate once a slip occurs, as with a real-world human slip event.*
>
> *At the recommended operating pressure of 25psi, the velocity of shoe contact (of about 11 inches per second) is thought to be within the range of velocities at which the heel contacts the floor in human ambulation.*

This thesis documents the evaluation of these claims through the use of high-speed video analysis and electronic speed gait analysis. It is important to determine if, in fact, the XL's test foot strikes the ground in a similar manner and speed to human heel-strikes. If the test foot does not live up to this impact speed claim then the affect on the COF readings needs to be understood. Having the scientific support that the XL mimics a significant biomechanical parameter of the human walking gate would lend credibility to its use in the forensic and safety fields.

2.4.1 Legal Issues

Legal issues and precedents abound concerning the duty that a property owner has to an invitee. The author is not an attorney and does not contend that the following information is complete, concise or authoritative. However, this topic needs discussed because it forms the framework of why the measuring of flooring COF is important.

2.4.2 Requirements of Property Owners and Tenants

It is common law that a property owner has a duty of care to provide a reasonably safe environment for invitees and to warn about any hazards [40]. The legal definition of an invitee is complicated and beyond the scope of this work but in general, if a business is open to the public then a person using the business is considered an invitee and the business owner has certain legal responsibilities for their safety. For instance, a restaurant owner has a legal duty to warn a patron if the plate of food being served is very hot and could burn them if touched. Excessive heat that could burn the patron’s hand is not readily visible so would constitute a hidden hazard unless warned against. The same situation occurs if the floor near the restroom has recently been mopped and could be more slippery than expected. The restaurateur has a legal duty to warn the patron that the floor may be slippery and thus a sign is usually placed in the damp area. If the property owner fails to warn of a known hazard then they could be found negligent and be legally liable for any injuries caused by that hazard. Every state has specific and varying laws and interpretations of this basic duty of care when it comes to premises liability.

A dilemma develops when there is no consensus on what constitutes a safe or unsafe floor. Just because there is liquid on the pathway does not automatically mean the surface is dangerous or unsafe. Many sidewalks are exposed to rain and remain safe to traverse. However some slip and fall accidents do not involve any contaminates at all. Therefore, it becomes difficult for a property owner, insurance company, or floor maintenance company to determine if they have slippery floors or not.

2.4.3 Actual or Constructive Knowledge of Defect

In Florida the tort laws are written in such a way that the business establishment only owes the duty of care to the patron if the dangerous condition is know or should have been discovered [41]. This legal concept is referred to as actual or constructive knowledge. An example of actual knowledge would be if a shopper spilled a drink on the floor of the grocery store and a store employee walked by it, saw it, and failed to clean it up or place a warning sign close by. That employee, and thus the store, had actual knowledge of a dangerous condition, i.e. the spilled drink. An example of constructive knowledge is a bit more tenuous in the sense that the practices and procedures of the establishment come into play. Suppose a shopper at a supermarket spills a drink in the aisle and a customer 10 seconds later comes along and slips and falls in that spilled drink. The establishment cannot be held negligent and liable for the patron’s injures because they did not have enough time to rectify the hazard. They had no actual knowledge of the defect or dangerous condition. However, if that same spilled drink stays on the floor for a period of time where the owner, using reasonable and prudent care, should have found the spill, then the establishment can be held negligent and liable for the injuries. In other words if the establishment had policies and procedures in place such that employees were regularly walking the isles and looking for problems then they likely would have found it and cleaned it up. However, if the establishment has no procedures, mops, signs, or insufficient employee training, then they could be held liable for any injuries sustained if a customer slips and falls in the spilled drink.

2.4.4 Fraud

Some slip and fall insurance claims are fraudulent in nature. The National Insurance Crime Bureau (NICB) published a study that suggests the number of questionable slip and fall claims has risen 57% from 2008 to 2010 [42]. According the NICB Injury Claim Investigation Guide a slip and fall case involves a person slipping or tripping and falling on a hazard allegedly created by the negligence of the property owner or tenant. This kind of claim can become criminal if it is an orchestrated event where the participant(s) create a false scenario with the intent of gaining financially [42]. These questionable claims are flagged in the insurance adjuster's notes as having some symptoms or indicators that the claim could be fraudulent in nature [43]. The 57% increase could be due to an increase in awareness and oversight on the insurance company or an actual increase in fraudulent claims. A person's lack of documented injuries and their desire to settle with the insurance company quickly, while suggesting fraud, would be virtually impossible to prove in a criminal court. Fraudulent slip and falls can be incredibly hard to detect without video surveillance available. In civil court, the injuries and behavior of the plaintiff can suggest to a jury that the slip and fall may be faked resulting in a zero dollar verdict.

2.5 Codes, Regulations and Standards

There are statutory codes, regulations and industry standards that expound upon safe pedestrian walking surfaces. Many of them are difficult to interpret, contradictory, and most lack important details. For instance, the Americans with Disabilities Act (ADA) demands that handicap ramps be slip resistant. Since the ADA requirements are usually codified by local jurisdictions that means, by law, ramps must be slip resistant. Unfortunately, the ADA regulations poorly define the term slip resistant and do not instruct how to measure or quantify it, or establish metrics to relate slippery surfaces to non-slippery surfaces. The ADA leaves the interpretation completely up to a builder or inspector to ‘know it when they see it’. An analogy would be if the 2010 International Building Code were to say all handrails must be waist high with no other explanation as to what ‘waist high’ means or how to measure it. This ambiguity would obviously lead to conflicts and safety issues with irregular placement of handrails. Table 1 is a list of agencies, regulations, codes, and standards that deal with the concept that walking surfaces should be slip resistant. Appendix A contains a detailed discussion of each item.

Table 1: List of agencies, codes, and standards relating to slippery walking surfaces

Organization	**Source**
The Occupational Health and Safety Administration (OSHA)	United States Department of Labor
Americans with Disabilities Act (ADA)	United States Department of Justice – Civil Rights Division
Model Building Codes	Florida Building Code (FBC) Council of American Building Officials (CABO) Standard Building Code (SBC) Uniform Building Code (UBC) International Building Code (IBC)
National Fire Protection Association	NFPA 101 Life Safety Code NFPA 102: Standard for Grandstands, Folding and Telescopic Seating, Tents, and Membrane Structures NFPA 1901: Standard for Automotive Fire Apparatus

American Society for Testing and Materials (ASTM)	F1637 – Standard Practice for Safe Walking Surfaces F1646 - Terminology Relating to Safety and Traction for Footwear F609 - Standard Test Method for Using a Horizontal Pull Slipmeter (HPS) C1028 - Standard Test Method for Determining the Static Coefficient of Friction of Ceramic Tile and Other Like Surfaces by the Horizontal Dynamometer Pull-Meter Method F2913 - Standard Test Method for Measuring the COF for Evaluation of Slip Performance of Footwear and Test Surface/Flooring Using a Whole Shoe Tester D2047 - Standard Test Method for Static Coffiecint of Friction of Polish-Coated Flooring Surfaces as Measured by the James Machine F2913 - Standard Test Method for Measuring the COF for Evaluation of Slip Performance of Footwear and Test Surface/Flooring Using a Whole Shoe Tester F462 - Standard Consumer Safety Specification for Slip-Resistant Bathing Facilities E303 – Standard Test Method for Measuring Surface Frictional Properties Using the British Pendulum Tester D5859 - Standard Test Method for Determining the Traction of Footwear on Painted Surfaces Using the Variable Incident Tester (Withdrawn 2005) F489 Standard Test Method for Using a James Machine (Withdrawn 2005) F1677 - Standard Test Method for Using a Portable Inclineable Articulated Strut Slip Tester (PIAST) (Withdrawn 2006) F1678 - Standard Test Method for Using a Portable Articulated Strut Slip Tester (PAST) (Withdrawn 2005)
Underwriters Laboratory (UL)	UL410 - Slip Resistance of Floor Material

American National Standards Institute (ANSI)	A137.1 - Specification for Ceramic Tile A1264.1 - Safety Requirements for Workplace Walking/Working Surfaces and their Access; Workplace, Floor, Wall and Roof Openings; Stairs and Guardrails System A1264.2 - Standard for the Provision of Slip Resistance on Walking/Working Surfaces A1264.2 - Provision of Slip Resistance on Walking/Working Surfaces B101.1 - Test Method for Measuring Wet SCOF of Common Hard-Surface Floor Materials B101.3 - Test Method for Measuring Wet DCOF of Common Hard-Surface Floor Materials Z124.8 - American National Standard for Plastic Bathtub Liners

Within the information listed in Table 1 there are some references to what would be considered a sufficient COF value for a particular surface. Acceptable COF measurements span the range of 0.04 for bathtub liners to 0.68 on a wet fire engine. Seven of the references provide acceptable COF values using a variety of tribometers and techniques. There is no consensus within the scientific community on an acceptable COF value much less the equipment or methods used to quantify COF.

Perhaps due to this lack of scientific consensus on an acceptable COF value, there has been a recent push in the walkway safety community to relate human perception of slippery conditions to tribometer test results [2, 15, 44, 45]. This new direction places less emphasis on an actual COF value for safe and unsafe floors and more emphasis on whether a tribometer can accurately rank and differentiate surfaces in the way that humans can. This push has been termed a gait-based assessment. The significance of this gait-based approach is that equipment measuring COF, while using characteristics of human walking, may become more accepted in the safety and engineering community. The XL Tribometer, used for experimentation for this thesis, reportedly mimics a human heel strike in both style and speed.

2.6 Data from Literature

There are few peer reviewed articles that measure and report the foot impact velocity during human ambulation. R. Cham and M. Redfern [46] used motion capture equipment to measure the dynamic movements of the body during slip and non-slip events in sixteen subjects walking on level, 5°, and 10° walkways. The walkways were either dry or contaminated with motor oil. The objective of this study was to determine the sliding velocity and the sliding distance of the foot during the slipping event and to see if these parameters shed light on whether the person would recover from the slip. This research identified vertical and horizontal heel velocities on level walking surface just prior to heel strike. At the end of the swing phase the heel rapidly decelerated and was gently brought down onto the floor. The vertical speed 0.020 seconds before heel strike was -3.9 in/s (downwards). The horizontal velocity in the direction of motion 0.020 seconds before heel strike was 21.3 in/s. Of note in this study is that all trials resulted in the participant’s foot becoming fully engaged with the floor. Even when the participant slipped and fell, there was enough time for the heel to strike, the ankle to rotate, and the whole shoe to become flat on the floor before sliding commenced. This finding is interesting because the development of slip testing equipment attempting to simulate a heel striking and sliding across the floor may in fact be a real world condition. Tribometers that can recreate this biomechanical feature may have an advantage over those that do not when using the gait-based assessment.

A series of experiments by Winter [22] analyzed the heel contact velocity and the toe clearance during the swing phase in 11 subjects walking 10 trials each. The male and female subjects ranged from 21 to 28 years old and were asked to walk at their natural cadence. These tests revealed that heel contact velocity was virtually zero vertically (only 1 subject was reported vertically and that vertical velocity was -0.2 in/s) and 34.5 in/s horizontally. Noted in this paper was a previous study of 15 fit and healthy elderly subjects having an average heel strike velocity of 45.2 in/s even though their walking velocities were much lower than the younger subjects.

Testing performed by Fischer, et al. [2] using 22 test persons walking a total of 176 trials resulting in average horizontal velocities of 19.4 in/s. This style of walking was referred to as Type A. The other 27% of the trials, classified as Type B, resulted in much higher horizontal heel strike velocities of 33.1 in/s. Figure 5 shows example paths of the two styles of heel strikes that were observed during these trials. With higher walking velocities type A walkers changed to type B walkers. These results suggest that any device attempting to mimic heel strikes should have a range of heel strike velocities.

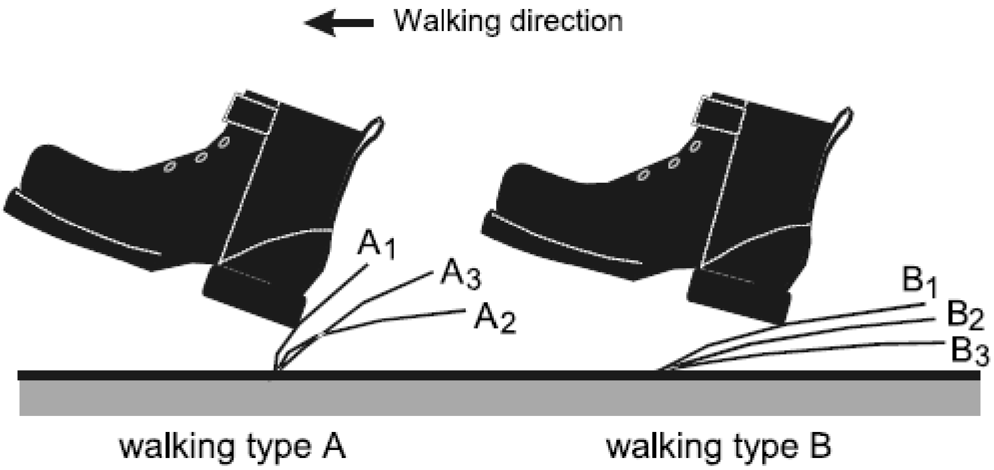

Figure 5: Paths of travel of the heel prior to heel strike of Type A and Type B walking styles[4]

Experiments performed by Chambers, et al [47] used five subjects walking across dry and slippery floors to obtain their foot movement data using a motion capture system. The objective of this study was to determine foot kinematics during expected and unexpected slippery conditions. The data provided shows that the average horizontal heel velocity prior to heel strike was 26.1 in/s. This data was for walking conditions where the participants knew the floor was dry and did not expect any slippery conditions. The gait changed dramatically for participants expecting and encountering slippery conditions. However, participants were able to rotate their foot to be flat on the floor in all trials, even the ones where they ultimately fell. This finding is the same result identified by R. Cham and M. Redfern [46] and again supports the idea that a tribometer simulating heel strike conditions, where the whole foot rotates and engages the floor, may be a real-world condition.

A study of shoe cushioning and ankle stability performed by Daniel Fong at the Chinese University of Hong Kong in 2007 [48] was conducted using 12 male students around 13 years

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[4] Reprinted by permission of author Thomas Moessner

old wearing five different kinds of shoes. The purpose of this study was to determine the protective functions of these types of shoes for school aged children performing normal running and jumping routines on the playground. It showed that during mild-intensity running at 11.8 ft/s an average vertical heel impact velocity of 45.3 in/s was observed.

Experiments performed by Beschorner, et al used a modified industrial robot and force plates to calculate DCOF at a variety of heel sliding speeds, heel strike angles and normal forces under contaminated conditions [32]. The robot was fitted with a shoe and programmed to impact the floor at 10° and 20° then slide across the floor at seven different speeds (.39, 2.0, 7.9, 13.8, 19.7, 29.5, 39.4 in/s) under five loading conditions (9, 18, 22.5, 45, 90 lbs). The DCOF was plotted for each set of conditions to determine the effect that each parameter (angle, speed, load) had upon the calculated DCOF. It was determined that the faster sliding speeds generated lower DCOF values. An increase in the normal force had a more complex relationship with the measured DCOF most likely due to the increased contact surface area that resulted. However, as the normal force was increased the DCOF also increased leaving one to suspect that any biofidelic tribometers that do not maintain the same impact force will measure different DCOF values under identical circumstances.

This study by Beschorner, et al. brought to light that sliding speed and impact angle influences the calculated DCOF and therefore could affect the measured DCOF on tribometers that use simulated heel strikes such as the XL. Since the XL Tribometer changes the impact angle as the means to determine the DCOF then it is important that the other variables that affect DCOF remain constant. If the foot speed does not remain constant then the user can not be sure the measured DCOF is due to the change in angle or due to the inconsistent test foot speed. The impact angle to impact speed aspect was investigated on the XL Tribometer and reported in the experimental portion of this thesis.

2.7 Devices Used to Measure Coefficient of Friction

Measuring the COF is the most accepted method when determining if a surface is slippery or not. There are a myriad of machines sold commercially that report to measure the COF of a walking surface or flooring material. Unfortunately, there is no universally accepted or absolute reference device for measuring COF of walking surfaces [39, 49]. Several studies have shown that different tribometers yield a variety of results on the same surfaces [15, 17, 49-54]. Much of this discrepancy is due to the variety of testing techniques, testing materials, users, inter-machine variation and other undetermined variables. Table 2 is a list of tribological equipment that is currently being used in the United States. In general, they all fall within three categories; Dragsled, Inclinable Mast and Pendulum. Since the XL Tribometer is the focus of this thesis it is not in this list and is described in detail in the next section. The list is not exhaustive but is complete in the sense that these machines are regularly used in scientific testing, court cases, or within the safety engineering community. More detailed descriptions of these tribometers along with photographs are contained in Appendix B.

Table 2: List of tribometers widely used in the US (See Appendix B for detailed descriptions)

Tribometer	**Category**
James Machine	Inclinable Mast/Dragsled
Monrow British Pendulum Tester	Pendulum
Tortus Slip Tester	Dragsled
BOT3000	Dragsled
American Slip Meter	Dragsled
Technical Products Model 80	Dragsled
Mark I	Inclinable Mast/Dragsled
Mark II, III	Inclinable Mast

2.7.1 XL Tribometer

The XL Tribometer is generally described as a Variable Incident Tribometer (VIT) [55] and is in the inclinable mast category. The machine has a pneumatic cylinder that, upon activation, thrusts a 1.5” diameter test foot toward the surface being tested. The test foot is mounted on a ball-and-socket connection at the end of the cylinder rod. This ball-and-socket simulates a human ankle and allows the pad to strike the test surface and rotate so that the whole surface area of the pad engages the test surface and mimics a heel strike [56, 57]. Figure 6 shows an XL Tribometer and nomenclature.

