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Stairway Uniformity Measurement: What Lateral Location Should Be Measured?

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STAIRWAY UNIFORMITY MEASUREMENT:
WHAT LATERAL LOCATION SHOULD BE MEASURED?

by

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Abstract

BACKGROUND: This project addressed an unresolved issue involving measurement methods for determining step uniformity. Leading experts on stairway safety agree that lack of step uniformity within a flight contributes to risk of missteps. A relatively new method for precisely measuring step dimensions is the nosing-to-nosing method. An issue in applying the method is lack of agreement on the lateral location to make the measurements. That location depends on where stairway users ascend and descend relative to the width of the steps. A prior investigator examined people descending to determine the lateral distance between the handrail center and the mid-line of the person's body. He found the median was 44 cm.

AIM: The two objectives of the experiment were to: (1) determine if a different set of stairway users will have the same median lateral distance from the handrail as those described in the prior observational study, and (2) determine if the lateral distance of participants is affected by their direction of travel and use of a handrail.

METHODS: The investigators established visible distance markers on one stairway in a campus building and videotaped volunteer students ascending and descending the flight of stairs. Each of the 16 participant ascended with and without using the handrail, and each descended with and without using the handrail. Images were printed and analyzed to determine their lateral distance between the inner edge of the handrail and a point midway between the participant's knees. Results were analyzed statistically to test hypotheses corresponding to the two objectives.

RESULTS: The previous study found a median lateral distance of 44 cm when measured from the center of the handrail. Using comparable data, the median found in this study was 25 cm.

Results of this study indicated that lateral distance from the handrail is significantly affected by the direction of travel and by use of the handrail. The greatest lateral distance was for ascending with the handrail. The shortest lateral distance was for descending without the handrail.

VALUE:
Committees develop and periodically revise standards for stairways leading to fire exits and workplace facilities. The practical value of this project is providing empirical evidence that standard developing committees may consider when convening to update their requirements and guidelines on how to measure step uniformity.

Keywords: Safety, Stairs, Stairways, Falls, Stair Standards, Step Uniformity.

Dedication

I would like to give a very special thank you to my two children, Jordan Calf Looking, and Dustilee Calf Looking for their encouragement, support, and trust. As a father, my children will always be my top priority to provide a safe and healthy life and positive learning environment. I am grateful for my Grandmother, Dorothy Rose for her continues encouragement and support throughout my educational endeavors.

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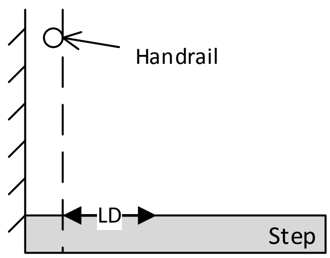
Glossary of Terms

Term	Definition
Flight	A series of steps connecting two floors, a floor and a landing, or two landings.
Lateral Distance	The horizontally measured length of a step nosing from a handrail midline or inner edge. For this project, the measurement was from the inner edge of a handrail (see below) to the mid-point between the participant's knees projected onto the nosing. 
Participant	Individuals who volunteered to participate in the study by ascending and descending a flight of stairs.
Principal Investigator	The graduate student author of this thesis, Lee Calf Looking.
Unit rise	A measure of the vertical distance between the nose of one step and the nose of the step below it. A "flight rise" is the vertical distance from the lower floor to the upper floor.
Riser	The vertical member of a step.
Unit run	A measure of the tread depth on a step. A "flight run" is the horizontal distance from the bottom nosing to the nosing at the top.
Step Uniformity	Consistency of the rise and run dimensions of all steps within a flight.
Tread	The horizontal member of a step.

1. Introduction

This thesis describes a project about measuring the dimensional uniformity of steps within a flight of stairs. One may ask why society should care about uniformity of step dimensions. The first reason is to prevent stairway falls due to non-uniform steps. A second is to determine if a flight of stairs complies with fire and building codes for stairways. A third is to standardize investigations of stairways fall injuries for purposes of litigation. These concerns are addressed in this Introduction.

1.1. Retrospective Information on Stairways Falls

Numerous retrospective studies have indicated that many people are injured from falling on stairs. Some of these looked at hospital emergency department records, others used data from occupational injury and illness systems such as those for workers' compensation claims. One paper reported an analysis of in-depth investigations of stairway falls that were litigated. A few of these papers and reports are mentioned in the following.

The Consumer Products Safety Commission (CPSC) maintains a network of hospital emergency departments that participate in a nationally-representative records system known as the National Electronic Injury Surveillance System (NEISS). The CPSC published a more recent report on emergency department visits related to stairs, ramps, landings, and floors. NEISS records showed the emergency department treated case rate for different age groups. The rate for people aged 65 and older was 2.8 times that of those 25 to 64. Unfortunately, the report does not single out falls on stairs from falls related to ramps, landing, and floors.

Stairway falls occur in many locations. The United Kingdom's Health and Safety Executive published a literature review on the topic of falls on stairways (Scott, 2005). Some findings reported in the literature review address the location of stairway falls and direction of travel when a fall occurred. The most common location of stairway fall injuries is in the home—Japan 68%, US 80%, Sweden 72%.

Some retrospective information about occupational stairway fall fatalities is available. The U. S. Bureau of Labor Statistics reported that in 2008 there were 700 fatal falls in U. S. workplaces, and four percent of these were falls down stairs.

The frequency of occupational stairway falls has some patterns. Descending accounts for more serious fall injuries than those while ascending. Nagata (1991) reported percentage for occupational falls on stairs in Japan while descending were 78 percent for males and 92 percent for females. Cohen, Templer, and Archea (1985) reported an analysis of workers' compensation claims in California and Ohio. Out of 688 stairway fall claims for which direction of travel was indicated, 636 (92%) occurred while descending. Another pattern, reported by Maynard and Brogmus in 2007, is that stairway falls at work tend to occur more often on the top three steps and the bottom three steps as compared to falls on the middle steps.

Romer (1983) provided retrospective occupational injury data from West Germany. Data came from a reporting system that required employers to report work accidents concerning an employee death, fatal injury, or more than three days absence from work. Falls preceded by "flexing the body, tripping, slipping, or falling" while using steps made up 16 percent of all cases and 24 percent of serious cases. Of these serious cases, 16 percent were on staircases. Using the data reported by Romer, the percentage of serious cases that occurred on staircases may be calculated by multiplying the percent of serious cases (24%) by the percent of cases that occurred in staircases (16%) to determine that about 4 percent of serious cases occurred in staircases.

1.2. Stairway Characteristics

Stairway characteristics important for safety and usability are step dimension, step uniformity, handrails, and guardrails. Cohen, LaRue, and Cohen (2009) synthesized findings from 80 stairway falls they investigated for litigation. They concluded that the most pervasive feature for stairway fall prevention is to provide uniform steps. They also noted that most of the injured people reported they were not using a handrail at the time of their fall.

Several standards-developing organizations provide guidelines and standards for the stairway characteristics. Three are most applicable to occupational safety. The Federal Occupational Safety and Health Administration (OSHA) has standards for stairways in workplace—both general industry and construction sites. The OSHA requirements have not been updated since being adopted in 1972. Two organizations provide current standards applicable to workplace safety. The National Fire Protection Association (NFPA) has standards for stairways leading to fire exits, and the American National Standards Institute (ANSI) has a standard for workplace stairways. Both NFPA and ANSI standards recognize the importance of having uniform steps by containing specific tolerances for both step riser height and step tread depth.

The NFPA and ANSI standards specify tight limits to dimensional variations between adjacent steps and within a whole flight. Both specify that the riser height on adjacent steps must not differ by more than ⅜ inch. The same specifications apply to adjacent step treads. The standard specifically for workplace stairs is the one developed by the ANSI A1264 Committee (2007). In order to check compliance with the ANSI step uniformity specification, a precise measurement system is needed. A relatively new measurement method, known as the nosing-to-nosing method, is a feasible and precise way to measure step dimensions (Johnson, 2005; Pauls, 1998; Jensen et al. 2013; Hicks et al. 2013). An unresolved issue with using the method is choosing the lateral location for taking measurements. The logical lateral location would be the path most people take when using the stairway, but empirical evidence of where that location, or locations, lies is very limited.

In the only prior study, a forensic human factors expert videotaped people descending a stairway in a multistory office building (Cohen, 2000). Using length markers visible on the step risers, he read from the videos the lateral distance between the midline of the person's body to the center of the handrail. He found the median distance was 17.5 inches (44 cm) with an interquartile range of 10 to 22.5 inches. He expressed concerns about the generalizability of the findings, and recommended additional studies using different stairways, different people, and more controlled measurement conditions.

The investigators developed this thesis project with objectives to: (1) determine if a different set of stairway users will have the same median lateral distance from the handrail as those described in the prior observational study by Cohen (2000), and (2) determine if the lateral distance of participants is affected by their direction of travel and/or use of a handrail.

1.3. Experimental Design and Hypotheses

To achieve both objectives, the Principal Investigator and faculty mentor planned a randomized complete block experiment, with the dependent variable being lateral distance (LD) between the inner edge of the handrail and the mid-point of the stair user's knees. The participants were the blocks in the experimental plan. The treatments were four tasks performed by each volunteer participant. Figure 1 depicts how the four tasks were defined. Each participant completed each task in random order.

	With Handrail	Without Handrail
Ascending	Task A	Task B
Descending	Task C	Task D

Figure 1. The four tasks performed by each participant

The randomized complete block design is an efficient way to test the null hypothesis that the mean LDs of the four treatments are equal, versus the alternative that at least two of the treatment means are not equal. These hypotheses are stated in Table I in two equivalent ways. The middle column states the hypotheses in sentence format, while the right column states it in statistical format.

