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An Engineering Psychology Based Analysis of Ladder Setup Procedures

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AN ENGINEERING PSYCHOLOGY BASED ANALYSIS OF LADDER SETUP PROCEDURES

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Accepted by:
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ABSTRACT

Accidents involving portable ladders are a common cause of serious occupational and non-occupational injuries throughout the industrialized world. Many of these injuries could be prevented with proper education, training and usage of portable ladders. This research focused on the human factors and engineering aspects of portable extension ladder usage. Results and analysis revealed evidence of unsafe acts that could lead to catastrophic ladder slide-out accidents in real-life situations. Six ladder setup methods were evaluated based on placement angles: the Basic, 75 Degree, Stand-Reach, L Sticker, 4:1, and Level methods. The level method produced the most accurate results with the lowest variability. Setup methods varied in complexity and level of instruction. Additional investigation included determining the coefficient of friction of common ladder setup surfaces in clean and contaminated conditions. Based on known ladder setup angles and coefficients of friction, a detailed engineering analysis was performed to determine the total number of slide-out failures for each ladder setup method. Analysis of the overall results revealed the need for additional user training and education. Based on test subjects' setup angles, the ladder slide-out failure rate would have been 12.2 percent for ladders set up on a surface with the lowest measured coefficient of friction. When broken down by ladder setup method, the 4:1 Method had a failure rate of 18.8 percent, the 75 Degree Method had a failure rate of 15.2 percent, and the Basic Method had a failure rate of 9.8 percent. Overall results have been considered for modifications of existing ladder standards as well as areas of additional research.

ACKNOWLEDGEMENTS

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CHAPTER 1

INTRODUCTION

Ladders are one of the primary contributing factors to occupational injuries and deaths in this country as well as in other parts of the industrialized world. In 2008 the U.S. Bureau of Labor and Statistics reported 5,214 fatal occupational injuries, with 700 of those attributable to falls and 119 or 17 percent related to falls from ladders (Bureau of Labor Statistics, 2008). Countless other non-fatal ladder-related injuries and near misses also occurred. When used safely, ladders can be one of the most useful and practical tools that are readily available and are simple enough to use by most individuals. They are commonly used by a diverse range of people from homeowners to handymen to heavy industrial contractors for a variety of applications and uses. However, if not used safely, ladders can be attributable to a wide range of injuries from minor bruises to permanent disabilities and even death. Ladders are typically either portable, such as stepladders and extension ladders, or they may be permanently affixed to a structure. This paper focuses on the human factors of portable extension ladders and the various effects of changes in ladder stability and resistance to sliding caused by ground slope, setup angle, and contaminated surfaces.

Ladder falls and accidents can be classified into three primary categories: physical failure of the ladder or its supporting surface, improper usage of the ladder, and improper ladder selection. Statistics from the Census of Fatal Occupational Injuries for 1992 – 1999 show falls as the leading cause of death in construction. Falls from ladders during this period accounted for 14 percent of the total deaths (Burkhart et al; 2004). A study published by Creighton University (2003) based on statistics from the Occupational Safety and Health Administration and the Bureau of Labor Statistics revealed more than 15 percent of all worker compensation cases are related to ladder accidents. The number of ladder related injuries in the United States increased by more than 50 percent from 1990 to 2005 with more than 2.1 million people being treated in hospital emergency rooms during the same period. Approximately 10 percent of those injured required hospitalization and 77 percent of all injuries occurred to males (Preidt, 2007). According to the Consumer Products Safety Commission in the United States there were 164,000 emergency room visits related to falls from ladders in 2004, an average of 449 injuries per day (Berendsohn, 2005).

Industry Standards

Although some extension ladders are constructed of wood, most are constructed of aluminum or fiberglass and come in a wide variety of lengths and load ratings. Allowable working loads range from 200 pounds for light duty ladders to 375 pounds for special duty ladders. Available lengths range from 16 foot ladders comprised of two sections up to 60 foot ladders comprised of three sections. The working length of extension ladders is always less than the total length due to the overlap of each section that is required to develop stiffness when extended. Depending on the ladder size, the minimum required overlap ranges from 32 inches for 16 foot ladders to 70 inches for 60 foot ladders (American Ladder Institute, 2000).

The manufacturing, testing, and usage of portable extension ladders are guided by numerous industry standards including those published by the American Ladder Institute and the Occupational Safety and Health Administration (OSHA) Department of Labor. OSHA standards are published in the Code of Federal Regulations 29CFR1910.26 for general industry and 29CFR1926.1000 for construction. The American Ladder Institute Standard is a consensus standard approved by the American National Standards Institute (ANSI) and is published as ANSI A14.2 American National Standard for Ladders – Portable Metal – Safety Requirements.

The recommended ideal setup angle for extension ladders is approximately 75 degrees on a level surface (ANSI A14.2). This is readily achieved by setting the base of the ladder a distance from the wall equal to one fourth the working length of the ladder. All angles addressed in this paper will be considered as measured from the horizontal. The working length of the ladder is measured from the base, along the rails, to the point of support at the top. If the ladder is used to gain access to higher levels, when properly utilized it should be tied to the upper access level and extend approximately three feet above the point of support (American Ladder Institute, 2000).

Hypothetically, if an extension ladder is set up at the recommended angle of 75 degrees on a clean, level surface such as concrete, asphalt, brick, or wood, the factor of safety against slide-out at the base is approximately 2.9 to 3.4 based on static loading; however, the factor of safety typically decreases during dynamic loading as one climbs (Chang, Chang, Matz, and Son, 2004). The factor of safety is a dimensionless number and indicates the actual reaction forces at the base of the ladder are 2.9 to 3.4 times greater than the point at which the ladder may begin to slide. If the ladder is set up in a manner that has a factor of safety less than 1.0 at the base, the ladder will experience a slide-out failure. If the setup angle is reduced to 65 degrees the factor of safety decreases to a marginally safe range of 1.6 to 1.9 for static loading. Typical detrimental factors include selecting a setup angle that is too shallow (less than 75 degrees), setting ladders up on minor slopes, surfaces contaminated with moisture, or dynamic loading. Dynamic load conditions will occur with moving loads such as one ascending or descending the ladder. Minor changes to any of these factors can have negative effects on stability and safety.

The resistance to sliding of the base of a ladder on a clean, dry surface is a function of the static coefficient of friction, which is a measure of the roughness of a surface. The static coefficient of friction is the ratio of the force required to move an object laterally relative to its weight. The surface must be clean and dry to ensure that the measurement of the force required to move the object is a true static coefficient of friction. For surfaces contaminated with moisture or foreign debris, the coefficient of friction becomes a slip index because the ratio of the force required to move an object relative to its weight is altered due to the presence of contaminants on the surface (English, 2003). After the ladder begins to slide, the static coefficient of friction becomes a dynamic coefficient of friction as the ladder begins in motion. The corresponding dynamic value is usually approximately 25 percent less than the static value (Beer & Johnston, 1976). All values addressed in this paper, both coefficient of friction and slip index, are considered to be static values because the ladder and its associated forces will be analyzed in a stable, non-moving condition. However, the effects of dynamic loading of the ladder as one climbs will be considered, but at no time will the ladder be tested in a sliding condition.

Human Factors

A detailed study evaluating the human factors of ladders related to setup angles was performed by Young and Wogalter (2000). Sixty eight people, with a mean age of 37 including 41 females and 26 males (one was disqualified), participated in the study. More than half of the participants owned a ladder and the average usage was 2.1 times per year. Five of the participants reported being previously injured while using a ladder and 34 others knew someone who had been injured. The participants were instructed to set up a ladder using various methods to achieve the recommended angle of 75 degrees. There are various methods and heuristics that can be used to approximate the recommended ladder setup angle of 75 degrees. These include simply estimating the angle, using the 4:1 rule (length to base ratio), using a spirit level, applying the Stand-Reach Method, or the L Sticker Method approximation. The ‘L’ sticker is an ‘L’ symbol located on the side of some ladders that provides a visual aid to proper setup angle and the Stand-Reach Method consists of one placing their toes at the base of the ladder and extending their hands straight out until their fingertips touch the ladder.

Six setup conditions were evaluated including the basic condition with no instructions, along with the additional five listed above, for subjects to achieve an approximate setup angle of 75 degrees. Testing was performed using a 20 foot aluminum, portable extension ladder. The results revealed the shallowest angles were produced by the basic condition followed by the Stand-Reach, L Sticker, and 75 Degree approximation condition; these angles ranged from 66.9 to 71 degrees. The 4:1 Method resulted in a steeper angle of 73.4 degrees and the Spirit Level Method was steepest and most accurate at 75.7 degrees. Oddly, the authors knew that the industry standard and recommended setup angle is 75 degrees but reported they did not understand this objective or whether it is actually a good benchmark (Young & Wogalter, 2000). Further empirical research was recommended to substantiate this figure and to define the acceptable level of deviation. Further investigation of these conditions are some of the goals of the present research. Friction requirements related to climbing conditions for portable extension ladders were investigated and reported by Chang, Chang, Matz, and Son (2004). From the standpoint of friction, these investigators found that the angle of inclination of the ladder and the climbing speed were the two most important factors for stability. Based on their survey of industrialized countries, occupational accidents involving ladders occurred at a rate of one out of each 2,000 employees and approximately 40 percent of those suffering an injury were absent from work for more than one month and at least half experienced continuing and possible permanent disability. Many of these ladder accidents were the direct result of improper setup and sliding at the base.

The study by Chang et al. (2004) involved 16 different climbing conditions, randomized for each subject with five repetitions. The subjects climbed up a total of 10 rungs on the ladder for each trial. Dependent variables included the normal and shear forces measured at the bottom of the ladder at the floor interface. The coefficient of friction was determined instantaneously by dividing the shear force by the normal force. Precise measuring was performed with a force plate at a sampling rate of 100 Hz and a harness was used by subjects to prevent any accidental falls. Five different independent variables were considered including body weight, ladder setup angle, and climbing speed. The most influential factor was the angle of the ladder, followed by climbing speed and body weight, with the remaining two variables causing a minimal effect. The setup angle and climbing speed were the most important factors. The subjects' location on the ladder affected the required coefficient of friction by almost a factor of two from 1.23-2.34 from top to bottom, respectfully. The authors concluded that the setup angle of the ladder is a critical parameter and one that many users do not understand. The development of practical guidelines for users to properly set up ladders was recommended as an important intervention.

A study was performed by Dewar (1977) to evaluate body movement during ladder climbing for ladders set up at the 70 and 75 degree angles. During his investigation of 248 accident reports, 66 percent of the accidents occurred when the ladder slipped, either with subjects climbing or working on the ladder. He also reported that many ladders were commonly used at the shallower 70 degree angle rather than the recommended 75 degree angle, possibly because of a feeling of insecurity at the steeper angle related to falling backwards. From an anthropometric standpoint a ladder is designed for the average man but tall and short men or women may be required to modify their preferred movement which could also be a contributing factor to some injuries.

One of the more detailed studies took into account not only the setup angle of ladders but also the actual, rather than required, coefficient of friction at the base of the ladder. This study considered several of the factors that are analyzed in this study. Häkkinen, Pesonen, and Rajamäki (1987) reported that typical ladder accidents involving portable extension ladders occur when a ladder either slides away from the surface to be ascended concurrently as the base slides, or as a worker loses his balance. The most frequently reported mechanism was sliding of the base of the ladder. This study involved the use of a force plate, a common instrument used to measure shear and normal forces at the base of the ladder. However, it also involved a displacement transducer at the wall adjacent to the base of the ladder so that the actual coefficient of friction between the ladder base and the supporting surface could be measured. Contaminants such as water, oil, or sand were also introduced onto the supporting surface. Tests were performed at 65 and 75 degree angles with standard plastic feet and non-skid rubber. A variety of results was determined based on the various setup angles and material combinations. For the non-skid rubber feet, the results were good to satisfactory for clean surfaces and were at least marginal even with contaminated surfaces. However, for standard ladder feet the factor of safety was marginal, even for the clean surfaces, which is very concerning. A marginal coefficient of friction below 0.3 was reported to be dangerous, 0.3 - 0.5 marginal, 0.5 - 0.7 satisfactory, and above 0.7 was considered good. For comparison purposes, the coefficient of friction of most clean floors or ground surfaces is near or above 0.7 which is acceptable. As a point of further discussion the authors reported the setup angle of ladders by subjects ranged from a shallow angle of 57 degrees to the steepest angle of 76 degrees. The steepest setup angle barely reached the recommended setup angle of 75 degrees, and 57 degrees would be considered extremely shallow and dangerous under many conditions.

The contributing factors to ladder accidents, as well as the cause and extent of injuries, was studied at a community hospital emergency department in an archival study during the period from January 1993 to December 1995 (Partridge, Virk, and Antosia, 1998). A computerized search of the hospital database identified a total of 147 patients, of whom 59 met the selection criteria; 86 of these patients had injuries caused by other ladder related accidents related to lifting, tripping, or falling. Those who had fallen reported an estimated fall distance from one to 15 feet and various injuries ranging from sprains, to lacerations, broken bones, and one fatality caused by a massive subdural hematoma. Post-accident interviews with 42 of the 59 patients revealed that half of the injuries were occupationally related. Overall, ninety three percent were able to identify the cause of the falls with 45 percent attributing their accident to ladder placement and 33 percent to excessive reaching. Interestingly, more than half of the non-occupationally related accidents were related to incorrect ladder placement but only 38 percent of those who were occupationally related. Additionally, Partridge et al. (1998) opined that the greater degree of non-occupational injuries may be attributable to less training and experience in ladder safety. Only one patient reported someone was holding the ladder for them at the time of the fall. The authors concluded that more than 90 percent of the reported injuries related to ladder falls were preventable. Although the authors did not specifically cite how to reduce the injury rate, they did suggest that all ladders should be OSHA compliant (rather than just those in the workplace) and improved ladder safety training would be beneficial.

Based on a study by Björnstig and Johnson (1992), injuries in Sweden related to ladder usage are also quite prevalent. Approximately 5,000 to 6,000 non-occupational injuries requiring hospital care occur each year along with 2,000 occupationally related injuries. During a one year period, a study was performed at a regional hospital to analyze fall mechanisms and consequences of ladder related falls. Based on selection criteria 114 patients were identified and interviewed initially and at 1-2 years after the accident. The majority of the injuries occurred outdoors and were non-occupational including work around the home; occupational injuries primarily occurred at construction, industrial, or commercial sites, including hospitals. Portable extension ladders were the most prevalent within this study at 73 percent, with step ladders at 20 percent, and fixed ladders 7 percent. Portable extension ladders were involved in 77 percent of the non-occupational injuries and 65 percent in the occupational setting. The primary cause of the majority of these accidents was sliding at the base of the ladder caused by improper ladder setup even though the ladders were equipped with non-skid feet consisting of plastic or rubber in 59 percent of the instances. It was reported that although these ladders were equipped with various slide protection devices the friction properties varied widely. The authors determined that one's setup location of the ladder is critical. If a ladder is properly set up at 75 degrees and one is at the top of a 5 meter ladder, the friction requirements are 17 times greater than when one is at the bottom of the ladder. The estimated cost of medical care related to these injuries at the time of the study was $16 million, not including the cost of disability.

