DESIGN AND VALIDATION OF A DEVICE TO AID IN EXTENSION LADDER SETUP

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ABSTRACT

The problem of ladder base slippage is a leading cause of workplace injuries and causes a number of annual deaths. Research has shown that ladder users tend to set up extension ladders at an angle between 66° and 69° above horizontal, which is much shallower than the specified standard of 75.5°. This results in an increase in the friction required at the base of the ladder to support the weight of the ladder and its user, and leads to an increased likelood of a slideout accident. To counteract the problem of ladder base slipping, a device was developed to aid the user in achieving a proper setup angle. The device uses a mechanical switch to wired to LEDs that provide the user feedback on setup angle. The device was tested in a laboratory environment, and was shown to positively impact the ability of the user to erect the ladder at a proper angle.

KEYWORDS: *Extension ladder, safety engineering*

1.0 INTRODUCTION

The problem of ladder base slippage is a leading cause of workplace injuries and causes a number of annual deaths. In 2008, ladders were responsible for 119 fatalities and over 17,500 serious injuries (Simeonov, et al. 2012) . It has been reported that 23% to 33% of straight ladder accidents result from slipping of the ladder's base (Chang, et al. 2005).

Slipping of a ladder's base is due primarily to improper angling of ladders above horizontal (i.e., setting the ladder to shallow), which causes an increase in the friction required at the base of the ladder to support the weight of the ladder and its user. Research indicates that ladder users tend to set up extension ladders at an angle between 66° and 69° above horizontal, which is much shallower than the specified standard of 75.5° (Simeonov, et al. 2012). In static loading, setting a ladder at 69° requires a coefficient of friction 50% greater than a

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properly installed ladder and may easily induce slipping of the base (Wilson, 1990).

The research of Campbell and Pagano indicates that instruction and training were not sufficient to ensure proper setup of an extension ladder (Campbell and Pagano, 2014). This was also indicated by Simeonov et al. (2012) which concluded that devices could be used to aid the user in obtaining a proper setup angle (Simeonov, et al. 2012). A patented device was developed by the Simeonov group. Other work on active warning systems for ladder safety have shown them to be effective (Musto, et al. 2013).

While the work of the Simeonov group has shown that active warning devices are more accurate and faster to use than traditional methods, the technology has not yet been commercialized. Current commercialized solutions are limited to standard L-labels, which are generally factory-applied, and bubble level devices, which can be found in the $15 US price range. The L-label method has been shown to be difficult and confusing to use, and results in a wide deviation in setup angle in user testing (Campbell, 2012). Bubble levels have been shown to be more effective than L-labels or unaided setup (Young and Wogalter, 2000), Cambell (2012), but are subject to human interpretation; they therefore require significant iteration and increase setup time (Simeonov, et al. 2013).

A newer approach is provided by the free or low-cost smart phone applications available for ladder safety. These products use the accelerometers in a smart phone to indicte ladder angle, and warn the user of a deviation from the proper setup angle. While these show promise as a safety device (Simeonov, et al. 2013), they require access to a smart phone, and are handheld devices. Since they are not attachable to the ladder, they may not be consistently used, and they cannot give feedback once climbing has begun.

In this paper, a novel device for aiding the user in obtaining a safe setup angle is detailed. This device was developed by undergraduate mechanical engineering students as part of the Senior Design sequence at the Milwaukee School of Engineering. The details of the device will be shown, including how the range of acceptable deviation from the nominal accepted angle was selected. Testing of the device, which demonstrates that it successfully aids a user iin achieving a safe setup angle, will be detailed.

