ABSTRACT

Title of Document: VIBRATION DOSAGE FOR HANDHELD POWER TOOLS BASED ON EXPOSURE-RESPONSE RELATIONSHIP FOR WHITE FINGER DISEASE

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Power-tool vibrations can cause a variety of health disorders, ranging from inconsequential to disastrous. These vibrations may not be harmful when received in small doses but can cause vasospastic disorders, such as vibration-induced white finger disease (VWF), with frequent use or accumulated over time. Existing occupational guidance does not adequately describe the health risks associated with power-tool vibrations. In the current study, vibration levels for major brands of reciprocating saws and impact drivers were measured under typical use conditions, along with user comfort levels after different usage times. Results are provided in terms of acceleration and comfort levels as a function of usage time, varied grip-force conditions, and with or without use of gloves. Based on the VWF-incidence data from prior occupational studies, guidance on restrictions on usage of power tools is provided. It is found that existing ISO guidance for Europe overestimates allowable times, compared to those determined here.

VIBRATION DOSAGE FOR HANDHELD POWER TOOLS BASED ON EXPOSURE-RESPONSE RELATIONSHIP FOR WHITE FINGER DISEASE

By

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Dedication

I would like to dedicate this thesis to my family and fiancée who have always been there for me and helped me to become the person I am today. I have received constant support and inspiration from them which have helped drive me to perform at my best. Without them I would not be where I am today.

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I would like to thank the following people for their help and support throughout my research. Without their assistance this report would have not been possible.

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Shreyas Parameshwaran always had kind words of encouragement and would take time out of his day if there was something I was preoccupied on. His suggestions have helped lead to successful findings.

Lastly, I would like to thank Mr. Majid Aroom for letting me use the PIRLS lab and machine shop facilities as my home away from home. Without the use of these facilities and his guidance, constructing prototypes would have been much more difficult.

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Chapter 1. Introduction

1.1. Everyday Vibrations

All around the world each and every day humans are exposed to many types of vibrations without even noticing it. One example of an unknown vibration is driving a car to get into work. Typically, once the trip is over and the individual arrives at work, they are not thinking about how they were vibrating on their drive in. This is because dampening techniques are specifically followed in order to reduce the amount of vibrations a human experiences when driving a car. Once the person gets out of the car, they no longer feel any vibration which may have been transmitted through their body. The vibration frequency and amplitude of the car are not hazardous to any part of the human body, under normal conditions.

On the other hand, in a case where a human holds onto a jackhammer for a very short period of time they may not feel anything afterwards. However if used for prolong periods of time, such as someone who would be operating it daily like construction workers, there may be long term side effects. These side effects can lead to anything from a slight amount of tingling in their hands to major motor skill complications such as Hand-Arm Vibration Syndrome. [1]

For these types of workers in Europe, regulations have been implemented in order to help keep them safe. These laws are knows as the European Physical Agents (Vibration) Directive. Power tool manufacturers are required to provide vibration emission data to the customer. However, in the United States Occupational Safety and Health Administration (OSHA) lacks regulation over vibration exposure to users. The only standards available are those such as ANSI S2.70-2006 which is a revision of the guidelines for measurement and evaluation of human exposure to vibration transmitted to the hand published in 1986. There are also ISO guidelines such as ISO 5349:2001, which give general requirements and practical guidance for those in the workplace. However, there are no set standards that protect the workers in the United States against vibration dosage.

1.2. Vibration Limits

Limits to the amount of vibration dosage an individual can receive in a given day’s work have been implemented in Europe. The Exposure Action Value (EAV) is the vibration dosage value which workers can work below without any further controls in place or actions from the company. With this value at 2.5 m/s^2 this lets companies know that if their employees are exposed to more than this they must then take actions to reduce the amount of vibration dosage to the employee. There is an Exposure Limit Value (ELV) of 5 m/s^2 which is the absolute maximum. At this point the employee would be required to cease working with vibration emitting tools for the day. To find the dosage amount an employee is receiving, it is more complicated than just measuring the vibration of a tool. Companies typically have a point system in place which is followed for calculating employee’s vibration dosage. The following process is a demonstration of the best way companies can estimate the vibration dosage of each employee efficiently. [13]

First they must determine how much time it will take for the employee to reach the exposure action value.

$$\left(\frac{exposure\ action\ value}{vibration\ value}\right)^2 \times 480\ min$$

Next they would measure the time it takes the employee to do 1 action with the tool. For example if using a drill, how long it would take to drill 1 hole.

Once this value is obtained, they can calculate how many applications the employee has the potential to do in a given day.

$$\left(\frac{Minutes\ to\ EAV\ \times 60}{Number\ of\ seconds\ for\ 1\ action}\right)$$

This value can then be compared to the exposure action value, which in the point system is typically 100, where the exposure limit value is four times that value at 400. This system allows companies to track employees’ vibration dosage levels and keep them safer. A good company log is generally taken of all power tools used in order to use for the above equations.

Depending on what type of power tool an employee is using, different amounts of gripping force are needed to properly operate the tool. For some tools there are also multiple positions which the user may grip. The employee must be able to endure the vibration energy transferred from the tool through their body. Below, Figure 1 gives a couple examples of power tools that emit relatively high amounts of vibration to the user while in operation.

Figure 1. Examples of high vibrating power tools (Left: Jackhammer, Right: Chainsaw) [18]

Many studies have been performed on the health effects of vibrations on the human body. Every power tool user wants to be safe while working. There are numerous problems for humans which come from being exposed to vibrations. Exposure can lead to back pain, decrease in hand sensation and dexterity, finger blanching, or carpal tunnel syndrome, as well as other problems.

Similarly, users can be affected by their grip strength. Studies show that when a power tool begins to vibrate there is an increase in the grip force users exert in order to continue properly holding the tool. [3] Typically there is approximately 7%-27% increase in gripping force; however this may change depending on the application the power tool is being used towards. Over time it has also been shown that vibrations weaken the grip strength of the power tool user. [4] It can lead to 20% decrease in grip strength the user has available before and after using the power tool for a period of time. There are many other factors that increase the chances of negative health effects, which are highlighted in Table 1. [5]

Table 1. Risk factors related to vibration syndrome

Vibration Characteristics	Processes and Tools	Exposure Conditions	Environmental Conditions	Personal Characteristics
Intensity	Tool Type	Duration	Air flow	Training of worker
Frequency	Tool Design	Exposure Profile	Humidity	Use of gloves
Direction	Use and tasks		Ambient temperature	Applied forces
			Noise	State of health
				Individual susceptibility

A study was performed in Italy where 570 quarry drillers and stone carvers, who were exposed to vibration and manual activity, went through interviews and health check-ups. It was found that 30.2% of the group had vibration induced white finger disorder. Another disorder called Raynaud's Phenomenon, dealing with nervous system tissue damage, was found in 4.3% of the drillers and carvers. Exposure data was recorded from the study which led to a correlation between the dose of vibrations and the problems found with the employees. [2]

As identified before, Europe has their rules and regulations in place which help to save many employees working with vibration emitting equipment on a daily basis from various maladies. Companies being required to log the amount of vibration dosage each employee receives during their work due to the European Physical Agents (Vibration) Directive sets their health and regulations system one step ahead of the United States in this field.

Therefore, it can be revealed that there is a need for formalized guidance on vibration dosage to those using power tools in the United States. The vibration health effects of future generations must be protected by an organization such as Occupational Safety & Health Administration (OSHA) as they help to keep workers safe in a variety of workplace related areas.

The following sections will contain background information regarding vibration related health problems, the experimental setup for each test procedure, the results and discussion of each test performed, a tool vibration comparison, the vibration dosage life-time effects, and finally the experimental conclusions.

Chapter 2. Background

2.1. Vibration Related Health Studies

Monitoring users who develop vibration related health problems can be quite difficult depending on their line of work, especially when no one would want to undergo testing which could lead to acquiring these problems. Some studies performed previously have been performed on vibratory health effects using rat tails to simulate how vibration dosage can affect the human body. [6] The rat tail was strapped down to a vibration plate which had adjustable frequencies and amplitudes. A rat tail has similar features such as arteries, veins, nerves, tendons, muscle, and vertebra, which can be found in human hands. The frequency and amplitudes of exposure were adjusted between 30 Hz to 800 Hz and 3.9 to 0.0055 mm respectfully. Through these tests notes and pictures were taken to monitor the condition of the rat tail. Additional studies were performed and used to inspect raw vibration emissions. [23]

Results from various studies [22] demonstrated patterns of vibration damage induced by vibration to arterial damage to the smooth muscle and endothelial cells. This can relate to what might happen to a human user after repetitive use of power tools exerting similar types of vibration frequency and amplitudes. Further studies were performed on vibration magnitude and frequencies of rat tails, since the natural frequency of a rat tail is between 161-368 Hz while human fingers are between 100-350 Hz. [7]

Other studies were done on human fingers; after it was clear the patient had one if not multiple health problems with their hand. However, in these studies, the dosage and time frames for how often power tools were used was not tracked. [9][10] Many of these studies did show deformation and damage to the finger tissues. Medical examinations were performed on a group of vibration exposed workers who filed for compensation due to vibration induced white finger which was then put through a study. The study demonstrated that there was a strong correlation between using power tools and the medical conditions presented. During the course of the study a majority of the workers experienced their conditions either staying stationary or worsening. [8]

This demonstrates how detrimental vibration exposure is to workers health and why more regulations should be put into place. Further research on how vibration dosage due to grip strength and other factors are presented in the following setups.

The Primary tool being studied in this report was the DEWALT DW304P reciprocating saw. DEWALT was selected because they currently hold a large market share as specified in 2010 reports. [14] The reciprocating saw is one of the more popular high vibration power tools used in the construction industry. A comparison within makes was also performed by using Brand 1 (Milwaukee Sawzall 6501-31) and Brand 2 (Ridgid R3002) reciprocating saws. These competitor tools are also used in the market intended for similar uses as the DEWALT tool.

An alternative power tool was studied to review a lower vibration tool used by construction workers. The DEWALT DCF885 cordless impact driver was selected as one of the leading market impact drivers used in the industry. [14]

The next section will go through the experimental setups for each of the tested areas performed.

Chapter 3. Experimental Setup

In the experimental setup, it will begin with the primary reciprocating saw, followed by the brand 1 and brand 2 reciprocating saws, then the impact driver, and finally the vibration plate. All setup procedures and reasoning's will be explained.

3.1. Primary Reciprocating Saw

The first set of testing was done using the Primary reciprocating saw, as previously mentioned, with a wood blade (DW4802). The reciprocating saw is used by professionals in a variety of different ways. Typical uses and holding styles are seen in Figure 2. This tool is ideal for consumers looking for a quick and rough cut through various materials.

Figure 2. Typical usage of reciprocating saw

(Left: Thin pipe cut, Middle: Floor plunge cut, Right: Beam cut) [15]

For these tests performed Premium Douglas Fir Lumber of dimensions 2 inch x 10 inch x 12 feet were used as this is a common material which is used by construction workers. Cut marks were made every 1.5 inches along the wood as shown in Figure 3 and then clamped to a cutting table in a vice.

Figure 3. Reciprocating saw cutting wood setup in vice with markings

Before the actual test was run, a data collection sheet was filled out, seen in Appendix A, to document important factors in each test. These factors include date, time, duration, room temperature, room humidity, a written test before and after, a line test before and after, grip strength before and after, number of cuts, a qualitative hand score, and qualitative hand notes section. The grip strength was measured using a CAMRY EH101 electronic hand dynamometer. The user would pull the handle and apply their maximum gripping force they could at that time. This device is displayed in Figure 4.

Figure 4. CAMRY EH101 electronic hand dynamometer used for grip strength testing

A picture of the users hand operating the switch on the tool was taken before and after the cuts. Once the before cutting sections were completed on the data sheet, the accelerometers were placed on the designated places as shown in Figure 5.

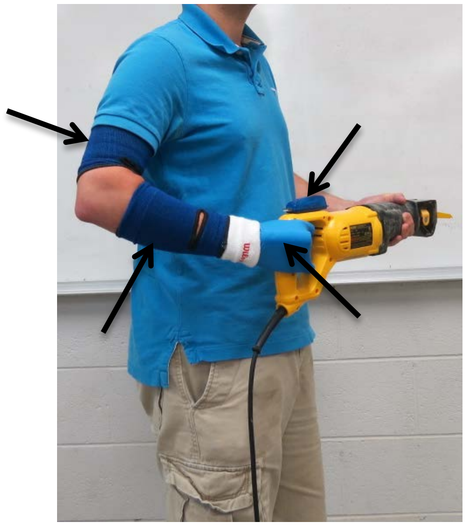

Figure 5. Accelerometer mounting locations (Tool, Hand, Forearm, Triceps), USB end of accelerometer pointed away from hand for consistency, flat side flush with skin

The vibration locations were chosen by how the human arm and hand react when gripping and holding a mass. [17] The first accelerometer was placed directly on the tool handle above where the users hand came into contact with the tool. Tests were performed with an accelerometer also mounted on the boot of the tool to ensure the vibration was similar in its given location. Additionally an accelerometer was mounted vertically where the users hand would be placed when cutting to ensure position orientation did not affect the results. These two setups can be seen in Figure 6. This accelerometer was rigidly attached to the reciprocating saw.

Figure 6. Accelerometer Mounting Position Test Setup (Left: Boot vs. Handle, Right: Horizontal vs. Vertical on Handle)

The second accelerometer was placed securely under a rubber glove on the top of the user's hand. A rubber glove was used as it did not add much padding or vibration absorbing features to the cutters hand which could reduce the vibration felt by the accelerometer. This is demonstrated in Figure 7.

Figure 7. Accelerometer under rubber glove for acceleration measurements

A wrist band was worn to help hold the accelerometer in place and ensure it did not back out of the glove. The third accelerometer, used for possible further data analysis, was placed on the fore arm held in place by a snug elastic brace. This would let the skin act as it would when experiencing vibrations but with an accelerometer held firm against the skin feeling the vibrations. This part of the arm was firm while the muscles were tight holding the weight of the tool and cutting. The final accelerometer, also used only for possible further data analysis, was placed on the user's triceps using the same brace as the fore arm. This final location was chosen due to the triceps not being tight during the gripping and cutting motions. These locations will help to determine how vibration emanates through the human body when the muscles are being tightened and gripping vs. not being directly used.

The accelerometers located on the tool and the users hand were Gulf Coast Data Concepts rechargeable accelerometers X16-2 set to record at 400 Hz sample rate and up to 18 minutes worth of data as shown in Figure 8.

Figure 8. Accelerometer X16-2

The last two accelerometers located on the arm were Gulf Coast Data Concepts X16-1C set to record at 200 Hz sample rate and up to 18 minutes worth of data. These had an identical outer appearance as the other model accelerometers.

A 10 lb. weight was placed around the boot of the reciprocating saw as shown in Figure 9. This helped relieve the amount of pressure the user was required to exert on the reciprocating saw in order to perform the numerous tests. Additionally, this removes the bias force which a user applies when cutting as this variable can change drastically on user strength and application. By adding the weight the force applied will remain constant for all cuts. Test cuts were performed with and without the weight in order to ensure comparable data.

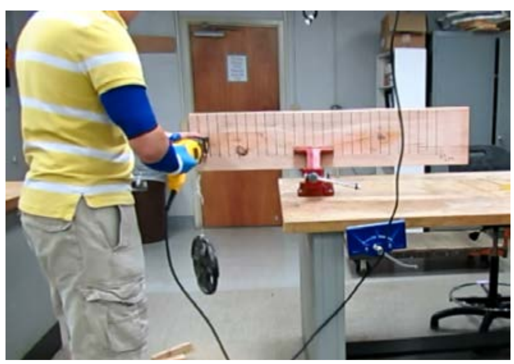

Figure 9. Primary reciprocating saw with bias weight

Various durations of cut time were repeated 5 times each to confirm the results were consistent. A special cut using vibration reduction gloves (DPG250) was also done to understand the impact and how much reduction was visible to the user.

After each run, the data sheet was filled out again to see the change in various areas due to the vibration. Each run was video recorded for review. After each set of 5 tests a new blade was installed in the blade clamp of the reciprocating saw. The noise was measured using an EXTECH 407736 sound meter. Lastly, the room temperature and humidity were measured by an Oregon Scientific weather station (BAR806HGA).

3.2. Brand 1 and Brand 2 Reciprocating Saw

The next testing set consisted of the Brand 1 and Brand 2 reciprocating saws shown in Figure 10. These tools were used as a make comparison. Identical cutting procedures on the Primary reciprocating saw were done using these tools. Three-minute run times were performed using Brand 1 and Brand 2 reciprocating saws.

Figure 10. Brand 1 (Left) and Brand 2 (Right) Reciprocating Saws

3.3. Impact Driver

The impact driver is another popular tool professionals rely on when needing not only a drill, but something giving a considerable amount of torque to drive a bolt or fastener into place. The typical holding styles and some usages are displayed in Figure 11.

Figure 11. Typical usage of impact driver (Left: Bolt tightening, Middle: Deck fastening, Right: Drill hole) [16]

Pine Pressure-Treated Lumber of dimensions 4 inch x 4 inch x 8 feet were setup with three holes across each separated by approximately 1 inch where ¼ inch x 3 inch galvanized lag screws were driven in to the wood. The wood was held in place on a table by two clamps. An example of this setup is shown in Figure 12.

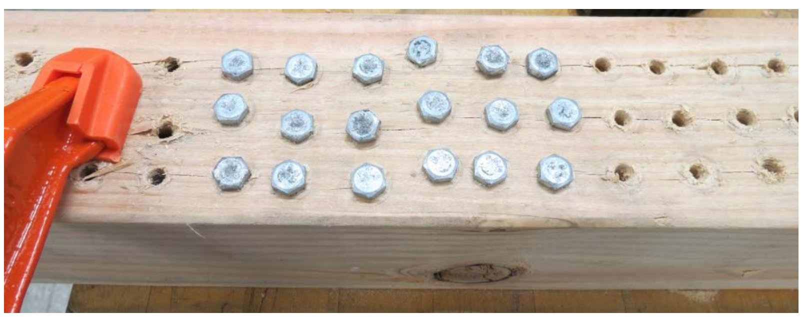

Figure 12. Bolts in wood with pattern setup

A similar data sheet, which was used for the reciprocating saw test, was used and filled out before the bolt runs were performed. The accelerometers were placed on similar locations on the human body as on the reciprocating saw, however the accelerometer located on the impact driver was placed just above the battery as shown in Figure 13. Testing was done with an accelerometer mounted just above the motor of the tool. The two gave similar results and the more convenient location was chosen, being down towards the battery.

Figure 13. Impact Driver accelerometer location

Different durations of bolt driving were performed 5 times each and recorded. After each test the data sheet was filled out again for comparison. After each set, the battery was fully charged to make sure full power was available for tool use.

3.4. Vibration Plate

The final test was performed using a lab fabricated vibration plate which was attached to a handle which the user could grip. The purpose for this test was to have a controlled experimental setup with less variation such as grip strength being exerted or mass of the tool. This handle was connected to a SPER SCIENTIFIC 840060 force gauge which connected via a serial cable to a computer which recorded the grip strength exerted on the handle. The vibration plate seen in Figure 14 was used to vibrate the handle. The knob on the right let the amplitude of acceleration to be adjusted. However, the frequency was set constant at 60 Hz as this is similar to the power tools being tested.

Figure 14. Vibration Plate

The vibration plate setup can be seen in Figure 15 below. The accelerometers on the user were in the same places as the tools, however the accelerometer which was mounted directly to the tool, was moved to mount directly to the top part right above the grip handle on the vibration plate.

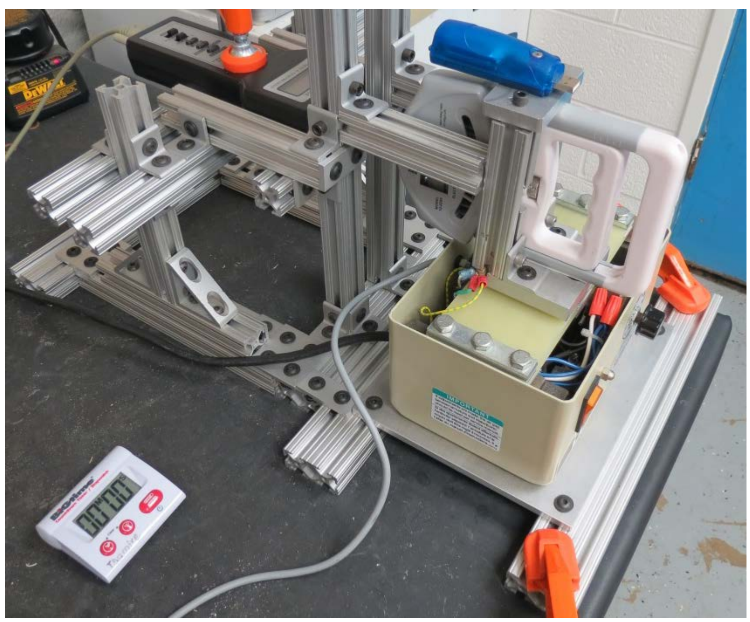

Figure 15. Vibration Plate lab fabricated setup

The testing was done by holding the handle in a similar position as a power tool for a period of time, while trying to maintain a given grip strength. Various settings were used for vibration levels on the vibration plate. Before and after each test the user filled out a similar data sheet which was used in the power tool section.

The grip strength was digitally logged every two seconds during the test and analyzed to ensure the average grip force exerted for each run was within 5% of the target value.

The next section will describe in detail the results for each setup along with the statistical analysis for the data recorded.

Chapter 4. Results/Discussion

Once the experimental setup was in place, the trials were conducted. Each trial was repeated five times for repeatability purposes. As stated before the tools tested were the reciprocating saw, impact driver, and vibration plate. Results for the reciprocating saws are presented first, followed by the impact driver, and finally the vibration plate. Other tests such as vibration suppression gloves effect, arm vibration location relevance, and hand color are presented as well. A map of the tested factors is displayed in Figure 16.

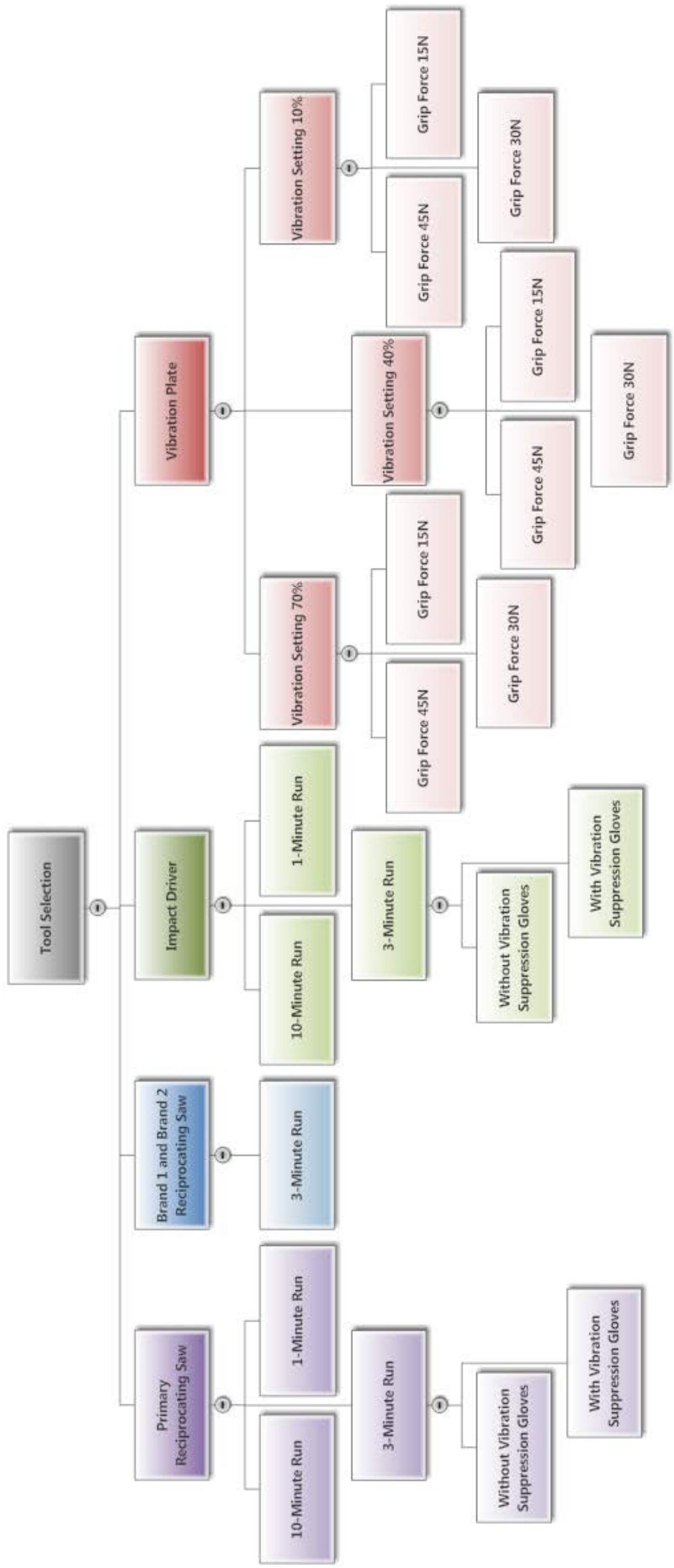

Figure 16. Experimental plan and factors tested

This experimental plan highlights the four main tool selections being the primary reciprocating saw, brand 1 and brand 2 reciprocating saw, impact driver, and the vibration plate. Under each tool the map displays what time intervals or settings were used for collecting the data for the resulting runs. Not all data collected is presented in this report.

4.1. Primary Reciprocating Saw

This section will begin with the short term effects perceived by the primary reciprocating saw, then reach into the measured vibration emission values, next give an overview of the statistical information, and finally a study on vibration suppression gloves.

4.1.1. Primary Reciprocating Saw; Short Term Effects Perceived

With the Primary reciprocating saw a number of tests were performed and various data sets were collected for analysis. There were three categories of testing done including the cutting time intervals of 10 minutes, 3 minutes, and 1 minute. The short term effects perceived are those which the user will feel and see directly after use of the tool such as change in hand color, variation in grip strength, precision, and overall hand discomfort.

4.1.1.1. Hand Color RGB Values

The first test was for hand color. Before and after each test a picture of the users hand was taken. A sample of the before and after pictures are shown below in Figure 17.

Figure 17. Hand Sample Picture (Left: Before Cut, Right: After Cut)

Using Abode Photoshop for mac software the background was removed from the hand so that all that was left was the hand part which would be processed. This was then analyzed in the image processing software to get the average RGB values present in the hand.

The average RGB value was taken from each run and combined to get an overall average color for before and after each run as seen in Table 2. These values are similarly referred to as the intensity. These values visually show the change in hand color. With these changes being somewhat visible to the eye a normalized relative redness value was found for how much the red value changed within the hand. The normalized relative redness value was calculated by using the following equation.

$$\left(\frac{R}{R+G+B}\right)$$

This equation was used with the before and after RGB values to determine the normalized relative redness difference between the color change in the users hand. As the results show, the Ten-minute run had the highest change in color, while the One-minute run have the least change in color. This model could use improvement that with hand colors, red are not the only color changing, all three colors change depending on blood flow and condition of the hand. However, from the hand pictures taken, it can clearly be seen that the hand changes colors from the before with regular hand color to the after with much redness now present in the users hand.

Table 2. Relative Redness of users hand, before vs. after hand RGB values of primary reciprocating saw

Cut Duration	Average Color Before (R,G,B)	Average Color After (R,G,B)	Relative Redness Difference $(R/(R+G+B))_{after}-(R/(R+G+B))_{before}$
Ten-Minute run	(176,112,95)	(174,96,84)	0.0319
Three-minute run	(184,109,92)	(176,90,80)	0.0307
One-minute run	(174,99,86)	(178,99,84)	0.0083

When a body part is exposed to vibration typically more blood is directed to that area known as perfusion. The more the red color in the hand, the more the perfusion is present in the hand. This image testing only confirms an increased perfusion based on the color of the hand. Having the perfusion temporarily increase due to repeated use of power tools over the years can lead to possible health problem. Further studies should be performed to confirm this.

For the Ten-minute run RGB values, a further analysis was considered. The data was normalized for comparison per a previous study on hand discoloration. [21] The 95% confidence interval was found for the Ten-minute run (Before Run: {0.450, 0.469} and After Run: {0.477, 0.505}). The two were graphed as shown in Figure 18.

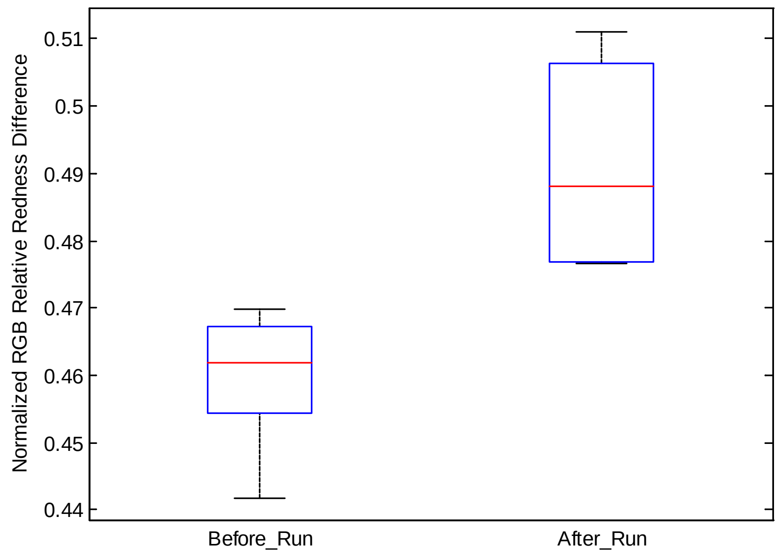

Figure 18. Normalized RGB Relative Redness Difference for Ten-Minute Primary Reciprocating Saw run between before and after hand color

The data was tested for significant difference and was found to be significantly different (p = 0.0061). The pairwise 95% confidence between the means is displayed in Table 3. These results confirm that the color of the hand increased in redness after the run when compared to the before pictures of the users hand.

Table 3. Normalized RGB Relative Redness Difference for Primary Reciprocating Saw run between before and after hand color percentage pairwise differences comparing Ten-minute runs

Parameters	95% Confidence Intervals for Pairwise Differences in Means
Before Run vs. After Run	$0.0119 \leq \mu_{After} - \mu_{Before} \leq 0.0516$

4.1.1.2. Variation in Grip Strength

The next data which was analyzed was the grip strength percentage difference. The users grip strength was taken in pounds before cutting and after the specified cut. As seen by the 95% confidence intervals (Ten-minute run: {8.60, 18.44}, Three-minute run: {4.26, 8.74}, and One-minute run: {1.75, 3.93}), the longer the cut time, the higher percentage of grip strength was lost by the user. This distribution of data is shown in Figure 19.

