STAIRWAY SAFETY:
A MEASUREMENT SYSTEM STUDY OF STEP DIMENSIONAL VARIATION ON CRAFTSMAN-BUILT STAIRS

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Abstract

Stairways can be thought of as hazardous locations that have the capability of being made acceptably safe by proper design, construction, and maintenance. According to the CDC (2008), "Falls are the leading cause of nonfatal injuries in the United States." Several factors contribute to these falls. Excessive variation in the dimensions of step risers and tread depths is a major risk factor for stairway falls. In order to evaluate a stairway for uniformity, a precise measurement system is needed. The current state-of-the-art measurement system is known as the nosing-to-nosing method. Measurements are conducted by measuring the distance and angle between the adjacent step nosings. Prior researchers on this topic recommended follow-up studies to more clearly define the precision of nosing-to-nosing measurement system.

The study had three purposes. The first had two parts: (a) determine if the overall true mean of step riser height is significantly affected by steps, measurer, and the interaction of these factors, and (b) determine if the overall true mean of step tread depth is significantly affected by steps, measurer, and the interaction of these factors. The second purpose of this experiment was to determine the precision of the nosing-to-nosing measurement system. The third purpose of this study was to evaluate the precision of the nosing-to-nosing measurement system against criteria for measurement systems adopted by the automotive industry.

Five older buildings on the Montana Tech Campus were assessed to determine which stair flights would be chosen for measurement. Most of the eight randomly chosen eight flights from these buildings were built by craftsmen. Each flight was measured twice on the same day by two measurers. This resulted in 324 riser height and 292 tread depth values. The ANOVA portion of this analysis determined that the steps, measurer, and their interaction significantly affected the riser height and the tread depth. The Gage R&R analysis determined that the measurement system contributed 1.18% and 2.61% of total variability in riser height and tread depth, respectively. These findings were evaluated against criteria for measurement systems adopted by the automotive industry. Both were within the 1-9% range the automotive industry considers acceptable depending on the application, the cost of the measuring device, cost of repair, or other factors.

Keywords: Step dimensional variation, Craftsman-built stairs, Step-riser height, Nosing-to-nosing measurement system

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1. Introduction

Stairways can be thought of as hazardous locations that have the capability of being made acceptably safe by proper design, construction, and maintenance (Jensen, 2012). Fall injuries occur in public places, residences, and workplaces. Several factors contribute to these falls. Personal factors such as age, gender, footwear, carrying items, handrail use, and drugs and alcohol are included in these factors. Environmental factors such as location, lighting, debris/wetness, and visual distractions are also fall contributors. Stairway physical factors include step dimensions, coverings, nosings, handrails, and guardrails.

Stair step variation is a risk factor because people do not expect variation in the steps, the step variations are not easily noticeable, people do not adjust their gait when needed because they are unaware the step variation exists, and the non-uniformity of adjacent step causes a misstep (Jensen, 2012). While step variation is recognized as a significant risk factor, research issues exist on matters of measurement methodology and acceptable size of step variation.

Two related studies addressing measurement of step uniformity were conducted prior to this study. The first study was conducted by Lea Jensen and Craig Ross (Jensen, Jensen, and Ross, 2013). The second, conducted by Chris Hicks and Joselynn Neary, was an exact replication of the first study (Hicks, Jensen, and Adams, 2013). That is, both studies measured the same six flights of stairs, used the same instruments, and followed the same procedures. Both of the prior studies had limitations because measurements were taken at three lateral points on each step, and a new marking was put on each step each time the stairs were measured which may have added unknown variation. Another difference that probably affected variation was that two of the flights had the linoleum replaced during the time between these studies.

According to Jones, Derby, and Schmidlin (2010), “An exact replication provides a moderate level of corroborations; whereas a partial replication has the potential to provide stronger corroboration.” The study reported here was undertaken as a partial replication.

2. Purpose and Hypotheses

The study had three purposes. The first had two parts: (a) determine if the overall true mean of step riser height is significantly affected by steps, measurer, and the interaction of these factors, and (b) determine if the overall true mean of step tread depth is significantly affected by steps, measurer, and the interaction of these factors. The experimental plan was to provide data for analysis using a two-way classification analysis of variance with interaction, according to the model:

$$H_{ijk} = \mu + S_i + M_j + (SM)_{ij} + \varepsilon_{ijk}$$

Where:

H_i is the height of step ijk,
μ is the overall mean of all step height measurements
S_i is true effect of the ith step,
M_j is the true effect of the jth measurer, and
$(SM)_{ij}$ is the effect of the interaction between S_i and M_j, and
ε_{ijk} is a random error component.

The following hypotheses will be tested using a common 0.05 significance level. Replacing H_{ijk} in the model with the tread depth (D_{ijk}), the same hypotheses can be tested.

H_0:	$S_i = 0$	(Steps had no significant effect)
H_A:	$S_i \neq 0$	(Steps had a significant effect)
H_0:	$M_j = 0$	(Measurers had no significant effect)
H_A:	$M_j \neq 0$	(Measurers had a significant effect)
H_0:	$(SM)_{ij} = 0$	(The interaction term had no significant effect)
H_A:	$(SM)_{ij} \neq 0$	(The interaction term had a significant effect)

The second purpose of this experiment was to determine the precision of the nosing-to-nosing measurement system. A statistical procedure used by quality control engineers breaks down precision into two components—repeatability and reproducibility (R&R). Known as Gage R&R, the procedure determines the percentage of total variability attributed to repeatability, reproducibility, and the actual differences in the dimensions of the steps.

The third purpose of this study was to evaluate the precision of the nosing-to-nosing measurement system against criteria for measurement systems adopted by the automotive industry. A very precise measurement system will have a small percentage of variability from R&R.

3. Background of Literature Review

3.1. Magnitude of the Problem

Fall injuries have a negative impact on individuals, society, and the healthcare system (Cohen, LaRue, and Cohen, 2009). According to the CDC (2008), "Falls are the leading cause of nonfatal injuries in the United States". There were 18,044 deaths and 701,000 hospitalizations because of stairway falls in 2003 (State & Territorial Injury Prevention Directors Association, 2006). According to Maynard and Brogmus (2007), "There were over 8 million people that were treated for fall related injuries in 2004." Falls have also contributed to 7.2 million emergency room visits that resulted in the treatment and release of patients (Cohen, LaRue, and Cohen, 2009).

A prior study of the economic burden of injuries in the United States reported in 2006 determined that $26.9 billion in healthcare expenses were due to fatal and non-fatal fall-related injuries, and is projected to increase to $32.4 billion (Finkelstein, Corso, and Miller, 2006). The common injuries that occur from these non-fatal falls are bruises, sprains, and fractures. Falls at home and falls in the workplace cause the same problematic injuries.

Pauls (1991) stated that, "One person in twenty is treated in an emergency room because of a fall." This ratio totals over twelve million people a year in the United States treated because of this type of accident (Pauls, 1991). When compared to motor vehicle accidents, falls are the second leading cause of fatal injuries in the U.S. In the early 1980s the Consumer Product Safety Commission (CPSC), using data from the National Electronic Surveillance System, estimated that 800, 000 injuries occur each year due to stair falls (CPSC, 1984). In 1978, Alessa et al. estimated that falls on stairs cost the United States society about $6,000,000,000 each year. This estimate includes lost wages, medical expenses, indirect costs in work accidents, and insurance

administration. According to Rice and Mackenzie et al. (1989), “The number of injuries could be substantially reduced by greater application of current knowledge.”

3.2. Risk Factor Studies

Behavior, maintenance, and design are the three major reasons for stair accidents (Roys, 2001). User behavior could include running downstairs, playing, or not paying attention. Behavior accidents are difficult to control and will most likely continue to occur (Roys, 2001). Maintenance is necessary in order to prevent deterioration of stair conditions, and is easier to control. Accidents that occur because of user behavior and maintenance can be addressed by accident reduction programs (Roys, 2001). Improving stair design would have the most impact on accident reduction when these falls are attributed to stair design flaws (Roys, 2001). Irregular sized risers and effective tread depth are examples of poor design because the next step is usually not anticipated correctly.