2.0 DESIGN OF THE DEVICE

The issue of extension ladders slipping at the base causes numerous significant injuries and several deaths each year. A leading cause for slipping of ladders is improper ladder usage; this often involves users setting the ladder at an improper angle. Several devices have been created and proposed to alleviate either the risk of slipping by increasing friction at the base or to mitigate user error in the setup of ladders. Many devices that measure the angle of ladders have been created, including smartphone apps written to measure angles of surfaces, bubble levels designed to specifically fit within a ladder's rung to aid the user in ladder setup, as well as more complex electronic devices developed to provide precise angle readouts to the user. Ladders with bubble level indicators have been shown to be significantly more time consuming to setup than continuous-feedback electronic devices used to setup the ladders (Simeonov, et al. 2013). However, the currently available electronic devices consist of several parts, contain complicated microprocessor circuitry, and have large displays that lead to high costs.

The purpose of this project was to develop a low-cost, easy-to-use sensor to aid users in the setup of extension ladders. The sensor allows the user to know whether the ladder is properly set within a certain range of the ANSI-specified angle of 75.5°. The overall goal of the project was to develop a sensor that will provide fast, accurate, and precise measurement of ladder angle to recommend whether or not a user should use the ladder as it is set, or to change the angle of the ladder. The project scope included development of the device, construction of a prototype, and testing of the prototype's functionality. The design of the device utilizes a pendulum-like mechanical switch to determine whether the ladder is set properly, too steep, or too shallow. Contact is made with one of two terminals if the angle is incorrect, and no contact is made when the angle is correct. This allowed for electrical circuitry to be designed to allow for the logic shown in Figure 1.

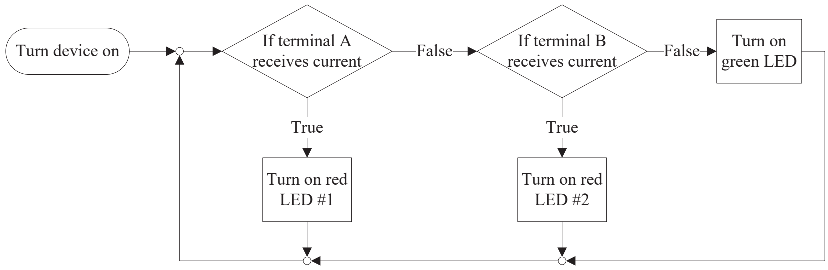

Figure 1. Switching logic

As shown in the logic diagram, the user interface consists of 3 LEDs that alert the user whether the ladder is set properly or improperly. The prototype designed for testing purposes is shown in Figure 2.

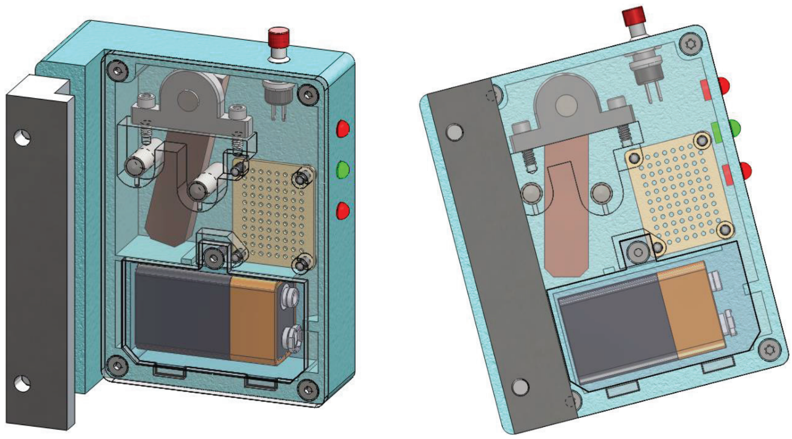

Figure 2. Mechanical design of the device

A key parameter in the design is the swing angle of the sensing pendulum. The swing angle of the pendulum corresponds to the allowable tolerance on ladder setup angle. To determine the acceptable tolerance, static calculations were performed on various ladder setup conditions. These analyses follow previous published analyses (Wilson, 1990, Barnett and Liber, 2004). For analysis, four setup scenarios were analyzed, assuming no additional devices were to be used to aid in the support of the ladder. Ladders and their feet may be made of several materials, including rubber (similar to that in a tire) and wood. Various materials may act as the ground support as well, including asphalt, grass, wood, concrete, and stone. Table 1 shows various friction coefficients for possible combinations of foot and ground materials (Engineers's Handbook, 2006)