Ladder related injuries have been documented to be prevalent in Swedish and German occupational accidents at rates similar to those in the United States. Axelsson and Carter (1995) reported that nearly 2 percent of all occupational accidents in these two countries were ladder related. The authors have attempted to evaluate these accidents and determine measures to prevent future occurrences in the construction industry. Portable extension ladders were reported to be involved in 70 percent of the serious occupational ladder accidents and sliding at the base was attributable to 50 percent of those accidents. Non-slip rubber feet are the best mechanism to prevent sliding, but these benefits are diminished if the floor or ground surface is contaminated with a substance such as oil or water. Similarly, oil on the floor with only plastic feet was determined to be a bad combination. Accident report information was obtained from the Swedish Labour

Inspectoratex and 85 interviews were conducted with participants. A standardized questionnaire with nearly 70 questions requesting detailed information related to the accident including profession, ladder experience, setup angle, and ground/floor surface conditions was utilized. Results of the survey revealed that sliding at the base was attributable to 56 percent of the accidents and ladder setup angle was related to 49 percent. It was not reported but these two conditions are likely highly correlated. Although most falls were from a relatively low height, serious injuries still occurred. Regarding user education, none of the occupational users reported receiving any training regarding safe ladder usage although some were familiar with the risks of shallow setup angles. Information programs and training about safe ladder usage was recommended.

Based on this review of relevant information, it is apparent that many ladder users may not understand the proper methodology required to set up a ladder in a safe manner. Some users may have an even more limited understanding of the consequences of setting up a ladder at shallow angles on contaminated surfaces or slopes. It is hypothesized that some subjects will set up a ladder in at least a marginally unsafe manner if not given proper instruction. Without proper instruction, ladder setup angles will be less than 75 degrees. When engineering analysis is performed, results will likely reveal the combination of factors that can cause ladder slide-out failures. The theoretical ideal setup angle for a ladder is 75.5 degrees and for purposes of this study 75 degrees will be utilized. Subjects will be asked to set up a ladder and will also be given a knowledge questionnaire.

The approach of this study will include preference, perception, and human factors that are based on setup angle selection combined with a detailed engineering analysis that includes coefficient of friction testing. The results will be combined to determine the ideal safe setup angle for a portable extension ladder used under a variety of conditions. Previous research such as that by Young and Wogalter studied preferred ladder setup angles but did not include an engineering analysis. Additionally, research by Chang et al., Dewar, and Häkkiner et al. performed studies that were specifically more engineering based. However, none of the studies combined human factors' based results with an engineering analysis using actual ladder shoes to evaluate resulting load combinations and conditions. Therefore, data from the human factors and coefficient of friction testing will be evaluated and incorporated into an engineering analysis to arrive at final conclusions and recommendations. These results will be compared to previous findings.

CHAPTER 2

METHODS

Overview

This study utilized two different methods of testing: human factors and also engineering analysis that included coefficient of friction measurements. Human factors based testing for Experiment 1 involved 92 Clemson University students performing various combinations of ladder setup tasks. Experiment 2 incorporated the human factors results into an engineering model to evaluate the level of risk of the test subjects based on setup angles, loading, and coefficient of friction. Coefficient of friction measurements were obtained using two different test procedures to measure the coefficient of friction of three common surfaces.

Participants

This phase of the study was performed with 92 Clemson University graduate and undergraduate students consisting of 24 males and 68 females. All participants were physically capable of performing this study with no known limitations that would affect their ability to complete the required testing or affect their associated results. All students signed an informed consent agreement explaining the study before participating. Each experimental session lasted approximately 30 minutes and all subjects were tested independently of the other participants. At the completion of the testing a questionnaire was administered to survey their understanding of ladder concepts and ladder related procedures. Test subjects were also asked if they had previously taken classes in calculus, trigonometry, or physics. The purpose of this specific question was to ascertain any previous academic training in subjects that may have provided an advanced understanding of approximating the coefficient of friction, sliding forces, and angles. All students were debriefed at the completion of testing. Course credit was provided through the Clemson Psychology Department in accordance with departmental guidelines.

Experiment 1: Human Subjects

Equipment

Testing for Experiment 1 required the use of a 16 foot portable aluminum extension ladder manufactured in accordance with ANSI A14.2. The subject ladder for these experiments was manufactured by Werner Ladders. Ladder setup angles were measured with a digital level capable of measuring angles to the nearest 0.1 degree. The level was certified accurate +/- 0.1 degree. Testing accuracy with a second digital level confirmed this to be correct. A retractable metal tape was used to take anthropometry measurements as necessary for the Stand-Reach Method. Additionally, a small removable spirit level was used for the Level Method.

Procedure

Prior to performing any testing, a suitable test area was identified on campus. A relatively level, open, grassy area at the base of the west wall of Rhodes Engineering Center was selected because of its ideal conditions. This location included a tall brick wall well above the height of the ladder with no window openings or obstructions (see Figure 2.1). The area was relatively secluded with no vehicle traffic, minimal foot traffic, and limited distractions. No overhead power lines or safety hazards were within the vicinity of the testing location. Participants were directed to set up a 16 foot portable aluminum extension ladder using three required methods and one of three optional methods for a total of four different setup methods. For each of the setup methods a digital level was used to measure ladder setup angles to the nearest 0.1 degree and experimenter comments were recorded on the questionnaire at the completion of testing. The ladder was reset to a neutral angle prior to the administration of each method.

Figure 2.1

Ladder setup procedures included the Basic, Level, 75 Degree, 4:1, Stand-Reach, and L Sticker Methods. All 92 test subjects performed the Basic, Level, and 75 Degree Methods. The group of 92 test subjects was subdivided into three separate subgroups of 32, 30, and 30. The 4:1, Stand-Reach, and L Sticker Methods were optional methods performed by the subgroups of 32, 30, and 30 test subjects, respectively. In order to eliminate any learning effects, it was necessary for the order of the ladder setup procedures to be the same for all test subjects. The Basic Method was first, 75 Degree Method was second, one of the three optional methods third, and the Level Method was last. Test subjects were not aware that 75 degrees was the target angle until they were informed at the conclusion of testing. After each individual test method was completed, the experimenter adjusted the ladder to a completely different angle until testing for each of the four selected methods was completed. Adjusting the angle assured that test subjects would begin each test at a new angle. Assistance was provided by the experimenter as needed for safety to lift and fully extend the ladder at the beginning of testing. While some ladder instructions remained visible on the ladder rails, during testing close attention was paid to ensure test subjects did not attempt to read these instructions. Descriptions of each of the six test methods are described as follows:

Basic Method

All 92 participants performed the Basic Method first with limited instructions. The experimenter assisted each participant to lift and fully extend the ladder without rotating it toward the wall for placement. Test subjects were instructed to place the ladder against the wall at the desired angle they preferred in the same manner as if they were performing a ladder related task at their home; no additional instructions were provided. At this time, test subjects rotated the ladder toward the wall for placement and proceeded to adjust the ladder setup angle without assistance. Errors such as setting the ladder up backwards (if rotated the wrong direction) or upside down were noted. If a setup error occurred, participants were advised at the completion of this test so that it did not carry through to subsequent test methods.

75 Degree Method

All 92 test subjects performed this method. Each participant was instructed to place the ladder against the wall at what they perceived to be a 75 degree angle, measured from the ground.

4:1 Method

32 of the participants were tested individually based on written instructions describing the 4:1 Method. Test subjects were required to set the ladder up based on a height to base ratio of 4:1 in accordance with written instructions provided by the experimenter. An excerpt from the instructions is shown in Figure 2.2.

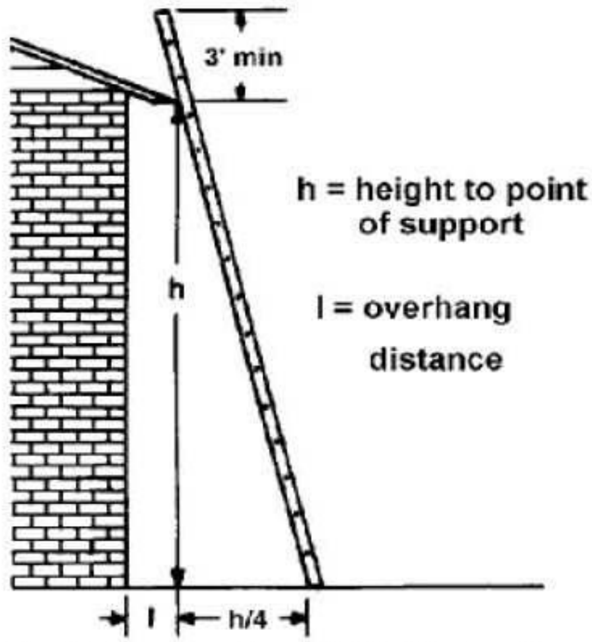


Figure 2.2. The base of the ladder should be placed at ¼ of the height (h) from the point of support on the wall. (Ladder Safety, 2007)

Stand-Reach Method

30 of the participants were tested individually based on the written instructions on the side rail of the ladder. These instructions are the consensus industry standard as specified in ANSI A14.2-2000. The instructions come standard as a diagram permanently affixed on most new ladders (see Figure 2.3). At the completion of the testing for this method, shoulder height and length of arm from center of shoulder to center of palm was measured and recorded. Errors related to improper hand and/or foot placement were noted.

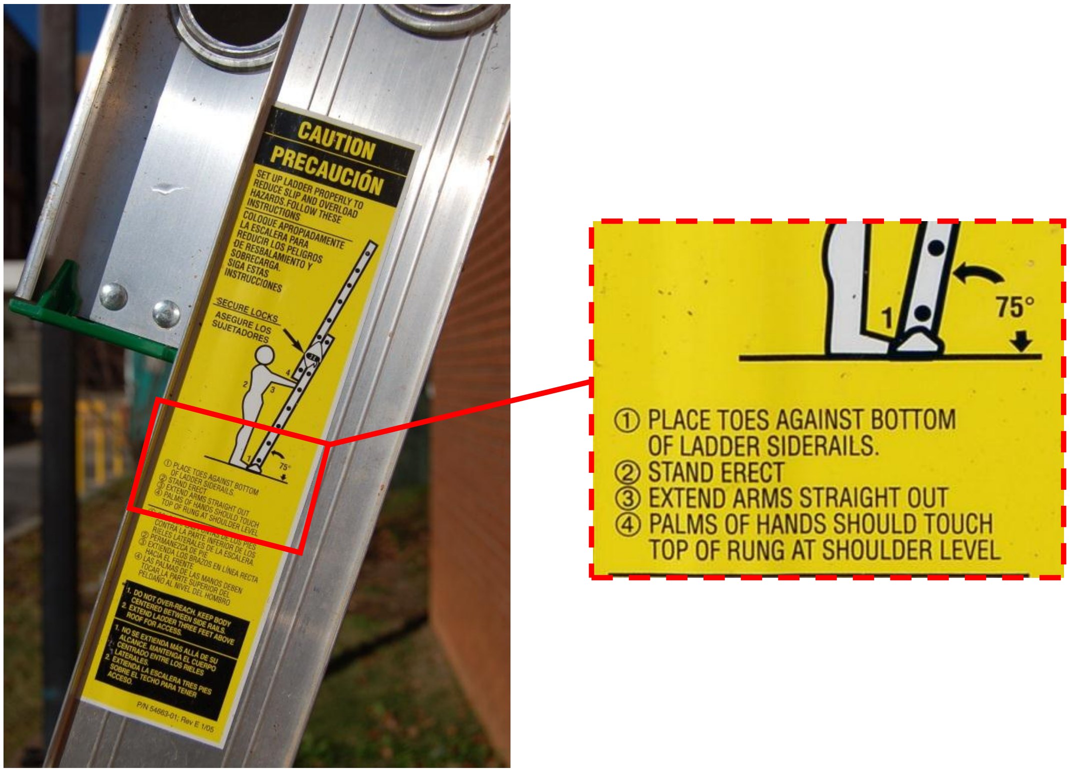


Figure 2.3.

L Sticker Method

30 of the participants were tested individually using an L Sticker visual aid and the associated written instructions. This method of ladder setup was quite common prior to adoption of the Stand-Reach Method. A standard L Sticker was recreated from an actual L Sticker on an older ladder manufactured prior to the adoption of the Stand-Reach Method. A picture was taken of the L Sticker, the image was printed, and then laminated. During this test, the L sticker was temporarily attached at the proper angle to the side rail of the ladder with Velcro. See Figure 2.4 for actual L Sticker from working ladder.

Figure 2.4.

Level Method

A small spirit level was affixed to the side of the ladder at approximately eye level (see Figure 2.5). All 92 participants were instructed to set the ladder up at 75 degrees by centering the bubble of the spirit level. This method was always performed last by all participants. Each test subject was asked if they were familiar with the use of a spirit level; all participants answered affirmatively and no additional instructions were required. When properly used and the bubble centered, the level afforded participants a visual aid to assist them to obtain a setup angle at or near 75 degrees, subject to the precision of the instrument. To verify accuracy of the spirit level, its placement at the correct angle on the ladder was verified with the digital level prior to participant testing.

Figure 2.5.

At the completion of the Level Method testing, a questionnaire was administered to all test subjects. Questionnaires for all methods had 18 questions with the exception of the Stand-Reach questionnaire that had three extra questions related to anthropometry. The range of questions covered experience and knowledge related to ladder usage as well as a survey of test subjects' opinions related to the various ladder setup methods. Ladder setup related questions asked test subjects to rate the method they deemed easiest and also the method that gave them the most confidence with respect to accuracy for the target angle of 75 degrees.

Experiment 2: Engineering Analysis

Coefficient of friction testing was performed to determine the slip resistance of three common ladder setup surfaces – wood, concrete, and asphalt. In order to obtain accurate results directly applicable to real-world ladder conditions, a standard pair of new ladder shoes provided by Werner Ladder Company, Greenville, Pennsylvania was attached to a rigid steel frame for test purposes (see Figures 2.6 - 2.7). In contrast, industry-standard coefficient of friction testing is usually performed with a neolite (rubber) pad to determine the slip resistance of footwear. Therefore, the modified ladder shoe assembly provided results representative of actual ladder shoes rather than a different material (such as neolite) which may provide results more representative of common footwear.

