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The Effect of Aircraft Manufacturing Riveting Tools on Hand-arm Vibrations and Muscle Fatigue

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THE EFFECT OF AIRCRAFT MANUFACTURING RIVETING TOOLS ON HAND-ARM VIBRATIONS AND MUSCLE FATIGUE

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ABSTRACT

The overall objective of this research was to compare four types of rivet guns varying by manufacturer and piston material (Tungsten vs. Steel), two rivet gun handle positions (Horizontal and Vertical), and three bucking bars including two with similar dimensions bars made of tungsten and steel, and a Honsa new technology spring dampener and tungsten combined bucking bar based on their impact on hand-arm vibrations and the effect of these vibration levels on muscle fatigue. This objective was covered in three parts. The first part consisted of examining the impact of these factors on riveters' vibration exposure and muscle fatigue, the second part of studying the impact of these factors on buckers' vibration exposure and muscle fatigue, and the third part of examining the impact of these tools on the joint vibration exposure of riveters and buckers. The vibration exposure was quantified using the unweighted-frequency acceleration Root Mean Square (RMS), and the muscle fatigue was determined by the percentage Maximum Voluntary Contraction (MVC) of Electromyography and the perceived level of exertion (Borg Scale). A laboratory experimental study involving 10 male participants (5 riveters and 5 buckers) was conducted. Each pair of participants performed all 24 experimental trials (4 rivet guns x 3 bucking bars x 2 rivet gun handle positions) in 2 days. The task consisted of setting at least 5 rivets in 30 seconds. The results show that the use of the different rivet gun types and gun handle positions had an effect on both the riveters and buckers' vibration exposure and respective major arm muscle fatigue, specifically the brachioradialis muscle for riveters and the palmaris longus muscle for buckers. However, the factor bucking bar type did not seem to have a significant impact on the riveters' vibration exposure and muscle fatigue. We recommend the use of rivet gun type 4 as it led to 43.27 % less buckers and riveters' joint vibration exposure compared to gun types 1 and 2, 56.7 % less riveters' brachioradialis muscle fatigue and 52.1% less buckers' palmaris longus muscle fatigue

compared to gun type 3. We also recommend the use of the spring dampener and tungsten combined bucking bar as it led to 24.46 % less buckers and riveters' joint vibration exposure, 64 % less major arm buckers' muscle fatigue, and kept the muscle fatigue experienced by the riveters to a minimum compared to the steel and tungsten bucking bars.

CHAPTER 1. INTRODUCTION

Hand Arm Vibration Syndrome is an occupational illness that affects a large portion of the workforce around the world. Approximately two million US workers experience hand-arm vibration in their workplace, and experts predict that around half of them will contract Hand-Arm Vibration Syndrome (HAVS) in the long term (Trotto, 2015). The UK medical research council reports in 1999 that around 4.9 million workers were exposed to Hand -Transmitted Vibration (HTV) in a week and a total of 288, 000 people were affected by HAVS in Great Britain alone (Palmer et al., 1999). This disease is generally associated with changes in muscles, bones, joints, vascular and nervous systems (Ayers & Forshaw, 2010). Studies also reported a strong correlation between HAVS and other illnesses such as carpal Tunnel syndrome (Palmer et al., 1999). For instance, Koskimies et al. (1990), after examining 125 forestry workers with carpal tunnel syndrome and with exposure to vibration, found that 43% of those workers had numbness of the hands, 15% experienced muscle strength reduction in their hands, and 27% had HAVS or Raynaud's phenomenon. In addition to studying HAVS impact on the physical health of workers, researchers have also examined the psychological and social state of workers affected by HAVS. Ayers and Forshaw (2010) in their study of the psychological ramification of HAVS found that male workers with this condition struggle with their inability to provide for their family not only financially, but also in daily home activities. They are in constant fear of losing their employment and face the fiscal implications for their future life. They are also frustrated to be unable to perform

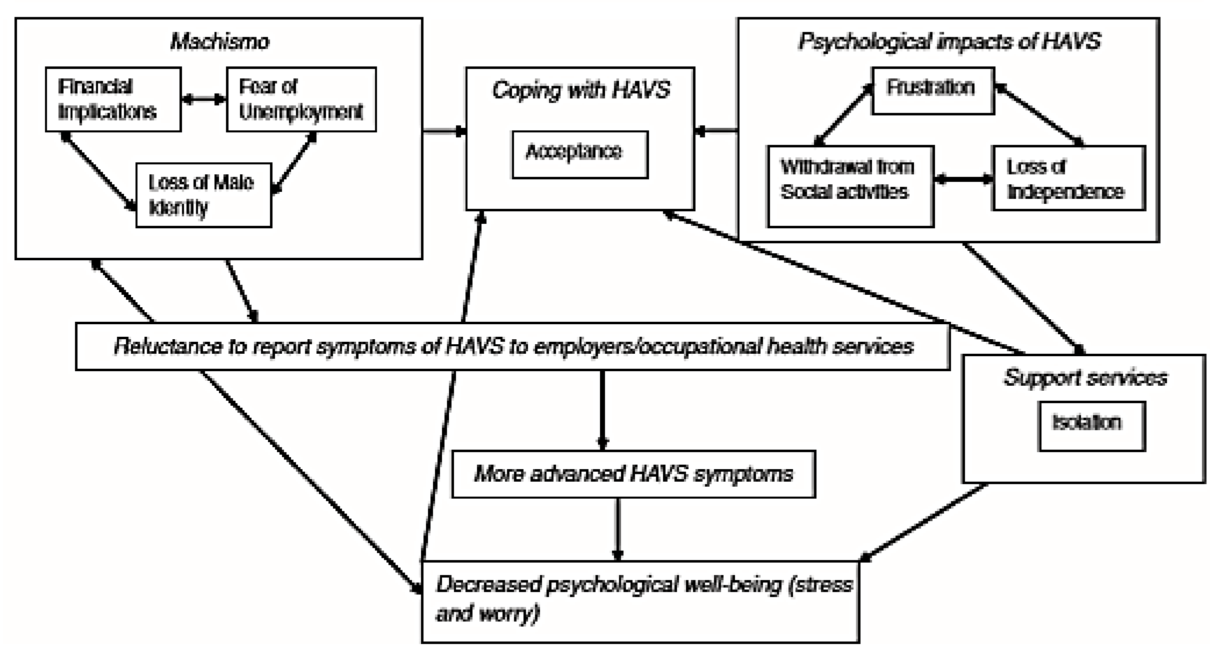


Figure 1. A Model of Interconnected Themes (Ayers & Forshaw, 2010)

certain tasks and enjoy the activities or sports that they used to practice in the past. These psychological effects of HAVS are summarized in the above model.

Although the impact of HAVS has been widely studied over the years, it is still important to expand our understanding of this disease by studying the common health risk exposures by occupation, by industry, and more specifically by the type of tools used in order to generate sufficient data for future improvement (Palmer et al., 1999).

Workers in construction are the most vulnerable to HAVS followed by workers in mining, forestry, foundry, automobile assembly and metal-working trade with the use of tools such as grinders, riveters, drills, jackhammers, and Chain saws (Chetter, Kent, & Kester, 1998; Trotto, 2015).

Pneumatic riveters are used in aircraft, automobile, agricultural equipment, and locomotive manufacturing as well as in construction and metal fabrication (US Dept of Labor, 2000). They are simultaneously used with a heavy tool called bucking bar. The riveting process often involves two people; one person on one side of the metal sheets holding the rivet gun and the other person on the other side holding the bucking bar. First, the rivets are inserted through pre-drilled holes. Then, a rivet gun combined with a rivet setter that matches the rivet head is used to set the rivet against the bucking bar which is held firmly perpendicular to the metal sheets by the bucker on the other side. Workers involved in such operations are exposed to a very high vibration level. According to ISO 5349-2 (2001), pneumatic hammers can produce a maximum acceleration ranging from 20,000 to 50,000 m/s^2. This high magnitude of vibrations can be easily transferred to the hand and finger of workers leading to hand-arm vibration-related illnesses. In addition to the exposure to high vibration frequency and amplitude level, these workers especially the buckers are at risk of forceful exertion, repetitive motion, awkward hand, and finger posture while holding the bucking bar (Kattel & Fernandez, 1999). The combination of high exposure to vibration and overexertion in riveting activities can cause drastic injuries. It is necessary to quantify and minimize workers' exposure to vibration in this industry. Several researchers have investigated the vibration magnitude emitted during riveting activities. Some of them compared different types of rivet guns varying by size, hammer material (Tungsten vs. Steel), design (Dampener vs Regular), and others focused on the bucker side by comparing different material of bucking bars (Tungsten vs Steel), different design (Spring dampener vs Regular), and other alternatives such as adding a handle or using antivibration gloves (Hull, 2007; Jorgensen, Khan, & Polsani; Jorgensen & Viswanathan, 2005; Kattel & Fernandez, 1999; T. W. McDowell, Warren, Xu, Welcome, & Dong, 2015; T. W. McDowell, Xu, Warren, Welcome, & Dong, 2018). However, few researches have discussed the vibration level emitted using different combinations of bucking bars and rivet guns as well as the vibration transmission when changing the rivet gun handle position. With the fast advancement of technology, there is always a need to study the newly designed tools and investigate their effect on workers. The objective of this study was to 1) quantify and compare the vibration transmitted to the hand and wrist of riveters when using different types of rivet guns with different bucking bars, and different rivet gun handle position, as well as the effect of these vibration levels on muscle fatigue, 2) quantify and compare the vibration level transmitted to the bucker's hand when using different bucking bars with different rivet guns, and rivet gun handle positions, and the relative effect of these vibration levels on muscle fatigue, and 3) quantify and compare the impact of these tools on the joint vibration exposure of riveters and buckers as well as their respective muscle fatigue.

CHAPTER 2. LITTERATURE REVIEW

Vibrations can be grouped into two categories which are whole-body vibration and segmental vibration including hand-arm vibration. Both types of vibrations have been described by studies as either beneficial or detrimental to human' s health. While whole-body vibration has been correlated with muscles' strength and described as an effective way to address diseases such as sarcopenia and osteoporosis, it has also been associated with musculoskeletal disorders such as spinal trauma and lower back-pain (Cardinale & Pope, 2003).

2.1. THE EFFECT OF VIBRATION ON WORKERS' HEALTH

2.1.1. WHOLE-BODY VIBRATION

Whole Body Vibration (WBV) happens when the body is on a vibrating surface. Heavy vehicle operators such as bus and truck drivers, armored vehicle drivers, and helicopter pilots are the most affected by WBV with a considerable percentage reporting back pain. Teschke et al. (1999) report several back abnormalities associated with the driving occupation including lumbago, sciatica, generalized back pain, and intervertebral disc herniation and degeneration. These disorders are not the result of vibration alone, but several other factors including working posture. Several other researchers have investigated different vibration factors that could affect humans' health. Nakashima (2004) reports that duration, frequency, and magnitude of vibration are important factors in determining the effect of vibrations on the human body. Alizadeh-Meghrazi et al. in their investigation on the effect of whole-body vibration on lower-limb EMG activity in subjects with and without spinal cord injury found that the amplitude factor of WBV have the greatest impact on lower limb EMG activation followed by the frequency parameter. They concluded that employing WBV with the adjustment of these parameters can help in the treatment of muscles and bone degradation in patients affected by traumatic spinal cord injury (2014).

2.1.2. HAND-ARM VIBRATION AND RAYNAUD'S PHENOMENON

Segmental vibration occurs when a body part is in direct contact with a vibratory tool or equipment. This type of vibration primarily affects the body part used to operate the tool, but can also be transmitted to and affect other parts of the body. Segmental vibration is very often associated with Hand-Arm Vibration Syndrome also called Raynaud or white fingers' phenomenon. It is a medical condition that is caused by prolonged contact with vibratory tools (House, 2010). The risk of contracting this disease is mostly influenced by the intensity, frequency, and duration of vibration exposure. House (2010) reported that workers in constant contact with vibrating surfaces can take from 6 weeks to 14 years to develop HAVS depending on the magnitude or intensity of the vibration. For instance, Miyashita et al. (1983) report that, in forestry workers, the symptoms related to Hand-Arm Vibration Syndrome generally appear after 2000 hours of exposure, but for more than 50 % of those workers the symptoms appear after 8000 hours of exposure.

HAVS is associated with vascular, neurological, and musculoskeletal anomalies (House, 2010). The vascular aspect is manifested by the blanching of the fingers, starting at the tip of the most affected finger and expanding to other fingers or even the whole hand as the condition worsens. Very severe cases involve a decrease in blood supply that may result in trophic changes in the fingers. This may cause the apparition of gangrene in those areas and later results in loss of digits (House, 2010). Workers exposed to vibrating tools are also at risk of developing thrombi in the arteries in the hands (Thompson & House, 2006). The neurological aspect of HAVS refers to the damage of the sensory nerve fibers and skin mechanoreceptors in the fingers, producing digital sensory neuropathy which is mostly manifested by finger numbness and tingling (House, 2010). There is evidence that Carpal Tunnel Syndrome (CTS), caused primarily by awkward wrist posture, forceful and repeated wrist movement, can also be affected by hand-arm vibration. After assessing 162 patients for HAVS, Lander et al. (2007) found out that 33% of those patients had CTS and 11% had ulnar neuropathy. HAVS is also associated with musculoskeletal abnormalities such as necrosis, fibrosis, structural disorganization, and motor nerve injury with secondary muscle denervation which might be related to a decrease in grip strength (Necking, Lundborg, Lundstrom, Thornell, & Friden, 2004).

Similarly, Lin et al. (2005) describe three stages of hand-arm vibration disease. In the first stage, only the tip of one or more fingers is affected including periodic pain or numbness and swellings. In the second stage, the digital and middle phalanges of one or more fingers are occasionally affected by Vibration White Finger (VWF) including a slight atrophy of hand muscles, neuron damages, and some Electromyography (EMG) abnormalities. In the third and last stage, there are frequent attacks of VWF affecting all phalanges and sometimes the whole hands. Severe hand deformations are often observed as well as acute EMG change.

As summarized above, Hand-Arm Vibration Syndrome (HAVS) is a condition that leads to vascular, neurological, and musculoskeletal abnormalities ranging from minor to severe depending on the time exposure, frequency, and intensity of the vibration. Therefore, it is important to better understand and quantify the vibration level experienced by workers in different industries. The primary objective of this study was to quantify and compare the vibration level experienced by workers in aircraft manufacturing while using different combinations of rivet guns and bucking bars.

2.1.3. Standards for Vibration Exposure

The American National Standards Institute (ANSI) standard S2.70 (2006) evaluates the health risk of hand-arm vibration based on two main values which are the frequency weighted RMS acceleration Daily Exposure Action Value (DEAV) and Daily Exposure Limit Value (DELV). These values, which are set to 2.5m/s2 and 5 m/s2 respectively, for an 8-hour exposure in any of the x, y, & z-axis, refer to limits at or above which the workers become vulnerable to high health risk, and start displaying abnormal symptoms. It is therefore important to use effective engineering controls in the design of vibrating tools to keep the vibration level below the health risk zone (Figure 2) or to use appropriate PPE such as special gloves to reduce workers' exposure to high vibration levels for tools already in use. Riveters and buckers are among those exposed to vibration level in the health risk zone with frequency-weighed (6.3-1250 Hz) acceleration ranging between 10-11 m/s2 (Jorgensen & Viswanathan, 2005).

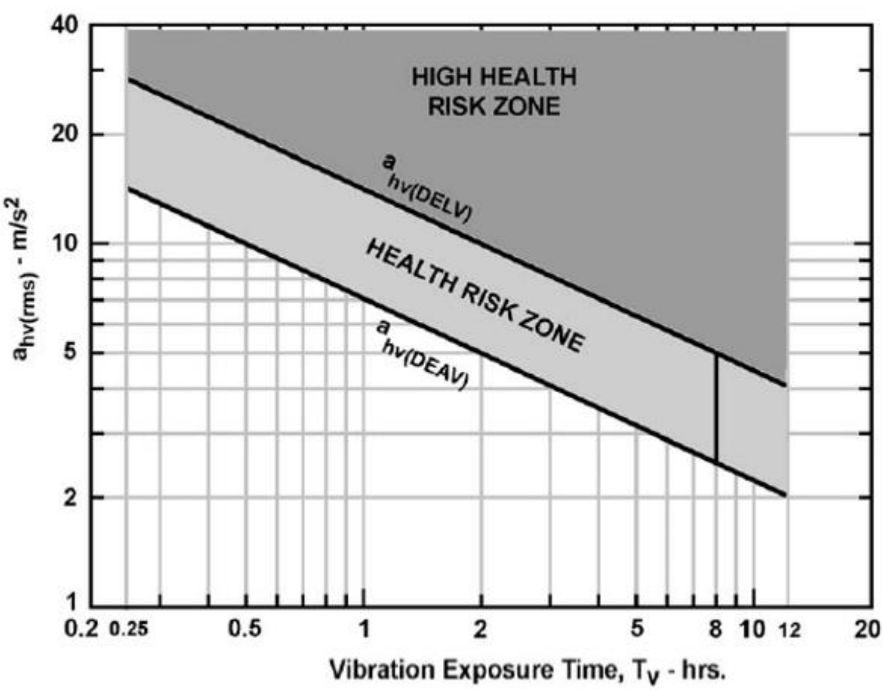


Figure 2. ANSI Health Risk Zones for DEAV and DELV (Wilhite. C., 2007)

However, Dandanell & Engström (1986) found that these workers are exposed to acceleration frequency far above 1000Hz and are therefore exposed to higher risk than what is communicated in the ISO 5349 standards. It is necessary to account for these high acceleration frequencies to better estimate workers' health risk exposure in this industry.

2.2. RIVET GUNS AND VIBRATIONS

Researchers have studied several factors influencing the vibrations emitted by rivet guns such as the rivet gun manufacturer, size, and hammer material (Tungsten vs. Steel) as well as the wrist position and force applied while riveting (Jorgensen et al.; Kattel & Fernandez, 1999). For instance, Kattel and Fernandez (1999) investigated the effect of rivet gun manufacturers (1, 2, 3, and 4), sizes (Small, Medium, and Large), wrist positions (neutral, 1/3 maximum flexion, and 1/3 maximum ulnar deviation), and applied force (8 and 12 lbs.), and concluded that the largest rivet gun from manufacturer 4 produced a significantly higher level of vibration compared to the other tools. The acceleration data along different axis gave different results. Along the x-axis, the neutral and 1/3 max. flexion wrist position produced significantly higher RMS value than 1/3 max. ulnar deviation. However, along the y-axis, the neutral posture of the wrist had significantly higher RMS value than the 1/3 max. flexion and 1/3 max. ulnar deviation wrist posture. The applied force was also significant along the y-axis with 8 lbs. producing significantly higher RMS values than 12 lbs. Only the applied force was significant along the z-axis with the RMS values associated with the applied force of 8 lbs. being significantly higher than the RMS values associated with 12 lbs. Considering the frequency-weighted acceleration sum at the coupling for all three axes, wrist posture, rivet gun manufacturer, rivet gun size, and interaction between rivet gun manufacturer and size were found statistically significant. Further statistical analysis revealed that the neutral posture of the wrist produced a significantly higher value of acceleration than max. flexion and max. ulnar deviation. The interaction effect shows that of all the size categories, type 4 had the highest vibration level compared to the other three types.

In a report by HumanTech, Inc. (2010), the vibration level generated by 4 different types of rivet guns (Chicago Pneumatic, Ingersoll Rand, Honsa Ergonomic Technologies with Steel Piston, and Honsa Ergonomic Technologies with Tungsten Piston) were compared. Level 6 rivet size (3/16") was used in this study. The results show that both Honsa Ergonomic Technologies with Steel Piston and with Tungsten Piston resulted in a significantly less peak value (43.2 m/s^2 and 48.2 m/s^2) and average vibration (11.8 m/s^2 and 13.0 m/s^2) compared to the other tools. The Honsa Ergonomics Technologies Rivet Guns produced 57-60% less vibration than the Chicago Pneumatic rivet gun, and 46-51% less vibration than the Ingersoll Rand rivet gun (2010) (See figures 3 and 4 below).