Table I. Hypothesis Statements for Initial Analysis of Variance

Hypothesis	**Verbal Statement of Hypothesis**	**Statistical Statement**
H_O:	The mean LDs of the four tasks are equal.	$\mu_A = \mu_B = \mu_C = \mu_D$
	The task effects on LD are equal.	$t_A = t_B = t_C = t_D$
H_A:	At least two of the treatment means are not equal.	At least one pair of the below differences $\neq 0$. $\lvert\mu_A - \mu_B\rvert$ $\lvert\mu_A - \mu_C\rvert$ $\lvert\mu_A - \mu_D\rvert$ $\lvert\mu_B - \mu_C\rvert$ $\lvert\mu_B - \mu_D\rvert$ $\lvert\mu_C - \mu_D\rvert$

Planning prior to the experiment recognized that much depended on the results of the primary Analysis of Variance (ANOV).

1. If the ANOV does not show a significant effect on LD, results would be limited to presenting descriptive findings. The overall distribution of our findings would be compared to that found by Cohen (2000).

2. If the ANOV shows a significant effect on LD, post-hoc analyses would explore the following questions.
    - Is there a difference in mean LD for using versus not using the handrail?
    - Is there a difference in mean LD when ascending compared to when descending?
    - Is LD significantly affected by Body Mass Index (BMI)?
    - Is LD affected by task order, gender, body weight, or height?

2. Methods

This section describes the materials, procedures, and statistical analyses.

2.1. Materials

Figure 1 is a photograph of the flight of stairs used for the experiment. Participants ascended and descended on the left half of the stairs as shown in the photo. The steps were measured using the nosing-to-nosing method to have a 35 degree slope, riser height of 7.4 inches (187 mm), and tread depth of 10.5 inches (268 mm).

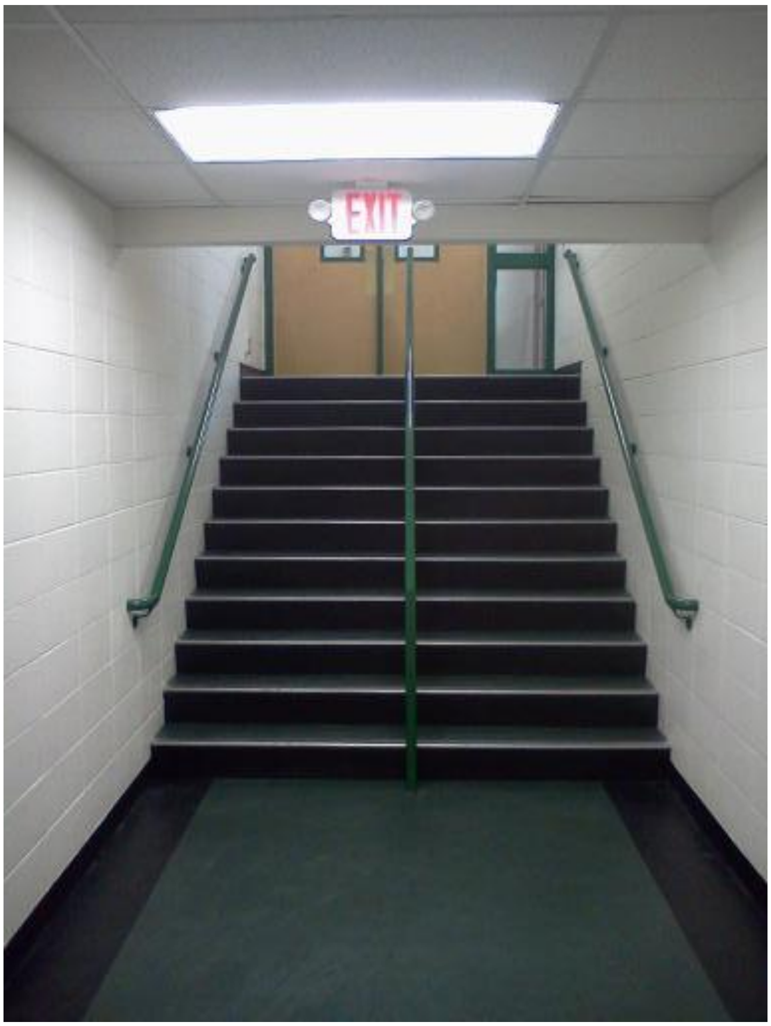


Figure 2. Photo of stairway

Instruments used in the study are listed in Table II along with the applicable parameters.

Table II. Instrumentation

Parameter	**Instrument**
Lateral Distance Marking	Yellow seamstress tape marked in cm
Video Images	Sony Handycam HDR-CX430
Distance between step nosings	Stainless steel ruler with mm markings
Angle formed by horizontal and the line from lower step nose to adjacent higher step nose	SmartTool™ from M-D Building Products
Body Weight	Standard Eye Level Scale
Standing Height	Height Measure Stick

2.2. Participants and Privacy Protection

Study participants were recruited from Montana Tech students majoring in Occupational Safety and Health or Industrial Hygiene. The recruiting process consisted of oral invitations in selected classes, and posting notices on bulletin boards located where OSH and IH students frequent. The notice is provided in Appendix A. The goal of recruiting eight volunteers of each gender was achieved.

Appointments times were coordinated with the availability of each participant. Upon arrival in a room next to the stairway, the Principal Investigator asked each participant to sign the informed consent form in Appendix A. He then obtained information on age and gender, and he measured the height and weight of each participant. The faculty advisor and Principal Investigator created the summary information found in Table III. Subsequently, the faculty advisor stored these personal records in a secure file cabinet in his office.

The participant attributes presented in Table III are age, weight, height, and BMI. Corresponding tables for each gender are in Appendix A. Attributes of individual participants are not reported in order to protect their privacy. As indicated in Table III, the participants ranged in age from 20-44 years with a median of 24. The BMI was calculated for each participant as the ratio of their weight (kilograms) to their squared height (meters squared). Prior to conducting the experiment, the Institutional Review Board of the University of Montana System approved the project and assigned an approval number 196 – 14. Each participant was given $5.00 as a token of appreciation.

Table III. Attributes of Participants

Parameter	Age	Weight (kg)	Height (m)	BMI (kg/m^2)†
Mean	26.25	76.9	1.717	25.78
Max	44	122	1.846	36.63
Min	20	43.6	1.564	17.82
Median	24	76.9	1.710	25.03
S.D.	7.308	21.3	0.095	5.52

† BMI is Body Mass Index

2.3. Procedures

The Principal Investigator prepared each volunteer by explaining the study and allowing time to read the informed consent form. After obtaining the participant's signature, the Principal Investigator measured their height with rod recorded in centimeters at an upright standing position, followed by the weighing the individual with a standard weighing scale recorded in kilograms. Next, the participant moved to the stairway located at the north entrance doors at the HPER facility.

Prior to arrival of participants, the Principal Investigator fixed a tape measure on the stairway approximately 2.2 inches below the nosing of the fourth and fifth stairs. On the floor, three feet from the bottom step, two maker locations were placed at 22 inches and 36 inches from the left wall. The Principal Investigator placed the camera at the marker dependent on the task; left spot for descents and right spot for ascents. Prior to the experiments, the faculty advisor developed the plan for ordering the tasks using Latin Squares, and assigning participants to an order. Details of this process are described in Appendix B. The participant performed the four tasks in the assigned order while the Principal Investigator operated the video camera. Next, the Principal Investigator downloaded video recording of participant(s) on camera to the Sony Play Memory Home Video Software. After freezing an appropriate image, and trimming the size, the Principal Investigator saved the image in a JPEG format. It was then printed on photo paper and labelled to indicate the participant's number.

On the photo paper, a pencil and 12-inch ruler were used to create vantage point by using the wall and handrail interior as a plane. Because the vantage point was above the photo, a blank piece of paper was taped to the top of the photo. The vantage point provided a single center point for drawing a line through the midpoint of the participant's knees down to the measuring tape on the lower step. Figure 2 is a photo of one participant with lines meeting at the vantage point.

The Principal Investigator recorded the distance of this intersection and later inputted it into a Microsoft Excel® spreadsheet. Figure 3 shows relevant distances from the wall. For the descending tasks, the LD was obtained by subtracted 100 mm from the initial measured distance due to the handrail edge being 100 mm from wall. For the ascending tasks, the LD was determined by taking the absolute difference between the left edge of the rail in the stairway center (1208 mm) and the midpoint of the participant's knees. The LD values were copied and pasted into Minitab 17 for analysis.