Table 1. Friction coefficients for various material combinations for a typical ladder

Ladder foot material	Ground material	Friction coefficient
Rubber	Asphalt, dry	0.9
Rubber	Asphalt, wet	0.25 - 0.75
Rubber	Dry Concrete	0.6 - 0.85
Rubber	Wet Concrete	0.45 - 0.75
Wood	Clean Wood	0.25 - 0.5
Wood	Wet Wood	0.2
Wood	Stone	0.2 - 0.4
Wood	Concrete	0.62

Based on the friction coefficient values in Table 3, the minimum friction coefficient at the base was assumed to be μ_A=0.25.

2.1 Case I Analysis

A static analysis was performed given a ladder set up on level ground, top supported by vertical wall, as shown in Figure 3.

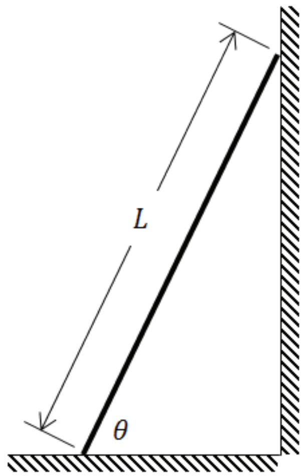

Figure 3. Setup of the ladder for Case I

For the setup, a free body diagram may be drawn and static equilibrium conditions may be applied, as shown in Figure 4, to determine the friction required at the base of the ladder.

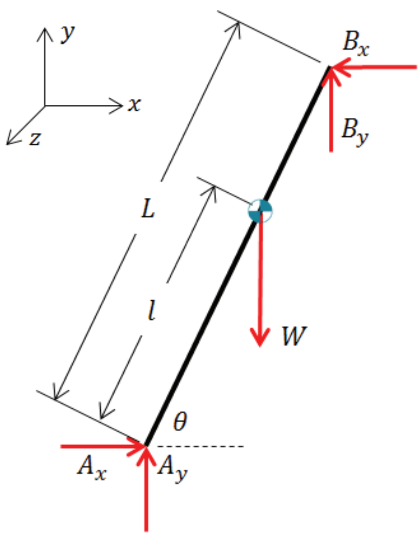

Figure 4. Free body diagram for the ladder Case I

The weight vector as shown in is the resultant of the weight of the ladder and the weight of the user, located between the center of the ladder (assumed to be the ladder's center of gravity) and the location of the user. Thus, the location l of the center of gravity of the system is given by Equation 1, where m_1 and l_1 are the mass of the ladder and location of its center of gravity, and m_2 and l_2 are the mass and location of the user.

$$l = \frac{\sum_{i=1}^{n} m_i l_i}{\Sigma m} = \frac{m_1 l_1 + m_2 l_2}{m_1 + m_2} \tag{1}$$

$$m = m_1 + m_2 \tag{2}$$

Thus, the equilibrium equations are,

$$\Sigma F_x = 0 = \mu_A A_y - B_x \tag{3}$$

$$F_y = 0 = A_y + \mu_B B_x - mg \tag{4}$$

$$\Sigma M_A = 0 = -(l \cos\theta) mg + B_x[(L\cos\theta)\mu_B + (L\sin\theta)] \tag{5}$$

where μ_A and μ_B are the coefficients ot friction at the bottom and top of the ladder respectively.

Simplifying and solving for the required coefficient of friction yields,

$$\mu_A = \frac{1}{\frac{L}{l}(\mu_B + \tan\theta) - \mu_B} = \left[\frac{L(m_1+m_2)}{m_1(0.5L) + m_2 l_2}(\mu_B + \tan\theta) - \mu_B\right]^{-1} \tag{6}$$

2.2 Case II Analysis

Certain situations require a ladder to be set with its top supported by an edge somewhere in the middle of the ladder. A schematic depicting the setup of the ladder of total length L_T on level ground set at angle θ is shown in Figure 5.