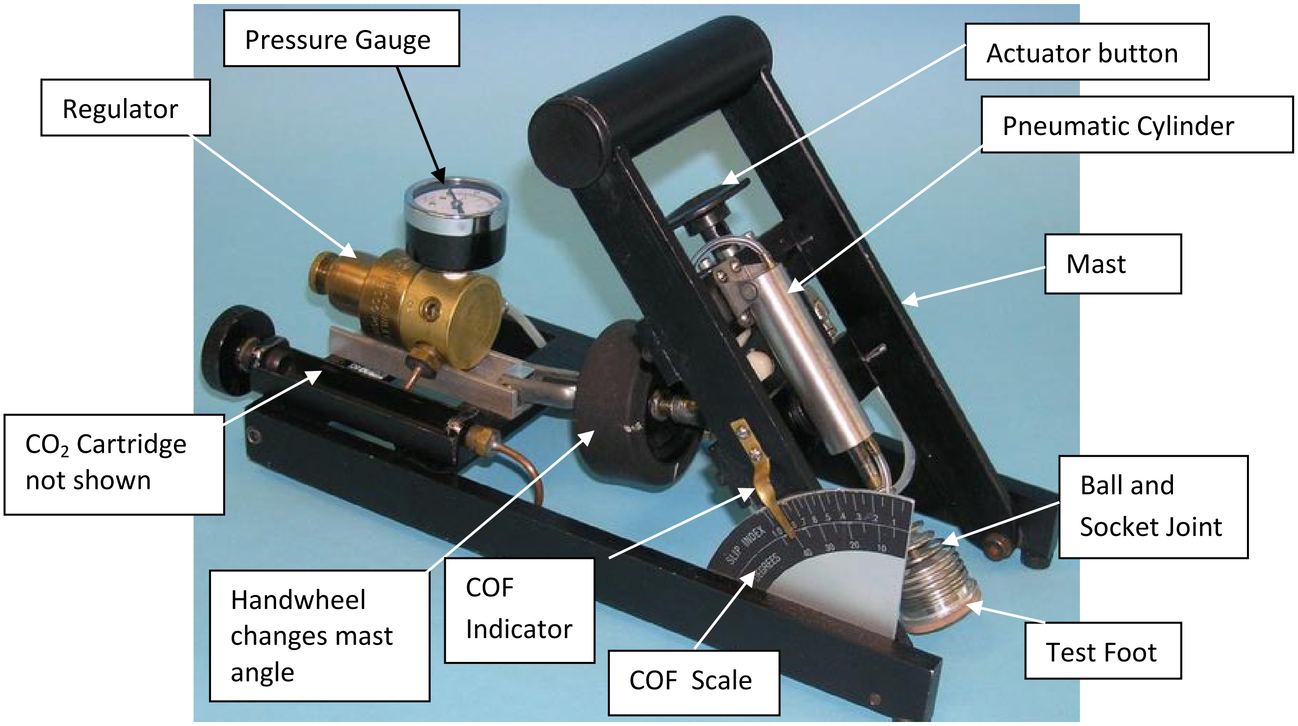

Figure 6: Nomenclature for Excel Tribometer

When the test foot strikes the test surface there is both a vertical and horizontal component to the velocity similar to the way a heel strikes the walking surface during a routine human stride. The pneumatic piston is powered by a 12 gram CO_2 cylinder that is regulated from around 850 psi down to a 25 psi operating pressure and supposedly drives the test foot at a speed relative to a normal human heel strike. The theory of operation is such that the angle of the mast and thus the pneumatic cylinder can be adjusted by the operator. When the actuator is pushed, the pneumatic cylinder fills with CO_2 and drives the test foot forward and strikes the surface. If the test foot strikes the surface and stops, then the COF developed between the foot and the test surface is sufficient to prevent a slip. As the operator decreases the angle, relative to the horizontal test surface, the test foot will eventually slip and the entire stroke of the cylinder is allowed to extend. At the point where the test foot slips there is insufficient COF to retard continued horizontal motion. This angle is correlated to a COF value and read from the gauge on the side of the machine.

The XL tribometer is widely used in the forensic engineering community, insurance industry, retailers, manufacturers, amusement parks and by property maintenance personnel. According to the manufacturer, there are currently 273 certified XL tribometrists [58]. More people are likely using the device but are not certified. The device is known to have some repeatability and reproducibility issues that the manufacturer has tried to address by developing a more robust user guide, adding features to remove human influence, conduct training classes, and to semi-automate the preparation of the test feet. The XL is use for the experimentation conducted for this thesis.

CHAPTER 3: Experimentation

The purpose of these experiments was twofold: Determine the velocity of impact of the XL Tribometer's test foot and to determine if the heel strike and slip mechanism are similar in nature to human heel strikes. Two measurement techniques were used to study these two issues: high speed video analysis and an optical speed gate. The test foot impact speed was found to vary so a sensitivity analysis was performed to determine the effect of this variance on the measure COF.

The benefit of using high speed video was to be able to observe the interaction of the test foot with the surface and contaminant at impact and to note any phenomena that may not be readily observable in real-time. An attempt was made to calculate impact speed using the high speed video but due to blurred test foot edges in each frame and the low number of data points this attempt was abandoned. The speed gate technique was used to directly measure the speed at the time that the test foot struck the surface. An advantage of the speed gate is that much more data could be collected and used for statistical analysis.

The only identified user adjustable features that could affect the speed of the XL test foot were the pressure setting (variable 1) and the mast angle (variable 2). During normal operation of the XL the pressure would be set to 25 psi but for these experiments it was necessary to determine the relationship between the pressure setting and the speed of deployment so three pressure settings were used. Another effect on the speed of impact could be the angle of the mast. If internal mechanical interactions, such as the piston on the tube wall, affected the speed of deployment then this information would become apparent if the mast angle were treated as an independent variable affecting velocity.

3.1 High Speed Video Analysis

The high speed video analysis was used to determine the motions of the test foot during impact with the surface and contaminant. In order to substantiate the claim by the manufacturer of having a functional ankle and freedom of the foot to accelerate once a slip event occurs, thus mimicking the biomechanical parameters of the human walking gait, the motion had to be slowed down. A high speed camera (Casio EX-F1) was used to capture video at 300 frames per second (fps) of the deployment of the test foot. The frame rate capture speed for the camera was verified using two styles of stop watches. A graduated machinist's scale was in the video-capture-screen so that as the foot moved through the frame the scale allowed the movement distance to be measured between frames.

Three XL Tribometers were filmed for a total of 91 foot impacts on a glass surface with water as the contaminant. In order to achieve various impact speeds, the pressure settings were changed from 10 psi to 25 psi to 45 psi. Achieving various impact speeds was important because the manufacturer's claims of mimicking significant biomechanical parameters of the human walking gait needed to be true across a variety of heel strike speeds. The speeds at impact were estimated using the video analysis approach.

Figure 7 is a series of still shots depicting a typical impact sequence. Frame 0 is when the foot just starts to move. Frame 9 occurs 0.03 seconds after movement starts and is the frame prior to first impact with the surface. Frame 15 occurs 0.05 seconds after initial movement and the test foot has rotated so that the entire foot is in contact with the surface. The water is being displaced by the entire surface of the foot. Frame 21 occurs 0.07 seconds after movement starts and the test foot remains flat against the surface and is accelerating forward as would be expected in a heel strike slip event.

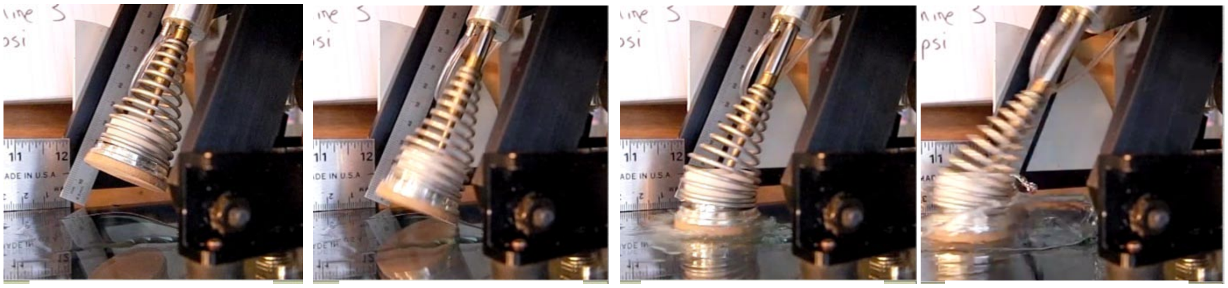
Frame 0 (0.00s) Frame 9 (0.03s) Frame 15 (0.05s) Frame 21 (0.07s)

Figure 7: Series of still shots from high speed video showing progression of slip event

As discussed earlier, the human walking studies showed that during slip events the participant's ankle was able to rotate and the whole foot became fully engaged with the floor before the forward sliding occurred. This is the same mechanism observed with the XL and confirms the manufacturer's claim of having a functional ankle, allowing the whole heel to contact the surface, and the foot to accelerate forward during the slip event.

3.2 Speed Gate Analysis

Speed gates are used in many areas of manufacturing and scientific study. The theory is that an object moving through a beam of light will break that beam and this break can be detected electronically by a microprocessor. If two beams are set at a known distance apart and an object passes through these beams sequentially, then the microprocessor can calculate the speed using its internal clock. In this case, two sets of emitter and receiver infrared LEDs were spaced 0.5

inches apart as depicted in Figure 8. The LED sets were mounted to a clear polycarbonate box. The box is hollow and open at the top and the bottom allowing an object to pass through. The box was mounted to the XL using the mast pivot bolts as reference positions so that the upper emitter-receiver pair was ¼” above where the test foot would impact the floor and the lower emitter-receiver pair was ¼” below where the test foot would impact the floor. All three XLs were manufactured the same, the emitter-receiver pairs were at the identical position on all three machines.

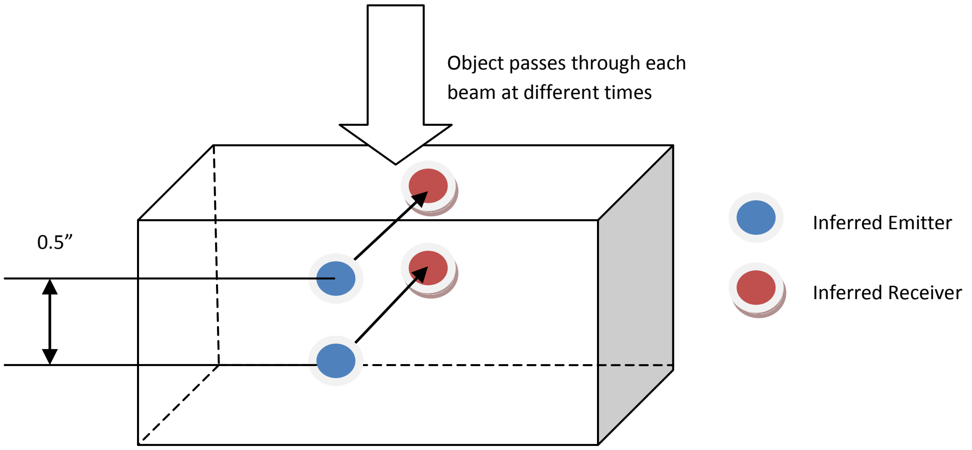

Figure 8: Schematic of speed gate operation

The XL, fitted with the speed gate, was clamped to a solid fixture so that activation of the foot would not move the machine during data collection. Figure 9 shows the speed gate attached to the XL during data collection. The same three XL Tribometers that were used in the high speed video analysis were used in this experiment. Machine 1, serial #1009056 was under current manufacturer calibration. Machine 2, serial #1009042 was under current calibration. Machine 3, serial #100705 was under current manufacturer calibration. All three machines were in good operational order and in use within the forensic engineering field.

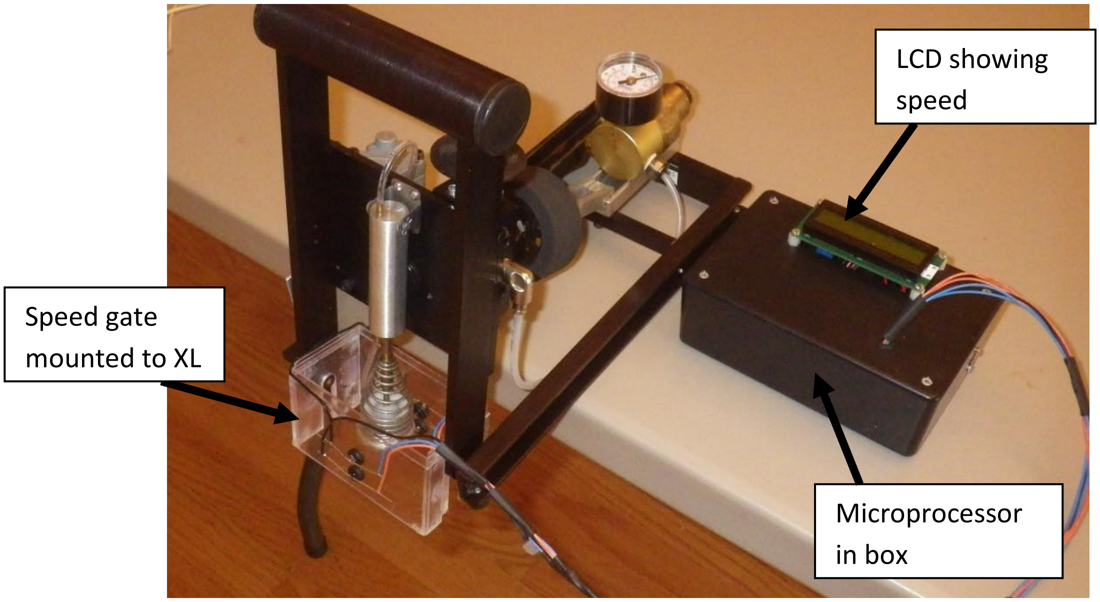

Figure 9: Speed gate equipment setup

The speed gate allowed a high number of data points to be collected because of its ease of use and quickly displayed results. However, it was necessary to determine the number of trials to run per configuration so that there were enough data points to be statistically significant but not excessive. The desired reliability was to determine the average impact speed within 0.5 in/s of the true speed with a 95% confidence level. The following equation was used to determine an appropriate sample size per setup [59].

$$n = \left(\frac{z\sigma}{E}\right)^2 = \left(\frac{(1.96)(1.614)}{0.5}\right)^2 = 40.03 \qquad \textbf{Equation 3}$$

Where:

n = number of trials to perform per test setup

z = z value associated with the confidence level of 95% = 1.960

σ = estimated from the highest standard deviation found during the high speed video analysis = 1.614 in/s (Machine #2 at 25 psi at 25° mast angle)

E = Sampling Error – self chosen as 0.5 in/s as an acceptable range of error for the calculated impact speed average per test setup.

For these parameters n was calculated to be 40 trials per test setup. This number was increased to 60 to decrease the sampling error and because collecting 60 data points per setup was not time prohibitive.

Each XL Tribometer was fitted with the speed gate and tested at three mast angles (90°, 70°, 50°) and three pressure settings (15, 25, 35psi). At each of these scenarios the foot was activated 60 times and recorded in an Excel spreadsheet resulting in 540 speed measurements per machine (3 angles x 3 pressures x 60 tests) for a total of 1620 data points.

3.3 Accuracy Testing and Calibration Factor

The speed gate data that was gathered was highly precise with the standard deviation of all trials being on the order of 1% or less of the average. However, there was no indication of how accurate the data were without comparing to a known value. In order for the scientific principle to work properly, the data collected must be both precise and accurate. In order to determine the accuracy and precision of the speed gate, a series of calibration trials were conducted to determine if any correction factor had to be incorporated to offset a bias. Even though the emitter-receiver pairs were spaced ½” apart, the effective detection area was unknown within each beam. Whatever the beam’s effective detection area was, it would remain a constant and could be factored out by running a series of calibration trials. A steel ruler was dropped through the speed gate from five different heights. The experimental setup is depicted in Figures 10 and 11. A thin steel ruler was used to minimize wind resistance effects, to ensure the beams were broken consistently, and the drop heights easily measured. The drop heights were relatively small at 0.75, 1.25, 2.25, 3.25 and 4.25 inches. Since the drop height is known, the velocity can be calculated using:

$$V = \sqrt{2gh} \qquad \textbf{Equation 4}$$

V is the instantaneous velocity, g is the acceleration due to gravity and h is the drop height.