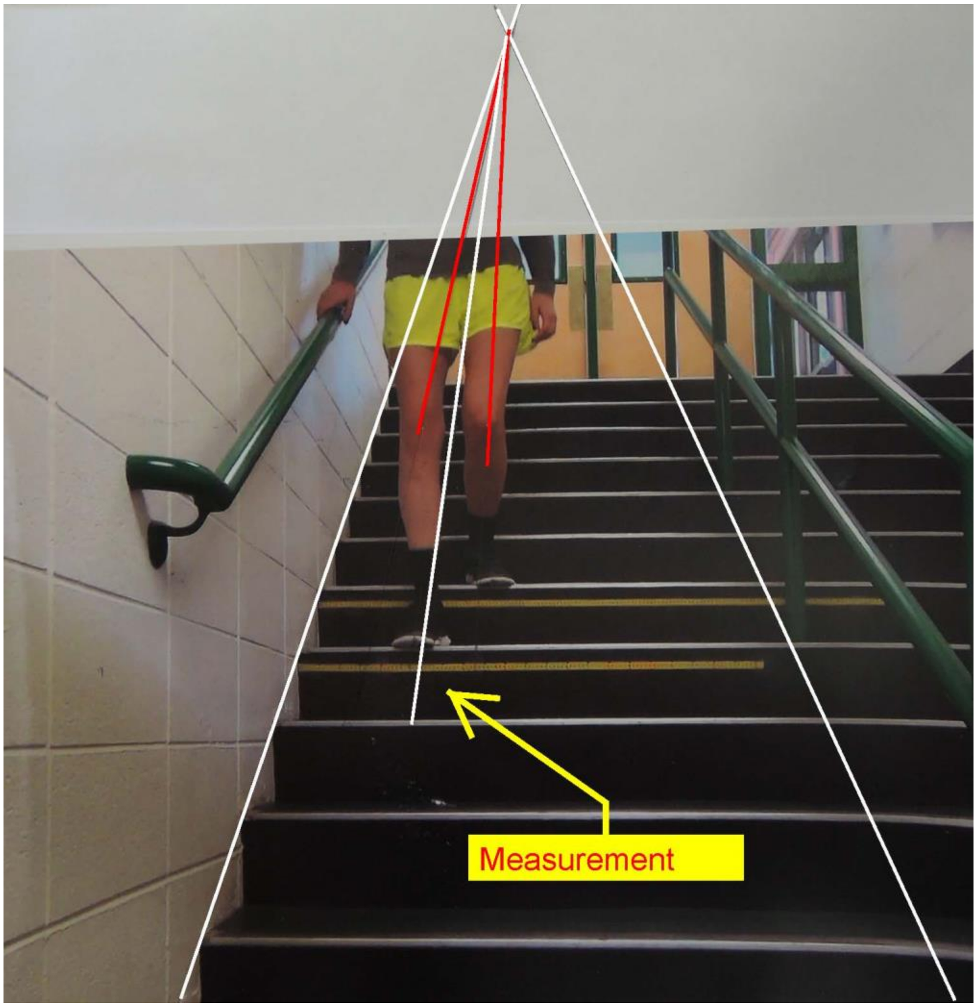


Figure 3. Photo of one participant with lines drawn to a common vantage point

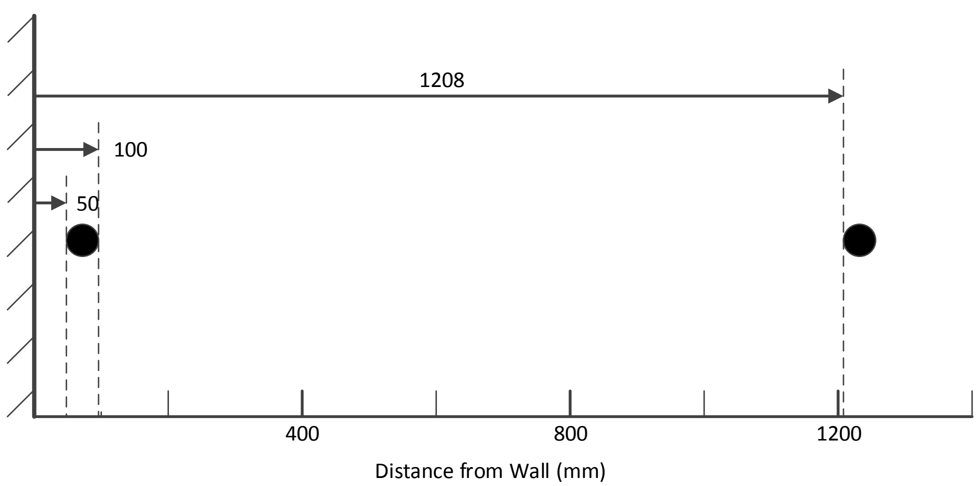


Figure 4. Distances in mm from the wall

2.4. Statistical Analyses

Data analyses used common statistical processes supported with the campus Minitab 17 software. These methods included paired data t-tests, analysis of variance (ANOV), and linear regression.

2.4.1. Primary Experiment Statistical Method

An ANOV examined the effects of the four tasks on LD. The data layout may be visualized as in Table IV. The initial hypothesis test is presented in Table I. The first null hypothesis statement is that the mean LDs of the four tasks (μ_A to μ_D) are equal. That test is equivalent to the second hypothesis statement that the four tasks effects (t_A to t_D) are equal (Rossi, p. 534).

The initial statistical procedure was a two-way, balanced ANOV with participants serving as a blocking factor. As described by Rossi (2010, p. 508), the model for this ANOV is

Equation 1. ANOV Model for Primary Hypothesis

$$\mathrm{LD}_{ij} = \mu + p_j + t_i + \varepsilon_{ij} \tag{1}$$

where: LD_{ij} is the value of LD obtained for the *j*th participant doing the *i*th task,

μ is the overall mean of the measured LDs,

p_j is the effect of the *j*th participant (the blocking variable),

t_i is the effect of the *i*th task, and

ε_{ij} is the error of the ANOV model for the value of LD in the *j*th block with the *i*th task.

The participants were considered to be random variables, while the tasks were regarded as fixed variables. LD is the response variable. Rossi (2010, p. 508) notes several assumptions associated with this model. The error terms are assumed to be independent random variables with mean zero, and with the same standard deviation. The error terms must be normally distributed for performing hypothesis tests and determining confidence limits. For the block effects term, assumptions are that block treatments do not interact, and the block effects are normally distributed with a mean of zero.

The two-way layout shown in Table IV has the participants in the rows and the treatments in the columns. To clarify the nomenclature, a few cells are filled in with variable designations. For example, cell LD_{B1} will become the value of LD for task A performed by participant 1. Most cells are left blank to reduce tedious typing. The measured values of LD filled the 64 cells in the table.

Table IV. Two-way Table for Observations.

Participant (subscript *j*)	**Task (subscript *i*)**			
	T_A	**T_B**	**T_C**	**T_D**
1	LD_{A1}	LD_{B1}	LD_{C1}	LD_{D1}
2				
3				
4				
5				
6				
7				
8		LD_{ij}		
9				
10				
11				
12				
13				
14				
15				
16	LD_{A16}			LD_{D16}
Task Mean:	μ_A	μ_B	μ_C	μ_D

2.4.2. Post-hoc Statistical Methods

After running the two-way ANOV, and rejecting the null hypothesis, post-hoc tests were performed. The first was to determine which task LD means differed. The second analyses examined effects of ascending vs. descending and using vs. not using a handrail using a paired-data t-test. For example, to run a t-test for using the handrail versus not using the handrail, the LD data were organized as shown in Table V.

The mean of block-specific differences (i.e., the 16 d_j values) is denoted μ_d. These difference values are in the right column of Table V. The paired data t-test indicates if the right column of data had a mean of zero or not, thus:

H_0: $\mu_d = 0$

H_1: $\mu_d \neq 0$

Table V. Organization of Data for Analyzing a Paired-Data t-test.

Participant (j)	Task A: Ascending With	Task B: Ascending Without	Difference (d_j)
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			
11			
12			
13			
14			
15			
16			

The paired data t-test was used to examine LD for:

- Descending with versus without the handrail
- Ascending with versus without the handrail

- Using the handrail while ascending versus descending
- Not using the handrail while ascending versus descending

A third analysis examined the effect of BMI on LD. The BMI is the ratio below using weight in kilograms and height in meters (Rossi, p. 35).

Equation 2. Body Mass Index

$$BMI = Weight \times Height^{-2} \quad (2)$$

Linear regression was used to determine if BMI significantly affected the experimental values of LD. Referring to Equation 3—the linear regression model—if BMI does not have a significant effect, then the experiment will find B_1 close to zero. The null and alternative hypotheses for this are $B_1 = 0$ and $B_1 \neq 0$, respectively (Rossi, p. 361).

Equation 3. Regression Model for Effect of BMI

$$\mathrm{LD} = B_0 + B_1\,(\mathrm{BMI}) + \varepsilon \quad (3)$$

Other statistical analyses examined possible effects of factors that might affects LD. These factors were order of tasks and the following participant factors—BMI, gender, weight, and height. Analyses for order used ANOV, while analyses for the participant variables used linear regression.

3. Results

Results are reported in four subsections. The first provides descriptive data for lateral distances found in the experiment. The second reports results of the primary, complete block experiment. The third provides findings from post-hoc analyses. The fourth explores possible effects from order of trials and personal attributes of participants.

3.1. All Data Lateral Distance

Descriptive statistics for the 64 values of LD are presented in Table VI. The key statistic for comparing with the findings of Cohen is the median. The median was 28.5 cm, and interquartile range was from 22.5 cm to 36.3 cm (13.8 cm total). The boxplot in Figure 4 depicts the spread of LD values with the second and third quartiles boxed.

Table VI. Descriptive Statistics for Lateral Distance (cm)

Mean	Std. Error	Std. Dev.	Min.	Q 1	Median	Q3	Max.
30.03	1.39	11.14	10.0	22.5	28.5	36.3	60

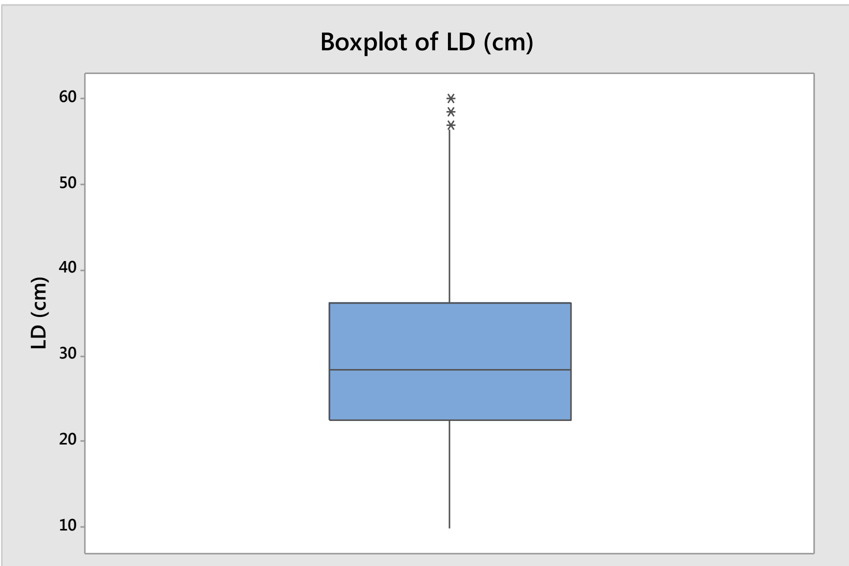


Figure 5. Boxplot of all 64 lateral distance values

3.2. Primary Experiment

Results of the primary ANOV are shown in Table VII. The four tasks significantly helped explain values of LD (p = 0.000). Thus, the null hypothesis is rejected in favor of the alternative hypothesis that at least two of the treatment means are not equal. The subjects are blocking variables, and therefore not of interest (Rossi, 2010, p, 508 – 512).