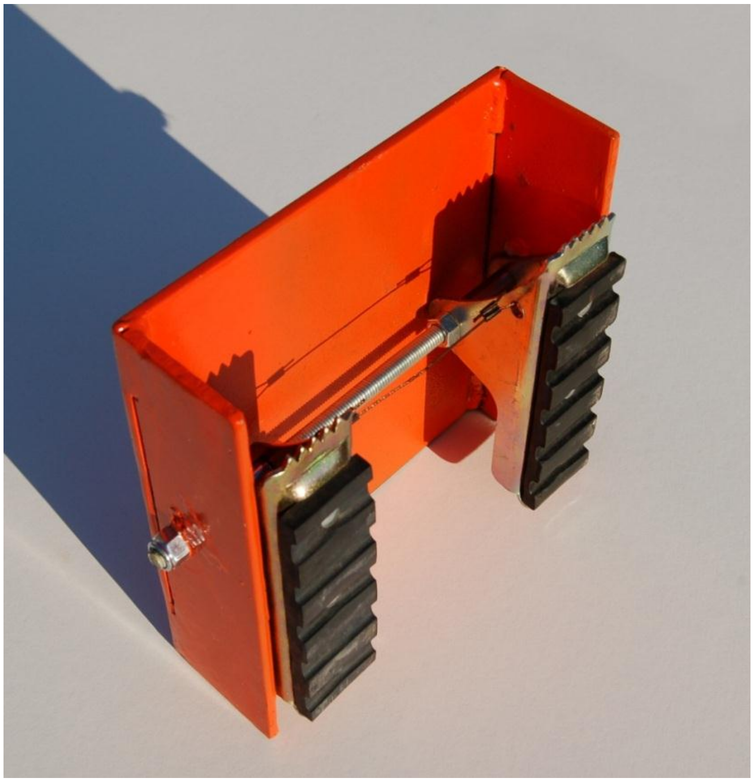


Figure 2.6. Actual ladder shoes were attached to a frame to be used for coefficient of friction testing.

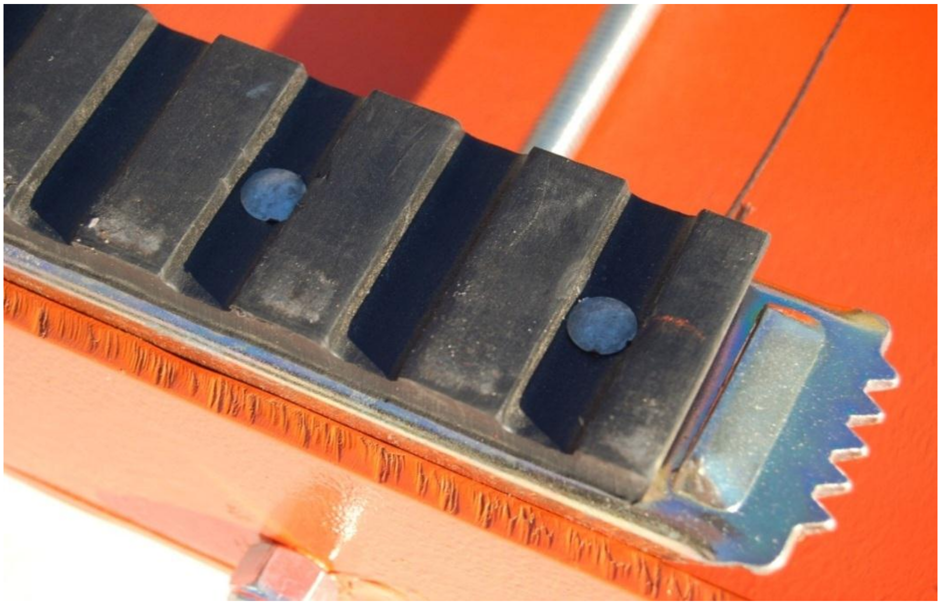


Figure 2.7. Close-up view of typical ladder shoe and spur plate for penetrable surfaces.

In addition to testing with the modified ladder shoe assembly, coefficient of friction testing of the three surfaces (concrete, asphalt, and wood) was also performed using two of the more common methods used in the industry. The first method was performed in accordance with ASTM C-1028 *Standard Test Method for Determining the Static Coefficient of Friction of Ceramic Tile and Other Like Surfaces by the Horizontal Dynamometer Pull-Meter Method*. All testing was performed as specified on uncontaminated concrete, asphalt, and wood to obtain baseline values. Additional testing was performed on all surfaces by substituting the modified ladder shoe frame in place of the standard neolite pad and plate (see Figure 2.8).

Figure 2.8. The ladder shoes and frame were modified to create a horizontal dynamometer pull-meter for coefficient of friction testing on a variety of surfaces. This procedure is in general accordance with ASTM C-1028.

The second industry standard method utilized was ASTM F-1679 *Standard Test Method for Using a Variable Incidence Tribometer* (see Figure 2.9). “The variable incidence tribometer is designed to determine slip resistance of walkway surfaces or surrogates and footwear bottom materials or surrogates under field or laboratory conditions so that their slip resistance properties may be evaluated” (American Society of Testing and Materials, ASTM F-1679, 2004, p. 1). The purpose for testing in accordance with ASTM F-1679 in addition to ASTM C-1028 was to measure the actual coefficient of friction values using a standardized procedure to compare those values with the ladder shoe assembly. The ASTM F-1679 method was performed as specified.

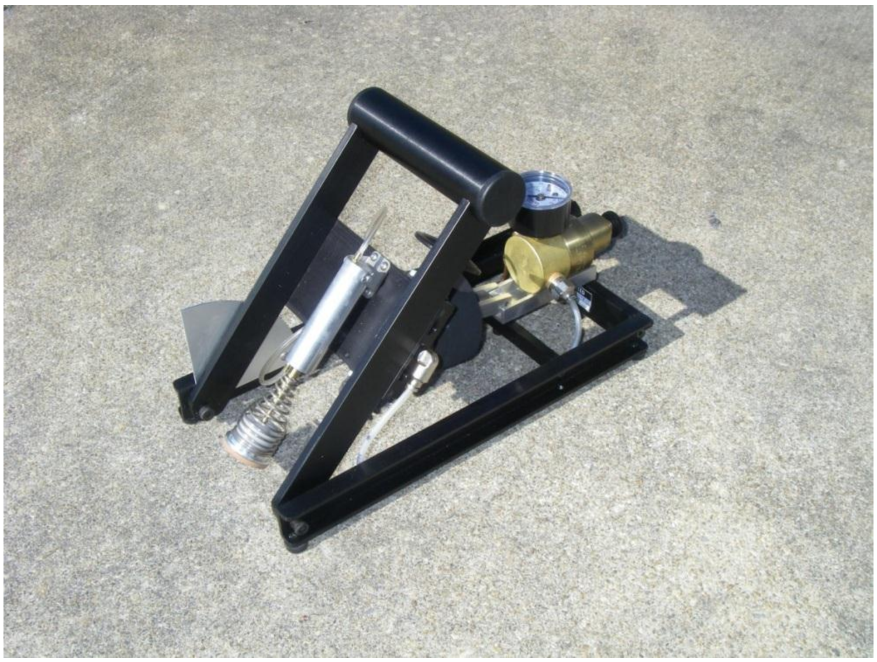


Figure 2.9. Variable incidence tribometer (VIT) for additional coefficient of friction testing.

All three surfaces were tested under the following conditions: clean/dry, clean/wet, dry/sand only, and wet/sand. A 12 inch x 16 inch test area was measured for testing the concrete and asphalt surfaces. The wooden surface was one side of an 8 x 8 wooden post and measured approximately 8 inches by 16 inches. See Figure 2.10 for a view of each test surface and the various test conditions.

Prior to testing in a clean/dry condition, the dry surface was brushed clean with a stiff bristle brush. To add dry sand, approximately one ounce of oven dry sand complying with ASTM-C33 *Standard Specification for Concrete Aggregates* was spread uniformly across each surface before testing (ASTM-C33). For wet testing, the dry sand was swept away and approximately a half gallon of potable water was poured across the surface until it was saturated. The wet/sand surface was created by saturating approximately one ounce of sand and spreading it uniformly across the previously saturated, clean surface. Testing was performed in accordance with the prescribed methods; values were recorded for each condition.


Clean/dry concrete


Dry concrete with sand


Wet concrete


Concrete with wet sand


Clean/dry asphalt


Dry asphalt with sand


Wet asphalt


Asphalt with wet sand


Clean/dry wood


Dry wood with sand


Wet wood


Wood with wet sand

Figure 2.10. Photographs of test surfaces.

An engineering analysis of the ladder forces was performed based on the results of the human factors and coefficient of friction testing to determine the resistance to sliding of the 16 foot portable aluminum extension ladder. Analysis was performed based on ladder setup angle, slip resistance and varying load conditions with a 200 pound user. All analysis was performed in accordance with accepted engineering principles.

A mathematical model was constructed of the ladder with supports at the top, to simulate a wall or roof eave, and at the bottom, to simulate the ground. Point loads were modeled along the length of the ladder to simulate loads related to a person ascending and descending the ladder. Reactions at the base of the ladder were recorded for these load conditions. The model reflects the angle at which the ladder was set up and was adjusted to determine the cause and effect of different load placements and setup angles. Reactions at the base are dependent on the angle of the ladder, the location of the point loads on the ladder, and the dimensions of the ladder. As an individual ascends or descends the ladder, reactions at the top and bottom of the ladder will change. For each ladder configuration, an engineering analysis was performed by modeling a subject climbing from the bottom to the top rung of the ladder.

CHAPTER 3

RESULTS

Experiment 1: Human Subjects Testing

Ladder setup testing was carried out by 92 test subjects utilizing the Basic, 75 Degree, and Level Methods. The within-subjects results are shown in Figure 3.1. A summary of the results of all testing is shown in Table 3.1. Overall results included three Z scores greater than $\pm$ 3. Analyses were performed with and without these results. Overall results did not change; therefore, no test results were deleted. A within-subjects ANOVA was performed to compare the results of this testing. Mauchly's test of Sphericity was significant ($p < 0.01$) and therefore, Huynh-Feldt degrees of freedom corrections were applied as necessary (Huynh & Feldt, 1976). Overall results for the within-subjects ANOVA revealed that method did have a significant effect on ladder setup angle F $(2,182) = 10.63$, $\eta_p^2 = 0.105$, $p < 0.05$. Bonferroni-corrected pairwise comparisons were conducted to examine mean differences in ladder setup angle. The mean setup angle for the Basic Method was not significantly different from the 75 Degree Method; however, the mean setup angle for the Level Method was significantly different from both the Basic and 75 Degree Methods, t (91) = - 4.60, $p < 0.01$ and t (91) = - 3.98, $p < 0.01$, respectively.

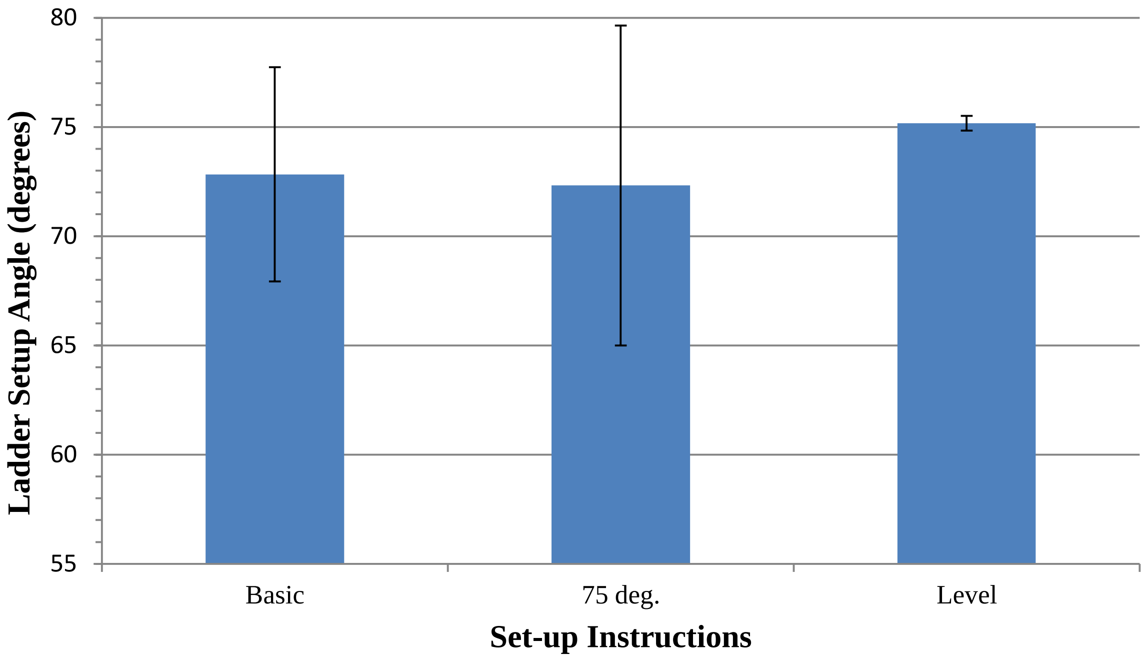


Figure 3.1. Mean angles and standard deviation at which the subjects placed the ladder for each of the three within-subjects conditions.

Table 3.1. Summary Chart of Ladder Angles from Test Subjects.

Method	n	*Mean Setup Angle* (Degrees)	Cohen's d[a]	*SD*	Range (Degrees)
Basic	92	72.6*	0.49	4.90	59.3 - 81.8
75 Degree	92	72.2*	0.39	7.13	47.6 - 85.8
Level	92	75.2*	0.59	0.34	73.7 - 75.9
4:1	32	70.1*	1.00	4.87	57.8 - 79.1
Stand-Reach	30	76.2	0.33	3.64	70.6 - 82.9
L Sticker	30	71.7*	0.98	3.36	63.7 - 77.7

*Mean ladder setup angle for this category of subject differs from test value of 75 degrees, $p < .01$.
[a]Significant results for the Level Method may be attributable to Cohen's d.

To evaluate the performance of individual test subjects, a correlation matrix was prepared based on the results of the within subjects analysis, as shown in Table 3.2. A resulting positive correlation should indicate that poor angle estimation in one method would also result in poor angle estimation in another method. Results revealed that the 75 Degree Method had a positive correlation with the Basic Method, $r = 0.222$ ($p < 0.05$), and the Level Method, $r = 0.324$ ($p < 0.01$). High scores on the 75 Degree Method were associated with high scores using the Level and Basic Methods. There was no correlation between the Basic Method and the Level Method, $r = -0.034$ ($p = 0.749$).

Table 3.2 Correlation Matrix of Within-Subjects Analysis.

Method		Deg75	Level
Basic	Pearson Correlation	.222*	-.034
	Sig. (2-tailed)	.034	.749
	N	92	92
Deg75	Pearson Correlation		.324**
	Sig. (2-tailed)		.002
	N		92

*Correlation is significant at the 0.05 level (2-tailed).
**Correlation is significant at the 0.01 level (2-tailed).