Because irregularities in step dimensions are risk factors, clarity about the dimensions and terminology is essential. Roys (2000) refers to effective tread depth as goings. If the pitch of the stairway is too large or the goings (aka effective tread depth) are too small, the risks involved with walking down the stairs is greatly increased (Roys, 2001). Figure 1 below shows simple stair geometry of a stairway.

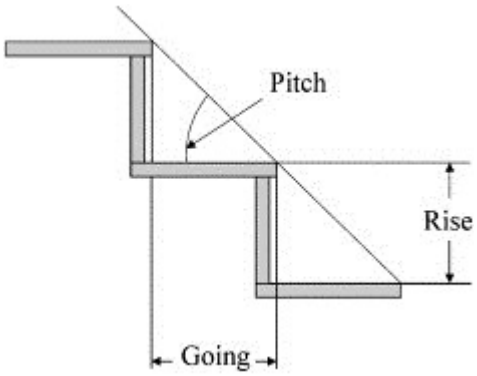

Figure 1. Stair geometry (Roys, 2001)

Roys (2001) provided an explanation that described the basic components of stair geometry. The “rise” is the vertical distance between the adjacent treads. The “going” (aka effective tread depth) is the horizontal distance between the two adjacent nosings. The “pitch” is the angle between the line that joins the adjacent nosing and the horizontal treads. Stair effective tread depth and pitch should be determined by safety instead of limited space.

Accidents tend to be more severe during stair descent because the stair user tends to fall forward and downwards (Roys, 2001). Accidents tend to be less severe during ascent because the center of gravity of the stair user is forward and the person tends to fall towards the higher steps (Roys, 2001). Falls that occur during stair descent most commonly lead to broken bones and head injuries.

A paper by Cohen, LaRue, and Cohen (2009) summarized their analyses of 80 stairway-fall incidents that occurred between 1992 and 2007. The user factors that contributed to these falls were directional ascent/descent, age, gender, footwear, carrying items, handrail use, and drug & alcohol use. The environmental factors that contributed to these falls were location, lighting, debris, and wetness. The stairway characteristics that contributed to these falls were riser and tread dimensions, dimensional inconsistencies, and nosing strips. These authors reported that, “Excessive dimensional variation appeared to be the most pervasive factor in stairway fall causation.”

Di Pilla (2010) provided an explanation of how stairway missteps occur. Stair missteps such as oversteps and heel scuffs are common stairway fall contributors. One type of overstep is rotation of the foot until the leg can no longer support the weight. When body weight is applied to the leading foot, it causes the person to collapse or fall forward. The second type of overstep occurs when the foot immediately slips off of the nosing. Rapid slipping causes loss of body

support and leads to a fall. Heel scuffs occur when a person tries to counterbalance foot placement to avoid overstepping the tread. Overstepping the tread leads to scuffing the heel against the riser. Di Pilla (2010) commented that these types of missteps occur because of undersized treads and irregular tread depths.

Missteps can occur because of user expectations. The variations of a step are hard to see, and step users do not usually expect the variations to be there (Archea et al, 1979). In descent, the ball of the foot should be placed near the nosing of the next step to prevent a misstep (Johnson, 2005). The ball of the foot can be placed too far forward if there is a variation in riser height or tread depth (Johnson, 2005).

People who use stairs usually only pay attention to the first and last three steps of the stair flight when ascending and descending the stair flight (Archae et al, 1979; Maynard and Brogmus, 2007). Research shows that 70% of stair accidents occur on the top and bottom three stairs of a stair flight (Di Pilla, 2010). Because of this, the dimensions of the top and bottom three stairs is of substantial importance.

3.3. Codes and Guidelines

Stairway falls can result from a combination of human, behavioral, environmental, and other factors that are related to the victim and location of the accident (Webber, 1985). A study was conducted by Webber (1985) that examined long-term trends of accidental falls in England and Wales. This information was retrieved from the Registrar General's Statistics on fatalities. The author believes that safety is the main purpose of Building Regulations. Webber (1985) reported that before 1965 there was an increase in accidents in homes that were a result of badly designed and constructed stairways in England and Wales. Regulations were introduced that controlled rise, effective tread depth, pitch, and headroom of stairways (Webber, 1985). The

study also assessed if there was evidence of a reduction of accident rates after regulations and standards were put into place. Deaths due to accidents in England and Wales are classified accordingly and published annually (Webber, 1985). After examining this data it was determined that there were 59 fatal accidents in 1973 that involved stairs.

In 1965 the British Standards and Building Regulations made some recommendations for different categories of stairs. Webber (1985) provided a brief explanation of those recommendations. The first set of recommendations was for common stairs. Between 1972 and 1976, some modifications were made to the recommendations of the rise, tread, and pitch. The upper limit of 38^{o} of the pitch for common stairs remained the same between 1965 and 1976. In 1976, the building regulations raised the minimum limit of the effective tread depth from 230 mm to 240 mm for common stairs. The second set of recommendations was for private stairs. The pitch recommendation of 42^{o} or less remained the same between 1965 and 1976.

Data were analyzed again in 1980 after the modifications were made to building codes to see if the number of fatalities due to stair accidents had declined. After evaluation of the data, they found that stair fall represented 7% of non-transport fatalities. In 1980, stair falls were 15% of all fall accidents (Webber, 1985). Eighty-five percent of these stair falls occurred at home (Webber, 1985). This study revealed the between 1954 and 1970 there was a slow decline in stair fall fatalities. This slow decline had a one third incidence rate decrease of about six falls for every million people. This study also revealed that between 1970 and 1980 there was a rapid decline in stair fall fatalities. This decline also had a one third incidence rate drop per million people, but in a shorter amount of time. The stair fatality incident rate dropped a total of two thirds between 1954 and 1980. Stair design regulations played an important role decreasing stair

fall incidents. The number of accidents analyzed annually for this may have led to some limitations because of underreporting.

According to Roys (2001), "Stair injuries can be prevented by making the stair effective tread depth larger than the feet of the users." Maynard and Brogmus (2007) recommend, "Keeping riser heights between 4 and 7 inches, minimum treads depths of 11 inches, and using slip resistant tread surfaces to reduce accidents during stairway use." The British Standards Institute (1984) made a new recommendation of a minimum of 280 mm for stair effective tread depth for public building stairways that have high traffic. The distance of 280 mm is roughly 11.04 inches, which falls within the 7-11 rule of thumb for stairs in the United States. This distance compares favorably to the foot size of the average adult population males and females that have a foot length less than 280 mm (Roys, 2001). The guidance from the British Standards Institute (1984) also calls for a minimum effective tread depth of 250 mm for public buildings with low traffic. Private stairs have a minimum effective tread depth recommendation of 220 mm. The rise range for domestic properties is 220 mm to100 mm. This limitation is acceptable for rise heights because it prevents the climb from being to excessive and the step from being so low that they become a tripping hazard. The effective tread depth limit for domestic properties is between 220 and 350 mm. The pitch limitation for domestic properties is 42^{o}. Stair manufacturers and designers cannot be stopped from making stairs with larger tread depths because the guidelines in Great Britain are only a minimum value (Roys, 2001). The author comments that this occurs because of the pressure for stairs to take up less floor space instead of more floor space. If larger treads were designed in new buildings, 5% of stair accidents, (1250 accidents and 2 deaths) that may be prevented each year (Roys, 2001).

There are three characteristics for safer stairs. These characteristics include steps that can be seen clearly, larger treads that have adequate footing clearance, and handrails that can be easily reached and grasped (Archea et. al, 1979). The matter of step geometry has been addressed as a formal debate in public hearings and in publication. A debate between stairway safety expert Jake Pauls and the National Association of Home Builders (NAHB) focused on the minimum requirements for stair treads and risers. Pauls argued for a minimum requirement for stair treads of at least 11 inches, and a stair riser maximum of 7 inches (Pauls, 1991). Table 1 below lists the different standards for stairs for different years in Great Britain and the United States.