Table VII. Results of ANOV for Model in Equation 1

Source	df	SS	MS	F	P
Task	3	3111.72	1037.24	19.34	0.000
Participant	15	2293.23	152.88	2.85	0.003
Error	45	2413.80	53.64		
Total	63	7818.75			

A concise explanation of the values in Table VII may be helpful. The ANOV procedure requires the analyst to specify a model. The model for Table VII is that the best estimate of a specified participant will be a summation of (1) the overall mean LD of the 64 measured values, (2) the effect of the particular task, (3) the effect of the particular participant, plus (4) a residual value the model is unable to account for—commonly called the residual or error term. The second, third, and fourth terms are listed in the left column. The second column indicates the degrees of freedom. The third column is the sum of 64 squared residuals, thus Σ ($residuals^2$). That value is divided by the degrees of freedom to obtain the mean of the squared errors (MS) found in column 3. For example, the Task factor MS is a result of dividing 3111.72 by 3 degrees of freedom. The F column contains the value obtained by dividing the applicable MS by the MS of the error term. For example, the F for the Task factor is a result of dividing 1037.24 by 53.64. The F value is a statistic for comparing with an F distribution. The comparison will tell us the probability of obtaining that value if the null hypothesis is true. That probability is shown in the far right column of Table VII. Quite commonly, researchers will reject the null hypothesis if the probability is less than 0.05.

Means for each of the four tasks are reported in Table VIII, and boxplots are shown together in Figure 8. As indicated in Table VIII, ascending with the handrail (task A) had the largest mean LD at 40.2 cm, while descending without using the handrail (task D), had the smallest mean LD at 20.5 cm. The means of subject-specific differences (N =16) in the right column provide data for comparing LD when using the handrail versus not using the handrail. For both ascending and descending, participants were further from the handrail when using the handrail. The means of subject-specific differences (N = 16) in the bottom row provide data for comparing LD when ascending versus descending. For both using and not using the handrail, participants were spaced further from the handrail while ascending.

Table VIII. Fourfold Table of Mean LDs (cm) of the Four Tasks with Differences

	Handrail Usage		
	With	Without	Mean Difference
Ascending	40.2	30.0	10.2*
Descending	29.3	20.5	8.8*
Mean Difference	10.9*	9.5*	

*Indicates the mean difference is significantly different from zero at 0.05 level.

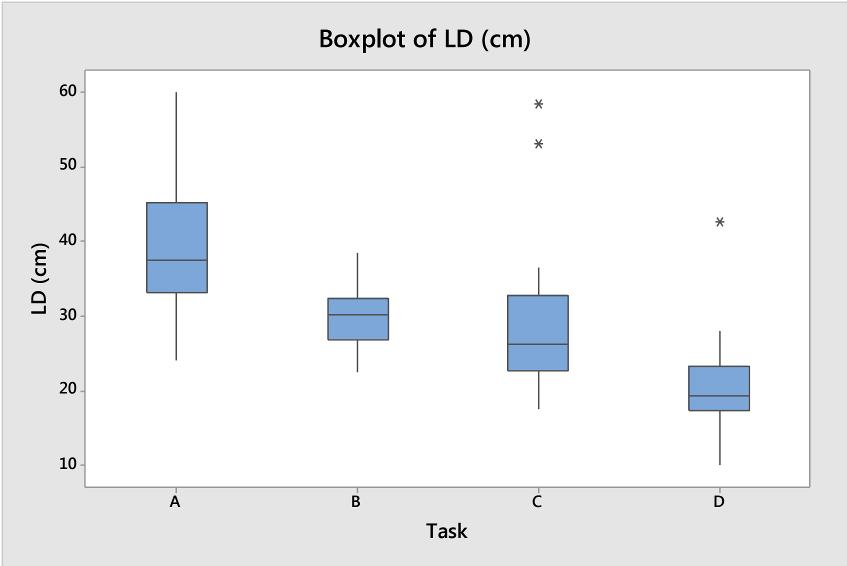


Figure 6. Boxplot for quartiles of LD values for each of the four tasks

To learn which tasks had different means LDs, a General Linear Model in Minitab was used. The confidence intervals for all pairwise differences are presented in Figure 7. If the confidence intervals do not cross the zero line, there is a difference. Only one pair crosses the zero line, thus LD_B is not significantly different from LD_C. All other pairs differ in means.

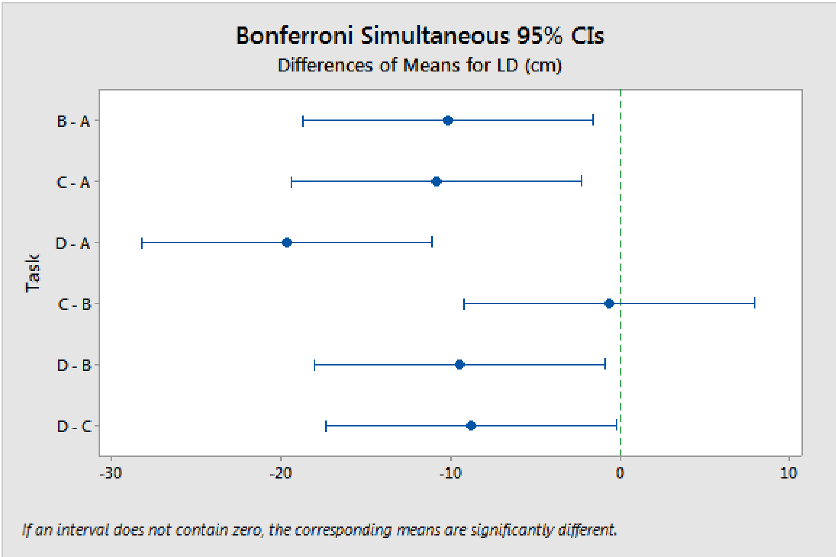


Figure 7. Pairwise comparisons of mean LDs of the tasks.

3.3. Comparison to Prior Study

A comparison of data from this study and that reported by Cohen (2000) is in Table IX. Because Cohen measured LD from the center of the handrail, the LD values for this study were adjusted to do the same. Also, because all of Cohen's observations were for descending stair users, the data from this study also used the descending observations. To facilitate comparisons, Table IX presents percentiles of descent data in inches and in centimeters. Figure 8 is a cumulative distribution graph with results of both studies.

Table IX. Comparison of LD Distributions Found by Cohen and in This Study, as Measured from the Handrail Center

	Inches		Centimeters	
Percentile	**Cohen**	**This Study**	**Cohen**	**This Study**
100	58.0	23.6	147.3	61.0
90	32.5	17.7	82.5	45.0
75	22.5	12.0	57.1	30.5
50	17.5	9.9	44.4	25.2
25	10.0	8.1	25.4	20.7
10	8.0	7.7	20.3	19.5
0	7.0	4.9	17.8	12.5

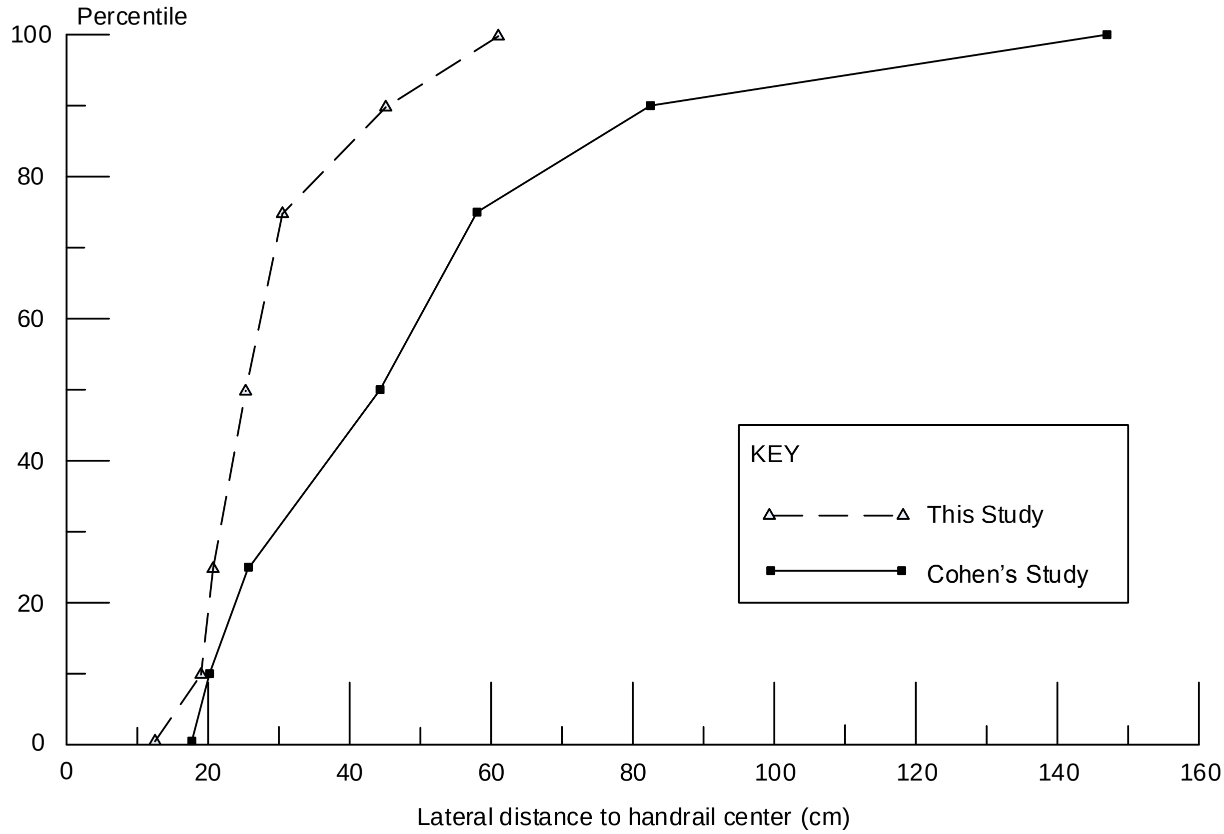


Figure 8. Cumulative distribution plots for comparing two studies

3.4. Other Factors that Might Influence Lateral Distance

This subsection describes analyses to explore possible effects of factors other than the primary ones (direction and handrail use). Specifically, analyses explored order of tasks and the following participant attributes—BMI, gender, weight, and height.