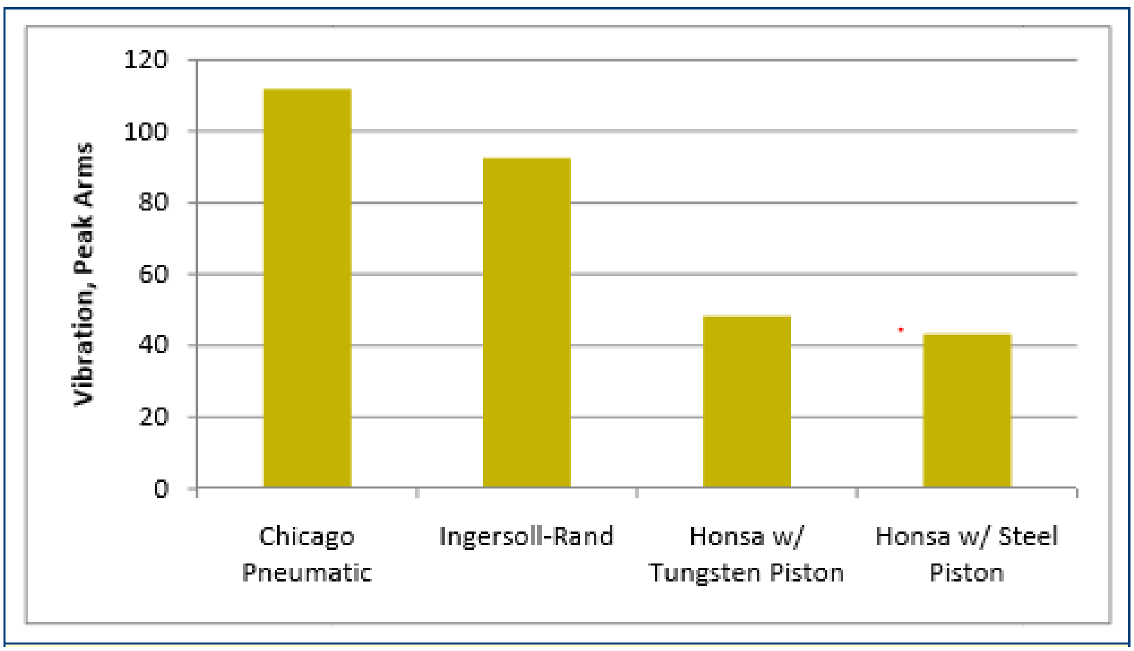


Figure 3. Peak Vibration (m/s^2) Transmitted to the Operator Hand and Arm (HumanTech, Inc., 2010)

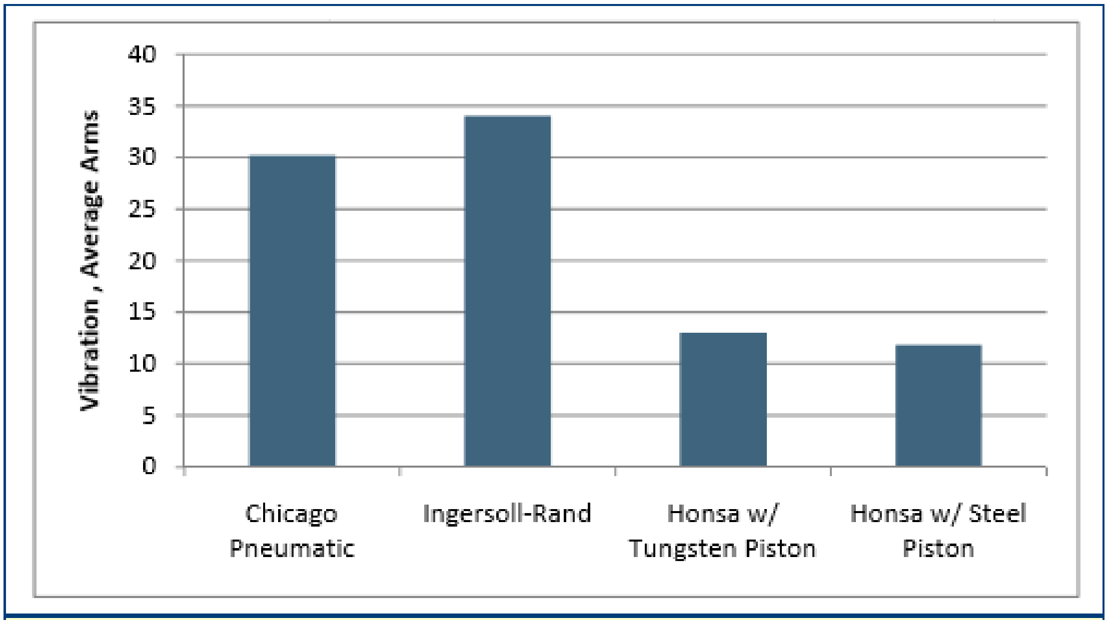


Figure 4. Average Vibration (m/s^2) Transmitted to the Operator Hand and Arm (HumanTech, Inc., 2010)

Also interested in the effect of rivet guns on workers' health, Jorgensen et al. (2006) tested 7 different rivet guns varying by Rotation Per Minute (RPM), hammer material (Tungsten vs. Steel), and types (Vibration dampened rivet gun vs. Regular rivet gun). Data were collected simultaneously from both bucking bars and rivet guns. The results from the accelerometer placed on the rivet guns show that the tungsten rivet guns, and the vibration dampened rivet gun resulted in significantly lower frequency weighted resultant acceleration compared to the other tools. However, the results obtained from the accelerometer positioned on the bucking bar reveal a lower frequency-weighted resultant acceleration for the steel piston rivet gun compared to the tungsten and vibration dampened rivet gun *as shown in Figure 5*. Based on the results of this study, F-E3T (tungsten piston) reduced the vibration level on both the riveter and bucker side. They concluded that the use of tungsten tools in riveting activities significantly decreases the level of vibration exposure experienced by the workers compared to the tools made of steel.

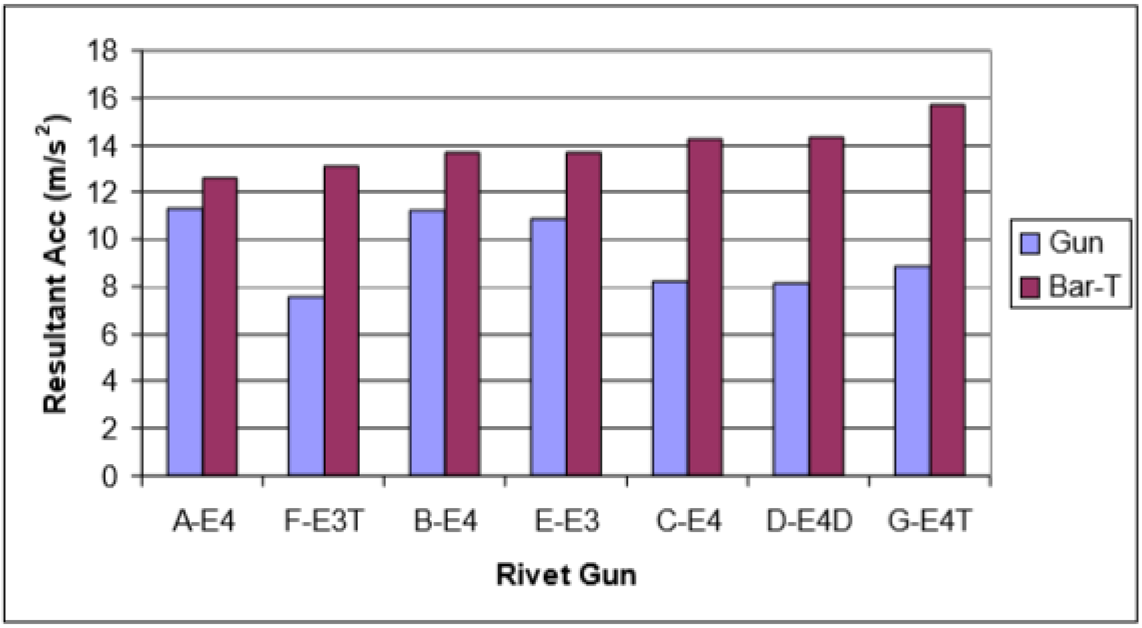


Figure 5. Resultant Vibration Measured on the Rivet Gun and the Tungsten Bucking Bar (Jorgensen et al., 2006)

2.3. BUCKING BARS AND VIBRATIONS

Riveting operations in aircraft manufacturing involves the use of rivet guns to drive and set rivets against a bucking bar that is used to close the rivet on the other side (Jorgensen et al., 2005). Bucking bars were originally made of steel material, but in recent years tungsten bucking bars were introduced as an effective way to reduce the amount of vibrations experienced by buckers. Indeed, heavier than the regular steel bucking bars of similar size, tungsten bucking bars were proven to dampen the vibrations emitted by rivet guns thereby protecting the bucker. Several researches have studied the role of tungsten bucking bar in reducing the vibrations experienced by workers in aircraft manufacturing. For example, McDowell et al. (2015) performed a study involving the testing of three traditional steel bucking bars, three similarly shaped tungsten alloy bars, and three spring-dampeners bars in both the laboratory and workplace. The results of this study indicate a significantly higher weighed and unweighted root mean square values for the traditional steel bucking bars compared to the newer bucking bar technologies involving tungsten material and spring-dampeners. This study explains that although the heavier mass of tungsten bucking bars significantly reduced the vibration level emitted by rivet guns, the additional weight may lead to other ergonomic issues. It is worth noting that this study involved only light riveting activities with bucking bars weight ranging between 0.83-1.47 kg for steel bucking bars and 1.98-2.80 kg for tungsten bucking bars. Thus, heavier riveting activities involving larger rivet size, heavier rivet guns, and bucking bars in addition to vibration may lead to an increase in the forearm muscle activities and a decrease in grip strength. Yet, few studies have focused on the possible effect of using these heavy-duty riveting tools on the worker forearm muscle activities and gripping strength.

2.4. EFFECT OF HAND-ARM VIBRATION ON MUSCLE ACTIVITIES AND STRENGTH

Research shows that gripping a vibrating surface in comparison to a static surface leads to a higher gripping force (Radwin, Armstrong, & Chaffin, 1987). Also, the Electromyography (EMG) of the finger flexor muscles increases with the gripping force (Gurram, Rakheja, & Gouw, 1995). Thus, as the vibration level increases, the workers tend to increase their grip force leading to an increase of the finger flexor muscle activity, and possibly fatigue. It becomes therefore crucial to investigate not only the vibration levels experienced by workers but also the muscle fatigue associated with exposure to vibrations.

Widia et al. (2011) studied the effect of hand-held vibrating tools, especially a bench drill and an electric drill, on muscle activities and grip strength. They found that the arm muscle activity increases with the level of vibration, and the grip strength decreases after the trials involving vibrations. They concluded that vibration might lead to muscle fatigue. The results of this study might be more significant in aircraft manufacturing riveting activities involving percussive rivet tools that produce a higher level of vibration and heavy bucking bars. Thus, the workers in this industry might be exposed to a higher risk of muscle fatigue and musculoskeletal disorders.

Other studies monitored the muscle activities during riveting activities. Jorgensen et al. (2005), after comparing the handgrip flexor or extensor muscle activity relative to the use of 4 different bucking bars (90% tungsten, >90% tungsten, cold-rolled and stainless steel) with similar size and shape and respective weights of 807.2 g, 902.3 g, 389.6 g, 385.5 g, found no statistically significant difference.

Hull (2007) evaluated the vibrations transmitted to the hand and elbow of 4 different interventions of bucking bars in aircraft manufacturing including a tungsten bucking bar, Viscolas rubber wrap adhered to a steel bucking bar, a steel bar paired with an anti-vibration glove, and a steel bucking bar with detachable handle with their respective effect on the flexor and extensor muscle groups of the forearm. The results show that there was no significant difference between the interventions for the extensor muscle group, but the intervention involving the handle resulted in the least forearm flexor muscle activity. Therefore, adding a handle to a bucking bar might decrease the exertion felt in the bucker's flexor muscle activity, and thereby reducing muscle fatigue and possible injuries.

As previously mentioned, several studies have focused on understanding Hand-arm vibration and its effect on workers by comparing the vibrations emitted by different riveting tools based on factors such as material (tungsten, steel), manufacturer, and design (vibration dampener vs regular tools). The conclusion was that the use of tungsten material in the design of riveting tools significantly decreases the amount of vibration experienced by workers.

2.5. RATIONALE

Despite the advancement of technologies and the automation of machinery, the operations or activities in aircraft manufacturing remain manual (Jorgensen & Viswanathan, 2005). Thus, workers in this industry are constantly exposed to a high level of vibration causing hand-arm vibration syndrome, musculoskeletal disorders, carpal tunnel syndrome, muscle fatigue to name just a few health disorders (Lin et al., 2005; T. W. McDowell et al., 2015; Miyashita et al., 1983; Thompson & House, 2006). Thus, it becomes important to minimize the vibration level experienced by workers in this field.

As detailed in the literature review of this document, past researches have studied different factors such as rivet gun manufacture, size, piston material (Tungsten vs. Steel), riveter wrist position (Neutral vs. 1/3 max. flexion vs. 1/3 max. ulnar deviation), bucking bar material (Tungsten vs Steel) and design (Regular vs. Spring Dampener). They evaluated those different factors using the weighed and unweighted-frequency RMS acceleration, the percentage Maximum Voluntary Contraction of EMG, and/or heart rate data, and/or Perceived level of exertion. Nevertheless, there is still a need to understand and quantify the effect of vibration on workers in this field using different variables and test the newly designed tools and their impact on workers. Also, sometimes riveters need to change the rivet gun handle position in order to reach unusual angles and areas of an aircraft; it is, therefore, important to study the different postures that might be involved in a riveting task. This research would address this need by comparing four different types of rivet guns, two different rivet gun handle positions (Vertical vs. Horizontal), and three types of bucking bars (steel, tungsten and Spring dampener) using three response variables which are the acceleration Root Mean Square (RMS) as a measure of vibration magnitude, the percentage Maximum Voluntary Contraction (MVC) of Electromyography, and the perceived level of exertion (Borg Scale) as a measure of muscle fatigue. The heart rate and grip strength percent change were used to determine the overtime fatigue experienced by participants. Also, in this study, data were collected simultaneously from riveter and bucker since the tools used by one can affect the other.

This research would be beneficial to the industry as it would help to recommend a combination of riveting tools that would simultaneously reduce the riveter and bucker’s exposure to vibration, thereby offering a safer working environment to workers. This research’s results combined with associated information such as rivet quality, productivity, and time efficiency can also help make better riveting tools selection.

2.6. OBJECTIVES

The objectives of this research are:

1. Quantify and compare the vibration transmitted to the hand and wrist of riveters when using different types of rivet guns with different bucking bars, and different rivet gun handle position, as well as the effect of these vibration levels on muscle fatigue.
2. Quantify and compare the vibration level transmitted to the bucker's hand when using different bucking bars with different rivet guns, and rivet gun handle positions, and the relative effect of these vibration levels on muscle fatigue.
3. Quantify and compare the impact of these tools on the joint vibration exposure of riveters and buckers as well as their respective muscle fatigue.

CHAPTER 3. METHOD AND PROCEDURES

The overall objective of this research was to investigate the effect of the different vibration levels generated when using different combination of rivet guns, gun handle positions, and bucking bars on hand-arm vibration, and the relative effect of these factors on riveters and buckers' muscle fatigue. This objective was addressed in three parts. The first part compares the effect of the different main factors (rivet guns, gun handle positions, and bucking bars) on riveters' exposure to vibration and muscle fatigue. The second part focuses on the bucker side by comparing the effect of the different main factors (rivet guns, gun handle positions, and bucking bars) on buckers' vibration exposure and muscle fatigue. The third part investigates the joint exposure of riveters and buckers when using different bucking bars, rivet guns, and rivet gun handle positions. The following methodology and procedure were used for all three parts.

3.1. PARTICIPANTS

A total of ten male participants took part in this study. Two of them had years of experience in aircraft manufacturing riveting activities and trained the other participants who were composed of students of age ranging between 19-27 years old. These participants were paired to perform the experimental trials.

3.2. EQUIPMENT

3.2.1. RIVETING ASSEMBLY

This study was performed in a laboratory. The riveting platform consisted of a 12 x 12 aluminum sheet with a thickness of 0.125" mounted as seen in Figure 6 below (describe the way the frame was built). Level 6 rivets were used in this study with a diameter of 3/16" and length of 3/8".

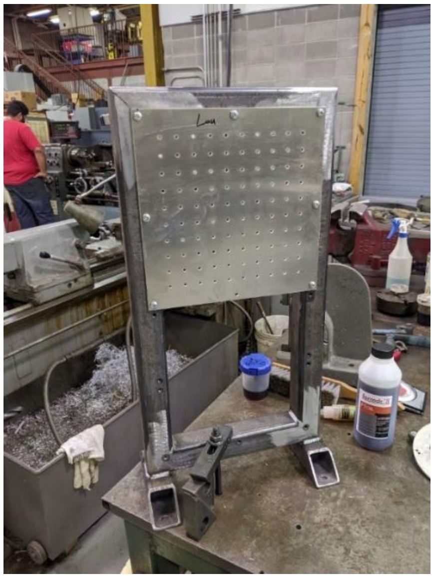


Figure 6. Riveting Assembly

3.2.2. Rivet guns

In this research, a total of four rivet guns varying by manufacturer and piston material (Tungsten vs. Steel) were tested. The details corresponding to each rivet gun are summarized in the following table.

Table 1. Rivet Gun Specifications

Thesis Appellation	Manufacture	Model	Blow Per Minute (BPM)	Bore & Stroke	Weight (lbs.)	Piston
Type 1	AERO US Industrial Aircraft	AERO-US Industrial Aircraft 4X	1740	1/2" x 3-1/16"	2.75	Steel
Type 2	Chicago Pneumatic	CP4444-RUTAB	1740	1/2" x 4"	2.7	Steel
Type 4	Honsa Ergonomic Technologies	HTOP38 4X	1740	1/2" x 3-1/16"	3	Steel
Type 3	Honsa Ergonomic Technologies	HTOP38 12T	2100	9/16" x 3"	3	Tungsten

3.2.3. BUCKING BARS

Three different bucking bars were tested which are a steel and tungsten bucking bar of similar size, and a newly designed spring dampener and tungsten combined bucking bar manufactured by Honsa Ergonomic Technologies. The size and weight of each bucking bar are summarized in the below table.

Table 2. Bucking Bar Specifications

Bucking Bar Types	Model	Size	Weight (lbs.)
Steel Bucking Bar	JBBT4545T	5-1/4” x 1” x 7/8”	1
Tungsten Bucking Bar	PN 15009	4.3” x 1.6” x 0.6”	2.8
Spring Dampener and Tungsten combined Bucking Bar	HVRBB-670A	8.71" x 1.75" x 1.75”	5

3.2.4. ELECTROMYOGRAPHY

BTS FREEEMG 1000 by BTS Bioengineering Corp., which is an instrument for electromyographic surface analysis, was used to assess the operators’ major arm muscle activities (see figure 7 below). This instrument is composed of sensors that are placed on the muscles of interest to collect the electric activity in the muscles while performing a task. The raw EMG data collected throughout the experiment were later smoothened by finding the Root Mean Square envelope. The data processing was achieved using BTS EMGAnalyser.

Figure 7. BTS FREEEMG 1000
(https://bts.elitemedicale.fr/wp-content/uploads/sites/11/2018/07/Manuel-utilisateur-première-partie.pdf)

3.2.5. ACCELEROMETER

In this study, two triaxial general-purpose ICP accelerometers model TLD356A02 manufactured by PCB Piezotronics were used to measure the vibration magnitude emitted by the riveting tools. The accelerometers were placed near the gripping zone where the vibrations enter the worker’s hand, and were mounted on a metal block and attached to the guns and bucking bars using two hose clamps as recommended by ISO 5349-2 (see figure 9 below). Mounting the accelerometer as previously described does not affect the operators’ grip. Also, one layer of rubber was placed between the metal block and the gun handle surface as a mechanical filter to prevent DC shift from the acceleration data (McDowell et al., 2012). The whole mounting assembly was wrapped with duct tape to prevent hand contact with any sharp edge.

Another triaxial slam stick accelerometer model S4-Aluminium by enDAQ was used on the wrist of the riveter to observe the change in vibration transmission when changing the rivet gun handle position (see figure 8 below).