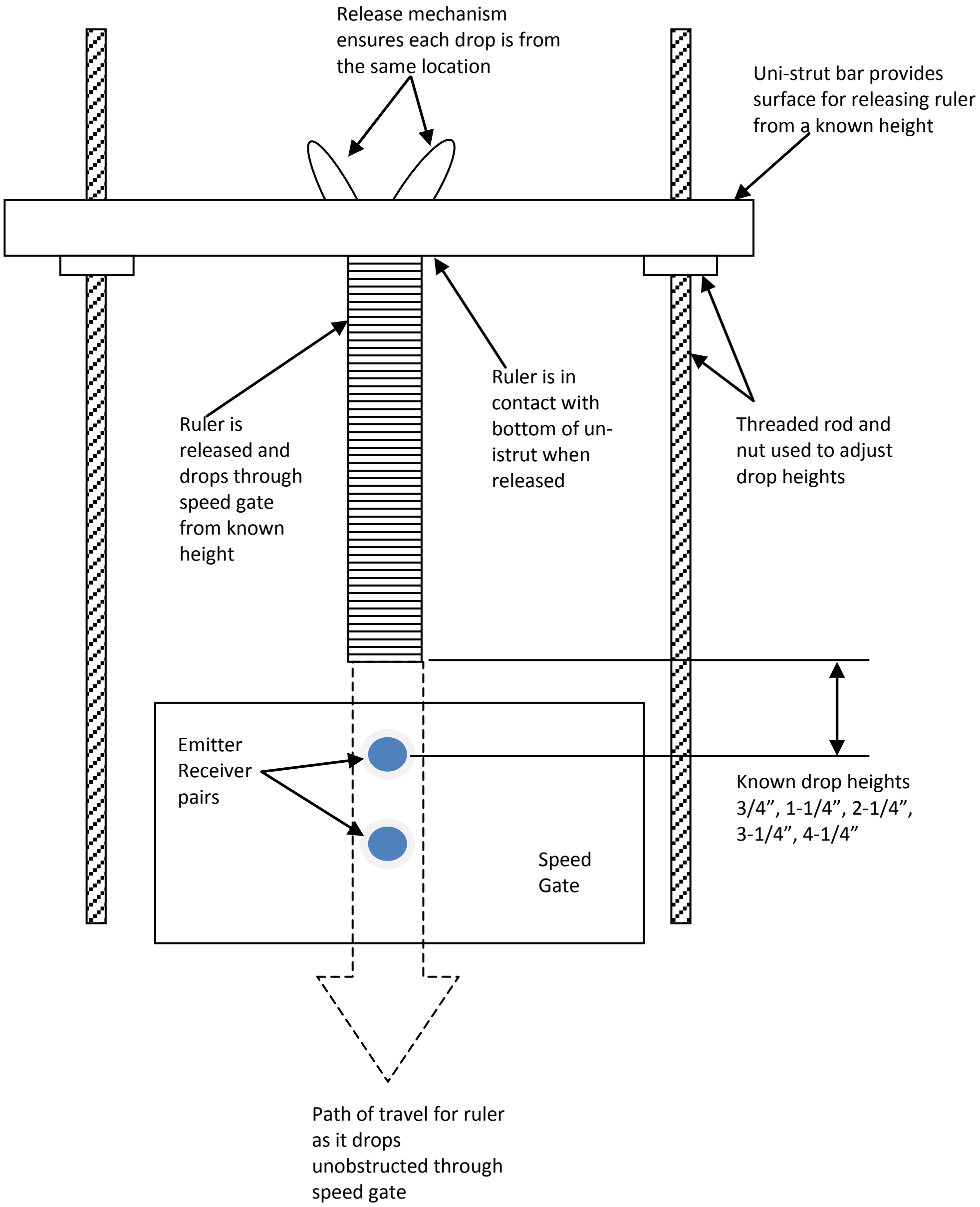

Figure 10: Schematic of calibration setup for the speed gate

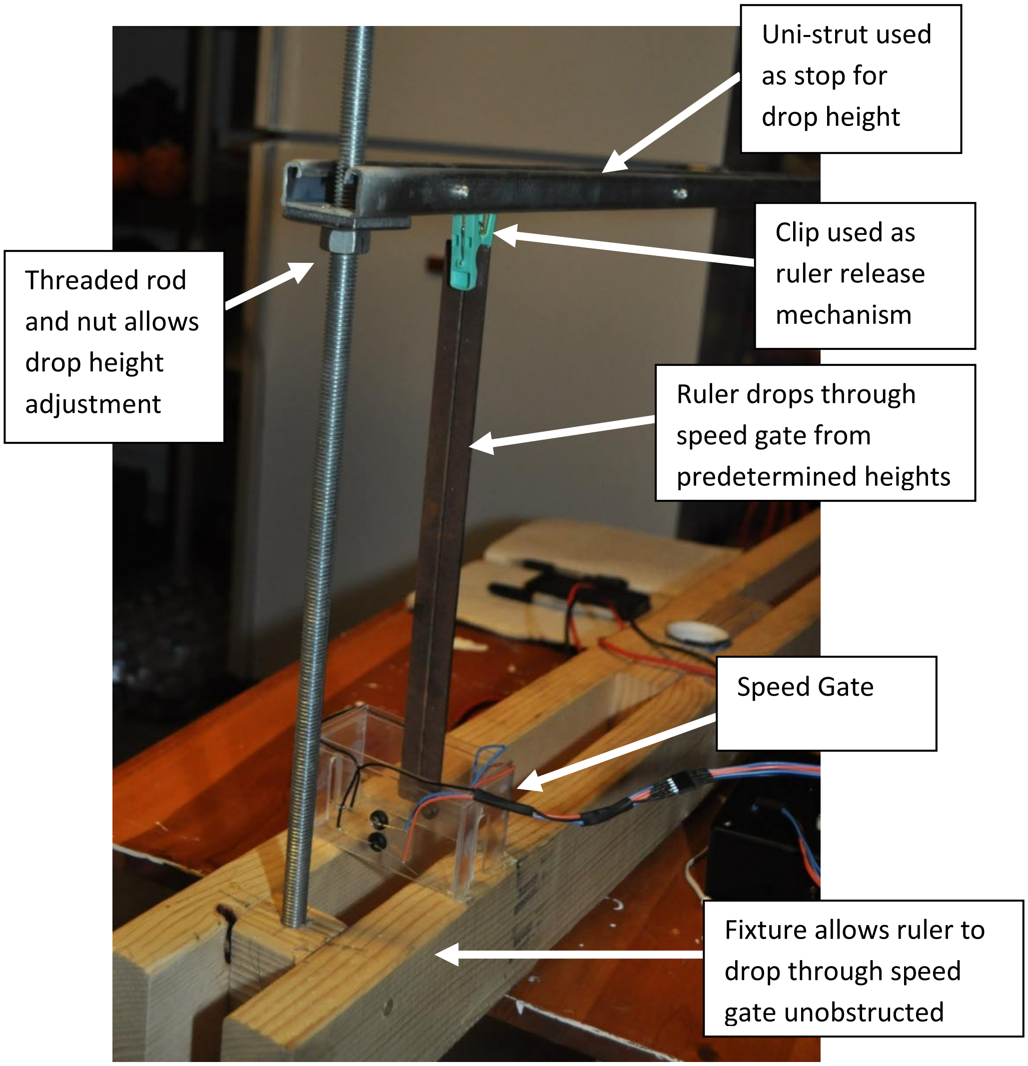

Figure 11: Calibration testing setup

The ruler was dropped through the speed gate twelve times at each of the preselected heights and the reported speeds averaged. These five averaged speeds were plotted against the calculated speed to verify a linear relationship and that the x-y intercept was zero. The slope of this line is the correction factor. A regression analysis was performed on this data to determine the slope. The R^2 for this regression was 0.999 which represents an excellent data fit. For this analysis the correction factor was determined to be 1.0184 as seen in Figure 12. The measured speed on the speed gate's LCD screen had to be increased by 1.84% for all trials. This correction was performed in the spreadsheet for the raw data prior to any statistical analysis. This calibration technique was performed prior to the tribometer testing and then verified after all the tribometer testing was completed to ensure the speed gate maintained consistency throughout testing.

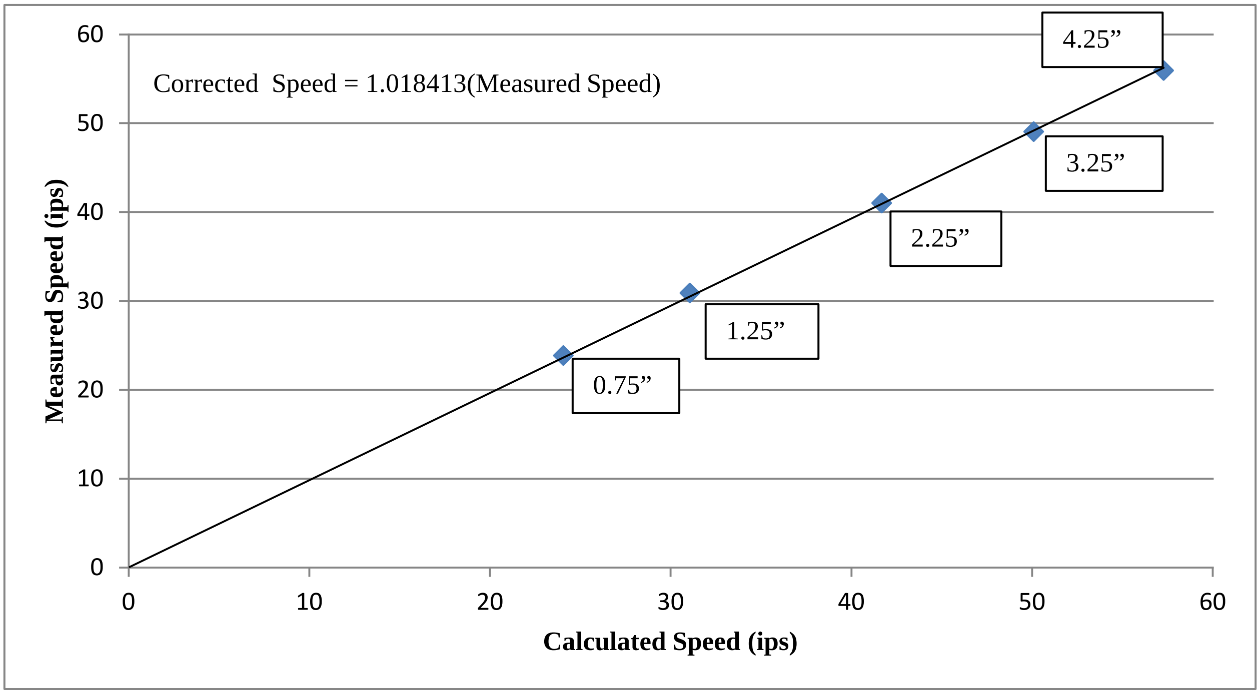

Figure 12: Calibration chart for speed gate

3.4 Analysis of Speed Gate Testing Results

For Machine #1 and #3 the speed increased with pressure as would be expected. However, with Machine #2, the speed did not increase with pressure and stayed relatively stable between 21.11 in/s and 22.28 in/s. These results contrasted sharply with Machine #1 which ranged from 14.95 in/s to 19.06 in/s and Machine #3 which ranged from 16.42 in/s to 19.95 in/s across all mast angles and all pressure settings. Table 3 contains selected statistical information on the results of the speed gate testing. Appendix C contains the ANOVA tables and excerpts from the statistical calculations performed on the data. The Excel spreadsheet contains eleven tabs showing the raw data and descriptive statics. The file name is ‘Data Collection for Speed Gate.xls’.

Table 3: Selected statistical results from speed gate testing

Machine Number	Pressure Setting (psi)	Mast Angle	Average Speed (in/s)	Standard Deviation (in/s)	Count	Average Speed all Angles	Standard Deviation
1	15	90	15.61	0.16	60	15.29	0.31
1	15	70	15.31	0.12	60		
1	15	50	14.95	0.15	60		
1	25	90	18.12	0.11	60	17.98	0.15
1	25	70	17.82	0.11	60		
1	25	50	17.99	0.05	60		
1	35	90	19.06	0.11	60	18.89	0.19
1	35	70	18.94	0.11	60		
1	35	50	18.68	0.07	60		
2	15	90	22.02	0.07	60	22.15	0.22
2	15	70	22.28	0.16	60		
2	15	50	22.15	0.28	60		
2	25	90	21.96	0.25	60	21.74	0.39
2	25	70	22.00	0.19	60		
2	25	50	21.26	0.14	60		
2	35	90	22.00	0.21	60	21.52	0.41
2	35	70	21.11	0.13	60		
2	35	50	21.46	0.21	60		
3	15	90	16.66	0.12	60	16.70	0.28
3	15	70	17.02	0.13	60		
3	15	50	16.42	0.10	60		
3	25	90	18.81	0.09	60	18.80	0.12
3	25	70	18.87	0.11	60		
3	25	50	18.71	0.10	60		
3	35	90	19.59	0.07	60	19.79	0.18
3	35	70	19.84	0.08	60		
3	35	50	19.95	0.12	60		

They hypotheses of this experiment were 3-fold; (1) that the average foot speed at impact between Machines 1, 2, and 3 at each pressure setting would be statistically the same; (2) that the angle of the mast would not influence the speed; (3) that thirdly the speed would increase with pressure.

For Machine #1 at 25 psi the mast angle did have a minor effect upon the average test foot speed from 17.99 in/s at 50°, 17.82 at 70° 18.12 in/s at 90°. ANOVA calculations with $p<0.05$ confirm that none of the average speeds for any mast angle come from the same population. However, the range of impact speeds was on the order of 0.30 in/s and is believed to unimportant since it is less than 2% of the average speed. The average foot speed for Machine #1 at 15 psi was 15.29 in/s across all three mast angles. The average speed for Machine #1 at 25psi was 17.98 in/s across all three mast angles. The average speed for Machine #1 at 35 psi was 18.89 in/s across all three mast angles. These results confirms that the foot speed for Machine #1 does increase with pressure as hypothesized and the mast angle does affect the speed and seems to increase slightly with angle. However, the variation in speed with mast angle is small in comparison to the change in speed with pressure.

For Machine #2 the mast angle had a minor effect upon the average test foot speed. When set to 25 psi the speed was 21.96 in/s at 90°, 22.00 in/s at 70°, and 21.26 in/s at 50°. There was no significant difference between the speeds measured at 25 psi for the 70° and 90° mast angles. Although the mast angle influences the speed, it is not a significant effect. The average foot speed for Machine #2 at 15 psi was 22.15 in/s across all three mast angles. The average foot speed for Machine #2 at 25psi was 21.74 in/s across all three mast angles. The average foot speed for Machine #2 at 35 psi was 21.52 in/s across all three mast angles. These results are contrary to the hypothesis in that the speed decreases with increase pressure for Machine #2. Even though the absolute speeds between the three pressures were not large in comparison to the other machines an ANOVA showed that the averages between the pressure settings were statistically different with a 95% confidence level.

The results for Machine #3 showed that the mast angle does influence the speed of the test foot but that influence is minor. When set to 25 psi the speed was 18.81 in/s at 90°, 18.87 in/s at 70°, and 18.71 in/s at 50°. However, the relationship of increase angle to increase speed as seen with Machine #1 was not found in Machine #3. There appears to be no relationship between mast angle and speed. ANOVA calculations support that the average speeds between mast angles at each pressure setting were statistically different with a 95% confidence level. The average foot speed for Machine #3 at 15psi was 16.70 in/s across all three mast angles. The average foot speed for Machine #3 at 25 psi was 18.80 in/s across all three mast angles. The average foot speed for Machine #3 at 35 psi was 19.79 in/s across all three mast angles. These results confirm that the foot speed for Machine #3 does increase with pressure as hypothesized.

Even though the three machines did not produce consistent foot speeds between machines at various pressure and mast angles, the data, as a whole, do suggest that the foot speed is highly affected by the pressure setting and only slightly by the mast angle. Machine #2 is perhaps an anomaly and may have some operational issues. The more important result is that none of the measured speeds were close to the manufacturer’s reported speed of 11 in/s and in fact were much higher. At the recommended pressure setting of 25 psi the average speed ranged from the lowest speed observed of 17.82 in/s (Machine #1) to the highest speed observed of 22.0 in/s (Machine #2). Figure 13 shows graphically how the impact speed changes between machines, mast angle and pressure settings.

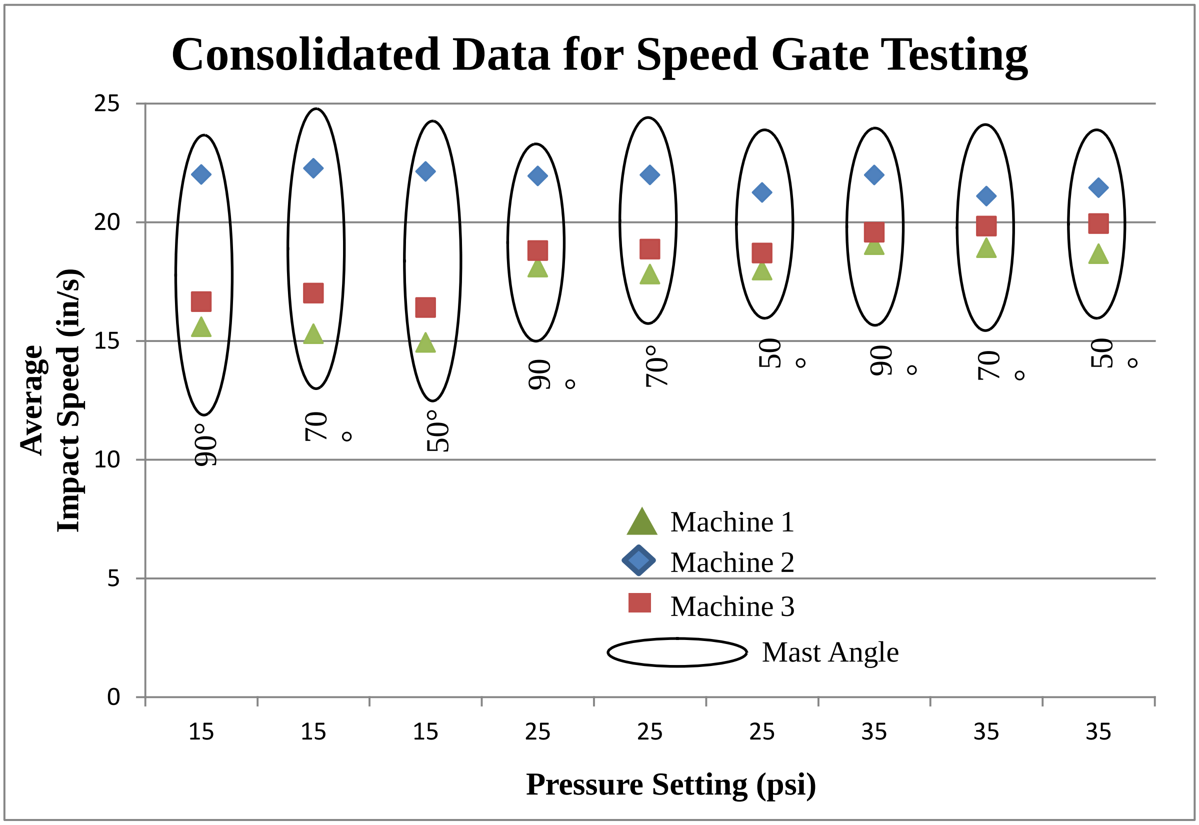

Figure 13: Chart showing relationship between impact speed, pressure setting and machine for speed gate experiment

A visual indicator of normality is shown in Figure 14 where the frequency of each speed is plotted for each machine when set to 25 psi. Represented in Figure 14 are the 540 foot speeds measured at 25 psi across three mast angles and all 3 XL Tribometers. It is obvious from the chart that the data are grouped into three distinct curves. Reporting a confidence interval, inclusive of all three machines would be inappropriate. Reporting the averages and standard deviations, or the ranges of impact speeds, are more descriptive statistics in this case.