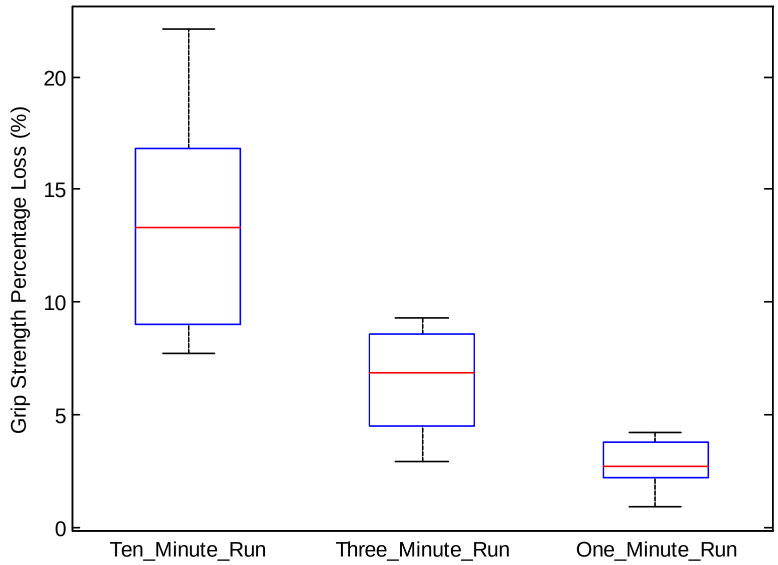

Figure 19. Results for distribution of the test data for loss in grip strength percentage difference comparing Ten-Minute, Three-Minute, and One-minute runs

To determine if these values were significantly different an ANOVA, followed by Tukey-Kramer test was performed. Results from the ANOVA analysis test above demonstrate that there is at least one mean time interval which is significantly different ($p = 0.0018$).

The results shown in Figure 20 display that there is a significant difference between the Ten Minute Run vs. the Three and One Minute Runs, but no significant difference between the Three Minute and One Minute Run. The amount of grip strength loss was overall a larger percentage as the duration increased for the user. The vibrations from the tool were not the only contributing factors to this. The tools mass also increased the rate of fatigue the user experienced in completing the experiments which could have increased the grip strength lost significantly.

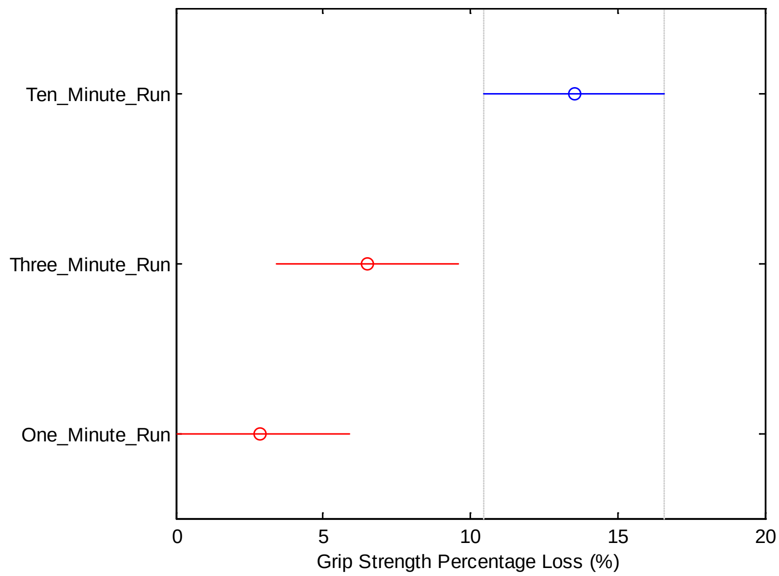

Figure 20. Visual representation of the differences in pair-wise means for loss in grip strength percentage difference comparing Ten-Minute, Three-Minute, and One-minute runs

Now knowing which runs were significantly different from each other, the 95% confidence intervals for the pairwise difference in their means were calculated and can be seen in Table 4.

Table 4. Loss in grip strength percentage pairwise differences comparing Ten-Minute, Three-Minute, and One-minute runs

Parameters	95% Confidence Intervals for Pairwise Differences in Means (%)
Ten-Minute Run vs. Three-Minute Run	$0.9813 \leq \mu_{10} - \mu_3 \leq 13.1507$
Ten-Minute Run vs. One-Minute Run	$4.5520 \leq \mu_{10} - \mu_1 \leq 16.8114$
Three-Minute Run vs. One-Minute Run	No significant difference

4.1.1.3. Precision Test; Line Traceability Test

The traced line offset test was performed by following an existing line which was horizontal across the data collection paper. The user tried to follow this line as close as possible before and after the use of the reciprocating saw. An example of this is seen in Figure 21 and Figure 22 below.

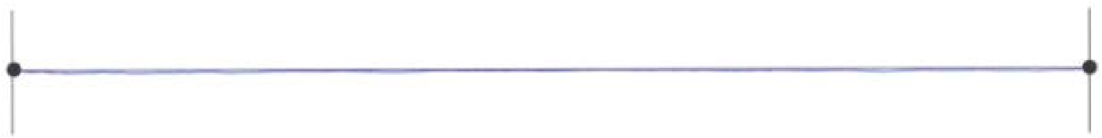

Figure 21. Before using tool sample traced line

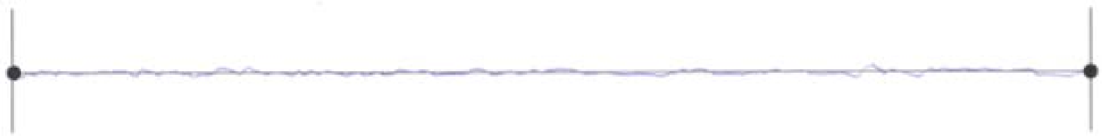

Figure 22. After using tool sample traced line

These forms were scanned after testing was completed and brought into GetData Graph Digitizer analysis software. This software measured the distance, in inches, that the hand drawn line was from the printed line already on the test paper and an r.m.s. value was received. The 95% confidence intervals were calculated (Before Run: {0.0161, 0.185}, Ten-minute run: {0.210, 0.0274}, Three-minute run: {0.0173, 0.0188}, and One-minute run: {0.0176, 0.0226}). The distribution is displayed below in Figure 23.

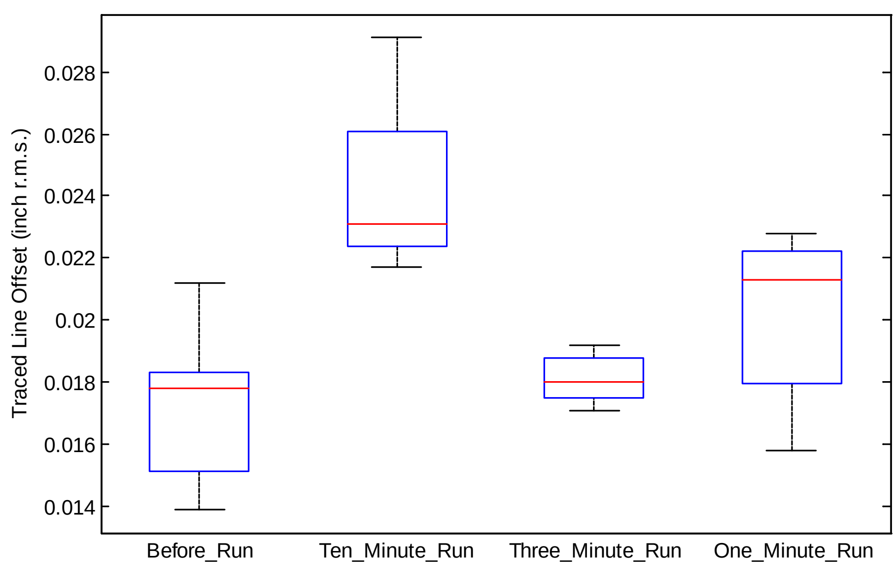

Figure 23. Results for distribution of the test data for traced line offset comparing Before, Ten-Minute, Three-Minute, and One-minute runs

When statistically analyzed for the 95% confidence interval, there was a significant difference (p = 0.0003) found between the samples. The significant difference is visually shown in Figure 24. From the results it is seem that all runs increased the lines offset from the before tracing of the line. The Three-minute run however was lower than the One-minute run, this could be due to a break in shifting the wood which was cut. In a typical use of a power tool by a construction worker, they will be required to shift material as they work.

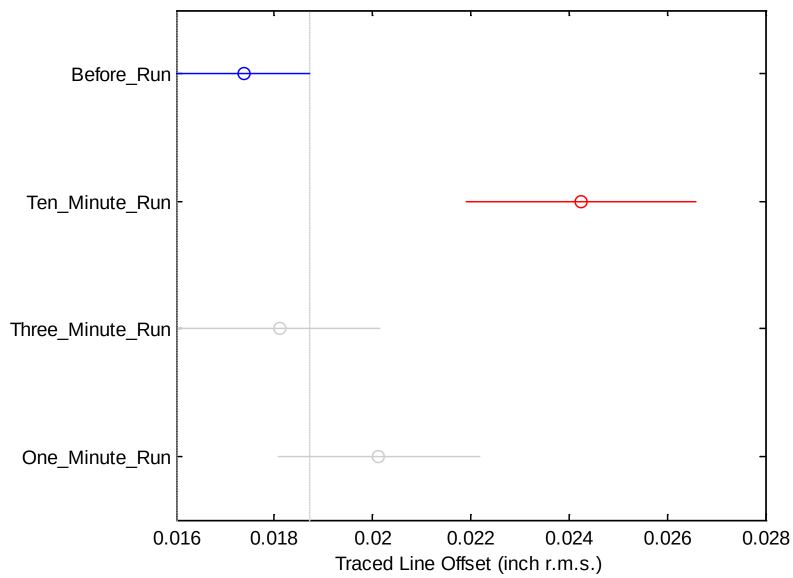

Figure 24. Visual representation of the differences in pair-wise means for Traced Line Offset comparing Before, Ten-Minute, Three-Minute, and One-minute runs

The statistical analysis demonstrated a significant difference between the Before run vs. the Ten-minute run. The Ten-minute run was significantly different from the Three-minute run. The pairwise differences in the means are displayed in Table 5.

Table 5. Traced line offset pairwise differences comparing Before, Ten-Minute, Three-Minute, and One-minute runs

Parameters	95% Confidence Intervals for Pairwise Differences in Means (inch)
Before Run vs. Ten-Minute Run	$0.0032 \leq \mu_{10} - \mu_{Before} \leq 0.0106$
Before Run vs. Three-Minute Run	No significant difference
Before Run vs. One-Minute run	No significant difference
Ten-Minute Run vs. Three-Minute Run	$0.0018 \leq \mu_{10} - \mu_{3} \leq 0.0105$
Ten-Minute Run vs. One-Minute Run	No significant difference
Three-Minute Run vs. One-Minute Run	No significant difference

4.1.1.4. Traced Line Offset Maximum Peak to Peak Distance

Similar to the previous traced line offset test, the maximum peak to minimum peak distance was measured using matlab software, in inches, to display overall amplitude distances between the drawn line. The same GetData Graph Digitizer analysis software was used here. With this information from the software a 95% confidence interval was formulated (Before Run: {0.0622, 0.0756}, Ten-minute run: {0.0824, 0.1214}, Three-minute run: {0.0754, 0.0866}, and One-minute run: {0.0611, 0.0864}). The range is wider and therefore the data appears to be further apart as seen in Figure 25.

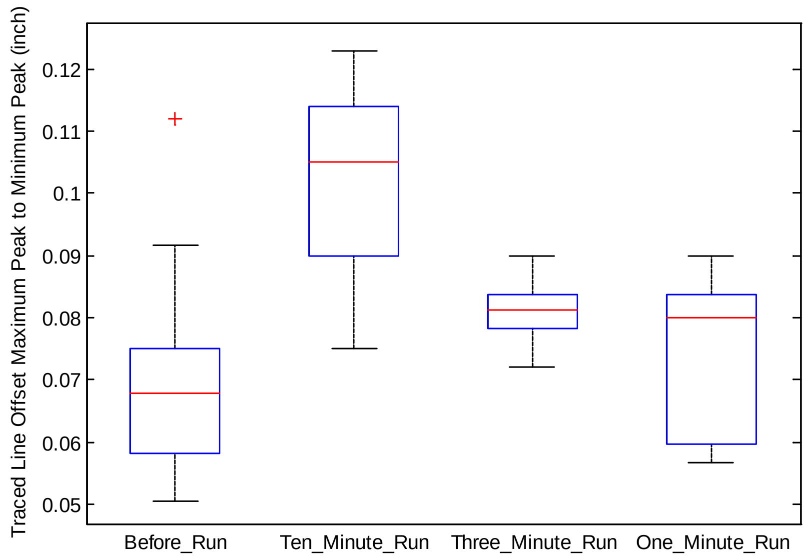

Figure 25. Results for distribution of the test data for traced line offset maximum peak to minimum peak comparing Before, Ten-Minute, Three-Minute, and One-minute runs

Analysis from the results above demonstrate that there is at least one mean time interval which is significantly different ($p = 0.0028$). The results shown in Figure 26 display that there is a significant difference between the Before Run vs. Ten-minute run and Ten-minute run vs. One-minute run, with the remaining not having any significant difference. The data demonstrates a fairly consistent trend of increasing in the maximum peak to minimum peak value as the duration increases. The users trouble to follow the line increased due to the fatigue and vibration feeling from the power tool.

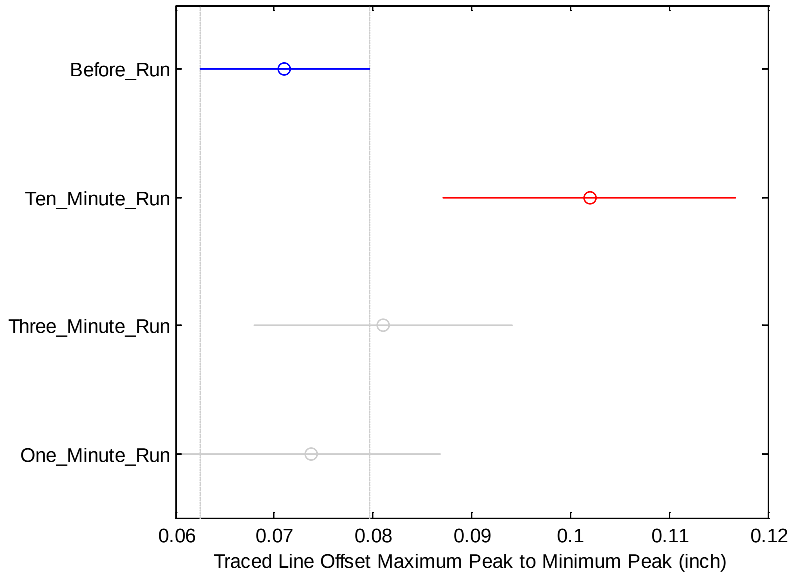

Figure 26. Visual representation of the differences in pair-wise means for traced line offset maximum peak to minimum peak comparing Before, Ten-Minute, Three-Minute, and One-minute runs

The 95% confidence intervals for the pairwise difference in their means were calculated and are displayed in Table 6.

Table 6. Traced line offset maximum peak to minimum peak pairwise differences comparing Before, Ten-Minute, Three-Minute, and One-minute runs

Parameters	95% Confidence Intervals for Pairwise Differences in Means (inch)
Before Run vs. Ten-Minute Run	$0.0111 \leq \mu_{10} - \mu_{Before} \leq 0.0549$
Before Run vs. Three-Minute Run	No significant difference
Before Run vs. One-Minute Run	No significant difference
Ten-Minute Run vs. Three-Minute Run	No significant difference
Ten-Minute Run vs. One-Minute Run	$0.0015 \leq \mu_{10} - \mu_1 \leq 0.0548$
Three-Minute Run vs. One-Minute Run	No significant difference

4.1.1.5. Intensity of Discomfort Felt by Hand Due to Vibration

The information analyzed was an intensity of vibration felt by the users hand rank score. This score was assigned using a scale from 1 to 10, where 1 was very little to no discomfort feeling and 10 was maximum discomfort due to vibration felt by the user after the test was concluded. A rating of 10 was given by the user if their hand had any signs of numbness, cold feeling, or trouble keeping the tool switch suppressed to operate the tool during cutting.

It was found that as the cut time duration increased the users discomfort due to vibration felt by hand increased. This is indicated by the 95% Bootstrap confidence intervals of median rank score (Ten-minute run: {9, 10}, Three-minute run: {8, 9}, and One-minute run: {7, 9}).

A box and whisker plot was formulated from this data and is shown in Figure 27. The spread and location of the data; further, it visually indicates that while the ten-minute run had the highest ranking, the one-minute runs had a broader deviation. The spread of data all fell between the ratings of 7 to 10.

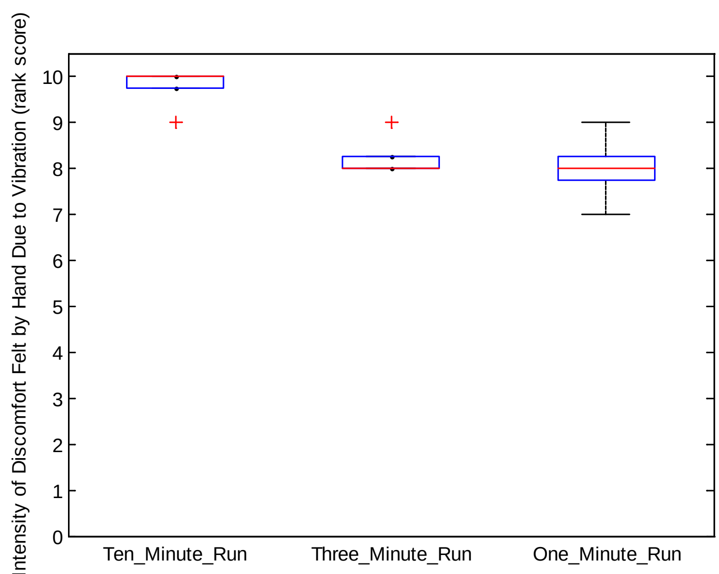

Figure 27. Results for distribution of the test data for intensity of discomfort felt by hand for reciprocating saw on a qualitative rank scale comparing Ten-Minute, Three-Minute, and One-minute runs

To determine if these values were significantly different a Kruskal-Wallis test was performed. Results from the Kruskal-Wallis analysis test above demonstrate that there is at least one median time interval which is significantly different ($p = 0.006$).

The results shown in Figure 28 display that there is a significant difference on the cumulative scale between the Ten Minute Run vs. the Three and One Minute Runs, but no significant difference between the Three Minute and One Minute Run. It was clear that the user had much more discomfort after the Ten-minute run than the Three-Minute and One-minute runs.

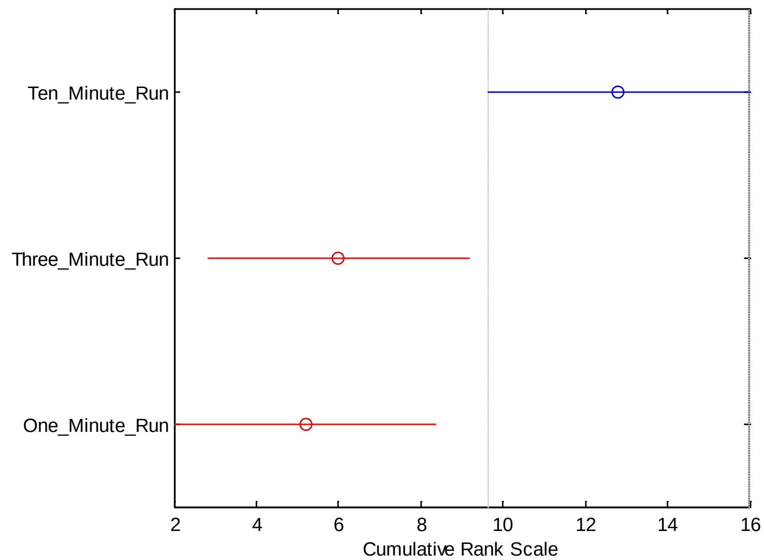

Figure 28. Visual representation of the differences in pair-wise medians, based on a cumulative rank scale comparing Ten-Minute, Three-Minute, and One-minute runs

4.1.2. Primary Reciprocating Saw; Measured Vibration Emission

This section will review the measured vibration emission results and the statistical analysis for each test.

4.1.2.1. Accelerometer Results for Tool Handle in g's

The following test was done by mounting the accelerometer to the handle of the reciprocating saw which the user cut the wood boards with. The raw data was taken off of the accelerometer in g's without any weighting and recorded. The data collected was communicated into a 95% confidence interval (Ten-minute run: {6.532, 8.171}, Three-minute run: {8.464, 8.816}, and One-minute run: {8.005, 8.374}). The Ten-minute run had a large variation compared to the others as seen in Figure 29.

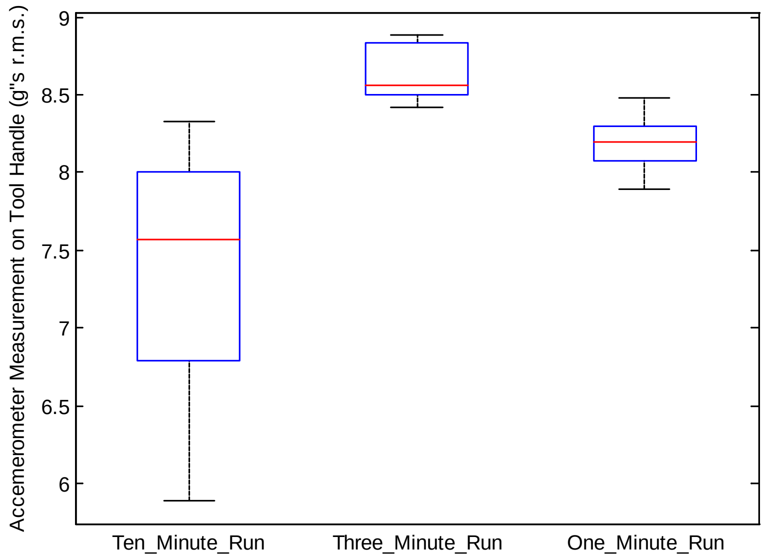

Figure 29. Results for distribution of the test data for accelerometer measurement on tool handle in g's comparing Ten-Minute, Three-Minute, and One-minute runs

This data analysis resulted in a significant difference between the data ($p = 0.0112$). Displayed in Figure 30, it is clear that the Ten-minute run and Three-minute run are significantly different. The Ten-minute run having a lower value is due to breaks taken to shift the wood material through the vice as would be needed on any typical construction site. These periods of rest where the saw was set down will lower the overall acceleration felt by the measuring accelerometer. The other runs are higher because of less rest time and as a result are not significantly different from each other.

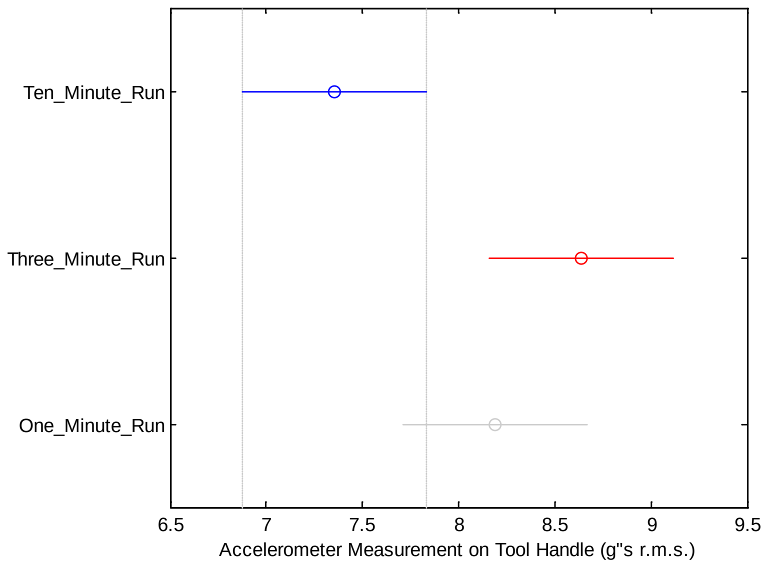

Figure 30. Visual representation of the differences in pair-wise means for accelerometer measurement on tool handle in g's comparing Ten-Minute, Three-Minute, and One-minute runs

From the data the 95% confidence intervals for pairwise differences between means was found and can be seen in Table 7.

Table 7. Accelerometer Measurement on Tool Handle in g's pairwise differences comparing Ten-Minute, Three-Minute, and One-minute runs

Parameters	95% Confidence Intervals for Pairwise Differences in Means (g's)
Ten-Minute Run vs. Three-Minute Run	$0.3339 \leq \mu_3 - \mu_{10} \leq 2.2423$
Ten-Minute Run vs. One-Minute Run	No significant difference
Three-Minute Run vs. One-Minute Run	No significant difference

4.1.2.2. ISO Frequency-Weighted Hand-Transmitted Vibration on Tool Handle

The collected data from previously on the reciprocating saw handle was taken and ISO frequency-weighting factors for hand-transmitted vibration were applied such that the magnitude of vibration which the hand was subjected to was found. The ISO weighting allows for proper analysis of the actual vibration which the human hand would feel. As each part of a human body has a natural frequency, the ISO weightings account for these and are able to depict which frequencies will play a larger factor on the human body and scale them as appropriate. This data was found using the r.m.s. values taken from the accelerometer. It was seen that the values and ranges did not vary too much as indicated by the 95% confidence intervals (Ten-minute run: {18.119, 22.401}, Three-minute run: {17.293, 26.310}, and One-minute run: {18.294, 20.871}). The distribution of the data is shown in Figure 31. With the ISO weighting it is expected that the tool should have similar accelerations seen as similar actions were used with the same tool.

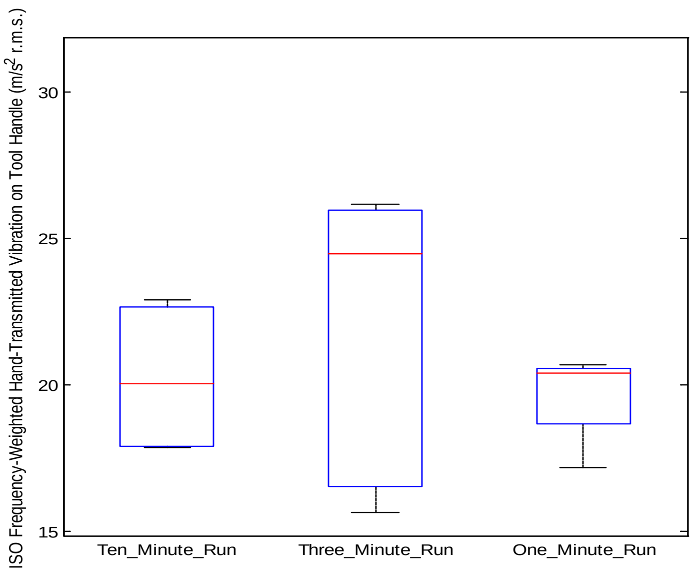

Figure 31. Results for distribution of the test data for ISO Frequency-Weighted Hand-Transmitted Vibration on tool handle comparing Ten-Minute, Three-Minute, and One-minute runs

The statistical analysis performed on this data resulted in no significant difference between the data samples ($p = 0.5849$).

4.1.2.3. Accelerometer Results for Hand in g's

Using an identical accelerometer from before, one was simultaneously mounted to the users hand while the cuts were performed. Similar data was taken from this accelerometer to produce a slightly different 95% confidence interval (Ten-minute run: {7.243, 8.627}, Three-minute run: {7.301, 7.735}, and One-minute run:

{7.223, 8.165}). A box and whisker plot was created from this data shown in Figure 32.

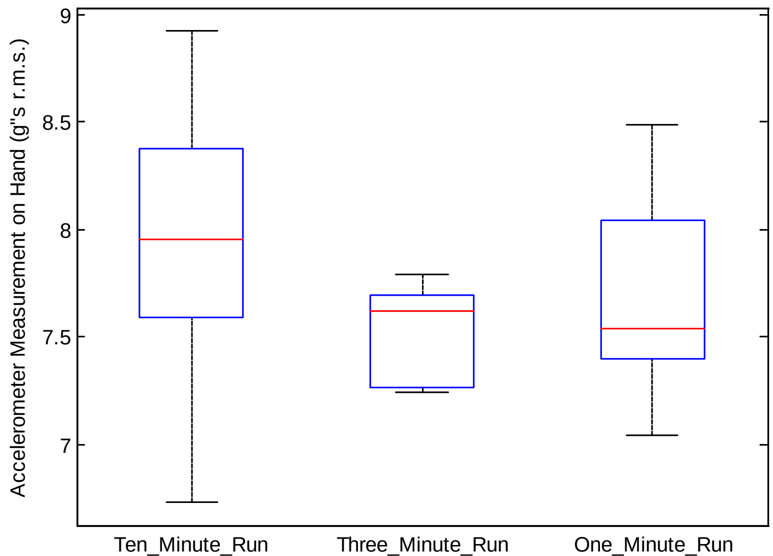

Figure 32. Results for distribution of the test data for accelerometer measurement on hand in g's comparing Ten-Minute, Three-Minute, and One-minute runs

This data sets resulted in no significant difference (p = 0.5268) between the measurements. With the hand moving in between cut times, the accelerometers would measure this movement, so where the results on the reciprocating saw show that the Ten-minute run drops, this will not be shown as prevalent since the hand was moving the wood board and moving the tool around.

4.1.2.4. ISO Frequency-Weighted Hand-Transmitted Vibration on Hand

As before, the pervious data taken and used with the ISO frequency-weighting factors for hand-transmitted vibration which were applied such that the magnitude of vibration which the hand was subjected to was established. Once this data was found, a 95% confidence interval was constructed (Ten-minute run: {17.423, 24.581}, Three-minute run: {15.281, 23.050}, and One-minute run: {16.052, 18.558}). The center and variation of the data is indicated in Figure 33.

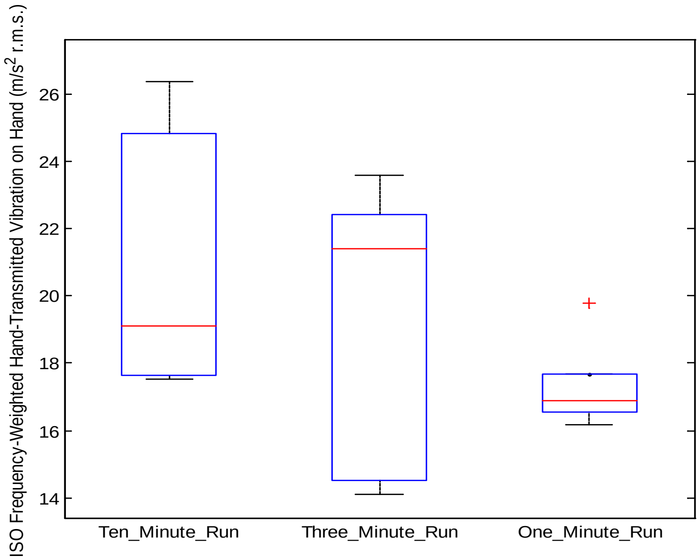

Figure 33. Results for distribution of the test data for ISO Frequency-Weighted Hand-Transmitted Vibration on hand comparing Ten-Minute, Three-Minute, and One-minute runs

From the Kruskal-Wallis statistical analysis there was not significantly different ($p = 0.2992$). With the weighted values, the Ten-minute run has some of the larger values, while the Three-minute run does have a mean that is higher. The One-minute run though is lowest, even though it would be the most concentrated dosage.

4.1.2.5. Accelerometer Results for Location in g's

While each cut was performed accelerometers were placed on the reciprocating saw and the users hand to gather the acceleration felt at this location. A review of how the two positions compared was taken into consideration. For this data the Three-minute run was used since it was similar to the others and further runs with alternate tools were used for this duration. The 95% confidence interval was found for both accelerometers (Tool: {8.464, 8.816}, Hand: {7.301, 7.735}). These ranges seemed to be very different as can be seen in Figure 34.