Between-subjects testing was carried out to compare the 4:1, Stand-Reach, and L Sticker setup Methods. Mean angles at which the subjects placed the ladder for each of the three between-subjects conditions are shown in Figure 3.2. These three methods were performed by 32, 30, and 30 test subjects, respectively. Levene's test of equality of error variances was not significant ($p = 0.086$), and therefore, the homogeneity of variance assumption was satisfied. Results from between-subjects testing revealed that optional setup method did have a significant effect on ladder setup angle F (2,89) = 18.76, η_p^2 = 0.297, $p < 0.05$. Bonferroni-corrected pairwise comparisons were conducted to examine mean differences in optional ladder setup method. The mean setup angle for the 4:1 Method was not significantly different from the L Sticker Method; however, mean setup angle for the Stand-Reach Method was significantly different from both the 4:1 and L Sticker Methods, t (31) = - 7.07, $p < .01$ and t (29) = - 7.328, $p < 0.01$, respectively. Additionally, all results from the between-subjects testing were compared to the results of the Basic Method from the within-subjects testing. The L Sticker Method was not significantly different ($p = 0.163$) from the Basic Method but the 4:1 Method t (31) = - 2.869, $p < 0.05$ and the Stand-Reach Method t (29) = 5.432, $p < 0.01$ were significantly different from the Basic Method.

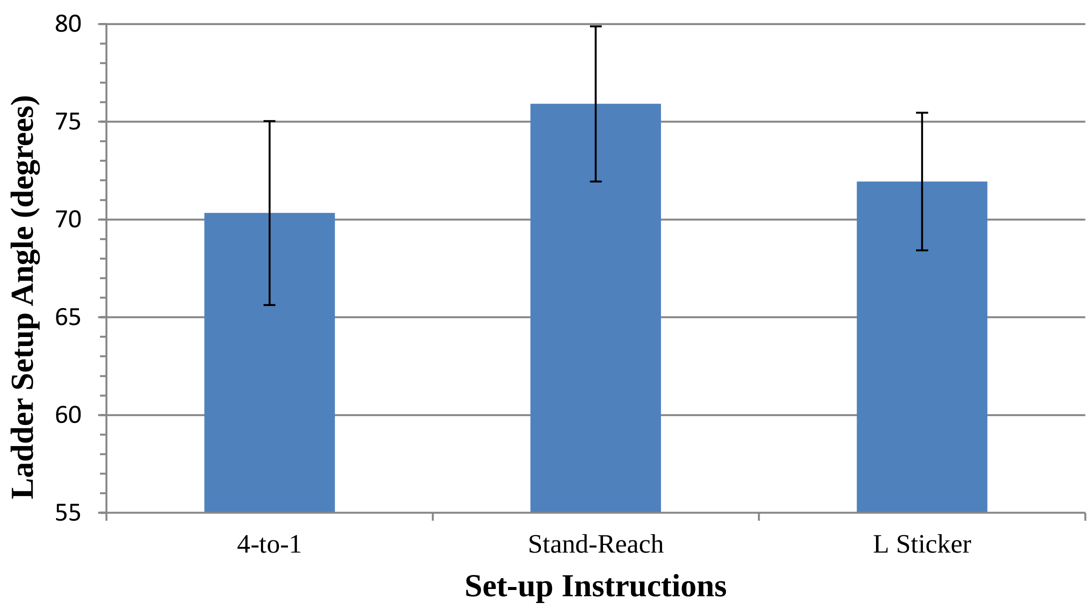


Figure 3.2. Mean angles and standard deviations at which the subjects placed the ladder for each of the three between-subjects conditions.

Questionnaire Responses

Responses from test subjects revealed that they found the Level Method to be the easiest and that they were also most confident with the results of this method. This response corresponds directly to the highest accuracy and lowest variability of the Level Method mean setup angles. The Basic Method yielded the least favorable responses for both questions. Low scores for the Basic Method may be related to minimal guidance and the absence of any visual aids or standard procedures. Although the questionnaires were subjective, the responses correspond to the results obtained from the various methods of ladder setup testing. Setup testing revealed the most accurate results were obtained by the Level Method and the test subjects found this method to be the easiest and they were also most confident with the results. Respondents provided rankings from one (best) to four (worst) for both questions; tabulated results are shown in Table 3.3.

Table 3.3. Mean ratings of questionnaire responses and standard deviations for each of the response modes in the experiment.

Question	Basic *Mean* (*SD*)	75 Degree *Mean* (*SD*)	Level *Mean* (*SD*)	4-1 *Mean* (*SD*)	Stand-Reach *Mean* (*SD*)	L Sticker *Mean* (*SD*)
Easiest	3.23 (0.94)	2.76 (0.75)	1.24 (0.58)	3.0 (0.95)	2.34 (0.94)	2.67 (0.88)
Most Confident	3.41 (0.92)	2.84 (0.70)	1.23 (0.65)	2.63 (0.94)	2.34 (0.86)	2.40 (0.72)

Subjects who had taken classes in calculus, physics, or trigonometry did not achieve better results than those who did not. Results for test subjects who had taken some or all of these classes were significantly different and lower than the target angle of 75 degrees while those who had not taken these classes were not significantly different.

Additionally, subjects were asked to self-rate their level of experience with ladders as either low, medium, or high. Only subjects who considered themselves to have a high experience level did not have ladder setup angles that were significantly different from 75 degrees. Typical examples of subjects that may fit into this category were those who had previously worked in a job that required ladder usage or who had a parent who worked in a construction-related trade. Results from between-subjects testing revealed that experience did have a marginal effect on ladder setup angle, $F(2,89) = 3.079$, $\eta_p^2 = 0.065$, $p = 0.051$. Similarly, Low Experience was marginally different from High Experience ($p = 0.046$). Tabulated results and a summary of the analysis are shown in Table 3.4.

Table 3.4. Questionnaire Response/Education and Experience.

	n	Angle	*SD*
Yes (C, P, T)[a]	83	73.07*	2.70
No (C, P, T)[b]	9	73.98	5.47
Low	29	72.54*	3.23
Medium	53	73.11*	2.78
High	10	75.24	3.28

C, P, T[a] = Test subject has taken classes in calculus, physics or trigonometry.
C, P, T[b] = Test subject has not taken classes in calculus, physics or trigonometry.
*Mean ladder setup angle for this category of subject differs from test value of 75 degrees, $p < .01$.

Discussion

For the within-subjects testing, the Basic and 75 Degree Methods were the least accurate and had the greatest variability. When performing these two methods test subjects had minimal guidance and almost total freedom to select a ladder setup angle; setup angles were based on personal preference (set the ladder up as you prefer) and perception (set the ladder up at 75 degrees), respectively. Additionally, they did not have the visual aids, guidance, or tools afforded by the remaining four methods. As predicted, when the ladder setup angle was left to the participants' own preferences using the Basic Method, the mean ladder setup angle was less than 75 degrees. However, the Basic Method did not produce the shallowest setup angle as expected. The 75 Degree Method had the lowest mean setup angle and it also had a larger standard deviation than any of the other methods.

The Basic and 75 Degree Methods were first and second in sequence, respectively. Observations during this initial testing revealed that many test subjects had limited knowledge and experience with ladders and appeared to be confused. Confusion and lack of experience was evidenced by setups where the ladder was either upside down or turned around backwards (16/92 = 17.4%). After the initial setup, subjects were advised of the error and it was corrected so as not to interfere with later results. Additionally, when portable ladders are set up on soft surfaces such as grass and soft ground, the spur plate should be engaged as shown in Figure 3.3. This procedure was not exercised by any of the test subjects (0/92 = 0%). These observations and findings would suggest a fundamental lack of knowledge regarding ladder safety and setup angles.

The Level Method, as predicted, was by far the most accurate of all methods utilized to achieve a setup angle closest to 75 degrees and it had the lowest variability, meaning that the subjects had the most accurate and consistent setup angles in this condition. From a practical standpoint, the Level Method substantially eliminated confusion, guessing, or estimation thus the lower variability. The small spirit level affixed to the side rail of the ladder during the Level Method testing provided a highly accurate, yet simple, visual aid.

Figure 3.3.

The 4:1 Method yielded the lowest mean setup angle of the six methods and a relatively large standard deviation. The mean setup angle of 70.13 degrees using this method was almost five degrees lower than the recommended target of 75 degrees. One of the issues related to this setup method was also related to an understanding of angles and geometry. Follow-up questioning at the end of testing revealed that test subjects erroneously assumed the vertical component of the height to the contact point on the wall was 16 feet because the ladder was fully extended. However, a fully extended 16 foot ladder has a partial overlap of the two rails and three rungs for rigidity, and therefore, is only approximately 13 feet long when fully extended. Many subjects also did not take into consideration the additional reduced vertical dimension of the ladder caused by the angled setup. Using the ratio produced by many of the participants' actual ladder setup angles of approximately 12:4 (3:1), versus their erroneously assumed ratio of 16:4 (4:1), may be the reason this method yielded the lowest setup angle. Based on this scenario, the lesser the vertical component (height of ladder at wall), the shallower the setup angle becomes.

Other than the Level Method, the Stand-Reach Method yielded the closest ladder setup angle to the target of 75 degrees. This method is the predominant procedure currently endorsed by the American Ladder Institute and the ladder industry (ANSI A14.2). A diagram and written instructions for this method are affixed to the side rail of all recently manufactured ladders. Written instructions on the side of the ladder are posted in English and Spanish.   Users are instructed to "1) place toes against bottom of ladder side rails, 2) stand erect, 3) extend arms straight out, and 4) palms of hands should touch top of rung at shoulder level". However, five of the test subjects for this method (16.7%), reported they were confused by this method because the image depicted on the side of the ladder shows a blunt appearance of the feet against the ladder side rails. It was their interpretation they were being instructed to place their feet under the center-line of the rungs rather than butting the tips of their toes into the ladder shoes at the base of the ladder even though this was contrary to the instructions. If one followed this erroneous interpretation, it generally yielded a shallower ladder setup angle.

Eight test subjects (26.7%) also made additional errors with the Stand-Reach Method such as placing their feet several inches away from the base of the ladder, not fully extending their arms, or touching the ladder rung only with their finger tips and not their palms. These errors appear to be attributable to confusion and improper interpretation. For those test subjects that did not fully extend their arms, they were simply adjusting their arms in a bent condition to match the angle of the ladder rather than adjusting the angle of the ladder to their fully extended arms. Therefore, although the mean ladder setup angle results for this method appear at face value to be quite accurate, a closer look at the setup errors and range of angles revealed it only yielded a mean value that happens to be close to 75 degrees as compared to the minimum value of 70.6 degrees and the maximum value of 82.9 degrees. Considering that some of the ladder setup angles for this method were over 80 degrees, there would generally only be a minimal danger of a slide-out failure, but this condition could ironically contribute to a tipping failure. Part of the inaccuracy of this method was attributable to the test subjects' confusion and failure to properly understand or interpret the instructions.

Although the Stand-Reach Method was the only procedure that did not yield results that were significantly different from the target angle of 75 degrees, the general applicability of these results may be considered somewhat suspect due to the large range and numerous setup errors that were observed. Therefore, calculations were performed based on the anthropometry of the test subjects in order to determine what their actual ladder setup angles would be if they had properly performed the Stand-Reach Method. These calculations were performed using trigonometry and required minor dimensional adjustments to account for the misalignment of the center-line of the ladder rail and the proper placement of the subjects' feet. The adjustments involved simply shifting the location of the test subjects' stance toward the ladder in a manner that aligned their feet with the center-line of the ladder rail and rungs based on shoe size and arm length. Dimensional adjustments were then made as necessary to perform the calculations. Final calculations revealed projected proper setup angles near 75 degrees and a narrow range of 72.6 degrees to 75.8 degrees. These calculations are similar to earlier results by Irvine and Vejvod (1977) who also found that Stand-Reach results based on anthropometric data will be less than 75 degrees; however, results from Clemson test subjects were closer to the target angle of 75 degrees. Further analysis revealed there is likely a logical explanation for this variance. The ratio of shoulder height to arm length of the test subjects that performed the Stand-Reach Method ranged from 2.11 to 2.41; the minimum angle of 72.6 degrees coincided with the 2.11 ratio and the maximum angle of 75.8 degrees coincided with the second highest ratio of 2.34. A summary of the anthropometric data obtained from the test subjects is shown in Table 3.5. A correlation matrix was run to compare test subject ladder setup angles and setup angles calculated from anthropometric data. Results were not significant ($r = 0.093$, $p = 0.624$) and there was no evidence of a correlation between the two Stand-Reach Methods.

Table 3.5. Anthropometric Data Summary.

	n	*Mean* (inches)	*SD*	Range (inches)
Arm Length	30	24.78	1.4	22.50 - 29.50
Shoulder Height	30	55.95	2.74	52.00 - 65.25
Shoulder Height / Arm Length Ratio	30	2.26	0.075	2.11 - 2.41

The L Sticker Method yielded relatively accurate ladder setup angles but was still significantly different than the recommended setup angle of 75 degrees. However, the range of values between 63.7 degrees and 77.7 degrees for subjects using this method is extreme. This method uses a visual aid affixed to the side rail of the ladder shaped like the letter ‘L’. The purpose of this symbol is to guide users to an approximate ladder setup angle of 75 degrees. Interviews with test subjects after completing their setup revealed several problems with this method. Four test subjects (13.3%), found it confusing and three others (10.0%) reported it gave them a distorted image. To be used properly, the ladder must be oriented in such a manner that the upright leg of the 'L' is vertical and the short leg of the 'L' is horizontal. Based on the orientation and alignment of the 'L' sticker on the ladder rail, this exercise should yield an approximate ladder setup angle of 75 degrees, if properly performed. However, three subjects (10%) reported it was difficult to properly align the upright leg of the 'L' vertically when it was affixed to the angled rail of the ladder. Test subjects also reported that because the 'L' sticker is relatively small it was hard to visualize proper orientation and the angle of the ladder became somewhat of a false horizon that distorted the view and threw off their ability to properly align the 'L' in a manner that yielded accurate results. Other than the Level Method, this approach did yield the lowest standard deviation, but similar to the 4:1 Method and Stand-Reach Method, it also confused many test subjects.

Experiment 2: Engineering Analysis

Coefficient of friction testing performed in accordance with ASTM F-1679, ASTM C-1028, and using the modified ladder shoe assembly revealed consistent results within a narrow range as shown in Table 3.6. Results were obtained using all three methods only for clean and uncontaminated surfaces. This methodology served to provide a baseline as a means to compare industry standard results to the modified ladder shoe results since it is not a traditional test method. The coefficient of friction of the three surfaces in various states of contamination was obtained using only the modified ladder shoe assembly. Results obtained using the other two methods would not have been useful for analysis purposes. As expected, the test results on the contaminated surfaces revealed a major decrease in value from the clean and uncontaminated conditions. Results from the coefficient of friction testing were used extensively in the ladder slide-out engineering model.