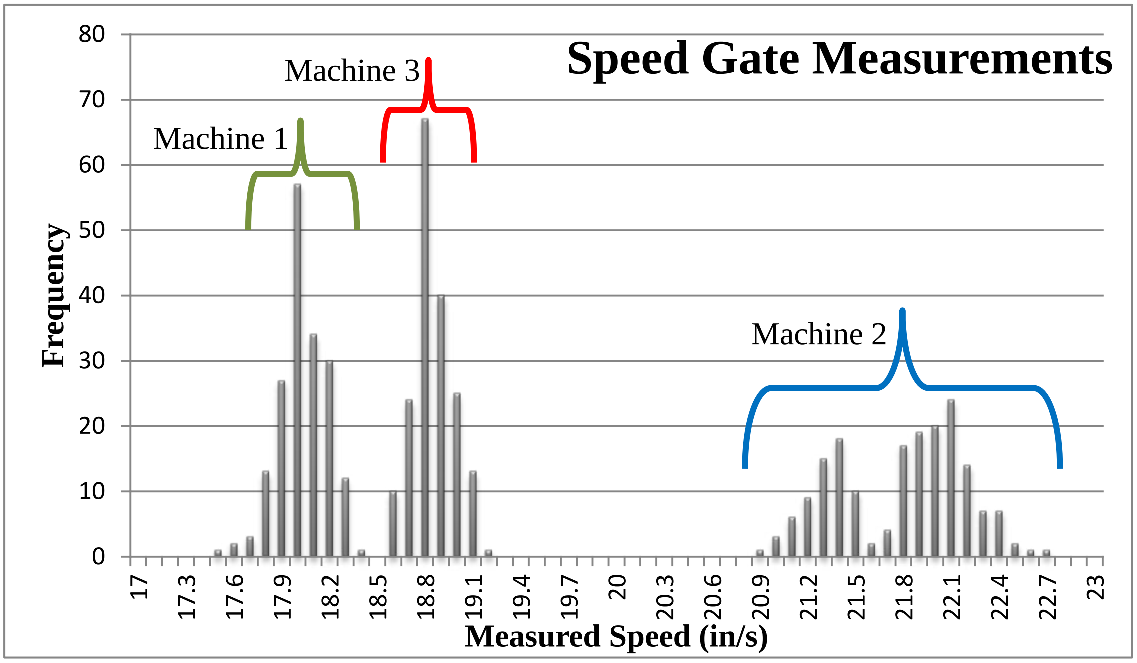

Figure 14: Frequency distribution of speeds from 3 XLs at 25 psi and 3 mast angles

It is visually obvious from Figure 14 that Machines 1 and 3 have a typically-shaped normal distribution. The kurtosis and skewness for Machines #1 and #3 were between ±1.0 which also suggests the data for these two machines are normally distributed [60]. Machine #2 appears to be a bimodal distribution where there may be a mixture of two normal distributions. A further analysis of the speed data for Machine #2, with regards to the mast angle, is shown in Figure 15. This chart indicates that the speed data for mast angles 70° and 90° are intertwined while the 50° mast angle is isolated. Therefore, the bimodal distribution that appears in Figure 14 is due to the finite mast angles chosen for testing. It is suspected that if speed data were taken at a 60° mast angle then the bimodal shape noticed in Figure 14 would be ‘filled in’ with this new data and the distribution would look normal as opposed to bimodal. The effect of the mast angle seems to be more dramatic for Machine #2 than for the other two machines thus causing a wider and shorter distribution.

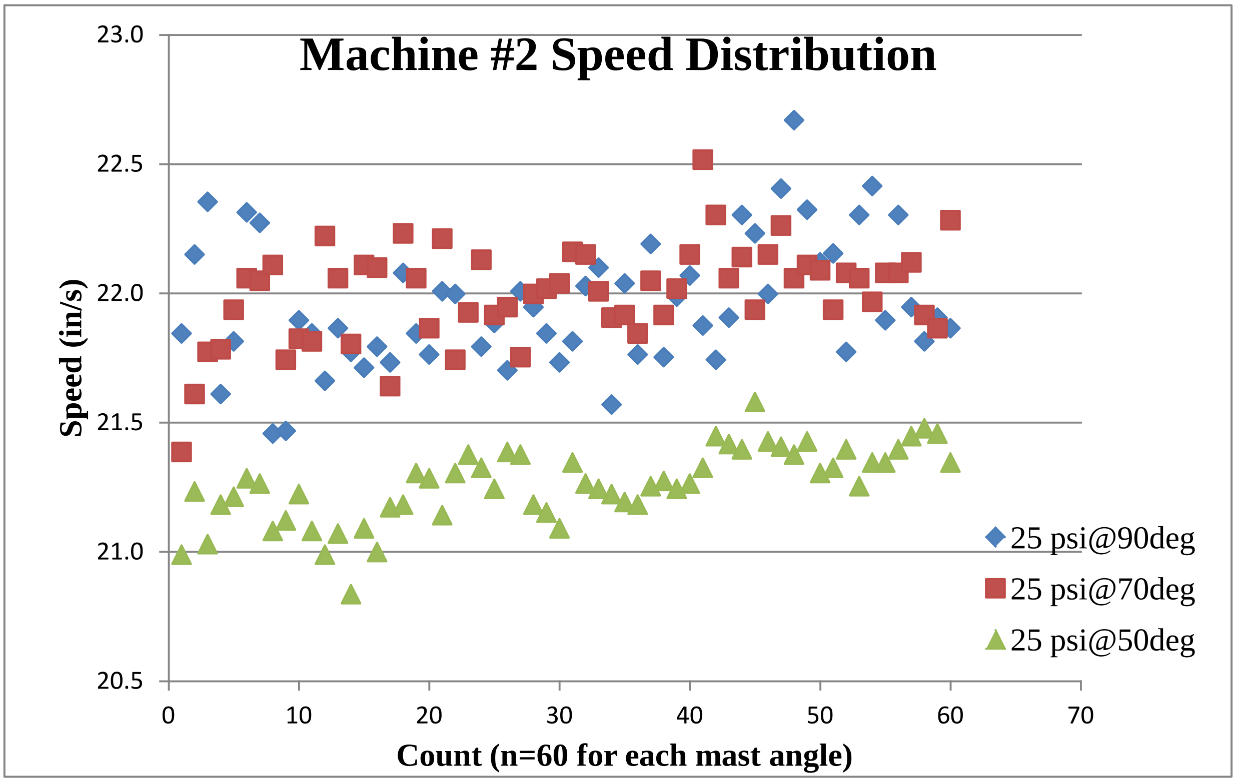

Figure 15: Machine #2 speed distribution for three mast angles at 25 psi

The speed distributions for Machines #1 and #3 are shown in Figures 16 and 17, respectively. The demarcations between mast angles are not as apparent as seen in Figure 15 for Machine #2 but they are present nonetheless. Figure 16 shows that the speed for a 70° mast angle is lower than for the 50° mast angle and both of these are lower than the 90° mast angle. However, the data have enough overlap to create the normal distribution observed in Figure 14. Figure 17 for Machine #3 has a similar pattern to Machine #2 in that the data for the 50° mast angle is lower than the other two mast angles. However, the data variance for the 50° mast angle is large enough that it overlaps into the data for the 70° and 90° mast angles, so that the distribution looks normal as seen in Figure 14.

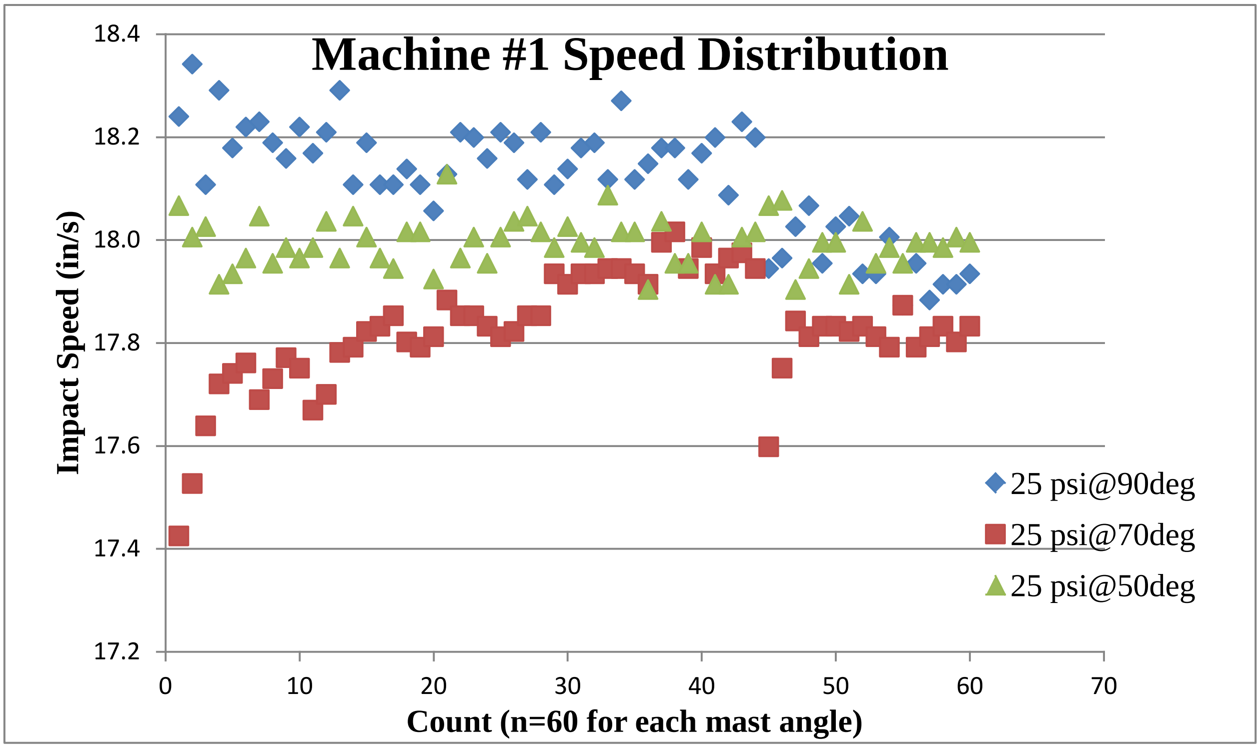

Figure 16: Machine #1 speed distribution for three mast angles at 25 psi

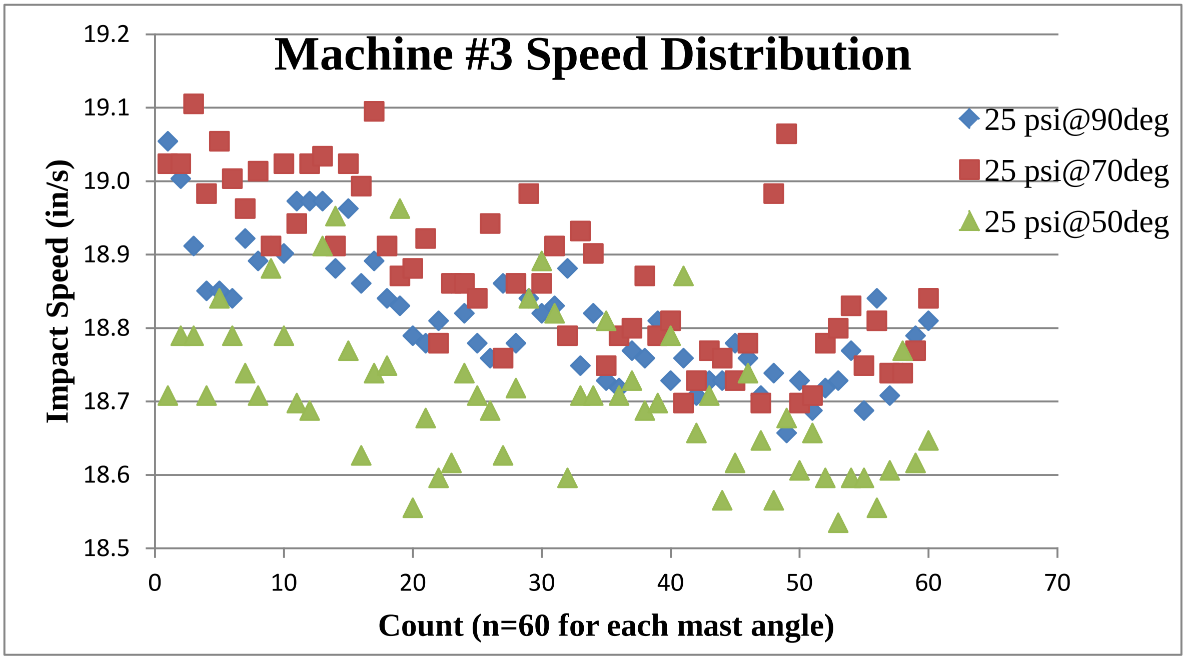

Figure 17: Machine #3 speed distribution for three mast angles at 25 psi

3.5 Sensitivity Analysis

The speed gate experimentation showed a difference in impact speed between machines when set to the operating pressure of 25 psi. Machine #1 averaged 17.98 in/s (σ=0.09), Machine #2 averaged 21.74 in/s (σ=0.19), and Machine #3 averaged 18.80 in/s (σ=0.10). The question then becomes, do these speed differences have an effect upon the COF measurements?

In order to determine if the impact speed influences the measured COF a series of experiments were performed using Machine #1, with the lowest average speed, and Machine #2, with the highest average speed. The pressure setting was set to normal operating pressure of 25 psi. The same test foot (S/N 2604) was used throughout the experiment and reconditioned after each 16 measurements using the manufacturer's recommended practice. Three different tiles were measured by each machine under identical conditions.

ASTM distributes a suite of four flooring surface tiles that are designated RS-A, RS-B, RS-C and RS-D. This suite of tiles is the reference surfaces used to validate a tribometer per ASTM F2508 – Standard Practice for Validation and Calibration of Walkway Tribometers using Reference Surfaces. These tiles were designed so that RS-A is more slippery than RS-B which is more slippery than RS-C, which is more slippery than RS-D. For this portion of the experiment, RS-B and RS-C were chosen as test materials along with a calibration tile provided by the manufacturer of the XL Tribometer. This calibration tile is used in the field to verify the machine is operating properly prior to on-site testing. These three tiles have sufficiently different surface characteristics such that the COF of each one is distinct from the others.

Table 5 shows the results of this sensitivity analysis. Both tribometers rank the tiles in the same order of increasing COF with RS-B being more slippery than the calibration tile which in turn is more slippery than RS-C. This data supports the intent of the ASTM tile suite where RS-B should have a lower COF than RS-C.

Table 4: Results of sensitivity analysis

	Machine #1				Machine #2		
	RS-B	RS-C	Cal. Tile		RS-B	RS-C	Cal. Tile
Average COF	0.181	0.252	0.204		0.155	0.231	0.178
Standard Deviation	0.011	0.012	0.025		0.010	0.011	0.017
Count	40	40	16		16	16	16
Confidence (95%)	0.003	0.004	0.012		0.005	0.006	0.008
Upper Mean	0.185	0.256	0.217		0.160	0.237	0.186
Lower Mean	0.178	0.248	0.192		0.150	0.226	0.169

The more interesting aspect of these results is the difference between COF measurements on the same tile using the same test foot but utilizing two machines that strike the surface at different speeds. Machine #2, which impacts at 21.74 in/s measures slightly lower COF values than Machine #1 which impacts at a slower 17.98 in/s. The COF of RS-B was 0.026 lower for the slower Machine #1 than for the faster Machine #2. The COF of RS-C was 0.021 lower for the slower Machine #1 than for the faster Machine #2. The COF of the reference tile was 0.027 lower for the slower Machine #1 than for the faster Machine #2. It appears from this sensitivity analysis that a higher impact speed results in a lower COF reading. This is the same result as found in the Beschorner study [32] discussed earlier. However, the difference is on the order of 0.02 to 0.03 which is small in comparison to the scale on the XL. Figure 15 is a photo showing the scale on the side of the XL Tribometer that is read when a slip event occurs. The resolution of the scale is marked at each 0.1 increments and there is a hash mark between each of these increments. The indicator itself covers an area of the scale on the order of 0.02. The difference in COF values found from the sensitivity analysis is far below the machine resolution and would not play a role in determining if a surface is slippery or not.

There is a statistical difference of COF values between machines on each of the tiles. The 95% confidence intervals do not overlap between machines #1 and #2 for any of the tiles which suggest that, statistically speaking, there is a significant difference between the COF measurements between the slower and faster machines. However, from a practical standpoint this difference is insignificant when used in the forensic engineering field. During field measurements of the COF it is route to encounter variations on the order of 0.05 between each foot deployment. This variation is expected and why the standard protocol, ASTM F1679, calls for 4 measurements to be taken orthogonal to each other, then averaged. Several areas of the subject walking surfaces are tested and the data consolidated to give the engineer an overall COF value that can be reported and opined upon. There should not be an instance where an engineer would have a COF difference of 0.02 between two walking surfaces and declare one dangerous and the other safe.

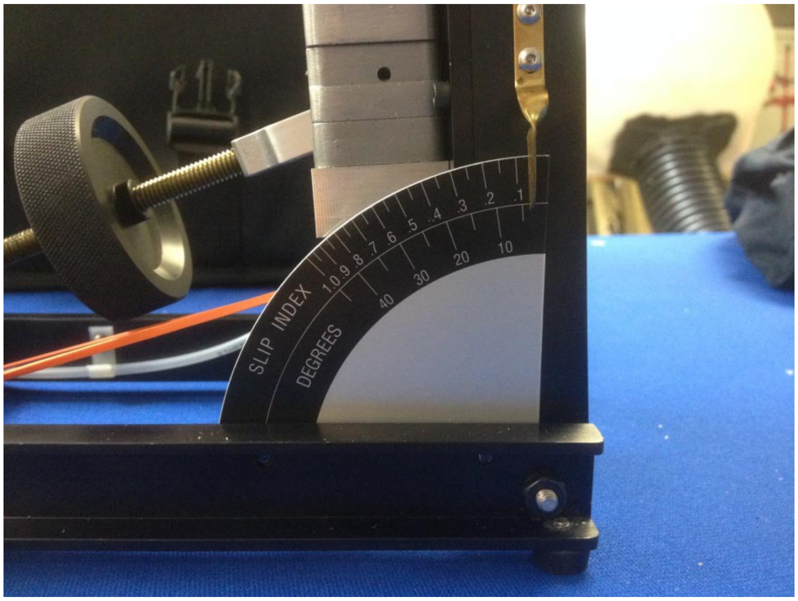

Figure 18: COF Scale on XL Tribometer

CHAPTER 4: Results Analysis and Discussion

According to the manufacturer and the inventor of the machine, the CO_2 powered test foot is designed to strike the testing surface at 11 in/s when set to 25 psi[57]. The speed of 11 in/s supposedly represents the speed of heel impact during normal human ambulation. However, scientific studies were identified that found a wide range of impact speeds during normal human ambulation, namely from 19 – 45 in/s so 11 in/s is outside of this range. Normal human ambulation - as defined in this thesis - includes healthy, young, elderly humans, walking and running.