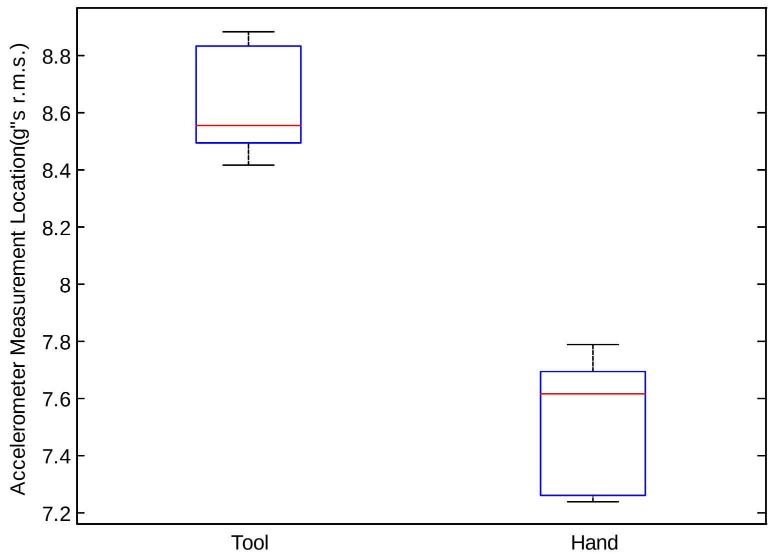

Figure 34. Results for distribution of the test data for accelerometer measurement location in g's comparing tool to hand measurements for Three-minute runs

With there being such a sizable gap between the two data sets there was a large significant difference ($p = 0.00$) between the mean accelerations. The mean differences are displayed in Figure 35 below. The tool recorded a much larger acceleration value on the tool than the hand which is expected. The hand did see a fairly large amount of vibration, however with the tool being the emitting device, it makes sense for this value to be larger.

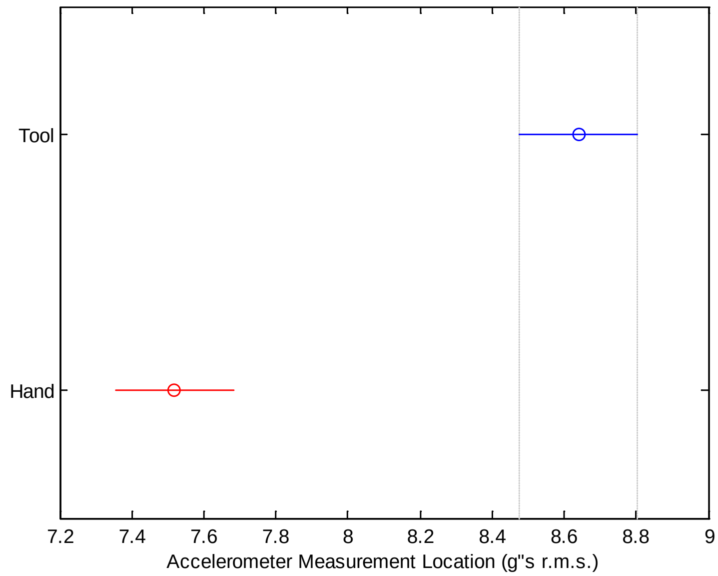

Figure 35. Visual representation of the differences in means for accelerometer measurement location in g's comparing tool to hand measurements for Three-minute runs

From these results the 95% confidence interval for pairwise differences was found and provided in Table 8.

Table 8. Accelerometer Measurement Location in g's differences comparing tool to hand measurements for Three-minute runs

Parameters	95% Confidence Intervals between Means (g's)
Tool vs. Hand	$0.7933 \leq \mu_{Tool} - \mu_{Hand} \leq 1.4509$

4.1.2.6. Accelerometer Results for Location in ISO Frequency-Weighted Hand-Transmitted Vibration

Lastly, the g's acceleration data from before was weighted with the ISO frequency-weighted hand-transmitted vibration calculation. This would adjust the acceleration the users hand is seeing taking into account the natural frequency of a human hand. The Three-minute run data was used. A 95% confidence interval was found (Tool: {17.293, 26.310}, Hand: {15.281, 23.050}). The distribution of this data is displayed in Figure 36.

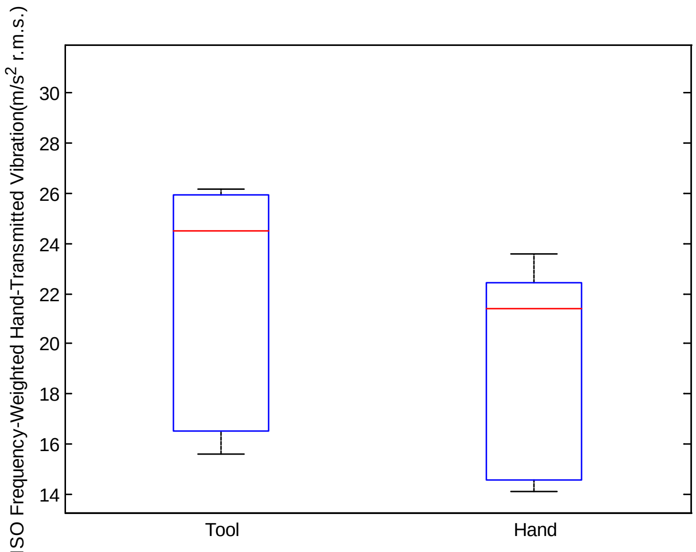

Figure 36. Results for distribution of the test data for accelerometer measurement location in ISO Frequency-Weighted Hand-Transmitted Vibration comparing tool to hand measurements for Three-minute runs

As shown, the data appear similar and there was no significant difference (p = 0.4106) given the 95% confidence interval evaluated. After the ISO weighting was considered, the tool and hand vibration values were much closer, this removed the repetitive aliasing frequencies seen and focused on only the ones which the hand would be experiencing the most around its natural frequency.

4.1.3. Primary Reciprocating Saw Test; Statistic Data Table

All the previous data statistics have been cumulated into an overview table for ease of viewing as shown in Table 9 below. Overall, it was seen that the longer duration of cut time lead to more discomfort and stability of the users hand. The users hand was seeing more vibration than one would think if only the overall acceleration was taken into consideration. When applying the ISO weighted frequency bands and giving more value to those which are around the natural frequency of a human hand, the tool and hand vibration measurements come much closer together revealing the hand actually receiving a larger dosage of vibration than an un-weighted reading.

Table 9. Test statistic data overview of primary reciprocating saw

	Test statistic	95% Bootstrap Confidence Interval for $\tilde{x}$		Median	Std. Dev.
Intensity of Discomfort Felt by Hand Due to Vibration (rank score)	Ten-Minute Run	9	10	10	0.447
	Three-Minute Run	8	9	8	0.447
	One-Minute Run	7	9	8	0.707
Variation in Grip Strength (%)	Test statistic	95% Confidence Interval for μ		Mean	Std. Dev.
	Ten-Minute Run	8.6	18.44	13.53	5.61
	Three-Minute Run	4.26	8.74	6.5	2.55
	One-Minute Run	1.75	3.93	2.84	1.24
Traced Line Offset (inch r.m.s.)	Test statistic	95% Confidence Interval for μ		Mean	Std. Dev.
	Before Run	0.0161	0.0185	0.0178	0.0022
	Ten-Minute Run	0.0210	0.0274	0.0231	0.0033
	Three-Minute Run	0.0173	0.0188	0.0180	0.0008
	One-Minute Run	0.0176	0.0226	0.0213	0.0028
Traced Line Offset Maximum Peak to Minimum Peak (inch)	Test statistic	95% Confidence Interval for μ		Mean	Std. Dev.
	Before Run	0.0622	0.0756	0.0689	0.0148
	Ten-Minute Run	0.0824	0.1214	0.1019	0.0198
	Three-Minute Run	0.0754	0.0866	0.081	0.0063
	One-Minute	0.0611	0.0864	0.0737	0.0144

	Run				
Accelerometer Measurement on Tool Handle in G's (g's r.m.s.)	Test statistic	95% Confidence Interval for μ		Mean	Std. Dev.
	Ten-Minute Run	6.532	8.171	7.352	0.935
	Three-Minute Run	8.464	8.816	8.64	0.201
	One-Minute Run	8.005	8.374	8.189	0.21
ISO Frequency-Weighted Hand-Transmitted Vibration on Tool Handle (m/s^2 r.m.s.)	Test statistic	95% Confidence Interval for μ		Mean	Std. Dev.
	Ten-Minute Run	18.119	22.401	20.26	2.442
	Three-Minute Run	17.293	26.31	21.802	5.143
	One-Minute Run	18.294	20.871	19.583	1.469
Accelerometer Measurement on Hand in G's (g's r.m.s.)	Test statistic	95% Confidence Interval for μ		Mean	Std. Dev.
	Ten-Minute Run	7.243	8.627	7.935	0.789
	Three-Minute Run	7.301	7.735	7.518	0.247
	One-Minute Run	7.223	8.165	7.694	0.537
ISO Frequency-Weighted Hand-Transmitted Vibration on Hand (m/s^2 r.m.s.)	Test statistic	95% Confidence Interval for μ		Mean	Std. Dev.
	Ten-Minute Run	17.423	24.581	21.002	4.083
	Three-Minute Run	15.281	23.05	19.166	4.431
	One-Minute Run	16.052	18.558	17.305	1.429
Accelerometer Measurement Location in G's (g's r.m.s.)	Test statistic	95% Confidence Interval for μ		Mean	Std. Dev.
	Tool	8.464	8.816	8.64	0.201
	Hand	7.301	7.735	7.518	0.247

Accelerometer Measurement Location in ISO Frequency-Weighted Hand-Transmitted Vibration (m/s^2 r.m.s.)	Test statistic	95% Confidence Interval for μ		Mean	Std. Dev.
	Tool	17.293	26.31	21.802	5.143
	Hand	15.281	23.05	19.166	4.431

4.1.4. Primary Reciprocating Saw; Vibration Suppression Gloves

The vibration suppression gloves were used by the user during a set of Three-minute runs using the Primary reciprocating saw. These were used to assess just how much vibration reduction was seen to the users hand when worn. The hand color test was not performed when using the vibration suppression gloves.

4.1.4.1. Variation in Grip Strength

The variation in grip strength was not effected much by the gloves. Due to the fact that the user is supporting the weight of the tool and exerting a force during cutting the same amount of strength would be needed here by the user. This is displayed in Figure 37. The 95% confidence intervals are also quite similar (No Gloves: {4.263, 8.749}, Gloves: {3.514, 9.035}).

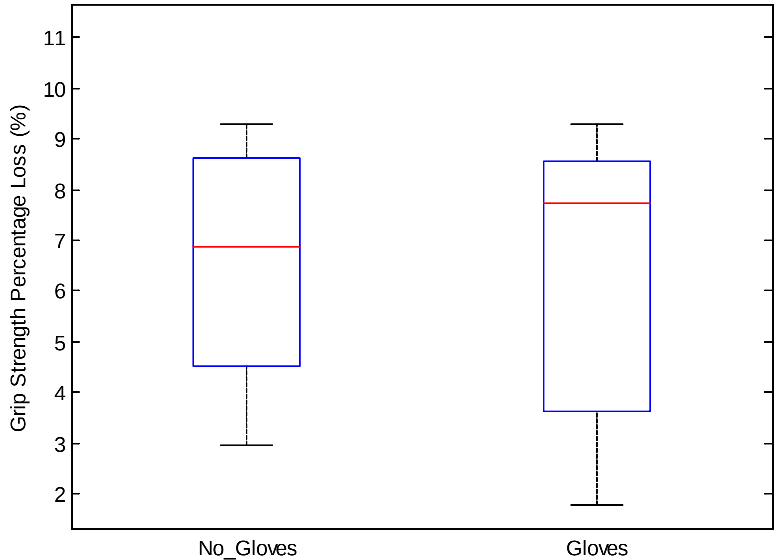

Figure 37. Results for distribution of the test data for loss of grip strength percentage difference comparing no gloves to gloves for Three-minute runs

From the statistical analysis it was found that the two data sets were not significantly different (p= 0.9018). The grip strength results are very similar. This shows that the vibration does not affect the overall decrease in grip strength, but the weight of the tool and duration of cut time. As the users arm becomes more fatigued, the grip strength will decrease.

4.1.4.2. Precision Test; Line Traceability Test

The traced line offset was compared between the Three-minute runs. The 95% confidence interval displays this trend (Before Run: {0.0155, 0.0184}. No Gloves: {0.0173, 0.0188}, and Gloves: {.0157, .0190}). The center and variation of the collected data are displayed in Figure 38.

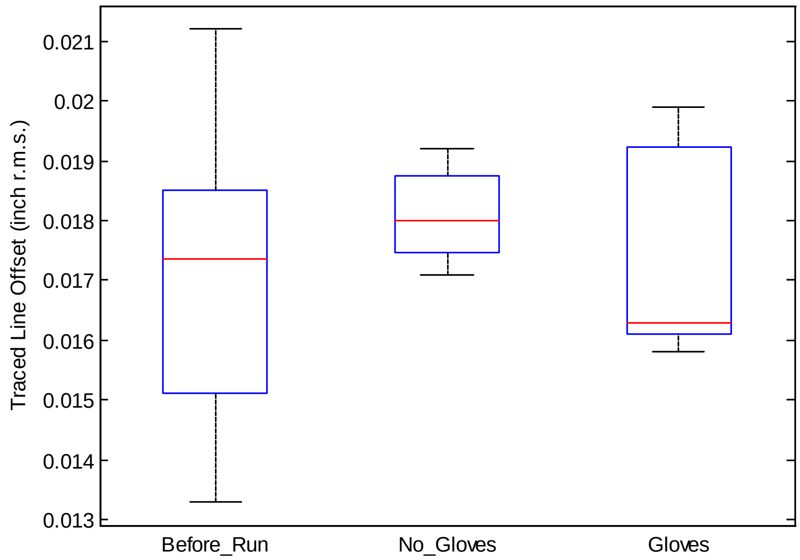

Figure 38. Results for distribution of the test data for traced line offset comparing before, no gloves, and gloves for Three-minute runs

There was no significant difference (p = 0.5886) between the line offset before and after the run wearing gloves or not wearing gloves. By wearing the gloves it helps to reduce the offset of tracing a line, however it is not significant enough to conclude that the gloves really do help with this over a large number of runs.

4.1.4.3. Intensity of Discomfort Felt by Hand Due to Vibration

The discomfort felt by the users hand rank score without gloves was higher than that with the gloves as seen in Figure 39. The confidence interval indicates a variation between the two data sets (No Gloves: {8, 9}, Gloves: {5, 6}).

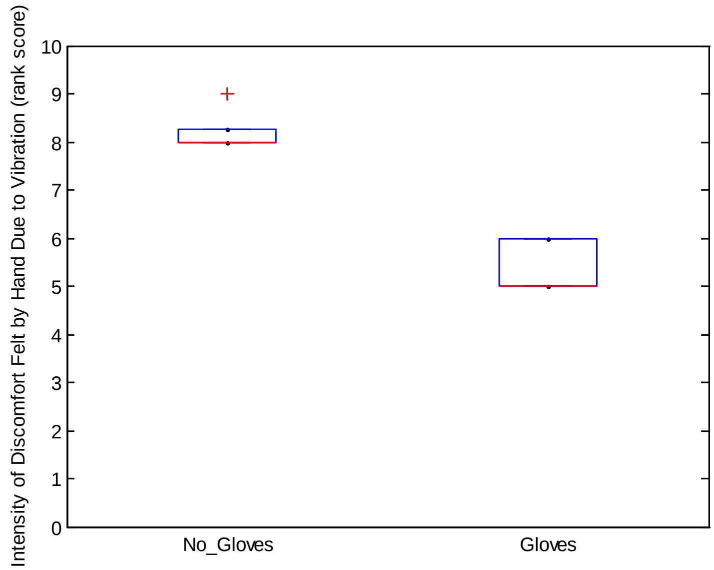

Figure 39. Results for distribution of the test data for intensity of discomfort felt by hand for reciprocating saw on a qualitative rank scale comparing no gloves to gloves for Three-minute runs

A statistical analysis was performed on the data sets for determining significant difference. The No Gloves vs. Gloves was found to be significantly different ($p = 0.0062$). A visual representation is displayed in Figure 40 below. It is clear that the discomfort felt to the users hand is reduced by wearing the vibration suppression gloves. The gloves help to protect and absorb some of the vibrations emitting from the reciprocating saw when in use.

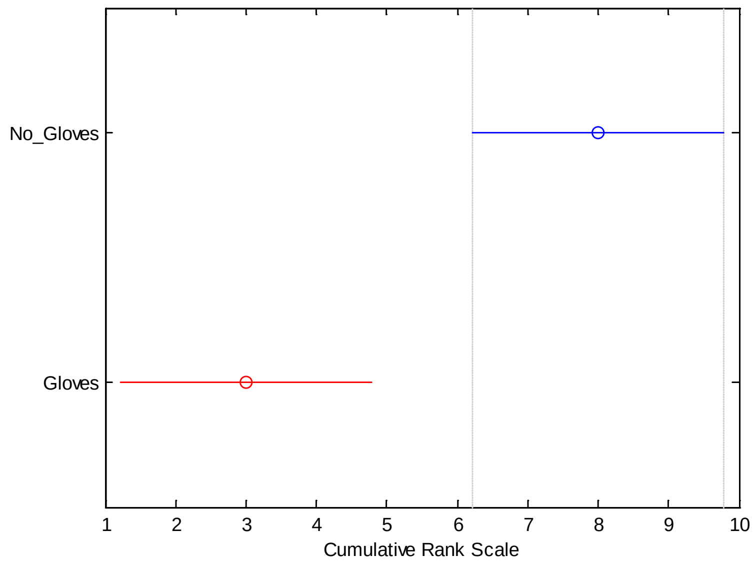

Figure 40. Visual representation of the differences in pair-wise medians, based on a cumulative rank scale comparing no gloves to gloves for Three-minute runs

4.1.4.4. Accelerometer Results for Tool Handle in g's

As shown below in Figure 41, it is seen that while wearing the gloves, the vibration levels on the tool handle appeared to be lower. This could be due to the fabric and materials in the glove acting as more of a damper then just the users hand. A 95% confidence interval was found and related that they seemed similar (No Gloves: {8.464, 8.816}, Gloves: {7.812, 8.650}).

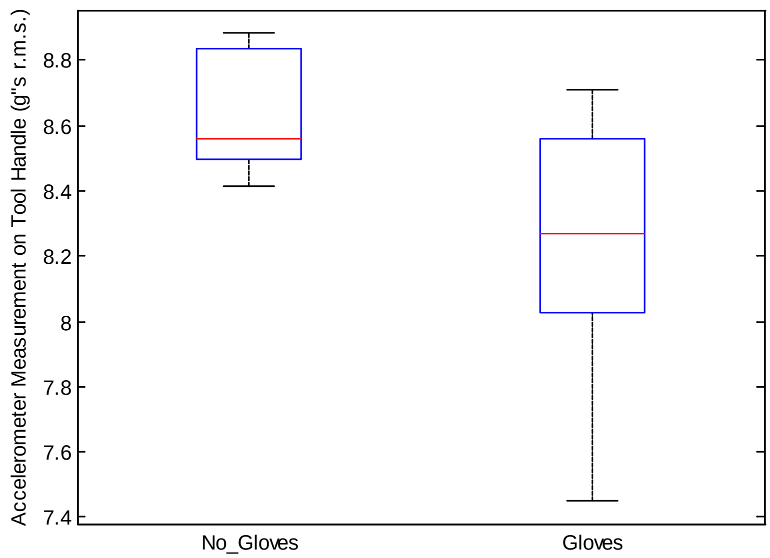

Figure 41. Results for distribution of the test data for accelerometer measurement on tool handle in g's comparing no gloves to gloves for Three-minute runs

There was no significant difference (p = 0.116) between No Gloves vs. Gloves on the tool handle vibration measurement. Surprisingly the gloves help to reduce the vibration measured from the accelerometer mounted directly to the tool; these gloves can act as dampers to help reduce the overall vibrations being seen. With no significant difference though, further studies would need to be done.

4.1.4.5. ISO Frequency-Weighted Hand-Transmitted Vibration on Tool Handle

Once the vibration values were weighted, they had even less variation in them as displayed in Figure 42. The 95% confidence intervals were quite similar (No Gloves: {17.293, 26.310}, Gloves: {16.888, 24.342}).

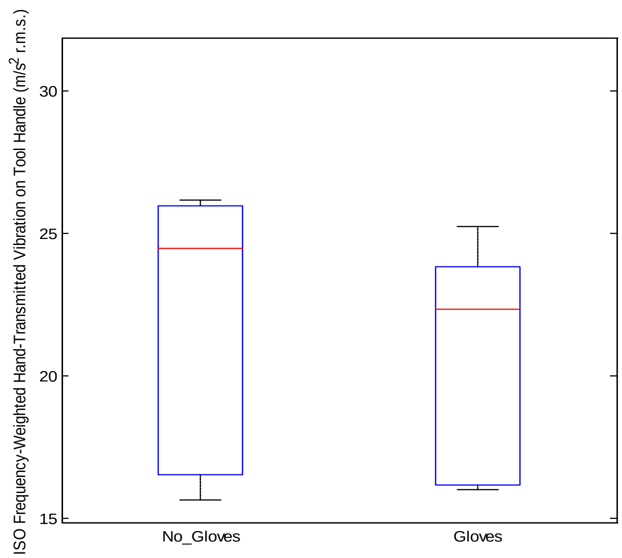

Figure 42. Results for distribution of the test data for ISO Frequency-Weighted Hand-Transmitted Vibration on tool handle comparing no gloves to gloves for Three-minute runs

There was no significant difference ($p = 0.7014$) between this data set. The ISO weightings were fairly similar, as even the g's measured did not have any significant difference with or without the gloves.

4.1.4.6. Accelerometer Results for Hand in g's

The accelerometer measurements on the hand measured higher on the glove then before. This is graphically shown in Figure 43. These values were only the raw g's taken from the accelerometers. This is also indicated by the 95% confidence intervals (No Gloves: {7.301, 7.735}, Gloves: {5.100, 5.646}).

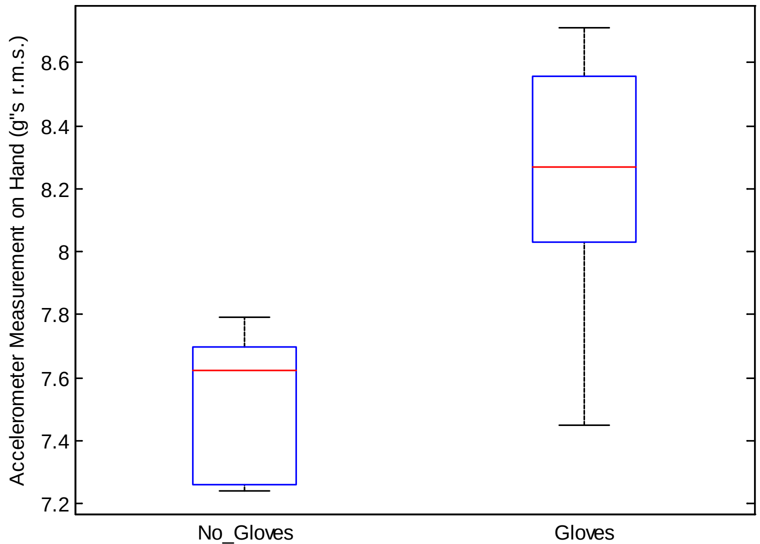

Figure 43. Results for distribution of the test data for accelerometer measurement on hand in g's comparing no gloves to gloves for Three-minute runs

There was a significant difference ($p = 0.018$) between using the gloves as found by the control vs. treatment statistical analysis. The 95% confidence intervals for the pairwise differences in the means are shown in Table 10. The gloves increased the overall g's seen to the hand, the tool g's did reduce though so this would be expected. Some frequencies, which may have been relevant to the natural frequency of the hand, could have been suppressed while other frequencies not in the hands natural frequency spectrum may have been enhanced. Further studies would be needed to conclude this.

Table 10. Accelerometer Measurement on Hand in g's pairwise differences comparing no gloves to gloves for Three-minute runs

Parameters	95% Confidence Intervals for Pairwise Differences in Means (g's)
No Gloves vs. Gloves	$1.7344 \leq \mu_{Gloves} - \mu_{No\ Gloves} \leq 2.5553$

4.1.4.7. ISO Frequency-Weighted Hand-Transmitted Vibration on Hand

After accounting for the frequency weightings the gloves overall seen vibration amount for the user was lower than without the gloves as displayed in

Figure 44. The 95% confidence interval also confirms that the No Gloves range is higher than with gloves (No Gloves: {15.281, 23.050}, Gloves: {11.771, 15.783}).

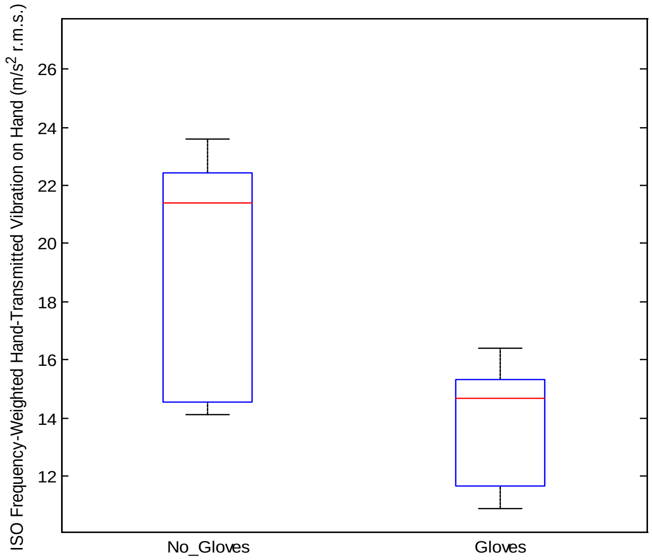

Figure 44. Results for distribution of the test data for ISO Frequency-Weighted Hand-Transmitted Vibration on hand comparing no gloves to gloves for Three-minute runs

There was found to be a significant difference ($p = 0.0421$) between wearing gloves and not wearing gloves while using the reciprocating saw. The ISO weighting for the gloves focuses on the main frequencies which will affect the users hand in the long run for health, and as it is shown the gloves to reduce the amount of vibration seen to the user's hand in the end. The pairwise differences in mean 95% confidence intervals are shown in Table 11.

Table 11. ISO Frequency-Weighted Hand-Transmitted Vibration on Hand pairwise differences comparing no gloves to gloves for Three-minute runs

Parameters	95% Confidence Intervals for Pairwise Differences in Means (m/s^2)
No Gloves vs. Gloves	$0.2448 \leq \mu_{No\ Gloves} - \mu_{Gloves} \leq 10.5321$

4.1.5. Primary Reciprocating Saw; Vibration Suppression Gloves Test Statistics Data Table

The statistical results from the vibration suppression glove tests are displayed in Table 12 below. Though the gloves overall have a slight assist to the user in helping to protect their hands, in the end the gloves do show that the overall weighted vibration dosage seen to the hands is lowered by wearing the gloves.

Table 12. Test Statistic Data Overview of vibration suppression gloves

	Test statistic	95% Bootstrap Confidence Interval for $\tilde{x}$		Median	Std. Dev.
Intensity of Discomfort Felt by Hand Due to Vibration (rank score)	No_Gloves	8	9	8	0.447
	Gloves	5	6	5	0.547
	Test statistic	95% Confidence Interval for μ		Mean	Std. Dev.
Variation in Grip Strength (%)	No_Gloves	4.263	8.749	6.506	2.558
	Gloves	3.514	9.035	6.275	3.149
	Test statistic	95% Confidence Interval for μ		Mean	Std. Dev.
Accelerometer Measurement on Tool Handle in G's (g's r.m.s.)	No_Gloves	8.464	8.816	8.64	0.201
	Gloves	7.812	8.65	8.231	0.477

ISO Frequency-Weighted Hand-Transmitted Vibration on Tool Handle (m/s² r.m.s.)	Test statistic	95% Confidence Interval for μ		Mean	Std. Dev.
	No_Gloves	17.293	26.31	21.802	5.143
	Gloves	16.888	24.342	20.615	4.251
Accelerometer Measurement on Hand in G's (g's r.m.s.)	Test statistic	95% Confidence Interval for μ		Mean	Std. Dev.
	No_Gloves	7.301	7.735	7.518	0.247
	Gloves	5.1	5.646	5.373	0.311
ISO Frequency-Weighted Hand-Transmitted Vibration on Hand (m/s² r.m.s.)	Test statistic	95% Confidence Interval for μ		Mean	Std. Dev.
	No_Gloves	15.281	23.05	19.166	4.431
	Gloves	11.771	15.783	13.777	2.288

4.1.6. Primary Reciprocating Saw; Arm Vibration

Through the various tests performed, three locations on the users hand and arm were monitored. All of the forearm and triceps locations were not shown as part of the main data analysis because of ISO weighting. With the arm at different locations having various weighting frequencies it was beyond the scope of this report to evaluate those values, however for the Three-minute runs on the Primary reciprocating saw, the results are shown below in g's.

4.1.6.1. Accelerometer Results for Arm Effect in g's

The accelerometer measurements taken from the Three-Minute Primary reciprocating saw tests were evaluated. As shown in Table 13 the mean values and confidence intervals had a wide variation between each other.

Table 13. Arm accelerometer measurement statistics for primary reciprocating saw Three-minute runs

Test statistic	95% Confidence Interval for μ (g's)		Mean	Std. Dev.
Tool	8.464	8.816	8.64	0.201
Hand	7.301	7.735	7.518	0.247
Forearm	3.837	4.662	4.249	0.47
Triceps	1.336	1.608	1.472	0.155

A visual representation of the data is graphed below in Figure 45. The tool handle had the most vibration while the triceps had the least amount of vibration. However, if weightings were placed on the hand, forearm, and triceps, the values could change drastically depending what the natural frequencies of those body parts are compared to the frequencies emitting from the tool.

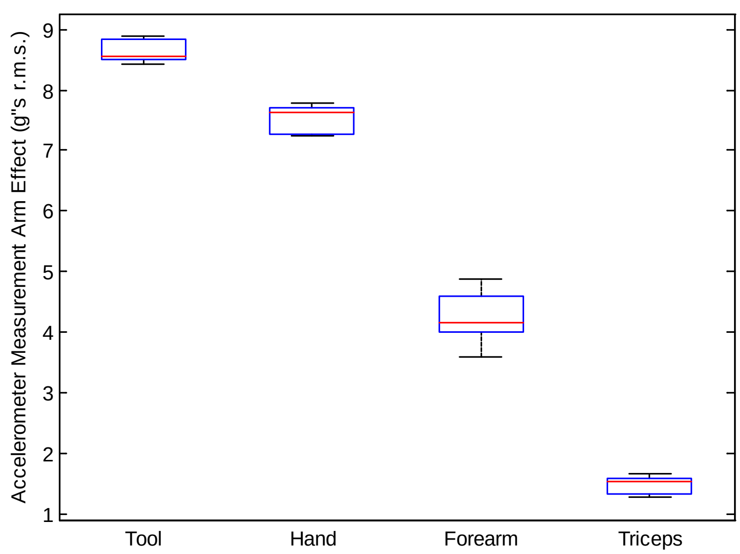

Figure 45. Results for distribution of the test data for accelerometer location measurement arm effects for primary reciprocating saw Three-minute runs

When conducting the ANOVA analysis, the data sets were significantly different (p = 0.00) in their values. While the vibration decrease as the measurement locations move further away from the tool, further analysis should be done on ISO weighting values of the arm in order to see if this gives any amplification to what is seen by the arm. Depending on the frequency rating scale of that part of the body, the arm could possibly be seeing the same amount of vibration dosage as the hand.