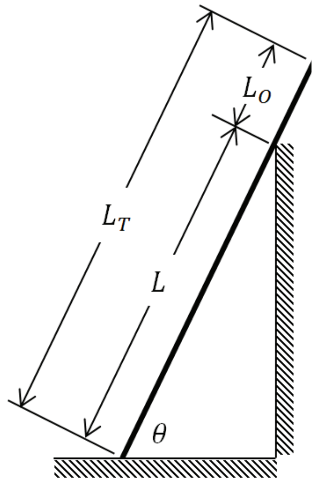

Figure 5. Setup of the ladder for Case II

For the setup, the free body diagram is shown in Figure 6.

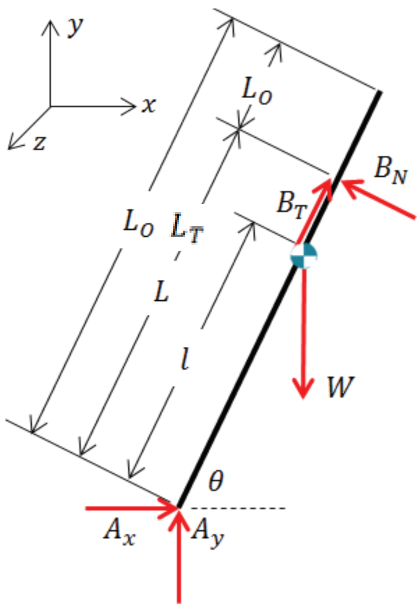

Figure 6. Free body diagram for the ladder in Case II

Performing equilibrium analysis as in the Case I analysis, and solving for the required coefficient of friction, yields,

$$\mu_A = \frac{(m_1(0.5L_T)+m_2l_2)\cos\theta(\sin\theta-\mu_B\cos\theta)}{L(m_1+m_2)-(m_1(0.5L_T)+m_2l_2)\cos\theta(\mu_B\sin\theta+\cos\theta)} \tag{7}$$

2.3 Case III Analysis

In certain cases, ladder users improperly set a ladder on sloped ground even though it is warned against by ladder manufacturers and standards. Understanding the effects of ground surfaces that may not be level is important in understanding usage of a device used to predict safe use of a ladder. Figure 7 shows the setup of a ladder supported by a wall on a sloped ground surface.

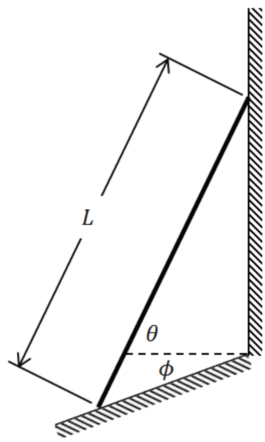

Figure 7. Setup of the ladder for Case III

Following the analysis of Barnett and Liber (Barnett and Liber, 2004), the static analysis was performed for this case. The required coefficient of friction that resulted is,

$$\mu_A = \frac{\tan\phi(m_1+m_2)(L\mu_B+L\tan\theta)+(m_1l_1+m_2l_2)(1-\mu_B\tan\phi)}{(m_1+m_2)(L\mu_B+L\tan\theta)-(m_1l_1+m_2l_2)(\tan\phi+\boldsymbol{\mu_B})} \tag{8}$$

2.4 Case IV Analysis

Mathematical analysis was performed on a ladder setup with sloped ground, supported by an edge, as shown in Figure 8.