3.4.1. Effect of Task Order

In the experimental design, the order of testing was randomly assigned for each participant. Because randomizing order does not guarantee there will be no effect, two questions about order were explored.

1) For ascending, was the mean LD the same regardless of using the handrail first or second?

2) For descending, was the mean LD the same regardless of using the handrail first or second?

These questions were examined using a paired-sample t-test without assuming equal variances. The hypotheses were the same for ascending and for descending. Specifically:

$$H_0: LD_1 - LD_2 = 0, \text{ versus } H_1: LD_1 - LD_2 \neq 0$$

where: LD_1 is the mean value of LD for participants who first performed the task without using the handrail, while LD_2 is the mean LD for those who used the handrail in their first task.

For ascending, the 95 percent confidence interval for the mean difference (in cm) was from − 8.21 to 15.46 cm. The actual mean difference was 3.62 cm, well within the confidence interval. Thus, the null hypothesis is not rejected. Figure 9 (upper) is a boxplot depicting the mean values for when participants first performed task A (without the handrail) compared to when they first performed task B (with handrail). The mean of both fall within the interquartile range of the other.

For descending, the 95 percent confidence interval for the mean difference, in cm, was from − 7.62 to 18.17 cm. The actual mean difference was 5.25 cm, well within the confidence interval. Thus, the null hypothesis is not rejected. Figure 9 (lower) is a boxplot depicting the mean values for when participants first performed task C (without the handrail) compared to when they first performed task D (with handrail). The mean of both fall within the interquartile range of the other.

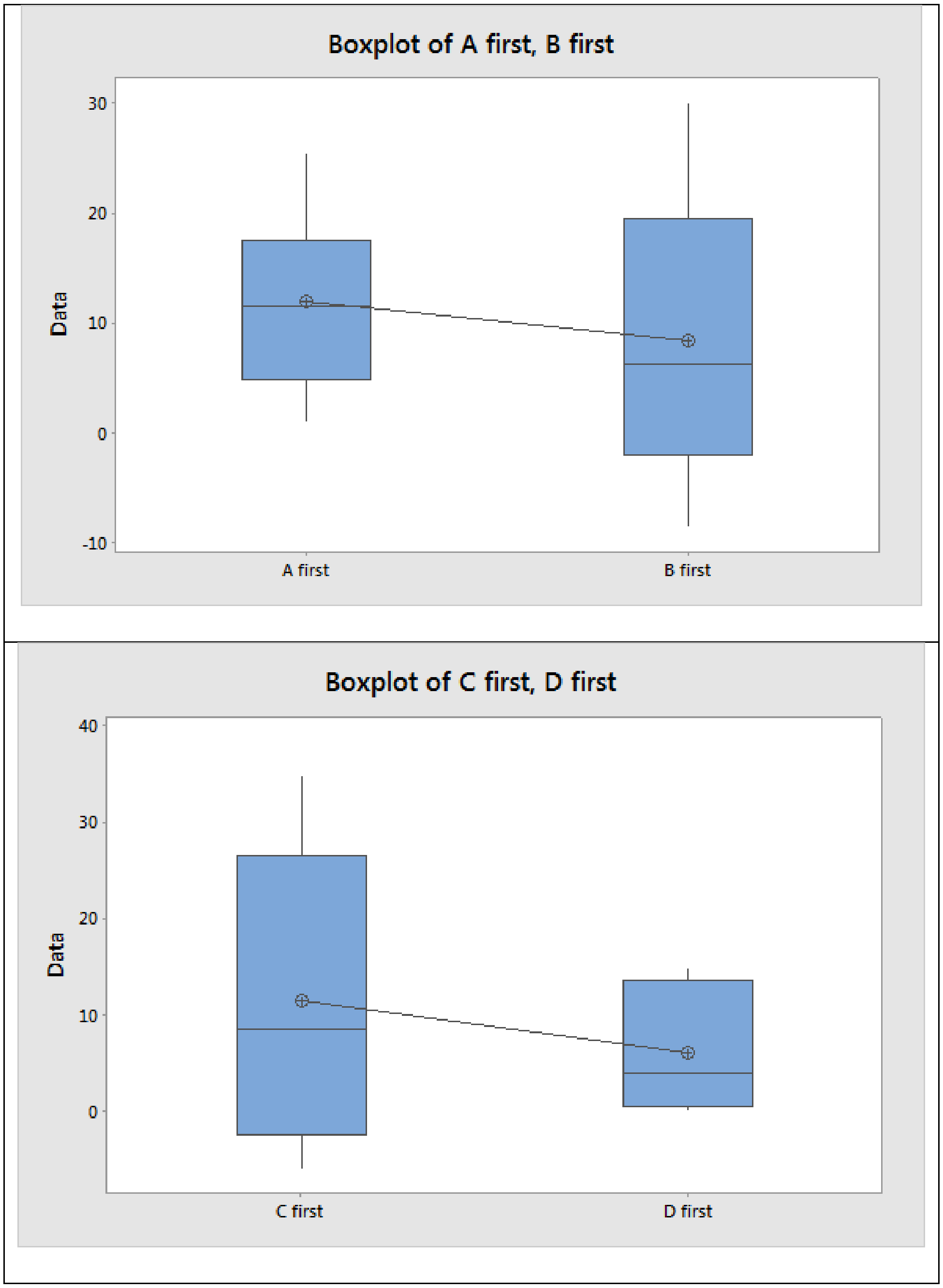


Figure 9. Boxplots for ascending in upper chart and descending in lower chart. The left side box plots are for not using the handrail first, while the right side are for using the handrail first.

3.4.2. Effect of BMI

The possible effects of BMI on LD were examined using a data plot and linear regression. The thought behind this was that a larger BMI means greater girth, which in turn limits how close the individual can get to the handrail. The hypothesis was that as BMI increases, LD will also increase. Figure 10 shows the linear regression line, LD = 19.31 + 0.416 BMI, and data points. The figure suggests a modest relationship between BMI and LD. However, the slope (0.416) was not significantly different from zero (p = 0.111). Clearly, the data are widely distributed about the line. Thus, this experiment does not support the proposition that as BMI increases, the LD of stairway users significantly increases.

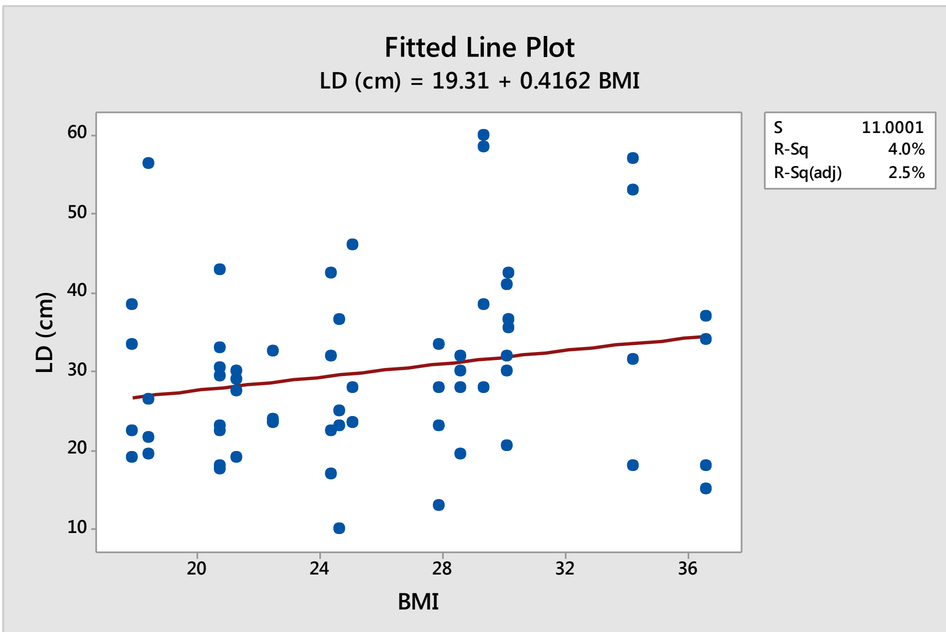


Figure 10. Regression line and scatter plot for LD related to BMI

3.4.3. Effect of Gender

Possible gender effects on LD were explored using ANOV for equal means. This test assumes the distributions are normally distributed. Plots of the distributions were generated by Minitab 17. One of the four histograms is shown in Figure 11. The other three are similar. All four tasks appear to have normal distributions for both females and males. Therefore, the assumption of normal distributions was met.