Data were collected simultaneously along the x, y, z-axis. According to ISO 5349-2 (2001), the simultaneous measurement of acceleration along three axes is the most preferred method to evaluate the vibrations emitted by tools. Several studies have used accelerometers as a way to evaluate the vibrations emitted during riveting activities.

Figure 8. Slam Stick Accelerometer Model S4-Aluminium

Figure 9. Triaxial Accelerometer Mounting on Bucking Bar and Rivet Gun

3.2.6. HEART RATE MONITOR

The Polar beat heart rate monitor H10 manufactured by POLAR, electrode gel, and an iPad with a polar heart rate application were used to monitor participants heart rate data throughout the experiment. An electrode gel was applied on the surface of the heart rate sensor and placed on the sternum of each participant. Real-time data were collected simultaneously from riveters and buckers throughout the experimental trials for the day. The data were later on exported to Excel and analyzed.

Figure 10. Polar Beat Heart Rate Sensors

3.3. EXPERIMENTAL DESIGN

The experimental design of this study was a Randomized Complete Block Design (RCBD) with Factorial, considering a pair of riveter and bucker to be a block. There was a total of five blocks, meaning five different pairs of buckers and riveters. Each pair (block) performed all treatment interactions (4 rivet guns X 3 bucking bars X 2 rivet gun handle positions), 24 totals experimental trials. The order of experimental trials was randomized in each block using JMP Design of Experiment (DOE), a statistical analysis software. A generalized linear model was performed on each response variable with rivet guns, bucking bars, and gun handle position as fixed effects, and “pair of participants” and “days of experiment” as random effects. Once the overall source of significance was found for each response variable, a Turkey post hoc test (pair-wise comparison) was performed to determine which levels or combinations were significantly different.

3.3.1. DEPENDENT AND INDEPENDENT VARIABLES

This study primary objective was to recommend a combination of tools that would result in the least acceleration values and least muscle fatigue. To meet that objective 3 independent variables were tested, which were four rivet guns varying by manufacturer and gun piston material (Tungsten vs. Steel), and three bucking bars varying by materials (Tungsten vs. Steel) and design (Regular vs Spring Dampener) (see figures 11 and 12 below), as well as two rivet gun handle positions (Horizontal vs Vertical). The responses or dependent variables that were measured throughout this study were the unweighted-frequency acceleration Root Mean Square (RMS) at the coupling (rivet guns and bucking bars) and the riveter's wrist as the measure vibration transmission, the percentage Maximum Voluntary Contraction (MVC) of the buckers and riveters' major arm muscles, and the riveters and buckers' perceived level of exertion from 0 to 10 (Borg Scale).

Heart rate and grip strength data were used to determine the fatigue experienced by both the riveter and bucker overtime. Heart Rate measures general fatigue while grip strength measures localized muscle fatigue.

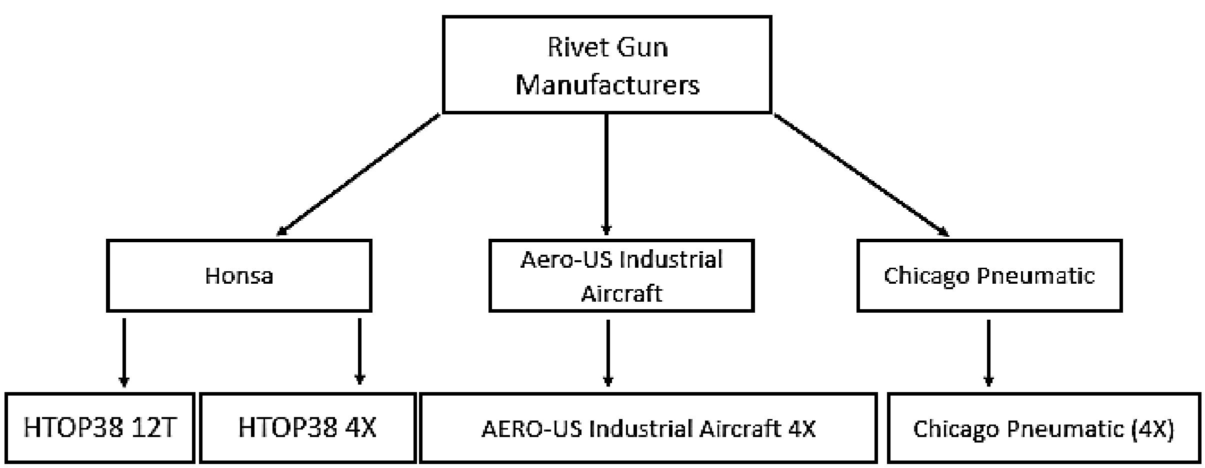


Figure 11. Rivet Guns Tested

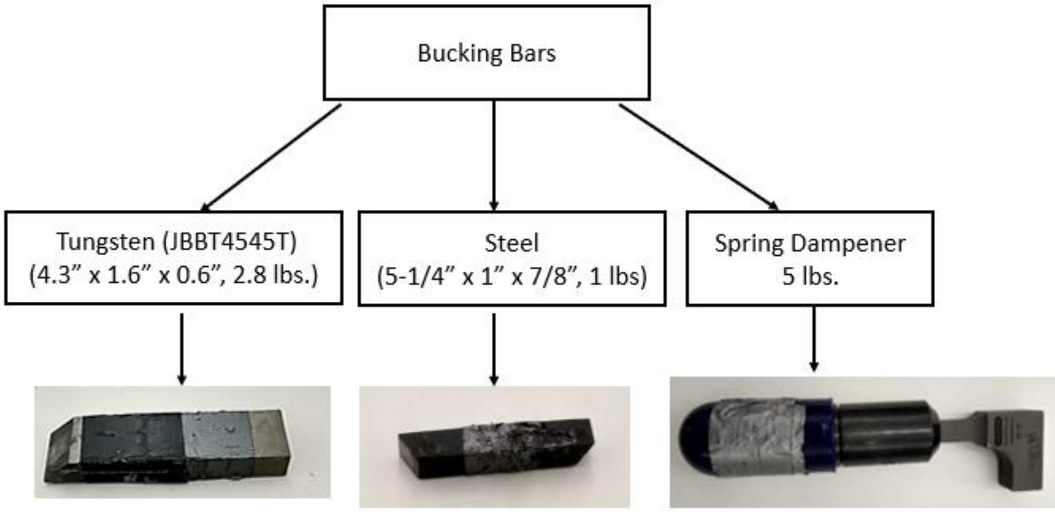


Figure 12. Bucking Bars Tested

3.3.2. Research Hypothesis

The following three objectives were addressed as three different parts in this thesis. The following hypothesis per objective were investigated.

Objective 1: Quantify and compare the vibration transmitted to the hand and wrist of riveters when using different types of rivet guns with different bucking bars, and different rivet gun handle positions, as well as the effect of these vibration levels on muscle fatigue.

Rivet gun factor

Hypothesis 1

H0: The rivet gun type does not affect riveters’ vibration exposure

H1: The rivet gun type affects riveters’ vibration exposure

Hypothesis 2

H0: The rivet gun type does not affect riveters’ muscle fatigue

H1: The rivet gun type affects riveters’ muscle fatigue

Bucking bar factor

Hypothesis 3

H0: The bucking bar type does not affect riveters' vibration exposure

H1: The bucking bar type affects riveters' vibration exposure

Hypothesis 4

H0: The bucking bar type does not affect riveters' muscle fatigue

H1: The bucking bar type affects riveters' muscle fatigue

Gun handle position factor

Hypothesis 5

H0: The rivet gun handle position does not affect riveters' vibration exposure

H1: The rivet gun handle position affects riveters' vibration exposure

Hypothesis 6

H0: The rivet gun handle position does not affect riveters' muscle fatigue

H1: The rivet gun handle position affects riveters' muscle fatigue

Interaction between main factors

Hypothesis 7

H0: The interaction between main factors does not affect riveters' vibration exposure

H1: The interaction between main factors affects riveters' vibration exposure

Hypothesis 8

H0: The interaction between main factors does not affect riveters' muscle fatigue

H1: The interaction between main factors affects riveters' muscle fatigue

OBJECTIVE 2: Quantify and compare the vibration level transmitted to the bucker's hand when using different bucking bars with different rivet guns, and rivet gun handle positions, and the relative effect of these vibration levels on muscle fatigue.

Rivet gun factor

Hypothesis 1

H0: The rivet gun type does not affect buckers' vibration exposure

H1: The rivet gun type affects buckers' vibration exposure

Hypothesis 2

H0: The rivet gun type does not affect buckers' muscle fatigue

H1: The rivet gun type affects buckers' muscle fatigue

Bucking Bar factor

Hypothesis 3

H0: The bucking bar type does not affect buckers' vibration exposure

H1: The bucking bar type affects buckers' vibration exposure

Hypothesis 4

H0: The bucking bar type does not affect buckers' muscle fatigue

H1: The bucking bar type affects buckers' muscle fatigue

Gun handle position factor

Hypothesis 5

H0: The rivet gun handle position does not affect buckers' vibration exposure

H1: The rivet gun handle position affects buckers' vibration exposure

Hypothesis 6

H0: The rivet gun handle position does not affect buckers' muscle fatigue

H1: The rivet gun handle position affects buckers' muscle fatigue

Interaction between main factors

Hypothesis 7

H0: The interaction between main factors does not affect buckers' vibration exposure

H1: The interaction between main factors affects buckers' vibration exposure

Hypothesis 8

H0: The interaction between main factors does not affect buckers' muscle fatigue

H1: The interaction between main factors affects buckers' muscle fatigue

OBJECTIVE 3: Quantify and compare the impact of these tools on the joint vibration exposure of riveters and buckers as well as their respective muscle fatigue.

Rivet gun factor

Hypothesis 1

H0: The average rivet gun and bucking bar acceleration RMS is the same for all rivet gun types

H1: The average rivet gun and bucking bar acceleration RMS varies per rivet gun type

Hypothesis 2

H0: The average riveters and buckers perceived level of exertion is the same for all rivet gun types

H1: The average riveters and buckers perceived level of exertion varies per rivet gun type

Bucking Bar factor

Hypothesis 3

H0: The average rivet gun and bucking bar acceleration RMS is the same for all bucking bars tested

H1: The average rivet gun and bucking bar acceleration RMS varies per bucking bar tested

Hypothesis 4

H0: The average riveters and buckers perceived level of exertion is the same for all bucking bars tested

H1: The average riveters and buckers perceived level of exertion varies per bucking bar tested

Gun handle position factor

Hypothesis 5

H0: The average rivet gun and bucking bar acceleration RMS is the same for the two gun handle positions tested

H1: The average rivet gun and bucking bar acceleration RMS varies per gun handle position

Hypothesis 6

H0: The average riveters and buckers perceived level of exertion is the same for the two gun handle positions tested

H1: The average riveters and buckers perceived level of exertion varies per gun handle position

3.4. EXPERIMENTAL PROCEDURE

Since 4 rivet guns, 3 bucking bars, and 2 rivet gun handle positions were tested, there was a total of 24 experimental trials. Each pair of participants performed all experimental trials in random orders. To minimize the effect of fatigue, each pair of participants performed the 24 experimental trials in 2 days. The MVC of each participant was collected each day before the experimental trials, and the grip strength was also collected each day prior and after the experimental tasks.

The task consisted of setting at least five single rivets in 30 s (Jorgensen et al., 2005, 2006; McDowell et al., 2012). During each task, acceleration data were collected simultaneously in the x, y, z-axis from the bucking bar, rivet gun, and riveter wrist, as well as EMG data from the riveter and bucker’s main arm muscles. Heart rate data were also monitored throughout the whole experiment. After each task, each participant was asked to rate their perceived level of exertion on a scale of 0 to 10 (Borg Scale).

3.4.1. TRAINING

Since eight of the participants in this study were students without experience in riveting activities, they were trained and prepared for data collection by two riveting professionals (the proper way to hold the tools and the proper posture). Prior to data collection, the participants became familiar with the tools by driving some rivets. This training session helped standardize the posture among all participants and avoid any type of variations in the results.

3.4.2. EXPERIMENTAL TRIALS

The following protocol was followed for the experimental trials. The same protocol was used in all three parts of this thesis.

1. As soon as the participants arrived in the laboratory, they were given protective equipment (PPE) such as eyeglasses and earplugs to protect them from any riveting task-induced hazards. The heart rate sensor was placed on the bucker and riveter's sternums and data started being recorded. The FITIV Pulse app was used to record the heart rate real-time data of the participant throughout the experiment. Participants were asked to rest for 10 min to allow the heart rate to go back to the resting level.
2. While the participants were resting, they were prepared for EMG installation. Alcohol was used to clean the skin before the application of the EMG sensors. EMG Sensors were placed on the riveter's major arm muscles (extensor digitorium, brachioradialis, and biceps brachii muscles) as well as the bucker's major arm muscles (extensor carpi radialis, palmaris longus, and biceps brachii muscles) identified in a pilot study.
3. Once the sensors were installed, the Maximum Voluntary Contraction (MVC) of each participant was recorded to later normalize the data. Here, the participants held a grip dynamometer with a neutral wrist position and a 90-degree elbow position (similar to a

riveting task with the rivet gun handle in vertical position) (see figure 13) as strongly as he can for three-5 seconds trials while recording EMG data. A rest period of 10 s was allowed between these tasks. The previous task was performed for the rivet gun handle horizontal position (see figure 14). The grip strength of each participant was also recorded before proceeding with the experimental trials.

4. Once the MVC of each participant was recorded, the participants continued resting while the riveting tools were being prepared. The accelerometer was attached to the riveter's wrist.
5. By the end of the 10-minute rest, the participants were prompted to get ready for the experimental trials and position themselves. The tools were given to the participants 30 s before the end of the 10-min rest. After the 10-min rest, at the 'START' command, the accelerometers and EMG were turned on, and the bucker and riveter set at least five individual rivets in 30 s. Data collection commenced at the 'START' command and lasted

Figure 13. Experimental Trial with Rivet Gun Handle Grip in Vertical Position

exactly 30 s. A rest period of approximately 5 min was allowed between trials to allow the data to be saved and the tools to be changed.

Figure 14. Experimental Trial Rivet Gun Handle Grip in Horizontal Position

The experimental protocol is summarized in the below chart.

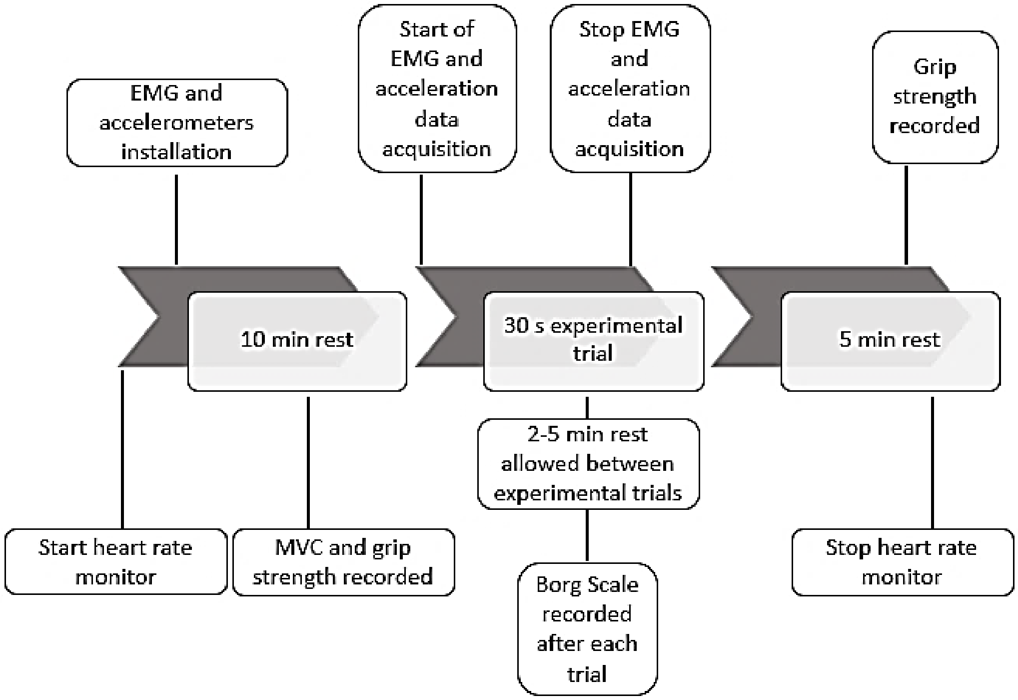


Figure 15. Experimental Protocol

3.4.3. DATA COLLECTION

The overall objective of this research was to study the vibration exposure experienced by riveters and buckers when using different combination of rivet guns and bucking bars, and the relative effect of these vibrations on muscle fatigue. The different variables applied in this study are summarized in the table below.

Table 3. Variables Descriptions

Variable Name	Description	Variable Name	Description
Pattern	Factorial levels combination. Three factors (gun with 4 levels, bar with 3 levels, gun handle position with 2 levels)	Gun Acc z	Dependent variable (unweighted-frequency acceleration RMS recorded at the gun coupling on the z-axis in m/s2).
Blocks	Pair of participants, there is a total of 5 pairs of participants.	Gun Acc Res	Dependent variable (Resultant of the 3 axes of the unweighted-frequency acceleration RMS recorded at the gun coupling in m/s2).
Days	24 experimental trials were performed in 2 days to minimize the effect of fatigue.	Bar Acc x	Dependent variable (unweighted-frequency acceleration RMS recorded at the bar coupling on the x-axis in m/s2).
Subject	Bucker or Riveter	Bar Acc y	Dependent variable (unweighted-frequency acceleration RMS recorded at the bar coupling on the y-axis in m/s2).
Grip strength BV	Average of the two grip strength values recorded prior to the experimental trials each day.	Bar Acc z	Dependent variable (unweighted-frequency acceleration RMS recorded at the bar coupling on the z-axis in m/s2).
Grip Strength AV	Average of the two grip strength values recorded after the experimental trials of the day.	Bar Acc Res	Dependent variable (Resultant of the 3 axes of the unweighted-frequency acceleration RMS recorded at the bar coupling in m/s2).
Gun	Independent variable (4 different guns tested)	Average Acc Res Gun and Bar	Dependent variable (average of the bucking bar and rivet gun acceleration RMS resultant)

Table cont'd

Variable Name	Description	Variable Name	Description
Bar	Independent variable (3 different bucking bars tested)	%MVC ED R	Dependent variable (Percentage Maximum Voluntary Contraction of the riveter's Extensor Digitorium muscle)
Gun handle position	Independent variable (horizontal vs. vertical gun handle position)	% MVC Br R	Dependent variable (Percentage Maximum Voluntary Contraction of the riveter's Brachioradialis muscle)
# of rivets set	Number of rivets set in 30 s per combination of main factors.	% MVC Bi R	Dependent variable (Percentage Maximum Voluntary Contraction of the riveter's Biceps Brachii muscle)
Borg Scale	Rate of perceived level of exertion (0-10)	%MVC ECD B	Dependent variable (Percentage Maximum Voluntary Contraction of the bucker's Extensor Carpi Radialis muscle)
Wrist Acc x	Dependent variable (unweighted-frequency acceleration RMS recorded from the riveter wrist on the x-axis in m/s2).	% MVC PL B	Dependent variable (Percentage Maximum Voluntary Contraction of the bucker's Palmaris Longus muscle)
Wrist Acc y	Dependent variable (unweighted-frequency acceleration RMS recorded from the riveter wrist on the y-axis in m/s2).	% MVC Bi B	Dependent variable (Percentage Maximum Voluntary Contraction of the bucker's Biceps Brachii muscle)
Wrist Acc z	Dependent variable (unweighted-frequency acceleration RMS recorded from the riveter wrist on the z-axis in m/s2).	Riveter Borg Scale	Dependent variable (riveter’s perceived level of exertion on a scale of 0 to 10)
Wrist Acc Res	Dependent variable (Resultant of the 3 axes of the unweighted-frequency acceleration RMS recorded from the riveter wrist in m/s2).	Bucker Borg Scale	Dependent variable (bucker’s perceived level of exertion on a scale of 0 to 10)

Table cont’d

Variable Name	Description	Variable Name	Description
Gun Acc x	Dependent variable (unweighted-frequency acceleration RMS recorded at the gun coupling on the x-axis in m/s2).	R and B Average Borg Scale	Dependent variable (average riveter and bucker perceived level of exertion)
Gun Acc y	Dependent variable (unweighted-frequency acceleration RMS recorded at the gun coupling on the y-axis in m/s2).		