Table 1. Stair Standards for Different Years and Countries

Source	Tread Depth		Riser Height		Pitch
	in.	mm.	in.	mm.	
British Standards Institute 1965 (common stairs)	9.06	230	-	-	38°
British Standards Institute 1976 (common stairs)	9.45	240	-	-	38°
British Standards Institute 1965 (private stairs)	9.06	230	-	-	42°
British Standards Institute 1965 (private stairs)	9.45	240	-	-	42°
British Standards Institute 1984 (private stairs)	8.66	220	-	-	42°
British Standards Institute 1984 (public building with high traffic)	11.04	280	-	-	42°
British Standards Institute 1984 (public building with low traffic)	9.84	250	-	-	42°
British Standards Institute 1984 (domestic properties)	8.66-13.78	220-350	8.66-3.94	220-100	42°
United States Rule of Thumb	11	279.4	7	177.8	30-35°

The ANSI/ASSE A1264, 1-2007 specifies step uniformity as follows, “Riser height and tread depth shall be uniform throughout any flight of stairs including any foundation structure used as one of more treads of the stairs.” The explanation associated with this specification is as

follows, “The tolerance between the largest and smallest riser or between the largest and smallest tread should not exceed 3/8 inches (9.5 mm) in any flight.” Additionally, the guidelines indicate that adjacent steps in a uniform stairway flight will not differ in tread depth or riser height by more than 3/16 inch (4.8 mm). Apparently, the code officials who establish these standards assumed that the 3/16 inch standard was feasible to measure that precisely—this study examines that assumption.

The main message is that authors and codes differ on what they consider proper step dimensions and permissible variability. Stairways that conform to applicable standards are generally regarded as safe, and non-conforming stairways are regarded as unsafe. Although an oversimplification, this distinction becomes important in litigation following a stairway fall injury.

3.4. Litigation

Many litigation issues exist that occur in the event of a fall. Understanding the concept of stair variation and how it can contribute to stairway falls is important. A forensic ergonomist can be called on to determine why someone falls on a stairway (Johnson, 2005). A forensic ergonomist measures step geometry and interviews the participant and witnesses to collect the details of the fall. Regarding step geometry, the attorneys expect the ergonomist to determine if the steps conformed to the building code or other applicable standards. The plaintiff wants to prove the stairway had a defect that caused the fall, and the defendant (building owner) wants to prove the stairway met code. The most important standard for these cases is dimensional variation in adjacent steps. For workplace stairs, an important standard in the U.S. is that of the American National Standards Institute (ANSI A1264 Committee, 2007).

History shows that building code officials modify code provisions based on accident statistics, research, findings, and litigation cases (Pauls, 1991). According to Pauls (1991), "Building codes and standards have the potential of drastically influencing the quality of environments as designed, built, maintained, and retrofitted." In his 1991 paper, Pauls reported that codes and standards have been changed because of litigation related investigations of stair fall cases, recent research, and observations of building use.

3.5. Measurement Systems

3.5.1. Physical Measurement of Step Dimensions

A common approach for specifying step dimensions is to use the 7-11 rule of thumb, i.e., 7 inch risers and 11 inch treads. It was mentioned by Hodgson as long ago as 1903. According to Johnson (2005), a study conducted by Templer (1974) found that missteps occurred on stairs and when the risers exceeded 7.2 inches and when the treads were shorter than 12.3 inches. This subsection explains the traditional measurement method and the newer nosing-to-nosing method. Figure 2 shows the common terms for measuring step dimensions.

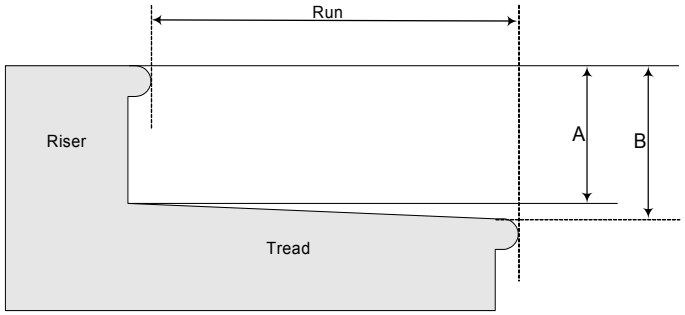

Figure 2. Terms and common lengths. Riser height B is most important.

Figure 3 shows the traditional measurement methods for measuring using a carpenter's square. The upper sketch shows how riser height is not fully accounted for when there is a slope in the tread. The lower sketch shows how a true measure of riser height (B) would need to add

length A and A2. Length A2 is very difficult to measure precisely using the carpenter's square method.

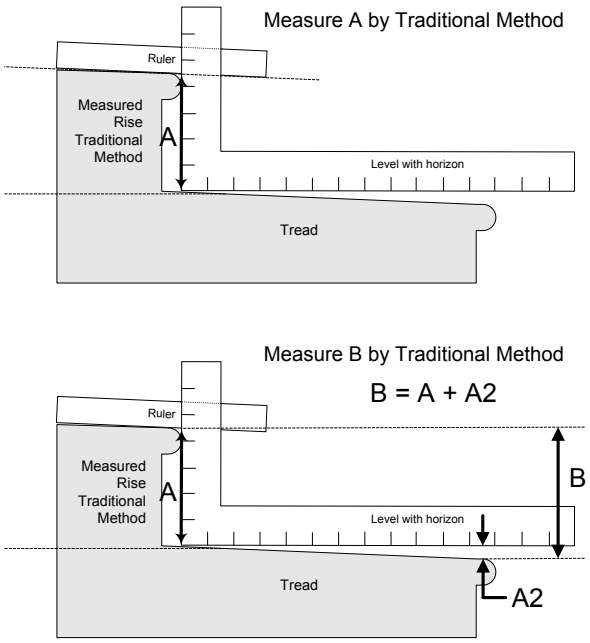

Figure 3. Traditional measurement methods using a carpenter's square. Slope in tread ignored in upper sketch, and accounted for in lower sketch.

The current method for measuring stair variation is called the nosing-to-nosing method. The nosing-to-nosing method is conducted by measuring the distance and angle between the adjacent stair nosings. The distance measured forms the hypotenuse of a right triangle (Johnson, 2005). The sine of the angle multiplied by the distance is the rise, and the cosine of the angle multiplied by the distance is the tread depth (Johnson, 2005). The rise height, tread depth length, and adjacent step differences can be determined using the nosing-to-nosing method. The traditional method is not reliable for determining if a stairway meets code (Johnson, 2005). The nosing-to-nosing method is quicker or more accurate for stair geometry measurement when it is compared to the traditional method (Johnson, 2005). Figure 4 shows the nosing-to-nosing method for measuring the angle and hypotenuse length of two adjacent stairs.

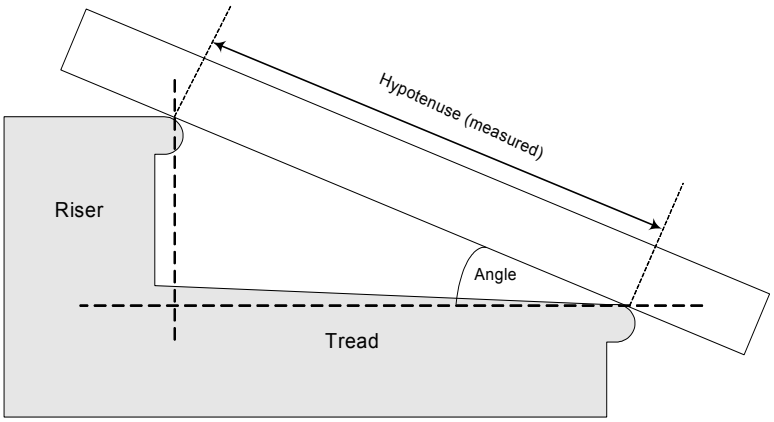

Figure 4. The angle and the hypotenuse length measurements.

There will always be variation when you measure the results of a process (Minitab, 2000). For the process of constructing a flight of stairs, the builder generally attempts to create uniform step geometry, but in practice, there will be variability. The variation occurs because there are differences between items measured, and the methods for taking measurements are not perfect. Because of this fact, repeating measurements does not always produce identical measurement results (Minitab, 2000).