The experimental data suggest that setting an XL Tribometer at the operational pressure of 25 psi creates an impact speed on average of 19.9 in/s (SD=2.36 in/s, n=599). This result is nearly double the intended speed of 11in/s as reported by the manufacturer. The minimum value found for all 599 trials at 25 psi was 17.43 in/s (Machine #1 at 70°) which exceeds the intended speed by 58%. The maximum value found for all 599 trials at 25psi was 22.7 in/s (Machine #2 at 90°) which is double the intended speed. Figure 16 shows visually that even though the XL impact speed varies on the order of 5.3 in/s, the speed is still within the lower range of human heel strike speeds. The sensitivity analysis suggests that if the XL operated in the mid-portion of this velocity range (approximately 30 in/s), the reported COF would be less than when operating at a velocity in the lower portion of the normal range. It should be noted that the influence of this sensitivity would produce a variance in the COF that would be a fraction of the 0.1 resolution of the device. As there is no defined legal threshold which delineates slippery from non-slippery, this small variance in COF would not mislead the user with an indication of whether or not a surface was dangerously slippery.

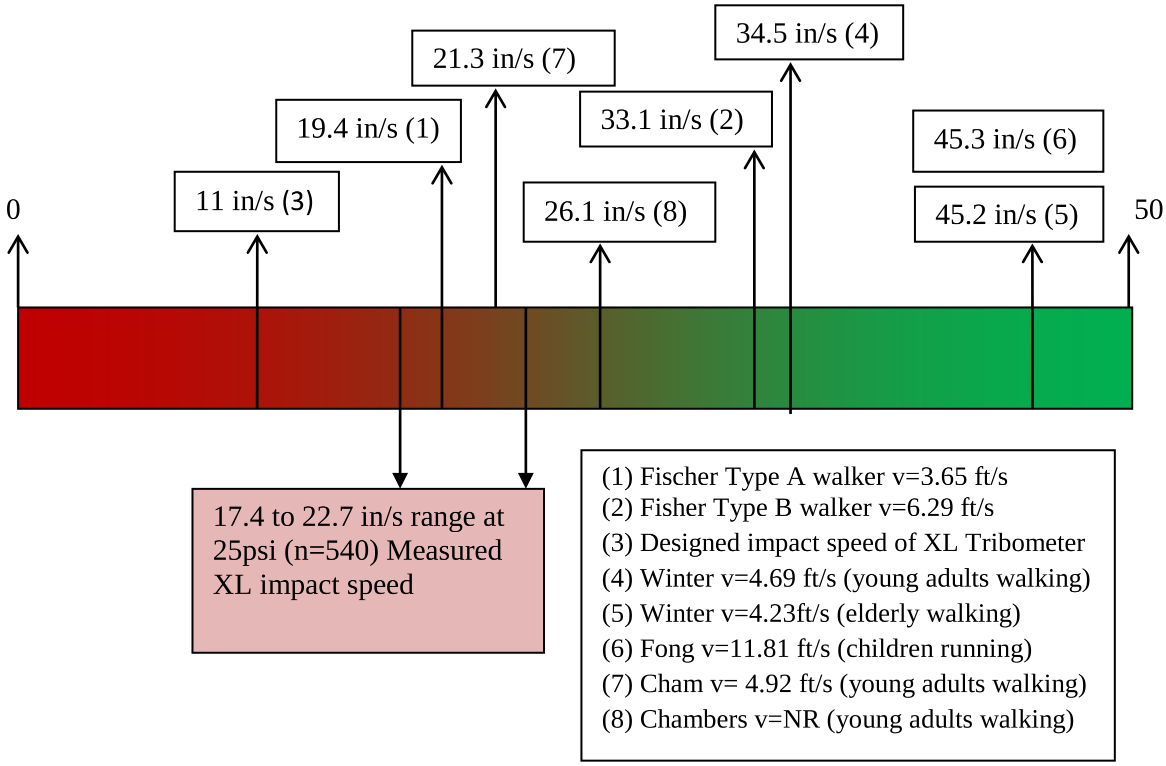

Figure 19: Range of heel impact speeds from human studies and XL Tribometer experiments. Legend contains study's author and reported walking velocity (v)

CHAPTER 5: Conclusions and Recommendation for Future Research

These experiments were conducted to determine four things. First, to determine if the speed of the test foot of the XL Tribometer was influenced by the pressure setting and/or the mast angle. The data showed that the pressure setting does have a significant effect on the test foot speed but the mast angle plays a minor role. Second, to determine if the speed of the test foot was consistent with human heel strike speeds as reported. The experimental data suggest that the test foot speed is on the low side of reported human heel strike speeds but still within the range. Third, to determine if the impact speed variation has an effect on the measured COF. A sensitivity analysis determined that the impact speed does influence the measured COF but has a minimal effect considering the resolution on the scale of the XL. The fourth and final objective of these experiments was to determine if the foot of the XL mimics a human heel strike. High speed video captured the movement of the test foot as it struck the flooring surface and proceeded to rotate similar to how an ankle works. Once a slip event occurred the test foot accelerated forward while maintaining contact with the floor similar to the way a heel would behave during a slip event. Therefore, the manufacturer's claim of mimicking a human heel strike and slip event is true. A wider study to include multiple machines and multiple operators should be conducted to verify these results.

Future research should be conducted on the force of impact. A major component when calculating COF is the normal force so understanding how the speed variation produced by various XL's contributes to the normal force component would be desirable. With an increase in impact speed an increase in kinetic energy and momentum occurs. Consideration should be given to the kinetic energy of a human heel strike compared to an XL's impact. Also, the contact patch of the XL is about 1.2 square inches. Considering that the whole foot or shoe comes into contact with the surface under human slip testing it would be interesting to compare the contact areas between a human and the XL. A larger contact patch may better replicate a human heel strike and slip event. Perhaps a larger contact patch along with an increase in impact speed would better simulate a human heel strike. This is research that could be performed to refine the machine design and make it even more accurately reflect a human heel strike and slip event.

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LIST OF APPENDICES

A. Discussion of laws, codes, and industry standards applicable to slippery walking surfaces

B. Discussion of tribological equipment in current use to measure COF of walking surfaces

C. Spreadsheet containing speed data and statistics for the speed gate portion of the study

APPENDIX A

There is a considerable amount of literature covering the topic of human slip and falls. The following appendices break down the relevant literature in two categories. The first category covers the laws and regulations that are in place to protect human life typically in the form of building codes and emergency evacuation plans. The second category covers industry standards that specifically address walking surfaces and means and methods of determining their suitability in a given environment. These industry standards typically are not codified into law but are considered ‘best practices’ sometimes they are referenced within a particular building code.

Appendix A1: Codes and Regulations

Occupational Health and Safety Administration (OSHA)

OSHA was created in 1970 by the US Congress to address the issue of workplace safety [61]. Its mandate is to assure safe and healthful working conditions by setting and enforcing standards of practice for most private sector employers and some public sector employers. OSHA is a department within the Department of Labor and has legal authority to fine and shut down a business that does not abide by the rules. The OSHA regulations are broken into four distinct areas that cover the majority of workplaces. 29CFR1910 covers general industry such as manufactures and retailers. 29CFR1926 covers the construction industry. 29CFR1915, 1917, and1918 covers maritime employment at shipyards and marine terminals. 29CFR1928 covers agricultural industry. The safety rules and regulations for each of these industries are unique and it would be impractical to have one set of rules for all industries.

Within 29CFR1910, 1915, 1917, 1918 and 1928 there are 96 references to surfaces having either a non-slip, non-skid or slip-resistant surface [62]. The only indication within these 96 references as to what OSHA feels is a slip resistant surface is in the general requirements of the working surface of a manlift:

> 1910.68(c)(3)(v)
>
> *Surfaces*. The upper or working surfaces of the step shall be of a material having inherent nonslip characteristics (coefficient of friction not less than 0.5) or shall be covered completely by a nonslip tread securely fastened to it.

The other 95 references to slip resistant surfaces have no values stated. Even when a value is stated such as above it leaves many details up to the code enforcer or the manlift manufacturer. For example, it does not indicate an apparatus or test protocol to measure the COF and as will be shown in Chapter 2 this is a contentious area of debate. Depending upon what machine is used a variety of COF values could be attained. Neither does it indicate if DCOF or SCOF is to be measured. This ambiguity leaves an excessive amount of interpretation available and is arguably an unenforceable regulation [63].

It is somewhat confusing that 1910.68(c)(3)(v) still states a minimum COF value of 0.5 considering the revocation of that requirement for structural steel [64]. OSHA had been receiving information that workers were slipping and falling when walking on painted or coated structural steel surfaces that were wet with condensation or rain. It seemed like a prudent idea to require these surfaces to be slip resistant, so in 2001 OSHA published 29CFR1926.754(c)(3) which established a minimum slip-resistance requirement for the walking surfaces of 0.5 when measured with an English XL Tribometer or other devices’ equivalent values using an appropriate ASTM standard. It became apparent to OSHA that employers were not going to be able to comply with this standard due to testing equipment reliability and precision and also the coatings industry inability to supply coatings that met this ambiguous requirement. Therefore OSHA revoked this requirement on January 11, 2006. To still have a minimum COF value for manlifts seems an oversight on OSHA's behalf.

Americans with Disabilities Act (ADA)

The ADA is a federal law that provides design guidelines for accessibility to commercial and government facilities. The Department of Justice codified the ADA as 28CFR Part 36 and is the authority that requires nondiscrimination on the basis of disability by public accommodations and in commercial facilities [65]. The law came into existence in 1990 but there had been a nationally recognized standard, ANSI A117.1 "*Accessible and Usable Buildings and Facilities*" which gave the technical specifications of making a building accessible and usable by persons with disabilities since 1961 [66, 67].

The ADA, section 302.1 "*General requirements for Floor and Ground Surfaces*", requires all floor and ground surfaces to be stable, firm and slip resistant. The advisory portion to this section states that "a slip-resistant surface provides sufficient frictional counterforce to the forces exerted in walking to permit safe ambulation" [65]. Section 903.7 deals with benches or seats located in wet areas such as showers. ADA requires that the seat not accumulate water and be slip resistant. There is no further definition of slip resistant or any methods or standards reference for measuring and quantifying slip resistance.

The ADA Guidelines have a complimentary document called "*Guidance on the 2010 ADA Standards for Accessible Design*" also published by the Department of Justice [68]. This document attempts to help interpret and explain some of the ADA requirements by giving examples or historical information that allows the reader to better understand the problem being resolved by that particular section. The information contained for 302.1 “*Floor or Ground Surfaces”* states that there is no generally accepted test method for the slip resistance of all walking surfaces under all conditions so the Department declines to assign a testing specification or a value for slip resistance. Therefore, we are left with a requirement to have [44] surfaces slip resistant per ADA but no means of testing or interpreting results rendering the requirement ambiguous at best.

The US Access Board is a federal agency that ensures handicap access to federally funded facilities. It publishes the ADA Accessibility Guidelines (ADAAG) [69]. In August 2003 the Board published Bulletin #4: “*Ground and Floor Surfaces”*. This document was published to disseminate research results concerning the walking surface demands of individuals with gait and mobility disabilities [17]. This research identified the difficulty of assigning a COF value for slippery and slip resistant surfaces. Four friction tester using four different shoe materials measured the COF of the exact same 8” x 8” ceramic tile. The COF readings ranged from a low of 0.29 to a high of 0.99 (n=30). Without specifying the machine and shoe material it would be impossible to assign a safe COF value.

Building Codes

Most cities and counties within the US require structures such as homes, schools, hospitals, office building, and shopping malls to be constructed in accordance with a model building code. In Florida, for instance, the International Building Code (IBC) with Florida modifications (FBC) is the model code that has been legislatively enacted [70]. All contractors building a structure must adhere to the provisions within the applicable code. There are and have been several model building codes published by a variety of organizations such as the Council of American Building Officials (CABO), International Code Council publishes the IBC, and the Southern Building Code Congress International (SBCCI) published the Standard Building Code (SBC) and the International Conference of Building Officials (ICBO) published the Uniform Building Code (UBC). All of these model codes have requirements for certain walking surfaces to be slip resistant. None address the definition or means of measuring whether a surface is slippery or slip resistant.

The 1994 version of the UBC indicates that the surface of ramps shall be roughed or be constructed of slip resistant materials on the means of egress for the building. All versions of the FBC since 2001 states that kitchens and bathrooms in hospitals, nursing homes, schools, swimming pool areas, water parks, and assisted living facilities shall have a nonslip surface. The FBC also demands that walking surfaces and ramps within a means of egress and the in-ground depth markers around a swimming pools shall be slip resistant under foreseeable conditions. It is interesting to note that the 1999 South Florida Building Code requires ramps within a means of egress to have a non-slip surface and then goes on to say that broomed concrete is accepted as a non-slip surface. The 1973 SBC requires ramps in auditoriums or other assembly structures to have a non-slip surface only if they are steeper than one in eight.

NFPA

The National Fire Protection Association (NFPA) is an authoritative body that publishes standards and codes that deal with the prevention and suppression of fire and public safety [71]. Architects and building owners are required to have evacuation plans in case of fire or other emergencies so that occupants can get out of danger safely and quickly. The plan includes an appropriate amount of exits and the establishment of a 'means of egress' from every occupied section of the building. These concepts are documented within NFPA 101: *The Life Safety Code* [72]. Local jurisdictions generally enforce the Life Safety Code via their Fire Marshal. Within NFPA 101 and specifically the chapter that describes the components of a means of egress there are provisions that require routes to have slip resistant surfaces. The 2009 version of NFPA has 14 references for slip resistant. Section 7.1.6.4 states that walking surfaces within the means of egress shall be slip resistant under foreseeable conditions and the slip resistance must be uniform along that path. This standard goes a bit further with the slip resistant criteria and not only demands the walking surface be slip resistant but it also has to be the same slip resistance throughout. This requirement can be interpreted to mean that the sidewalk just outside a hotel must have the same COF value as the 8th floor hallway leading to the emergency exit stairs. The Appendix within NFPA 101 does at least address the idea that slip resistance needs to be defined and pushes that definition to ASTM F1637 "*Standard Practice for Safe Walking Surfaces*". A review of F1637 shows it does not define slip resistance only saying walking surfaces should be slip resistant under expected environmental conditions[73]. As will be shown in the next section, ASTM does attempt to define slip resistance and means of testing but as of this writing there is no consensus on an acceptable COF value that defines a slip resistant surface.

There are other NFPA standards that require slip resistant walking surfaces such as NFPA 102: "*Standard for Grandstands, Folding and Telescopic Seating, Tents, and Membrane Structures*". This standard also states that the means of egress for mobile stands and tents must be slip resistant [74].

Another NFPA standard has a unique and much more comprehensive slip resistant requirement when it comes to the construction and design of fire engines and other motorized fire suppression equipment. NFPA 1901: "*Standard for Automotive Fire Apparatus*" requires the contractor building the fire engine to provide a certification of slip resistance of all stepping, standing, and walking surfaces[75]. What makes this particular standard unique is that it continues on to tell the manufacture how to test for the COF and what values are acceptable. All exterior walking or standing surfaces must have a COF of 0.68 when tested under wet conditions using an XL Tribometer or 0.52 when using a Mark II tribometer. All interior walking or standing surfaces must have a COF of 0.58 when tested under dry conditions using an XL Tribometer or 0.47 when using a Mark II tribometer. The tribometers must use a Neolite foot and follow the manufactures instructions for testing. These are proprietary field-testing tribometers and will be described in Chapter 1.3.3 Devices.

Appendix A2: Industry Standards

The following literature deals with the standards promulgated by scientific organizations that have a bearing on pedestrian safety. These scientific bodies publish standards that professionals can use as guidelines and recommendations to ensure that they have used best practices when performing their duties. The standards are not required by law to be used and are voluntary in most cases. However, if they are considered in the course of performing professional work then they can provide a basic standard of care and help to prevent problems in the future.

American Society for Testing and Materials (ASTM)

ASTM is a body of technical experts and business professionals that write and modify 12,000 standards used throughout the world to enhance safety, improve quality, and to build consumer confidence in manufactured products. They publish test methods, specifications, guides and generally accepted practices that support industries and government organizations [76]. ASTM has 143 technical standards-writing committees that publish diverse types of standards from acoustic qualities of buildings, to electrical qualities of conductors, to the preservation methods of lumber and wood products [77]. The particular committee that deals with walkway safety is F13 – Pedestrian/Walkway Safety and Footwear which controls 16 current standards distributed between seven subcommittees. Appendix B at the end of this document lists each subcommittee within F13 and the standards that are active and withdrawn. Some slip resistant standards exist in technical committees on floor polishes and ceramic tiles and possibly explain some of the overlap and confusing terminology.

Standard F1637 – "*Standard Practice for Safe Walking Surfaces*" is cited in many court cases, organizations, and authoritative texts as the standard of care when designing and maintaining a walking surface [40, 57, 63, 72, 78-80]. The verbiage used in this standard is directed toward designers, engineers, constructors, and maintenance personnel. It addresses slippery walking surfaces in two areas. Section 5.1.3 states that walkway surfaces shall be slip resistant under expected environmental conditions and that painted walkways need an abrasive additive. Section 5.7.1.1 states that exterior walkways shall be slip resistant. This standard leaves the definition of slip-resistance and slip-resistant to ASTM F1646 "*Terminology Relating to Safety and Traction for Footwear*".

ASTM F1646 defines Slip Resistance as:

> The relative force that resists the tendency of the shoe or foot to slide along the walkway surface. Slip resistance is related to a combination of factors including the walkway surface, the footwear bottom, and the presence of foreign materials between them.
>
> "Discussion – Slip resistance is dependent upon many factors, such as material and condition of the walkway surface, material and condition of the shoe sole or heel material, the physical abilities of the user, the attempted or proposed activities of the user, the presence of any contaminants on any or both of the surfaces, and other factors."

ASTM F1646 defines Slip Resistant as:

> The provision of adequate slip resistance to reduce the likelihood of slip for pedestrians using reasonable care on the walking surface under expected use conditions.