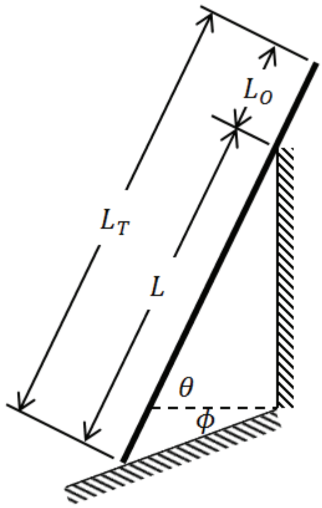

Figure 8. Setup of the ladder for Case IV

Again following Barnett and Liber (Barnett and Liber, 2004), the required coefficient of friction was determined to be,

$$\mu_A = \frac{L\sin\phi(m_1+m_2)+(m_1(0.5L_T)+m_2l_2)\cos\theta(\sin(\theta-\phi)-\mu_B\cos(\theta-\phi))}{L\cos\phi(m_1+m_2)+(m_1(0.5L_T)+m_2l_2)\cos\theta(-\mu_B\sin(\theta-\phi)-\cos(\theta-\phi))} \quad (9)$$

2.5 Comparison of Loading Cases

In order to determine allowable deviation from the nominal setup angle for the sensor, these four cases were analyzed using some typical ladder values. It was assumed that the ladder user had a weight of 200 lb, a ladder weight of 40 lb, ladder length of 24 ft, μ_B=0.6, and user location of 20.25 ft up the ladder, which, on most extension ladders, would be about the maximum recommended climbing height. For Cases III and IV, ground slopes of 1° and 5° were used. The resulting minimum values for ground friction can be seen in Figure 9.

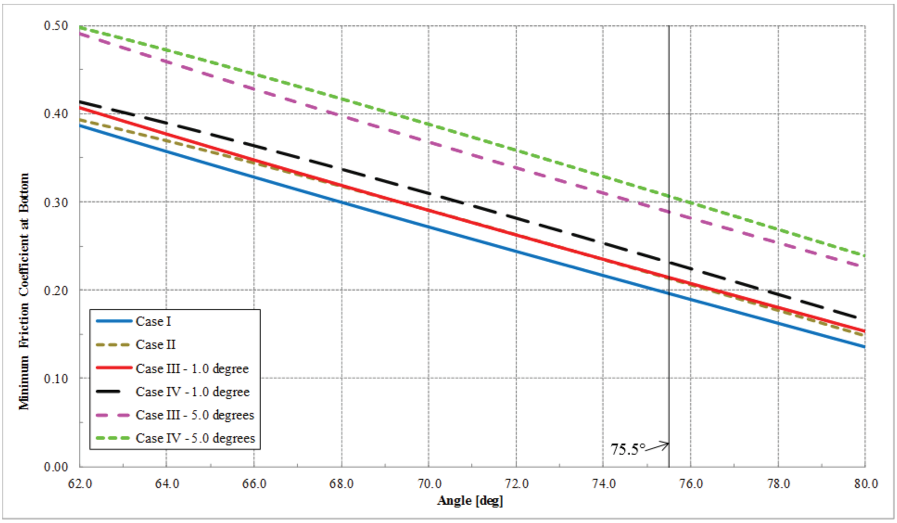

Figure 9. Plot comparing the minimum required friction at the base

At 73.5°, the minimum required friction coefficient is about 0.25. Based on the values in Table 3, the minimum friction coefficient between rubber and wet asphalt is about 0.25. Thus, the sensor must be able to sense the angle within 2.0° of the proper setup angle. As can be seen through the analysis, decreasing the angle to 69°, as one study suggests is within the range that untrained users tend to set ladders (Wilson, 1990), requires about 50% more friction than a properly set ladder. This justifies the need for a product to measure the setup angle within the specified accuracy of the device under development. To meet the required angle sensing constraints, the system utilizes a pendulum-like switch, similar to the test switch developed, as shown in Figure 10.

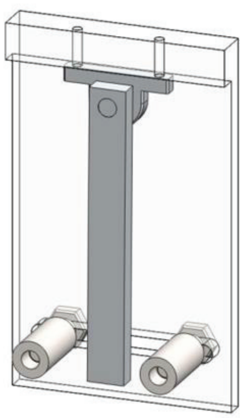

Figure 10. Pendulum-type switch developed for testing its feasibility

The pendulum creates contact with one of the two terminals when rotated, closing one of two circuits. A bearing at the pivot of the pendulum allows for low-friction rotation. The constraints for the device required the switch to allow for accurate reading of a high or low signal by the analog logic circuitry implemented into the device. Testing of the prototype based on this switch mechanism will be detailed in the following section.