3.4.3.1. Heart Rate

The heart rate of both the bucker and riveter was simultaneously and continuously monitored using a polar heartbeat monitor attached to their chests; beginning at their arrival in the lab until the end of the 5 min rest period after the experimental trials of the day.

3.4.3.2. Electromyography

EMG Sensors were placed on the major arm muscles identified in the pilot study.

Maximum Voluntary Contraction (MVC)

The participant held a grip dynamometer with a neutral wrist position and a 90-degree elbow position (similar to a riveting task with a vertical rivet gun handle) as strongly as he could for three-5 second trials while recording EMG data. A rest period of 10 s was allowed between these tasks. The previous task was performed for the horizontal rivet gun handle position.

Experimental trials

EMG data were collected simultaneously on the riveter and bucker. Data collection started at the START command (beginning of the experimental trial) and ended after exactly 30 s (end of experimental trial). EMG data were collected for all experimental trials and later analyzed using BTS EMG Analyzer. EMG data were reported as % MVC calculated using the following formula.

$$\%MVC\ muscle\ x = \frac{Average\ of\ the\ highest\ envelop\ pick\ of\ muscle\ x}{MVC\ of\ muscle\ x}$$

The numerator represents the average of the highest pick of a trial (see figure 16 below). The denominator represents the pick value of the maximum contraction of the muscle of interest.

3.4.3.3. Accelerometer

The experimental task consisted of setting at least five single rivets in 30 s (Jorgensen et al., 2005, 2006; McDowell et al., 2012). During each task, acceleration data were collected simultaneously in the x, y, z-axis from the bucking bar, rivet gun, and riveter's wrist (ISO 5349-2, 2001). Acceleration data were reported as unweighted-frequency RMS in m/s2 on the x, y, z-axis as well as the resultant (ISO 5349-2, 2001). The acceleration RMS on each axis was obtained using the formula below.

$$Acceleration\ RMS_{x-axis} = \sqrt{mean(acceleration\ values)^2}$$

The resultant or the vector sum of the unweighted-frequency acceleration RMS was calculated using the formula below.

$$a_{hv} = \sqrt{a_{hwx}^2 + a_{hwy}^2 + a_{hwz}^2}$$

Where a_{hwx}, a_{hwy}, a_{hwz}, are the unweighted RMS acceleration values for the x-, y-, and z-axis, respectively.

3.4.3.4. Perceived level of exertion (borg scale)

The Borg's CR 10 Scale is generally used to measure the intensity of a task or an activity, and estimate musculoskeletal pain (Borg, 1998). After each experimental trial, the participants were asked to rate their perceived level of exertion. This perception referred to how heavy and strenuous the activity felt to them (feeling of physical stress, effort, pain, and fatigue). A copy of the Borg Scale instruction is provided in Appendix C of this document.

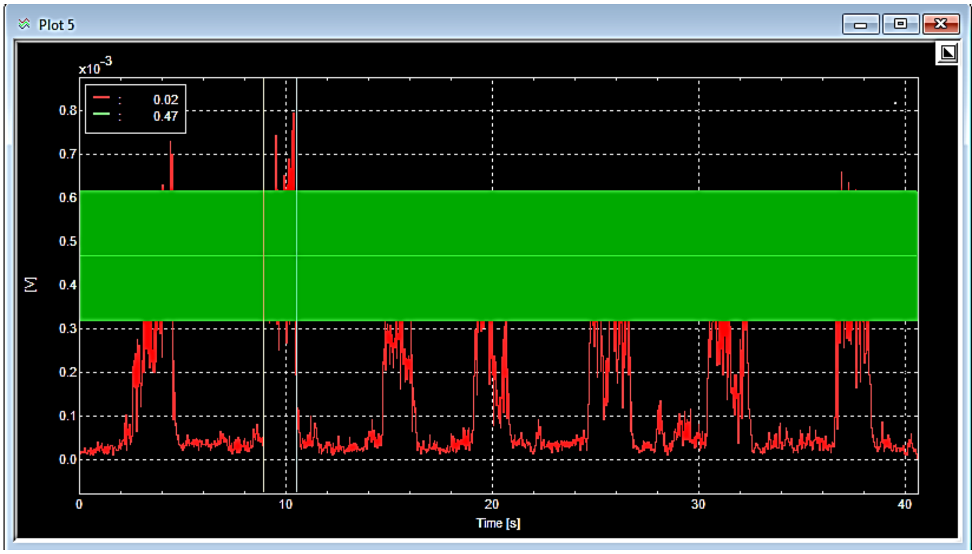


Figure 16. Average Highest Envelop Pick of a Bucker's Palmaris Longus Muscle

CHAPTER 4. PART 1- THE EFFECT OF RIVETING TOOLS ON RIVETERS' VIBRATION EXPOSURE AND MUSCLE FATIGUE

4.1. INTRODUCTION

Riveters and buckers in aircraft manufacturing are subjected to very high vibration levels (10 and 11 m/s^2 respectively) exceeding the frequency-weighted RMS acceleration daily exposure action value (DEAV = 2.5 m/s^2) and daily exposure limit value (DELV = 5 m/s^2) set by the American National Standards Institute (ANSI) standard s2.70. Besides, Dandanell & Engström (1986) found that these workers are exposed to acceleration frequency far above 1000hz and are therefore exposed to higher risk than what is reported in ISO 5349-2 standards. It is necessary to account for these high acceleration frequencies to better estimate workers' health risk exposure in this industry. Studies successfully simulated a riveting task in a laboratory in comparing different types of rivet guns varying by size, piston material (tungsten vs steel), and design (dampener vs regular). However, few researches have discussed the vibration transmission when changing the rivet gun handle position (vertical vs. horizontal) necessary when working on certain angles of the plane. Besides, with the fast advancement of technology, there is always a need to study the newly designed tools and investigate their effect on workers. The objective of part 1 of this thesis was to investigate the factors influencing the vibration experienced by riveters during a riveting task. To attain this objective, we tested four different types of rivet guns varying by manufacturer and piston material (Tungsten and Steel), two rivet gun handle positions (Vertical vs. Horizontal), and three different bucking bars varying by material (Tungsten vs. Steel) and design (Dampener vs. Regular). The results of this study would help recommend tools and a gun handle position that would lessen the vibration exposure to the riveter, thereby promoting a safer working environment to workers.

4.2. DEPENDENT AND INDEPENDENT VARIABLES

Several independent variables were tested in part 1, which are 4 types of rivet guns, 3 bucking bars, as well as two rivet gun handle positions. The comparisons were based on the following dependent variables which are the unweighted-frequency acceleration Root Mean Square (RMS) at the rivet gun coupling and the wrist as a measure vibration transmission on the x, y, z-axis and the resultant of the 3 axes, the percentage Maximum Voluntary Contraction (MVC) of the riveters' extensor digitorium, brachioradialis, and biceps brachii muscles, and the perceived level of exertion (Borg Scale) of the riveters as a measure of muscle fatigue. Heart rate and grip strength percentage change were used to estimate the overtime fatigue. The data collection was achieved following the protocol on page 46 of this document.

4.3. RESULTS

Part 1 focuses on the riveter side by studying the effect of using different types of rivet guns, different rivet gun handle positions, and different bucking bars on the riveter vibration exposure and muscle fatigue. A generalized linear model was performed on each response variables with rivet guns, bucking bars, and gun handle positions as fixed effects, and "pair of participants" and "days of experiment" as random effects. Once the overall source of significance was found for each response variable, a Turkey post hoc test (pair-wise comparison) was performed to determine which levels of the main factors were significantly different. This section will address sequentially the results found for each response variable.

4.3.1. UNWEIGHTED-FREQUENCY ACCELERATION ROOT MEAN SQUARE (RMS) AT THE WRIST

An accelerometer was placed at the riveter wrist to determine how much vibration is transmitted to the wrist of riveters when using different types of rivet guns. The results were reported as unweighted-frequency RMS in m/s^2 on the x, y, z-axis as well as the resultant. The following table summarized the source of significance found for this specific response variable.

Table 4. Statistical Sources of Significance (Wrist Acc)

	Wrist Ac X	Wrist Acc Y	Wrist Acc Z	Wrist Acc Res
Guns	* <0.003	0.0554	* 0.0067	* 0.0003
Bars	0.9296	0.4581	0.9796	0.8441
Gun Handle Position	* <0.0001	0.2672	* 0.0211	* <0.0001
Guns * Bars	0.3572	0.2984	0.3501	
Gun * Gun Handle Position	0.0.0694	* 0.0495	* 0.0158	
Bars * Gun Handle Position	0.7883	0.6585	0.4523	
Guns * Bars * Gun Handle Position	0.908	0.7852	* 0.0186	
Block & Random	0.2035	0.5447	0.2383	
Days & Random	0.7852	0.598	0.2084	

The variables "pair of participants" (block) and "days of experiment" were considered as random effects and did not have any significant effect on the response variable on any axis. Thus, blocking these two variables in our model was justified.

4.3.1.1. Unweighted-frequency acceleration Root Mean Square (RMS) at the wrist X-Axis

The results on the x-axis show that the gun type and the gun handle position were statistically significant (see table below).

Table 5. Fixed Effect Test (Wrist Acc X-Axis)

Source	**DF**	**F Ratio**	**Prob > F**
Gun Handle	1	51.513	<.0001*
Guns	3	6.9608	0.0003*
Guns*Gun Handle	3	2.4399	0.0694
Bars*Gun Handle	2	0.2385	0.7883
Guns*Bars	6	0.3572	0.9039
Guns*Bars*Gun Handle	6	0.3503	0.9080
Bars	2	0.0730	0.9296

The interaction between gun type and gun handle position also explained a considerable variability ratio in the response variable, but was not statistically significant. The rest of the variables did not seem to influence the response variable on the x-axis.

After performing a turkey post hoc analysis, we found that the horizontal rivet gun handle position resulted in 40 % less unweighted-frequency acceleration RMS compared to the vertical handle position.

Table 6. Connecting Letter Report Gun Handle Position Wrist ACC X
(levels not connected by the same letter are significantly different)

Level	Least Sq Mean	Std Error	Std Deviation
Horizontal	5.67	0.64	1.97
Vertical	8.33	0.63	2.74

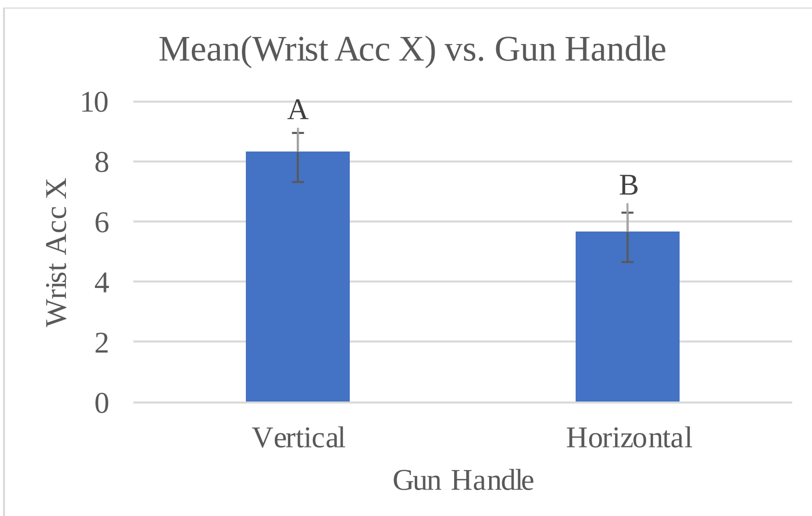


Figure 17. Mean Wrist Acc X vs. Gun Handle Position

The results of the Turkey post hoc analysis performed on the gun show that type 2 rivet gun generated the highest unweighted-frequency RMS (8.3 m/s^2) compared to types 1, 3 & 4 with acceleration values of 7.22 m/s^2, 6.07 m/s^2, and 6.42 m/s^2 respectively. Types 1 & 2 as well as types 3 & 4 were not statistically different, but types 3 & 4 resulted in approximately 22.6 % less mean acceleration RMS compared to types 1 & 2 (see figure and connected letter report below).

Table 7. Connecting Letter Report Gun Type Wrist Acc X (levels not connected by the same letter are significantly different)

Level		Least Sq Mean	Std Error	Std Deviation
Type 2	A	8.30	0.69	3.73
Type 1	A B	7.22	0.70	3.09
Type 4	B	6.42	0.68	1.58
Type 3	B	6.07	0.68	1.3

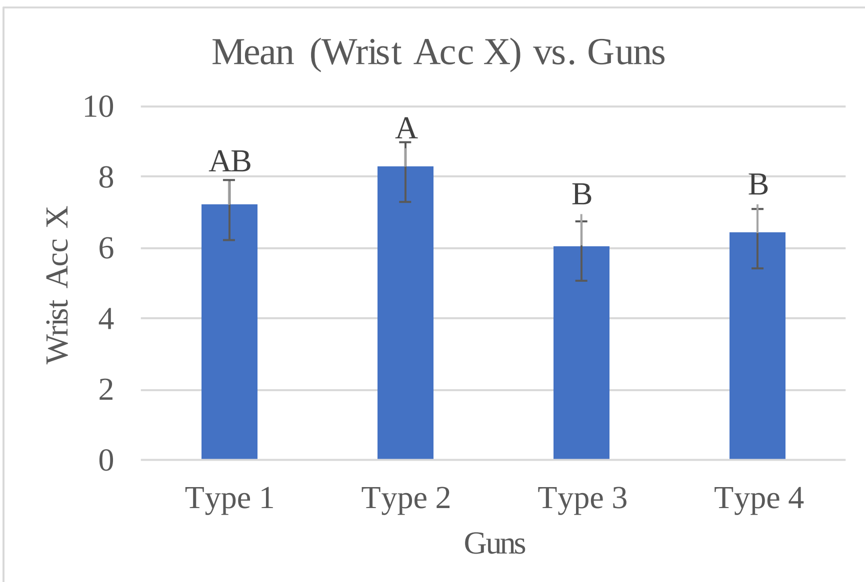


Figure 18. Mean Wrist Acc X vs. Gun Type

4.3.1.2. Unweighted-frequency acceleration Root Mean Square (RMS) at the wrist Y-Axis

In the Y direction, only the interaction between the gun and gun handle position appears marginally significant, yet some further analysis did not support that. We can see from the Turkey test that all combinations to be statistically similar (see graph and connected letter report below).

Table 8. Connecting Letter Report Two-way Interaction between Gun and Gun Handle Position Wrist Acc Y (levels not connected by the same letter are significantly different)

Level		Least Sq Mean	Std Error
Type 2,Vertical	A	13.32	0.34
Type 1,Horizontal	A	12.83	0.32
Type 4,Vertical	A	12.79	0.37
Type 4,Horizontal	A	12.67	0.32
Type 3,Vertical	A	12.64	0.32
Type 3,Horizontal	A	12.61	0.32
Type 1,Vertical	A	12.40	0.32
Type 2,Horizontal	A	12.01	0.32

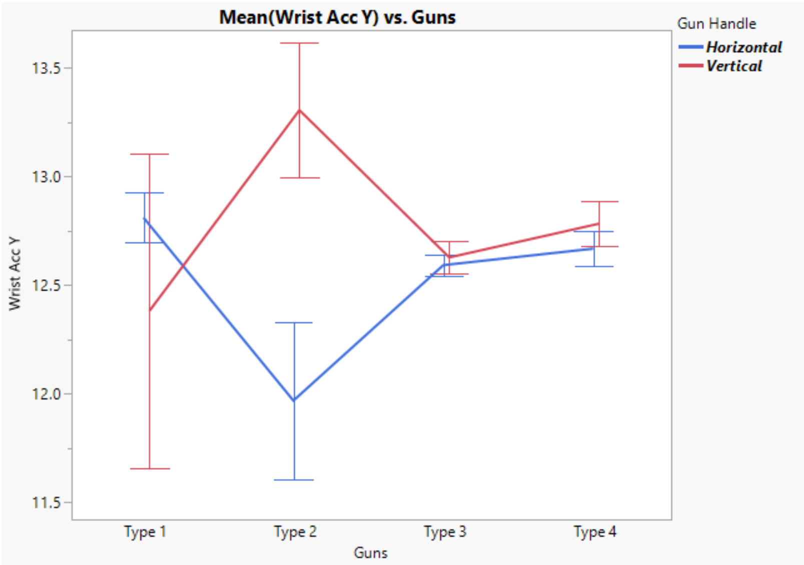


Figure 19. Mean Wrist Acc Y vs. Two-way Interaction between Gun Type and Gun Handle Position

4.3.1.2 . Unweighted-frequency acceleration Root Mean Square (RMS) at the wrist Z-Axis

The acceleration on the z-axis is the output variable which many of the explanatory variables of our experiment seem to have the most effect on. The gun type, the two-way interaction between the gun type and handle position, the three-way interaction between the bar, gun type, and gun handle position were all significant with p-values of 0.0067, 0.0158, 0.0186, 0.0211 respectively (see table below).

Table 9. Fixed Effect Test (Wrist Acc Z-Axis)

Source	**DF**	**F Ratio**	**Prob > F**
Guns	3	4.3431	0.0067*
Guns*Gun Handle	3	3.6302	0.0158*
Guns*Bars*Gun Handle	6	2.6983	0.0186*
Gun Handle	1	5.5071	0.0211*
Guns*Bars	6	1.1449	0.3501
Bars*Gun Handle	2	0.8004	0.4523
Bars	2	0.0206	0.9796

The type 2 rivet gun was found to have the highest unweighted-frequency RMS value 10.26 m/s^2 compared to type 1 (8.08 m/s^2), type 3 (8.64 m/s^2), and type 4 (8.63 m/s^2) rivet guns. On the z-axis, only rivet gun types 1 and 2 were statistically different, with gun type 1 resulting in 21.22 % less mean unweighted-frequency acceleration RMS compared to gun type 2 (see table 10 and figure 20).

The horizontal rivet gun handle position resulted in a statistically smaller RMS value (8.38 m/s^2) compared to the vertical gun handle position (9.43 m/s^2), around 11.14 % (see table 11 and figure 21).

Table 10. Connecting Letter Report Gun Wrist Acc Z (levels not connected by the same letter are significantly different)

Level			**Least Sq Mean**	**Std Error**	**Std Deviation**
Type 2	A		10.26	0.66	3.97
Type 3	A	B	8.64	0.70	1.99
Type 4	A	B	8.63	0.64	2.12
Type 1		B	8.08	0.63	2.7

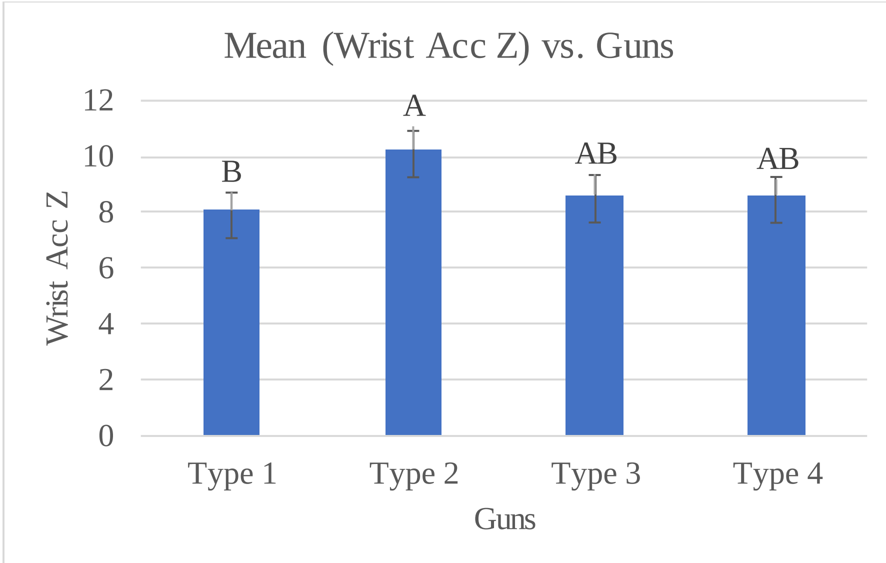


Figure 20. Mean Wrist Acc Z vs. Gun Type

Table 11. Connecting Letter Report Gun Handle Position Wrist Acc Z (levels not connected by the same letter are significantly different)

Level			**Least Sq Mean**	**Std error**	**Std Deviation**
Vertical	A		9.43	0.56	3.82
Horizontal		B	8.38	0.59	1.24

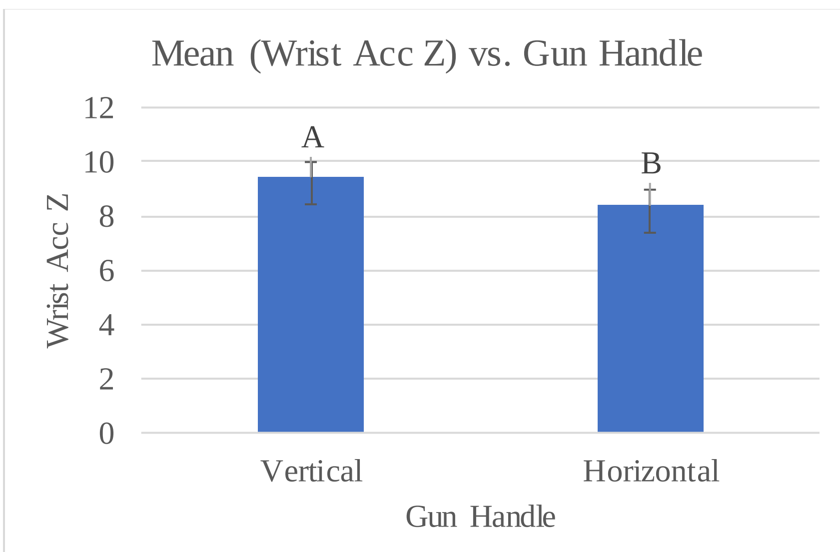


Figure 21. Mean Wrist Acc Z vs. Gun Handle Position

The three-way interaction shows that using a type 2 rivet gun with the steel bucking bar leads to the highest unweighted-frequency RMS (15.83 m/s^2) especially when using the rivet gun in a vertical handle position. This three-way interaction was not statistically different from the following combinations: Type 4 Spring Dampener Vertical, Type 2 Tungsten Vertical, Type 2 Tungsten Horizontal. All other combinations resulted in significantly less mean acceleration RMS (see table 12 and figure 22).