ASTM has five current and five withdrawn standards that detail methods of measuring the COF of flooring or walking surfaces. F609 "*Standard Test Method for Using a Horizontal Pull Slipmeter (HPS)*" outlines the process for measuring the SCOF of a dry surface in the field and laboratory [81]. It requires the use of a force gauge mounted to a piece of steel with both parts weighing 6 lbs combined. The steel plate has 3 test feet that ride on the tested surface. The gauge and plate are pulled via a string attached to a power unit in an attempt to remove any operator influence. The force gauge is set to maximum and when the power unit pulls the block it records the maximum force needed to get the block into motion. This value is scaled on the gauge and provides a slip index or the SCOF. There is no definition as to acceptable or unacceptable values for the SCOF when using this method. It is necessary to note that section 4 of F609 specifically states it can only be used under dry conditions and that readings, when used in wet conditions, will not give useful information and not provide an effective assessment of walkway slipping hazards.

A similar standard ASTM C1028 "*Standard Test Method for Determining the Static Coefficient of Friction of Ceramic Tile and Other Like Surfaces by the Horizontal Dynamometer Pull-Meter Method*" outlines the process and equipment for measuring SCOF under both wet and dry conditions [33]. This standard also uses a force gauge attached to a block of steel being pulled by a string. Different from F609, is that the string is pulled by the operator and the steel sled weighs 50 lbs. The bigger difference is what is missing in C1028. C1028 outlines the test procedure for both wet and dry conditions and there is no mention of this method being inappropriate for testing under wet conditions as seen in F609. The methodology between the two standards is similar enough (dragging a weight along the surface and measuring the pulling force) to cause confusion when wet COF testing needs conducted. A possible source of conflict is the fact that F609 is under the control of ASTM F13 committee on Pedestrian/Walkway Safety and Footwear while C1028 is under the control of ASTM Committee C21 Ceramic Whitewares and Related Products. These two ASTM committees have different concerns and responsibilities and may not fully appreciate what each other are doing.

ASTM F2913 "*Standard Test Method for Measuring the COF for Evaluation of Slip Performance of Footwear and Test Surface/Flooring Using a Whole Shoe Tester*" can measure the SCOF and DCOF under both wet and dry conditions in a laboratory environment [30]. The shoe or surface being tested is loaded into a SATRA STM603 (http://satratechnology.com/slip-test-details.php) machine and a vertical load of 50N (11.2 lbs) is applied between the shoe and the flooring material. Within 0.2 seconds the vertical load is increase from 50N to 500N (112lbs) and once the larger force is achieved, the flooring surface moves horizontally at 0.3 m/s (11.8in/s) relative to the shoe. The output graph shows time on the x-axis and force and COF on the two y-axes and a plot of the vertical force (F_N), horizontal force (F_T), displacement, and the running calculation of DCOF (F_T / F_N). This machine can not be used for field measurements but being able to determine the SCOF and DCOF use a particular shoe on a particular surface with various contaminants in a controlled environment is attractrive to shoe manufactures, flooring manufactures, and forensic analysts. F2913 is only a testing method describing equipment and processes and does not attempt to interprete testing results.

ASTM D2047 "*Standard Test Method for Static Coffiecint of Friction of Polish-Coated Flooring Surfaces as Measured by the James Machine*" outlines the means and methods for determining the SCOF of dry polished flooring materials with respect to human locomotion safety [82]. It is not intended for wet testing and uses leather as the testing material as opposed to Neolite used in other standards. What is unique about this standard is that upon defining slip resistance it interpretes the results obtained. Section 3.1.5 Slip Resistance states that by using this method and achieving a SCOF of 0.5 or greater constitutes an adequate slip resistance of the flooring material being tested and provides a nonhazardous walkway. Unfortunatly the James Machine is a laboratory device and can not do field measurements but it is used by flooring and coating companies to evaluate their product and report on its slip resistance. By using these slip resistant products this gives archetects, engineers and specifiaction writers the necessary due dillegence or standard of care required when stipulating floor coverings for various applications. The standard goes on to caution the user that the SCOF of 0.5 is only applicable to this test method and to apply this value for other methods or equipment is improper. The James Machine will be described in detail in section 1.3.3.1. It has been in existance since 1975 and much data has been published using it as a 'gold standard' for measuring slip resistance.

ASTM F462 "*Standard Consumer Safety Specification for Slip-Resistant Bathing Facilities*" is a consumer safety specification that attempts to reduce slip and falls in bathtub and showers [23]. This standard is controlled by ASTM committee F15 on consumer products and subcommittee F15.03 Safety Standards for Bathtub and Shower Structures. It was introduce in 1979 and is still considered a viable standard with reapproval in 2007. This standard requires the use of a NIST-Brungraber testing machine (Mark I) and a soap solution ½" deep in a bathtub. The soap solution specified is made from coconut oil fatty acids, saponified with potassium hydroxide with pH corrected with acetic acid. EDTA acid is added as a chelating agent and the solution must be used at a temperature of 70° ± 5° F. If the soap solution shows any signs of curd, it must be replaced. Nine sections of the bottom of the tub or shower are tested and if any of the nine areas fall below a .04 COF then the tub fails the test. The test foot uses medical grade silicon rubber called Silastic 382. Since the machine is no longer available, the complexity of the soap solution along with the unique nature of the test foot, makes this standard difficult if not impossible to use for a forensic analysis. Section 1.3.3.7 describes the Mark I in detail.

For a variety of reasons ASTM has withdrawn five standards that described methods and equipment for determining COF. Withdrawn standards would not normally be addressed in an assesment of current technology but the equipment described in these withdrawn standards are still being manufactured and used so it is reasonable to expect the potential reinstatemnt of these standards in the future.

ASTM D5859 "*Standard Test Method for Determining the Traction of Footwear on Painted Surfaces Using the Variable Incident Tester*" (Withdrawn 2005) describes the process and equipment needed to determine the COF of painted walkways such as found in crosswalks or treatead concrete sidewalks [83]. The standard specifies the use of a propriatary machine called, the English XL under both wet and dry conditions. The company and equipment has recently been renamed Excel Tribometers [56]. This machine will be described in detail in section 1.3.3.8 as it is the basis for the experiments performed for this thesis. The test foot is propelled toward the painted surface by a pnuematic cylinder pressurized at 40 psi (276 kPa)[5] at continually decreasing angles until the foot slips forward due to the increased F_T. The angle at which the foot slips forward is calibrated to a COF scale on the side of the machine. This COF reading is reported as the SCOF[6] of the surface and test foot. Again, this standard does not attempt to interpret results of the testing.

ASTM F489 "*Standard Test Method for Using a James Machine*" (Withdrawn 2005) outlines the methods and equipment used to measure the dry SCOF of shoe sole and heel materials on

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[5] According to the equipment manual the operating pressure should be 25 psi to achieve a foot speed of 12 in/s. It is not clear why this standard called for an operating pressure of 40 psi.

[6] The inventor of this device has written on several occasions that his machine measures DCOF and not SCOF. It is unclear as to why this standard reports an output of SCOF.

walking surface materials[31]. F489 seems to be a supporting document for ASTM D2047 "*Test Method for SCOF of Polish-Coated Floor Surfaces as Measured by the James Machine*" in that F489 tells the basics on how to use, maintain, calibrate and report the results of the James Machine but D2047 is for its use on specific floor materials. It also seems somewhat redundant and this could be the basis for its withdrawl in 2005 along with having no precision and bias data as required by ASTM [84].

ASTM F1677 "*Standard Test Method for Using a Portable Inclineable Articulated Strut Slip Tester (PIAST)*" (Withdrawn 2006) outlines the operational procedures and equipment used to measure slip resistance under wet and dry conditions. It can be used both in the lab and under field conditions but is a patented and propriatary machine. Section 1.3.3.7 will detail how the machine works. An interesting aspect of this standard is that it does not use the terms COF, SCOF, or DCOF. It only reference the measurement as slip resistance. There is also not a precision and bias report as required by ASTM.

ASTM F1678 "*Standard Test Method for Using a Portable Articulated Strut Slip Tester (PAST)*" (Withdrawn 2005) outlines the operational procedures and equipment use to measure slip resistance of footwear against walking surfaces under dry conditions. This machine is generally referred to as the Mark I and is no longer supported or in production by the manufacture.

Underwriters Laboratory (UL)

Underwriters Laboratories (UL) has a similar standard to D2047 "*Standard Test Method for Static Coffiecint of Friction of Polish-Coated Flooring Surfaces as Measured by the James*

Machine" called UL410 *"Slip Resistance of Floor Material"*. Products that meet the 0.5 SCOF requirement using the James Machine can be registered and labeled with the UL approved symbol[85]. One big difference between D2047 and UL410 is that UL410 allows for testing of abrasive flooring materials (FTM-4 and WCM) using water and cutting oils. Even wet and oiled flooring material must meet the 0.5 requirement to pass the standard. Using a leather test foot for wet testing in not appropriate due to its high sensitivity to humidity, lack of homogeneity, and changing properties during the testing process [86]. This UL label gives consumers a sense of confidence that the flooring product being purchased and used is slip resistant in expected environmental conditions.

American National Standards Institute (ANSI)

ANSI is an organization that facilitates and coordinates voluntary private sector consensus standard and approves standard-making organizations [87]. ANSI does not write standards but has a watchdog role in ensuring that development conformity exists within the organizations that write the standard. This accreditation by ANSI serves to increase consumer confidence in the product, service, or process that abides by the requirements of the voluntary standard. ANSI standard designations are typically paired with the organization, industry sector or technical body stakeholders that have written the standard. For instance, NFPA is an accredited standard developer and can develop ANSI standards that deal with the safety, efficiency, and compatibility of fire suppression related products or systems. ANSI standards ensure that fire truck hoses can connect to building water supplies and fire hydrants. They also promote the effectiveness of sprinkler systems in warehouses, garages, hotels, schools, and other public and private buildings.

ANSI A137.1 "*Specification for Ceramic Tile*" was developed by the Tile Council of North America (TCNA) [88]. This standard specifies the physical properties of various grades and types of ceramic tile and serves as a guide for manufacturer's quality control and buyer's basis for acceptance. It defines slip-resistant tile as tile having a greater slip-resistant characteristic due to an abrasive admixture, abrasive particles in the surface, grooves or patterns in the surface, or a glaze specifically designed for increased coefficient of friction. It references ASTM C1028 as the method used to test for SCOF. However, there is no specified value for SCOF that would be considered slip resistant. A137.1 states that if SCOF data is required for a specific project then the testing shall conform to ASTM C1028 and the required value of SCOF is to be agreed upon between the manufacturer and the purchaser because COF can be affected by the area of use and the maintenance by the owner of the installed tile. A problem is created for tile installers that purchase through a wholesaler or retail and does not have access to the manufacturer.

ANSI A1264.1 "*Safety Requirements for Workplace Walking/Working Surfaces and their Access; Workplace, Floor, Wall and Roof Openings; Stairs and Guardrails System*" was developed by the American Society of Safety Engineers (ASSE) [89]. Its intended purpose is to establish safety guidelines that will protect people while they do their jobs in industrial and workplace situations and in areas where danger exists from floor, roof, and wall openings or from platforms, ramps and stairs. This standard requires that stairs used in the workplace to have treads and nosings that are slip-resistant. The explanatory portion of this requirement directs the reader to ANSI A1264.2 "*Standard for the Provision of Slip Resistance on Walking/Working*

Surfaces", the IBC, NFPA 101, OSHA, and building codes for more information on the definition of slip-resistance.

ANSI A1264.2 *"Provision of Slip Resistance on Walking/Working Surfaces"* was also developed by ASSE [9]. Its purpose is to establish flooring guidelines for employees pursuing foreseeable activities during the course of their job. This standard defines Slip Resistance as the tendency of two surfaces in contact to resist relative motion under prevailing conditions. It also addresses areas where slippery conditions are inherent such as food processing, rendering, and chemical processing and gives the user ways of dealing with these hazards. The standard requires the flooring to provide acceptable slip resistance under foreseeable conditions and if it's not practical to replace a slippery floor then consider etching, scoring, grooving, appliqués, or coatings on the existing surface. This standard is unique in that in the explanatory section it recommends a COF of 0.5 or greater for dry surfaces and to use an appropriate ASTM standard to perform the testing. It also suggests the use of Neolite for the test pad due to its uniform properties and resistance to contamination. The standard goes on to explain that even if a floor has a COF of less than 0.5 under dry conditions it does not mean the floor is hazardous. Slips can occur on relatively high values of slip-resistance so this standard does not recommend an absolute value which would eliminate the possibility of a slip occurring. The ANSI A1264 committee writing A1264.2 suggests that when testing wet surfaces that a device that has no residence time be used to avoid sticktion and adhesion. This recommendation further suggests that for wet conditions the DCOF should be measured rather than the SCOF.

ANSI B101.1 "*Test Method for Measuring Wet SCOF of Common Hard-Surface Floor Materials"* was written by the National Floor Safety Institute (NFSI)[90]. NFSI is a nonprofit organization that aids in the prevention of slips, trips-and-falls, through education, research, and standard development [4]. NFSI has a certification process for flooring products and walkway auditors. B101.1 gives the test method and appropriate measurements for traction on common floor surfaces such as ceramic tile, vinyl, and wood laminates along with the coatings and polishes that may be applied. Even thought the standard states that any recognized or approved tribometer designed to measure wet SCOF can be used, only the BOT3000 has the required NFSI approval. Section 1.3.3.4 contains a detailed description of the BOT3000. The tester must use a Neolite test foot to comply with this standard. B101.1 defines slip resistance as the property of a floor or walkway that acts in sufficient opposition to those forces and movements exerted by a pedestrian under all normal conditions of human ambulation. Static Friction is defined as the resistance opposing the force required to start movement of one surface on or over another. The letter of interpretation that accompanies B101.1 states that only machines capable of measuring wet SCOF can be used with this standard and specially identifies the Excel, Mark I, II, and II, and all pendulum based devices as not being able to measure wet SCOF.

B101.1 categorizes the SCOF measurements into 3 areas; high traction, moderate traction, and minimal available traction. If a floor has a wet SCOF of 0.60 or higher then it is in the high traction category and pedestrians have a lower probability of slipping. If a floor has a wet SCOF of between 0.40 and less than .060 then it is categorized as having moderate traction and pedestrians have an increased probability of slipping. If the SCOF is less than 0.40 it has minimal available traction and pedestrians have a higher probability of slipping. There is no mention of adhesion or sticktion as mentioned in other standards such as the ASSE sponsored ANSI A1264.2.

ANSI B101.3 “*Test Method for Measuring Wet DCOF of Common Hard-Surface Floor Materials (Including Action and Limit Thresholds for the Suitable Assessment of the Measured Values)*” is also written by NFSI. It is very similar to B101.1 as there is only one device capable of measuring flooring using this standard and three categories for the results. However, the test pad used is of Styrene Butadiene Rubber (SBR) rather than Neolite. Another difference is that B101.1 specified using water as the wet contaminant but this standard requires a surfactant of sodium lauryl sulfate (SLS) be added to the water to increase surface wetting. The test results are compared within 3 categories; High, Acceptable, and Low. If the test results are greater than 0.45 on an inclined surface or greater than 0.42 on a level surface then the floor is considered to have high traction and a lower probability of pedestrians slipping. If the test results are between 0.30 and 0.45 on an inclined surface or between 0.30 and .042 on a level surface then the floor has an acceptable amount of traction. If the test results are less than 0.30 the floor has low traction and increases the probability of pedestrians slipping.

ANSI Z124.8 “*American National Standard for Plastic Bathtub Liners*” covers the requirements, materials, workmanship, installation and testing methods for plastic bathtub liners. This standard is written by the International Association of Plumbing and Mechanical Officials (IAPMO). Bathtub liners are commonly used as a custom installed insert or replacement cover for existing cast iron or steel bathtubs. This standard requires the manufacturer to use the latest edition of ASTM F462 if they represent to the consumer that their bathtub liner is slip resistant. As mentioned earlier ASTM F462 is the Standard Consumer Safety Specification for Slip-Resistant Bathing Facilities and requires a COF of 0.04 or greater to be considered slip resistant.

APPENDIX B: Devices Used to Measure Coefficient of Friction

As discussed earlier there are case law and liability rules that put the responsibility on the property owner to provide a reasonably safe environment for their workers and invited guests. Therefore property owners use tribometers, and other techniques, to evaluate their walking surfaces to ensure that they are not slippery and do not create a hazardous environment. Safety professionals routinely use tribometers to evaluate a floor or stair after a slip and fall accident and give expert opinions in court. Friction measurement is one of the major approaches in assessing floor slipperiness. Unfortunately there is no universally accepted or absolute reference device for measuring COF of walking surfaces [39, 49]. Several studies have shown that different tribometers yield a variety of results on the same surfaces [15, 17, 49-54]. Much of this discrepancy is due to the variety of testing techniques, testing materials, users, machine variation and other undetermined variables.

Considering the number of standards introduced in 1.3.2 "*Codes and Regulations*" it should come as no surprise that the number of machines used to measure COF is high. It is outside the scope of this research to introduce every machine as there are hundreds on the market throughout the world that purports to determine if a walking surface is safe. This paper introduces the most common types found in the US and primarily focuses on field-use machines. Several non-field-use machines are described because of their prominence in this particular branch of science.

In general there are categories to these machines; Dragsled, Inclinable Mast and Pendulum. Dragsled are placed on the test surface and moved along either by an operator or by itself. If the surface is contaminated with a liquid such as water, then placing the device onto the surface displaces the water. As the test foot is being dragged the water is pushed out of the way or a thin film is created. The inclinable mast machines measure the COF by applying the normal and horizontal forces quickly and simultaneously. The inclinable mast machines are believed to be more similar to human ambulation as the pedestrian's heel strikes the walking surface during a normal gait. The pendulum type has an elevated weighted test pad that swings through an arc striking the test surface. The loss of energy corresponds to the amount of friction encountered between the test pad and the test surface. Some of these three types of devices are used in a laboratory environment and some are portable enough to be used in the field. Field measurements are an important feature when evaluating an already-installed floor.

James Machine

The James machine as shown in Figure 17 was developed in 1975 by Underwriters Laboratories to measure the slip resistant characteristics of flooring material as a way for flooring manufacturers to obtain UL approval [39]. The test method incorporates an 80 lb weight and is only used in a laboratory environment as it is a large and heavy device. This machine is of the dragsled variety in that the test pad sits on the surface with a known vertical force [31]. An articulated arm pushes the test pad that sits in contact with the testing surface. The COF is obtained by observing the angle of the articulated arm at the moment the power of the machine causes the test foot to slip on the sample. A horizontal force is slowly applied to the pad until it slips along the test surface. ASTM F489 "*Standard Test Method for Using a James Machine*" and UL 410 "*Standard for Slip Resistance of Floor Surface Materials*" and ASTM D2047 "*Standard Test Method for Static Coefficient of Friction of Polish-Coated Flooring Surfaces as*

Measured by the James Machine" cover the use and validity of this machine. It is referenced in many standards and scientific papers. The James machine has been used to test shoe sole and heel materials against standardized surfaces and to test surfaces under standardized shoe material.