Table 3.6. Coefficient of Friction Summary.

Surface Condition	Surface	Method		
		Ladder shoes	VIT[A]	HDP[B]
Clean/ Uncontaminated	Concrete	0.89	0.87	0.84
	Asphalt	0.74	0.80	0.78
	Wood	0.82	0.89	0.78
Dry Sand	Concrete	0.47	NA	NA
	Asphalt	0.54	NA	NA
	Wood	0.48	NA	NA
Wet Surface	Concrete	0.82	NA	NA
	Asphalt	0.66	NA	NA
	Wood	0.73	NA	NA
Wet Sand	Concrete	0.47	NA	NA
	Asphalt	0.48	NA	NA
	Wood	0.43	NA	NA

VIT[A]: Variable incidence tribometer, ASTM F-1679.
HDP[B]: Horizontal dynamometer pull-meter, ASTM C-1028.

An engineering analysis to evaluate the likelihood of a ladder slide-out failure was performed based on the results obtained in Experiment 1. All 368 setup angles from Experiment 1 were combined for test purposes with the coefficients of friction listed in

Table 3.6. Calculations were performed to determine the minimum required ladder setup angle to achieve a factor of safety equal to 1.0 based on the coefficient of friction testing. The angle at which the factor of safety equals 1.0 is the Critical Angle. A review of the ladder setup angle test results was performed to determine the number of slide-out failures that would have occurred based on these conditions. The static condition is based on a stationary load at a specific location while the dynamic condition represents a user climbing from rung to rung. Previous testing by Chang and Chang (2005) revealed that up to a 6.5 percent increase of the coefficient of friction is required based on dynamic climbing conditions as opposed to simple static conditions. Based on the research by Chang and Chang, all static coefficient of friction values were adjusted to reflect the necessary 6.5 percent increase to prevent sliding due to dynamic conditions. Therefore, based on these calculations, the number of slide-out failures from dynamic conditions was also determined. This analysis was performed based on the free body diagram shown in Figure 3.4. All setup angles less than the Critical Angle for each condition would result in a slide-out failure at the specified coefficient of friction. This analysis was performed by applying all ladder setup angles and measured coefficients of friction into the engineering model. A summary of these results are shown in Table 3.7. Sample output form the ladder analysis model is shown in Figure 3.5.

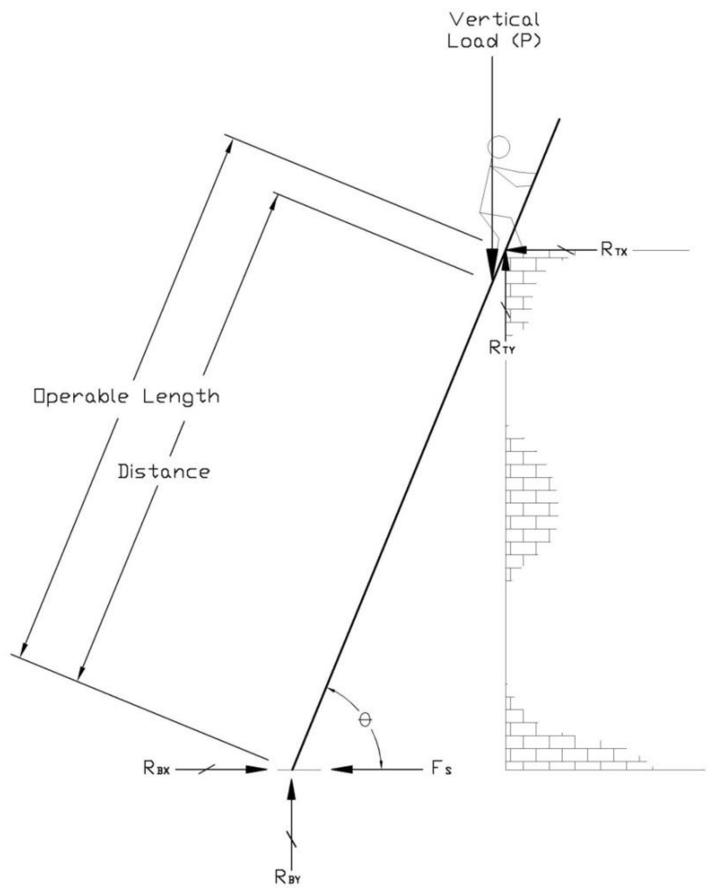


Figure 3.4. Free body diagram.
A slide-out failure occurs when the sliding force, F_S, exceeds the horizontal resisting force, R_{BX}.

Table 3.7. Coefficient of Friction, Critical Angle, and Number of Slide-Out Failures for Static and Dynamic Conditions Based on Actual Ladder Setup Angles from Experiment 1.

Ground Material	Coefficient of Friction	Critical Angle for Factor of Safety* = 1.0	[a] Number of Failures Based on Test Results (%)	[b] Number of Failures Based on Dynamic Climbing Condition (%)
Dry concrete	0.89	46.23	0 (0)	1 (0.3)
Dry concrete w/sand	0.47	63.73	21 (5.7)	28 (7.6)
Wet concrete	0.82	48.74	1 (0.3)	1 (0.3)
Concrete w/wet sand	0.47	63.73	21 (5.7)	28 (7.6)
Dry asphalt	0.74	51.75	1 (0.3)	1 (0.3)
Dry asphalt w/sand	0.54	60.38	8 (2.2)	15 (4.1)
Wet asphalt	0.66	55.04	1 (0.3)	1 (0.3)
Asphalt w/wet sand	0.48	63.25	17 (4.6)	26 (7.1)
Dry wood	0.82	48.74	1 (0.3)	1 (0.3)
Dry wood w/sand	0.48	63.25	17 (4.6)	26 (7.1)
Wet wood	0.73	52.16	1 (0.3)	1 (0.3)
Wood w/wet sand	0.46	64.24	23 (6.3)	30 (8.2)

[a]Represents number of slide-out failures that would have occurred based on actual test results and given coefficient of friction in static condition. Tipping failures were not considered.
[b]Represents number of slide-out failures that would have occurred based on actual test results and given coefficient of friction in dynamic condition. Tipping failures were not considered.
*Factor of safety calculated as worst case scenario with user at top of ladder such as stepping from ladder to roof.

Ladder Parameters		
Extended ladder length:	13	ft
User weight (P):	200	lb
Ladder angle (Θ):	64.24	deg
Top of wall height:	50	ft
Coefficient of friction:	0.46	
Operable length:	13.00	ft
Top support condition:	Wall abutment	

Results

Reaction	Force (lb)	Distance (ft)
R_{BX}	75.27	12.5
R_{BY}	198.55	0.5
R_{TX}	75.27	12.5
R_{TY}	36.32	12.5

Ladder is safe to climb

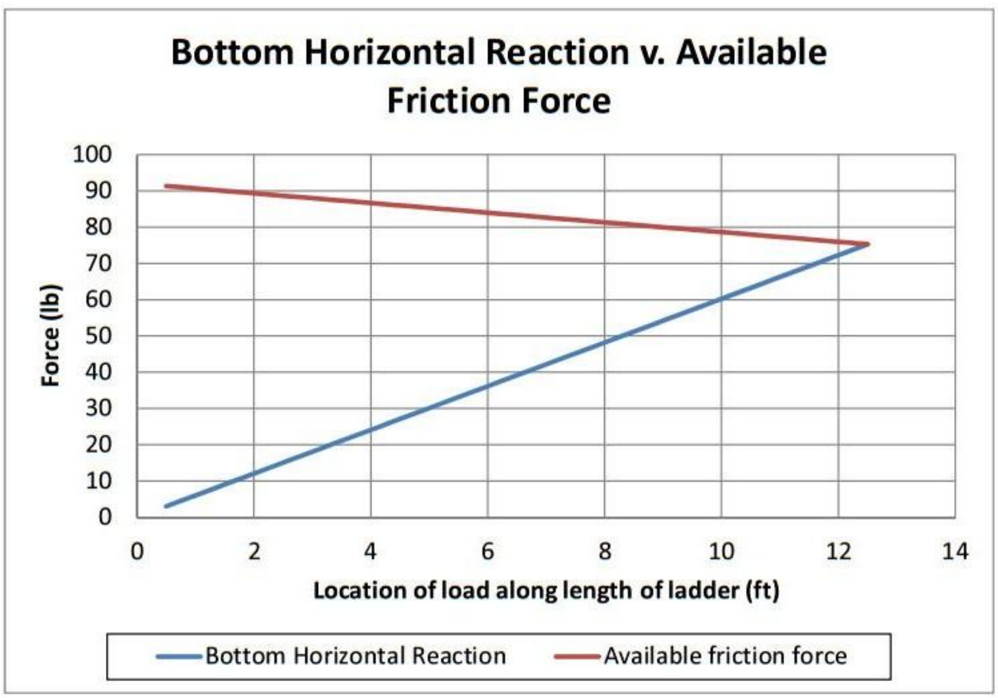


Figure 3.5. Ladder model output from engineering analysis. Example shown represents Critical Angle and factor of safety = 1.0. Input data shown in Ladder Parameters. If Horizontal Reaction Line and Friction Force Line cross, then factor of safety < 1.0 and critical load occurs at point of intersection.

Discussion

The engineering analysis represents a comprehensive evaluation of a wide range of setup angles and conditions. These results, based on static and dynamic conditions, raised areas of concern. Dry concrete provided the highest coefficient of friction at 0.89, and therefore, the greatest resistance to a ladder slide-out failure. In contrast, wood with a thin film of wet sand was the worst condition with a coefficient of friction of 0.46. However, concrete with either wet or dry sand, dry wood with sand, and asphalt with wet sand were almost equal with a coefficient of friction range of 0.47-0.48. Based on results from the test subjects' ladder setup angles, dry concrete was the only static condition that would not have resulted in a slide-out failure. However, for the dynamic analysis, all conditions including clean dry concrete would have resulted in at least one slide-out failure. For the worst case dynamic conditions mentioned above with a coefficient of friction of 0.46, the number of slide-out failures based on the total number of setups combined for all methods would have been 12.2 percent (30/246). When broken down by method and the worst case scenario of a coefficient of friction of 0.46, the 4:1 Method was the worst with a failure rate of 18.8 percent (6/32). The 75 Degree Method was also highly inaccurate with a failure rate of 15.2 percent (14/92). It is interesting to note that the 4:1 Method that provided setup instructions was far more dangerous than the Basic Method that provided essentially no guidelines and was based simply on personal preference (9.8 percent, 9/92). Actual number of failures based on each ladder setup method and static or dynamic condition is shown in Figure 3.6.

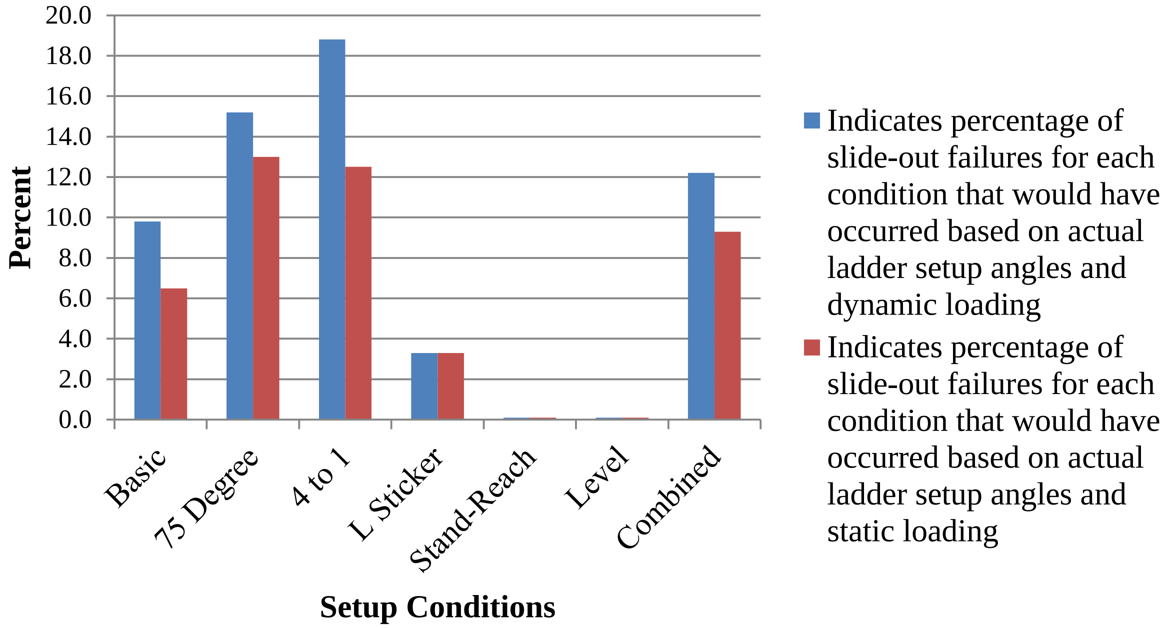


Figure 3.6. Slide-out Failures by Condition with 0.46 Coefficient of Friction

CHAPTER 4

GENERAL DISCUSSION

Testing was carried out using two different methodologies and approaches in order to obtain the data necessary to perform a detailed analysis and fully complete each phase of the study. The first approach, involving human subjects, was performed with 92 Clemson University students utilizing a combination of methods to set up a 16 foot, portable extension ladder. The second experiment focused primarily on physics and engineering mechanics to obtain the coefficient of friction of three common ladder setup surfaces. Each surface was evaluated in both contaminated and uncontaminated conditions. The overall results from all testing was used to perform an engineering analysis and determine the factor of safety against a slide-out failure based on the actual ladder setup angles selected by the test subjects.

Experiment 1 from this study focused primarily on the human factors of setting up a portable extension ladder. When test subjects were allowed to set up the ladder at their own preferred angle, they selected an angle less than 75 degrees as expected. However, even if they were directed to set the ladder up at what they perceived to be 75 degrees, the test subjects had a wide margin of error with a range of setup angles from 47.6 to 85.8 degrees. The extreme values of this range would be considered quite dangerous for most ladder users.

While the Basic and 75 Degree Methods were based primarily on preference and perception, respectively, the 4:1, Stand-Reach, and L Sticker Methods provided instructions and visual aids for the test subjects. However, even with instructions, the latter three methods produced major setup errors and revealed a general lack of precision. The 4:1 and L Sticker Methods produced results that included relatively low setup angles of 57.8 and 63.7 degrees, respectively, while the results from the Stand-Reach Method included a very high setup angle of 82.9 degrees. A low setup angle can cause a slide-out failure while a high setup angle can cause a tipping failure; both extremes can be equally dangerous. Additionally, when one of these failures occurs, the loads are most critical when the user is at the top of the ladder. The consequences of these conditions are often catastrophic, especially with tall ladders. Even falls from shorter ladders can be problematic due to users falling onto the hard edges of the ladder itself. Of these five methods, the Stand-Reach Method produced the narrowest range at 12.3 degrees and the closest mean to 75 degrees at 76.2 degrees.