3.5.2. Research into Measurement Systems

Repeatability is a term for the extent of consistency when the same person performs a measurement repeatedly using the same tool (Minitab, 2000). The variation in measured values may also be called intra-measurer variability. Reproducibility occurs when two different measurers perform the same measurement repeatedly using the same tool (Minitab, 2000). The variation in measured values due to the measurers may be called inter-measurer variability. Quality control specialists refer to an experimental design for determining reproducibility and repeatability as a Gage R&R Study. The experiment involves two or more measurers using a measurement system to measure a batch of parts twice each. This provides data for determining

intra-measurer variability and inter-measurer variability. To study the nosing-to-nosing measurement system, instead of measuring parts with a gage, we measure step dimensions using the nosing-to-nosing measurement system.

The two components that make up total variance are step-to-step variation and measurement system variation. Repeatability and reproducibility are the two components of the measurement system variation. Figure 5 below depicts the variance breakdown for total variance.

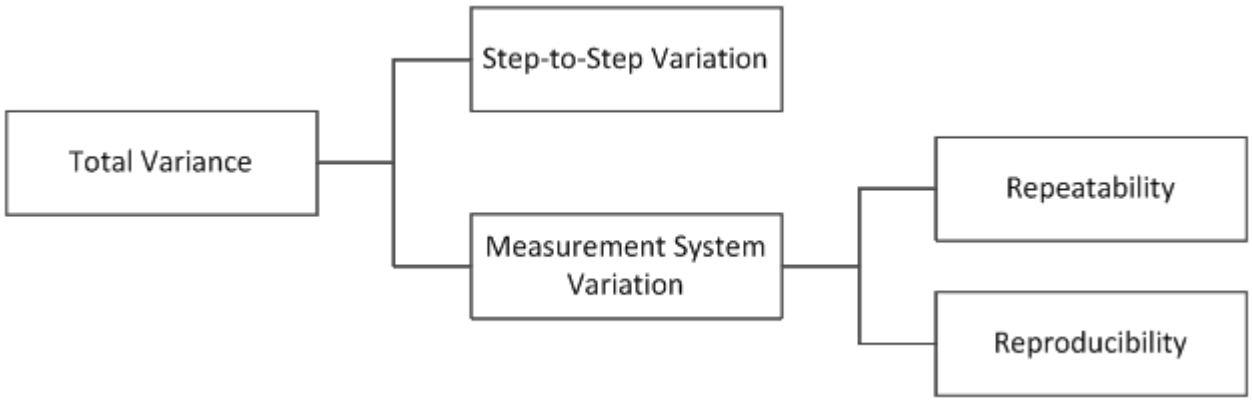

Figure 5. Components of total variance

4. Methodology

4.1. Stairway Sample

Five buildings were assessed to determine which stair flights would be chosen. The Science and Engineering Building, Engineering Building, Main Hall, Museum Building, and Health and Sciences Buildings were the buildings that were assessed. These had numerous craftsmen-built stairways. Some stairways were steel forms with concrete fill and covering applied by craftsmen. In the five buildings, all flights with eight or more steps were identified. This created a list of 26 flights eligible for this study. The list of these flights is located in Appendix A. The 26 flights were assigned flight numbers. Eight of the 26 flights were chosen by using a random numbers formula from the Microsoft Excel program. The steps with these eight flights were assigned step numbers in order to randomly choose a measurement order for the measurers.

4.2. Procedure

The eight flights were measured on the same day by both measurers. The procedure for measurements for each flight consisted of one marking, two measurers, and two measurement repetitions by each measurer. The marking was placed on each step approximately 407mm from the railing or wall on the left side of each flight. The reference point for the left side of the staircase is looking up from the bottom of the flight to the top of the flight. The left side was chosen because it is commonly the stair descent side of stair traffic. A chalk line was used to line up all markings on each flight. The results for measurements for all eight flights are located in Appendix B.

The measurements were taken with an electronic level called a Smarttool®. A Smarttool® is accurate to the 0.1 degree. A straightedge metal ruler was used to measure the distance

between the points on the adjacent nosings. This method is done by measuring from the nosing of one step to the nosing of the next step. The measurements were taken from the same marks on each step on the same day to reduce limitations and errors. The measured distance and angle between adjacent nosings formed the hypotenuse of a right triangle were used to compute riser height and tread depth.

4.3. Analyses

4.3.1. Descriptive Statistics

Raw data were initially recorded on a Microsoft Excel spreadsheet. Rise and tread depth lengths were determined by inserting the hypotenuse and angle into a Microsoft Excel formula sheet. This resulted in 324 riser height and 292 tread depth values. The raw data are in Appendix B. Adjacent step differences were completed, and subsequently transferred to Minitab 16 using the Gage Repeatability and Reproducibility (Crossed Study) program. This program was used to perform statistical analyses, starting with descriptive statistics.

4.3.2. Statistical Analyses

For purpose 1 of this project, the ANOVA portion of this analysis breaks down reproducibility by measurer and measurer-by-step interactions (Minitab, 2000). The following two-factor ANOVA model for a balanced experiment was used.

$$H_{ijk} = \mu + S_i + M_j + (SM)_{ij} + \varepsilon_{ijk}$$

For purpose 2 of this project, the Gage R&R analysis determined how much of the total variation was due to measurement variation (Minitab, 2000; Montgomery, 2013). The Gage

R&R (crossed) analysis was used because each step was measured twice by each measurer (Minitab, 2000).

For purpose 3 of this project, the nosing-to-nosing measurement system was evaluated against criteria for measurement systems adopted by the automotive industry. The following criterion for variation was proposed by the Automobile Industry Action Group (AIAG) to determine if a measurement system was acceptable (Automotive Industry Action Group, 2002). The Gage R&R total contribution to total variance was compared to these automotive guidelines as described in table 2.

Table 2. Measurement System Acceptability

Contribution to Total Variability (%)	Level of Acceptability
Less than 1%	The measurement system is acceptable.
Between 1% and 9%	The measurement system is acceptable depending on the application, the cost of the measuring device, cost of repair, or other factors.
Greater than 9%	The measurement system is unacceptable and should be improved.

5. Results

Analyses were conducted separately for tread depth and riser height. Appendix C includes all rise and run and computations, along with the average and median values for each flight and measurement set. Subsections 5.1 and 5.2 present results for tread depth and riser height, respectively. Within each subsection, the ANOVA results are presented first and the Gage R&R second.

5.1. Tread Depth Analyses

For tread depth, Tables 3 and 4 show the results from the ANOVA and the Gage R&R analysis, respectively.

Table 3. Results Table for Tread Depth

Source	*df*	*SS*	*MS*	*F*	*p*
Step	72	117908	1631.076	261.076	0.000
Operator	1	117	117.46	18.726	0.000
Step*Operator	72	452	6.27	3.233	0.000
Repeatability	146	283	1.94		
Total	291	118761			

Note on column heads. *df* = degrees of freedom. *SS* = sum of squares. *MS* = mean square = *SS/df*. *F* = the test statistic. *p* = probability the factor has no effect on the dependent variable.

Table 4. Gage R&R Variance Contribution to Tread Depth Measurements

Source	Variance Component	% Contribution (of Variance Component)
Total Gage R&R	4.868	1.18
Repeatability	1.940	0.47
Reproducibility	2.928	0.71
Operator	0.762	0.18
Operator*Step	2.166	0.52
Nosing-to-Nosing	407.835	98.82
Total Variation	**412.703**	**100.00**

The ANOVA results in Table 3 indicate virtually no probability of any of factor term being zero (p = .000 for each). Thus, the null hypotheses are rejected in favor of the alternative hypothesis. In other words, all three terms significantly contributed to variance of the tread depth measurements. The highest F value is always the strongest for significance. The physical step dimensions contributed most significantly to the variance resulting in the F value of 261.076.

The Gage R & R results in Table 4 indicate that R & R contributed 1.18% of the total variance from the measurers. The 1.18% measurement variability consists of 0.47% repeatability and 0.71% reproducibility. Between the significance values from the ANOVA analysis, and the percent contribution percentages from the Gage R & R analysis, the main contributor to total step variation was due to actual step differences. Figure 6 below is a box plot to compare the measurements of the two measurers. It shows a very small difference in means and similar distributions of measured values.