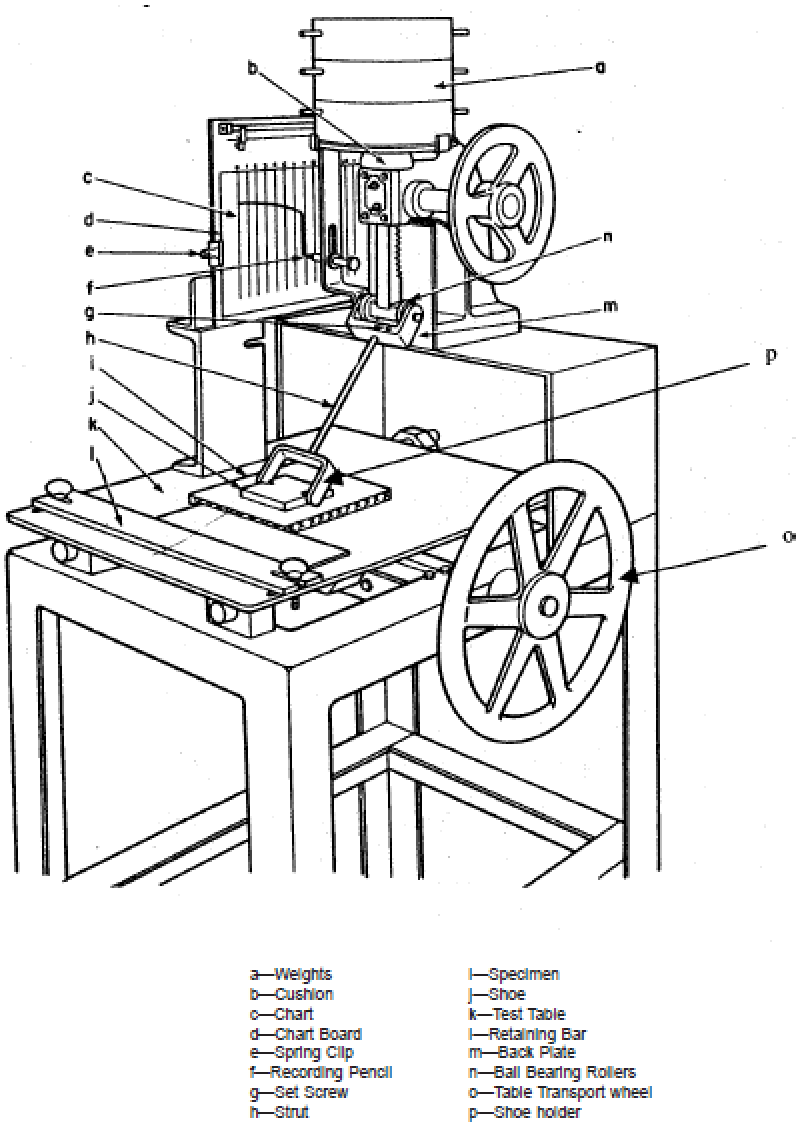

Figure 20: James Machine[7]

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[7] Reprinted, with permission: From D2047-11 Standard Test Method for Static Coefficient of Friction of Polish-Coated Flooring Surfaces as Measured by the James Machine, copyright ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA 19428

The procedure of operation is to load the 12” x 12” flooring material (i) onto the movable test table (k). The table is positioned so that the strut (h) is vertical and can support the weights (a). A paper chart (c) is loaded so that the recording pencil (f) marks a line as the test table is moved forward. The test table, along with the flooring material, is moved forward via the large hand wheel (o) at a rate of 1in/s (there’s no mechanism to ensure this movement rate). As the table is moved forward the strut becomes more angled and thus the horizontal component of the weight increases. When the horizontal force being applied by the strut exceeds the tangential friction force, F_t, between the test pad and the surface the test pad slips forward and the weights drop. This motion is being recorded by the pencil onto the chart. The marking will be horizontal and then have an abrupt vertical line. This transition point from horizontal to vertical is the COF. The flooring surface is rotated 90° and repeated 3 times so that 4 measurements can be averaged. The charts are preprinted and scaled to show COF. It is interesting to note that ASTM F489 insists that there be less than 5 seconds between the time the test pad is sat on the surface and the 1in/s motion is started. There is no explanation for this requirement but it may have to do with an adhesion effect, sticktion, between the two surfaces becoming more aggressive as time elapses [27, 57].

Pendulum Type Testers

The Pendulum tester concept is similar to an Izod or Charpy impact test where a known mass is swung from a known height and allowed to slide across the test surface at the valley of the arc path [51]. Figure 18 shows a version of the pendulum type testers called a British Pendulum Tester. After the impact the hammer continues to travel along the arc path having dissipated some of the kinetic energy overcoming the frictional resistance. The distance that the arm continues to travel is calibrated to a scale where a ‘follower’ indicator needle stays when the hammer reaches its apex and starts to swings back the other direction. This location on the scale corresponds to DCOF of the surface being tested. The hammer is fitted with a rubber swatch that makes contact with the testing surface for a specified length. The machine can be used in a laboratory or in the field although field usage is limited due to the cumbersome size, weight, and setup routine. There is a calibration procedure that ensures the pendulum swings to the appropriate level when not striking a surface. Also, the length of the contact surfaces (124 – 126 mm) between the pad and the tested surface is critical and difficult to manage [27]. The machine can be used on wet or dry material and according to the manufacture used on astro turf and carpet [91]. The test surface must remain stationary on the base and the operator must catch the hammer on the backstroke as to not damage the rubber swatch and the sample being tested. At the point of contact between the rubber and the tested surface the hammer is moving at 138in/s (3.5 m/s) [63, 92].

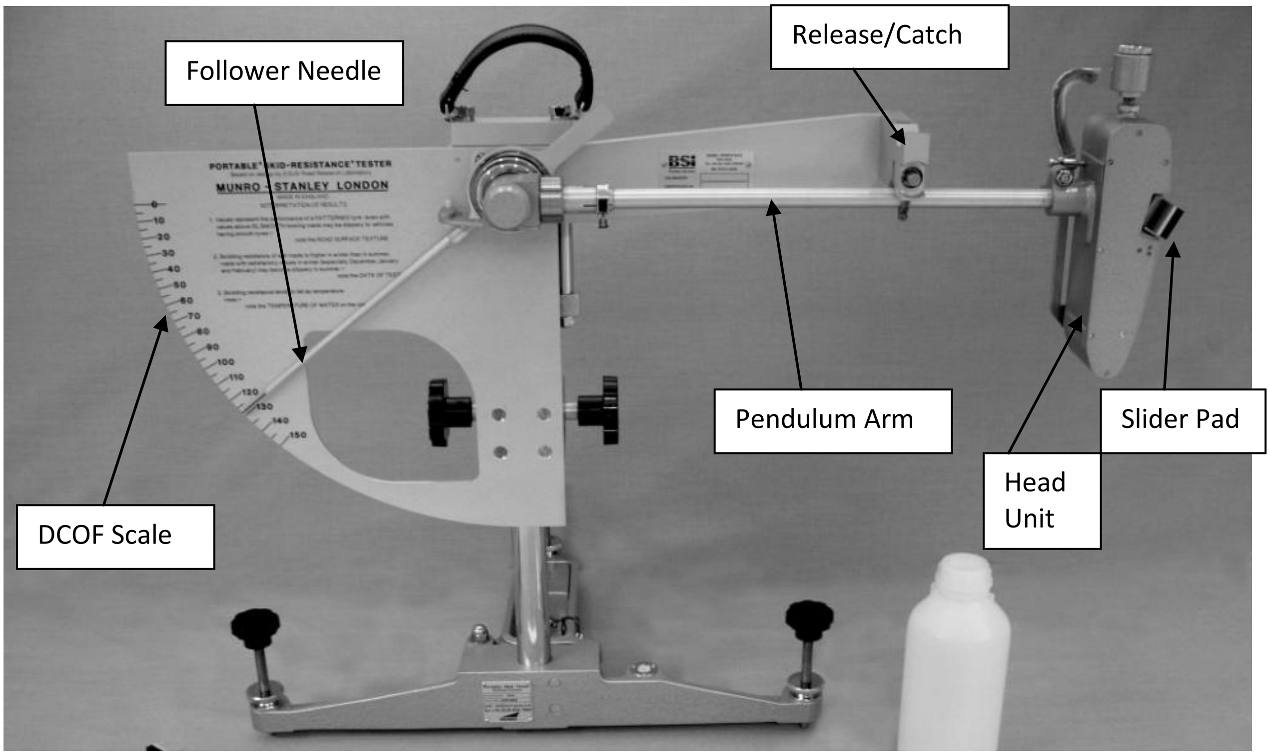

Figure 21: Munro British Pendulum Tester[8]

This type of tribometer is rarely used in the United States but is cited in some standards and tested against other machines in scientific studies [39]. The concept was developed in the US by Percy Siegler during the 1940's and redeveloped in the United Kingdom by Wessex to research slippery roadways [91, 93]. ASTM E303-93(2008) "*Standard Test Method for Measuring Surface Frictional Properties Using the British Pendulum Tester* covers the method of its use [94]. This standard is under the control of E17 committee on Vehicle – Pavement Systems and specifically written by subcommittee E17.23 on Surface Characteristics Related to Tire Pavement Slip Resistance. This committee is interested in the interaction between automobile tires and pavement and do not necessarily appreciate the interaction between pedestrians and walking surfaces.

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[8] Reprinted by permission from Munro Instruments Ltd, Gilbert House, 406 Roding Lane South, Woodford Green, Essex, IG8 8EY, UK

Tortus Slip Tester

The Tortus slip tester is self propelled and measures the SCOF and the DCOF on both wet and dry surfaces [91, 95]. Figure 19 shows the device sitting on tile flooring. It displays the SCOF on the digital readout and prints the instantaneous results and graph on a paper output[51]. Its principle of operation is that the weight of the machine, 13.2 lb (6 kg), provides a constant normal force onto the 0.375 inch (9.5mm) diameter test foot. The 4S rubber (standard shoe sole material) test foot is mounted on a leaf spring assembly and is held in contact with the test surface by the machine’s weight. The horizontal force is measured by strain gauges mounted to the leaf spring assembly and the microprocessor reads the strain gauge signal and converts to a COF value. The reported COF is the relationship between the known normal force and the measured horizontal forces. The test pad can be replaced with any material that the user wants to test against the surface. The Tortus is considered a dragsled device and is subject to the phenomena creating a temporary bond between the two surfaces known as sticktion. It is believed that this phenomenon is related to the amount of time that the two surfaces sit idle to one another and affects the SCOF but not the DCOF [44].

Figure 22: Tortus Slip Testers

BOT3000

The BOT3000 is manufactured by Regan Scientific Instruments, Southlake, TX [96]. Figure 20 is a photo of the machine. It is self propelled at 7.9in/s (20 cm/s) and measures the SCOF and the DCOF on both wet and dry surfaces with very little operator input. It is similar in operation to the Tortus except that the test pad is not spring loaded and applies a normal force of 4.8 lbs (21.3 N) only after the user activates the test which tends to lessen the effects of sticktion. The machine propels itself along the floor and the horizontal force applied to the pad is digitally measured and logged by means of strain gauges. As the machine moves the COF is calculated internally and both the static and dynamic COF is logged and displayed in real-time. Since this data is stored in onboard memory it can be graphed and the minimum and maximum readings are easily available. There is a USB port for downloading the data for use in spreadsheets or reports. The test pad holder has electronic functionality that lets the machine processor know what type of slider material is being used during the test and will warn the user if an inappropriate material is inserted. The test pad itself is larger than the Tortus and has a slight curvature in the direction of travel making the contact patch between the slider and the floor surface 0.12 x 1.1 inches (3 x28mm). The slider materials available are leather, neolite, and SBR in order to accommodate the various material requirements of standards discussed previously. The BOT3000 weighs 15.2 lbs (6.9 Kg) and is 11.5” long x 8” wide x 6.5” tall.

The BOT3000 is the only machine approved and recognized to perform material testing according to ANSI B101.1 “*Test Method for Measuring Wet SCOF of Common Hard-Surfaced Floor Materials Standard”* and ANSI B101.3 “*Test Method for Measuring Dry SCOF of Common Hard-Surfaced Floor Materials Standard”* [97]. The BOT 3000 is the only device approved for use by the Tile Council of North America (TCNA) for assessing and measuring the COF of tile[98]. TCNA had been using ASTM C1028 “*Standard Test Method for Determining the Static Coefficient of Friction of Ceramic Tile and Other Like Surfaces by the Horizontal Dynamometer Pull-Meter Method”* as the method for measuring the SCOF of tiles. In April 2012 an updated version of ANSI A137.1 “*Specifications for Ceramic Tile”* incorporates a DCOF testing method using the BOT3000.

Figure 23: Photo of a BOT3000

The BOT 3000 is based on the dragsled method of measuring COF and that method has been questioned because the test slider moves across the wet test surface acting like a squeegee and removing the contaminant from the surface [15, 57, 63]. The draglsed method is the mechanism of foot slippage after the slipping is initiated but does not simulate the dynamic interaction of the foot and floor prior to slippage.

American Slip Meter Model 725 and 825

The ASM machine is essentially a force gauge that is pulled across the test surface by the user. It is considered a dragsled device. The gauge on the model 725 has a dial and uses a needle and needle follower to tell the user how much force is being exerted to pull it across the test surface[99]. Model 825 uses a digital gauge rather than the dial. See Figure 21. The output is not in units of force but rather internally correlated to a COF value based upon the known weight of the unit. The calibration check is to hold the unit vertical by the string and the output should read 1.0 (the weight of the machine). If it does not read 1.0 then the adjustment screw should be turned until it does.

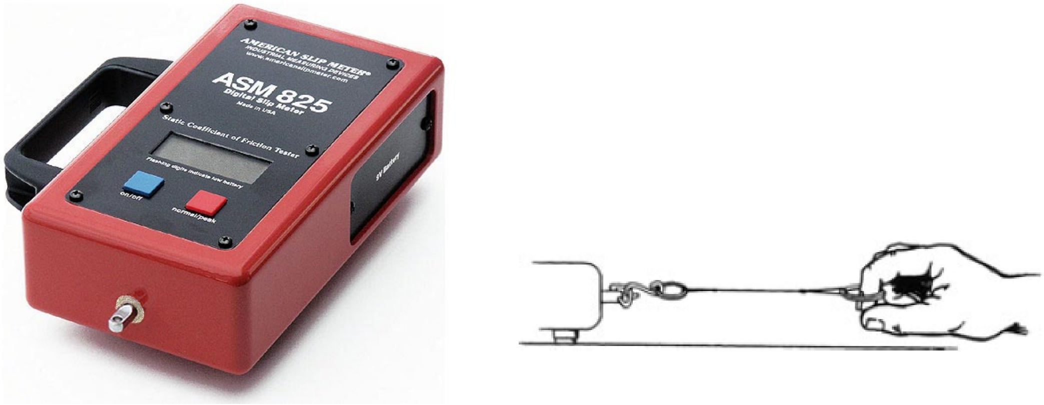

Figure 24: Photo ASM 825 and operational method

The ASM has three Neolite test pads or feet mounted on the bottom. These three pads are in contact with the test surface as the user pulls a string attached to the body of the ASM. The machine will show SCOF but the user must watch the gauge if DCOF is to be determined. The manufacturer says that the machine is usable under wet conditions as long as a calibration factor is applied [100]. The machine operator determines the rate of pulling force and the amount of applied force thus the output will vary from operator to operator [101]. This variation cannot be accounted for by routine engineering calibration. The operational procedures also produce a variation in the residence time between the testing surfaces resulting in various degrees of sticktion. If the operator, while watching the gauge, does not pull parallel to the surface then a vertical force is introduced tending to raise the device or placing additional normal force on the front of the device.

Technical Products Model 80

The Model 80 uses a 10 lb lead weight with three, 7/16” diameter, leather pads attached to the bottom [102]. See Figure 22. A force gauge is hooked to the weight and the operator drags it along the test surface and reads the SCOF from the gauge. The manufacture states that the leather test feet are not appropriate for testing under wet conditions as the leather has considerable variability from one sample to another. For wet testing the manufacture offers Ethylene Vinyl Acetate (EVA) or silicone rubber for the sensor pads.

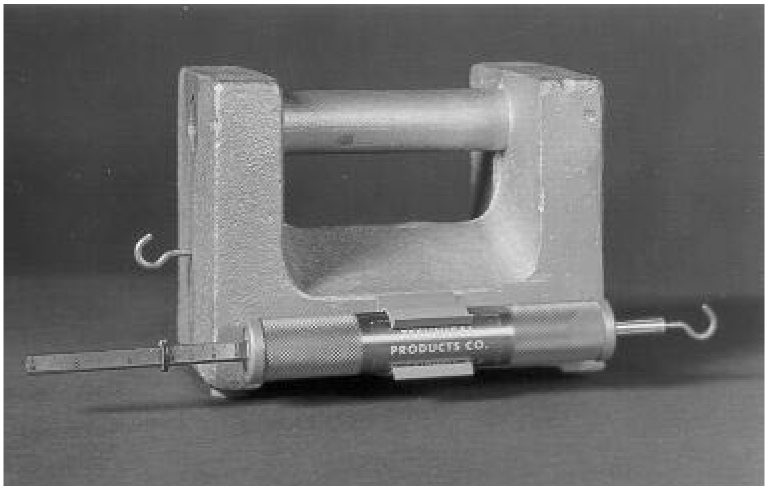

Figure 25: Technical Products Model 80 Floor & Footwear Friction Tester

The Model 80 is considered a dragsled type device and subject to sticktion and other error inducing issues as described for the ASM 725 [101]. The manufacturer makes the argument that leather is the appropriate test material to use when a correction factor is applied based upon the humidity during testing [103]. The argument continues in that measuring SCOF under dry conditions using leather is the best determinant as to the safety of a walking surface. The only reason to measure under wet conditions is to help support the dry findings. This contention is not scientifically supported and is only an assumption. Most slip and falls occur on contaminated surfaces so testing under these conditions is necessary and easily performed with other equipment.