Anthropometric analysis was performed to further evaluate the results of the Stand-Reach Method. Arm length (measured from centerline of shoulder to middle of palm at centerline of rung), shoulder height, and shoe size were recorded for test subjects who performed this method. These results revealed that if properly performed, the Stand-Reach Method is capable of producing results with a narrow range that are close to 75 degrees. Based on anthropometric data and associated calculations, setup angle is substantially proportionate to the shoulder height/arm length ratio; the lower the ratios, the lower the setup angle. Ratios obtained during this experiment were 2.11 to 2.41. The 2.11 ratio corresponded to the lowest computed setup angle and the 2.41 ratio corresponded to the second highest computed setup angle.

The final ladder setup method performed by all test subjects was the Level Method. There is no record that this method is widely used or endorsed by the ladder industry. However, from a results standpoint, the Level Method produced the most accurate results with a mean setup angle of 75.2 degrees and a narrow range of 73.7 to 75.9 degrees. This mean setup angle varies only 0.2 degrees or approximately ¼ percent from the target angle of 75 degrees. With minor modifications and minimal expense, spirit levels could be added to all new ladders and this method could be incorporated into future ladder specifications as a new and improved ladder setup standard. It is also likely that the number and severity of ladder slide-out failures would be reduced through the adoption of this method.

At the completion of ladder setup testing, a questionnaire was administered to all test subjects. Review and analysis of questionnaire results revealed that test subjects found the Level Method to be easiest to use and they were also most confident that this method yielded the most accurate results. The current industry standard, the Stand-Reach Method, was chosen second in each category. Not surprisingly, the Basic Method, which was based purely on personal preference and offered no other instructions or visual aids, was last in each category.

Additional questions related to higher education that might provide a greater level of insight based on an understanding of angles, including ladder setup angles, revealed counterintuitive results. Test subjects that had not previously taken calculus, physics, or trigonometry achieved more accurate setup angles than test subjects who had taken these subjects. Additionally, test subjects who had not taken these subjects produced setup angles that were not significantly different from 75 degrees; those who had taken these subjects produced results that were significantly different. Based on previous ladder experience, only test subjects who reported a high level of ladder experience achieved results that were not significantly different from 75 degrees.

Experimenter observations made during testing, along with post-test discussions with some test subjects, revealed a theme of general confusion during the testing. The level of confusion ranged from a fundamental lack of knowledge of ladder usage to failure to accurately interpret or comprehend instructions related to the various setup methods. Setting the ladder up backwards or upside down is a clear indication of the absence of a grasp of the fundamentals of ladder usage. Additionally, subjects were confused by the written instructions and visual aids associated with the 4:1, Stand-Reach, and L Sticker Methods. More specifically, test subjects were not able to accurately compute a 4:1 ratio, did not accurately interpret the diagram that accompanied the Stand-Reach Method, and found that the L Sticker Method produced a distorted image that caused somewhat of a false horizon due to short dimensions of the 'L' on an angled ladder. Results related to these conditions produced highly inaccurate results. Observations, discussions, and results related to the Level Method did not produce similar problems and inaccuracies related to confusion or misinterpretation. Similarly, results from the Level Method were highly accurate.

The human subjects testing in Experiment 1 was performed in a manner similar to previous testing by Young and Wogalter. Results from the 75 Degree, L Sticker, and Level Methods were very similar. However, results from the Basic, 4:1, and Stand-Reach Methods showed large variability. In particular, Young and Wogalter results for Stand-Reach were 70.55 degrees and results from this experiment were 76.2 degrees. They partially attributed their large deviation from 75 degrees to anthropometry. Results from this study, Young and Wogalter, as well as Irvine and Vejvod do suggest that variances in anthropometry can introduce an increased margin of error even when the procedure is performed correctly.

Results from the coefficient of friction testing provided the necessary values for directly applicable, real-world results. In particular, the results were obtained from a modified ladder shoe assembly using new ladder shoes. However, worn ladder shoes could produce lower values due to worn threads or embedded/impregnated contamination. The range of values for concrete, asphalt, and wood in both clean and contaminated conditions were a high of 0.89 for clean, dry concrete to a low of 0.46 for wood contaminated with wet sand. The values for concrete and asphalt contaminated with wet sand were similar at 0.47 and 0.48, respectively. The concept of any one of these surfaces being contaminated with wet sand is not unusual. Almost all outdoor surfaces are covered with a thin film of soil, leaves, grass clippings, or similar material and these materials will become wet with precipitation. Moisture can also be introduced by weather, pressure washing, sprinklers, and condensation. Icy conditions would pose an even greater risk. As a specific example, the experimenter has knowledge of a ladder slide-out accident involving pressure washing using a soapy solution with the ladder set up on a concrete surface. The ladder setup angle at the time was not known.

Engineering analysis using the human subjects test results and the measured coefficients of friction provided true insight regarding the likelihood of a ladder slide-out failure and how they occur. Based on proven and accepted engineering principles, if the factor of safety against ladder slide-out is less than 1.0, the ladder becomes unstable and begins to slide. Furthermore, during climbing (dynamic condition), the minimum coefficient of friction to prevent sliding may need to be as much as 6.5 percent higher than a simple static condition with a stationary user on a single rung. Based on all results obtained in this study, the only condition that did not produce a slide-out failure was the static condition with the ladder set up on clean concrete. All other conditions would have caused at least one and as many as 23 slide-out failures based on the test subjects' actual results. However, based on the required increase of the coefficient of friction to prevent a slide-out failure in the dynamic condition, at least one failure would have occurred for every surface and coefficient of friction, including clean concrete. Furthermore, for the condition of wood with wet sand (the surface with the lowest coefficient of friction), a total of 30 slide-out failures would have occurred. A failure rate this high greatly raises the level of concern for user safety. Referring once again to the pressure washing example, the flow of pressurized water from the wand produces a lateral force that could further contribute to a slide-out failure. Similar conditions could be created by carpenters and painters. These forces have not been computed or considered in the calculations but could be included in future analysis.

Additionally, it is not likely known by most ladder users that setting up a ladder on a downhill slope effectively reduces the ladder setup angle by the amount of slope. For example, if a ladder set up at what would be 75 degrees on level surface is set up on a seven degree slope, the effective ladder setup angle is actually 68 degrees. The experimenter has personally observed this condition in the field and the users made no attempt to compensate for the effectively reduced setup angle.

CONCLUSIONS

Many factors identified during the course of this study may be beyond the control and knowledge of the average ladder user. However, the results and analysis bring into focus many of the problems that exist related to lack of training and confusion caused by current ladder setup methods in use. The results also emphasize the need for further improvements to current standards. It is clear that for some users, the Stand-Reach Method produced results that were reasonably accurate when compared to 75 degrees, but it also revealed evidence of confusion and user error. Even though test subjects studied the instructions before setting up the ladder, the wide range of results is alarming. Similarly, confusion with the instructions associated with the 4:1 and L Sticker Methods created setup errors. Additionally, based on personal observations and interviews, many users in real-world conditions rely heavily upon the Basic Method which is based purely on personal preference and experience. The large number of real-world ladder slide-out failures that occur on an annual basis are a clear indication of the reoccurrence of deficiencies and errors identified by this study and the existence of related problems.

One of the goals of this study was to evaluate the effectiveness and safety of the recommended setup angle of 75 degrees. Based on engineering analysis and the likely range of the coefficient of friction of common ladder setup surfaces, this value would appear to be ideal because of the factor of safety it affords. At a ladder setup angle of 75 degrees on a level surface, and the lowest measured coefficient of friction of 0.46, the factor of safety against a slide-out failure is 1.79. However, if the effective ladder setup angle is lowered to 65 degrees (based on ladder angle and/or ground slope) the factor of safety against a slide-out failure is dangerously close to 1.0 with a value of 1.03 in a static condition. In a dynamic condition the factor of safety is less than 1.0 and a slide-out failure would occur. Many of the setup angles measured during this study were less than 65 degrees. Therefore, maintaining the recommended setup angle at 75 degrees allows a reasonable factor of safety in the presence of contaminated conditions and sloped surfaces.

The easiest solution to obtain accurate ladder setup angles at or near 75 degrees is the Level Method. This conclusion was confirmed by the participants' performance in the ladder placement task as well as their questionnaire responses. This solution could be easily accomplished by attaching a small spirit level to the side rail of the ladder near the eye level of the average user. These levels are relatively inexpensive and readily available. If mass produced and installed at the factory, the costs would likely be negligible. Based on the findings of this study, changing the industry from using the Stand-Reach Method to the Level Method would both increase the level of accuracy of setup angles and reduce confusion related to user interpretation of instructions. It should also increase the level of safety among users and reduce the number of accidents and injuries related to slide-out failures.

APPENDICES

A: ANSI A14.2 Ladder Instructions

SAFETY FIRST

STEPLADDER — FOR YOUR SAFETY READ CAREFULLY

PROPER SELECTION

1. Select ladder of proper length to reach working height.
2. IMPORTANT: Ladders are designed to support one person plus materials and tools not more than the working load on the notice sign on this ladder
3. Select ladders within the following:

TYPE	DUTY RATING	WORKING LOAD
IAA	SPECIAL DUTY	375 lbs
IA	INDUSTRIAL-EXTRA HEAVY	300 lbs
I	INDUSTRIAL-HEAVY	250 lbs
II	COMMERCIAL-MEDIUM	225 lbs
III	HOUSEHOLD-LIGHT	200 lbs

INSPECTION

1. Inspect upon receipt and before each use, never climb a damaged, bent or broken ladder. All parts must be in good working order.
2. Make sure all rivets, joints, nuts, and bolts are tight; steps, spreaders, and braces secure; spreaders and pail shelf function properly.
3. Keep ladder clean, free from grease, oil, mud, snow, wet paint, and other slippery material. Keep your shoes clean, leather soles should not be used.
4. Never make temporary repairs of damaged or missing parts
5. Destroy ladder if broken, worn or if exposed to fire or chemical corrosion

PROPER SET-UP

1. DANGER! METAL CONDUCTS ELECTRICITY! Do not let ladders of any material come in contact with live electrical wires.
2. Make sure ladder is fully open, spreaders are secure, pail shelf in position.
3. Place on firm level surface with a secure footing. Do not use on slippery surfaces. Do not place on boxes, unstable bases or scaffolds to gain additional height. Do not place in front of door opening toward ladder.

PROPER CLIMBING AND USE

1. DO NOT USE LADDERS if you tire easily, or are subject to fainting spells, or are using medicine or alcohol, or are physically impaired.
2. To protect children, do not leave ladder set up and unattended.
3. Face ladder when climbing up or down; keep body centered between side rails.
4. Maintain a firm grip. Use both hands in climbing.
5. Never climb ladder from the side unless ladder is secured against side-wise motion.
6. Do not overreach; move ladder when needed.
7. Do not "walk" or "jog" ladder when standing on it.
8. Do not stand, climb or sit on braces, spreaders, pail shelf, back section, or above second step from top of ladder.
9. Do not overload. Ladders are meant for one person. Do not use as brace, platform or plank.
10. Keep ladder close to work; avoid pushing or pulling off to the side of ladders.

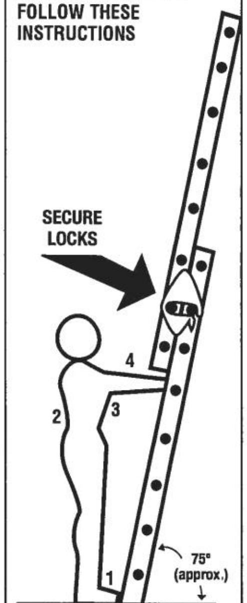
PROPER CARE AND STORAGE

1. Store ladder in safe and dry place.
2. Properly secure and support ladder while in transit.
3. Never store materials on ladder.
4. Keep ladder clean and free of all foreign materials

Marking No. 4

CAUTION

SET UP LADDER PROPERLY TO REDUCE SLIP AND OVERLOAD HAZARDS. FOLLOW THESE INSTRUCTIONS



① PLACE TOES AGAINST BOTTOM OF LADDER SIDE RAILS.
② STAND ERECT
③ EXTEND ARMS STRAIGHT OUT
④ PALMS OF HANDS SHOULD TOUCH TOP OF RUNG AT SHOULDER LEVEL

1. DO NOT OVER-REACH. KEEP BODY CENTERED BETWEEN SIDE RAILS
2. EXTEND LADDER ONE TO THREE FEET ABOVE ROOF FOR ACCESS

Marking No. 5

B: 4:1 Method Setup Instructions

PENNSTATE

Environmental Health and Safety

www.ehs.psu.edu / 814-865-6391

LADDER SAFETY

Falls from portable ladders (step, straight, orchard, combination and extension) are a leading cause of occupational injuries. To prevent injuries, use the following procedures:

A. SELECT PROPER LADDER- Choose the ladder based on work to be performed

1. **Step Ladders**- Work at lower heights from 3 to 20 feet and inside buildings on level flat surfaces. Best for their light weight and uncomplicated use for tasks nearer the ground. A shelf holds tools or paint.

2. **Orchard Ladder**- Used frequently in orchards and for landscaping. Ladder has two front legs like a regular step ladder and one rear leg which allow getting into trees, bushes and on uneven ground. **Tripod/electrician's** ladders are similar but have a spreader bar and are convenient when working around equipment.
3. **Straight/Extension Ladders**- For work at greater heights (e.g. 10 to 40 feet). These ladders are light for their size, easy to set up, and more rigid than multiuse models when used as a straight ladder.

4. **Ladder material**- Ladders are constructed of wood, aluminum or fiberglass. Use the material best suited for the job. Avoid electrical hazards and do not use aluminum ladders near power lines or when performing electrical work.

B. USE LADDERS WITH THE PROPER LOAD RATINGS- The weight of the person and the equipment being used on the ladder must not exceed the load rating. Look for the load rating of the ladder on the sticker on the ladder.

TYPE	DUTY RATING	WORKING LOAD
1AA	Industrial- Special heavy duty	375 pounds maximum
IA	Industrial- Extra heavy duty	300 pounds maximum
I	Industrial- Heavy duty	250 pounds maximum
II	Commercial- Medium duty	225 pounds maximum
III	Household- Light duty	200 pounds maximum

C. INSPECT THE LADDER BEFORE USE

1. **Wood ladders**- Look for splits, cracks, chips, and loose rungs or steps. Don't use painted ladders as paint may hide a defect in the wooden ladders.
2. **Aluminum ladders**- Should have no sharp edges, dents, or bent steps, feet, or rails. Check for loose rivets.
3. **Fiberglass**- Check for cracks, chips, and missing components. Because they can cause the ladder to suddenly fail, any of these problems signals the need for a new ladder.
4. Keep ladders clean and dry. Wipe away water, oil, and other slippery substances from steps and rails before you try to climb the ladder, and wipe the ladder clean after each use to prevent deterioration.
5. Tighten reinforcing rods beneath steps, hinges, and other parts, such as bolts, but do not over tighten.
6. Check the rope and pulley on extension ladders for wear and fraying. If you need to replace them, follow the manufacturer's instructions.
7. Tag defective ladders "DEFECTIVE - DO NOT USE" and remove them from service.