Table 12. Connecting Letter Report Three-way Interaction between Gun Type, Gun Handle Position, and Bar Wrist Acc Z (levels not connected by the same letter are significantly different)

Level			**Least Sq Mean**
Type 2,Steel (1lb),Vertical	A		15.83
Type 4,Spring Dampener (5lbs),Vertical	A	B	10.07
Type 2,Tungsten (2.7lbs),Vertical	A	B	10.04
Type 2,Spring Dampener (5lbs),Vertical		B	10.00
Type 3,Spring Dampener (5lbs),Vertical		B	9.55
Type 3,Tungsten (2.7lbs),Vertical		B	9.22
Type 2,Tungsten (2.7lbs),Horizontal	A	B	9.18
Type 4,Tungsten (2.7lbs),Vertical		B	9.08
Type 1,Spring Dampener (5lbs),Horizontal		B	8.88
Type 2,Spring Dampener (5lbs),Horizontal		B	8.81
Type 1,Tungsten (2.7lbs),Horizontal		B	8.80
Type 3,Steel (1lb),Horizontal		B	8.80
Type 1,Tungsten (2.7lbs),Vertical		B	8.44
Type 3,Spring Dampener (5lbs),Horizontal		B	8.42
Type 4,Steel (1lb),Vertical		B	8.37
Type 4,Tungsten (2.7lbs),Horizontal		B	8.34
Type 4,Steel (1lb),Horizontal		B	8.19
Type 3,Tungsten (2.7lbs),Horizontal		B	8.15
Type 4,Spring Dampener (5lbs),Horizontal		B	7.75
Type 2,Steel (1lb),Horizontal		B	7.72
Type 3,Steel (1lb),Vertical		B	7.69
Type 1,Steel (1lb),Vertical		B	7.65
Type 1,Steel (1lb),Horizontal		B	7.46
Type 1,Spring Dampener (5lbs),Vertical		B	7.28

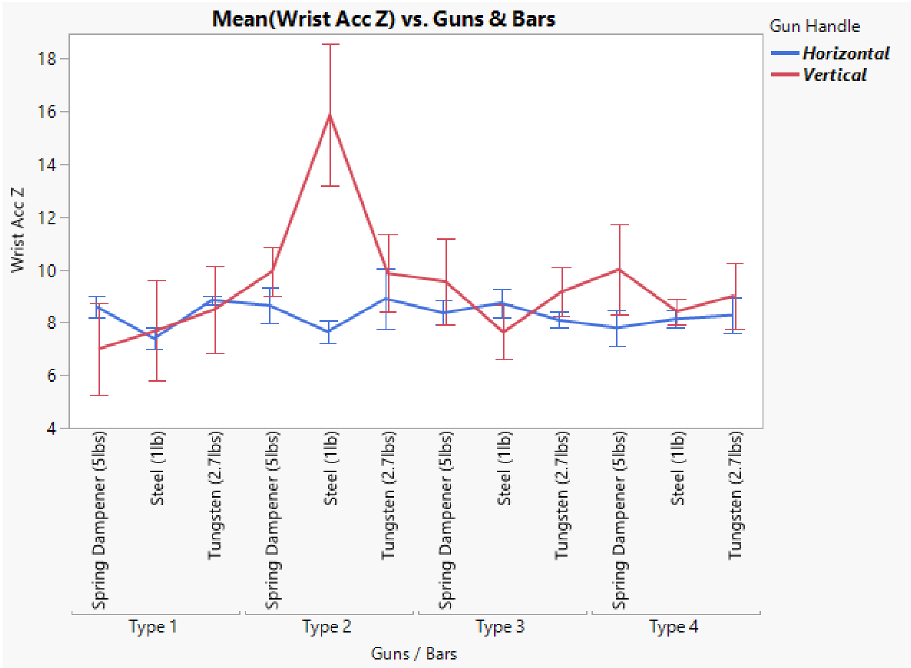


Figure 22. Mean Wrist Acc Z vs. Three-way Interaction between Gun Type, Gun Handle Position, and Bar

The two-way interaction shows a greater difference in acceleration values between the horizontal (8.57 m/s^2) and vertical (11.95 m/s^2) gun handle position when using type 2 rivet gun. Using rivet gun type 2 in the vertical handle position resulted in a significantly higher mean unweighted-frequency acceleration RMS value compared to the combination of all other levels. The combination of type 2 rivet gun with the vertical gun handle position resulted in a 35% higher mean acceleration value compared to the combination of type 1 rivet gun with the horizontal gun handle position (see graph and connected letter report below).

Table 13. Connecting Letter Report Two-way Interaction between Gun Type and Gun Handle Position, Wrist Acc Z (levels not connected by the same letter are significantly different)

Level			**Least Sq Mean**
Type 2,Vertical	A		11.95
Type 4,Vertical		B	9.17
Type 3,Vertical		B	8.82
Type 2,Horizontal		B	8.57
Type 3,Horizontal		B	8.46

Table cont'd

Level		Least Sq Mean
Type 1,Horizontal	B	8.38
Type 4,Horizontal	B	8.09
Type 1,Vertical	B	7.79

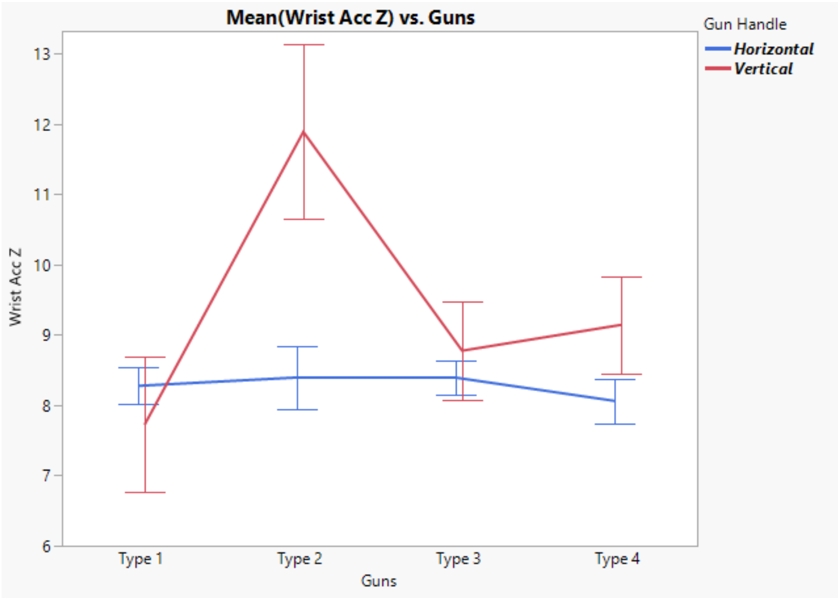


Figure 23. Mean Wrist Acc Z vs. Two-way Interaction between Gun Type and Gun Handle Position

4.3.1.3 . Unweighted-frequency acceleration Root Mean Square (RMS) at the wrist resultant

The generalized linear model results for the resultant acceleration RMS at the wrist show that the gun and gun handle position was significant with p-values of 0.0003 and <0.0001 respectively (see table 14).

Table 14. Fixed Effect Test (Wrist Acc Resultant)

Source	DF	F Ratio	Prob > F
Guns	3	6.9258	0.0003*
Bars	2	0.1697	0.8441
Gun Handle	1	35.3547	<.0001*

The Turkey post hoc test performed on the gun reveals that the rivet gun type 2 resulted in a significantly higher mean acceleration RMS value compared to gun types 1, 3 & 4 (8.58%, 11.37%, and 10.03% respectively). Rivet gun types 1, 3, & 4 were not statistically different from each other (see table 15 and figure 24).

Table 15. Connecting Letter Report Gun Type Wrist ACC Resultant (levels not connected by the same letter are significantly different)

Level			**Least Sq Mean**	**Std Error**	**Std Deviation**
Type 2	A		18.64	0.62	3.77
Type 1		B	17.04	0.61	2.06
Type 4		B	16.77	0.6	1.67
Type 3		B	16.52	0.6	1.42

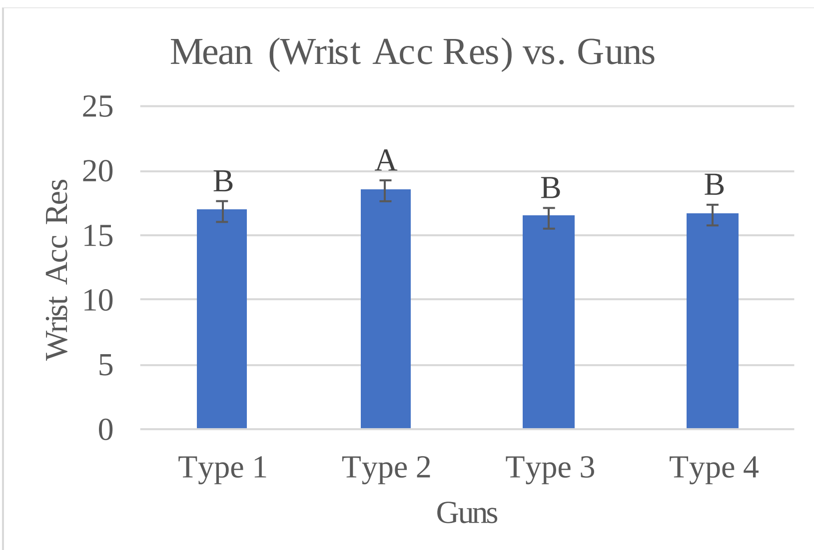


Figure 24. Mean Wrist Acc Resultant vs. Gun Type

The results of the post hoc test performed on the gun handle orientation are similar to the x and z-axis with the horizontal handle position leading to 52% less mean unweighted-frequency acceleration RMS value compared to the vertical rivet gun handle orientation (see table 16 and figure 25).

Table 16. Connecting Letter Gun Handle Position Wrist Acc Resultant (levels not connected by the same letter are significantly different)

Level		Least Sq Mean	Std Error	Std Deviation
Vertical	A	18.31	0.54	3.05
Horizontal	B	16.18	0.55	2.00

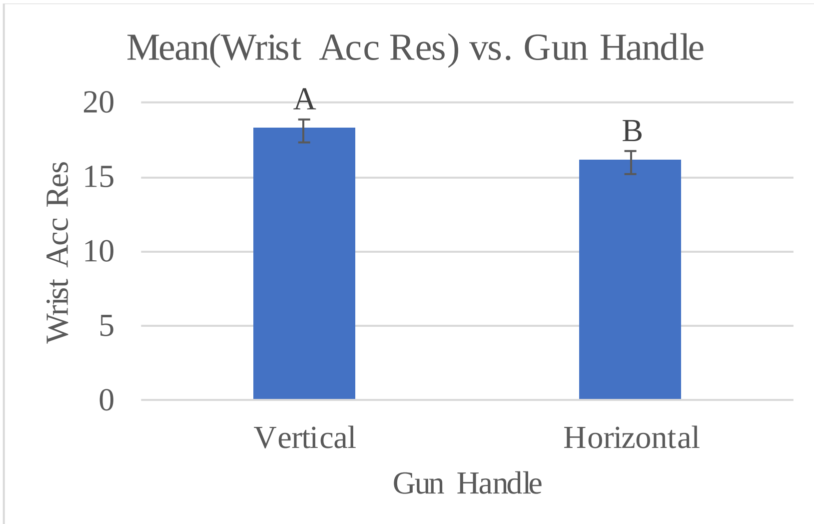


Figure 25. Mean Wrist Acc Resultant vs. Gun Handle Position

4.3.2. UNWEIGHTED-FREQUENCY ACCELERATION ROOT MEAN SQUARE (RMS) AT THE RIVET GUN COUPLING

Another accelerometer was mounted on the rivet gun near the gripping zone to measure the vibration transmitted to the fingers and hand of the riveter. The different sources of significance are summarized in the below table.

Table 17. Statistical Sources of Significance (Gun Coupling Acc)

	Gun Acc X	Gun Acc Y	Gun Acc Z	Gun Acc Res
Guns	* <0.0001	* 0.0001	* <0.0001	* <0.001
Bars	0.5793	0.9218	0.954	0.8487
Gun Handle Position	* 0.0054	* 0.0078	* 0.0007	* 0.0024
Guns * Bars	0.5675	0.49	0.746	0.6482
Gun * Gun Handle Position	0.3929	0.5993	0.3902	0.4306

Table cont'd

	Gun Acc X	Gun Acc Y	Gun Acc Z	Gun Acc Res
Bars * Gun Handle Position	0.8162	0.9926	0.8088	0.8957
Guns * Bars * Gun Handle Position	0.9487	0.9486	0.8618	0.9287
Block & Random	0.3918	0.4747	0.3054	0.3764
Days & Random	0.8497	0.9783	0.8837	0.8457

The random effects did not seem to explain a significant percentage of variability in this response variable. Both random effects were not significant; our model is therefore justified.

4.3.2.1 . Unweighted-frequency acceleration Root Mean Square (RMS) at the rivet gun coupling X-Axis

On the x-axis, both the gun and gun handle positions were significant with a p-value of <.0001, and 0.0054 respectively (see table 18).

Table 18. Fixed Effect Test (Acc Coupling X-Axis)

Source	**DF**	**F Ratio**	**Prob > F**
Guns	3	15.040	<.0001 *
Gun Handle	1	8.1178	0.0054 *
Guns*Gun Handle	3	1.0081	0.3929
Guns*Bars	6	0.8064	0.5675
Bars	2	0.5491	0.5793
Bars*Gun Handle	2	0.2036	0.8162
Guns*Bars*Gun Handle	6	0.2721	0.9487

The turkey post hoc analysis reveals that gun type 1 and type 2 produced the highest RMS values of 23.02 and 20.71 m/s^2 respectively compared to type 3 (10.6 m/s^2) and type 4 (12.75 m/s^2). Types 1 & 2 were not statistically different from one another but generated around 54% higher unweighted RMS values compared to types 3 and 4 (see graph and connected letter report below).

Table 19. Connecting Letter Report Gun Type (Gun Coupling Acc X) (levels not connected by the same letter are significantly different)

Level			**Least Sq Mean**	**Std Error**	**Std Deviation**
Type 1	A		23.02	1.92	12.52
Type 2	A		20.71	1.98	9.47
Type 4		B	12.75	1.88	5.18
Type 3		B	10.60	1.89	4.61

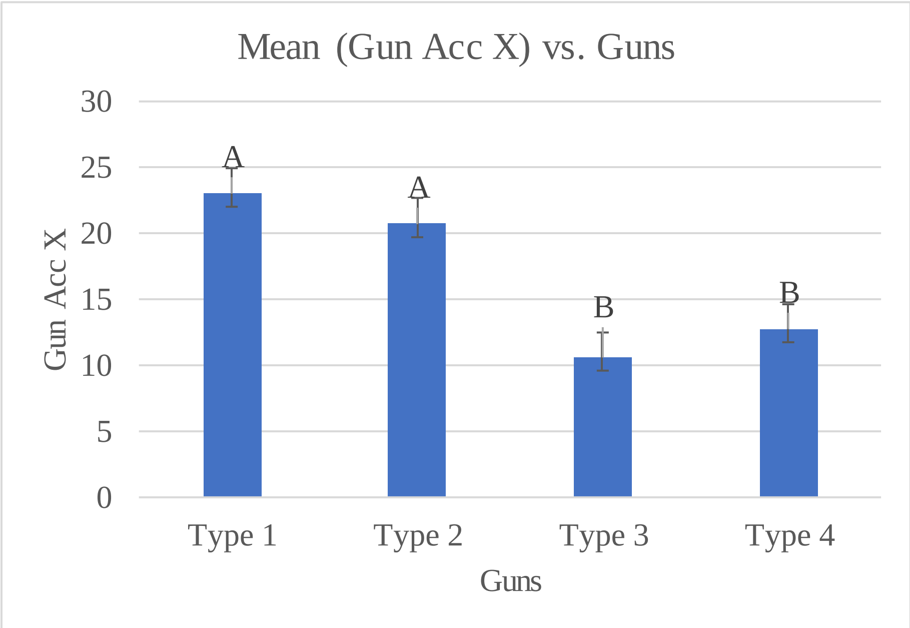


Figure 26. Mean Gun Acc X vs. Gun Type

The horizontal gun handle position led to the least unweighted-frequency acceleration RMS value (14.57 m/s^2) compared to the vertical rivet gun handle position (18.97 m/s^2), around 23% difference (see table 20 and figure 27).

Table 20. Connecting Letter Report Gun Handle Position (Gun Coupling Acc X) (levels not connected by the same letter are significantly different)

Level			**Least Sq Mean**	**Std Error**	**Std Deviation**
Vertical	A		18.97	1.55	11.84
Horizontal		B	14.57	1.61	7.03

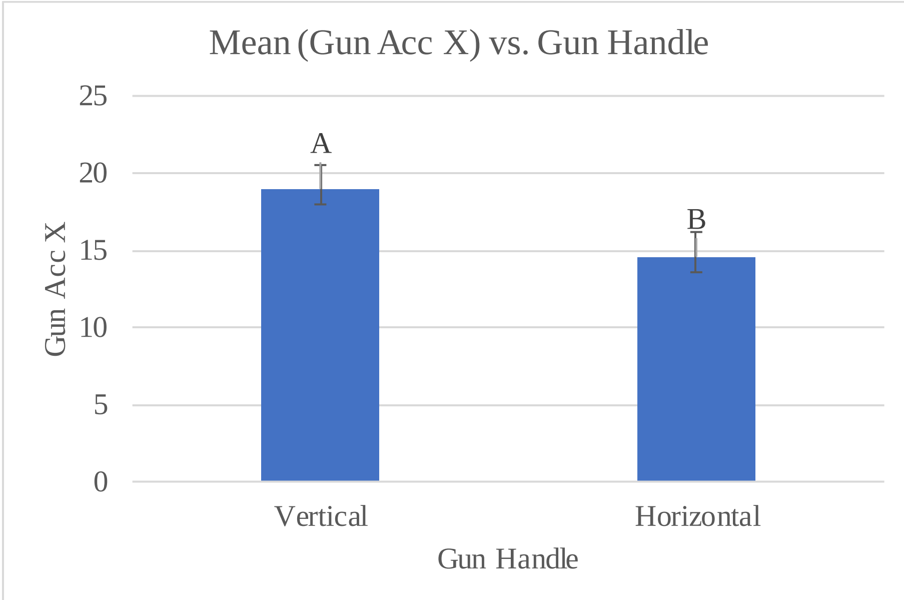


Figure 27. Mean Gun Acc X vs. Gun Handle Position

4.3.2.2 . Unweighted-frequency acceleration Root Mean Square (RMS) at the rivet gun coupling Y-Axis

Similar to the x-axis, the results along the Y-axis show that only the gun (p-value <.0001) and gun handle position (p-value = 0.0078) were significant (see table below).