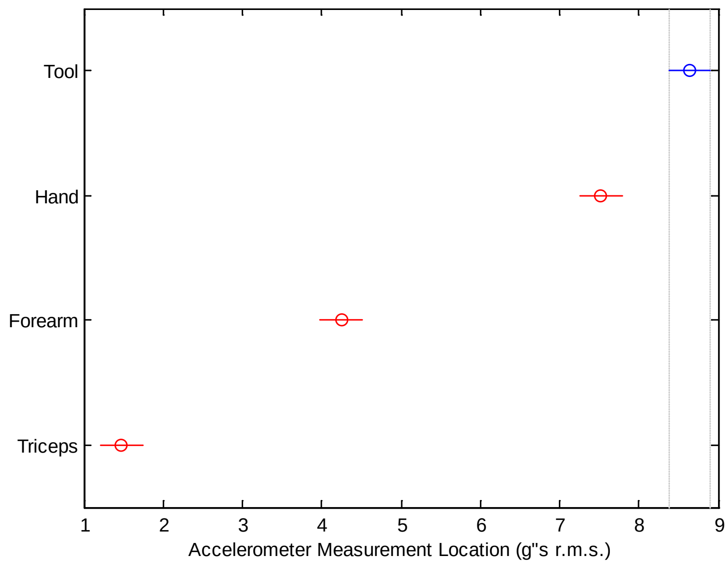

Figure 46. Visual representation of the differences in pair-wise means accelerometer location measurement arm effects for primary reciprocating saw Three-minute runs

With such a large variation between the data all the data sets were significantly different from each other. The pairwise differences between the means for the 95% confidence intervals can be seen in

Table 14. Accelerometer Measurement Arm Effect pairwise differences for primary reciprocating saw Three-minute runs

Parameters	95% Confidence Intervals for Pairwise Differences in Means (g's)
Tool vs. Hand	$0.5891 \leq \mu_{Tool} - \mu_{Hand} \leq 1.6551$
Tool vs. Forearm	$3.8574 \leq \mu_{Tool} - \mu_{Forearm} \leq 4.9235$
Tool vs. Triceps	$6.6352 \leq \mu_{Tool} - \mu_{Triceps} \leq 7.7012$
Hand vs. Forearm	$2.7353 \leq \mu_{Hand} - \mu_{Forearm} \leq 3.8014$
Hand vs. Triceps	$5.5131 \leq \mu_{Hand} - \mu_{Triceps} \leq 6.5791$

Forearm vs. Triceps	$2.2447 \leq \mu_{Forearm} - \mu_{Triceps} \leq 3.3107$

4.2. Brand 1 and Brand 2 Reciprocating Saw

This section will focus on the short term effects perceived by the brand 1 and brand 2 reciprocating saws, then the measured vibration emission for them, and finally a summary of the statistics in a table format.

4.2.1. Brand 1 and Brand 2 Reciprocating Saw; Short Term Effects Perceived

The Brand 1 and Brand 2 reciprocating saw experimental testing was done following the same setup and procedure as the Primary reciprocating saw. All the following data was recorded from Three-minute runs. Each Three-minute run consisted of five recorded data sets.

4.2.1.1. Variation in Grip Strength

The variation in grip strength was done using the various brands of reciprocating saws. The data seemed to have a wide range of variation as seen in the 95% confidence intervals (Primary Reciprocating Saw: {4.263, 8.749}, Brand 1 Reciprocating Saw: {9.666, 13.040}, and Brand 2 Reciprocating Saw: {8.547, 15.778}). The distribution of the data is shown in Figure 47 below.

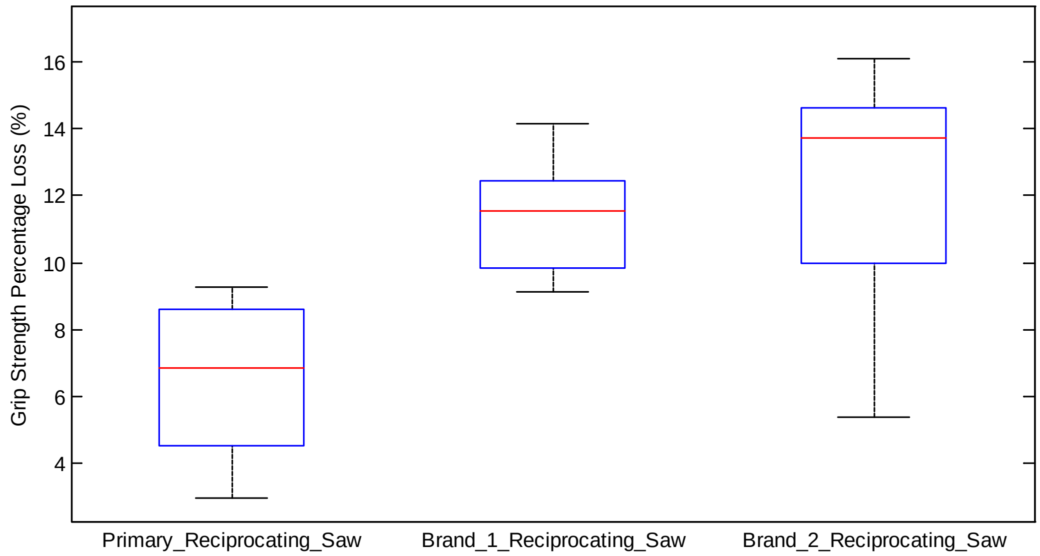

Figure 47. Results for distribution of the test data for loss of grip strength percentage difference comparing primary, brand 1, and brand 2 reciprocating saw Three-minute runs

A statistical analysis was done to review the data for significant difference. The results from the data analysis were indeed significantly different (p = 0.0243). It can be seen in Figure 48 below that there is a significant difference between the Primary reciprocating saw and the brand 2 reciprocating saw, but no significant difference between the Primary and brand 1 reciprocating saw or brand 1 and brand 2 reciprocating saw. The primary reciprocating saw had the least effect on loss in grip strength, while brand 2 had a result of the user losing the most grip strength.

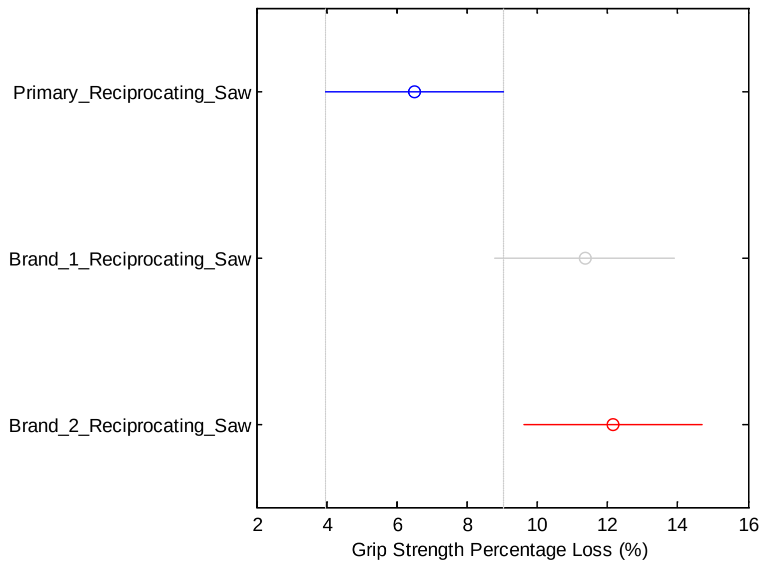

Figure 48. Visual representation of the differences in pair-wise means for grip strength percentage difference comparing primary, brand 1, and brand 2 reciprocating saw Three-minute runs

After review of the significantly different data, the pairwise differences in the mean values were calculated, which can be seen in Table 15.

Table 15. Variation in Grip Strength pairwise differences comparing primary, brand 1, and brand 2 reciprocating saw Three-minute runs

Parameters	95% Confidence Intervals for Pairwise Differences in Means (%)
Primary Reciprocating Saw vs. Brand 1 Reciprocating Saw	No significant difference
Primary Reciprocating Saw vs. Brand 2 Reciprocating Saw	$0.5693 \leq \mu_{Brand\ 2\ Recip\ Saw} - \mu_{Recip\ Saw} \leq 10.7444$
Brand 1 Reciprocating Saw vs. Brand 2 Reciprocating Saw	No significant difference

4.2.1.2. Precision Test; Line Traceability Test

The traced line offset line was repeated for the brand 1 and brand 2 reciprocating saws. The ranges were all fairly similar upon inspection of the 95% confidence intervals (Before Run: {.0.158, 0.0176}, Primary Reciprocating Saw: {0.0173, 0.0188}, Brand 1 Reciprocating Saw: {0.0187, 0.0217}, and Brand 2

Reciprocating Saw: {0.0168, 0.0234}). The results displayed in Figure 49 show how similar each set seems to be.

Figure 49. Results for distribution of the test data for traced line offset comparing before, primary, brand 1, and brand 2 reciprocating saw Three-minute runs

There was a significant difference (p = 0.0051) in the traced line offset test before or after the performed cuts. The visual representation of the differences between the sampled data is shown in Figure 50. While the brand 1 reciprocating saw had a mean value of the user deterring from the line the most, the brand 2 reciprocating saw overall had the highest value seen in the results. This could go along with the grip strength results, that with less strength in the hand, it would be harder to follow a precision line.

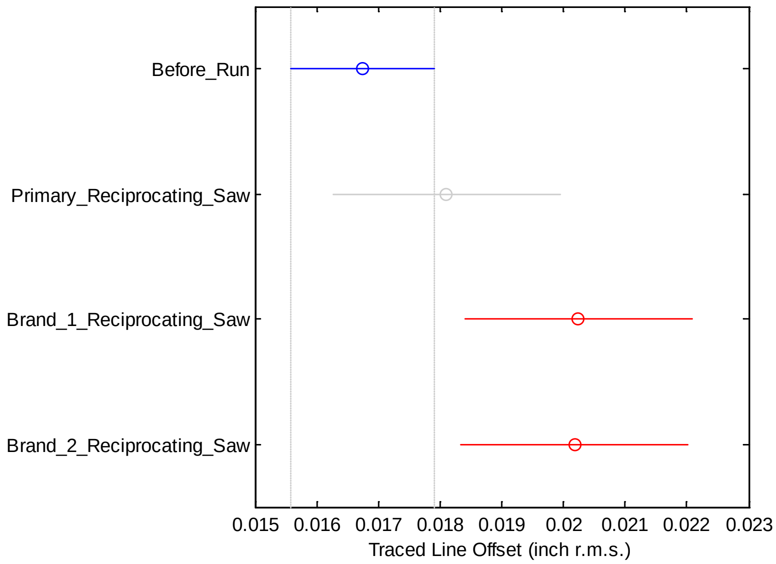

Figure 50. Visual representation of the differences in pair-wise means for Traced Line Offset comparing before, primary, brand 1, and brand 2 reciprocating saw Three-minute runs

While there was no significant difference between the before and after run for the Primary reciprocating saw, there was a significant difference between the before run and the brand 1 and brand 2 reciprocating saw after runs. This can be seen in Table 16.

Table 16. Traced Line Offset pairwise differences comparing before, primary, brand 1, and brand 2 reciprocating saw Three-minute runs

Parameters	95% Confidence Intervals for Pairwise Differences in Means (inch)
Before Run vs. Primary Reciprocating Saw	No significant difference
Before Run vs. Brand 1 Reciprocating Saw	$0.0005 \leq \mu_{Brand\ 1\ Recip\ Saw} - \mu_{Before} \leq 0..0065$
Before Run vs. Brand 2 Reciprocating Saw	$0.0004 \leq \mu_{Brand\ 2\ Recip\ Saw} - \mu_{Before} \leq 0.0064$
Primary Reciprocating Saw vs. Brand 1 Reciprocating Saw	No significant difference
Primary Reciprocating Saw Run vs. Brand 2 Reciprocating Saw	No significant difference
Brand 1 Reciprocating Saw vs. Brand 2 Reciprocating Saw	No significant difference

4.2.1.3. Traced Line Offset Maximum Peak to Peak Distance

With there being no significant difference in the traced line offset, by visual inspection there was a difference in how the lines were drawn. The maximum peak to minimum peak of the lines drawn was analyzed. A 95% confidence interval was formulated for each data set (Before Run: {0.0626, 0.0743}, Primary Reciprocating Saw: {0.0754, 0.866}, Brand 1 Reciprocating Saw: {0.0691, 0.0869}, and Brand 2 Reciprocating Saw: {0.0749, 0.0116}). Figure 51 displays the distribution of the data.

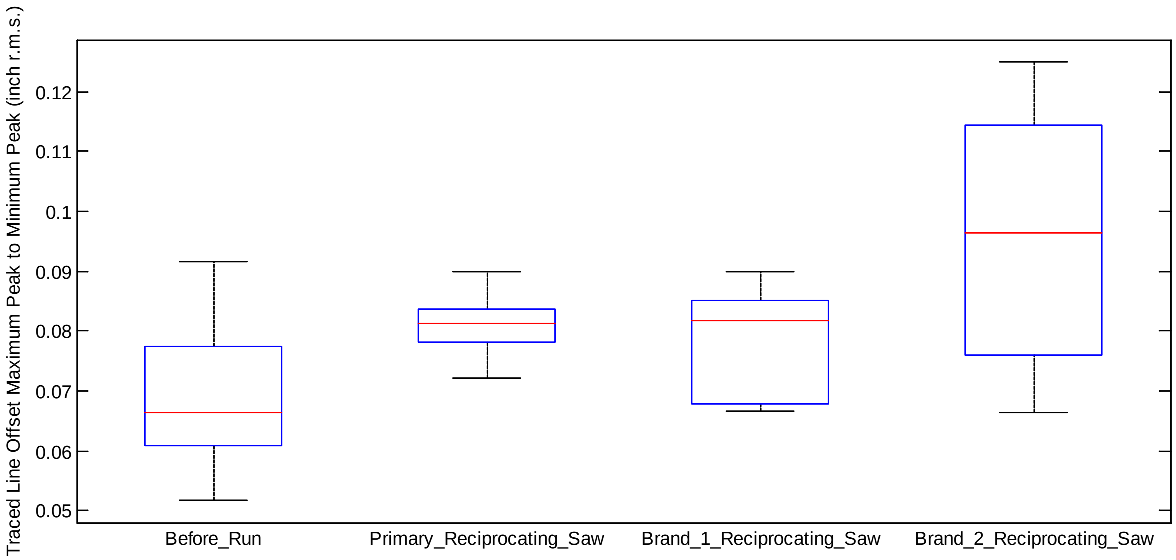

Figure 51. Results for distribution of the test data for traced line offset maximum peak to minimum peak comparing before, primary, brand 1, and brand 2 reciprocating saw Three-minute runs

Once again, there was a significant difference ($p = 0.005$). As graphed in Figure 52 below, it is seen that there are significant differences between the data using a 95% confidence interval. The primary reciprocating saw and the brand 1 reciprocating saw were fairly similar, and only slightly higher than the before line tracing. The brand 2 reciprocating saw though saw much larger than the others.

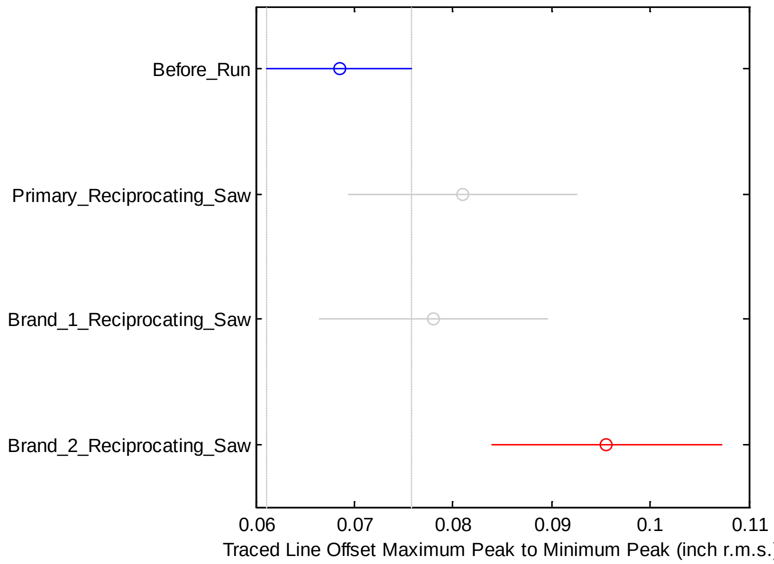

Figure 52. Visual representation of the differences in pair-wise means for Traced Line Offset Maximum Peak to Minimum Peak comparing before, primary, brand 1, and brand 2 reciprocating saw Three-minute runs

There is a significant difference between the Before run vs. Brand 2 reciprocating saw. The Primary reciprocating saw had no significant difference between the Brand 1 and Brand 2 reciprocating saw. Finally, Brand 1 and Brand 2 have no significant difference between themselves. The pairwise differences between their means are given in Table 17.

Table 17. Traced Line Offset Maximum Peak to Minimum Peak pairwise differences comparing before, primary, brand 1, and brand 2 reciprocating saw Three-minute runs

Parameters	95% Confidence Intervals for Pairwise Differences in Means (inch)
Before Run vs. Primary Reciprocating Saw	No significant difference
Before Run vs. Brand 1 Reciprocating Saw	No significant difference
Before Run vs. Brand 2 Reciprocating Saw	$0.0082 \leq \mu_{Brand\ 2\ Recip\ Saw} - \mu_{Before} \leq 0.0460$
Primary Reciprocating Saw vs. Brand 1 Reciprocating Saw	No significant difference
Primary Reciprocating Saw Run vs. Brand 2 Reciprocating Saw	No significant difference
Brand 1 Reciprocating Saw vs. Brand 2 Reciprocating Saw	No significant difference

4.2.1.4. Intensity of Discomfort Felt By Hand Due to Vibration

The Primary reciprocating saw was compared against Brand 1 and Brand 2 reciprocating saws. The intensity of discomfort felt by the user due to vibration hand rank score was the first test comparing the three. The same rating from 1, being the lowest, and 10 being the highest vibration discomfort was applied.

There was a slight difference displayed by the data. This can be seen in the 95% confidence intervals (Primary Reciprocating Saw: {8, 9}, Brand 1 Reciprocating Saw: {8, 9}, and Brand 2 Reciprocating Saw: {7, 9}). The location and variation of the data is indicated in Figure 53.

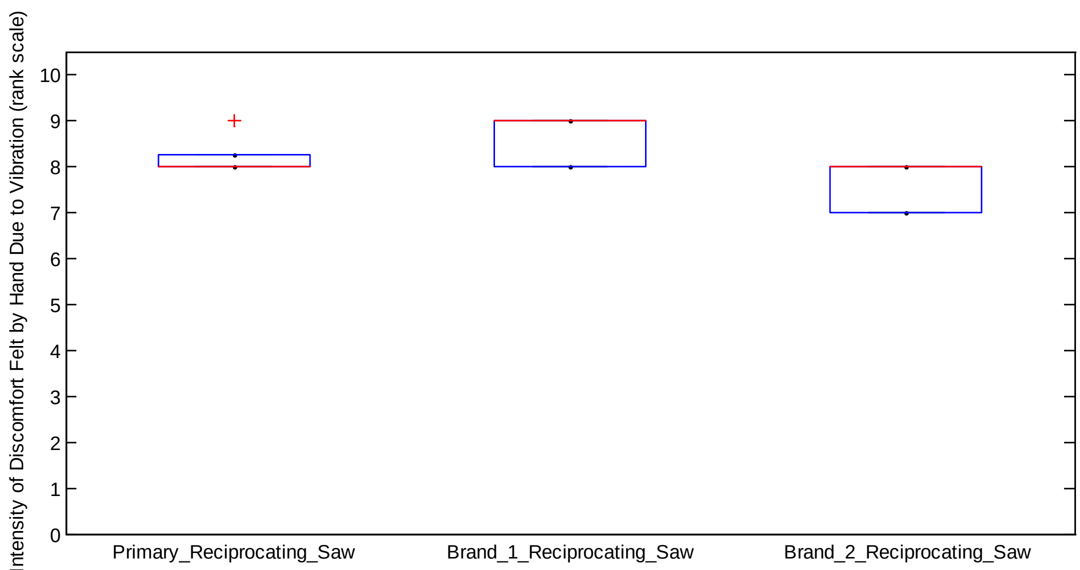

Figure 53. Results for distribution of the test data for intensity of discomfort felt by hand for reciprocating saw on a qualitative rank scale comparing primary, brand 1, and brand 2 reciprocating saw Three-minute runs

The results from the Kruskal-Wallis statistical test analysis provided there was at least one median time interval set containing a significant difference ($p = 0.047$). The data shown in Figure 54 demonstrate that there is a significant difference between the brand 1 and brand 2 reciprocating saw, but no significant difference between the Primary reciprocating saw and the other brands. Brand 1 had the highest hand discomfort to the user. A factor that plays a part in this which was noted was the ergonomics of the tool, although they all emitted vibrations, depending how the ergonomics were on each tool gave a more or less comfortable grip for the user. The smaller the trigger the harder it was for the user to keep the tool in operation as time passed due to more force needed in one spot rather than over a larger surface.

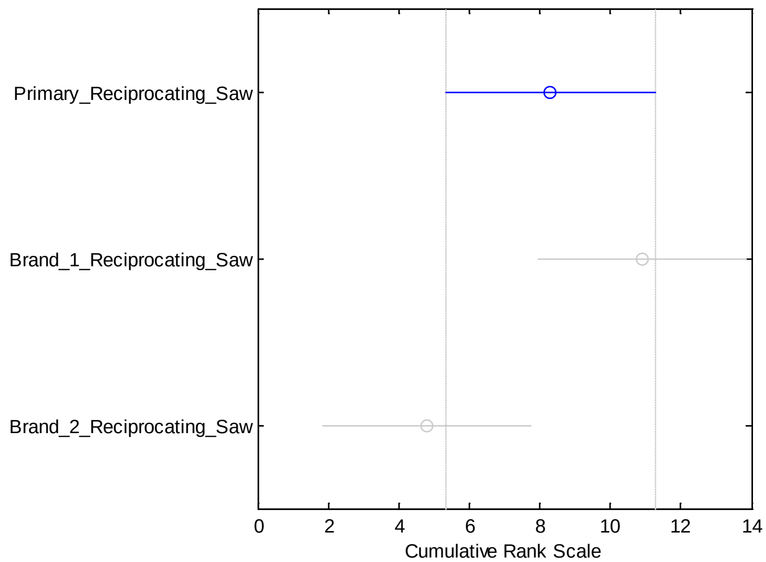

Figure 54. Visual representation of the differences in pair-wise medians comparing primary, brand 1, and brand 2 reciprocating saw Three-minute runs

4.2.2. Brand 1 and Brand 2 Reciprocating Saw; Measured Vibration Emission

In this section, the brand 1 and brand 2 reciprocating saw measured vibration emission values will be presented along with their statistical analysis.

4.2.2.1. Accelerometer Results for Tool Handle in g's

The accelerometer measurements between the tool brands handle was reviewed and compared. The 95% confidence intervals were found to have quite a difference between them (Primary Reciprocating Saw: {8.464, 8.816}, Brand 1 Reciprocating Saw: {8.228, 8.487}, and Brand 2 Reciprocating Saw: {9.865, 10.781}). As shown in Figure 55 there is a large range even between where brand 2 and the other reciprocating saws are distributed.

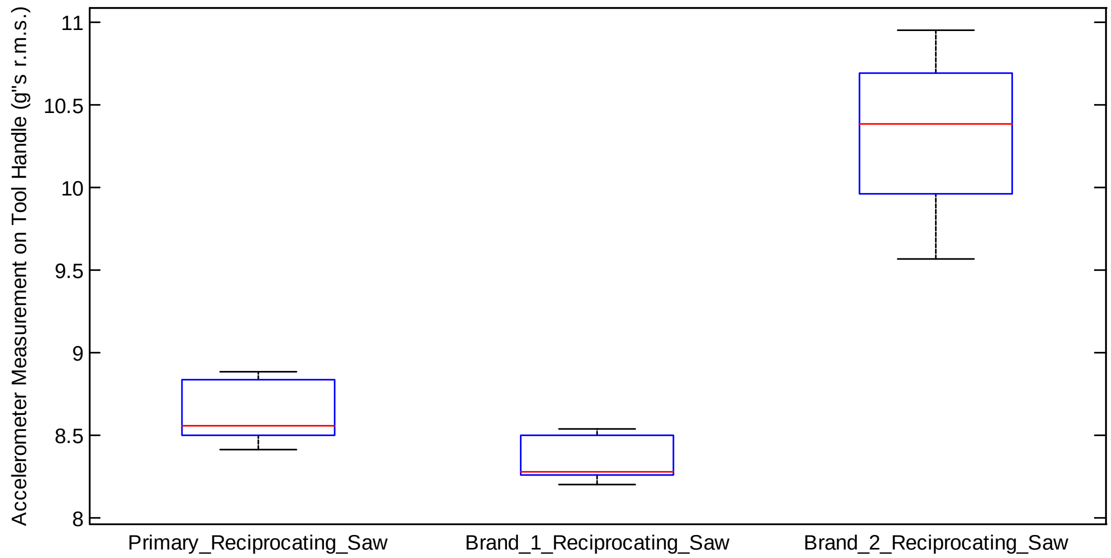

Figure 55. Results for distribution of the test data for accelerometer measurement on tool handle in g's comparing primary, brand 1, and brand 2 reciprocating saw Three-minute runs

As done before, the data were statistically tested for significant difference and it was confirmed the results were significantly different ($p = 0.00$). The results displayed in Figure 56 give a good feel for how far apart the results truly lay. From the accelerometer results mounted directly to the reciprocating saws, it was seen that the g values of the brand 2 reciprocating saw were much larger than that of the primary or brand 1 reciprocating saw. This could be an overall characteristic of the tool however some things which could affect this would be cutting speed, or tool power levels. These could further be analyzed in the future to determine if they are factors at all.

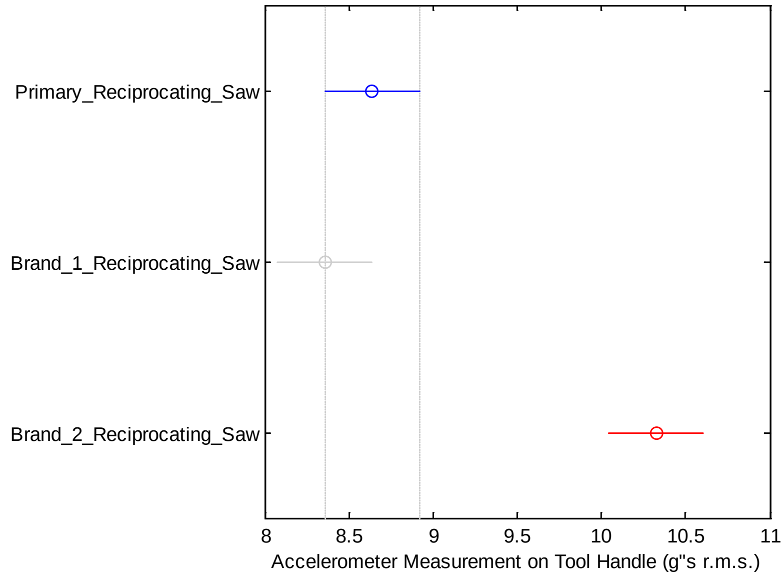

Figure 56. Visual representation of the differences in pair-wise means for accelerometer measurement on tool handle in g's comparing primary, brand 1, and brand 2 reciprocating saw Three-minute runs

Upon analyzing the results, the Primary reciprocating saw was not significantly different from the brand 1 reciprocating saw, however the brand 2 reciprocating saw was significantly different from the Primary and brand 1 reciprocating saw. This is revealed in Table 18 below.

Table 18. Accelerometer Measurement on Tool Handle in G's pairwise differences comparing primary, brand 1, and brand 2 reciprocating saw Three-minute runs

Parameters	95% Confidence Intervals for Pairwise Differences in Means (g's)
Primary Reciprocating Saw vs. Brand 1 Reciprocating Saw	No significant difference
Primary Reciprocating Saw vs. Brand 2 Reciprocating Saw	$1.1195 \leq \mu_{Brand\ 2\ Recip\ Saw} - \mu_{Recip\ Saw} \leq 2.2478$
Brand 1 Reciprocating Saw vs. Brand 2 Reciprocating Saw	$1.4014 \leq \mu_{Brand\ 2\ Recip\ Saw} - \mu_{Brand\ 1\ Recip\ Saw} \leq 2.5297$

4.2.2.2. ISO Frequency-Weighted Hand-Transmitted Vibration on Tool Handle

The raw acceleration values were converted from g's to the ISO frequency-weighted hand-transmission values. The tool handle values were used to find the 95% confidence intervals (Primary Reciprocating Saw: {17.295, 26.310}, Brand 1

Reciprocating Saw: {19.765, 23.155}, and Brand 2 Reciprocating Saw: {20.653, 24.049}). The box and whisker plot is expressed in Figure 57.

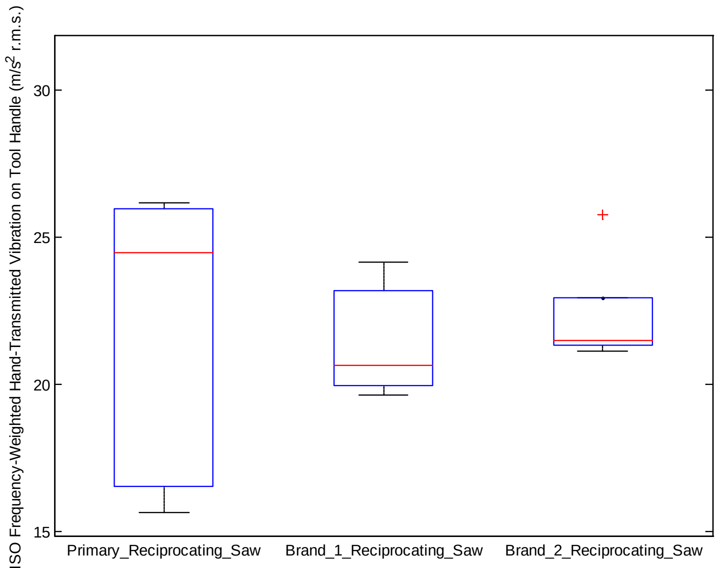

Figure 57. Results for distribution of the test data for ISO Frequency-Weighted Hand-Transmitted Vibration on tool handle comparing primary, brand 1, and brand 2 reciprocating saw Three-minute runs

The data seen above does not appear to have any significant difference and a statistical analysis confirmed this. No significant difference ($p = 0.9152$) was between the data sets. After the ISO frequency weighting, the values of all the tools became similar. There was not much difference at all between the different mean values.

4.2.2.3. Accelerometer Results for Hand in g's

The results from the accelerometer measurements on the hand were now reviewed. This data set was also taken in g's. The confidence intervals were formulated (Primary Reciprocating Saw: {7.301, 7.735}, Brand 1 Reciprocating Saw: {7.056, 7.954}, and Brand 2 Reciprocating Saw: {8.789, 9.937}). A similar type of plot from when measured on the tool is displayed for the hand accelerometer location in Figure 58.