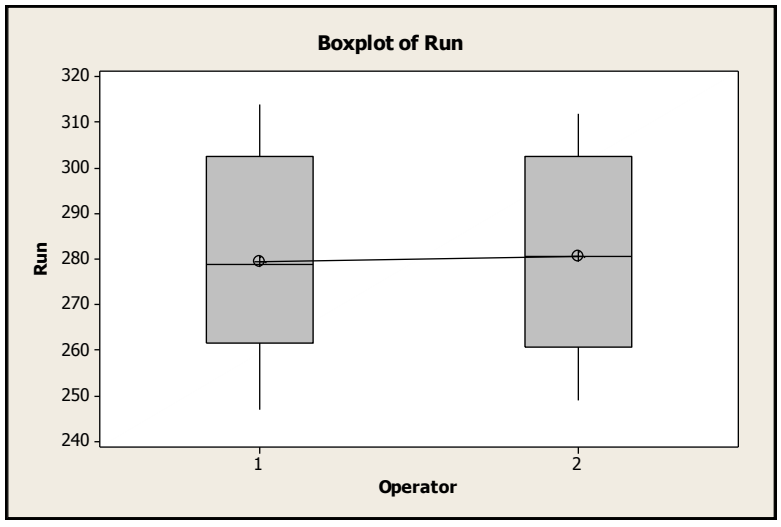

Figure 6. Boxplot for tread depth measurements for Measurers 1 and 2.

5.2. Riser Height Analyses

For riser height, Tables 5 and 6 show the results from the ANOVA and the Gage R&R analysis, respectively.

Table 5. Results Table for Riser Height

Source	*df*	*SS*	*MS*	*F*	*p*
Step	80	29371.7	367.146	107.431	0.000
Operator	1	48.0	48.006	14.047	0.000
Step*Operator	80	273.4	3.418	3.802	0.000
Repeatability	162	145.6	0.899		
Total	**323**	**298.38.7**			

Note: See footnote to Table 3 for column headers.

The ANOVA results in Table 5 indicate virtually no probability of any of the terms being zero (p = .000 for each). Thus, the null hypotheses are rejected in favor of the alternative hypothesis. In other words, all three terms significantly contributed to variance of the riser height measurements. The physical step dimensions resulted in an F value of 107, which indicates it was the strongest contributor to significance.

Table 6. Gage R&R Variance Contributions for Riser Height Measurements

Source	VarComp	% Contribution (of VarComp)
Total Gage R&R	2.4335	2.61
Repeatability	0.8990	0.96
Reproducibility	1.5345	1.64
Operator_1	0.2752	0.29
Operator_1*Step_1	1.2593	1.35
Nosing-to-Nosing	90.9320	97.39
Total Variation	**93.3655**	**100.00**

The results of the Gage R&R analysis in Table 6 indicate that 2.61% of the variance came from the measurers. The 2.61% measurement variability consists of 0.96% repeatability and 1.64% reproducibility. Between the two analyses of riser height, physical step dimension was the main contributor to total step variation, and reproducibility was the main contributor to the measurement variation results. Figure 7 below is a box plot to compare the measurements of the two measurers. It shows a very small difference in means and similar distributions of measured values.

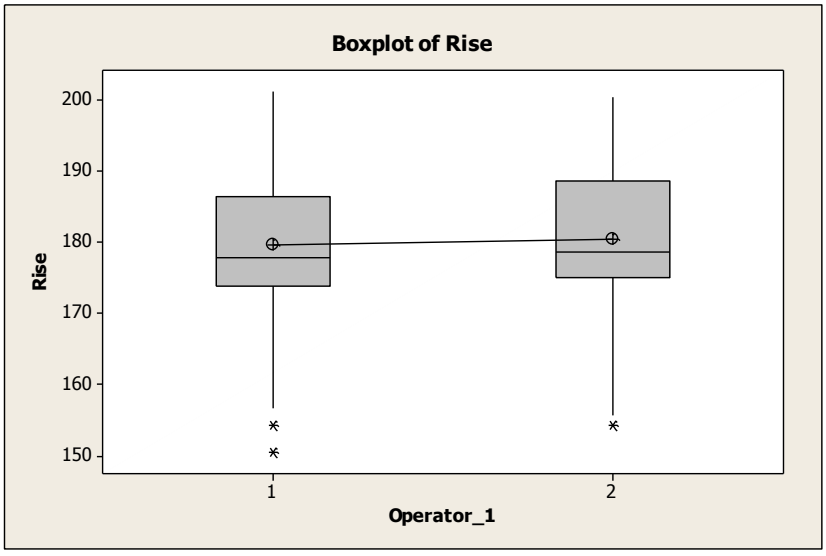

Figure 7. Boxplot for rise measurements for Measurers 1 and 2

5.3. Measurement System Acceptability

Guidelines proposed by AIAG were considered to assess the acceptability of the measurement system (Automotive Industry Action Group, 2002). These guidelines apply to the R&R contribution to total variance. Table 7 summarizes the results of the Gage R&R analyses.

Table 7. Gage R&R Variance Analysis for Measurers

	Total Gage R&R	Repeatability Contributor	Reproducibility Contributor
Riser Height	1.18%	0.47%	0.71%
Tread Depth	2.61%	0.96%	1.64%

Results of this experiment fell into the middle range—acceptable depending on the application, the cost of the measuring device, cost of repair, or other factors.

6. Discussion and Conclusions

The study had three purposes. Purpose 1 had two parts: (a) determine if the overall true mean of step riser height is significantly affected by steps, measurer, and the interaction of these factors, and (b) determine if the overall true mean of step tread depth is significantly affected by steps, measurer, and the interaction of these factors. This determination was made using a two-way ANOVA system. Purpose 2 was to determine the precision of the nosing-to-nosing measurement system using the Gage R&R procedure. Purpose 3 was to evaluate the precision of the nosing-to-nosing measurement system against criteria for measurement systems adopted by the automotive industry.

For both parts of Purpose 1, the overall true mean of step riser height and tread depth were significantly affected by the steps, measurer, and the interaction between the steps and measurer. The physical step dimensions proved to be the strongest contributor to significance. The *p* values for riser height and tread depth were all below 0.05, so the null hypotheses for Purpose 1 are rejected, and it is concluded that the alternative hypotheses are accepted. Thus, all three terms significantly affect both tread depth and riser height.

For Purpose 2, the percentage of the variability for the rise data and tread data was attributed to steps, measurer, and the interaction between steps and measurer. This analysis also showed that physical step dimensions were the main contributor to the measurement variation results.

For Purpose 3, the findings indicate the measurement system is more than 1% and therefore is not unequivocally acceptable. Rather, the variation due the measurer variability were within the second category (1–9%), and are therefore acceptable if no better alternative is feasible.

Descriptive statistics were obtained for riser height, tread depth, adjacent step differences for riser height, and adjacent step differences for tread depth in flights of stairs in buildings on the Montana Tech campus. The descriptive data showed relatively no difference between the first and second measurements by each measurer, but there was some difference between the measurements taken by the two measurers.

The project has limitations. First, the sample of stairways was small and cannot be claimed to be representative of stairways other than those in the five buildings. A second limitation is that the project did not include analyzing the adjacent-step dimensional differences.

7. Future Recommendations

Some suggestions for follow-up studies are offered below.

1. Examine the adjacent step differences in tread depth and riser height. Data from this experiment and the two earlier experiments can be used. Use these data sets to compute the measurement systems variability for the adjacent-step differences. This would be more directly applicable to the ANSI/ASSE/ standard than riser height and tread dimensions.
2. The lateral position of the chalk line for taking measurements is unspecified in the standards. Consider an experiment to have a group campus students descend and ascend a stairway using a handrail. Use video-taping to record the distance from handrail to the mid-plane of the body. Results could be used to recommend a standard lateral position for taking measurements.