Table 21. Fixed Effect Test (Acc Coupling Y-Axis)

Source	**DF**	**F Ratio**	**Prob > F**
Guns	3	25.4635	<.0001 *
Gun Handle	1	7.4111	0.0078 *
Guns*Bars	6	0.9123	0.4900
Guns*Gun Handle	3	0.6272	0.5993
Bars	2	0.0815	0.9218
Guns*Bars*Gun Handle	6	0.2723	0.9486
Bars*Gun Handle	2	0.0074	0.9926

The Turkey post hoc analysis performed on the gun type reveals that type 1 and type 2 rivet guns produced the highest RMS values of 27.33 m/s^2 and 24 m/s^2 respectively compared to type 3

(11.89 m/s^2) and type 4 (14.63 m/s^2). Type 1 & 2 as well as type 3 & 4 were not statistically significant. However, types 3 & 4 resulted in around 56.5 % less vibration compared to types 1 & 2 (see table 22 and figure 28).

Table 22. Connecting Letter Report Gun Type (Gun Coupling Acc Y) (levels not connected by the same letter are significantly different)

Level			**Least Sq Mean**	**Std Error**	**Std Deviation**
Type 1	A		27.33	1.68	10.78
Type 2	A		24.00	1.75	9.09
Type 4		B	14.63	1.65	4.52
Type 3		B	11.89	1.63	5.45

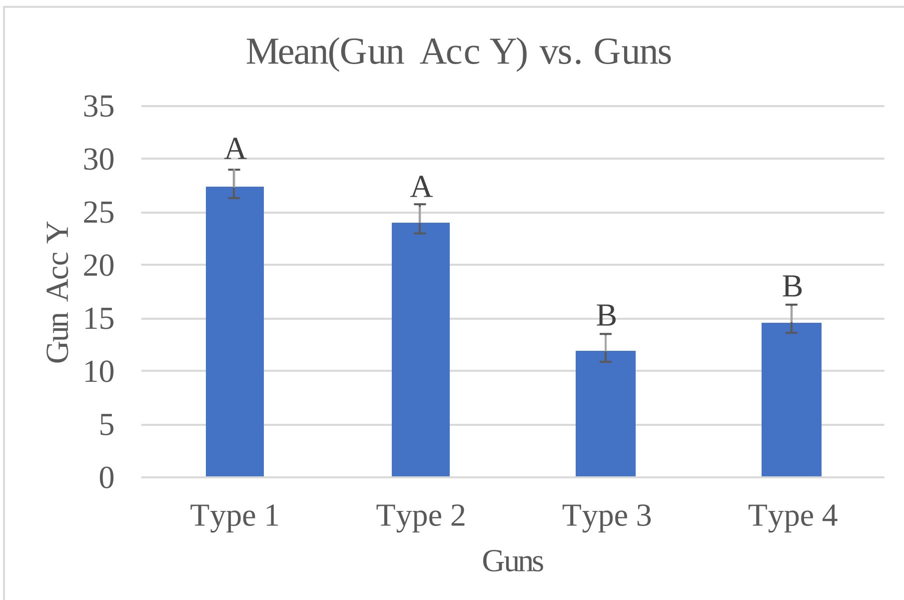


Figure 28. Mean Gun Acc Y vs. Gun Type

The results of Turkey post hoc analysis performed on the gun handle position show a higher unweighted-frequency RMS value for the vertical gun handle position (21.44 m/s^2) compared to the horizontal gun handle position (17.48 m/s^2), around 18.5% difference (see table 23 and figure 29).

Table 23. Connecting Letter Report Gun Handle Position (Gun Coupling Acc Y) (levels not connected by the same letter are significantly different)

Level		Least Sq Mean	Std Error	Std Deviation
Vertical	A	21.44	1.29	11.73
Horizontal	B	17.48	1.36	7.73

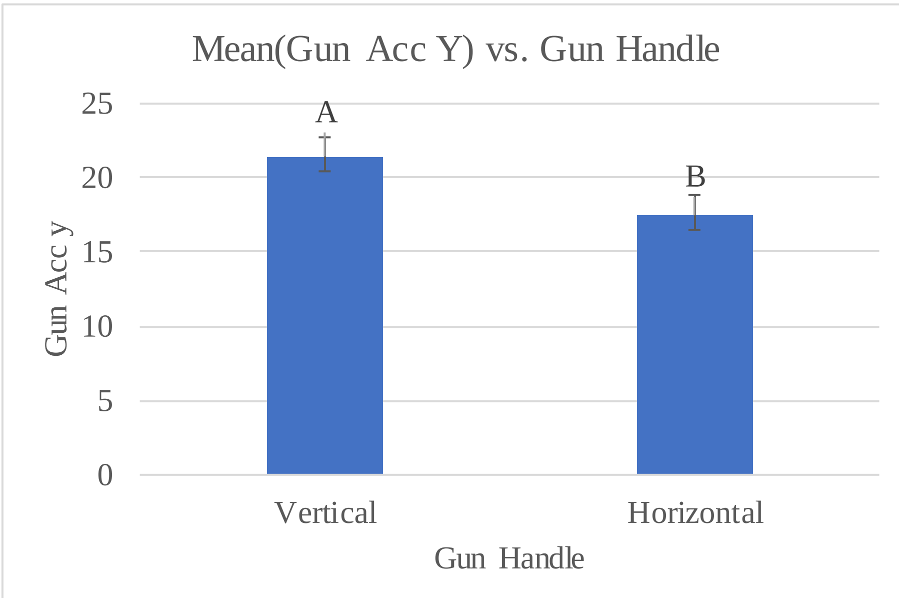


Figure 29: Mean Gun Acc Y vs. Gun Handle Position

4.3.2.3 . Unweighted-frequency acceleration Root Mean Square (RMS) at the rivet gun coupling Z-Axis

In the z-direction as well, only the gun (P<.0001) and gun handle position (P=0.0007) were significant (see table 24).

Table 24. Fixed Effect Test (Acc Coupling Z-Axis)

Source	**DF**	**F Ratio**	**Prob > F**
Guns	3	39.2208	<.0001*
Gun Handle	1	12.2414	0.0007*
Guns*Gun Handle	3	1.0142	0.3902
Guns*Bars	6	0.5792	0.7460

Table cont'd

Source	DF	F Ratio	Prob > F
Bars*Gun Handle	2	0.2127	0.8088
Guns*Bars*Gun Handle	6	0.4233	0.8618
Bars	2	0.0471	0.9540

The Turkey post hoc test show similar results to the previous axes with gun types 1 & 2 generating significantly higher mean unweighted-frequency RMS values (27.83 and 24.27 m/s^2 respectively) compared to types 3 & 4 (15.25 m/s^2 and 13.02 m/s^2 respectively), approximately 49% difference between types 1 & 2 and types 3 & 4 (see table 25 and figure 30).

Table 25. Connecting Letter Report Gun Type (Gun Coupling Acc Z) (levels not connected by the same letter are significantly different)

Level			Least Sq Mean	Std Error	Std Deviation
Type 1	A		27.83	1.53	9
Type 2	A		24.27	1.56	7.19
Type 4		B	15.25	1.50	4
Type 3		B	13.02	1.51	4.19

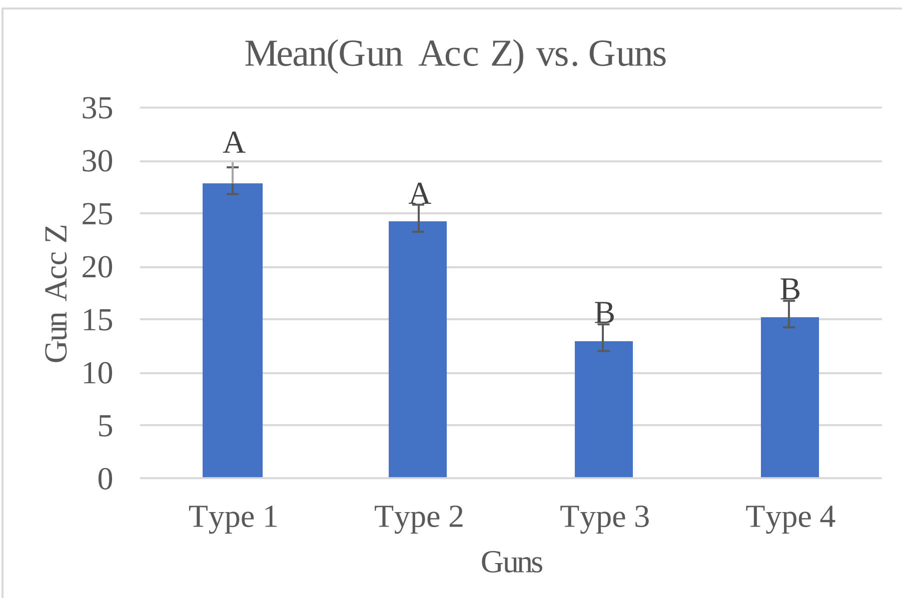


Figure 30. Mean Gun Acc Z vs. Gun Type

Similar to the previous axis the highest unweighted-frequency RMS value was found for the vertical rivet gun handle position (22.06 m/s^2) compared to the horizontal handle position (18.12 m/s^2), around 18.86 % difference (see table 26 and figure 31).

Table 26. Connecting Letter Report Gun Handle Position (Gun Coupling Acc Z) (levels not connected by the same letter are significantly different)

Level			Least Sq Mean	Std Error	Std Deviation
Vertical	A		22.06	1.28	10.31
Horizontal		B	18.12	1.32	6.61

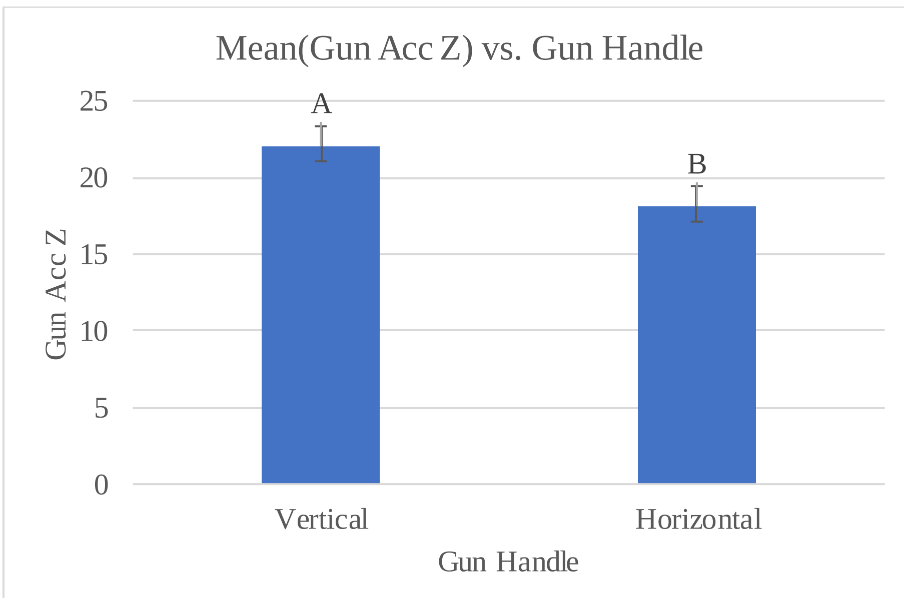


Figure 31. Mean Gun Acc Z vs. Gun Handle Position

4.3.2.4 . Unweighted-frequency acceleration Root Mean Square (RMS) at the rivet gun coupling resultant

Since the results are consistent on the x, y, z-axis, the resultant of the three axes shows the same trend with significance found for the gun (<.0001) and gun handle (0.0024) (see table 27). The Turkey post hoc analysis results are also consistent with the results found on the individual axis with rivet gun types 1 & 2 generating higher values of unweighted-frequency acceleration RMS (45.6 and 40.29 m/s^2) compared to gun types 3 & 4 (20.74 and 24.94 m/s^2). Gun types 3

& 4 generated 54.5 % less mean acceleration RMS than gun types 1 & 2 (see table 28 and figure 32).

Table 27. Fixed Effect Test (Acc Coupling Resultant)

Source	**DF**	**F Ratio**	**Prob > F**
Guns	3	27.5533	<.0001 *
Gun Handle	1	9.7246	0.0024 *
Guns*Gun Handle	3	0.9280	0.4306
Guns*Bars	6	0.7026	0.6482
Bars	2	0.1643	0.8487
Bars*Gun Handle	2	0.1102	0.8957
Guns*Bars*Gun Handle	6	0.3131	0.9287

Table 28. Connecting Letter Report Gun Type (Gun Coupling Acc Resultant) (levels not connected by the same letter are significantly different)

Level			**Least Sq Mean**	**Std Error**	**Std Deviation**
Type 1	A		45.60	2.86	18.07
Type 2	A		40.29	2.93	14.03
Type 4		B	24.94	2.80	7.06
Type 3		B	20.74	2.81	7.87

Similarly, the rivet gun horizontal handle position reduces the unweighted-frequency acceleration RMS value by 24 % compared to using the gun in a vertical handle position (see table 29 and figure 33).

Table 29. Connecting Letter Report Gun Handle Position (Gun Coupling Acc Resultant) (levels not connected by the same letter are significantly different)

Level	**Least Sq Mean**	**Std Error**	**Std Deviation**
Vertical	36.42	2.32	19.08
Horizontal	29.37	2.4	11.75

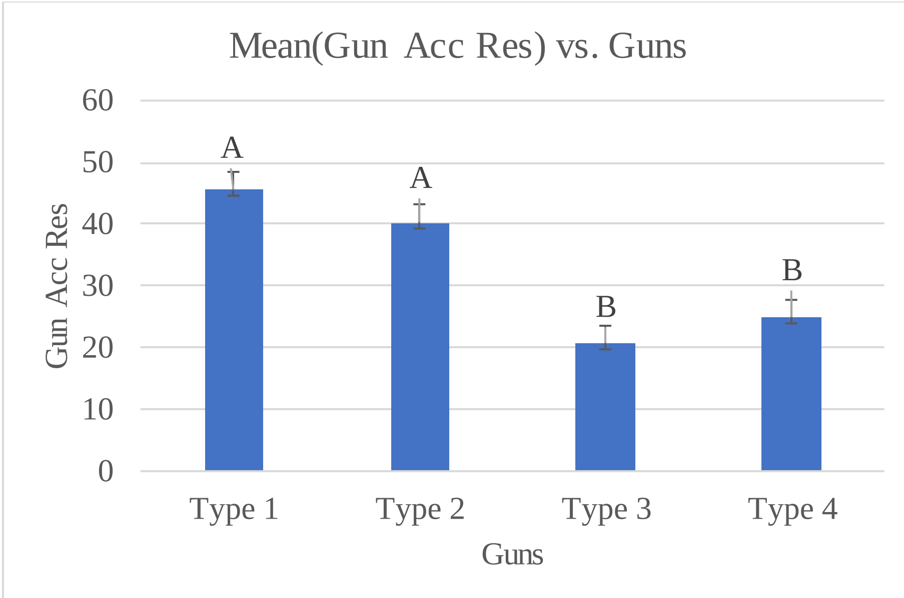


Figure 32. Mean Gun Acc Resultant vs. Gun Type

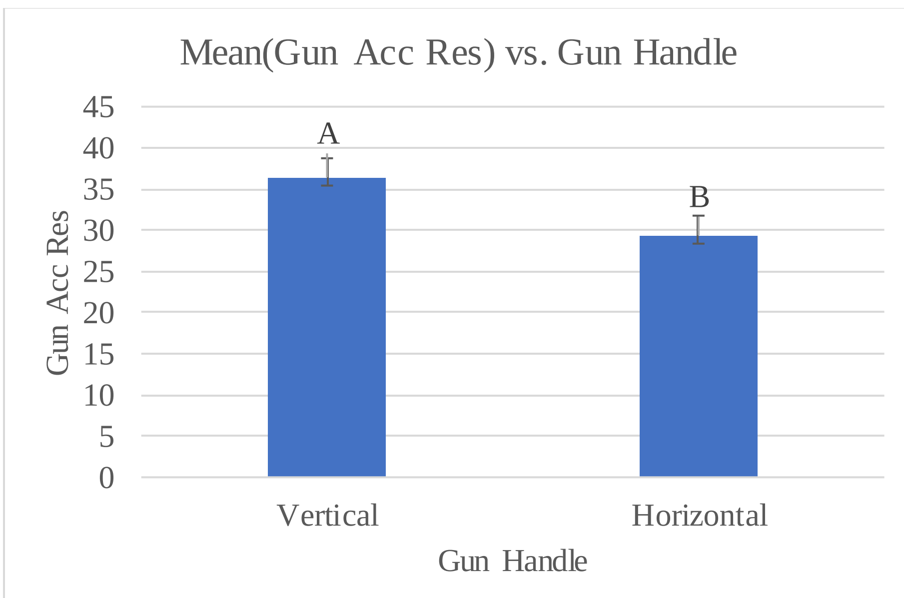


Figure 33. Mean Gun Acc Resultant vs. Gun Handle Position

4.3.3. Percentage Maximum Voluntary Contraction (MVC) of Electromyography (EMG)

The riveter muscle activity was recorded using Electromyography in order to determine the effect of the rivet gun type and rivet gun handle position on muscle fatigue. The EMG sensors were placed on three different riveters' arm muscles which are the extensor digitorium, brachioradialis, and biceps brachii muscles. EMG data were reported as % MVC. The table below summarizes the different sources of significance for the 3 different muscles.

Table 30. Statistical Sources of Significance (Muscle Fatigue)

	%MVC ED R	%MVC Br R	% MVC Bi R	Borg Scale
Guns	0.4823	* 0.0335	0.2803	0.7517
Bars	0.282	0.3375	0.3479	* 0.0407
Gun Handle Position	* <0.0001	* 0.0182	* <0.0001	* 0.0076
Guns * Bars	0.7254	0.1625	* 0.0122	0.9263
Gun * Gun Handle Position	0.9002	0.1257	0.3863	0.8254
Bars * Gun Handle Position	0.0919	0.5845	0.7229	0.755
Guns * Bars * Gun Handle Position	0.99	0.3022	* 0.0281	0.9716
Block & Random	0.1945	0.2602	0.1848	
Days & Random	0.5734	0.5095	0.4227	

After performing the generalized linear model on the percentage Maximum Voluntary Contraction of EMG for all three muscles, the two random effects were not significant. Blocking the "pair of participants" (block) and "day of experiment" in our model is therefore justified.

4.3.3.1 . Percentage Maximum Voluntary Contraction (MVC) of the extensor digitorium muscle (Extensor muscle group)

Only the rivet gun handle position was significant for this response variable with a p-value <.0001 (see table 31). The Turkey post hoc analysis reveals that the vertical gun handle position resulted in less mean % MVC (50.68%) compared to the horizontal handle position (82.09%), around 38.26 % difference (see table 32 and figure 34).