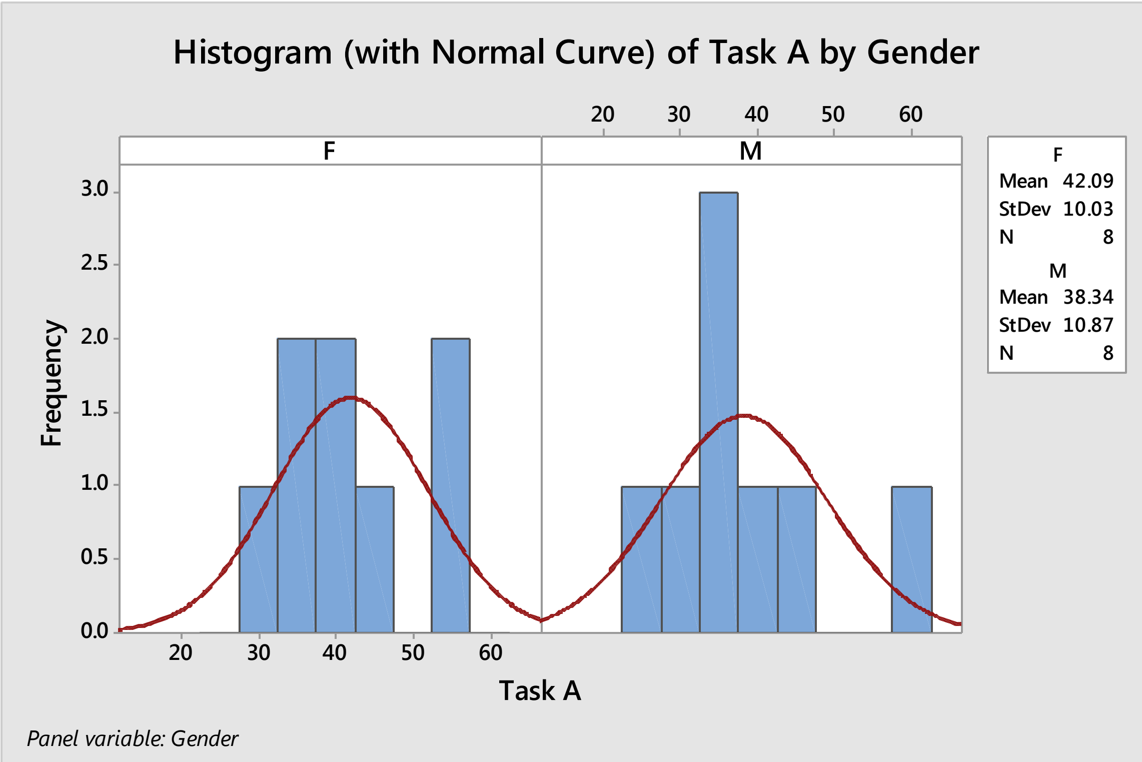


Figure 11. Distributions of gender-specific LD values for a representative task

An ANOV effects of gender on LD showed no significant effect (p = 0.46). Table X reports the means LD of each gender for each task. Each mean is for eight participants. The task-specific differences in the right column do not indicate a pattern of gender difference.

Table X. Gender-Specific Mean LD by Task with Differences

	Mean LD (cm)		
Task	**Females**	**Males**	**Difference**
A	42.1	38.3	3.8
B	28.0	32.0	-4.0
C	27.9	30.7	-2.8
D	17.9	23.2	-5.3
Column Mean	29.0	31.1	-2.1

3.4.4. Effect of Body Weight

A possible effect of body weight on LD was explored using regression. The hypothesis was that body weight affects LD. The initial regression equation for predicting LD from weight was found to be LD = 22.42 + 0.0990 Weight.

This regression line is shown in Figure 12 along with a scatter plot of all observation. The slope of the regression line was not significantly different from zero (p = 0.145). Thus, this experiment does not support the proposition that weight significantly affects LD.

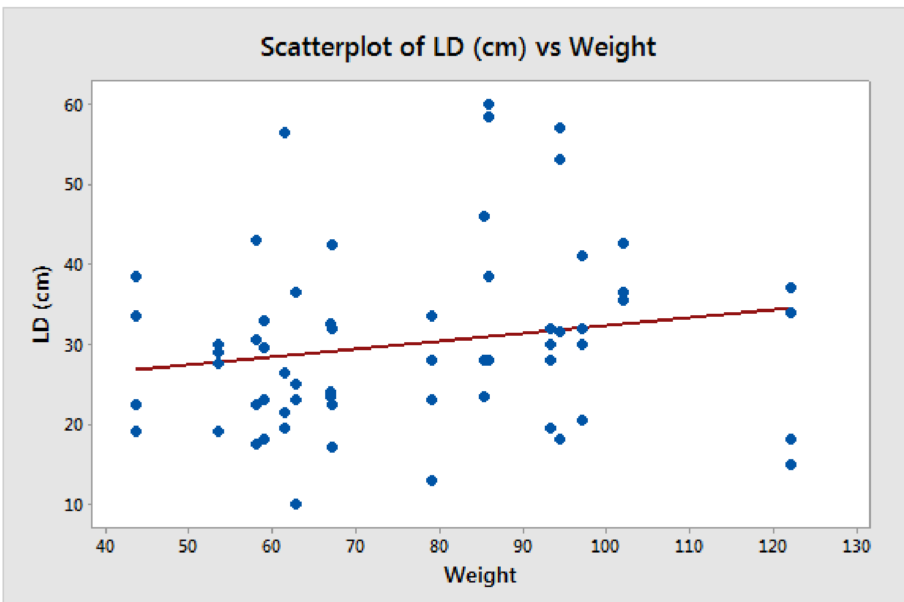


Figure 12. Regression line and scatter plot for LD related to weight

Looking more deeply into the weight effect, one might hypothesize that weight would affect LD differently for the different tasks. To explore this, a regression was run with two independent variables—task and weight. Minitab returned the task-specific regression equations found in Table XI. These indicate that each task has a different LD at the intercept where Weight equals zero, but they share the same gradual slope of 0.099 x Weight. However, the slope of these regressions is not significantly different from zero.

Table XI. Task-specific Regression Equations Relating LD to Weight

Task	Regression Equation
A	LD = 32.60 + 0.0990 Weight
B	LD = 22.41 + 0.0990 Weight
C	LD = 21.73 + 0.0990 Weight
D	LD = 12.92 + 0.0990 Weight

3.4.5. Effect of Height

A possible effect of participant height on LD was explored using regression. The hypothesis was that height effects LD. The initial regression equation for predicting LD from height was found to be LD = 7.7 + 13.0 Height. This regression line is shown in Figure 13 along with a scatter plot of all observations. The slope of the regression line was not significantly different from zero (p = 0.395). Thus, this experiment does not support the proposition that height significantly affects LD.

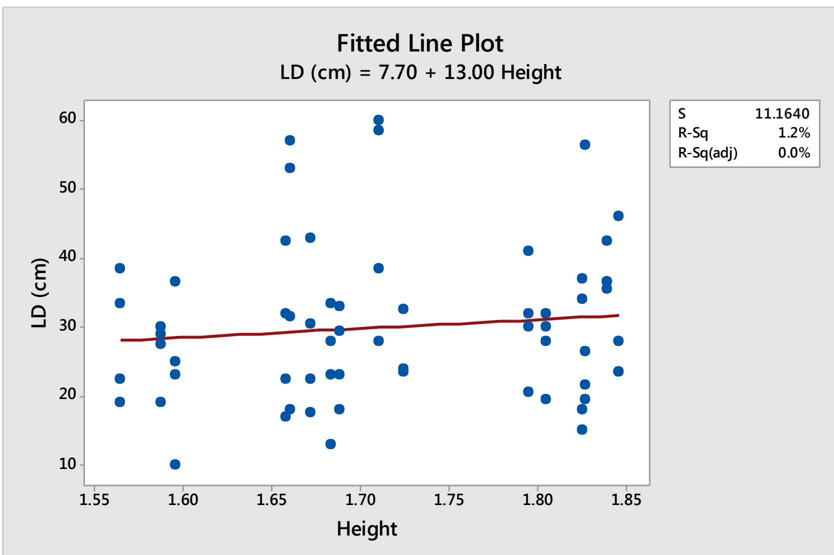


Figure 13. Regression line and scatter plot for LD related to height

4. Discussion

The two objectives of the experiment were to: (1) determine if a different set of stairway users will have the same median lateral distance from the handrail as those described in the prior observational study by Cohen (2000), and (2) determine if the lateral distance of participants is affected by their direction of travel and use of a handrail.

4.1. Achievement of Objectives

Regarding objective 1, the two medians were compared based on measurements from the center of the handrail. Cohen's study found a median of 44 cm, while this study found a median of 25 cm. The cumulative distributions seen in Figure 8 show the differences getting larger as the percentiles increase. Four possible explanations could account for this. One is the measurement method differed in two ways. One way was that Cohen (2000) positioned the video camera to aim at the midline of the stairs, whereas in this study two camera positions were used; one position for descents and another for ascents. The second way was Cohen (2000) used the center of the person's body as his point for measurement, whereas this study used the center of the person's knees as the point of measurement. The third explanation is that the width of the stairways differed. Cohen's stairway was 66 inches (167.6 cm), while the stairs in this study were 47.5 inches (120.8 cm). The fourth, and most likely reason is that Cohen observed people who freely choose their route. Some of them chose to descend closer to the handrail on their left hand side. In this study, participants were instructed to use the handrail on their right side for tasks B and D. They received no instructions on lateral position for the task without the handrail (tasks A and C). This could explain why the cumulative distribution plot (Figure 8) from this study is consistently left of that for the Cohen study.

Regarding objective 2, findings of this study indicate that lateral distance from the handrail is affected by the direction of travel and by use of the handrail. The greatest lateral distance was for ascending with the handrail. The shortest lateral distance was for descending without the handrail.