C: Questionnaires

HPR 10174 QUESTIONNAIRE **4:1 METHOD**
PARTICIPANT #____________

1. Have you used a stepladder previously? If so, how many times (circle one): >10 or <10?
2. Have you used an extension ladder previously? If so, how many times (circle one): >10 or < 10?
3. If you have used an extension ladder, do you remember what size(s)? Length(s)_____________
4. Do you or your parents own a ladder? If so what kind(s) and what size(s)? Y_____ N______
5. Have you ever had a ladder accident? If so, please explain briefly. Y______ N______
6. Do you know anyone who has had a ladder accident? Y______ N______
7. Have you ever had any training in the usage of ladders? Y______ N______
8. How would you rate your understanding in the use of ladders? Low______Med______High______
9. Do you understand the effect on the stability of the ladder by changing the setup angle? If so, explain briefly. Y______ N______
10. Do you understand the effect of setting the ladder up on a sloping surface versus a level surface? If so, explain briefly. Y______ N______
11. Do you understand the effect of setting the ladder up on a slippery surface? If so, explain briefly. Y______ N______
12. Do you know the meaning of the term "coefficient of friction"? Y_____ N_____
13. Which method did you find easiest to follow to achieve a 75 degree set up angle? (Rank 1-4, best to worst): 1) Basic______ 2) 75 Degree Method______ 3) 4:1 Method______ 4) Level______
14. Which method were you most confident would be the safest and also the closest to a 75 degree set angle? (Rank 1-4, best to worst): 1) Basic______ 2) 75 Degree Method______ 3) 4:1 Method______ 4) Level______

The following personal information would be helpful if there is no objection:

15. Gender M______ F______
16. Have you had classes in calculus, trigonometry, or physics? Y______ N_______
17. What is your class standing (year)? F______ S______ J______ S______
18. Basic _________75° _________ 4:1 Method _________ Level_________.

HPR 10174 QUESTIONNAIRE **'L' STICKER METHOD**

PARTICIPANT #__________

1. Have you used a stepladder previously? If so, how many times (circle one): >10 or <10?
2. Have you used an extension ladder previously? If so, how many times (circle one): >10 or < 10?
3. If you have used an extension ladder, do you remember what size(s)? Length(s)_____________
4. Do you or your parents own a ladder? If so what kind(s) and what size(s)? Y_____ N______
5. Have you ever had a ladder accident? If so, please explain briefly. Y______ N______
6. Do you know anyone who has had a ladder accident? Y______ N______
7. Have you ever had any training in the usage of ladders? Y______ N______
8. How would you rate your understanding in the use of ladders? Low______Med______High______
9. Do you understand the effect on the stability of the ladder by changing the setup angle? If so, explain briefly. Y______ N______
10. Do you understand the effect of setting the ladder up on a sloping surface versus a level surface? If so, explain briefly. Y______ N______
11. Do you understand the effect of setting the ladder up on a slippery surface? If so, explain briefly. Y______ N______
12. Do you know the meaning of the term "coefficient of friction"? Y_____ N_____
13. Which method did you find easiest to follow to achieve a 75 degree set up angle? (Rank 1-4, best to worst): 1) Basic______ 2) 75 Degree Method______ 3) 'L' Sticker Method______ 4) Level______
14. Which method were you most confident would be the safest and also the closest to a 75 degree set angle? (Rank 1-4, best to worst): 1) Basic______ 2) 75 Degree Method______ 3) 'L' Sticker Method______ 4) Level______

The following personal information would be helpful if there is no objection:

15. Gender M______ F______
16. Have you had classes in calculus, trigonometry, or physics? Y______ N_______
17. What is your class standing (year)? F______ S______ J______ S______
18. Basic _________75° _________ L-Sticker Method _________ Level_________.

HPR 10174 QUESTIONNAIRE **STAND-REACH METHOD**

PARTICIPANT #__________

1. Have you used a stepladder previously? If so, how many times (circle one): >10 or <10?
2. Have you used an extension ladder previously? If so, how many times (circle one): >10 or < 10?
3. If you have used an extension ladder, do you remember what size(s)? Length(s)______________
4. Do you or your parents own a ladder? If so what kind(s) and what size(s)? Y_____ N______
5. Have you ever had a ladder accident? If so, please explain briefly. Y______ N______
6. Do you know anyone who has had a ladder accident? Y______ N______
7. Have you ever had any training in the usage of ladders? Y______ N______
8. How would you rate your understanding in the use of ladders? Low______Med______High______
9. Do you understand the effect on the stability of the ladder by changing the setup angle? If so, explain briefly. Y______ N______
10. Do you understand the effect of setting the ladder up on a sloping surface versus a level surface? If so, explain briefly. Y______ N______
11. Do you understand the effect of setting the ladder up on a slippery surface? If so, explain briefly. Y______ N______
12. Do you know the meaning of the term "coefficient of friction"? Y_____ N_____
13. Which method did you find easiest to follow to achieve a 75 degree set up angle? (Rank 1-4, best to worst): 1) Basic______ 2) 75 Degree Method______ 3) Stand Reach Method______ 4) Level______
14. Which method were you most confident would be the safest and also the closest to a 75 degree set angle? (Rank 1-4, best to worst): 1) Basic______ 2) 75 Degree Method______ 3) Stand Reach Method______ 4) Level______

The following personal information would be helpful if there is no objection:

15. Gender M______ F______
16. Have you had classes in calculus, trigonometry, or physics? Y______ N_______
17. What is your class standing (year)? F______ S______ J______ S______
18. Height at top of shoulder: ___________
19. Shoe size: ___________
20. Arm length from centerline of should to middle of palms with arms extended horizontally forward (as in stand reach method): ___________
21. Basic __________75° __________ Stand Reach Method __________ Level__________.

Designation: F 1679 – 04$^{\epsilon 1}$

An American National Standard

Standard Test Method for Using a Variable Incidence Tribometer (VIT)[1]

This standard is issued under the fixed designation F 1679; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

ϵ^1 NOTE—Section 11 was corrected editorially in July 2005.

1. Scope

1.1 This test method covers the operational procedures for using a variable incidence tribometer[2] (VIT) for determining the slip resistance of planar walkway surfaces or walkway surrogates (test surfaces) and can be used for footwear bottom materials and surrogates (test feet) in either the laboratory or field under dry, wet, or contaminated conditions. This test method does not address all methodological issues (for example, test surface and test foot material selection and preparation, experimental design, or report preparation).

1.2 The values stated in inch-pound units are to be regarded as the standard.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *ASTM Standards:*

F 1646 Terminology Relating to Safety and Traction for Footwear[3]

3. Terminology

3.1 *Definitions*—For definitions of terms, refer to Terminology F 1646.

4. Significance and Use

4.1 The VIT is designed to determine the slip resistance of walkway surfaces or surrogates and footwear bottom materials or surrogates under field or laboratory conditions so that their slip-resistant properties may be evaluated.

4.2 The measurement made by this apparatus relates to slip resistance. Other factors such as environmental conditions can affect slip resistance. When this test method is used in field tests, relevant factors shall be described.

5. Apparatus

5.1 *Mast Assembly*—A rigid metal frame attached to the chassis with a hinge joint permitting its inclination to any angle from vertical to 45°. A hand wheel is attached between the mast assembly and the chassis to adjust the angle of the mast. The top of the mast assembly consists of a round metal handle that can be used to carry the tester or to apply a downward force while testing to prevent slippage. A pointer on the mast assembly indicates the slip index value for each inclination of the mast.

5.2 *Actuating Cylinder*—A pneumatic cylinder mounted to the mast assembly by a hinged joint to permit the test foot assembly to swing when a slip occurs.

5.3 *Test Foot Assembly*—The combination of (*1*) the actuating cylinder, (*2*) the piston, (*3*) a round aluminum shoe that screws onto a nylon nut holding it on the piston ball joint, (*4*) the test foot that is glued onto the shoe, and (*5*) a spring that holds the shoe perpendicular to the piston.

5.4 *Pressure System*—The pneumatic system that drives the actuating cylinder consists of a 12-g carbon dioxide cylinder, tubing that runs to a variable pressure regulator, and tubing that runs to the actuating valve. Pressing the actuating valve pressurizes the actuating cylinder and drives the test foot onto the surface being tested.

6. Test Foot Preparation and Test Surfaces

6.1 *Test Foot Preparation*:

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[1] This test method is under the jurisdiction of ASTM Committee F13 on Pedestrian/Walkway Safety and Footwear and is the direct responsibility of Subcommittee F13.10 on Traction.

Current edition approved Sept. 1, 2004. Published September 2004. Originally approved in 1996. Last previous edition approved in 2000 as F 1679 – 00.

[2] The English XL is covered by a patent held by William English. The sole source of supply of the apparatus known to the committee at this time is William English, Inc., 20500 North River Rd., Alva, FL 33920. If you are aware of alternative suppliers, please provide this information to ASTM International Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee [1], which you may attend.

[3] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For Annual Book of ASTM Standards volume information, refer to the standard's Document Summary page on the ASTM website.

6.1.1 Securely attach a 1.25-in. diameter disc of the desired test foot material to the round aluminum shoe. Attachment methods include epoxy cement, super glue, or double-sided carpet tape cut to fit the size of the foot.

6.1.2 Preparation of the test foot surface will depend on the material, and should be described in detail in reporting so it can be reproduced. If footwear bottom material or surrogate is used, employ a preparation method suitable for that material.

6.1.3 If Neolite[4] Test Liner is used, use 180 grit silicon carbide paper in the dry condition using a sanding block to keep the sandpaper flat and rigid. Sand in a circular motion five cycles.

6.2 *Test Surface*—The test surface shall not be less than 2 in.^{2} (5 cm^2) and should be surrounded by enough material of similar thickness or placed in a suitable fixture so that the tribometer feet will be at the same elevation as the top of the specimen. The test foot material shall fit within the area of the test surface.

7. Reagents and Materials

7.1 *Gas Cartridge*—Carbon dioxide cylinder, 12 g.

7.2 *Epoxy Adhesive*, or equivalent.

7.3 *Neolite Test Liner.*[4]

NOTE 1—While the intended test foot material for this instrument is Neolite[4] Test Liner, this does not preclude the use of other materials.

7.4 *Silicon Carbide Paper*, 180–grit.

7.5 *Water Dispensing Bottle.*

7.6 *Dust brush or compressed air, or both.*

8. Operational Check

8.1 Place the tester on a flat surface.

8.2 Insert a pressurized gas cartridge into the holder on the chassis, and tighten the clamp screw until the pressure registers on the gage. Adjust the operating pressure to 25.0 ± 2 psi (172 ± 10 kPa).

8.3 Cycle the tester by pressing the actuating valve to stabilize the working pressure, and verify that the piston rod moves freely. Upon activation, the heel of the test foot should contact the test surface first.

9. Operational Procedure

9.1 Specific testing procedures may vary depending on the test foot material, surface, and contaminants used.

9.2 Install an appropriately prepared test foot onto the piston.

9.3 When testing dry floors, prepare the Neolite[4] Test Liner test foot after each slip. When testing wet or contaminated floors, preparation should be between flooring samples when there is reason to believe the test foot has become scuffed, polished, or contaminated. Prepare the test foot material in accordance with 6.1.2 or 6.1.3. Remove sanding residue with a dry brush or compressed air, or both, at a sufficient distance away from the test area to assure that sanding residue does not contaminate the test surface. Screw the test foot onto the ball joint until snug and then back-off one-quarter turn.

9.4 Place the tester onto the test surface. The test surface must be in the same plane as the tribometer's feet.

9.5 Adjust the pressure to 25 ± 2 psi.

9.6 Adjust the mast to a position vertical enough to obtain three actuations before a slip occurs.

9.7 Check to assure the pneumatic cylinder is resting against the rubber stop on the cross member of the mast.

9.8 For wet testing, apply water to the test surface so as to provide an unbroken film of water prior to each stroke.

9.9 Keep the chassis stationary and fully depress the actuating valve for approximately ½ s. If the test foot does not "kick out" with the piston fully extended, increase the slip index reading by turning the hand wheel no more than a one-quarter turn and retest. When the test foot "kicks out" with the piston fully extended, read and record the slip index protractor, estimating results to the nearest 0.01 slip index unit.

9.10 At least four determinations should be performed, at approximately 90° angles from each other. Average the readings to establish the slip index unit.

NOTE 2—For the purposes of activities such as controlled studies, a greater number of determinations may be appropriate.

9.11 *Testing Stairs and Inclined Surfaces*:

9.11.1 *Inclined Surfaces*—Sloped surfaces such as ramps are tested in the same manner as level surfaces. When testing in a downhill direction, the pneumatic cylinder must rest against the rubber stop prior to actuation. If the slope is so steep as to cause the cylinder to move away from the rubber stop, erroneous results will be produced.

9.11.2 *Stair Testing*—When testing stairs, affix the stair fixture to the underside of the chassis. Adjust its height to the approximate dimension of the riser height so that the tester is supported in the same plane as the tread when its front soft feet are positioned on the nosing of the tread. The tester will then be in a "head-on" position so that the actuation thrust will be parallel to the direction of pedestrian travel on stairs.

10. Environmental Conditions

10.1 When testing dry surfaces using Neolite[4], high humidity (90 to 95% RH) can yield slip resistance readings up to 6 % higher than low (20 to 24 % RH) or moderate (50 to 56 %) humidity environments. This variance is more pronounced on polished surfaces, and less so on textured surfaces. Low and moderate humidity environments have no measurable impact on dry test results. Similarly, wet testing is unaffected by humidity levels.

11. Precision and Bias

11.1 The precision and bias of the tester is being determined.

12. Keywords

12.1 dry surface testing; environmental contaminants; field testing; slip resistance; tribometers; wet surface testing

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[4] Neolite®, registered trademark with Goodyear Tire and Rubber Company is a suitable test foot material. The sole source of supply of the apparatus known to the committee at this time is Smithers Scientific Services, Inc., 425 West Market Street, Akron, OH 44303. Specify "Standard Neolite® Liner," Nominal size, 6 by 6 in.; 3 mm, color, Natural 11; specific gravity, 1.27 +/- 0.02. If you are aware of alternative suppliers, please provide this information to ASTM International Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee [1], which you may attend.