Table 31. Fixed Effect Test (MVC ED R)

Source	DF	F Ratio	Prob > F
Gun Handle	1	34.2828	<.0001*
Bars*Gun Handle	2	2.4509	0.0919
Bars	2	1.2834	0.2820
Guns	3	0.8271	0.4823
Guns*Bars	6	0.6054	0.7254
Guns*Gun Handle	3	0.1941	0.9002
Guns*Bars*Gun Handle	6	0.1431	0.9900

Table 32. Connecting Letter Report Gun Handle Position (%MVC ED R) (levels not connected by the same letter are significantly different)

Level	Least Sq Mean	Std Error	Std Deviation
Vertical	50.68	11.37	23.83
Horizontal	82.09	11.48	41.89

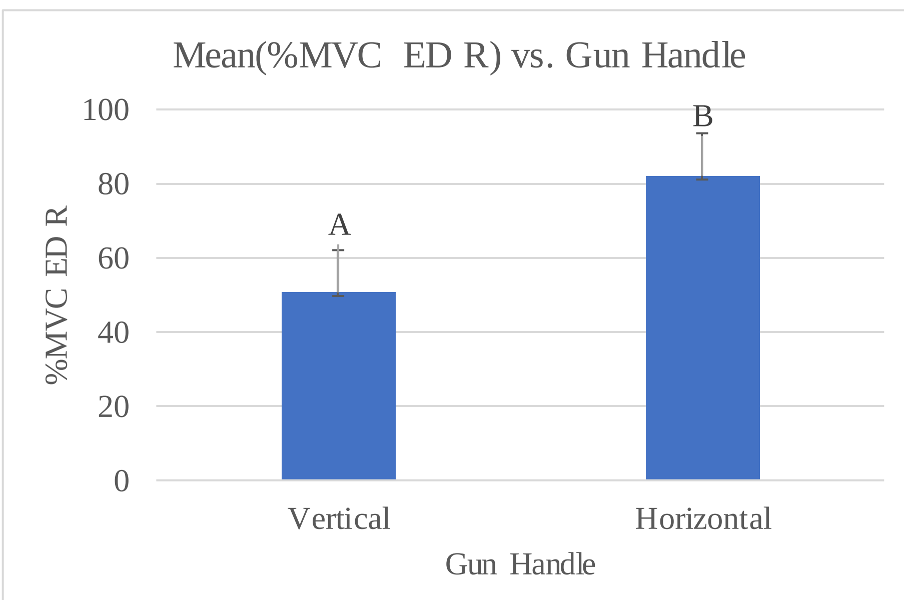


Figure 34. Mean %MVC ED R vs. Gun Handle Position

4.3.3.2 . Percentage Maximum Voluntary Contraction (MVC) of the brachioradialis muscle (Flexor muscle group)

The results for the brachioradialis muscle show that both the gun handle position and gun were significant with p-values of 0.0182 and 0.0335 respectively (see table below).

Table 33. Fixed Effect Test (MVC BR R)

Source	**DF**	**F Ratio**	**Prob > F**
Gun Handle	1	5.7819	0.0182 *
Guns	3	3.0266	0.0335 *
Guns*Gun Handle	3	1.9590	0.1257
Guns*Bars	6	1.5778	0.1625
Guns*Bars*Gun Handle	6	1.2223	0.3022
Bars	2	1.0991	0.3375
Bars*Gun Handle	2	0.5405	0.5843

The Turkey post hoc test performed on the gun handle reveals that the vertical rivet gun handle position led to less mean % MVC (27.19) compared to the vertical rivet gun handle position (49.32%) (see table 34 and figure 35), approximately 44.9 % difference.

Table 34. Connecting Letter Report Gun Handle Position (%MVC Br R) (levels not connected by the same letter are significantly different)

Level			**Least Sq Mean**	**Std Error**	**Std Deviation**
Vertical	A		49.32	16.39	79.43
Horizontal		B	27.19	16.64	14.75

The Turkey post hoc analysis performed on the gun type shows that rivet gun type 3 resulted in a statistically significant higher mean % MVC (61.83%) compared to type 1 (30.87%), type 2 (33.55%), and type 4 (26.79%). No statistical significance was found between types 1, 2, & 4 rivet guns. Gun type 4 resulted in 56.7 % less mean percentage MVC of the brachioradialis muscle compared to gun type 3. (see table 35 and figure 36).

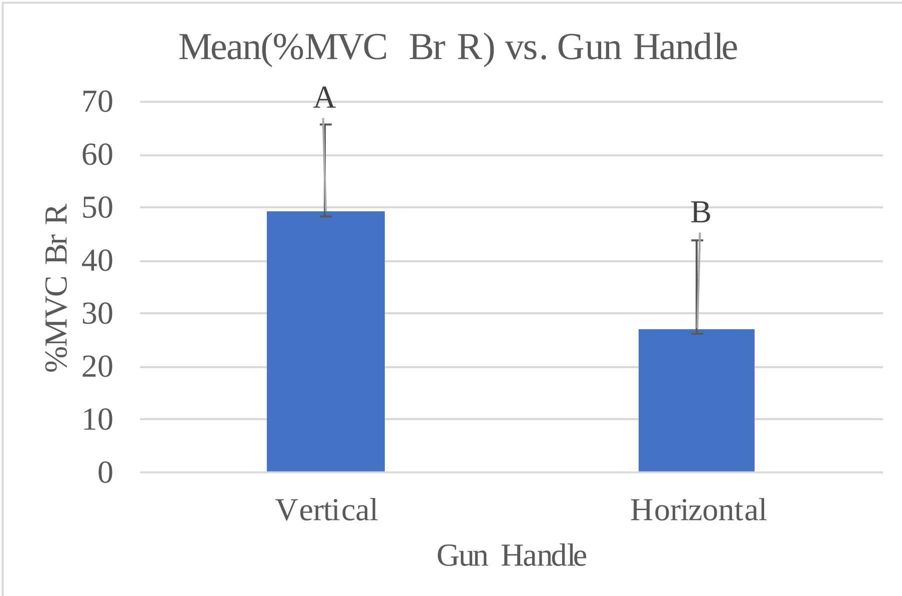


Figure 35. Mean %MVC Br R vs. Gun Handle Position

Table 35. Connecting Letter Report Gun Type (%MVC Br R) (levels not connected by the same letter are significantly different)

Level			**Least Sq Mean**	**Std Error**	**Std Deviation**
Type 3	A		61.83	17.47	101.34
Type 2	A	B	33.55	17.92	43.35
Type 1	A	B	30.87	17.83	21.14
Type 4		B	26.79	17.76	21.35

4.3.3.3. Percentage Maximum Voluntary Contraction (MVC) of the biceps brachii muscle (Upper-Arm muscle group)

The generalized linear model for this response variable reveals that the gun handle position, the two-way interaction between guns and bars, and the three-way interaction between bars, guns, and gun handle position were all significant with p-values of <.0001, 0.0122, and 0.0281 respectively (see table 36).

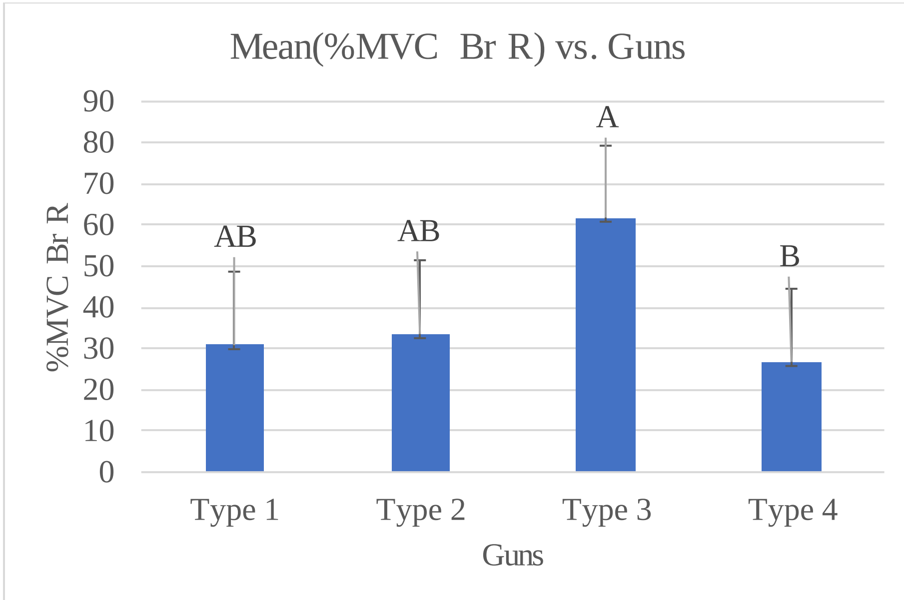


Figure 36. Mean %MVC Br R vs. Gun Type

Table 36. Fixed Effect Test (MVC Bi R)

Source	**DF**	**F Ratio**	**Prob > F**
Gun Handle	1	95.8532	<.0001 *
Guns*Bars	6	2.9731	0.0122 *
Guns*Bars*Gun Handle	6	2.4921	0.0281 *
Guns	3	1.2973	0.2803
Bars	2	1.0686	0.3479
Guns*Gun Handle	3	1.0230	0.3863
Bars*Gun Handle	2	0.3256	0.7229

The Turkey post hoc analysis performed on the gun handle position shows that the vertical gun handle position led to 34.49% MVC of the biceps brachii muscle compared to the horizontal gun handle position which only led to a 7.11% MVC, around 79.4 % difference (see table and figure below).

Table 37. Connecting Letter Report Gun Handle Position (%MVC Bi R) (levels not connected by the same letter are significantly different)

Level			**Least Sq Mean**	**Std Error**	**Std Deviation**
Vertical	A		34.49	5.78	26.92
Horizontal		B	7.11	5.88	7.31

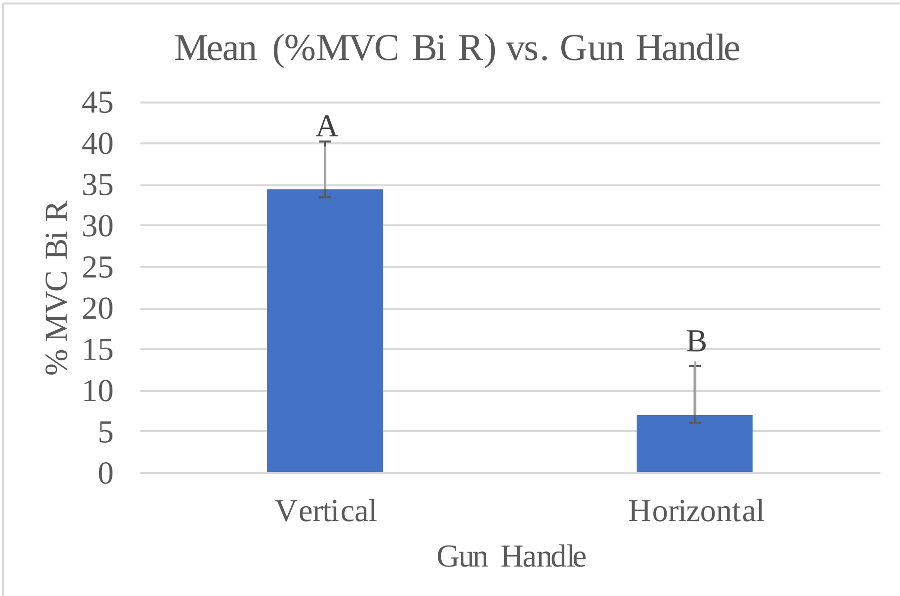


Figure 37. Mean %MVC Bi R vs. Gun Handle Position

The Tukey post hoc test results for the two-way interaction between the bucking bar and rivet gun reveal a more pronounced difference in mean % MVC between the three bucking bars for rivet gun type 3. Using this gun with the tungsten bucking bar led to the highest mean % MVC (37.62%) compared to the combination of the other types of rivet guns with the tungsten bucking bar. The combination of type 3 gun and tungsten bucking bar resulted in 68.3 % higher mean percentage EMG of the biceps muscle compared to the combination of gun type 2 with the tungsten bucking bar (see table 38 and figure 38 below). Considering the three-way interaction between the bucking bar, rivet gun, and rivet gun handle position, the turkey post hoc results reveal that the difference in mean %MVC between the different bucking bars and rivet gun handle positions is much more pronounced when using type 3 rivet gun.

Table 38. Connecting Letter Report Two-way Interaction between Gun Type and Bar (%MVC Br R) (levels not connected by the same letter are significantly different)

Level			Least Sq Mean
Type 3,Tungsten (2.7lbs)	A		37.63
Type 3,Steel (1lb)	A	B	25.18
Type 2,Steel (1lb)	A	B	24.99
Type 1,Steel (1lb)	A	B	24.20
Type 4,Spring Dampener (5lbs)	A	B	22.18
Type 2,Spring Dampener (5lbs)	A	B	21.89
Type 1,Tungsten (2.7lbs)	A	B	19.95
Type 4,Steel (1lb)	A	B	19.73
Type 1,Spring Dampener (5lbs)	A	B	15.76
Type 3,Spring Dampener (5lbs)		B	13.17
Type 4,Tungsten (2.7lbs)		B	12.96
Type 2,Tungsten (2.7lbs)		B	11.94

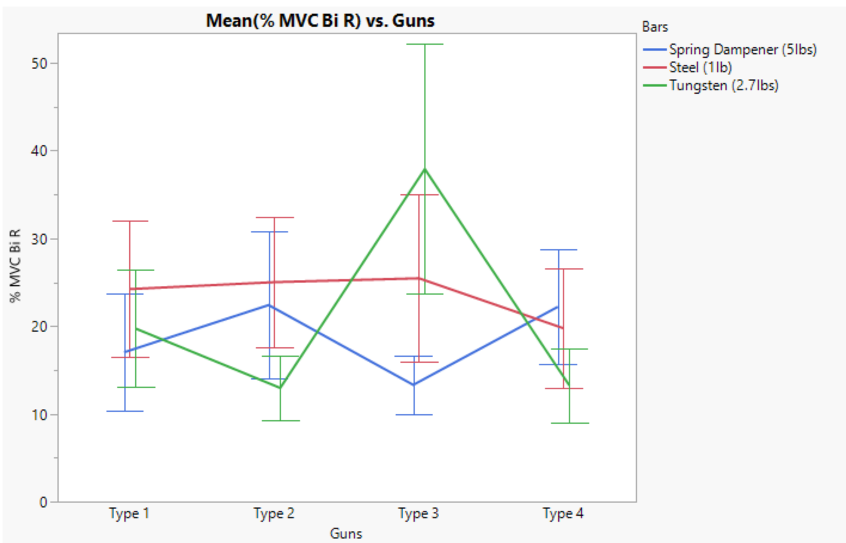


Figure 38. Mean %MVC Bi R vs. Two-way Interaction between Gun Type and Bucking Bar

The difference in mean % MVC for the biceps brachii muscle is much larger between the vertical (66.31%) and horizontal (8.94%) rivet gun handle position when using type 3 rivet gun jointly with the tungsten bucking bar (see table 39 and figure 39 below).

4.3.4. Perceived Level of Exertion (Borg Scale)

After each experimental trial, the participants were asked to rate their perceived level of exertion on a scale of 0-10. This perception referred to how heavy and strenuous the activity felt to them (feeling of physical stress, effort, pain, and fatigue). The results of the generalized linear model performed on this response variable show that only the gun handle position was significant (p = 0.0076) (see table 40).

Table 39. Connecting Letter Report Three-way Interaction between Gun Type, Bar, and Gun Handle Position (%MVC Br R) (levels not connected by the same letter are significantly different)

Level						**Least Sq Mean**
Type 3,Tungsten (2.7lbs),Vertical	A					66.31
Type 2,Steel (1lb),Vertical	A	B	C			43.77
Type 3,Steel (1lb),Vertical	A	B		D		42.24
Type 2,Spring Dampener (5lbs),Vertical	A	B	C	D	E	38.94
Type 4,Spring Dampener (5lbs),Vertical	A	B	C	D	E	35.74
Type 1,Steel (1lb),Vertical	A	B	C	D	E	34.50
Type 4,Steel (1lb),Vertical	A	B	C	D	E	33.12
Type 1,Tungsten (2.7lbs),Vertical	A	B	C	D	E	31.35
Type 1,Spring Dampener (5lbs),Vertical		B	C	D	E	28.02
Type 4,Tungsten (2.7lbs),Vertical		B	C	D	E	21.14
Type 2,Tungsten (2.7lbs),Vertical		B	C	D	E	19.62
Type 3,Spring Dampener (5lbs),Vertical		B	C	D	E	19.13
Type 1,Steel (1lb),Horizontal		B	C	D	E	13.90
Type 3,Tungsten (2.7lbs),Horizontal		B	C	D	E	8.94
Type 4,Spring Dampener (5lbs),Horizontal		B	C	D	E	8.63
Type 1,Tungsten (2.7lbs),Horizontal		B	C	D	E	8.56
Type 3,Steel (1lb),Horizontal		B	C	D	E	8.13
Type 3,Spring Dampener (5lbs),Horizontal				D	E	7.20
Type 4,Steel (1lb),Horizontal					E	6.33
Type 2,Steel (1lb),Horizontal					E	6.22
Type 2,Spring Dampener (5lbs),Horizontal					E	4.83
Type 4,Tungsten (2.7lbs),Horizontal					E	4.79
Type 2,Tungsten (2.7lbs),Horizontal			C		E	4.27
Type 1,Spring Dampener (5lbs),Horizontal					E	3.50

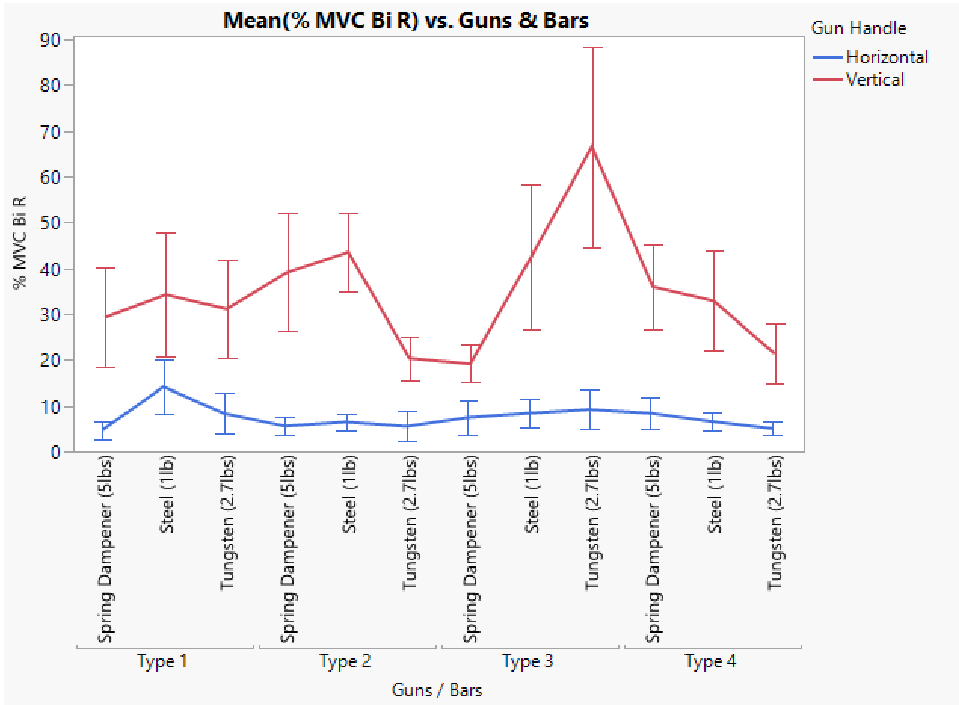


Figure 39. Mean %MVC Bi R vs. Three-way Interaction between Gun Type, Bucking Bar, and Gun Handle Position

Table 40. Effect Test (Perceived Level of Exertion)

Source	**DF**	**L-R ChiSquare**	**Prob>Chi Sq**
Guns	3	1.2054399	0.7517
Bars	2	6.4053961	0.0407*
Gun Handle	1	7.1140238	0.0076*
Guns*Gun Handle	3	0.9002477	0.8254
Guns*Bars	6	1.9271758	0.9263
Bars*Gun Handle	2	0.5621051	0.7550
Guns*Bars*Gun Handle	6	1.301415	0.9716

The graph below shows that the riveters felt less exertion when using the rivet gun in the vertical handle position compared to the horizontal handle position. Their average rates were 22.1 % higher for the horizontal position (SD = 1.15) compared to the vertical position (SD = 1.31).