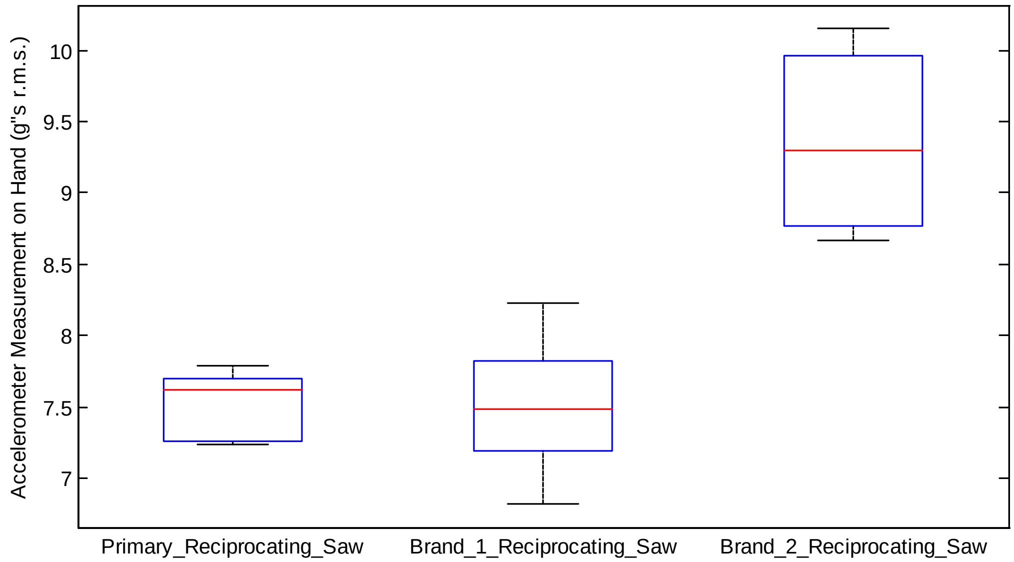

Figure 58. Results for distribution of the test data for accelerometer measurement on hand in g's comparing primary, brand 1, and brand 2 reciprocating saw Three-minute runs

As before the statistical review led to significant difference (p = 0.00) in at least pair of data results. The significant difference can be seen between the brand 2 reciprocating saw vs. the primary and brand 1 reciprocating saw. The primary and brand 1 reciprocating saw had no significant difference as seen in Figure 59. Previously seen, the brand 2 reciprocating saw had a higher tool vibration level so this follows the trend that the hand would have a larger vibration amount transferred to the user.

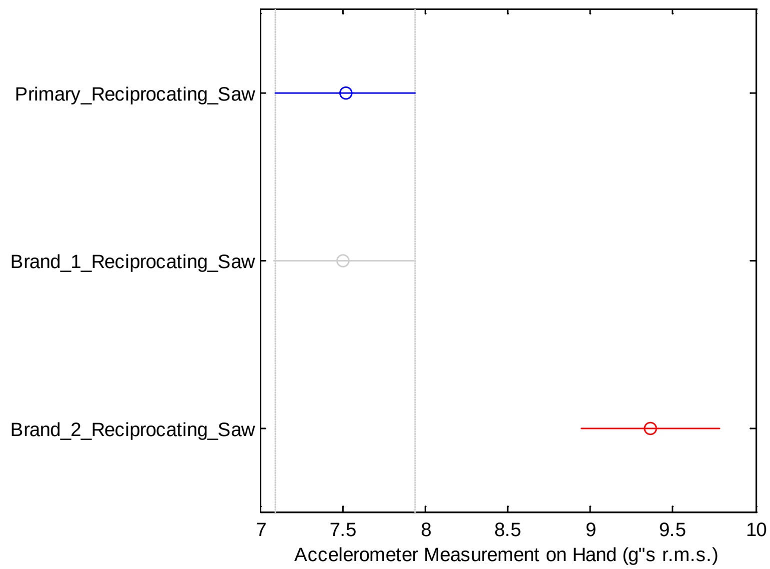

Figure 59. Visual representation of the differences in pair-wise means for accelerometer measurement on hand in g's comparing primary, brand 1, and brand 2 reciprocating saw Three-minute runs

The pairwise differences in the mean values are displayed in Table 19.

Table 19. Accelerometer Measurement on Hand in g's pairwise differences comparing primary, brand 1, and brand 2 reciprocating saw Three-minute runs

Parameters	95% Confidence Intervals for Pairwise Differences in Means (g's)
Primary Reciprocating Saw vs. Brand 1 Reciprocating Saw	No significant difference
Primary Reciprocating Saw vs. Brand 2 Reciprocating Saw	$1.0004 \leq \mu_{Brand\ 2\ Recip\ Saw} - \mu_{Recip\ Saw} \leq 2.6904$
Brand 1 Reciprocating Saw vs. Brand 2 Reciprocating Saw	$1.0132 \leq \mu_{Brand\ 2\ Recip\ Saw} - \mu_{Brand\ 1\ Recip\ Saw} \leq 2.7032$

4.2.2.4. ISO Frequency-Weighted Hand-Transmitted Vibration on Hand

The ISO frequency-weighted hand-transmitted vibration values were then computed from these raw values and the 95% confidence intervals were found (Primary Reciprocating Saw: {15.281, 23.050}, Brand 1 Reciprocating Saw: {20.995, 23.567}, and Brand 2 Reciprocating Saw: {16.804, 23.520}). The centers and variation of the data can be seen in Figure 60. The upper range was fairly similar while the bottom value varied.

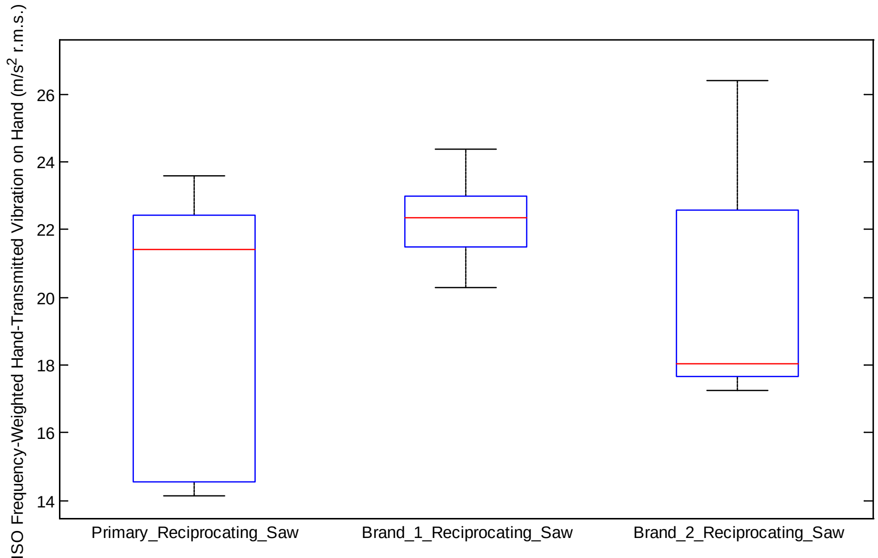

Figure 60. Results for distribution of the test data for ISO Frequency-Weighted Hand-Transmitted Vibration on hand comparing primary, brand 1, and brand 2 reciprocating saw Three-minute runs

The data results were not significantly different (p = 0.3828) from each other. As seen with the comparison of the tool data results, once the ISO frequency weighting was implemented the results between the saws became more similar. The most prominent frequencies the hand is able to see in the natural frequency range are visible in all three tools.

4.2.2.5. Accelerometer Results for Location in g's Brand 1

The next steps were to review how the tools handle vibration value compared to the vibration felt to the users hand from the brand 1 reciprocating saw. A comparison between the tool and hand accelerometer measurement revealed a 95% confidence interval (Tool Accelerometer: {8.228, 8.487} and Hand Accelerometer: {7.056, 7.954}). While the tool had an overall higher vibration level, the hand saw a wider range of vibration values as displayed in Figure 61.

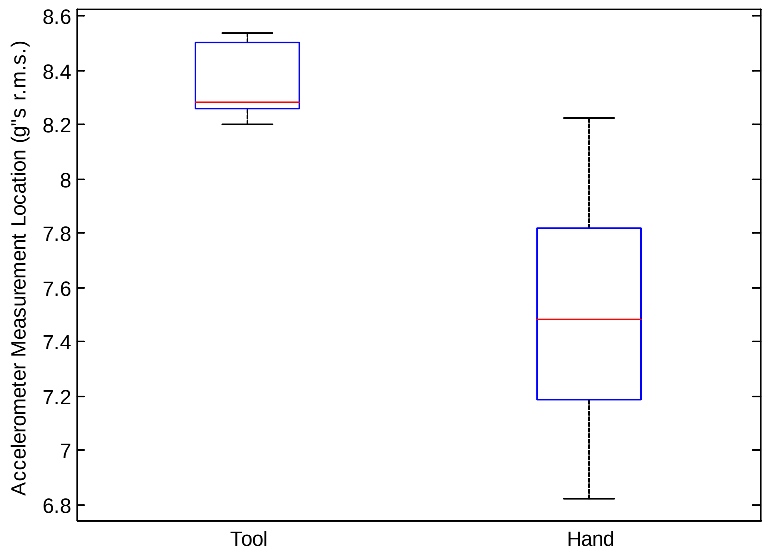

Figure 61. Results for brand 1 distribution of the test data for accelerometer measurement location in g's comparing tool to hand measurements for Three-minute runs

The statistical comparison test resulted in a significant difference ($p = 0.0072$) between the tool and hand acceleration data. The pair-wise differences can be seen in the visual representation of Figure 62. The results from the brand 1 reciprocating saw demonstrated a larger vibration on the tool than what the users hand was experiencing in g's. There were some high values seen on the user's hand which are close to the lower quartile of what was registered from the tool.

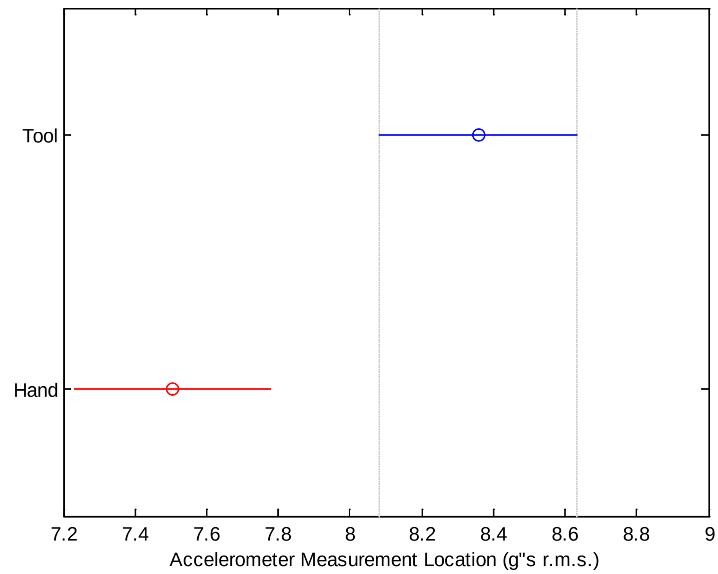

Figure 62. Visual representation of brand 1 differences in pair-wise means for accelerometer measurement location in g's comparing tool to hand measurements for Three-minute runs

The tools pairwise difference in means was calculated and displayed in Table 20.

Table 20. Accelerometer Measurement Location in g's Brand 1 pairwise differences comparing tool to hand measurements for Three-minute runs

Parameters	95% Confidence Intervals for Pairwise Differences in Means (g's)
Tool vs. Hand	$0.3030 \leq \mu_{Tool} - \mu_{Hand} \leq 1.4030$

4.2.2.6. Accelerometer Results for Location in g's Brand 2

The brand 2 results were reviewed next. The confidence interval for this tool also indicated that the tool had a higher overall acceleration then the hand measurements (Tool Accelerometer: {9.865, 10.781} and Hand Accelerometer: {8.789, 9.937}). The distribution of the data is shown in Figure 63.

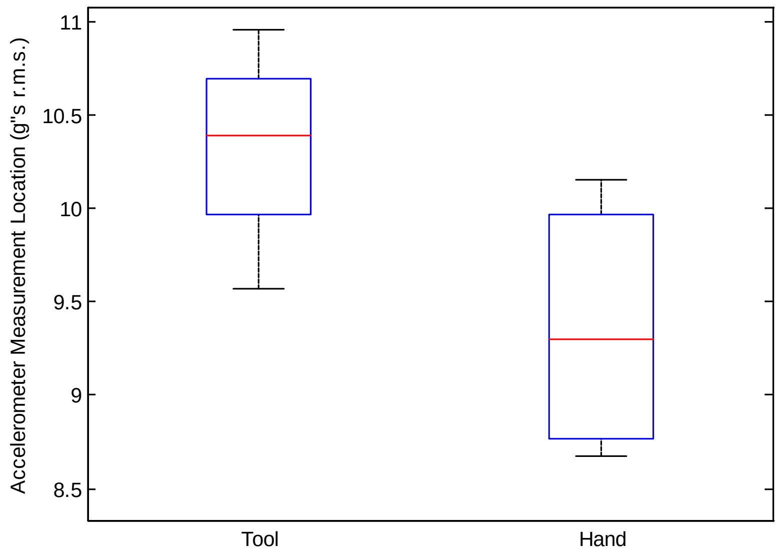

Figure 63. Results for distribution of brand 2 test data for accelerometer measurement location in g's comparing tool to hand measurements for Three-minute runs

There was a significant difference ($p = 0.0335$) in the data seen above, the visual representation of this can be seen in Figure 64. The brand 2 reciprocating saw, had higher values seen on the hand than the brand 1 reciprocating saw. Some of the measurements recorded on the user's hand were above the lower results measured on the tool. If the tool results were being used here by a company to determine dosage information, it would be inaccurate, however the mean value measured on the hand was lower than that of the tool.

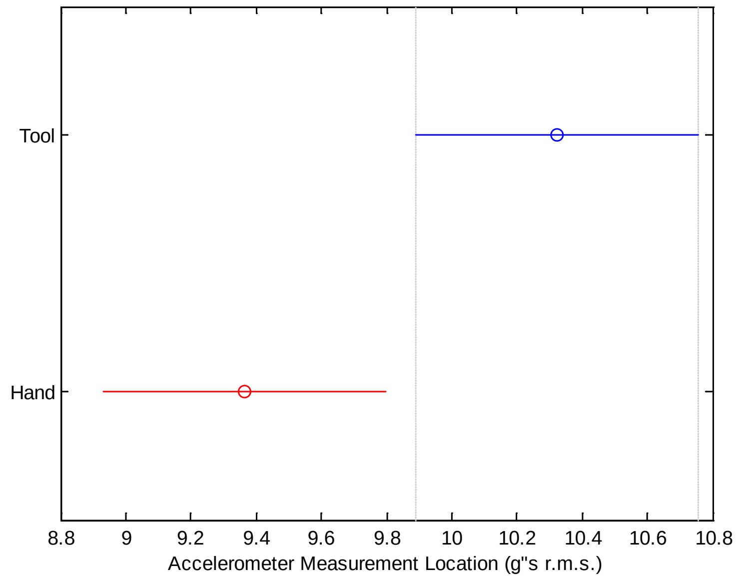

Figure 64. Visual representation of brand 2 differences in pair-wise means for accelerometer measurement location in g's comparing tool to hand measurements for Three-minute runs

The pairwise differences between the means can be seen in Table 21.

Table 21. Accelerometer Measurement Location in g's Brand 2 pairwise differences comparing tool to hand measurements for Three-minute runs

Parameters	95% Confidence Intervals for Pairwise Differences in Means (g's)
Tool vs. Hand	$0.0965 \leq \mu_{Tool} - \mu_{Hand} \leq 1.8242$

4.2.2.7. Accelerometer Results for Location in ISO Frequency-Weighted Hand-Transmitted Vibration Brand 1

The data collected from the accelerometers was adjusted to the ISO frequency-weighted hand-transmitted vibration amounts for the brand 1 reciprocating saw. The confidence intervals were calculated for 95% (Tool Accelerometer: {19.765, 23.155} and Hand Accelerometer: {20.995, 23.567}). The distribution of the data between the tool handle and the users hand is shown in Figure 65.

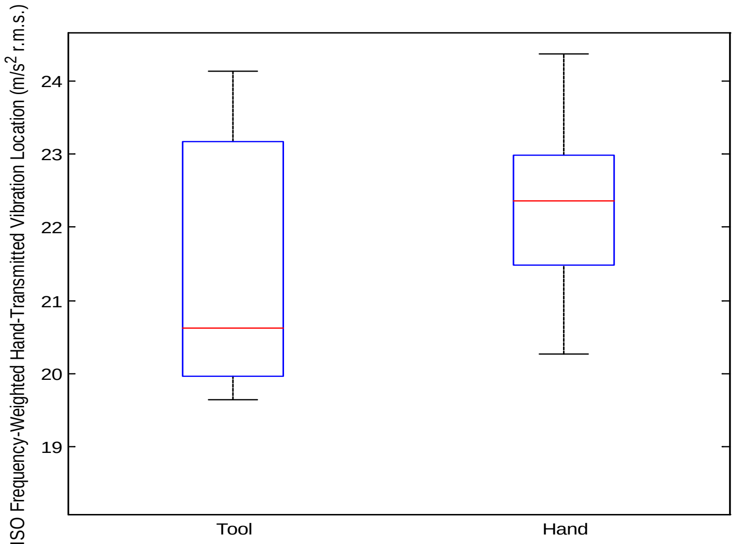

Figure 65. Results for distribution of the test data for accelerometer measurement location in ISO Frequency-Weighted Hand-Transmitted Vibration comparing tool to hand measurements for Three-minute runs

The ISO values for the tool and hand measurements were statistically analyzed and were found to not be significantly different ($p = 0.4711$). Once the ISO weighting was taken into account, the user's hand was now seeing a mean vibration dosage higher than that of what was measured directly on the tool. With this if a company was using the vibration measurement from a monitor on the tool, it would be possibly an inaccurate measurement. This is due to the natural vibration frequencies of a human hand which attenuate and can build in amplitude when excited by the reciprocating saw.

4.2.2.8. Accelerometer Results for Location in ISO Frequency-Weighted Hand-Transmitted Vibration Brand 2

The same test was reviewed for the brand 2 reciprocating saw, which had a similar confidence interval to brand 1 (Tool Accelerometer: {20.653, 24.049} and Hand Accelerometer: {16.804, 23.520}). The tool seemed to have a less broad variation as can be seen in Figure 66.

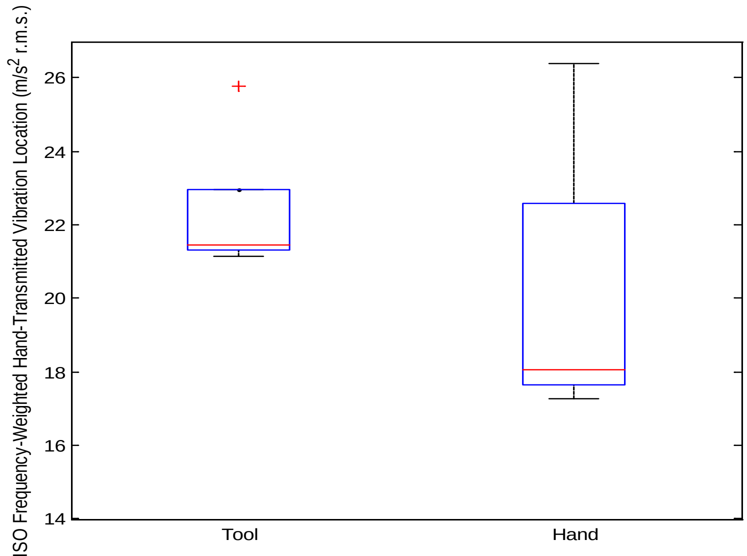

Figure 66. Results for distribution of the test data for accelerometer measurement location in ISO Frequency-Weighted Hand-Transmitted Vibration comparing tool to hand measurements for Three-minute runs

The data was similarly reviewed by a statistical analysis and was found to not be significantly different ($p = 0.2873$). Similar to when other ISO factors are accounted for, the hand vibration levels measured become much more similar to those measured on the tool and in some cases are even larger.

4.2.3. Brand 1 and Brand 2 Reciprocating Saw; Test Statistics Data Table

The data from the primary, brand 1, and brand 2 reciprocating saw tests are summarized below in Table 22. It is important to note that in some cases once the ISO hand-vibration frequencies were taken into account the vibration dosage seen by the hand was greater than that measured on the tool itself. This could be a problem for companies currently following standards which only have measurements taken directly on the tool itself and not on the human body.

Table 22. Test Statistic Data Overview of primary, brand 1, and brand 2 reciprocating saws Three-minute runs

	Test statistic	95% Bootstrap Confidence Interval for $\tilde{x}$		Median	Std. Dev.
Intensity of Discomfort Felt by Hand Due to Vibration (rank score)	Primary Reciprocating Saw	8	9	8	0.447
	Brand 1 Reciprocating Saw	8	9	9	0.547
	Brand 2 Reciprocating Saw	7	9	8	0.547

	Test statistic	95% Confidence Interval for μ		Mean	Std. Dev.
Variation in Grip Strength (%)	Primary Reciprocating Saw	4.263	8.749	6.506	2.558
	Brand 1 Reciprocating Saw	9.666	13.04	11.355	1.926
	Brand 2 Reciprocating Saw	8.547	15.778	12.162	4.125

	Test statistic	95% Confidence Interval for μ		Mean	Std. Dev.
Traced Line Offset (inch r.m.s.)	Before Run	0.0158	0.0176	0.0167	0.0169
	Primary Reciprocating Saw	0.0173	0.0188	0.0181	0.0180
	Brand 1 Reciprocating Saw	0.0187	0.0217	0.0202	0.0201
	Brand 2 Reciprocating Saw	0.0168	0.0234	0.0201	0.0195

	Test statistic	95% Confidence Interval for μ		Mean	Std. Dev.
Traced Line Offset Maximum Peak to Minimum Peak (inch)	Before Run	0.0626	0.0743	0.0685	0.0115
	Primary Reciprocating Saw	0.0754	0.0866	0.0810	0.0063
	Brand 1 Reciprocating Saw	0.0691	0.0869	0.0780	0.0101
	Brand 2 Reciprocating Saw	0.0749	0.1162	0.0956	0.0235

	Test statistic	95% Confidence Interval for μ		Mean	Std. Dev.
Accelerometer Measurement on Tool Handle in G's (g's r.m.s.)	Primary Reciprocating Saw	8.464	8.816	8.64	0.201
	Brand 1 Reciprocating Saw	8.228	8.487	8.358	0.147
	Brand 2 Reciprocating Saw	9.865	10.781	10.323	0.522

	Test statistic	95% Confidence Interval for μ		Mean	Std. Dev.
ISO Frequency-Weighted Hand-Transmitted Vibration on Tool Handle (m/s^2 r.m.s.)	Primary Reciprocating Saw	17.295	26.31	21.802	5.143
	Brand 1 Reciprocating Saw	19.765	23.155	21.46	1.933
	Brand 2 Reciprocating Saw	20.653	24.049	22.351	1.937

Accelerometer Measurement on Hand in G's (g's r.m.s.)	Test statistic	95% Confidence Interval for μ		Mean	Std. Dev.

	Primary Reciprocating Saw	7.301	7.735	7.518	0.247
	Brand 1 Reciprocating Saw	7.056	7.954	7.505	0.512
	Brand 2 Reciprocating Saw	8.789	9.937	9.363	0.654
ISO Frequency-Weighted Hand-Transmitted Vibration on Hand (m/s^2 r.m.s.)	Test statistic	95% Confidence Interval for μ		Mean	Std. Dev.
	Primary Reciprocating Saw	15.281	23.05	19.166	4.431
	Brand 1 Reciprocating Saw	20.995	23.567	22.281	1.466
	Brand 2 Reciprocating Saw	16.804	23.52	20.162	3.83
Accelerometer Measurement Location in G's Brand 1 (g's r.m.s.)	Test statistic	95% Confidence Interval for μ		Mean	Std. Dev.
	Tool	8.228	8.487	8.358	0.147
	Hand	7.056	7.954	7.505	0.512
Accelerometer Measurement Location in G's Brand 2 (g's r.m.s.)	Test statistic	95% Confidence Interval for μ		Mean	Std. Dev.
	Tool	9.865	10.781	10.323	0.522
	Hand	8.789	9.937	9.363	0.654
Accelerometer Measurement Location in ISO Frequency-Weighted Hand-Transmitted Vibration Brand 1 (m/s^2 r.m.s.)	Test statistic	95% Confidence Interval for μ		Mean	Std. Dev.
	Tool	19.765	23.155	21.46	1.933
	Hand	20.995	23.567	22.281	1.466
Accelerometer Measurement Location in ISO Frequency-	Test statistic	95% Confidence Interval for μ		Mean	Std. Dev.

Weighted Hand-Transmitted Vibration Brand 2 (m/s^2 r.m.s.)	Tool	20.653	24.049	22.351	1.937
	Hand	16.804	23.52	20.162	3.83

4.3. Impact Driver

In this section the impact driver will be explored for short term effect perceived, followed by the measured vibration emissions, and finally the test statistics data table.

4.3.1. Impact Driver; Short Term Effects Perceived

Bolt fastening intervals of 10 minutes, 3 minutes, and 1 minute were each examined. This was done to compare how the vibration dosage varied between different power tools.

4.3.1.1. Variation in Grip Strength

The variation in grip strength was also reviewed for the impact driver. As the duration of tool use increased, the grip strength percentage difference increases as specified by the 95% confidence interval (Ten-minute run: {10.330, 13.467}, Three-minute run: {5.124, 7.796}, and One-minute run: {0.109, 1.312}). The variation between the data can be seen in Figure 67. The data displays a noticeable difference between how much grip strength is lost depending on the duration of use.

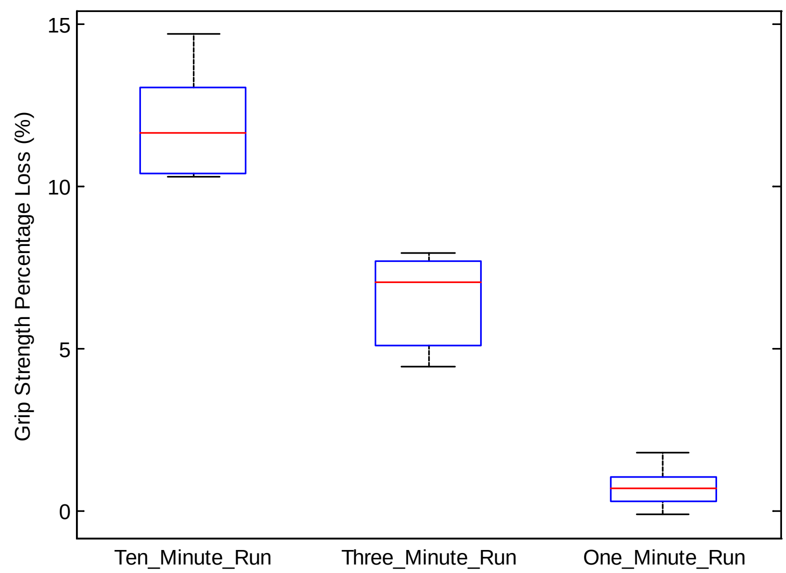

Figure 67. Results for distribution of the test data for loss of grip strength percentage difference comparing Ten-Minute, Three-Minute, and One-minute runs

After reviewing the plot above, a statistical analysis was performed and revealed that at least one of the data sets was significantly different from the other ($p = 0.00$). This can be seen in Figure 68 below. The three runs have a substantial space between each. The loss of grip strength the user was able to exert changed given the duration of bolt fastening. The vibration could be one of the factors, however it was noted that a force was needed from the user to push the tool downward for each fastening action. Over time, this tired the users arm which could have led to some of the decrease in grip strength as well.

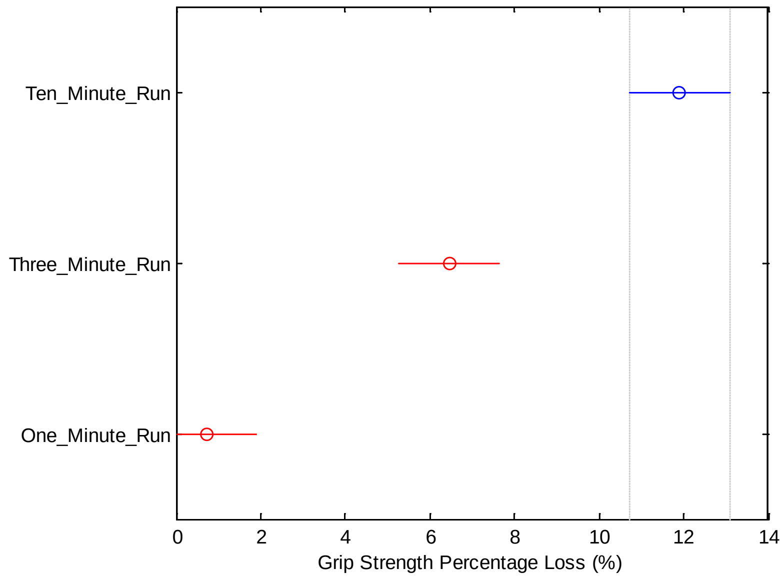

Figure 68. Visual representation of the differences in pair-wise means for grip strength percentage difference comparing Ten-Minute, Three-Minute, and One-minute runs

It can be seen that all three duration times are significantly different from each other. The pairwise differences between the means was found and displayed in Table 23.

Table 23. Variation in grip strength for impact driver pairwise differences comparing Ten-Minute, Three-Minute, and One-minute runs

Parameters	95% Confidence Intervals for Pairwise Differences in Means (%)
Ten-Minute Run vs. Three-Minute run	$3.0527 \leq \mu_{10} - \mu_3 \leq 7.8241$
Ten-Minute Run vs. One-Minute Run	$8.8021 \leq \mu_{10} - \mu_1 \leq 13.5735$
Three-Minute Run vs. One-Minute Run	$3.3637 \leq \mu_3 - \mu_1 \leq 8.1351$

4.3.1.2. Precision Test; Line Traceability Test

With the traced line offset, as the run time went from One-Minute to Three-Minutes the line became more variant from the line which was being traced. However, for the Ten-minute run it was closer to the line, but not as close as after the One-minute run. The 95% confidence interval displays this trend (Before Run: {0.0158, 0.0185}. Ten-minute run: {0.0159, 0.0201}, Three-minute run: {0.0178, 0.0245}, and One-minute run: {0.0149, 0.0184}). The center and variation of the collected data are displayed in Figure 69.

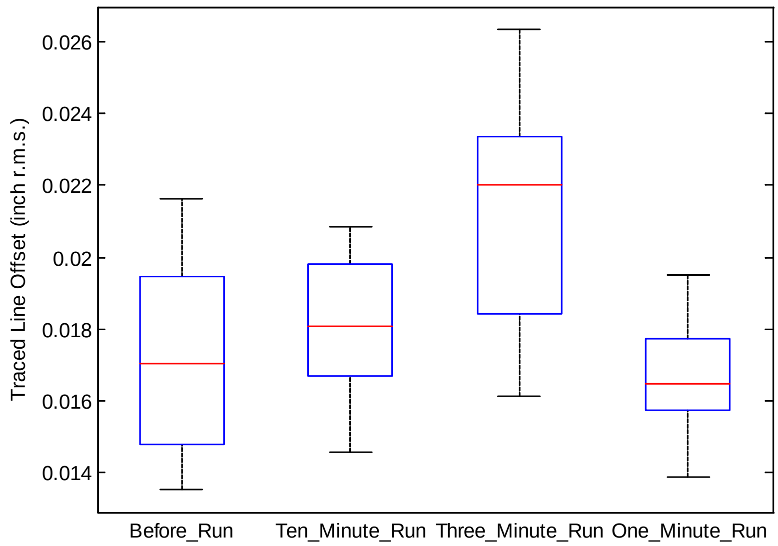

Figure 69. Results for distribution of the test data for traced line offset comparing before, Ten-Minute, Three-Minute, and One-minute runs

The data was found to be statistically different (p = 0.0424). The visual representation of this data is plotted in Figure 70. The only set of data which was significantly different was the Before Run and Three-minute run. The other runs were not significantly different. With the impact driver, the offset from the line was not as much of a difference to the reciprocating saws, however the Three-minute run seemed to have the most offset from the before. The Ten-Minute and One-minute run were almost not effected at all with the before and after results. The mass of the tool being quite light could possibly help the user not become as fatigued like the reciprocating saw and was able to keep better control after use.