3.0 LABORATORY TESTING OF THE DEVICE

The prototype ladder angle sensor was tested to determine whether or not it aided ladder users in a significant and positive manner. The test was setup to mimic a previously published test in which data was collected to determine the effectiveness of various ladder setup techniques. This test included unassisted setup and assisted setup using various methods, including a bubble level, another electronic sensor device, and anthropometric methods (Simeonov, et al. 2013)

The test was performed with fifteen participants of varying experience and skill level. All participants were required to answer a short survey regarding their ladder usage habits in order to gain an understanding of the experience level of testers. Questions included on the survey were,

- Have you ever had on-the-job training or experience in extension ladder safety?
- Have you received classroom education in extension ladder safety?
- Rate your knowledge of and experience with ladder safety (0 = None, 5 = Expert)
- Have you ever used any device to aid in extension ladder setup?
- What is the proper straight ladder setup angle?
- How often do you use extension ladders? (Daily, weekly, monthly, rarely)
- Which concerns you more? (Ladder base slipping, ladder tipping backwards)

Answers to survey questions are attached at the end of the report with other test data. Out of the fifteen participants, one knew the proper setup angle, one has received classroom training on ladder safety, all participants rated themselves as novices or intermediate ladder users, two participants use ladders more than a few times a year, and the majority (73%) were most concerned about ladders slipping than tipping backward. There were no significant peculiarities in the experience or knowledge of the device testers, but it should be noted that most participants were engineering students who deal with angular measurements on a weekly basis. This is a somewhat different demographic than other published tests, but the overall experience and skill matched closely to the previously published study.

The test consisted of three individual sets of tests, using both extended and retracted ladders. The test was split into three sets of testing, which were performed in the order below,

- Test 1 – The test participants set the ladder without being educated on the proper setup angle, both extended and retracted positions tested, not timed
- Test 2 – The test participants set the ladder with knowledge that the proper setup angle is 75.5°, both extended and retracted positions tested, not timed
- Test 3 – The test participants set the ladder using the aid of the prototype device, both extended and retracted positions, timed

Each test was set up with the ladder starting in a near vertical position, with the base located 0.1 m from the wall. The user was then asked to set the ladder in the correct position. Time was recorded for the user to set the ladder for Test 3 in order to compare to values in the previously published test. The angle of the ladder was measured using a digital inclinometer with a precision of 0.1°. Images of the prototype on the ladder used for the test are shown in Figure 11.

Figure 11. Prototype device on the ladder used for testing

The distribution of the data is shown in Figure 12, and the averaged results for the setup angle with one standard deviation are shown in Figure 13.