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Appendix A: Stairway List

STAIRWAY LIST		
Building	**Flight**	**Number of Steps**
S & E Building	NE 2nd Floor to midlanding	10
S & E Building	SE 2nd Floor to midlanding	10
S & E Building	NE Midlanding to 2nd floor	9
S & E Building	SE Midlanding to 2nd floor	9
S & E Building	NE Ground floor to midlanding	10
S & E Building	SE Ground floor to midlanding	10
S & E Building	Tunnel access midlanding to ground floor	10
Engineering Hall	Tunnel access midlanding to ground floor (top step excluded)	12
Main Hall	Tunnel access to midlanding	15
Main Hall	Ground floor to midlanding	14
Main Hall	NE Midlanding to 2nd floor	13
Main Hall	SE Midlanding to 2nd floor	13
Main Hall	Midlanding to 3rd floor	16
Museum Building	Tunnel access midlanding to ground floor	11
Museum Building	SW Ground floor to midlanding	14
Museum Building	NE Ground floor to midlanding	14
Museum Building	SW 2nd floor to midlanding	8
Museum Building	NE 2nd floor to midlanding	8
Health Sciences Building	NW Basement to midlanding	10
Health Sciences Building	SW Basement to midlanding	10
Health Sciences Building	NW Midlanding to first floor	10
Health Sciences Building	SW Midlanding to first floor	10
Health Sciences Building	NW 1st floor to midlanding	10
Health Sciences Building	SW 1st floor to midlanding	10
Health Sciences Building	NW Midlanding to 2nd floor	10
Health Sciences Building	SW Midlanding to 2nd floor	10

Appendix B: Raw Data Measurement Results for all Flights

S & E Building-NE Midlanding to 2nd floor						
Measurer 1						
Measurement 1			Measurement 2			
Step	Angle	Hypot. Length (mm)	Step	Angle	Hypot. Length (mm)	Measure by assigned sample #
1	34.1	325	1	34.2	325	8
2	34.8	325	2	34.8	324	1
3	34.6	318	3	34.5	318	7
4	33.6	320	4	33.7	320	9
5	34.4	322	5	34.3	323	2
6	33.8	320	6	33.8	320	4
7	34.8	327	7	35	327	6
8	33.1	318	8	33.1	316	3
9	31.3	320	9	31.3	320	5
S & E Building-NE Midlanding to 2nd floor						
Measurer 2						
Measurement 1			Measurement 2			
Step	Angle	Hypot. Length (mm)	Step	Angle	Hypot. Length (mm)	Measure by assigned sample #
1	33.8	327	1	34.1	332	8
2	34.8	333	2	34.9	330	1
3	34.6	325	3	34.6	322	7
4	33.7	330	4	33.6	330	9
5	34.4	330	5	34.3	328	2
6	33.8	328	6	33.8	325	4
7	35	334	7	35	333	6
8	33.1	326	8	33.1	325	3
9	31.1	320	9	31.1	320	5

S & E Building- SE Midlanding to 2nd floor						
Measurer 1						
Measurement 1			Measurement 2			
Step	Angle	Hypot. Length (mm)	Step	Angle	Hypot. Length (mm)	Measure by assigned sample #
1	33.7	315	1	33.5	314	5
2	34.6	323	2	34.6	325	7
3	34.4	323	3	34.4	323	9
4	34.7	322	4	34.7	325	2
5	33.7	325	5	33.8	323	4
6	33.8	324	6	34.1	324	8
7	34.5	329	7	34.8	326	1
8	33.5	320	8	33.5	320	3
9	34.2	320	9	33.9	320	6

S & E Building- SE Midlanding to 2nd floor						
Measurer 2						
Measurement 1			Measurement 2			
Step	Angle	Hypot. Length (mm)	Step	Angle	Hypot. Length (mm)	Measure by assigned sample #
1	33.5	316	1	33.7	314	5
2	34.6	327	2	34.6	324	7
3	34.3	324	3	34.5	325	9
4	34.8	330	4	34.7	326	2
5	33.9	325	5	33.8	324	4
6	33.9	325	6	34	325	8
7	34.8	330	7	34.7	330	1
8	33.5	324	8	33.6	324	3
9	32.6	320	9	33.5	320	6

Main Hall-Ground floor to midlanding						
Measurer 1						
Measurement 1			Measurement 2			
Step	Angle	Hypot. Length (mm)	Step	Angle	Hypot. Length (mm)	Measure by assigned sample #
1	29.8	347	1	29.8	347	12
2	31.6	360	2	31.6	358	3
3	30.4	348	3	30.4	348	13
4	30	350	4	30	346	2
5	31.3	355	5	31.3	358	5
6	30.5	351	6	30	357	4
7	30.7	345	7	30.6	344	7
8	30.1	350	8	30.1	350	14
9	30.2	350	9	30.1	350	11
10	29.1	350	10	29.1	349	9
11	29.1	349	11	29	354	10
12	30.2	356	12	30.1	354	1
13	27.7	348	13	27.6	348	8
14	25.7	347	14	26.4	347	6

Main Hall-Ground floor to midlanding						
Measurer 2						
Measurement 1			Measurement 2			
Step	Angle	Hypot. Length (mm)	Step	Angle	Hypot. Length (mm)	Measure by assigned sample #
1	29.8	351	1	29.8	350	12
2	31.5	362	2	31.6	362	3
3	30.3	350	3	30.3	351	13
4	30	351	4	30	350	2
5	31.3	350	5	31.3	349	5
6	30.4	349	6	30.5	349	4
7	30.6	348	7	30.5	346	7
8	30.1	352	8	30	350	14
9	29.9	351	9	30.2	348	11
10	29.1	350	10	29.2	349	9
11	29	355	11	28.8	350	10
12	30.1	355	12	30.2	348	1
13	27.7	350	13	27.6	347	8
14	26	352	14	26.4	350	6

Main Hall-SE Midlanding to 2nd floor						
Measurer 1						
Measurement 1			Measurement 2			
Step	Angle	Hypot. Length (mm)	Step	Angle	Hypot. Length (mm)	Measure by assigned sample #
1	28.4	351	1	28.4	350	3
2	29.8	357	2	29.5	357	6
3	29.3	350	3	29.3	350	1
4	28.2	350	4	28.1	348	4
5	29.6	348	5	29.6	347	13
6	28.4	357	6	28.5	353	12
7	29.5	349	7	29.4	345	8
8	29.4	347	8	29.4	346	9
9	28.8	349	9	28.8	355	7
10	28.4	350	10	28.5	345	5
11	30.1	345	11	30.1	345	2
12	29.8	350	12	29.8	350	11
13	27	345	13	27.2	345	10

Main Hall-SE Midlanding to 2nd floor						
Measurer 2						
Measurement 1			Measurement 2			
Step	Angle	Hypot. Length (mm)	Step	Angle	Hypot. Length (mm)	Measure by assigned sample #
1	28.4	354	1	28.3	352	3
2	29.4	358	2	29.4	354	6
3	29.2	350	3	29.3	349	1
4	28.2	353	4	28.2	351	4
5	29.5	348	5	29.7	347	13
6	28.4	350	6	28.5	350	12
7	29.6	349	7	29.6	348	8
8	29.4	350	8	29.4	346	9
9	28.6	354	9	28.8	350	7
10	28.5	355	10	28.4	347	5
11	30.2	349	11	30.2	348	2
12	29.8	350	12	29.8	351	11
13	26.9	346	13	26.9	347	10

Museum-SW 2nd floor to midlanding						
Measurer 1						
Measurement 1			Measurement 2			
Step	Angle	Hypot. Length (mm)	Step	Angle	Hypot. Length (mm)	Measure by assigned sample #
1	32.9	332	1	32.9	332	1
2	32.5	332	2	32.3	333	5
3	32.3	330	3	32.3	330	3
4	32.2	332	4	32.3	332	2
5	32	331	5	32.1	332	4
6	32.1	331	6	32.2	332	7
7	32	330	7	32.1	330	6
8	31.3	334	8	31.4	334	8