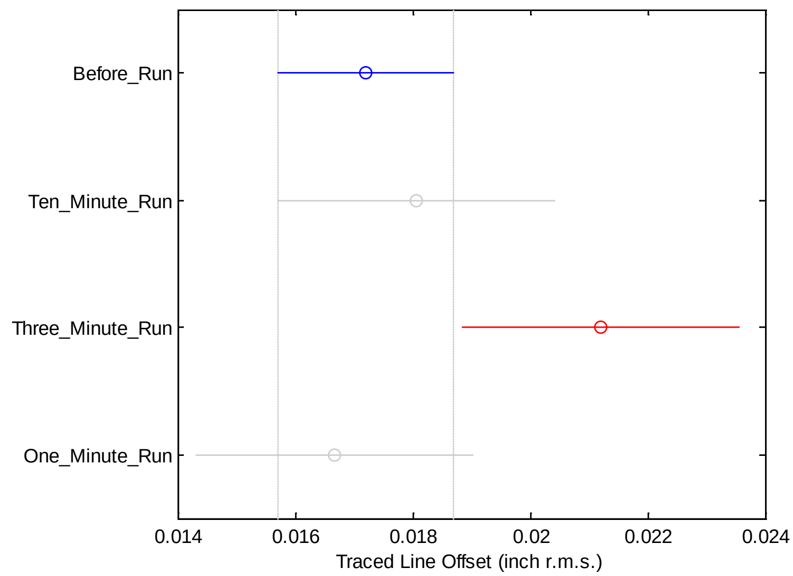

Figure 70. Visual representation of the differences in pair-wise means for traced line offset comparing before, Ten-Minute, Three-Minute, and One-minute runs

The pairwise differences in the means for the 95% confidence interval were taken. The significant difference between the Before Run and Three-minute run can be seen in Table 24.

Table 24. Traced line offset for impact driver pairwise differences comparing before, Ten-Minute, Three-Minute, and One-minute runs

Parameters	95% Confidence Intervals for Pairwise Differences in Means (inch)
Before Run vs. Ten-Minute Run	No significant difference
Before Run vs. Three-Minute Run	$0.0002 \leq \mu_3 - \mu_{Before} \leq 0.0078$
Before Run vs. One-Minute Run	No significant difference
Ten-Minute Run vs. Three-Minute Run	No significant difference
Ten-Minute Run vs. One-Minute Run	No significant difference
Three-Minute Run vs. One-Minute Run	No significant difference

4.3.1.3. Traced Line Offset Maximum Peak to Peak Distance

The traced line offset maximum peak to minimum peak demonstrated that as the run times increased, the lines became further away from the traced line. The confidence intervals display this trend (Before Run: {0.0656, 0.0814}, Ten-minute run: {0.0835, 0.1120}, Three-minute run: {0.0957, 0.1161}, and One-minute run: {0.0769, 0.0879}). The distribution of the data is shown in Figure 71.

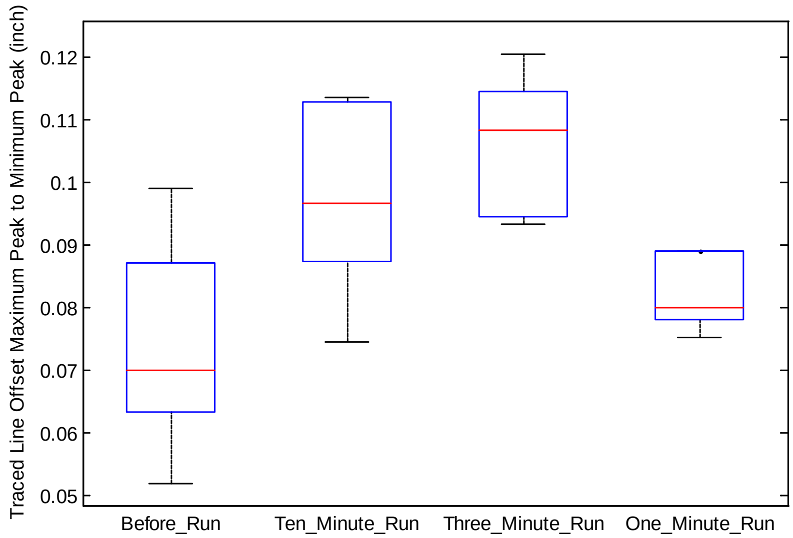

Figure 71. Results for distribution of the test data for traced line offset maximum peak to minimum peak comparing before, Ten-Minute, Three-Minute, and One-minute runs

The statistical analysis provided evidence of there being a significant difference (p = 0.0005) between at least two sets of data. The graphic representation of this is shown in Figure 72. While the r.m.s. values were similar to one another, the maximum peak to minimum peak values were different from the before run line tracing. The fatigue in grip strength could possibly help the user have a better control, however the overall quality of the line would of worsened if comparing the before and after traced line.

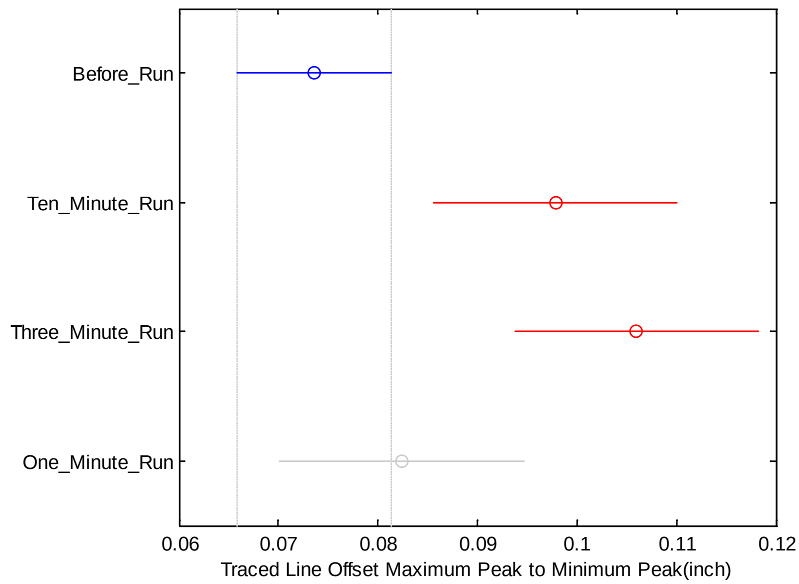

Figure 72. Visual representation of the differences in pair-wise means for traced line offset maximum peak to minimum peak comparing before, Ten-Minute, Three-Minute, and One-minute runs

There was a significant difference between the Before vs. Ten-minute run and the Before vs. Three-minute run. The other runs contained no significant difference in the data. The pairwise differences in means can be seen in Table 25.

Table 25. Traced line offset maximum peak to minimum peak for impact driver pairwise differences comparing before, Ten-Minute, Three-Minute, and One-minute runs

Parameters	95% Confidence Intervals for Pairwise Differences in Means (inch)
Before Run vs. Ten-Minute Run	$0.0043 \leq \mu_{10} - \mu_{Before} \leq 0.0443$
Before Run vs. Three-Minute Run	$0.0124 \leq \mu_{3} - \mu_{Before} \leq 0.0525$
Before Run vs. One-Minute Run	No significant difference
Ten-Minute Run vs. Three-Minute Run	No significant difference
Ten-Minute Run vs. One-Minute Run	No significant difference
Three-Minute Run vs. One-Minute Run	No significant difference

4.3.1.4. Intensity of Discomfort Felt by Hand Due to Vibration

The intensity of discomfort felt to the users hand due to vibration displayed a similar trend as before. This is indicated by the 95% confidence interval (Ten-minute run: {6, 7}, Three-minute run: {3, 5}, and One-minute run: {2, 2}). The results displayed in Figure 73 show the increasing trend as the duration increased. This was similarly seen in the reciprocating saw power tools.

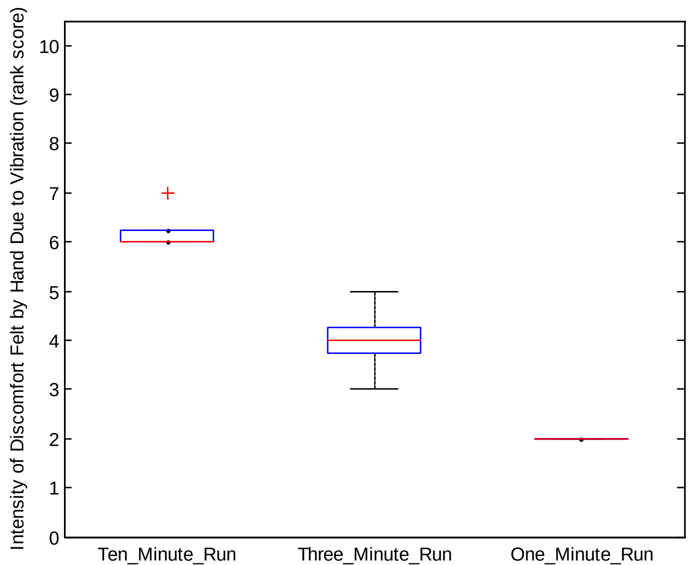

Figure 73. Results for distribution of the test data for intensity of discomfort felt by hand for impact driver on a qualitative rank scale comparing Ten-Minute, Three-Minute, and One-minute runs

The ANOVA statistical analysis was performed to see if the data was significantly different. After this analysis it was found to be significantly different ($p = 0.0013$). A visual representation of the significantly different data can be seen in Figure 74. The Ten-minute run is significantly different to the One-minute run, but not the Three-minute run. The Three-Minute and One-minute run are not significantly different either. The vibration intervals were much less when installing each bolt when compared to the reciprocating saws for time to complete one action. The tool did heat up much more near the users hand when in use though. The Ten-minute run lead to the most discomfort as could be expected as the user went through the testing.

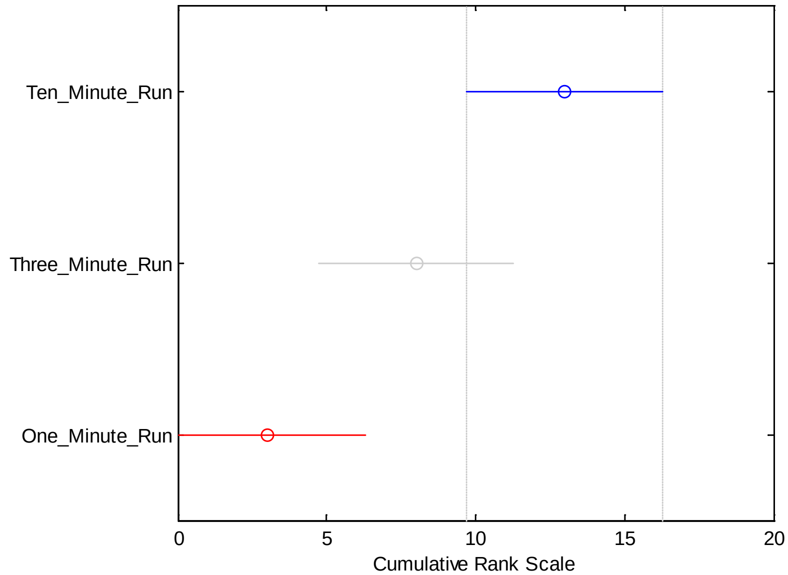

Figure 74. Visual representation of the differences in pair-wise medians, based on a cumulative rank scale comparing Ten-Minute, Three-Minute, and One-minute runs

4.3.2. Impact Driver; Measured Vibration Emission

This section will detail the measured vibration emission for the impact driver and its statistical analysis results.

4.3.2.1. Accelerometer Results for Tool Handle in g's

The impact driver's acceleration was measured on the handle. These results were recorded in g's. The acceleration data seemed fairly similar between the Three-Minute and One-minute run, however increased in the Ten-minute run. This is displayed in Figure 75 and confirmed in the 95% confidence intervals (Ten-minute run: {3.762, 4.541}, Three-minute run: {3.508, 3.805}, and One-minute run: {3.318, 3.905}).

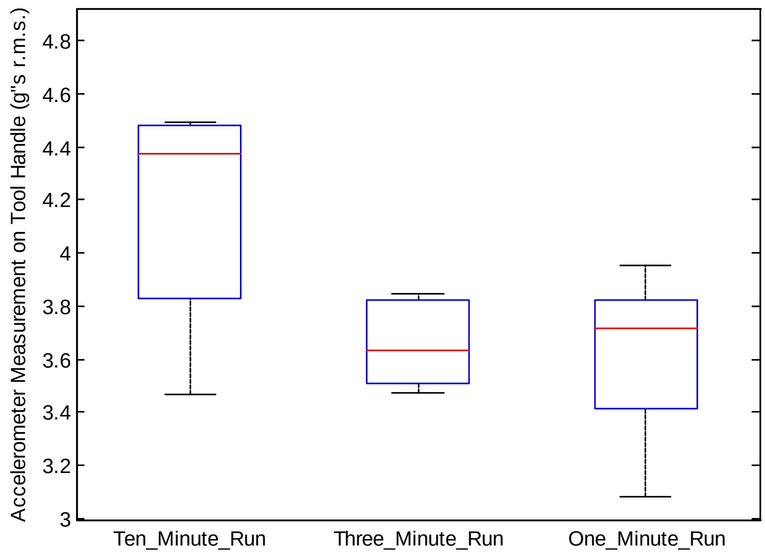

Figure 75. Results for distribution of the test data for accelerometer measurement on tool handle in g's comparing Ten-Minute, Three-Minute, and One-minute runs

The ANOVA analysis discovered a significant difference (p = 0.0471) between at least two sets of the collected data. This visual representation can be seen in Figure 76. Though there appeared to be a significant difference between two upon further investigation, the Ten-Minute and One-minute run almost had a significant difference. As time increased the trend was to increase, however the Three-minute run was similar to the One-minute run. There was no break for having to move any material with the impact driver, and therefore the whole run vibrations were being experienced. This would explain the increase in g's seen on the Ten-minute run.

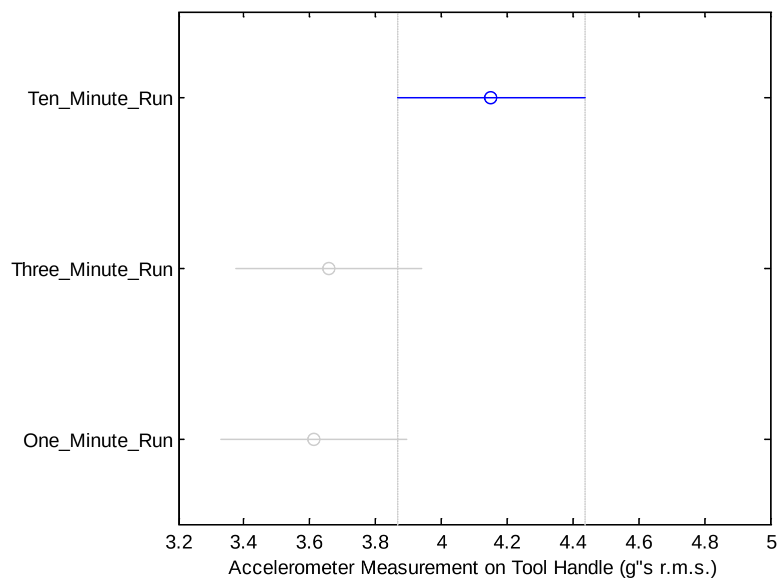

Figure 76. Visual representation of the differences in pair-wise means for accelerometer measurement on tool handle in g's comparing Ten-Minute, Three-Minute, and One-minute runs

4.3.2.2. ISO Frequency-Weighted Hand-Transmitted Vibration on Tool Handle

The ISO Freqneucy-Weighted Hand-Transmitted vibration values from the tool handle seemed to be mostly similar as exhibited in Figure 77. The confidence intervals did not appear to vary suggestively (Ten-minute run: {11.394, 14.539}, Three-minute run: {13.827, 15.779}, and One-minute run: {12.614, 15.885}).

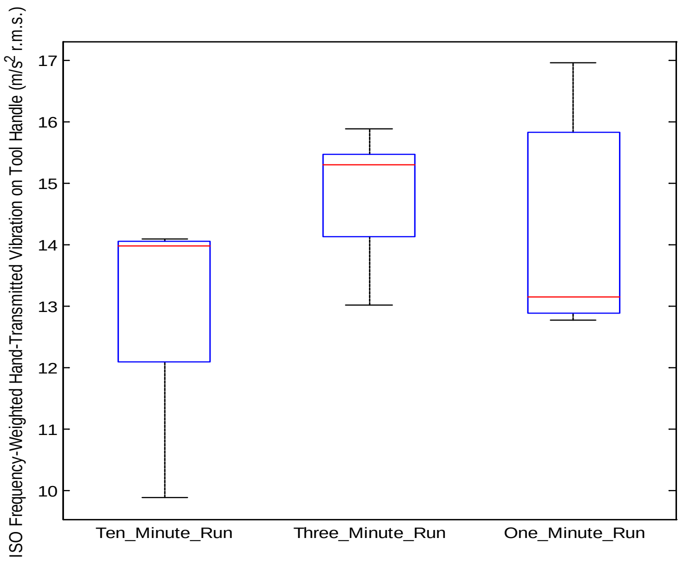

Figure 77. Results for distribution of the test data for ISO Frequency-Weighted Hand-Transmitted Vibration on tool handle comparing Ten-Minute, Three-Minute, and One-minute runs

Performing a significant difference test on the data, it was found that there was no significant difference ($p = 0.2281$) between the three runs performed. The mean values were all fairly similar for the impact driver runs after the ISO freqneucy-weighting was considered. However, the variation was quite large. When the impact driver was being used, some placed the bolt would have trouble entering the wood which could of led to some error in measurements, but this would be something experienced by construction workers as they try to put bolts in various places.

4.3.2.3. Accelerometer Results for Hand in g's

The accelerometer measurements taken from the hand all seemed to fall within the same area, with some variation in the data points, which is presented in Figure 78. The confidence intervals shown small variation within the 95% confidence interval (Ten-minute run: {1.693, 1.956}, Three-minute run: {1.766, 1.901}, and One-minute run: {1.675, 1.994}).

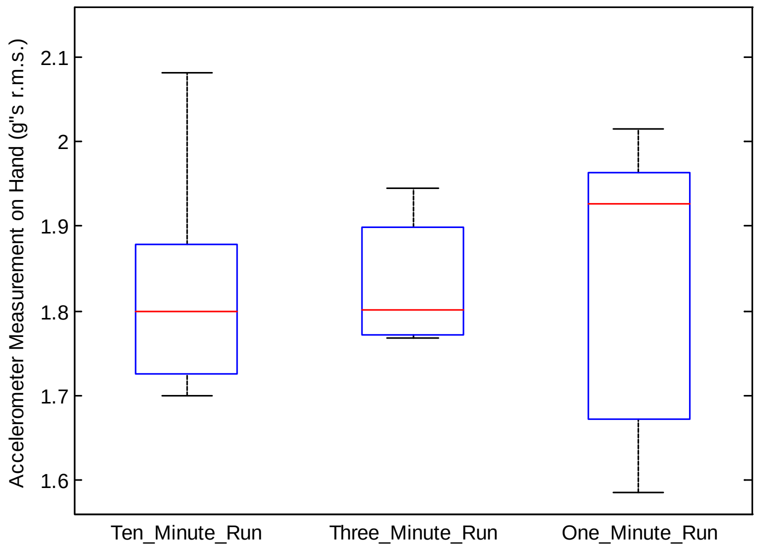

Figure 78. Results for distribution of the test data for accelerometer measurement on hand in g's comparing Ten-Minute, Three-Minute, and One-minute runs

From the statistical analysis there was no significant difference (p = 0.9924) found between the data samples. As stated before, because the material was not in need of adjustment for the runs, and the bolt fastening was continued without interruption throughout the runs, the measurements of vibration on the hand are very similar between all runs.

4.3.2.4. ISO Frequency-Weighted Hand-Transmitted Vibration on Hand

The ISO Frequency-Weighted Hand-Transmitted vibration exposed to the hand of the user was similar in the One and Three-minute runs, however it decreased in the Ten-minute run, this could be expected by an increase in number of breaks taken by the user to insert the bolts. The 95% confidence interval indicates this trend as well (Ten-minute run: {3.400, 4.719}, Three-minute run: {5.355, 6.021}, and One-minute run: {4.217, 6.128}). The trends can be perceived in Figure 79.

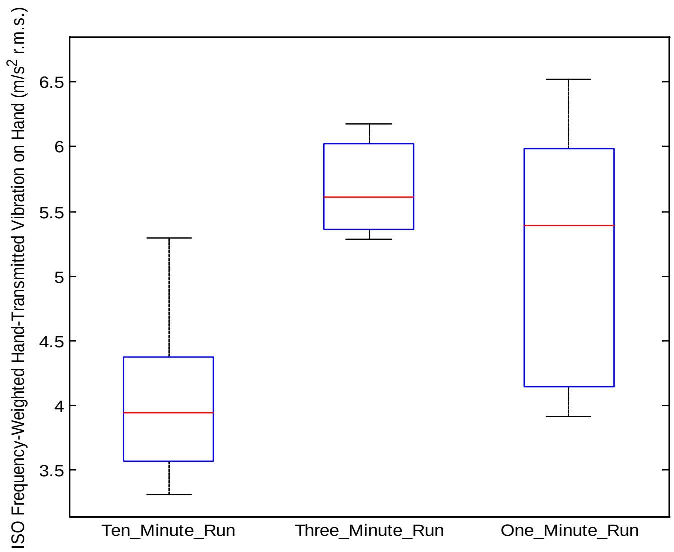

Figure 79. Results for distribution of the test data for ISO Frequency-Weighted Hand-Transmitted Vibration on hand comparing Ten-Minute, Three-Minute, and One-minute runs

The ANOVA statistical analysis revealed there was a significant difference ($p = 0.0204$) in the data between the run times. The visual representation of this can be seen below in Figure 80. Once the ISO frequency weighting was calculated the results became a little more far apart, because after each bolt was fastened a very quick break as the user was reaching for the next bolt, over the duration of the Ten-minute run, because this would have had the most breaks, this could explain why the reading on the users hand was the lowest for this run. The other two have a very similar mean with different variations.

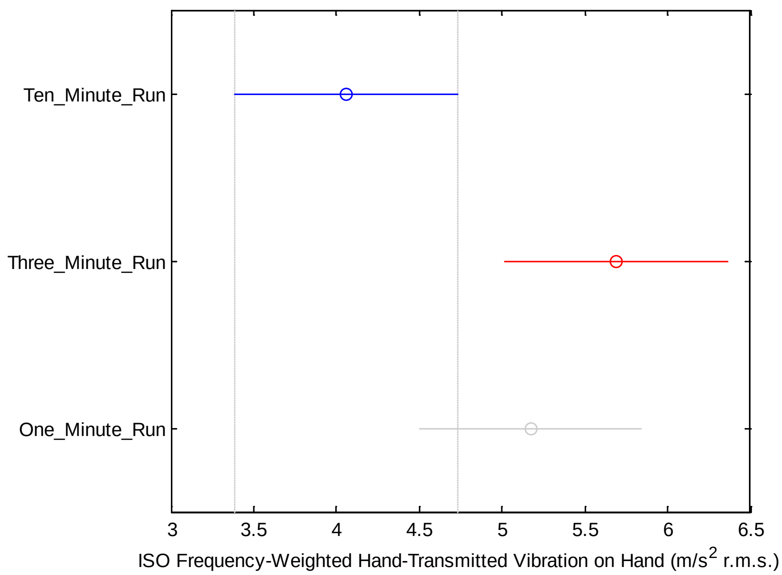

Figure 80. Visual representation of the differences in pair-wise means for ISO Frequency-Weighted Hand-Transmitted Vibration on hand comparing Ten-Minute, Three-Minute, and One-minute runs

The Ten-Minute and Three-minute runs were significantly different while the Three vs. One-Minute and Ten vs. One-minute runs were not significantly different. The pairwise differences between the means for the 95% confidence interval were solved and displayed in Table 26.

Table 26. ISO Frequency-Weighted Hand-Transmitted vibration on hand for impact driver pairwise differences comparing Ten-Minute, Three-Minute, and One-minute runs

Parameters	95% Confidence Intervals for Pairwise Differences in Means (m/s^2)
Ten-Minute Run vs. Three-Minute Run	$0.2869 \leq \mu_3 - \mu_{10} \leq 2.9710$
Ten-Minute Run vs. One-Minute Run	No significant difference
Three-Minute Run vs. One-Minute Run	No significant difference

4.3.2.5. Accelerometer Results for Location in g's

The accelerometer measurement locations were compared between the tool handle and the users hand for the Three-minute runs. The results seemed to have a large difference as can be seen with the 95% confidence intervals (Tool: {3.508, 3.805}, Hand: {1.766, 1.901}). The difference is able to visual be seen in Figure 81.

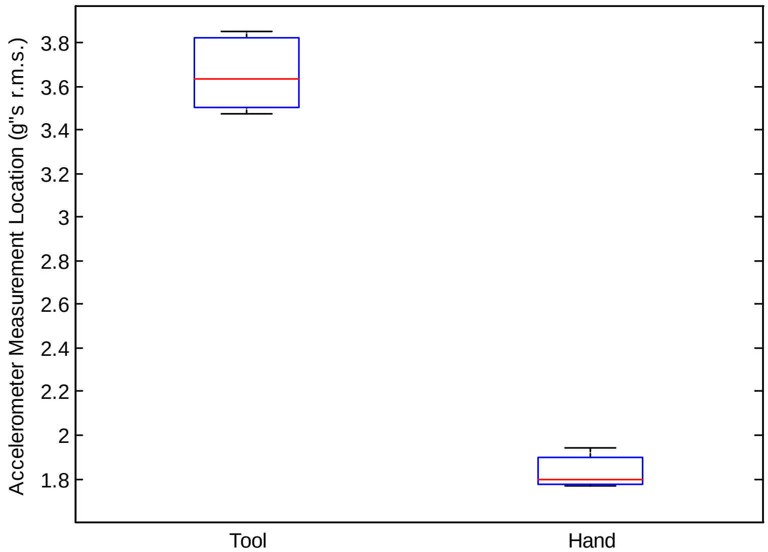

Figure 81. Results for distribution of the test data for accelerometer measurement location in g's comparing tool to hand measurements for Three-minute runs

There appeared to be a significant difference and the statistical analysis confirmed this. As shown in Figure 82 there is a significant difference ($p = 0.00$) between the vibration measured on the tool and the vibration levels measured on the users hand. The tool had a much larger result than that measured on the hand for the vibration level in g's. Since the impact driver does not put off nearly as much vibration emission as the reciprocating saw, there is even less transmitted to the hand.

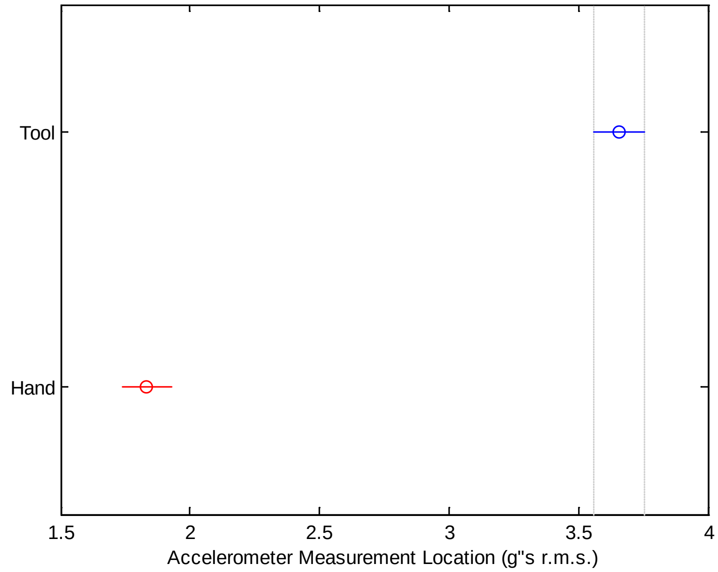

Figure 82. Visual representation of the differences in pair-wise means for accelerometer measurement location in g's comparing tool to hand measurements for Three-minute runs

The pairwise difference intervals was found for the 95% confidence intervals between the means and is displayed in Table 27 below.

Table 27. Accelerometer measurement location in g's for impact driver pairwise differences comparing tool to hand measurements for Three-minute runs

Parameters	95% Confidence Intervals for Pairwise Differences in Means (g's)
Tool vs. Hand	$1.6310 \leq \mu_{Tool} - \mu_{Hand} \leq 2.0151$

4.3.2.6. Accelerometer Results for Location in ISO Frequency-Weighted Hand-Transmitted Vibration

The data recorded in g's was converted to the ISO Frequency-Weighted Hand-Transmitted vibration values and compared again between the tool and the hand for levels of vibration. Only the Three-minute run was compared. Once again the tool vibration values are much higher than the vibration measured on the user's hand. This difference is visually shown in Figure 83 below. The 95% confidence intervals for this data also indicate a difference (Tool: {13.827, 15.779}, Hand: {5.355, 6.021}).

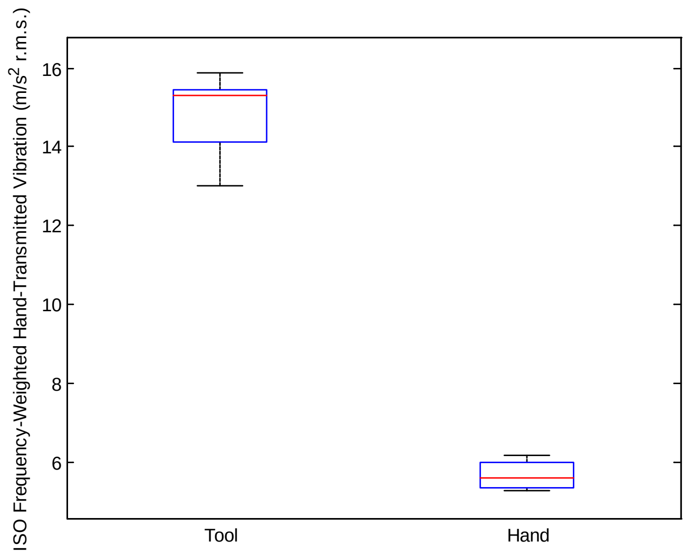

Figure 83. Results for distribution of the test data for accelerometer measurement location in ISO Frequency-Weighted Hand-Transmitted Vibration comparing tool to hand measurements for Three-minute runs

From the statistical analysis there was a significant difference (p = 0.00) seen between the two measurement locations. A graphical representation of this can be seen in Figure 84. The ISO weighted frequency acceleration value on the hand is still much lower than the tool; this could be due to the frequency being produced by this particular tool, that its main operating frequency is not near the natural frequency of a human hand. Also the fact that the tool produces less vibration dosage than that of a reciprocating saw would contribute to how much is seen to the users hand.

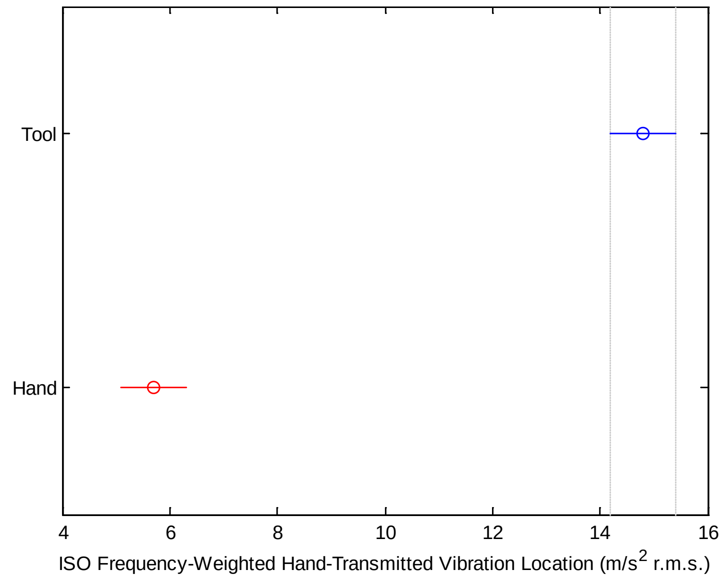

Figure 84. Visual representation of the differences in pair-wise means for accelerometer measurement location in ISO Frequency-Weighted Hand-Transmitted Vibration comparing tool to hand measurements for Three-minute runs

There was quite a large variation in the data between the two locations. The pairwise differences for this confidence interval were calculated between the means and displayed in Table 28.