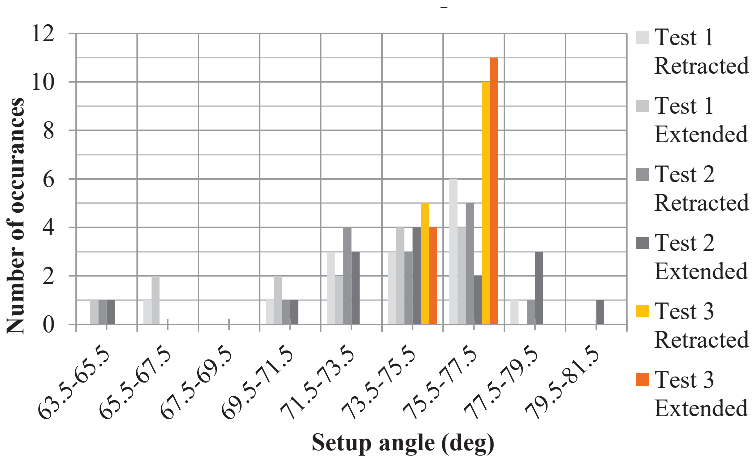

Figure 12. Distribution of the data from the test

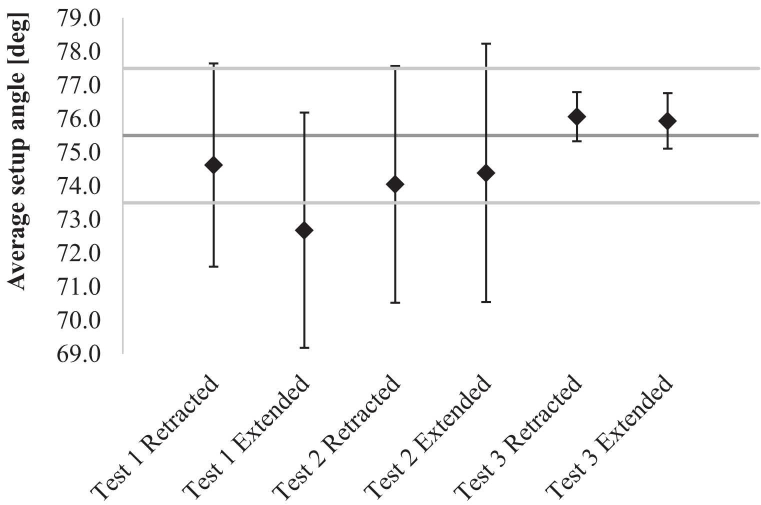

Figure 13. Results for the three tests, extended and retracted, with one standard deviate error bars

From the results of the test, it appears that the prototype device yielded a significant improvement in the setup of the ladder, with no data being outside of the acceptable range limits when the device was used. The averages of the tests only fell out of the acceptable range for Test 1 – extended, but the range of the data was widespread for the data sets from tests 1 and 2. To further analyze the data, F-tests were performed to validate the effectiveness of the device. The F-test was used to determine the probability that the data contained within two tests were statistically similar. The results of the F-tests are shown below in Table 2, showing the probability that data sets are statistically similar.

Table 2. Probability that two tests are statistically similar as determined by the F-test

	1 R	1 E	2 R	2 E	3 R	3 E
1R	1.00000	0.59499	0.57740	0.38269	**0.00000**	**0.00002**
1E		1.00000	0.97950	0.73070	**0.00000**	**0.00000**
2R			1.00000	0.75007	**0.00000**	**0.00000**
2E				1.00000	**0.00000**	**0.00000**
3R					1.00000	0.64639
3E						1.00000

From the F-test results, it appears that the prototype device significantly changed the setup of the ladder. To further analyze the data, T-tests were performed to find p-values for hypotheses regarding the correlation between data sets to determine. The null hypotheses tested were,

- Hypothesis 1 – Extending the ladder has no effect – compare all data for extended setup to corresponding data from retracted
- Hypothesis 2 – Education on the proper setup angle has no effect – compare all Test 1 data to corresponding Test 2 data
- Hypothesis 3 – Use of the prototype device has no effect on ladder setup – compare all Test 1 data to corresponding Test 3 data, and compare all Test 2 data to corresponding Test 3 data

Hypothesis 1 was tested to determine if all the data could be grouped together for analysis in addition to providing a better understanding of the setup of ladders. Hypothesis 2 was tested to determine whether or not significant improvement could be detected once a ladder user was instructed on the proper setup angle. Hypothesis 3 was tested to determine the probability that the device produces a significant change in the setup of the ladder. The T-test analysis utilized the assumption of a one-tailed distribution, as the data in Figure 12 shows a skew in the data, biased to the left of the peak occurrence. The results of the analyses performed are shown in the table below. A 95% confidence interval ($p=0.05$) was used as the threshold for rejecting a hypothesis. The results are shown in Table 3.