Going beyond the two objectives, analyses indicated that LD was not significantly affected by order of tasks, gender, BMI, body weight, or height.

4.2. Limitations

Limitations of the study include the following. The participants were not chosen randomly from a larger population of students, or from a large population of workers. This limits the ability to claim they represent a larger population of people in general or people in the workforce. Another limitation was the participants were instructed to use the handrail on their right side for two of the four tasks. People in general and people in the workforce do not typically receive any such instruction.

4.3. Recommendations

Recommendations for the lateral distance to measure, based on the 50th percentile, differ in this experiment from that found be Cohen (2000). We found 25 cm and Cohen found 44 cm based on measuring from the center of the handrail; or 22.5 cm and 42.5 cm if measured from the inside edge of the handrail. Part of the difference could be explained by the differences in methods.

The Principal Investigator and faculty advisor share the opinion that measuring from the inside edge of the handrail is preferable to measuring from the center of the handrail. Our reasoning is that handrails come in many shapes, it is the inside edge that matters to a user. However, this is not based on empirical studies. Thus, this is a possible topic for further research.

Other recommendations for further student research include: (a) replicate this study with different participants, (b) examine the effect of stair width on LD using similar methods as in this experiment, and (c) examine stairways with substantially different handrail shapes and sizes to determine how these handrail attributes influence LD.

At this point, it appears that when measuring a flight of stairs for uniformity of step dimensions, the preferred place to measure is within the range of about 22 to 43 cm from the inside edge of the handrail. These distance correspond to the 50^{th} percentile LDs in this experiment and the Cohen field observations, respectively. Further, the handrail to measure from should be the one most commonly used—the one on the right hand side of a person descending because descending is where the most serious injuries occur.

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Appendix A: Participant Recruitment and Ethics

This appendix contains three items: (1) gender-specific attribute tables, (2) recruitment notice, and (3) Consent Form.

Item 1: Gender-Specific Attribute Tables

Table A.1: Attributes of Male Participants

Parameter	Age	Weight (kg)	Height (m)	BMI
Mean	29.4	96.9	179.9	29.86
Max	44	122	189	36.63
Min	21	79	168.3	25.03
Median	26.5	95.1	181.5	29.72
S.D.	8.86	14.40	6.99	3.31

Table A.2: Attributes of Female Participants

Parameter	Age	Weight (kg)	Height (m)	BMI
Mean	22.3	63.4	167.9	22.25
Max	26	102	183.9	30.16
Min	20	43.6	156.4	17.82
Median	21.5	60.15	166.5	20.98
S.D.	1.98	17.10	10.48	4.02

Item 2: Recruitment Notice and Informed Consent Form

Attention OSH & Industrial Hygiene Students

Seeking Volunteers to Participate in a Stairway Safety Study

For a M. S. Thesis Project by

Industrial Hygiene Student
Lee Calf Looking

Will involve no more than 30 minutes in the HPER Building
The time will be arranged to fit your schedule
Receive $5 for ascending and descending a flight of stairs, twice
Video and/or camera recordings will be made

Project Title:
Stairway step uniformity: What lateral location should be measured?

To volunteer or learn more, please contact either:
Lee Calf Looking at 406-845-8042
or
Roger Jensen at 406-496-4111

The project is approved by the University of Montana Institutional Review Board,
___196 - 14____

Item 3. Consent Form

SUBJECT INFORMATION AND INFORMED CONSENT

Study Title: Stairway uniformity measurement: What lateral location should be measured?

Investigator(s):

Principal Investigator: Lee Calf Looking, Montana Tech Graduate Student

Faculty Supervisor: Roger C. Jensen UM Position: Professor

Work phone: 406-496-4111

Department:

Safety, Health, and Industrial Hygiene Office Location: S&E 319, Montana Tech

Special Instructions:

This consent form may contain words that are new to you. If you read any words that are not clear to you, please ask the person who gave you this form to explain them to you.

Purpose:

You have been invited to participate in a stairway uniformity measurement experiment. This is a project for a Master's degree in Industrial Hygiene. The objectives of the experiment are: (1) to determine if a different set of stairway users will have the same median lateral clearance from the handrail as those in the prior field study, and (2) determine if the participants had the same lateral distance for ascending and descending.

Methods:

The investigators will establish visible distance markers on one stairway in a campus building, video tape and photograph volunteer students ascending and descending the flight of stairs, and subsequently reviewing the images to determine the distance between each participant's mid-sagittal plane and the handrail centerline. Results will be analyzed statistically to test hypotheses corresponding to the two objectives.

Value:

The practical value of the project will be to strengthen the science underlying the methods used to conduct stairway fall incident investigations.

Procedures:

If you agree to take part in this study, you will be asked to ascend (walk up) and descend (walk down) a set of stairways while using the handrail. You will need to provide your age, gender, height and weight for only data use. Videotapes and photographs will be ottained as you perform the stair-case activity. A time and date will be given to you before taking part in this experiment.

Risks/Discomforts:

There is a minimal risk of falling, you will use the stairway in the same way you normally use stairs. If you experience discomfort you have the right to withdraw from experiment.

Benefits:

You may feel good about helping a fellow student complete a thesis project. Results will contribute to scientific knowledge about measuring stairways for step uniformity. After completion of the thesis project, it will be reported in a thesis manuscript and as a paper for publications in a conference proceeding. The distances measured in the experiment are not intended for generalization to larger population. The publication may be used as a basis for obtaining a grant to support a study using more diverse stairways and participants.

Confidentiality:

Confidentiality means the researcher will maintain records with personal identifiers but will not release information to unauthorized personnel. Anonymity means that records will not include any personal identifiers or code numbers that may link a participant to specific information.

Your records will be kept confidential and will not be released without your consent except as required by law.

Your identity will be protected and kept private in this project:

The exercise will be videotaped but will only focus on the subject's mid-sagittal plane (middle part of body to feet) which excludes their head while using the staircase. Your name will be protected and not revealed in the results. The Faculty Advisor will provide descriptive data for a table to go into the thesis and paper. The Faculty Advisor will assign numbers to participants and retain a key in electronic form. The PI will not have access to the key or personal identifiers. The original data forms with personal information will be shredded.

Voluntary Participation/Withdrawal:

You may withdraw from this research study at any time. You will not be penalized for withdrawing.

Questions:

If you have any questions about the research now or during the study contact: Lee Calf Looking, Montana Tech Graduate Student at (406) 845-8042.

If you have any questions regarding your rights as a research subject, you may contact the UM Institutional Review Board (IRB) at (406) 243-6672.

Statement of Your Consent:

I have read the above description of this research study. I have been informed of the risks and benefits involved, and all my questions have been answered to my satisfaction. Furthermore, I have been assured that any future questions I may have will also be answered by a member of the research team. I voluntarily agree to take part in this study. I understand I will receive a copy of this consent form.

Compensation for Injury:

In the event that you are injured as a result of this research you should individually seek appropriate medical treatment. If the injury is caused by the negligence of the University of Montana or any of its employees, you may be entitled to reimbursement or compensation pursuant to the Comprehensive State Insurance Plan established by the Department of Administration under the authority of M.C.A., Title 2, Chapter 9. In the event of a claim for such injury, further information may be obtained from the University's Risk Manager (406-243-2700; kathy.krebsbach@umontana.edu) or the Office of Legal Counsel (406-243-4742; legalcounsel@umontana.edu). (Reviewed by University Legal Counsel, May 9, 2013)

Printed Name of Subject

____

Subject's Signature Date

I give my consent to be videotaped and photographed. The videotaped and photographed images attained will only reveal my mid-sagittal plane (middle part of body to feet) which excludes my head while using the staircase. The videotape and photographs will be used after this project is completed for future staircase reviews and projects on the Montana Tech Campus.

____

Subject's Signature Date

Appendix B: Procedures for Randomizing

Randomization is required for the statistical hypothesis tests described in the Methods section. This appendix explains (a) how treatments were defined by the tasks performed by participants, (b) how the order of scheduling was completely balanced, and (c) how individuals were randomly assigned to treatments.

Treatments were defined by the four tasks each participant performed. These involved ascending and descending with or without using a handrail. The four combinations (i.e., treatments) were denoted with the letters A, B, C, and D. Table B.1 shows the task for each treatment. For example, for treatment A, the participant's task was to ascend the flight of stairs without using the handrail, while in treatment B, the participant's task was to ascended the stairs using the handrail on their right side.

Table B.1. Treatments Defined by Direction and Handrail Usage

	Task	
Treatments	Direction	Handrail
A	Ascend	No
B	Ascend	Yes
C	Descend	No
D	Descend	Yes

In order to remove treatment order as a possible factor, Latin Squares were constructed. In Table B.2, the first four rows and four columns makes one 4-by-4 Latin Square. It was constructed by starting row one with treatment A, followed by B, C, and D. For the second row, the treatment letters were shifted left. This process led to filling the first four rows. Note that each treatment occurs once in each column, and once in each row. Rows 5 through 8 make a second Latin Square. It was constructed by starting each rows in reverse order, from treatment D through A, respectively. The third Latin Square is the same as the first, and the fourth is the same as the second. The combination of four Latin Squares has 16 rows. Note that each treatment occurs four times in each column, and once in each row.

Table B.2. Four Treatments Arranged in Balanced Order

Order of Treatments A, B, C, and D			
1st	**2nd**	**3rd**	**4th**
A	B	C	D
B	C	D	A
C	D	A	B
D	A	B	C
D	C	B	A
C	B	A	D
B	A	D	C
A	D	C	B
A	B	C	D
B	C	D	A
C	D	A	B
D	A	B	C
D	C	B	A
C	B	A	D
B	A	D	C
A	D	C	B

The next task was to randomly assign participants to treatments. Each participant was denoted a number corresponding to the order they signed their consent form. A random number table was used to assign participant numbers to a list. The random number table has 5-digit columns of random numbers (Montgomery, p. 413). Procedurally, starting in the fourth column, the two left digits were searched from top to bottom looking for numbers from 01 to 16. When one of these numbers was found, it went into the list. If that number was found again, it was ignored. After scanning to the bottom of the fourth column, the scanning proceeded to the fifth column on the right. The scanning process continued in this manner until all numbers from 01 to

15 were found. All number except 11 were found, so it was assigned to the sixteenth place on the list. This list of number was used to assign participants to the respective 16 rows. Table B.3 shows the assigned treatment for each participant.