Table 28. Accelerometer Measurement Location in ISO Frequency-Weighted Hand-Transmitted Vibration for impact driver pairwise differences comparing tool to hand measurements for Three-minute runs

Parameters	95% Confidence Intervals for Pairwise Differences in Means (m/s^2)
Tool vs. Hand	$7.9015 \leq \mu_{Tool} - \mu_{Hand} \leq 10.3280$

4.3.3. Impact Driver; Test Statistics Data Table

The impact driver's previous statistical data is displayed in Table 29. Overall, the impact driver had significantly lower vibration emission levels than were seen by the reciprocating saw. While most results followed a similar path as the reciprocating saw, the ISO weightings did however not match with natural frequency of a human hand, which do not amplify the results.

Table 29. Test Statistic Data Overview of Impact Driver

	Test statistic	95% Bootstrap Confidence Interval for $\tilde{x}$		Median	Std. Dev.
Intensity of Discomfort Felt by Hand Due to Vibration (rank score)	Ten-Minute Run	6	7	6	0.447
	Three-Minute Run	3	5	4	0.707
	One-Minute Run	2	2	2	0
	Test statistic	95% Confidence Interval for μ		Mean	Std. Dev.
Variation in Grip Strength (%)	Ten-Minute Run	10.33	13.467	11.898	1.789
	Three-Minute Run	5.124	7.796	6.46	1.524
	One-Minute Run	0.109	1.312	0.711	0.686
	Test statistic	95% Confidence Interval for μ		Mean	Std. Dev.
Traced Line Offset (inch r.m.s.)	Before Run	0.0158	0.0185	0.0171	0.0026
	Ten-Minute Run	0.0159	0.0201	0.018	0.0023
	Three-Minute Run	0.0178	0.0245	0.0211	0.0038
	One-Minute Run	0.0149	0.0184	0.0166	0.002

	Test statistic	95% Confidence Interval for μ		Mean	Std. Dev.
Traced Line Offset Maximum Peak to Minimum Peak (inch)	Before Run	0.0656	0.0814	0.0735	0.0156
	Ten-Minute Run	0.0835	0.112	0.0978	0.0162
	Three-Minute Run	0.0957	0.1161	0.1059	0.0116
	One-Minute Run	0.0769	0.0879	0.0824	0.0062
	Test statistic	95% Confidence Interval for μ		Mean	Std. Dev.
Accelerometer Measurement on Tool Handle in G's (g's r.m.s.)	Ten-Minute Run	3.762	4.541	4.151	0.444
	Three-Minute Run	3.508	3.805	3.657	0.169
	One-Minute Run	3.318	3.905	3.611	0.334
	Test statistic	95% Confidence Interval for μ		Mean	Std. Dev.
ISO Frequency-Weighted Hand-Transmitted Vibration on Tool Handle (m/s^2 r.m.s.)	Ten-Minute Run	11.394	14.539	12.967	1.793
	Three-Minute Run	13.827	15.779	14.803	1.113
	One-Minute Run	12.614	15.885	14.249	1.866

	Test statistic	95% Confidence Interval for μ		Mean	Std. Dev.
Accelerometer Measurement on Hand in G’s (g’s r.m.s.)	Ten-Minute Run	1.693	1.956	1.825	0.149
	Three-Minute Run	1.766	1.901	1.834	0.077
	One-Minute Run	1.675	1.994	1.835	0.182
ISO Frequency-Weighted Hand-Transmitted Vibration on Hand (m/s^2 r.m.s.)	Test statistic	95% Confidence Interval for μ		Mean	Std. Dev.
	Ten-Minute Run	3.4	4.719	4.059	0.752
	Three-Minute Run	5.355	6.021	5.688	0.379
	One-Minute Run	4.217	6.128	5.173	1.089
Accelerometer Measurement Location in G’s (g’s r.m.s.)	Test statistic	95% Confidence Interval for μ		Mean	Std. Dev.
	Tool	3.508	3.805	3.657	0.169
	Hand	1.766	1.901	1.834	0.077
Accelerometer Measurement Location in ISO Frequency-Weighted Hand-Transmitted Vibration (m/s^2 r.m.s.)	Test statistic	95% Confidence Interval for μ		Mean	Std. Dev.
	Tool	13.827	15.779	14.803	1.113
	Hand	5.355	6.021	5.688	0.379

4.4. Vibration Plate

In this section, first will be the short term effect perceived by the vibration plate, then the measured vibration emission, and finally the test statistics data table.

4.4.1. Vibration Plate; Short Term Effects Perceived

Grip force intervals of 3 minutes were examined using the vibration plate setup shown previously. Three grip forces at 15N, 30N, and 45N were examined. These forces were chosen after measuring the force needed to hold the trigger down for the impact driver and reciprocating saw tool to operate which was around 33N. A value similar to those, 30N was chosen, as well as, a lower and higher value to see what results would arise. The vibration plate had settings between 0% to 100% vibration amplitude. Data was taken for the three grip forces at vibration amplitude ratings of 10%, 40%, and 70%. However, the closest setting to our power tools was the 70% vibration amplitude rating and thus a setting of 70% vibration amplitude was used in the experimental runs presented below.

4.4.1.1. Variation in Grip Strength

The grip strength percentage difference increased slightly as the larger forces were exerted to hold the handle. This can be perceived in Figure 85 and goes along with the calculated 95% confidence intervals (Grip Force 45N: {5.353, 11.315}, Grip Force 30N: {3.499, 8.739}, and Grip Force 15N: {5.972, 8.204}).

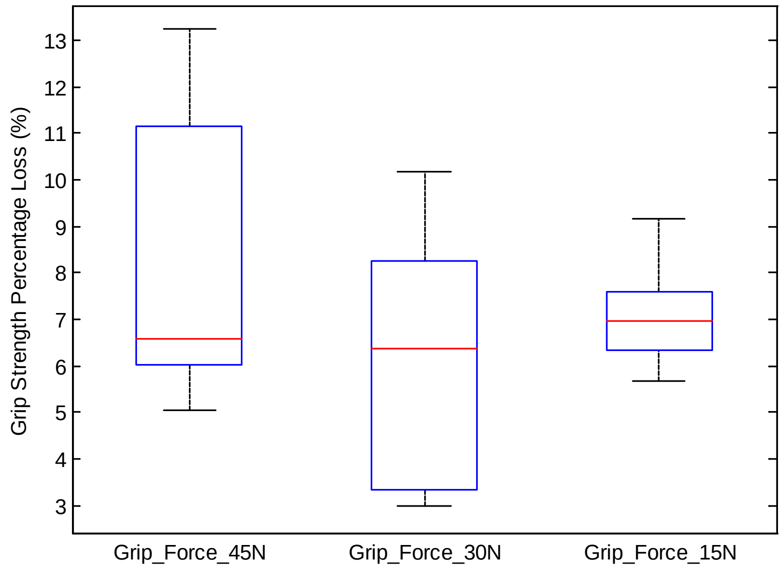

Figure 85. Results for distribution of the test data for loss of grip strength percentage difference comparing 45N, 30N, and 15N grip force for Three-minute runs

The data had no significant difference (p = 0.4572) when statistically analyzed. One reason which there may not have been seen as much decrease was when using the other tools there was a mass acting on the users hand. This would add additional vibration the user would feel as they are gripping and holding the mass of the tool while operating. The loss of grip force for all the forces was very similar in the means, however overall the 45N grip force did have the highest loss of grip force.

4.4.1.2. Intensity of Discomfort Felt by Hand Due to Vibration

The intensity of discomfort felt by the user holding the vibration plate handle was much less than the reciprocating saws. There was little difference between the 30N and 15N grip force, and a slight increase in the 45N grip force as seen in Figure 86. The 95% confidence interval revealed that the results did not have much variation (Grip Force 45N: {5, 5}, Grip Force 30N: {4, 4}, and Grip Force 15N: {4, 4}).

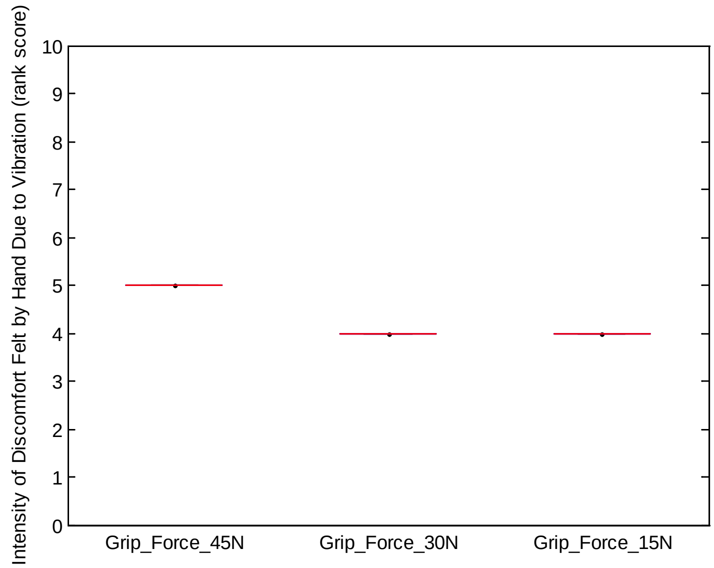

Figure 86. Results for distribution of the test data for intensity of discomfort felt by hand for vibration plate on a qualitative rank scale comparing 45N, 30N, and 15N grip force for Three-minute runs

From a statistical analysis of the data it was found that there was a significant difference ($p = 0.0009$) between at least one pair of samples. This is graphed in Figure 87 and it can be seen that the 45N grip force is significantly different from the 30N and 15N grip force. The 30N and 15N grip forces are not significantly difference however. The vibration plate had much less vibration present than that of a reciprocating saw, plus there was no mass of a tool. This only left the vibration feeling for the user to withstand. The discomfort was much less than those of using an actual power tool.

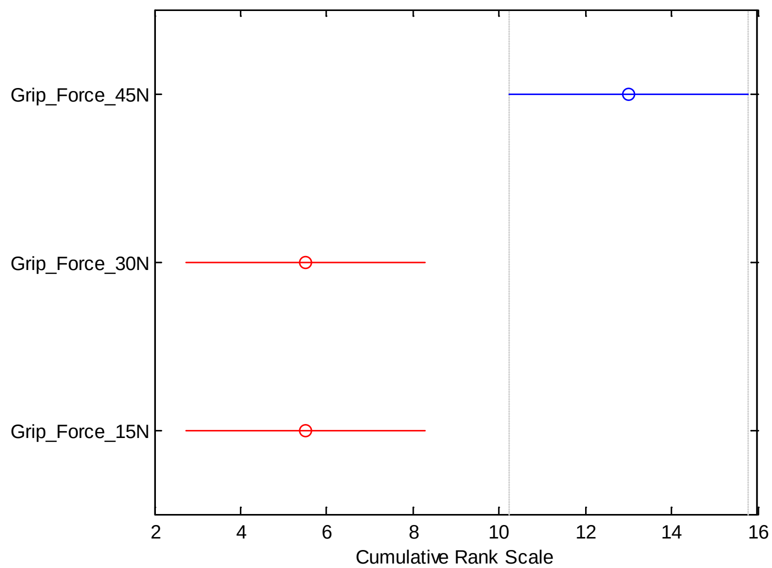

Figure 87. Visual representation of the differences in pair-wise medians, based on a cumulative rank scale comparing 45N, 30N, and 15N grip force for Three-minute runs

4.4.2. Vibration Plate; Measured Vibration Emission

In this section the vibration plate measured vibration emissions with statistical analysis will be presented.

4.4.2.1. Accelerometer Results for Tool Handle in g's

The accelerometer measurement on the tool handle provided interesting results. The accelerometer mounted on the vibration plate as seen in Figure 15 previously was considered the tool handle for the following tests. As seen in Figure 88, the more grip force applied to the handle, the less g's was read. This was also indicated by the 95% confidence intervals (Grip Force 45N: {4.832, 5.209}, Grip Force 30N: {5.178, 5.576}, and Grip Force 15N: {5.493, 5.952}).

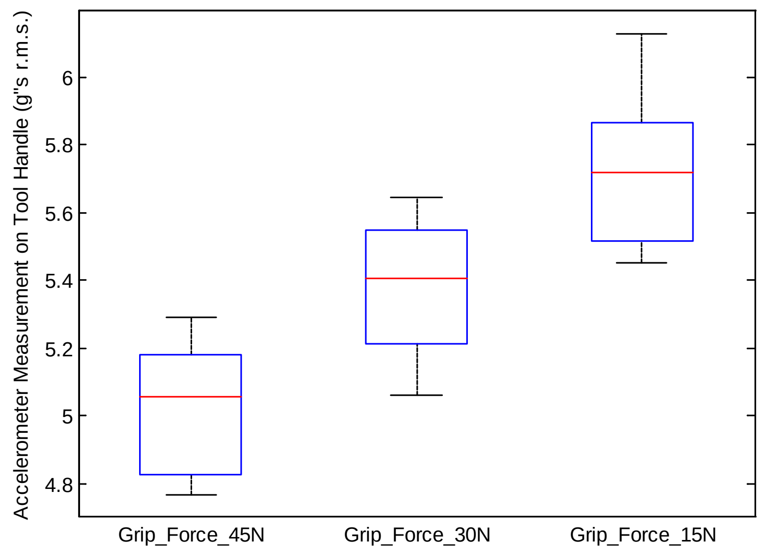

Figure 88. Results for distribution of the test data for accelerometer measurement on tool handle in g's comparing 45N, 30N, and 15N grip force for Three-minute runs

These results were statistically analyzed by the ANOVA analysis and it was found the data was significantly different ($p = 0.0019$). It is shown in Figure 89 that the 45N and 15N grip force are significantly different but the 30N grip force is not significantly different from the two. An interesting trend set here, that as the grip force increases on the tool, the vibration level decreases. This is because as the hand is holding the handle with greater grip force, the more vibration the hand will absorb acting as a damper.

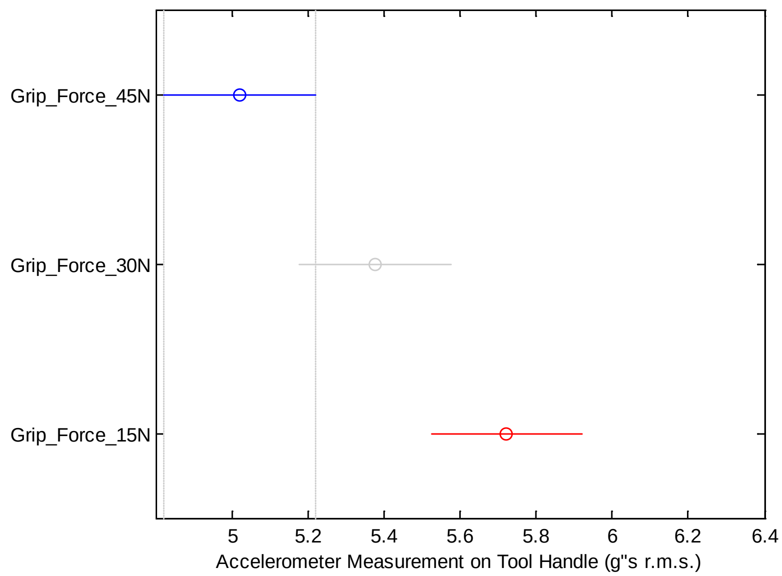

Figure 89. Visual representation of the differences in pair-wise means for accelerometer measurement on tool handle in g's comparing 45N, 30N, and 15N grip force for Three-minute runs

The pairwise differences in means were calculated for the significantly different data at 95% confidence as shown in Table 30.

Table 30. Accelerometer Measurement on Tool Handle in g's pairwise differences comparing 45N, 30N, and 15N grip force for Three-minute runs

Parameters	95% Confidence Intervals for Pairwise Differences in Means (g's)
Grip_Force_45N vs. Grip_Force_30N	No significant difference
Grip_Force_45N vs. Grip_Force_15N	$0.3046 \leq \mu_{15} - \mu_{45} \leq 1.0986$
Grip_Force_30N vs. Grip_Force_15N	No significant difference

4.4.2.2. ISO Frequency-Weighted Hand-Transmitted Vibration on Tool Handle

These previously found data values were taken and converted to the ISO Frequency-Weighted Hand-Transmitted vibration amounts. Once weighted the values were all fairly similar to one another as seen in Figure 90. The confidence intervals for 95% do show some variation however the means are all similar (Grip Force 45N: {6.832, 8.727}, Grip Force 30N: {7.645, 9.072}, and Grip Force 15N: {8.122, 9.553}).

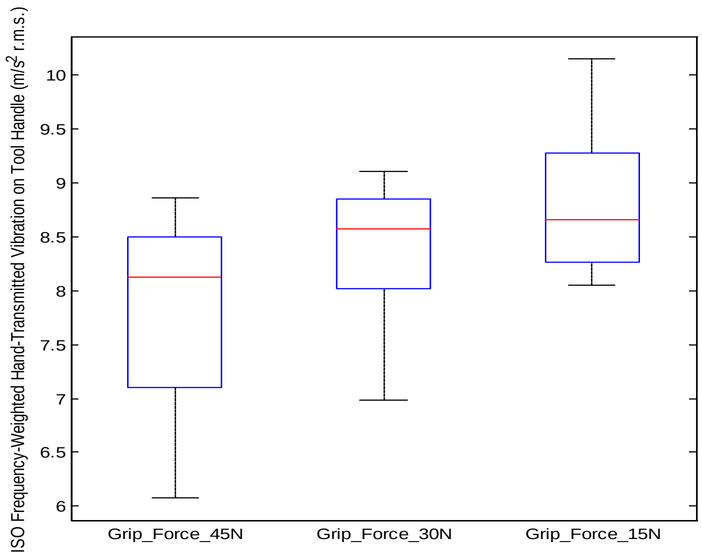

Figure 90. Results for distribution of the test data for ISO Frequency-Weighted Hand-Transmitted Vibration on tool handle comparing 45N, 30N, and 15N grip force for Three-minute runs

Through statistical analysis the three sets of data were found to not be significantly different (p = 0.2262) from each other. The ISO frequency weighting were similar to the g's in that as the grip force was increasing, the vibration level was decreasing.

4.4.2.3. Accelerometer Results for Hand in g's

The data measured from the hand showed an inverse relationship to what was found when measuring the vibration amounts on the vibration plate handle. As displayed in Figure 91, it can be seen that the hand is now receiving more vibration as the grip force increases. This is also indicated by the 95% confidence intervals (Grip Force 45N: {2.723, 4.200}, Grip Force 30N: {2.998, 3.328}, and Grip Force 15N: {2.332, 3.366}).

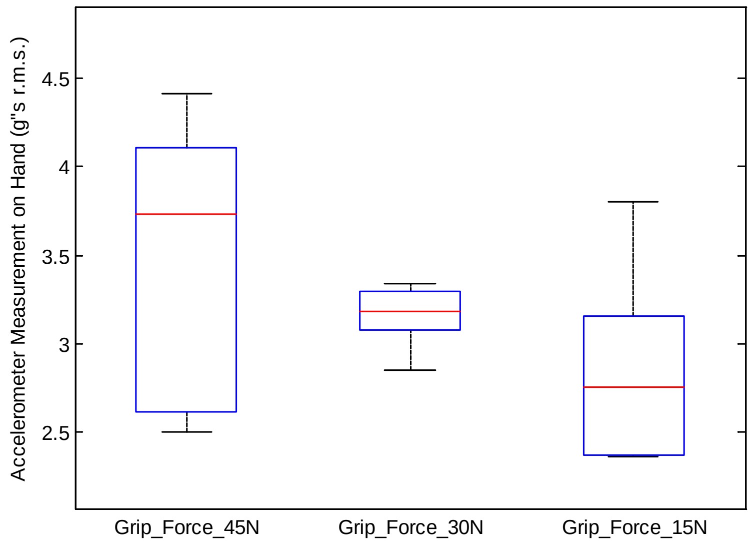

Figure 91. Results for distribution of the test data for accelerometer measurement on hand in g's comparing 45N, 30N, and 15N grip force for Three-minute runs

The data was reviewed for significant differences, however from statistical analysis no significant difference ($p = 0.312$) was found between the data sets. The opposite effect can be seen as in the vibration plate handle here, as the grip force increases the hand sees more vibration. Because the hand is giving a larger gripping force more dampening is occurring and the hand is receiving more vibration dosage.

4.4.2.4. ISO Frequency-Weighted Hand-Transmitted Vibration on Hand

The ISO Frequency-Weighted Hand-Transmitted vibration values were found and these results are displayed in Figure 92. The grip force of 45N had a much larger variation than the others as indicated by the 95% confidence intervals (Grip Force 45N: {4.237, 7.292}, Grip Force 30N: {4.321, 4.871}, and Grip Force 15N: {4.027, 4.575}).

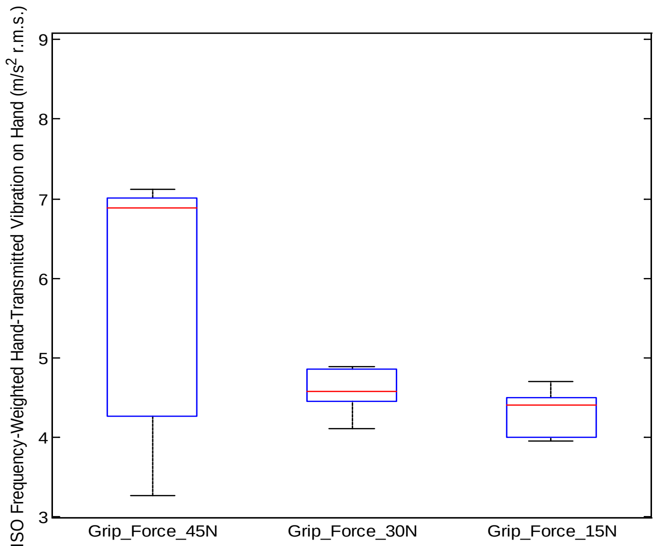

Figure 92. Results for distribution of the test data for ISO Frequency-Weighted Hand-Transmitted Vibration on hand comparing 45N, 30N, and 15N grip force for Three-minute runs

The values were tested for significant difference using the ANOVA method. This set of data was not found significantly different ($p = 0.102$). The statistical analysis was repeated at 80% and found significant difference between the values. Figure 93 gives a visual representation of this difference. The ISO frequency weighting had a similar curve as the g's. As the grip force increases, the vibration absorbed increases. While the vibration reading on the vibration plate handle decreases.

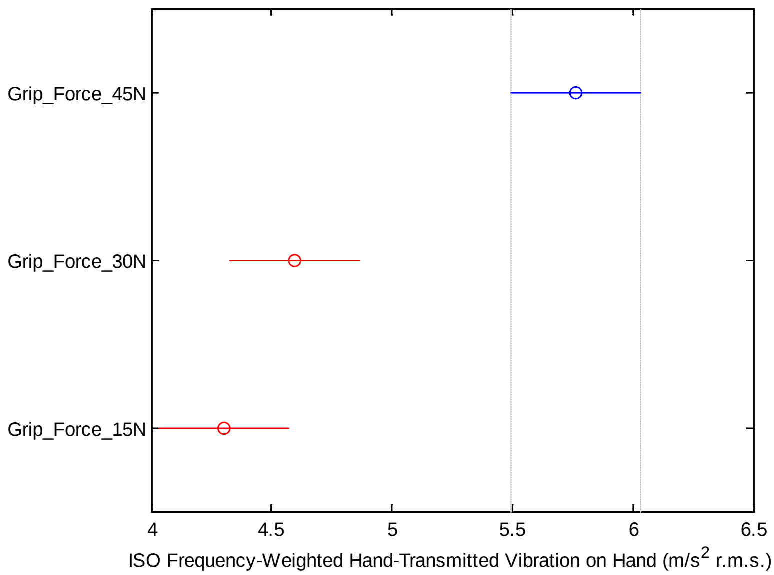

Figure 93. Visual representation of the differences in pair-wise means for ISO Frequency-Weighted Hand-Transmitted Vibration on Hand comparing 45N, 30N, and 15N grip force for Three-minute runs

The grip force of 45N is significantly higher than the 30N and 15N grip force, however the 30N and 15N grip force are not significantly different from each other. The 80% pairwise confidence intervals were calculated and presented in Table 31.

Table 31. ISO Frequency-Weighted Hand-Transmitted Vibration on Hand pairwise differences comparing 45N, 30N, and 15N grip force for Three-minute runs

Parameters	80% Confidence Intervals for Pairwise Differences in Means (m/s^2)
Grip_Force_45N vs. Grip_Force_30N	$0.6321 \leq \mu_{45} - \mu_{30} \leq 1.7052$
Grip_Force_45N vs. Grip_Force_15N	$0.9269 \leq \mu_{45} - \mu_{15} \leq 2.0000$
Grip_Force_30N vs. Grip_Force_15N	No significant difference

4.4.2.5. Accelerometer Results for Location in g's

The accelerometer measurement locations were reviewed for the 30N grip force only. The vibration plate handle had a much higher vibration level as depicted in Figure 94. The 95% confidence intervals were also much higher (Tool: {5.178, 5.576}, Hand: {2.998, 3.328}).

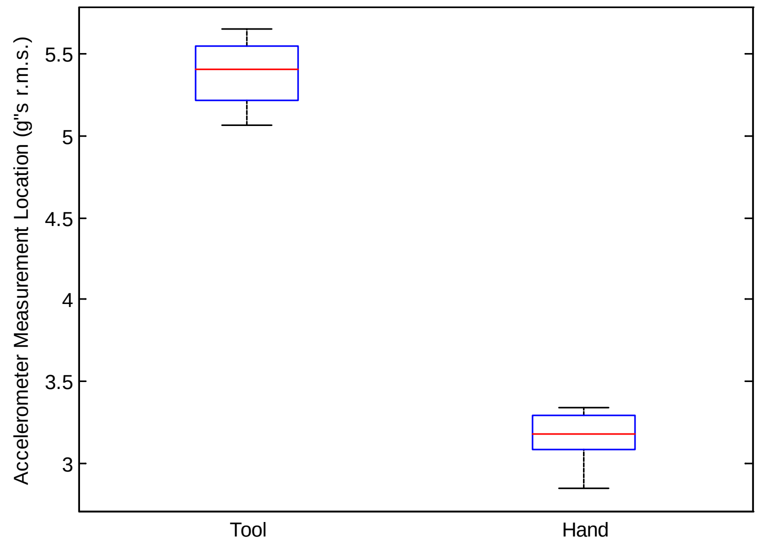

Figure 94. Results for distribution of the test data for accelerometer measurement location in g's comparing tool to hand measurements for 30N grip force in Three-minute runs

From the statistical analysis it was determined that the tool and handle measurements were significantly different ($p = 0.00$). There is a large variation which can visually be represented in Figure 95. Overall, the tool had a larger vibration reading than the hand. This is expected as even though the vibration in the hand increases as the grip force is increased, it does not reach a level where it surpasses the vibration level of the vibration plate itself.

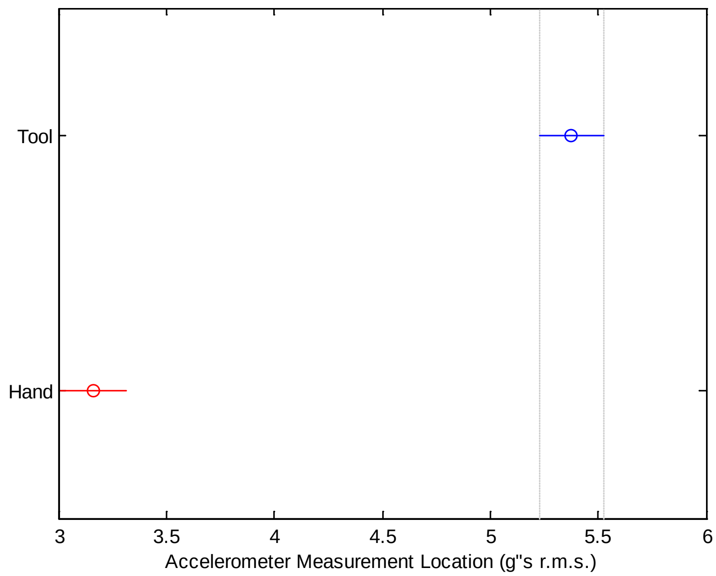

Figure 95. Visual representation of the differences in pair-wise means for accelerometer measurement location in g's comparing tool to hand measurements for 30N grip force in Three-minute runs

The 95% confidence interval for pairwise differences between the means was then found as seen in Table 32.

Table 32. Accelerometer Measurement Location in g's pairwise differences comparing tool to hand measurements for 30N grip force in Three-minute runs

Parameters	95% Confidence Intervals for Pairwise Differences in Means (g's)
Tool vs. Hand	$1.9104 \leq \mu_{Tool} - \mu_{Hand} \leq 2.5180$

4.4.2.6. Accelerometer Results for Location in ISO Frequency-Weighted Hand-Transmitted Vibration

The prior data was transferred to the ISO Frequency-Weighted Hand-Transmitted vibration values. As displayed in Figure 96 there is still a large variation between the vibration plate handle and the users hand. This is also indicated in the 95% confidence intervals (Tool: {7.645, 9.072}, Hand: {4.321, 4.871}).

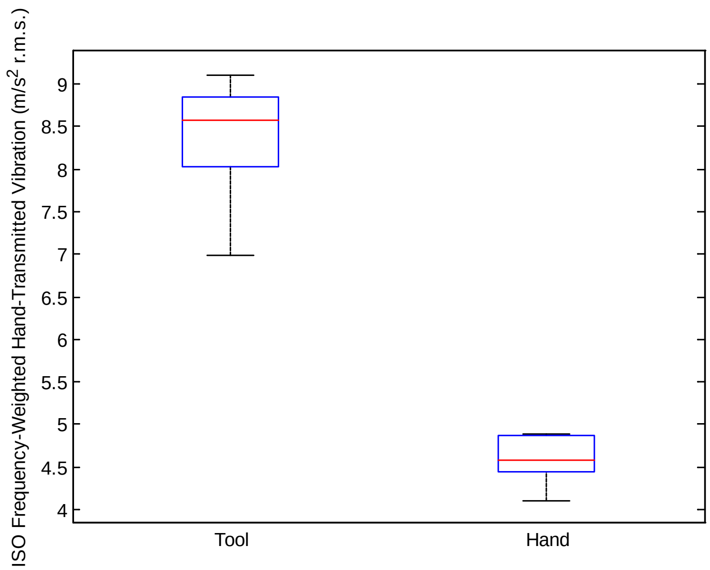

Figure 96. Results for distribution of the test data for accelerometer measurement location in ISO Frequency-Weighted Hand-Transmitted Vibration comparing tool to hand measurements for 30N grip force in Three-minute runs

The statistical analysis provided feedback that the results were significantly different ($p = 0.00$). The visual representation of these values can be seen in Figure 97 below. The ISO weighting gives results that the tool has higher vibrations than the hand when measured. Because of the frequency of the vibration plate, it is outside of the natural frequency range of the hand, so it will not get an amplified response.