Designation: C1028 – 07$^{\varepsilon 1}$

Standard Test Method for Determining the Static Coefficient of Friction of Ceramic Tile and Other Like Surfaces by the Horizontal Dynamometer Pull-Meter Method[1]

This standard is issued under the fixed designation C1028; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

ε[1] NOTE—14.1 was editorially revised in February 2010.

1. Scope

1.1 This test method covers the measurement of static coefficient of friction of ceramic tile or other surfaces under both wet and dry conditions while utilizing Neolite heel assemblies.[2] This test method can be used in the laboratory or in the field.

1.2 The values stated in inch-pound units are to be regarded as standard. The values given in parentheses are mathematical conversions to SI units that are provided for information only and are not considered standard.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 *Rubber Manufacturing Association (RMA) Standard:*
HS-3 Method of Test for Evaluating Adhesive Bondability of Shoe Soling Materials (1975)[3]

3. Terminology

3.1 *Definitions:*

3.1.1 *coefficient of friction*—the ratio of the horizontal component of force required to overcome or have a tendency to overcome friction to the vertical component of the object weight or normal force applied through the object which tends to cause the friction.

3.1.2 *friction*—the resistance developed between the physical contacting surface of two bodies when there is movement or tendency for movement of one body relative to the other parallel to the plane of contact.

3.1.3 *static coefficient of friction*—the ratio of the horizontal component of force applied to a body that just overcomes the friction or resistance to slipping to the vertical component of the weight of the object or force applied to it.

4. Significance and Use

4.1 The horizontal dynamometer pull meter and heel assemblies are designed to determine the static coefficient of friction of tile and like materials.

4.2 The measurement made by this apparatus is believed to be one important factor relative to slip resistance. Other factors can affect slip resistance, such as the degree of wear on the shoe and flooring material; presence of foreign material, such as water, oil, and dirt; the length of the human stride at the time of slip; type of floor finish; and the physical and mental condition of humans. Therefore, this test method should be used for the purpose of developing a property of the flooring surface under laboratory conditions, and should not be used to determine slip resistance under field conditions unless those conditions are fully described.

4.3 Because many variables may enter into the evaluation of slip resistance of a particular surface, this test method is designed to evaluate these surfaces under both laboratory and actual site installation conditions.

4.4 The static coefficient of friction is determined under both wet and dry conditions with Neolite heel assemblies over both unprepared and prepared (cleaned) test surfaces.

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[1] This test method is under the jurisdiction of ASTM Committee C21 on Ceramic Whitewares and Related Products and is the direct responsibility of Subcommittee C21.06 on Ceramic Tile.

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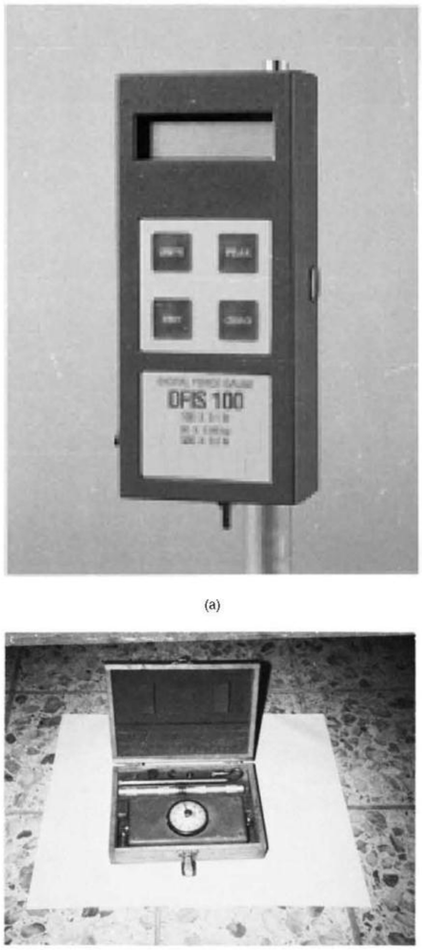
[2] Neolite or an equivalent has been found satisfactory. Neolite is a registered trademark of the Goodyear Tire and Rubber Co., Shoe Product Division, Windsor, VT 05089 and may be obtained from Smithers Scientific Services, Inc., 425 W. Market St., Akron, OH 44303 (Attn: Technical Director). Specify "Neolite (Break-in Compound)," RMA Spec. HS-3, Size 36 by 44 in., 6 irons, Color: Natural 11, Specific Gravity 1.27 ± 0.02, Hardness Shore A93-96.

[3] Available from Rubber Manufacturers Association, 1901 Pennsylvania Ave., NW, Washington, DC 20006. RMA Specification #HS-3.



(a)

(b)

FIG. 1 Dynamometer Pull Meters

5. Apparatus

5.1 *Dynamometer Pull Meter*, horizontal capable of measuring 100 lbs.-force (lbf.), accurate to 0.1 lbf., and capable of holding the peak value. (see Fig. 1).

5.2 *Weight*, 50-lb (22-kg) Weight shall be either cylindrical (approximately 6 in. in diameter and approximately 8 in. tall) or of rectangular dimensions with the base measuring approximately 6 by 8 in. Weight must be stable, and have a uniform distribution of weight. (see Fig. 2).

FIG. 2 Test Assembly

5.3 *Standard Neolite Sled Assemblies*, two, one to be used for each of the wet and dry conditions.

5.3.1 Two assemblies, constructed from 8 by 8 by ¾-in. 6061-T6 aluminum plate or similar material, with 3 by 3 by ⅛-in. Neolite material attached to the aluminum plate with contact adhesive.

5.3.2 Sheen must be removed from the Neolite surface prior to use. To prepare the assembly surface prior to initial use:

5.3.2.1 Place a sheet of 400 grit wet or dry silicon carbide paper (attached to a flat surface, such as a piece of float glass) on a flat and stable surface.

5.3.2.2 Sand Neolite material by moving the assembly once across the sandpaper towards the operator for a distance of about 4 in. (102 mm) while applying between 15-20 lbs-force to the assembly,

5.3.2.3 Remove the sled assembly and brush off any accumulated Neolite dust from the silicon carbide paper and sled assembly using a dry brush; brush to be such that it effectively removes the Neolite dust but causes no damage to the silicon carbide paper or the Neolite on the sled assembly.

5.3.2.4 Rotate the sled 90° (clockwise) and sand the Neolite again with the same procedure (one single pull towards the operator followed by removing the Neolite dust is considered one stroke).

5.3.2.5 Repeat sanding in this fashion (rotating the sled assembly by 90°, clockwise, and brushing off the Neolite dust each time between strokes) for a total of eight (8) strokes. Eight strokes equals one (1) resurfacing cycle.

5.3.2.6 Continue sanding the Neolite until all the sheen (glossy surface produced during the manufacturing process) is removed, usually no more than 500 strokes.

5.4 *Standard Tile*. Standard tiles were manufactured under controlled conditions, assigned a unique identifying number and are available from the Tile Council of North America.[4]

[4] The sole source of supply of the standard tile known to the committee at this time is Tile Council of North America, 100 Clemson Research Blvd. Anderson, SC 29625. If you are aware of alternative suppliers, please provide this information to ASTM International Headquarters. Your comments will receive careful consideration at a meeting of the responsible technical committee,[1] which you may attend.

6. Reagents and Materials

6.1 *Silicon Carbide Paper*, wet or dry, 400 grit.

6.2 *Renovator,*

6.3 *Neolite,*[2] Standard Neolite Cement Liner (see 2.1).

6.4 *Rags, Sponge, or Paper Towels.*

6.5 *Water*, distilled.

7. Calibration (Dry)

7.1 Because many variables are associated with this test procedure, it is important that the operator calibrates the Neolite Heel Assembly surface with the Standard Tile each time the test is performed.

7.2 For uses other than the initial use, resurface the assembly with 400 grit wet or dry silicon carbide paper, four cycles.

7.3 Determine the total weight, *W*, of the 50-lb (22-kg) weight plus the Neolite Heel Assembly.

7.4 Clean the Standard Tile with a renovator.

7.5 Place the Neolite Heel Assembly and the 50-lb (22-kg) weight on the Standard Tile surface. Using a dynamometer, determine the force required to set the test assembly in motion. Record the highest reading.

7.6 Make a total of four pulls, each perpendicular to the previous pull.

7.7 Calculate the dry calibration factor as follows:

$$X_D = 0.86 - \frac{R_D}{NW} \quad (1)$$

where:

X_D = dry calibration factor,
R_D = sum of the four recorded dry force readings, lb (kg),
N = number of pulls (4), and
W = weight of heel assembly plus 50-lb (22-kg) weight, lb (kg).

NOTE 1—The 0.86 factor is the static coefficient of friction value as determined by the Tile Council of North America for the standard tile (see 5.4) and confirmed by ASTM ILS in February 2007.

8. Test Procedure (Dry)

8.1 Test the following surfaces:

8.1.1 The test area or separate test specimens shall not be less than 4 by 4 in. (102 by 102 mm). Bond the separate test specimens of small-sized tile, such as 1 by 1 in. (25 by 25 mm) and 2 by 2 in. (51 by 51 mm) to a suitable surface to provide the 4 by 4 in. or larger size.

8.1.2 Test the surface in the as-received condition.

8.2 Place the 50-lb (22-kg) weight assembly with Neolite material attached on the test surface. Using a dynamometer, determine the force required to set the test assembly in motion. Record the highest reading.

8.3 Four pulls perpendicular to the previous pull on each of three surface areas or three test specimens constitute the twelve necessary readings to calculate the static coefficient of friction.

8.4 Record all readings.

8.5 Under no conditions should additional tiles be tested without performing a new calibration.

9. Calibration (Wet)

9.1 Immerse the Neolite portion of the sled assembly in water for a minimum of 5 min. after resurfacing the sled per 7.2. (See 5.3.)

9.2 It is important that the operator calibrates the assembly surface each time the test is performed. Repeat the procedure in 7.2-7.5 with one exception: Saturate the surface with distilled water and repeat the calibration with the surface wet, keeping the surface saturated.

9.3 Calculate the wet calibration factor as follows:

$$X_W = 0.51 - \frac{R_W}{NW} \quad (2)$$

where:

X_W = wet calibration factor,
R_W = sum of the four recorded wet force readings, lb or kg,
N = number of pulls (4), and
W = weight of heel assembly plus 50-lb (22-kg) weight, lb (kg).

NOTE 2—The 0.51 factor is the static coefficient of friction value as determined by the Tile Council of North America for the standard tile (see 5.4) and confirmed by ASTM ILS in February 2007.

10. Test Procedure (Wet)

10.1 Repeat the procedure in 8.2 and 8.3 with one exception: Saturate the surface with distilled water and repeat the test with the surface wet, keeping the surface saturated.

10.2 Record all readings.

11. Test Procedure Using Prepared Test Specimens

11.1 Test the prepared test specimens, both wet and dry, after cleaning the test specimens with a renovator.

12. Calculation

12.1 Calculate the static coefficient of friction as follows:

12.1.1 *Dry*:

$$F_D = (R_D/NW) + X_D \quad (3)$$

12.1.2 *Wet*:

$$F_W = (R_W/NW) + X_W \quad (4)$$

where:

F_D = static coefficient of friction for dry surface,
F_W = static coefficient of friction for wet surface,
R_D = total of the 12 dry force readings, lb (kg),
R_W = total of the 12 wet force readings, lb (kg),
N = number of pulls (12),
X_D = dry calibration factor,
X_W = wet calibration factor, and
W = total weight of the heel assembly plus 50-lb (22-kg) weight, lb (kg).

13. Report

13.1 Report the following information:

13.1.1 Type of tile or surface and

13.1.2 The individual and average static coefficient of friction for:

13.1.2.1 dry surfaces (both as-received and after cleaning) and

TABLE 1 Static Coefficient of Friction for Dry Surfaces

Surface	Average $\bar{x}$	Standard Deviation Sx	Repeatability Standard Deviation sr	Reproducibility Standard Deviation sR	Repeatability Limit r	Reproducibility Limit R
1	0.7971	0.0351	0.0242	0.0391	0.0678	0.1093
2	0.8093	0.0479	0.0183	0.0496	0.0513	0.1390
3	1.0007	0.0379	0.0228	0.0412	0.0639	0.1154
4	0.8700	0.0328	0.0173	0.0350	0.0485	0.0980
5	0.8543	0.0493	0.0093	0.0497	0.0259	0.1392

TABLE 2 Static Coefficient of Friction for Wet Surfaces

Surface	Average $\bar{x}$	Standard Deviation Sx	Repeatability Standard Deviation sr	Reproducibility Standard Deviation sR	Repeatability Limit r	Reproducibility Limit R
1	0.6757	0.0113	0.0093	0.0131	0.0259	0.0367
2	0.5129	0.0269	0.0220	0.0311	0.0617	0.0871
3	0.3200	0.0338	0.0196	0.0365	0.0550	0.1023
4	0.7321	0.0269	0.0191	0.0301	0.0534	0.0843
5	0.4993	0.0137	0.0144	0.0170	0.0403	0.0477

13.1.2.2 wet surfaces (both as-received and after cleaning).

14. Precision and Bias

14.1 *Precision*— The precision of this test method is based on an interlaboratory study of C1028-06, Standard Test Method for Determining the Static Coefficient of Friction of Ceramic Tile and Other Like Surfaces by the Horizontal Dynamometer Pull-Meter Method, conducted in February 2007. Each of seven laboratories tested five different materials. Every "test result" is calculated using twelve individual force readings. The laboratories obtained two replicate test results for each material, under both wet and dry conditions.[5]

14.1.1 *Repeatability*—Two test results obtained within one laboratory shall be judged not equivalent if they differ by more than the "*r*" value for that material; "*r*" is the interval representing the critical difference between two test results for the same material, obtained by the same operator using the same equipment on the same day in the same laboratory.

14.1.1.1 "*Sr*" represents the repeatability standard deviation

14.1.2 *Reproducibility*—Two test results shall be judged not equivalent if they differ by more than the "*R*" value for that material; "*R*" is the interval representing the difference between two test results for the same material, obtained by different operators using different equipment in different laboratories.

14.1.2.1 "SR" represents the reproducibility standard deviation

14.1.3 Any judgment in accordance with these two statements would have an approximate 95 % probability of being correct.

14.2 *Bias*—At the time of the study, there was no accepted reference material suitable for determining the bias for this test method, therefore no statement on bias is being made.

14.3 The precision statement was determined through statistical examination of 140 results, from seven laboratories, on five materials. Descriptions of the surfaces tested follow:

Surface 1: unglazed porcelain
Surface 2: glazed porcelain, lightly textured
Surface 3: glazed ceramic, lightly textured
Surface 4: unglazed porcelain, lightly textured
Surface 5: Standard Tile, glazed

To judge the equivalency of two test results, it is recommended to choose the surface closest in characteristics to the test surface.

15. Keywords

15.1 dynamometer; friction

[5] Supporting data have been filed at ASTM International Headquarters and may be obtained by requesting Research Report RR:C21-1005.

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