Table B.3. Participants Randomly Assigned to Treatments

	Order of Treatments A, B, C, and D			
Participant	1st	2nd	3rd	4th
2	A	B	C	D
16	B	C	D	A
7	C	D	A	B
10	D	A	B	C
3	D	C	B	A
8	C	B	A	D
9	B	A	D	C
14	A	D	C	B
12	A	B	C	D
6	B	C	D	A
13	C	D	A	B
4	D	A	B	C
15	D	C	B	A
5	C	B	A	D
1	B	A	D	C
11	A	D	C	B

Table B.3 served as a guide when a participant started their tasks. The Principal Investigator told the participant which treatment to perform first, second, third, and fourth.

Appendix B: Reference

Montgomery, D. C. (1976). Design and Analysis of Experiments (p. 413). New York: Wiley.

Appendix C: Test of Assumptions for ANOV

A proper randomized complete analysis requires two important assumptions. One is that the residuals are normally distributed. The other is the LDs for each task have equal standard deviations. The faculty advisor tested these assumptions using statistical methods not taught in the Industrial Hygiene statistics class.

To test assumptions, Minitab generates a figure with four graphs. The four graphs in Figure C.1 provide considerable information. The upper-left graph plots the 64 residuals on a line. If the residuals are normally distributed, the points will fall close to the line, with no non-linear trend. That is the case. The upper-right graph compares the residuals by the values of LD fitted by the model. This graphs does not show any pattern to suggest a relationship. The lower-left figure is a histogram of the residuals. The bars indicate an approximately normal distribution. The lower-right graph shows the residuals based on the order of observations. It does not show any tendency for residuals to change with order.

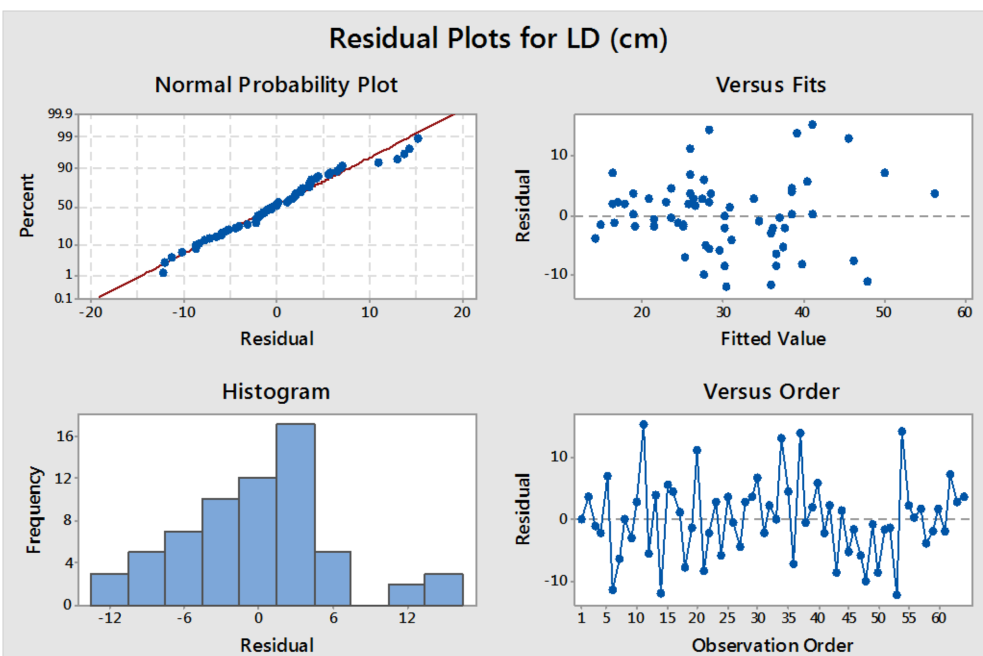

Figure C.1. Residual plots for the ANOV

The ANOV for this randomized complete block experiment requires that the LDs for each task have equal standard deviations. This was tested using Minitab to compute Bonferroni confidence intervals for standard deviations. The intervals shown in Figure C.2 overlap between 6.48 and 8.28 cm. The null hypotheses that the standard deviations are the same was not rejected (p = 0.115). Therefore, the standard deviations are not significantly different, and the ANOV requirement is met.

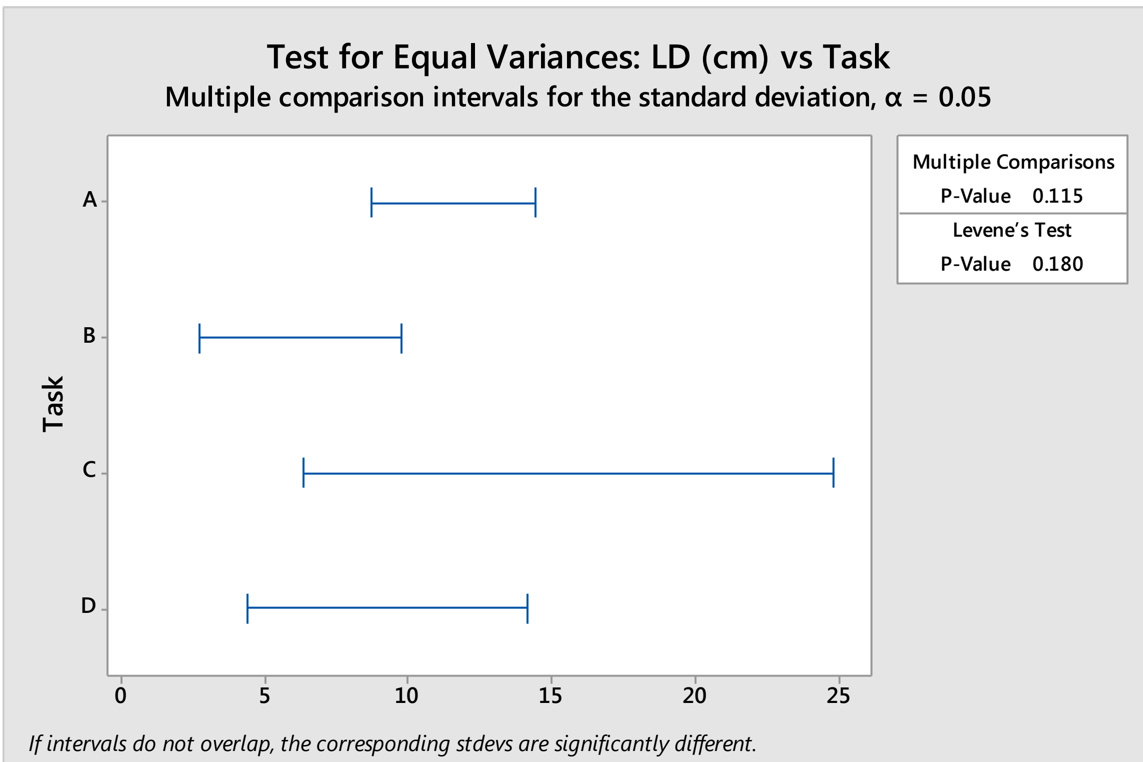

Figure C.2. Results of test for the four tasks having equal standard deviations

Appendix D: Participant Data

Table D.1 provides participant-specific data.

Table D.1. All Participant-specific Data

Participant	Measured Lateral Distance (cm)				Gender	Age	Weight (kg)	Height (m)	BMI (kg/m^2)
	Task A	Task B	Task C	Task D					
1	40.8	33.0	30.0	20.5	M	41	97.0	1.80	30.11
2	59.8	38.5	58.5	28.0	M	31	85.8	1.71	29.34
3	33.3	23.0	28.0	13.0	M	29	79.0	1.68	27.89
4	33.8	37.0	18.0	15.0	M	24	122.0	1.83	36.63
5	56.8	31.5	53.0	18.0	F	21	94.3	1.66	34.22
6	36.3	35.5	36.5	42.5	M	44	102.0	1.84	30.16
7	29.8	29.0	27.5	19.0	F	20	53.5	1.59	21.24
8	38.3	22.5	33.5	19.0	F	22	43.6	1.56	17.82
9	32.8	29.5	23.0	18.0	F	24	59.0	1.69	20.71
10	36.3	23.0	25.0	10.0	F	23	62.7	1.60	24.65
11	56.3	26.5	21.5	19.5	F	26	61.3	1.83	18.36
12	31.8	30.0	28.0	19.5	M	21	93.2	1.81	28.61
13	42.3	32.0	22.5	17.0	F	21	67.0	1.66	24.37
14	23.8	32.5	23.5	23.5	M	31	66.8	1.72	22.48
15	45.8	28.0	23.5	23.5	M	21	85.3	1.85	25.03
16	42.8	30.5	17.5	22.5	F	21	57.9	1.67	20.71

SIGNATURE PAGE

This is to certify that the thesis prepared by Lee Calf Looking entitled "Stairway Uniformity Measurement: What Lateral Location Should be Measured?" has been examined and approved for acceptance by the Department of Safety, Health, and Industrial Hygiene, Montana Tech of the University of Montana, on this 11th day of May, 2015.

Roger Jensen, PhD, Professor
Department of Safety, Health, and Industrial Hygiene
Chair, Examination Committee

Theresa Stack, M.S., Assistant Professor
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