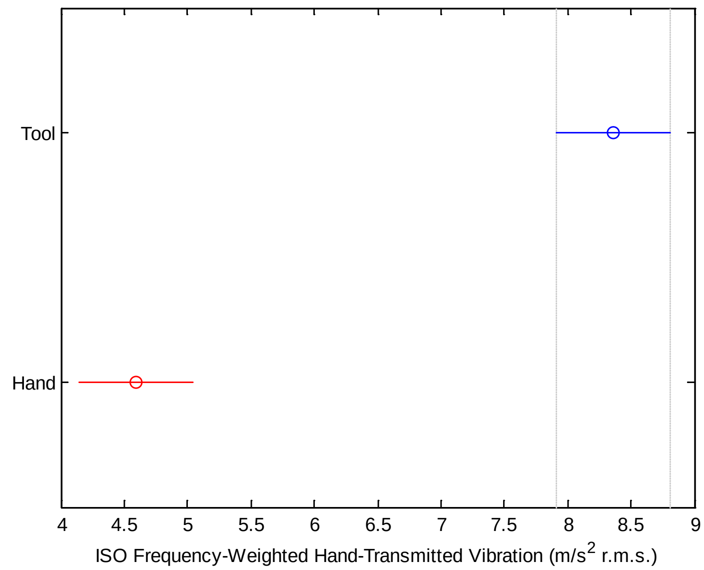

Figure 97. Visual representation of the differences in pair-wise means for accelerometer measurement location in ISO Frequency-Weighted Hand-Transmitted Vibration comparing tool to hand measurements for 30N grip force in Three-minute runs

From the results the pairwise differences in means 95% confidence intervals were calculated and tabulated in Table 33.

Table 33. Accelerometer Measurement Location in ISO Frequency-Weighted Hand-Transmitted Vibration pairwise differences comparing tool to hand measurements for 30N grip force in Three-minute runs

Parameters	95% Confidence Intervals for Pairwise Differences in Means (m/s^2)
Tool vs. Hand	$2.8633 \leq \mu_{Tool} - \mu_{Hand} \leq 4.6621$

4.4.3. Vibration Plate; Test Statistics Data Table

The overview of the impact driver statistical data for the vibration plate is displayed in Table 34 below. From this data, it was shown that as the grip force is increased on the vibration plate, there is a correlation between how much vibration the vibration plate measures and how much the user’s hand measures. With an increase in grip force, the vibrations seen on the vibration plate decrease while the hand increases and visa-versa.

Table 34. Test Statistic Data Overview of vibration plate

	Test statistic	95% Bootstrap Confidence Interval for $\tilde{x}$		Median	Std. Dev.
Intensity of Discomfort Felt by Hand Due to Vibration (rank score)	Grip_Force_45N	5	5	5	0
	Grip_Force_30N	4	4	4	0
	Grip_Force_15N	4	4	4	0
	Test statistic	95% Confidence Interval for μ		Mean	Std. Dev.
Variation in Grip Strength (%)	Grip_Force_45N	5.353	11.315	8.334	3.401
	Grip_Force_30N	3.499	8.739	6.119	2.989
	Grip_Force_15N	5.972	8.204	7.088	1.273
	Test statistic	95% Confidence Interval for μ		Mean	Std. Dev.
Accelerometer Measurement on Tool Handle in G's (g's r.m.s.)	Grip_Force_45N	4.832	5.209	5.0211	0.214
	Grip_Force_30N	5.178	5.576	5.377	0.226
	Grip_Force_15N	5.493	5.952	5.722	0.261

	Test statistic	95% Confidence Interval for μ		Mean	Std. Dev.
ISO Frequency-Weighted Hand-Transmitted Vibration on Tool Handle (m/s^2 r.m.s.)	Grip_Force_45N	6.832	8.727	7.78	1.081
	Grip_Force_30N	7.645	9.072	8.359	0.813
	Grip_Force_15N	8.122	9.553	8.838	0.816

	Test statistic	95% Confidence Interval for μ		Mean	Std. Dev.
Accelerometer Measurement on Hand in G’s (g’s r.m.s.)	Grip_Force_45N	2.723	4.2	3.461	0.842
	Grip_Force_30N	2.998	3.328	3.163	0.187
	Grip_Force_15N	2.332	3.366	2.849	0.59

	Test statistic	95% Confidence Interval for μ		Mean	Std. Dev.
ISO Frequency-Weighted Hand-Transmitted Vibration on Hand (m/s^2 r.m.s.)	Grip_Force_45N	4.237	7.292	5.764	1.743
	Grip_Force_30N	4.321	4.871	4.596	0.313
	Grip_Force_15N	4.027	4.575	4.301	0.312

	Test statistic	95% Confidence Interval for μ		Mean	Std. Dev.
Accelerometer Measurement Location in G’s (g’s r.m.s.)	Tool	5.178	5.576	5.377	0.226
	Hand	2.998	3.328	3.163	0.187

Accelerometer Measurement Location in ISO Frequency-Weighted Hand-Transmitted Vibration (m/s^2 r.m.s.)	Test statistic	95% Confidence Interval for μ		Mean	Std. Dev.
	Tool	7.645	9.072	8.359	0.813
	Hand	4.321	4.871	4.596	0.313

4.5. Tool Vibration Comparisons

In collecting all the data shown, it was important to relate this data to what companies are releasing to consumers. The company provided data was acquired from the tool manufactures for the same tools used through the performed experiments. The tests run by the company were similar in that they used a wood board for the test, cutting with the reciprocating saw. These runs are performed by companies and comply with the European Vibration Directive [24] measurement process. They do not specify the number of runs performed to get these results or how they weight their data though. As seen in Figure 98, the company provided center and variation are displayed along with the measured center and variation from these studies. The plotted data for the measured values was taken from the Primary Three-Minute reciprocating saw runs. It can be seen that the measured data is slightly higher than the company provided data. This would mean even if companies are using the higher limit of the company provided information for vibration dosage, employees could still be receiving a larger dosage then found acceptable by laws and health regulations. These measurements are measured on the users handle as described in standards such as EN61029.

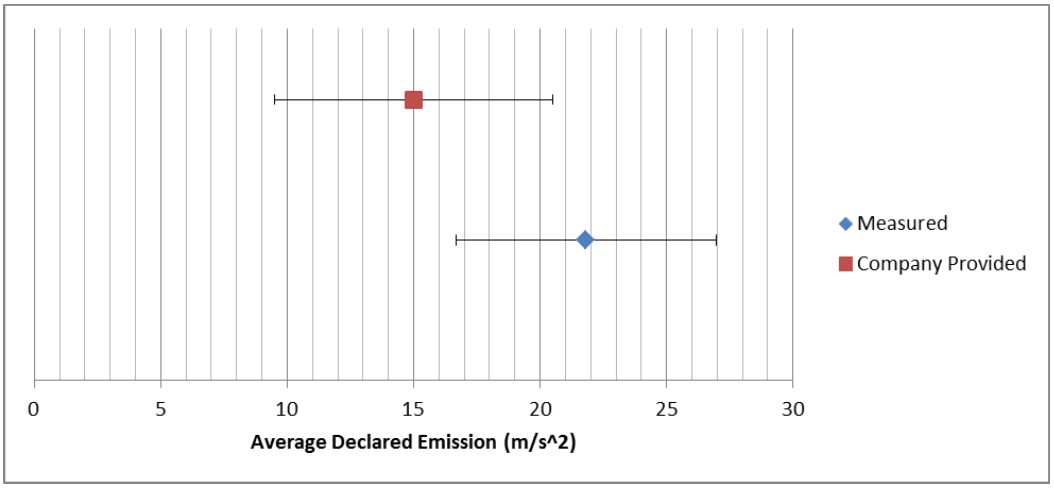

Figure 98. Primary Reciprocating Saw Measured Results vs. Company Provided Declared Emissions for Three-minute run

The impact driver was also reviewed and plotted against the provided company values, which can be seen in Figure 99 below. The measured data was significantly higher than the company provided data. This would show that employees are getting a much higher vibration dosage then companies are allotting.

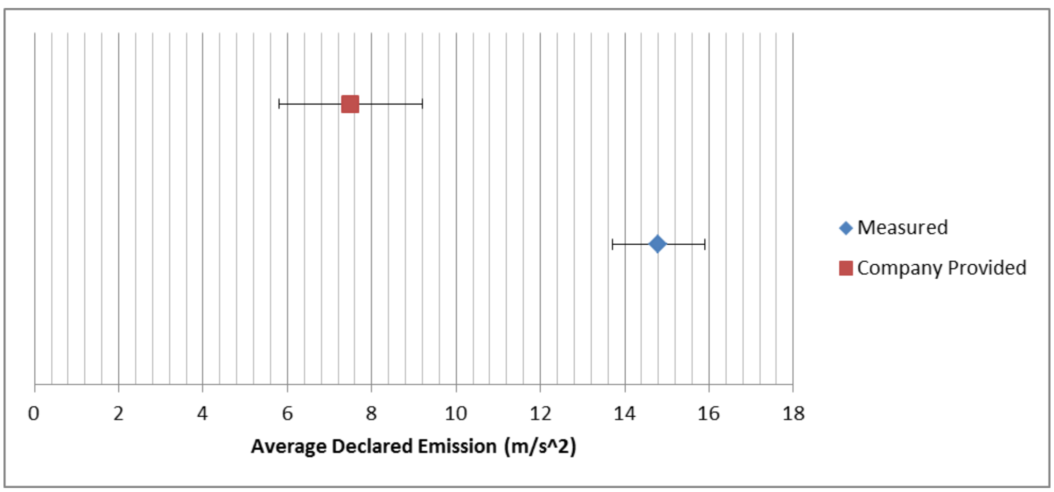

Figure 99. Impact Driver Measured Results vs. Company Provided Declared Emissions for Three-minute run

The measured data for the Three-minute runs was taken and placed in a table to compare. Table 35 below displays the vibration magnitude which was found from the experimental measurements. Using the exposure limit equations presented previously the EAV and ELV limits were calculated for each tool. It can be seen that the reciprocating saw tools all have a very short time period before companies are required to take action to reduce the vibration dosage their employee are receiving. Reducing the vibration is done with useful accessories such as vibration suppression gloves. Even the final ELV time at which point an employee would be required to stop using vibration emission tools for the day is not long when compared to how long employees are needed on job sites.

Table 35. Measured Tool Exposure Limits for Three-minute runs

Tool	Vibration Magnitude (m/s^2 r.m.s.)	Exposure points per hour	Time to reach EAV 2.5 m/s^2 A(8)		Time to reach ELV 5 m/s^2 A(8)	
			Hours	Minutes	Hours	Minutes
Reciprocating Saw	21.8	950	0	6	0	25
Brand 1 Reciprocating Saw	21.46	921	0	7	0	26
Brand 2 Reciprocating Saw	22.35	999	0	6	0	24
Impact Driver	14.8	438	0	14	0	55
Vibration Plate 30N	8.35	139	0	43	2	52

In order to give a better representation of how the tools lay on the vibration limit scale, Figure 100 gives a visual representation of the vibration magnitude vs. how long an employee would be able to use it. The green is below the EAV value which companies are required to take any action. The yellow it between the EAV and the ELV value, where companies are required to try and reduce the amount the employee is receiving. Finally, the red is above the ELV value, which employees would no longer be able to work that day.

Vibration magnitude m/s²	15 m	30 m	1 h	2 h	3 h	4 h	5 h	6 h	8 h	10 h
40	800									
30	450	900								
25	315	625	1250							
20	200	400	800							
19	180	360	720	1450						
18	160	325	650	1300						
17	145	290	580	1150						
16	130	255	510	1000						
15	115	225	450	900	1350					
14	98	195	390	785	1200					
13	85	170	340	675	1000	1350				
12	72	145	290	575	865	1150	1450			
11	61	120	240	485	725	970	1200	1450		
10	50	100	200	400	600	800	1000	1200		
9	41	81	160	325	485	650	810	970	1300	
8	32	64	130	255	385	510	640	770	1000	1200
7	25	49	98	195	295	390	490	590	785	865
6	18	36	72	145	215	290	360	430	575	720
5.5	15	30	61	120	180	240	305	365	485	605
5	13	25	50	100	150	200	250	300	400	500
4.5	10	20	41	81	120	160	205	245	325	405
4	8	16	32	64	96	130	160	190	255	320
3.5	6	12	25	49	74	98	125	145	195	245
3	5	9	18	36	54	72	90	110	145	180
2.5	3	6	13	25	38	50	63	75	100	125
2	2	4	8	16	24	32	40	48	64	80
1.5	1	2	5	9	14	18	23	27	36	45
1	1	1	2	4	6	8	10	12	16	20
	Daily exposure time									

Figure 100. Vibration Magnitude vs. Daily Exposure Time [11]

As discussed before, the different parts of the human body have different natural frequencies. When these vibrations are matched with something such as a power tool being used; it amplifies the vibration amount seen to that part of the body. From Figure 101 below it is shown that the hand gripped is between 150Hz-200Hz while the lower arm is 16Hz-30Hz. Depending on the type of power tool used, different parts of the human body natural frequencies could be matched and could lead to health problems.

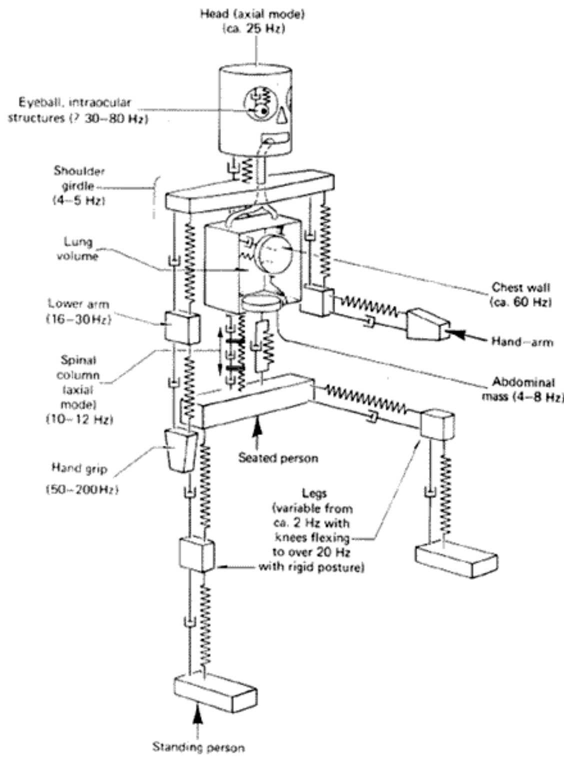

Figure 101. Human Body Natural Frequencies [12]

4.6. Vibration Dosage Life-Time Effects

The long term effects of vibration dosage to the human body are what safety groups, doctors, and workers themselves worry about. Even with safety regulations and standards being followed, over time the body's tissues and well-being can suffer. There have been many studies done on measuring vibrations and visually following what happens, but each person can be slightly different in their body structure or how they react to the vibration dosages. One of the ISO standards in 2001 graphs the likeliness of seeing first signs of white finger in the workers given vibration dosages over time as seen in Figure 102 below. As an example, if you were to look at a reciprocating saw, which companies claim have around 15 m/s^2 r.m.s. weighted acceleration value, after 2 years of continued use health problems could start to occur in some workers. From the measured value taken from above of 22 m/s^2 for the same reciprocating saw companies claimed have 15 m/s^2, the time for that would be around 1.25 years of use, which is significantly less time than prior.

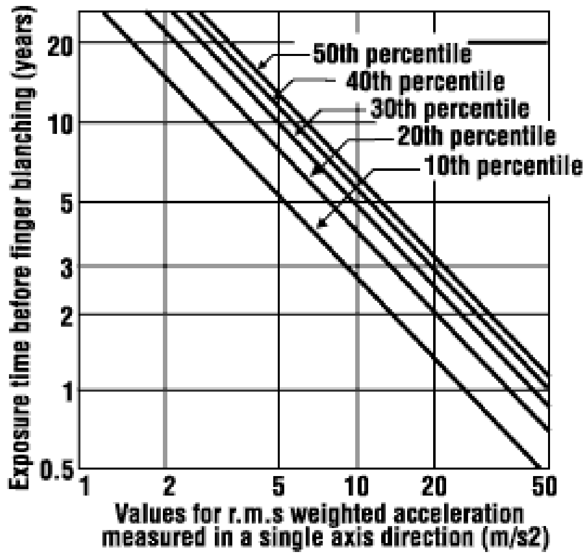

Figure 102. Curves for exposure times of percentiles of population groups (ISO 5349) to suffer mild effects on tip of finger [19]

There are many other vibration factors which can play a part in workers' health as shown in Figure 103. Most of these effects are permanent once a worker reaches a certain exposure value of vibrations, however, the exact vibration dosage value can vary from worker to worker.

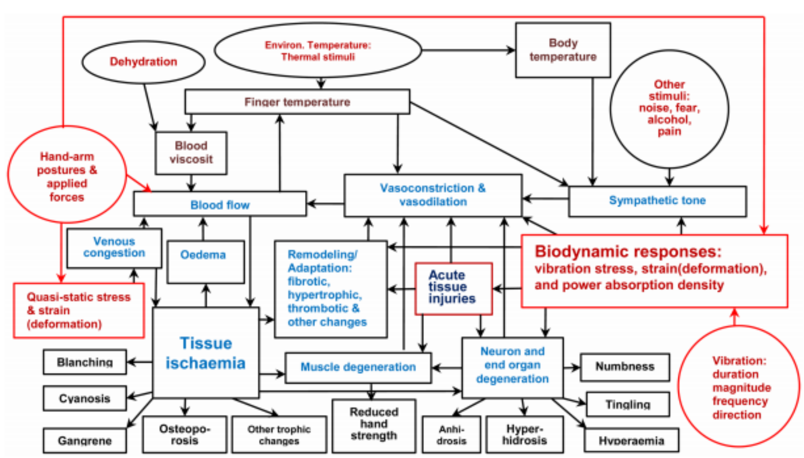

Figure 103. Hypothetical model of vibration-induced vascular disorders [20]

In a study investigating the white finger claims of construction workers it was found that a large percentage of construction workers had symptoms leading to health issues. As displayed in Figure 104 it can be seen that between these two groups of workers, who would be using similar tools as tested in the results, that various stage of symptoms exist. The average exposure time for the grinders was 2.5 hours per day, 200 days per year, for 21 years. While for the mechanics their average exposure time was 2 hours per day, 200 days per year, for 23 years.

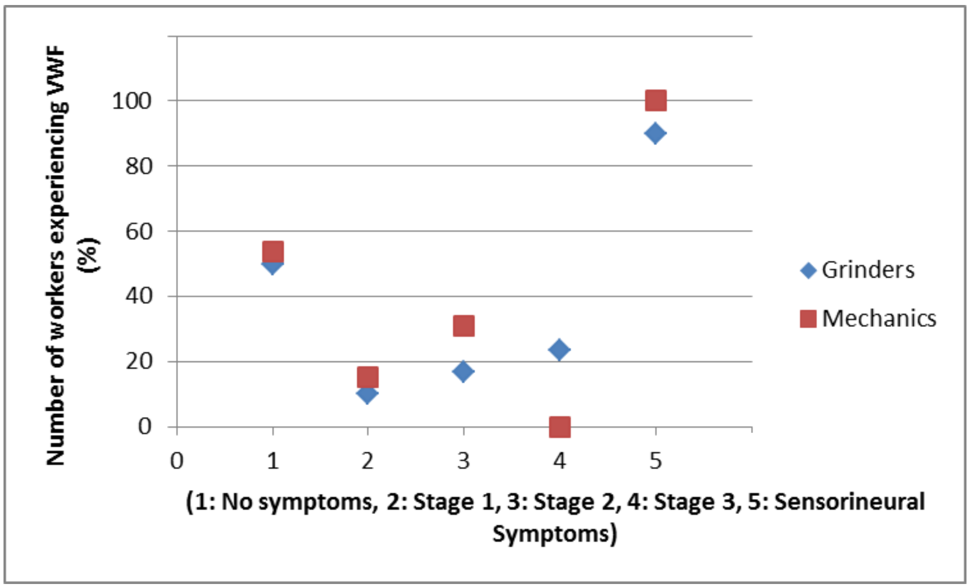

Figure 104. Characteristics of worker types to percentage containing VWF Symptoms [8]

One of the major findings here is that if companies are using the tool acceleration values given by manufactures, the output vibration dosage is seen to be higher than what is claimed. Other European evaluations also claim, in some cases, the value manufactures give is lower. [26] A comparison of our study to the manufacture is shown in Table 36.

Table 36. Manufacturers given tool vibration dosage vs. our study for primary reciprocating saw [25]

	Manufacturer		Our Study			
	EAV	ELV	EAV	ELV	EAV	ELV
Tool acceleration r.m.s. (m/s^2)	15		21.8			
Daily usage (minutes)	12	50	12	50	6	25
A(8) (m/s^2)	2.5	5	2.5	5	2.4	5
Lifetime from ISO (years)	11	5.5	11	5.5	11	5.5
Number of working days/year	200					
Lifetime Dose ((m^2h^3/s^4)/10^7)	21.7 x 10^7	22.6 x 10^7	46 x 10^7	47.9 x 10^7	23 x 10^7	23.9 x 10^7
Likelihood of VWF Incidence (%)	13.6	13.8	16.4	16.6	13.8	13.9
Lifetime dose for 7% Incidence	14.9 x 10^7					
Daily Usage time for 7% Incidence (minutes)	0.8	3.3	0.4	1.5	0.4	1.5

The tool acceleration is what the manufacture provides to companies to calculate the vibration dosage a worker would endure. The daily dose is continual usage of the tool or the time the worker is actually operating the time. These times were calculated using the vibration dosage calculator [11] for the exposure action value (EAV) and exposure limit value (ELV). The A(8) is the total acceleration dosage the user would receive in a given work day. Lifetime from ISO is taken from the ANSI exposure chart for number of years someone could operate the tool under the specified A(8) values. [25] Finally the lifetime dose is calculated by the following equation. Where $a_{h,w}$ is the frequency weighted acceleration measured on the tool (m/s^2), t_h is the individually estimated daily exposure (h/day), t_d is the number of working days/year, and t_y is the number of years worked with the tool. If more than one tool was used the summation of each calculated dosage would be taken.

$$\sum (a_{h,w} * t_h)^{0.5} * t_d * t_y)^2 \; m^2h^3/s^4$$

With the lifetime dosages calculated, compared to Figure 105 below, it can be seen that the workers have approximately a 14% chance of occurrence for VWF. This is following all European health regulations of not going past the ELV and still there is risk of having health problems for workers.

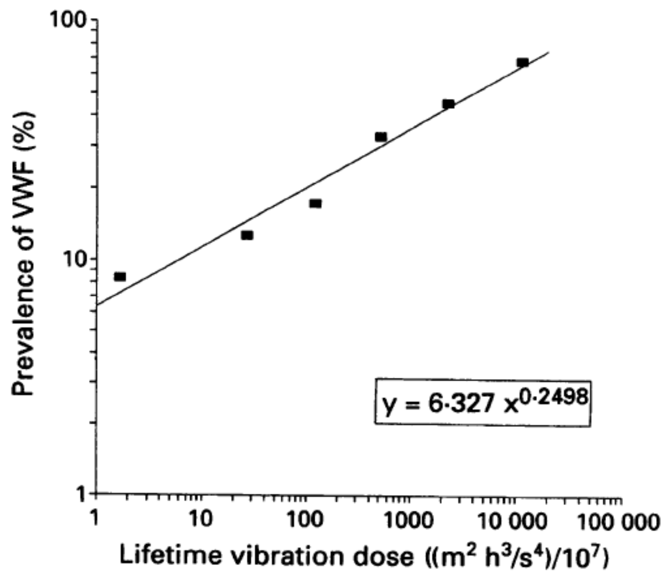

Figure 105. Relation between the prevalence of VWF and the estimated lifetime vibration dose to construction workers [2]

Imagine a scenario that may exist in today's workforce; if companies are taking the manufacture vibration emission values and using these to calculate the dosages, their employees will be receiving more dosage than they expect to in their lifetime. The longer use time frame calculated from the manufacture data with the higher vibrations emitting from the tool gives a lifetime exposure dose of 46 x 10^7 m^2h^3/s^4. Taking another look at Figure 105 this now places employees at 17% occurrence of VWF. It is critical that the dosage values are properly calculated for companies to use in order to keep their employees safe.

Not much is known between the exact correlation of health and vibration dosage. There have been biopsy studies done on patients with vibration-induced white finger. [9] These workers were known to use chain saws and pneumatic hammers over a range of 5 to 23 years with a mean of 17 years. The findings from these biopsies are shown in Table 37. These grade rankings follow the Stockholm Workshop classification scale. Where a grade of 0 would mean exposure to vibration buy no symptoms and grade 3 would be intermittent or persistent numbness, reduced tactile discrimination and/or manipulative dexterity. [1]

Table 37. Pathohistological changes in small arteries of workers with VWF [9]

Pathological change	Biopsies from VWF patients[a] (N = 60)				Biopsies from referents[a] (N = 7)	
	Grade 0	Grade 1	Grade 2	Grade 3	Grade 0	Grade 1
Increase of adventitia	—	5	22	33	7	—
Thickening of media						
Hypertrophy of muscle	—	2	9	49	7	—
Increase of collagen	36	24	—	—	7	—
Destruction of internal elastic layer (T elastica interna)	54	1[b]	2[b]	3[b]	7	—
Intimal sclerosis	39	17[b]	4[b]		4	3[b]

[a] Grade 0 = no change, grade 1 = minor change, grade 2 = moderate change, grade 3 = severe change. NOTE: 3 = the most intensely increased thickness of the musle layer of about threefold or more, 2 = a moderately increased thickness of about twice or more, 1 = increased thickness of less than twice.
[b] With arteriosclerosis.

Future work is needed to help relate the exact association between the pathological changes as time dependent variables for exposure to vibration emitting devices.

The energy which a power tool directs into a workers hand is another effect which can have a negative impact health. This energy can be found using various setups which measure the acceleration and grip force. The amplitude of the energy dissipated through the workers hand and arm from damping is shown below. [27]

$$E_D = \frac{\ddot{X}^2 \sin \emptyset}{2w^4 \, X/F}$$

In this equation E_D is the amplitude of energy dissipated. The frequency is represented by w in radians/second. X is the measured amplitude of acceleration at w (m/s^2). X/F defines the dynamic compliance (m/N). Finally, ∅ is the radians.

Knowing what amplitude of energy is dissipated through the workers hand, it is also important to know the energy stored in the workers hand. This kinetic and potential energy is transferred back and forth between the vibrating power tool and the workers hand.

$$E_S = \frac{\ddot{X}^2 \cos \emptyset}{2w^4 \, {}^{X}\!/_{F}}$$

To accurately account for everything in a workers hand and arm, each component needs accounting for such as skin, bone, muscle, and many others. This creates a very complex system which needs further studies performed in order to help determine the dosages and health effects which workers may face when using power tools.

Chapter 5. Conclusion

Millions of people are exposed to vibration emitting power tools every day; this is a large risk to workers health. The lack of regulation and safety for power tool vibration dosage in the United States cannot continue. The studies performed on rat tails and human worker subjects show there is a need for regulation. [6] It is clear that vibration dosage from power tools correlates to various diseases as shown through this report. The standards for measuring power tool vibration and weighting them for various human body parts natural frequencies have been well established in the United States. It is now time for companies to follow guidelines to protect the workers dealing with vibration emitting equipment on a daily basis.

Measured

Through this study popular power tools such as the reciprocating saw and impact driver were selected in order to analyze their vibration dosage and short term effects to the human body. Various models of the tools were examined along with other vibration impacting factors such as vibration suppression gloves and cut times. Finally, a lab-fabricated vibration plate was used in order to have a controlled experimental setup for testing grip strength.

In the experiments performed with the primary reciprocating saw, it was found that hand color and grip strength loss percentage are related to the duration of use times, with longer times resulting in worse hand color and increased grip strength loss. It was also established that the longer duration of tool use leads to precision loss as seen by the line tracing tests. The overall hand discomfort is directly related to tool use duration. The vibration measurements found that as cut time increases the g's recorded decreases due to material shifting time breaks; however, the ISO weightings when measuring on the tool are not affected. The location of measurement was found to produce significantly different values in g's but not once the ISO frequency weighting was taken into consideration. The vibration suppression gloves did assist in reducing the vibration felt by the user, however they did not present grip strength loss or precision loss. Finally, the measurements of vibration taken on the arm, do show significantly different values when plotted with g's, but further analysis is needed with ISO weighting frequencies taken into account to include how the human body's natural frequencies play a part in vibrations seen.

The various brands of reciprocating tools demonstrated that similar tools can have significantly different outcomes when it comes to retaining grip strength, precision, and overall hand discomfort. As mentioned before, ergonomics can play a large part in how comfortable the tool is overall as the user is cutting. The weight of the tool also plays a large role in fatigue as cut times increase. The vibration measurements were also significantly different between the tools, which could be due to speed of cut or power. Once the ISO weighted frequencies were considered the tools were much closer. The measurements between the tool handle and hand demonstrated that it is possible for the hand to have an overall higher vibration dosage than the tool due to ISO weighting and considering the natural frequencies of the human hand. This is important when considering companies current standards for vibration measurement are to only have measuring point directly on specific parts of the tool and none on the human performing the actions. The impact driver followed the overall same findings as the reciprocating saw, but with all around lower vibration levels.

The vibration plate established an important point that as the grip strength increases, the tool vibration decreases. This could further be studied to discover at what grip strength the hand match exceeds the tool vibration values being recorded.

Available Data

A vital discovery was that the vibration emission values for power tools obtained from companies did not directly match our measured values. The experiments performed in our setups were similar to those done in industry when measuring vibration. When taking these vibration emission results and calculating how long a worker can use the tool for before reaching their dosage limit, the exposure limit value varied greatly depending on the initial vibration level used. As discussed, the prevalence of VWF can change from 14% to 17% when an incorrect vibration emission level is used to calculate how long a worker can use a particular power tool.

Damage Evidence Available

Finally, depending on the vibration emission of the power tool, it does not take much to reach the vibration exposure limit value of high vibration tools. This is important for workers to know about to protect their health. If the vibration dosage is not limited, or even while being limited, use for prolonged periods of time can have a large impact of the wellbeing of that worker. This was demonstrated with the cadaver biopsy reports presented. The increase in thickened small arteries with medial muscular hypertrophy and perivascular fibrosis leads to problems as seen with vibration-induced white finger disorder. [9]

Chapter 6. Future Directions

With many conclusions leading to vibration emissions affecting the health of the human body, there is a strong need for studies to continue. Reviews between vibration levels, perfusion, and damage to musculoskeletal all have gaps missing such as short-term and accumulated effects. The relation between short term and long term damage to the human body is needed to help assess the current ISO ratings in place to protect those operating vibrating equipment. With our results indicating a higher level of vibration emission than specified by manufactures, it leads to a new policy possibly needing to be placed by a government organization which would monitor and rate the true vibration emissions coming from power tools. The need to also adjust the current ISO limits for use over a lifetime is in need of review by the results presented. With possible new VWF studies being completed, new damage threshold times may be required. These future research areas can help to save many workers health problems through their career.

Appendices

Appendix A. Vibration Testing Documentation Form

Date: ______________ Time Started: ______________ Duration: ____________

Temperature: ______________ Humidity: _________________ Noise: ______________

Writing: UNIVERSITY OF MARYLAND

Before:

____

Line:

After:

____

Line:

Grip Strength Before: _________________________

Grip Strength After: __________________________

Number of Cuts: ____________________________

Hand Notes:

Hand Rank Score (1-10): ________________

(1- No Vibration, 10- Max Vibration)

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