Table 3. Results of T-tests performed on the three hypotheses

Hypothesis	*p-value*	*Reject if p<0.05*
1 - Extension has no effect	0.0662	Cannot reject
2 - Training has no effect	0.2482	Cannot reject
3 - Device has no effect (Test 1 to Test 3)	0.0004	Must reject
4 - Device has no effect (Test 2 to Test 3)	0.0073	Must reject

Result
1 - No detected difference between extended and retracted
2 - No detected difference with knowledge of proper angle
3 - Significant improvement with use of device
4 - Significant improvement with use of device

As seen in Table 3, education on the proper setup angle cannot be proven to have any significant effect on the setup of the ladder, and length of the ladder made no detectable difference in ladder setup. However, use of the prototype angle sensor was shown with over 99.9% confidence to improve the setup of the ladder from uneducated setup, and over 99.2% percent confidence for improvement over educated setup.

In addition to the angle measurements, time measurements were taken for Test 3. These time measurements are shown in comparison to setup time for other methods of determining ladder angle. The methods of setup used in the previously published test were,

- No instruction – nearly identical conditions to this experiment's no instruction test
- Anthropometric – utilization of the geometry of the human body to determine proper setup angle
- Bubble indicator – use of a bubble level specifically designed to show proper ladder setup angle
- Multimodal indicator – use of an expensive, high-precision electronic device designed specifically for determining proper ladder setup angle

A plot with showing the data from this test compared with the results of previous published testing (Simeonov, et al. 2013) is shown in Figure 14.

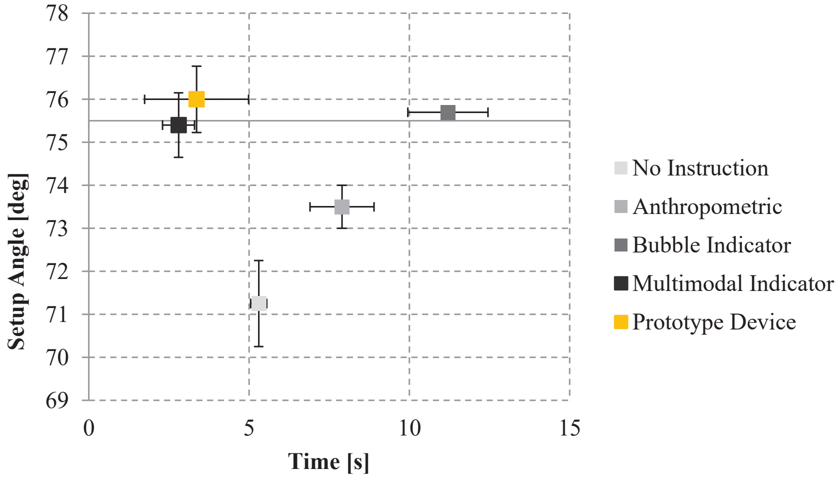

Figure 14. Setup time required for the prototype device compared to other ladder setup methods from previously published data (Simeonov, et al. 2013)

The prototype device developed was shown to be comparable in accuracy and setup time (about 3 seconds) to the multimodal indicator, which performed best in the previously published study. From the testing of the prototype it can be determined that the device performs functionally and produces the desired results. The performance is comparable to or better than all other ladder setup methods that have been tested previously.

4.0 CONCLUSIONS

In this paper, a new device for aided in the proper setup of extension ladders has been presented. The device was designed to be more reliable and simpler to use than other passive devices (e.g. bubble levels), and to be a low-cost alternative to the active sensing alternatives available. The design was detailed, and the acceptable range of sensor accuracy was justified using static analysis. Prototype testing was also detailed; this testing demonstrated that the prototype device dramatically improves the likelihood of proper setup angle, with a confidence level of over 99%. In addition, the testing demonstrated an accuracy and setup time comparable with the more expensive multimodal indicator devices. The prototype shows great promise as a device to improve industrial ladder safety. The cost of the prototype was approximately \$175.00 US. Major cost drivers were the cost of the prototype housing, and the cost of the plating process required for switch contacts. These costs will be greatly reduced in mass production; initial cost estimates show that the device could be produced in the range of $14.00 US in large quantities. Future work is continuing on the optimization of the design for mass production.

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