Museum-SW 2nd floor to midlanding						
Measurer 2						
Measurement 1			Measurement 2			
Step	Angle	Hypot. Length (mm)	Step	Angle	Hypot. Length (mm)	Measure by assigned sample #
1	32.6	331	1	32	334	1
2	32.4	334	2	32.5	333	5
3	33.1	332	3	32.3	334	3
4	32.3	334	4	32.3	334	2
5	32.1	333	5	32.1	335	4
6	32.2	332	6	32.2	334	7
7	32.1	334	7	32	334	6
8	31.3	336	8	31.4	336	8

Museum-NE 2nd floor to midlanding						
Measurer 1						
Measurement 1			Measurement 2			
Step	Angle	Hypot. Length (mm)	Step	Angle	Hypot. Length (mm)	Measure by assigned sample #
1	32.6	333	1	32.6	332	6
2	32	328	2	32.1	327	2
3	32.4	332	3	32.3	330	7
4	32.2	333	4	32.2	331	8
5	33.2	333	5	32.8	332	1
6	31.9	334	6	32	331	4
7	32.3	330	7	32.3	330	5
8	31.2	335	8	31.4	337	3

Museum-NE 2nd floor to midlanding						
Measurer 2						
Measurement 1			Measurement 2			
Step	Angle	Hypot. Length (mm)	Step	Angle	Hypot. Length (mm)	Measure by assigned sample #
1	32.7	336	1	32.6	335	6
2	32	334	2	31.9	332	2
3	32.2	335	3	32.4	333	7
4	32.1	335	4	32.2	334	8
5	32.9	334	5	33	334	1
6	31.9	335	6	31.9	336	4
7	32.2	331	7	32.2	334	5
8	30.8	336	8	31.3	338	3

Health and Sciences Building-NW Midlanding to 1st floor						
Measurer 1						
Measurement 1			Measurement 2			
Step	Angle	Hypot. Length (mm)	Step	Angle	Hypot. Length (mm)	Measure by assigned sample #
1	37.8	327	1	37.8	328	1
2	38	323	2	38	322	5
3	37.3	322	3	37.3	322	9
4	37.6	315	4	37.5	317	10
5	37.5	322	5	37.5	322	8
6	36.5	325	6	36.5	323	4
7	37.9	323	7	37.9	322	2
8	36.5	316	8	36.5	319	7
9	36.5	322	9	36.6	320	6
10	33.7	321	10	33.6	320	3

Health and Sciences Building-NW Midlanding to 1st floor						
Measurer 2						
Measurement 1			Measurement 2			
Step	Angle	Hypot. Length (mm)	Step	Angle	Hypot. Length (mm)	Measure by assigned sample #
1	37.9	326	1	37.8	326	1
2	38	321	2	38.1	321	5
3	36.8	320	3	37.4	320	9
4	37.3	317	4	37.5	316	10
5	37.6	321	5	37.6	322	8
6	36.5	322	6	36.6	323	4
7	38	321	7	38.1	321	2
8	36.5	319	8	36.5	318	7
9	36.5	320	9	36.6	320	6
10	33.5	334	10	33.6	328	3

Health and Sciences Building-SW Midlanding to 1st floor						
Measurer 1						
Measurement 1			Measurement 2			
Step	Angle	Hypot. Length (mm)	Step	Angle	Hypot. Length (mm)	Measure by assigned sample #
1	38.4	315	1	38.3	315	2
2	37.1	320	2	37.2	318	8
3	37.3	315	3	37.3	315	7
4	37	323	4	37.2	321	3
5	36.6	320	5	36.5	319	5
6	37.4	315	6	37.4	313	4
7	36.3	323	7	36.4	323	1
8	36.2	317	8	36.2	318	6
9	37	322	9	37.1	320	9
10	34.8	326	10	34.5	325	10

Health and Sciences Building-SW Midlanding to 1st floor						
Measurer 2						
Measurement 1			Measurement 2			
Step	Angle	Hypot. Length (mm)	Step	Angle	Hypot. Length (mm)	Measure by assigned sample #
1	38.2	317	1	38.2	318	2
2	37.1	321	2	37.1	319	8
3	37.4	318	3	37.3	316	7
4	37	321	4	37.2	322	3
5	36.6	318	5	36.6	319	5
6	37.4	315	6	37.6	314	4
7	36.3	321	7	36.4	321	1
8	36.3	318	8	36.3	316	6
9	37.2	320	9	37.1	320	9
10	34	334	10	34.4	333	10

Appendix C: Descriptive Statistics for all Stair Flights

Tread depth Data for Flight 1

	JN-1	JN-2	KT-1	KT-2
	269.1196	268.8012	271.7319	274.916
	266.8735	266.0523	273.4427	270.6501
	261.7574	262.0721	267.5193	265.0499
	266.5348	266.2253	274.5449	274.864
	265.6865	266.8297	272.2875	270.9602
	265.915	265.915	272.5629	270.07
	268.5158	267.8627	273.5968	272.7776
	266.3946	264.7191	273.0963	272.2586
Median	**266.4647**	**266.1388**	**272.8296**	**271.6094**
Average	**266.3496**	**266.0597**	**272.3478**	**271.4433**

Rise Data for Flight 1

	JN-1	JN-2	KT-1	KT-2
	182.2077	182.6771	181.9087	186.1321
	185.4819	184.9112	190.0476	188.8081
	180.5743	180.1172	184.5492	182.8457
	177.0853	177.5502	183.0987	182.6192
	181.9194	182.0189	186.4391	184.8365
	178.0146	178.0146	182.465	180.7961
	186.6233	187.5595	191.5745	191.001
	173.6604	172.5682	178.0292	177.4831
	166.2461	166.2461	165.2907	165.2907
Median	**180.5743**	**180.1172**	**183.0987**	**182.8457**
Average	**179.0903**	**179.0737**	**182.6003**	**182.2014**

Tread depth Data for Flight 2

	JN-1	JN-2	KT-1	KT-2
	262.0655	261.8401	263.5079	261.2336
	265.873	267.5193	269.1656	266.6962
	266.5117	266.5117	267.6558	267.841
	264.7304	267.1968	270.9792	268.019
	270.3851	268.408	269.754	269.239
	269.239	268.2915	269.754	269.4372
	271.1375	267.6946	270.9792	271.3075
	266.8435	266.8435	270.179	269.8665
Median	**266.6776**	**267.3581**	**269.754**	**268.629**
Average	**267.0515**	**266.8515**	**269.081**	**268.0299**

Rise Data for Flight 2

	JN-1	JN-2	KT-1	KT-2
	174.776	173.3082	174.4121	174.2212
	183.4135	184.5492	185.6849	183.9814
	182.4843	182.4843	182.5824	184.082
	183.308	185.0158	188.3355	185.5851
	180.3244	179.6835	181.2672	180.2398
	180.2398	181.647	181.2672	181.7377
	186.3477	186.0526	188.3355	187.8622
	176.6198	176.6198	178.8276	179.2989
	179.8667	178.4784	172.4067	176.6198
	180.3244	181.647	181.2672	181.7377
Median	**180.82**	**180.871**	**181.4577**	**181.5142**
Average	**174.776**	**173.3082**	**174.4121**	**174.2212**

Tread depth Data for Flight 3

	JN-1	JN-2	KT-1	KT-2
	301.1146	301.1146	304.5857	303.7179
	306.6217	304.9182	308.6557	308.3252
	300.1548	300.1548	302.1884	303.0518
	303.1089	299.6448	303.9749	303.1089
	303.3329	305.8963	299.0606	298.2061
	302.4318	309.1711	301.0173	300.7086
	296.649	296.0953	299.5382	298.1237
	302.803	302.803	304.5333	303.1089
	302.4962	302.803	304.2808	300.7676
	305.8203	304.9465	305.8203	304.6498
	304.9465	309.6154	310.49	306.7073
	307.6818	306.2636	307.1288	300.7676
	308.117	308.3988	309.8878	307.5126
Median	**303.1089**	**304.9182**	**304.5333**	**303.1089**
Average	**303.483**	**303.9866**	**304.7047**	**302.9812**