Mark I, II, III

There are currently three tribometers commercially available in the United States that measure the COF of walking surfaces using a method that reportedly simulates a biofidelic heel-strike condition in that both a vertical and horizontal component of velocity is applied to the tested surface at the same time [15, 27, 46, 57]. These three machines are the XL, the Mark II and Mark III Tribometers. However, there are no studies that report the impact speed and angle of these machines with the impact speed and angle of actual pedestrian heel strikes. Therefore, one does not know if the machine's impact with the walking surface is similar in mechanism or velocity to an actual human gait. Therefore it is important to fully appreciate the mechanism of operation and appropriateness of using these machines to evaluate walking surfaces. Specifically it is important to determine if the reported similarity to pedestrian heel strikes is supported by scientific research.

The Mark II and III are considered Portable Inclinable Articulated Strut Tribometers (PIAST). See Figure 23. The Mark II and III have similar functionality in that the 3" x 3" test foot is moving and has both horizontal and vertical velocity when impacting the test surface. The Mark II uses a 10 lb weight to drive the test foot while the Mark III uses a spring to drive the test foot.

The use of the spring makes the Mark III lighter and easier to use in field conditions. The normal force exerted on the floor surface is significantly different between the Mark II than for the Mark III and results in different COF readings for the same surface [49].

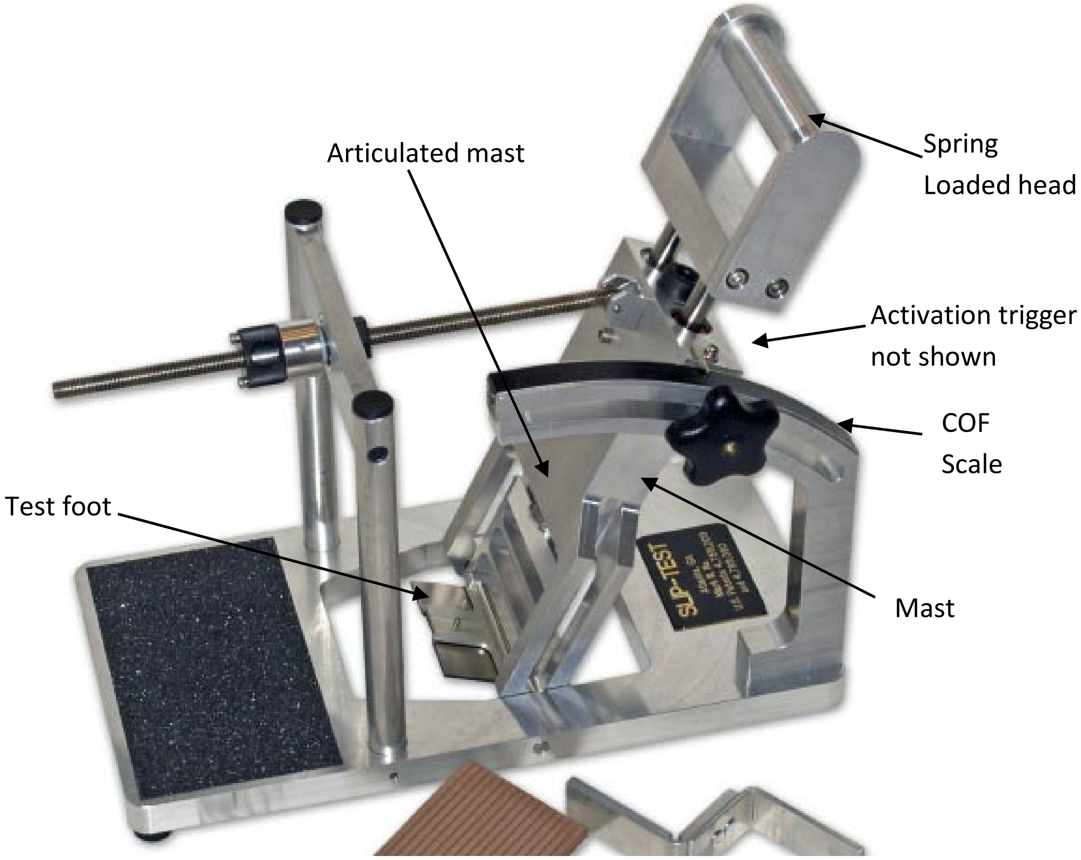

Figure 26: Nomenclature for the Mark III Tribometer

The strut mechanism has an articulated joint that connects the upper and lower halves of the mast. The test foot is hinged and allowed to rotate during impact so that the entire test foot makes contact with the test surface. This movement mechanism simulates a heel strike and ankle rotation. As the weighted mast is dropped (or force downward with a spring in the Mark III) the test foot strikes the test surface at a set angle. If the resistant frictional force between the foot and the surface is sufficient to resist horizontal motion then the two halves of the mast remain inline. If there is insufficient force to resist motion then the bottom half of the mast is allowed to rotate relative to the top half allowing the test foot to slip forward. The user varies the angle of the mast before each test until the test foot slips. This angle is correlated to a COF reading on the scale.

The speed of the test foot for the Mark II is determined by how far the weight is allowed to drop and theoretically governed by the equation $V = \sqrt{2gh}$. According to the manufacturer's literature the test foot drops between $^{1}/_{8}$" and ¼" thus generating a velocity of 9.8 to 13.9in/s [104]. There are no identified studies that have verified this speed or how it may relate to normal human heel strikes.

APPENDIX C: Excerpts from Excel Spreadsheets Containing Speed Gate Experimentation Data

Machine #1 Angle = 90 degrees (0 degrees on gauge)

	15 psi	*25 psi*	*35 psi*
Mean	15.61	18.12	19.06
Standard Error	0.020	0.014	0.015
Median	15.59	18.14	19.03
Mode	15.57	18.11	19.14
Standard Deviation	0.158	0.112	0.114
Sample Variance	0.025	0.013	0.013
Kurtosis	0.544	-0.434	-0.553
Skewness	-0.016	-0.564	0.441
Range	0.75	0.47	0.49
Minimum	15.23	17.87	18.88
Maximum	15.98	18.34	19.37
Count	60	60	60
Confidence Level(95.0%)	0.0399	0.0283	0.0287
Upper Mean (95% CL)	15.65	18.15	19.09
Lower Mean (95% CL)	15.57	18.09	19.03

Machine #1 Angle = 70 degrees (20 degrees on gauge)

	15 psi	*25 psi*	*35 psi*
Mean	15.31	17.82	18.94
Standard Error	0.015	0.014	0.014
Median	15.31	17.83	18.95
Mode	15.31	17.83	18.98
Standard Deviation	0.118	0.111	0.107
Sample Variance	0.014	0.012	0.011
Kurtosis	0.818	2.351	0.182
Skewness	-0.032	-1.062	0.298
Range	0.64	0.59	0.54
Minimum	14.96	17.43	18.72
Maximum	15.60	18.02	19.26
Count	60	60	60
Confidence Level(95.0%)	0.0299	0.0280	0.0271
Upper Mean (95% CL)	15.34	17.85	18.96
Lower Mean (95% CL)	15.28	17.80	18.91

Machine #1 Angle = 50 degrees (40 degrees on gauge)

	15 psi	*25 psi*	*35 psi*
Mean	14.95	17.99	18.68
Standard Error	0.019	0.006	0.010
Median	15.00	18.00	18.70
Mode	15.00	18.02	18.74
Standard Deviation	0.148	0.048	0.075
Sample Variance	0.022	0.002	0.006
Kurtosis	0.410	0.107	-0.556
Skewness	-0.842	0.193	-0.582
Range	0.73	0.22	0.29
Minimum	14.50	17.90	18.51
Maximum	15.24	18.13	18.80
Count	60	60	60
Confidence Level(95.0%)	0.0376	0.0121	0.0189
Upper Mean (95% CL)	14.98	18.00	18.70
Lower Mean (95% CL)	14.91	17.98	18.66

Machine #2 Angle = 90 degrees (0 degrees on gauge)

	15 psi	*25 psi*	*35 psi*
Mean	22.02	21.96	22.00
Standard Error	0.009	0.032	0.027
Median	22.02	21.90	21.98
Mode	22.07	21.84	22.20
Standard Deviation	0.070	0.247	0.209
Sample Variance	0.005	0.061	0.044
Kurtosis	0.286	0.148	-0.452
Skewness	-0.499	0.510	-0.158
Range	0.31	1.21	0.89
Minimum	21.83	21.46	21.49
Maximum	22.14	22.67	22.37
Count	60	60	60
Confidence Level(95.0%)	0.0177	0.0626	0.0529
Upper Mean (95% CL)	22.04	22.02	22.05
Lower Mean (95% CL)	22.00	21.89	21.94

Machine #2 Angle = 70 degrees (20 degrees on gauge)

	15 psi	*25 psi*	*35 psi*
Mean	22.28	22.00	21.11
Standard Error	0.020	0.024	0.017
Median	22.28	22.04	21.09
Mode	22.26	22.06	21.07
Standard Deviation	0.158	0.187	0.128
Sample Variance	0.025	0.035	0.017
Kurtosis	6.157	1.499	-0.549
Skewness	-1.478	-0.451	0.442
Range	1.03	1.13	0.49
Minimum	21.56	21.39	20.89
Maximum	22.59	22.52	21.38
Count	60	60	60
Confidence Level(95.0%)	0.0399	0.0474	0.0325
Upper Mean (95% CL)	22.32	22.05	21.14
Lower Mean (95% CL)	22.24	21.95	21.07

Machine #2 Angle = 50 degrees (40 degrees on gauge)

	15 psi	*25 psi*	*35 psi*
Mean	22.15	21.26	21.46
Standard Error	0.036	0.019	0.026
Median	22.15	21.26	21.44
Mode	22.21	21.18	21.38
Standard Deviation	0.280	0.143	0.205
Sample Variance	0.078	0.021	0.042
Kurtosis	2.947	0.285	-0.418
Skewness	-0.629	-0.499	0.214
Range	1.70	0.74	0.88
Minimum	21.05	20.84	21.03
Maximum	22.75	21.58	21.91
Count	60	60	60
Confidence Level(95.0%)	0.0708	0.0363	0.0519
Upper Mean (95% CL)	22.22	21.30	21.51
Lower Mean (95% CL)	22.07	21.22	21.41

Machine #3 Angle = 90 degrees (0 degrees on gauge)

	15 psi	*25 psi*	*35 psi*
Mean	16.66	18.81	19.59
Standard Error	0.015	0.011	0.009
Median	16.65	18.81	19.58
Mode	16.62	18.73	19.57
Standard Deviation	0.116	0.088	0.068
Sample Variance	0.014	0.008	0.005
Kurtosis	-0.400	-0.073	0.409
Skewness	0.541	0.620	0.193
Range	0.45	0.40	0.33
Minimum	16.49	18.66	19.43
Maximum	16.94	19.05	19.76
Count	60	60	60
Confidence Level(95.0%)	0.0294	0.0222	0.0172
Upper Mean (95% CL)	16.69	18.84	19.60
Lower Mean (95% CL)	16.63	18.79	19.57

Machine #3 Angle = 70 degrees (20 degrees on gauge)

	15 psi	*25 psi*	*35 psi*
Mean	17.02	18.87	19.84
Standard Error	0.017	0.015	0.010
Median	17.03	18.86	19.84
Mode	17.14	19.02	19.84
Standard Deviation	0.130	0.115	0.079
Sample Variance	0.017	0.013	0.006
Kurtosis	-0.278	-1.104	0.198
Skewness	-0.223	0.240	0.321
Range	0.57	0.41	0.42
Minimum	16.70	18.70	19.68
Maximum	17.27	19.11	20.09
Count	60	60	60
Confidence Level(95.0%)	0.0329	0.0290	0.0201
Upper Mean (95% CL)	17.06	18.90	19.87
Lower Mean (95% CL)	16.99	18.85	19.82

Machine #3 Angle = 50 degrees (40 degrees on gauge)

	15 psi	*25 psi*	*35 psi*
Mean	16.42	18.71	19.95
Standard Error	0.013	0.013	0.015
Median	16.40	18.71	19.94
Mode	16.38	18.71	19.92
Standard Deviation	0.102	0.102	0.119
Sample Variance	0.010	0.010	0.014
Kurtosis	-0.927	-0.176	-0.229
Skewness	0.260	0.516	0.296
Range	0.37	0.43	0.53
Minimum	16.24	18.54	19.73
Maximum	16.61	18.96	20.26
Count	60	60	60
Confidence Level(95.0%)	0.0257	0.0259	0.0301
Upper Mean (95% CL)	16.44	18.74	19.98
Lower Mean (95% CL)	16.39	18.68	19.92

Machine #1 Anova:
15psi@90deg&15psi@70deg

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
15 psi @ 90 deg	60	936.3904	15.60651	0.024809
15 psi @70 deg	60	918.8024	15.31337	0.013971

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2.577814	1	2.577814	132.9451	4.63E-21	3.921478
Within Groups	2.288028	118	0.01939			
Total	4.865842	119				

Machine #1 Anova:
15psi@70deg&15psi@50deg

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
15 psi @70 deg	60	918.8024	15.31337	0.013971
15 psi @ 50 deg	60	896.8352	14.94725	0.022035

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	4.021307	1	4.021307	223.3693	5.45E-29	3.921478
Within Groups	2.124349	118	0.018003			
Total	6.145656	119				

Machine #1 Anova:
15psi@90deg&15psi@50deg

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
15 psi @ 90 deg	60	936.3904	15.60651	0.024809
15 psi @ 50 deg	60	896.8352	14.94725	0.022035

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	13.03843	1	13.03843	556.6798	1.7E-46	3.921478
Within Groups	2.76377	118	0.023422			
Total	15.8022	119				

Machine #1 Anova:
15psi@90deg&15psi@70deg&15psi@50deg

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
15 psi @ 90 deg	60	936.3904	15.60651	0.024809
15 psi @70 deg	60	918.8024	15.31337	0.013971
15 psi @ 50 deg	60	896.8352	14.94725	0.022035

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	13.0917	2	6.545852	322.9075	8.74E-60	3.047012
Within Groups	3.588074	177	0.020272			
Total	16.67978	179				

Machine #2 Anova:
15psi@90deg&15psi@70deg

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
15 psi @ 90 deg	60	1321.055	22.01759	0.004899
15 psi @70 deg	60	1336.739	22.27898	0.024829

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2.049785	1	2.049785	137.9025	1.45E-21	3.921478
Within Groups	1.753955	118	0.014864			
Total	3.80374	119				

Machine #2 Anova:
15psi@70deg&15psi@50deg

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
15 psi @70 deg	60	1336.739	22.27898	0.024829
15 psi @ 50 deg	60	1328.724	22.1454	0.078334

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.535324	1	0.535324	10.37819	0.001648	3.921478
Within Groups	6.086627	118	0.051582			
Total	6.62195	119				

Machine #2 Anova:
15psi@90deg&15psi@50deg

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
15 psi @ 90 deg	60	1321.055	22.01759	0.004899
15 psi @ 50 deg	60	1328.724	22.1454	0.078334

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.490069	1	0.490069	11.7758	0.000828	3.921478
Within Groups	4.910757	118	0.041617			
Total	5.400826	119				

Machine #2 Anova:
15psi@90deg&15psi@70deg&15psi@50deg

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
15 psi @ 90 deg	60	1321.055	22.01759	0.004899
15 psi @70 deg	60	1336.739	22.27898	0.024829
15 psi @ 50 deg	60	1328.724	22.1454	0.078334

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2.050118	2	1.025059	28.45748	1.92E-11	3.047012
Within Groups	6.375669	177	0.036021			
Total	8.425788	179				

Machine #3 Anova:
15psi@90deg&15psi@70deg

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
15 psi @ 90 deg	60	999.7662	16.66277	0.013504
15 psi @70 deg	60	1021.336	17.02227	0.016909

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	3.877206	1	3.877206	254.9729	2.87E-31	3.921478
Within Groups	1.794349	118	0.015206			
Total	5.671555	119				

Machine #3 Anova:
15psi@70deg&15psi@50deg

SUMMARY

Groups	Count	Sum	Average	Variance
15 psi @70 deg	60	1021.336	17.02227	0.016909
15 psi @ 50 deg	60	984.9381	16.41564	0.010309

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	11.04018	1	11.04018	811.2483	1.04E-54	3.921478
Within Groups	1.605847	118	0.013609			
Total	12.64602	119				

Machine #3 Anova:
15psi@90deg&15psi@50deg

SUMMARY

Groups	Count	Sum	Average	Variance
15 psi @ 90 deg	60	999.7662	16.66277	0.013504
15 psi @ 50 deg	60	984.9381	16.41564	0.010309

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1.832271	1	1.832271	153.8926	3.96E-23	3.921478
Within Groups	1.404928	118	0.011906			
Total	3.237199	119				

Machine #3 Anova:
15psi@90deg&15psi@70deg&15psi@50deg

SUMMARY

Groups	Count	Sum	Average	Variance
15 psi @ 90 deg	60	999.7662	16.66277	0.013504
15 psi @70 deg	60	1021.336	17.02227	0.016909
15 psi @ 50 deg	60	984.9381	16.41564	0.010309

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	11.16644	2	5.583218	411.3233	2.88E-67	3.047012
Within Groups	2.402562	177	0.013574			
Total	13.569	179				

BIOGRAPHICAL SKETCH

Henry Thomas Baker was born and raised at various military facilities throughout the country and oversees. He has three younger sisters and two younger brothers. Having attended four high schools over the four years, he graduated from Pulaski County High School, KY with no intent of pursuing higher education. After several years working in construction and low wage retail jobs he decided to give school another chance and enrolled at Florida Junior College in Jacksonville, FL. After transferring to Jacksonville University and then to Georgia Tech he earned a Bachelor's degree in Physics and a Bachelor's degree in Mechanical Engineering. Since graduating from college he has headed engineering teams and managed a variety of projects, capital improvements, and new product launches with companies like Maxwell House Coffee, Lummus Corporation, Hager Companies, and Hunter Fans. During that time he met and married his wife Gina. He has two children with the older one currently pursuing his engineering degree at FSU in Tallahassee, FL. Mr. Baker is a registered professional engineer in Florida and Alabama and resides in Ponte Vedra Beach, Florida. He works as a consulting engineer for CED Investigative Technologies.