Rise Data for Flight 3

	JN-1	JN-2	KT-1	KT-2
	172.45	172.45	174.4379	173.9409
	188.6349	187.587	189.1445	189.6829
	176.0997	176.0997	176.5847	177.0892
	175	173	175.5	175
	184.4293	185.9878	181.8317	181.3122
	178.146	178.5	176.6058	177.1309
	176.1373	175.1102	177.1464	175.6083
	175.5288	175.5288	176.5318	175
	176.057	175.5288	174.9692	175.0509
	170.2174	169.731	170.2174	170.263
	169.731	171.6226	172.1074	168.6138
	179.0751	177.5348	178.0363	175.0509
	161.765	161.227	162.6947	160.7637
	150.4797	154.2884	154.3066	155.6223
Median	**175.7929**	**175.3195**	**176.0159**	**175.0255**
Average	**173.8394**	**173.8712**	**174.2939**	**173.5806**

Tread depth Data for Flight 4

	JN-1	JN-2	KT-1	KT-2
	308.7566	307.877	311.3956	309.928
	309.7923	310.717	311.8945	308.4097
	305.2242	305.2242	305.5227	304.3522
	308.4562	306.9801	311.1001	309.3375
	302.5842	301.7147	302.8838	301.4151
	314.0345	310.2224	307.877	307.586
	303.7541	300.5688	303.4537	302.5842
	302.3112	301.44	304.9248	301.44
	305.831	311.0889	310.806	306.7073
	307.877	303.1919	311.9801	305.2381
	298.4772	298.4772	301.6319	300.7676
	303.7179	303.7179	303.7179	304.5857
Median	**305.5276**	**304.4711**	**306.6999**	**304.9119**
Average	**305.9014**	**305.1017**	**307.2657**	**305.196**

Rise Data for Flight 4

	JN-1	JN-2	KT-1	KT-2
	166.9441	166.4685	168.371	166.879
	177.4197	175.7952	175.7435	173.7799
	171.2839	171.2839	170.7509	170.7945
	165.3928	163.9121	166.8104	165.8653
	171.8918	171.3978	171.3634	171.9242
	169.7978	168.437	166.4685	167.0056
	171.8558	169.3618	172.3857	171.8918
	170.3436	169.8527	171.8163	169.8527
	168.132	171.0226	169.4569	168.6138
	166.4685	164.6198	169.3914	165.0416
	173.0212	173.0212	175.554	175.0509
	173.9409	173.9409	173.9409	174.4379
	156.6267	157.6988	156.5424	156.9948
Median	**170.3436**	**169.8527**	**170.7509**	**169.8527**
Average	**169.4707**	**168.9856**	**169.8919**	**169.0871**

Tread depth Data for Flight 5

	JN-1	JN-2	KT-1	KT-2
	278.7538	278.7538	278.8517	283.2481
	280.006	281.4722	282.0055	280.8494
	278.9364	278.9364	278.1226	282.3175
	280.9361	280.6269	282.3175	282.3175
	280.7039	281.2445	282.0916	283.7858
	280.3974	280.9361	280.9361	282.6285
	279.8559	279.5502	282.9387	283.2481
Median	**280.006**	**280.6269**	**282.0055**	**282.6285**
Average	**279.9413**	**280.2172**	**281.0377**	**282.6278**

Rise Data for Flight 5

	JN-1	JN-2	KT-1	KT-2
	180.3339	180.3339	178.3331	176.993
	178.3835	177.9393	178.9661	178.9208
	176.3363	176.3363	181.3059	178.4737
	176.9149	177.405	178.4737	178.4737
	175.4033	176.4243	176.9557	178.0185
	175.8929	176.9149	176.9149	177.9807
	174.8734	175.3615	177.4871	176.993
	173.5194	174.0172	174.5584	175.0592
Median	**176.1146**	**176.6696**	**177.9101**	**177.9996**
Average	**176.4572**	**176.8416**	**177.8744**	**177.6141**

Tread depth Data for Fight 6

	JN-1	JN-2	KT-1	KT-2
	280.5366	279.6942	282.7476	282.2216
	278.1598	277.0089	283.2481	281.8586
	280.3169	278.9364	283.4747	281.1612
	281.7823	280.0899	283.7858	282.6285
	278.6425	279.0681	280.433	280.116
	283.5565	280.7039	284.4055	285.2545
	278.9364	278.9364	280.0899	282.6285
	280.5366	279.6942	282.7476	282.2216
	278.1598	277.0089	283.2481	281.8586
Median	**280.3169**	**279.0681**	**283.2481**	**282.2216**
Average	**280.2759**	**279.2054**	**282.5978**	**282.267**

Rise Data for Flight 6

	JN-1	JN-2	KT-1	KT-2
	179.4107	178.8719	181.5207	180.4882
	173.8135	173.7673	176.993	175.4415
	177.8945	176.3363	178.5136	178.4303
	177.4478	176.382	178.0185	177.9807
	182.3386	179.8471	181.4203	181.9094
	176.4984	175.4033	177.0268	177.5553
	176.3363	176.3363	176.382	177.9807
	173.539	175.5802	172.0464	175.5975
	176.9731	176.3363	177.5227	177.9807
Median	**177.1598**	**176.5656**	**177.7402**	**178.1729**
Average	**179.4107**	**178.8719**	**181.5207**	**180.4882**

Tread depth Data for Flight 7

	JN-1	JN-2	KT-1	KT-2
	258.3807	259.1708	257.2414	257.5905
	254.5275	253.7395	252.9515	252.6061
	256.1425	256.1425	256.234	254.2127
	249.5712	251.493	252.1651	250.6997
	255.4598	255.4598	254.325	255.1173
	261.2535	259.6458	258.8419	259.31
	254.8742	254.0851	252.9515	252.6061
	254.0188	256.4303	256.4303	255.6265
	258.8419	256.9016	257.2342	256.9016
Median	**255.4598**	**256.1425**	**256.234**	**255.1173**
Average	**255.8967**	**255.8965**	**255.375**	**254.9634**

Rise Data for Flight 7

	JN-1	JN-2	KT-1	KT-2
	200.4206	201.0335	200.257	199.8077
	198.8587	198.243	197.6273	198.0685
	195.1283	195.1283	191.6876	194.3603
	192.1957	192.9774	192.0983	192.3686
	196.0212	196.0212	195.8566	196.4667
	193.3174	192.1278	191.5329	192.5806
	198.4141	197.7998	197.6273	198.0685
	187.964	189.7485	189.7485	189.1536
	191.5329	190.792	190.3433	190.792
	178.1051	177.0853	184.347	181.5124
Median	**194.2228**	**194.0528**	**191.8929**	**193.4705**
Average	**193.1958**	**193.0957**	**193.1126**	**193.3179**

Tread depth Data for Flight 8

	JN-1	JN-2	KT-1	KT-2
	246.8634	247.2046	249.1166	249.9025
	255.2269	253.2965	256.0244	254.4293
	250.5741	250.5741	252.6238	251.3696
	257.9593	255.6861	256.362	256.4826
	256.9016	256.4303	255.296	256.0988
	250.2406	248.6518	250.2406	248.7789
	260.3148	259.9807	258.703	258.3709
	255.8064	256.6134	256.2852	254.6733
	257.1606	255.2269	254.8896	255.2269
Median	**255.8064**	**255.2269**	**255.296**	**254.6733**
Average	**254.5609**	**253.7405**	**254.3935**	**253.9259**

Rise Data for Flight 8

	JN-1	JN-2	KT-1	KT-2
	195.6616	195.2304	196.0355	196.6539
	193.0266	192.2625	193.6298	192.4233
	190.8863	190.8863	193.1455	191.4923
	194.3863	194.0763	193.1826	194.6809
	190.792	189.7485	189.5995	190.1957
	191.3234	190.1086	191.3234	191.5856
	191.2203	191.6743	190.0362	190.4875
	187.222	187.8126	188.2602	187.0762
	193.7844	193.0266	193.4717	193.0266
	186.0526	184.082	186.7704	188.134
Median	**191.2718**	**191.2803**	**192.2345**	**191.539**
Average	**191.4355**	**190.8908**	**191.5455**	**191.5756**

This thesis has been examined and approved for acceptance by the Safety, Health and Industrial Hygiene Department, Montana Tech of The University of Montana, Butte, Montana, on this 22nd day of April, 2014.

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