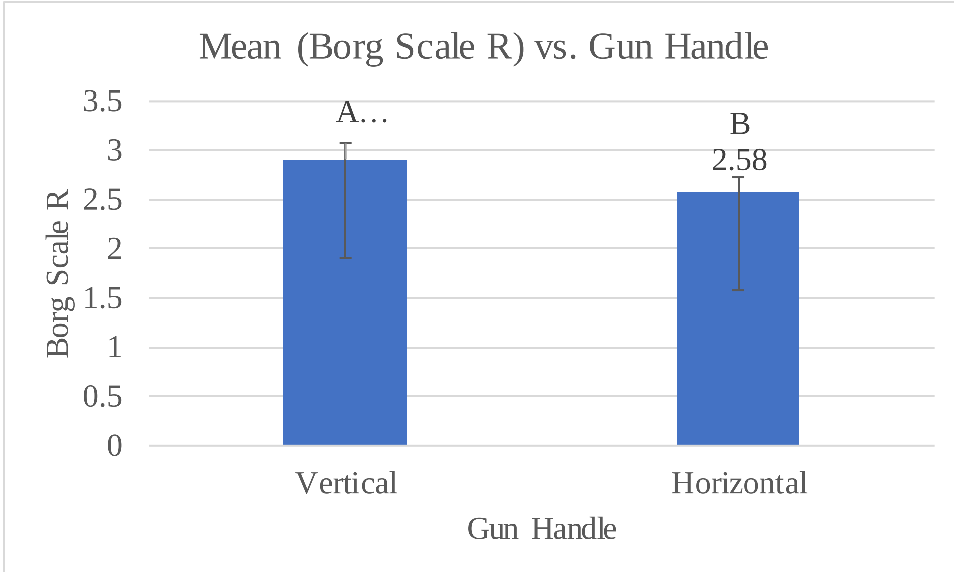


Figure 40. Mean Riveters' Perceived Level of Exertion vs. Gun Handle Position

4.3.5. Summary of the Generalized linear model Results for all Response Variables

The generalized linear model results previously discussed per response variable are summarized in the below table. For each response variable, the rivet guns with the same letter are not statistically different, but the guns with different letters (a, b, c) are statistically different. According to the results in the table below, rivet gun type 4 resulted in the least riveter wrist acceleration RMS, least gun coupling acceleration RMS, and least % MVC of the flexor muscle group represented by the brachioradialis muscle. Although gun type 3 resulted in the least % MVC of the extensor digitorium and biceps brachii muscle, the differences were not statistically significant among all guns tested.

Table 41. Summary Generalized Linear Model (Rivet Gun Type)
(levels not connected by the same letter are significantly different)

	Type 3	Type 4	Type 1	Type 2
Wrist Acc	(a) 16.52	(a) 16.77	(a) 17.04	(b) 18.64
Gun Acc	(a) 20.74	(a) 24.94	(b) 45.6	(b) 40.29
%MVC ED	(a)72.35	(a) 60.46	(a) 66.62	(a) 66.122
%MVC BR	(a) 61.832	(b) 26.79	(ab) 30.87	(ab) 33.55

Table cont'd

	Type 3	Type 4	Type 1	Type 2
%MVC BI	(a) 25.32	(a) 18.29	(a) 19.97	(a) 19.6
Borg Scale	(a) 2.37	(a) 2.13	(a) 2.33	(a) 2.1

The rivet gun handle position was also tested. The results of the generalized linear model are summarized in the table below per response variable.

Table 42. Summary Generalized Linear Model (Gun Handle Position)
(levels not connected by the same letter are significantly different)

	Horizontal Rivet Gun handle position	Vertical Rivet Gun handle position	% Difference
Wrist Acc Res	(a) 5.67	(b) 8.33	31.93
Gun Acc Res	(a) 29.37	(b) 36.42	19.36
%MVC ED	(a) 82.09	(b) 50.68	-38.26
%MVC BR	(a) 27.20	(b) 49.32	44.85
%MVC BI	(a) 7.11	(b) 34.49	79.39
Borg Scale	(a) 2.57	(b) 1.9	-26.07

According to the summary table, the horizontal rivet gun handle position led to the least wrist acceleration resultant, least gun acceleration, least % MVC of the brachioradialis muscle (flexor group), and the biceps brachii muscle (upper arm group). However, the horizontal handle position caused 38.26 % more exertion on the extensor digitorium muscle (extensor group) compared to the vertical handle position.

4.4. DISCUSSION

The objective of part 1 was to study the effect of using different types of rivet guns, different rivet gun handle positions, and different bucking bars on the riveter vibration exposure and muscle fatigue. The vibration was measured in terms of unweighted-frequency acceleration Root Mean Square (RMS) at both the gun coupling and the wrist, and the muscle fatigue was measured in terms of Maximum Voluntary Contraction (MVC) of the extensor digitorium, brachioradialis, and biceps brachii muscle, and the perceived level of exertion (Borg Scale). Also, the grip strength was measured before and after the experimental trials of the day as a way to determine the overtime fatigue.

The different hypotheses of this study are listed based on the rivet guns, rivet gun handle position, and bucking bar as independent variables and the unweighted-frequency acceleration RMS, the % MVC of the three muscle of interest listed above as dependent variables. The outcomes of this study are discussed per dependent variables in the subsections below.

4.4.1. EFFECT OF USING DIFFERENT RIVETING TOOLS ON THE VIBRATION TRANSMITTED TO THE RIVETER'S WRIST

The results found when the acceleration is measured from the wrist of the riveter show that the gun and gun handle position were both significant on the x and z-axis. The type 2 rivet gun generated the highest unweighted-frequency RMS (8.3 m/s2), around 24.6% compared to type 3 gun. However, gun types 3 & 4, which difference resides in the piston material (tungsten vs. steel respectively), were not significantly different. A study by HumanTech (2010) on the effect of using different guns varying by manufacturer and piston material, also reports no significant difference between similar tungsten vs. steel rivet guns piston material. However, Jorgensen et al. (2006) after studying the effect of using different types of rivet guns on Hand-Arm Vibration (HAV) found that the tungsten piston rivet gun significantly decreases the vibration experienced by riveter compared to similar steel piston guns. This might be due to some other factors involved in the comparison such as rivet gun size and manufacturer.

Besides, the horizontal rivet gun handle position resulted in a statistically smaller acceleration RMS value compared to the vertical gun handle position, around 40% difference on the x-axis and 11.14`% difference on the z-axis. Changing the rivet gun handle position from vertical to horizontal involves some changes in the wrist and shoulder position. A study by Kattel and Fernandez (1999) on the effect of using different riveting wrist postures which are: neutral referring to the vertical gun handle position, 1/3 max. flexion, and 1/3 max. ulnar deviation from the neutral position, found similar results with the neutral wrist position leading to the second-highest frequency-unweighted acceleration RMS value following the 1/3 max. flexion wrist posture which led to the highest RMS value on both the x and y-axis.

The interaction between gun and gun handle position was statistically significant on the y and z-axis. Using rivet gun type 2 in the vertical handle position resulted in a higher mean unweighted-frequency acceleration RMS value compared to the combination of all other levels.

The three-way interaction between the gun, bar, and gun handle position was only significant on the z-axis with the combination of type 2 rivet gun with the steel bucking bar leading to the highest unweighted-frequency RMS (15.83 m/s2) especially when the rivet gun was used in a vertical handle position.

4.4.2. EFFECT OF USING DIFFERENT RIVETING TOOLS ON THE VIBRATION TRANSMITTED TO THE RIVETER'S HAND AND FINGERS

The results of the generalized linear model performed on the unweighted-frequency acceleration RMS at the gun coupling show that the gun and gun handle position were statistically significant on all axis and the resultant. When measuring the acceleration RMS from the gun coupling, Kattel and Fernandez (1999) also found that the neutral position of the wrist (gun vertical handle position) resulted in the highest unweighted-frequency acceleration RMS compared to the 1/3 max. flexion and the 1/3 max. ulnar deviation wrist postures. Although shifting from the neutral position of the wrist and the conventional shoulder and elbow position when the gun is in a vertical handle position lessens the vibration transmitted to the hand of riveters, it might also involve other muscle overexertion problems, especially at the shoulder. Widia and Dawal (2011) found that the trapezius pars descendenz muscle responds to changes in working posture. They found that this muscle activity increases when the hand is subjected to vibration. Thus, studying the effect of changing the rivet gun handle position from vertical to horizontal on the riveter's shoulder muscle activity might be of interest.

4.4.3. EFFECT OF USING DIFFERENT RIVETING TOOLS ON THE PERCENTAGE MAXIMUM VOLUNTARY CONTRACTION OF THE RIVETER'S MAJOR ARM MUSCLES (EMG)

Three different riveter's arm muscles were tested in this study, the extensor digitorium (extensor group), the brachioradialis (flexor group), and the biceps brachii (upper-arm group) muscles. The results of the generalized linear model on EMG data reveal that the gun handle position was significant for all three muscles tested. Changing the rivet gun handle orientation from vertical to horizontal significantly decreased the mean % MVC of the brachioradialis and biceps brachii muscle, but increased the mean % MVC of the extensor digitorium muscle. The extensor digitorium muscle extends through all the fingers except the thumb and help moving them. This muscle also helps in the movement of the wrist and elbows (https://www.healthline.com/human-body-maps/extensor-digitorum-muscle#1). Since changing the gun handle orientation from vertical to horizontal involves changes in the wrist, elbow, shoulder, and possibly fingers combined with vibration exposure, we expect to see an increase in this muscle activity when changing gun handle orientation from vertical to horizontal. Certain parameters such as gripping, pushing force, and posture influence vibration transmission in the body (Widia and Dawal, 2011).

The gun was only significant for the brachioradialis muscle. This finding might be explained by the fact that the brachioradialis muscle was the most sensitive to the change in vibration levels from the different rivet guns due to its location.

The two-way interaction between the gun and bar as well as the three-way interaction between the gun, bar, and gun handle position were significant only for the biceps muscle activity.

In other words, the type of bucking bar used by the bucker had an effect on the riveter's biceps brachii muscle activity.

4.4.4. Effect of using different riveting tools on the riveter's perceived level of exertion (Borg Scale)

The results of the generalized linear model show that the participants felt less exertion when using the gun in the vertical handle position compared to the horizontal position, around 22.1 % difference. This difference in perceived level of exertion might be the result of additional stress felt in the shoulder or neck of riveters when using the gun in a horizontal position, or simply of some discomfort felt by the riveter when using the gun in that position. A more focused study on the effect of riveting tools on the riveters' perceived level of exertion per body segment is necessary to draw any conclusion.

4.5. CONCLUSION

The objective of this part was to study the effect of using different types of rivet guns, different rivet gun handle positions, and different bucking bars on the riveters' vibration exposure and muscle fatigue. The vibration exposure was measured in terms of unweighted-frequency acceleration Root Mean Square (RMS) at both the gun coupling and the wrist, and the muscle fatigue was measured in terms of Maximum Voluntary Contraction (MVC) of the extensor digitorium, brachioradialis, and biceps brachii muscle, and perceived level of exertion (Borg Scale). Also, the grip strength was measured before and after the experimental trials of the day as a way to determine the riveters overtime fatigue.

The results show that the rivet gun type 4 resulted in the least riveter wrist acceleration RMS, least gun coupling acceleration RMS, and least % MVC of the brachoradialis muscle, extensor digitorium, and biceps brachii muscle. Although, the gun was not a significant factor for the perceived level of exertion (Borg Scale), and the activity of the extensor digitorium and biceps brachii muscle, the mean % MVC of those two muscles was the smallest for rivet gun types 3 & 4 and the mean riveters rating was the second smallest for rivet gun type 4 (2.13) after rivet gun type 2 (2.1). As one can see, the results were consistent on all response variables with rivet gun type 4 resulting in the least vibration exposure as well as muscle fatigue. However, rivet gun type 3 which was not significantly different from the gun type 4 in terms of mean wrist acceleration and gun acceleration (smallest mean acceleration value), resulted in the highest mean % MVC of all three riveters' muscles. This is inconsistent with our hypothesis that the gun which generates the least vibration amplitude would also lead to the least muscle activity. This discrepancy might be explained by the fact that rivet type 3 is different from other guns by its Blow Per Minute (BPM) value of (2100) compared to other rivet gun types (1740). Having a higher BPM suggests that rivet gun type 3 hammers faster than the other rivet gun, which might require the riveter to exert more grip force and flexor muscle activity to stabilize the rivet gun.

The results also show that the horizontal rivet gun handle position led to the least wrist acceleration resultant, least gun acceleration, least % MVC of the brachioradialis muscle (flexor group), and biceps brachii muscle (upper arm group). However, the horizontal handle position caused 38.26 % more exertion on the extensor digitorium muscle (extensor group) compared to the vertical handle position. This difference in observation might be due to the function of the extensor digitorium muscle relative to the posture of the riveter when using the gun in a horizontal handle position. In fact, the extensor digitorium muscle intervenes in the motion of the wrist and elbow. Since changing the gun handle orientation from vertical to horizontal involves changes in the wrist, elbow, shoulder, and possibly fingers, we expect to see an increase in this muscle activity when changing the gun handle position from vertical to horizontal.

Since the bar factor and the interaction between the type of guns and bars were not significant factors when considering the acceleration RMS at the wrist and gun, we can conclude that the type of the bucking bar used by the bucker does not affect the riveter exposure to vibration. Nevertheless, the fact that the two-way interaction between the bar and the gun was significant for the % MVC of the riveter's biceps brachii muscle suggests that certain combination of bucking bar and rivet gun have a higher impact on the riveter's biceps brachii muscle activity compared to other combination of tools. In this study, the combination of rivet gun type 3 and tungsten bucking bar led the highest mean value of %MVC of the riveter's biceps brachii muscle. This combination was statistically different from the combination of gun type 3 and the spring dampener and tungsten combined bucking bar, gun type 4 and the tungsten bucking bar, and gun type 2 and the tungsten bucking bar. Nevertheless, these combinations were not significantly different from all other combinations.

Overall, the riveter's extensor muscle group (Extensor digitorium) seemed to be the most affected by the gun vibration with the highest mean % MVC values followed by the flexor muscle group (Brachioradialis) and the upper-arm muscle group (Biceps brachii). The same observation was found when comparing the difference in the rivet gun handle position.

The riveters' heart rate was monitored throughout the experimental trials and their grip strength was measured prior and after the experimental trials of each day as a way to determine the overtime fatigue. The results were inconclusive with no statistical significance. This outcome is understandable since the riveters were exposed to vibration for only 6 min per day with resting periods every 30 s. The time of exposure and intensity of the task were not high enough to cause a significant difference in heart rate or grip strength for the riveters.

CHAPTER 5. PART 2- THE EFFECT OF RIVETING TOOLS ON BUCKERS' VIBRATION EXPOSURE AND MUSCLE FATIGUE

5.1. INTRODUCTION

Studies have shown that buckers are at higher risk of developing HAVS and other vibration-induced disorders since they experienced higher vibration levels compared to riveters. In addition to the exposure to high vibration frequency and amplitude level, buckers are at risk of forceful exertion, repetitive motion, awkward hand, and finger posture, when holding the bucking bar (Kattel & Fernandez, 1999). The combination of high exposure to vibration and overexertion increases the risk of injuries. Thus, it is necessary to quantify and minimize buckers' exposure to vibration.

Bucking bars were originally made of steel material, but in recent years tungsten bucking bars were introduced as an effective way to reduce the amount of vibrations experienced by buckers. Indeed, heavier than the regular steel bucking bars of similar size, tungsten bucking bars were proven to dampen the vibrations emitted by rivet guns thereby protecting the bucker. Several researches have studied the role of tungsten bucking bar in reducing the vibrations experienced by workers in aircraft manufacturing. For example, McDowell et al. (2015) performed a study involving the testing of three traditional steel bucking bars, three similarly shaped tungsten alloy bars, and three spring-dampeners bars in both the laboratory and workplace. The results of this study indicate a significantly higher weighed and unweighted root mean square values for the traditional steel bucking bars compared to the newer bucking bar technologies involving tungsten material and spring-dampeners. This study explained that although the heavier mass of tungsten bucking bars significantly reduced the vibration level emitted by rivet guns, the additional weight may lead to other ergonomic issues. It is worth noting that this study involved only light riveting activities with bucking bars weight ranging between 0.83-1.47 kg for steel bucking bars and 1.98-

2.80 kg for tungsten bucking bars. Thus, heavier riveting activities involving larger rivet size, larger rivet guns, and bucking bars in addition to vibration may lead to an increase in the arm muscle activities and a decrease in grip strength. Yet, few studies have focused on the possible effect of using these heavy-duty riveting tools on workers' upper arm and forearm muscle activities and gripping strength. This study addressed that gap by monitoring and comparing the effect of the different vibration levels on buckers' upper arm, extensor, and flexor muscle group. The grip strength, heart rate, and perceived level of exertion (Borg Scale) were also used as fatigue indices (Hull, 2007; Jorgensen et al., 2005; Widia et al.; 2011).

This part main goal was to determine the effect of using different bucking bars, different rivet guns, and gun handle positions on the buckers' vibration exposure and muscle fatigue. Similar to the part 1, the was based on the unweighted-frequency acceleration (RMS) and the muscle fatigue associated with the vibration experienced by the bucker.

5.2. DEPENDENT AND INDEPENDENT VARIABLES

Three independent variables were tested in part 2, which are 4 types of rivet guns, 3 bucking bars, as well as two rivet gun handle positions. The comparisons were based on the following dependent variables: the unweighted-frequency acceleration Root Mean Square (RMS) at the bucking bar coupling as a measure vibration transmission on the x, y, z-axis and the resultant of the 3 axes, the percentage Maximum Voluntary Contraction (MVC) of the buckers' extensor carpi radialis, palmaris longus, and biceps brachii muscles, and perceived level of exertion (Borg Scale) of the buckers as a measure of muscle fatigue. Heart rate and grip strength percentage change were used to estimate the overtime fatigue of buckers. The data collection was achieved following the protocol on page 46 of this document.

5.3. RESULTS

Part 2 focuses on the bucker side by studying the effect of using different bucking bars, different types of rivet guns, and different rivet gun handle positions on the buckers' vibration exposure and muscle fatigue. A generalized linear model was performed on each response variable with rivet guns, bucking bars, and gun handle position as fixed effects, and "pair of participants" and "days of experiment" as random effects. Once the overall source of significance was found for each response variable, a Turkey post hoc test (pair-wise comparison) was performed to determine which levels of the main factors were significantly different. This section will address sequentially the results found for each response variable.

5.3.1. UNWEIGHTED-FREQUENCY ACCELERATION ROOT MEAN SQUARE (RMS) AT THE BUCKING BAR COUPLING

A triaxial accelerometer was mounted on the bucking bar close to the gripping zone in order to measure the vibration transmitted to the fingers and hand of the buckers. The acceleration data were reported as unweighted-frequency RMS in m/s^2 on the x, y, z-axis as well as the resultant. The table below summarizes the different sources of significance.

Table 43. Statistical Sources of Significance (Bar Coupling Acc)

	Bar Acc X	Bar Acc Y	Bar Acc Z	Bar Acc Res
Guns	0.4873	0.5965	0.3502	0.46
Bars	* <0.0001	* <0.0001	* <0.0001	* <0.0001
Gun Handle Position	0.9124	0.9776	0.8717	0.9723
Guns * Bars	* 0.0002	* 0.0007	* <0.0001	* 0.0001
Gun * Gun Handle Position	0.4691	0.3763	0.5127	0.4511
Bars * Gun Handle Position	0.8722	0.9486	0.9129	0.9154
Guns * Bars * Gun Handle Position	0.4223	0.2845	0.3863	0.348
Block & Random	0.6025	0.4406	0.2982	0.4027
Days & Random	0.6695	0.6209	0.5982	0.6184

The two random effects, “pair of participants” (block) and “day of experiment”, were not significant when performing a generalized linear model on the unweighted-frequency acceleration Root Mean Square (RMS) at the bucking bar coupling. Blocking these two variables in our model is therefore justified.

5.3.1.1 . Unweighted-frequency acceleration Root Mean Square (RMS) at the bucking bar coupling X-Axis

On the X-axis, both the bar and the two-way interaction between the gun and the bar were significant with p-values of <0.0001 and 0.0002 respectively (see table below).

Table 44. Fixed Effect Test (Bar Coupling Acc X-axis)

Source	**DF**	**F Ratio**	**Prob > F**
Bars	2	28.8015	<.0001 *
Guns*Bars	6	4.9364	0.0002 *
Guns*Bars*Gun Handle	6	1.0124	0.4223
Guns*Gun Handle	3	0.8520	0.4691
Guns	3	0.8177	0.4873
Bars*Gun Handle	2	0.1369	0.8722
Gun Handle	1	0.0122	0.9124

The results of the Turkey post hoc analysis performed on the bars reveal that the spring dampener and tungsten combined bucking bar resulted in the lowest unweighted-frequency acceleration RMS (4.17 m/s^2) compared to the tungsten (11.87 m/s^2) and steel (12.23 m/s^2) bucking bars, around 66% difference. The tungsten and steel bucking bars were not statistically different (see table 45 and figure 41).

The combination of type 1 rivet gun with the steel bucking bar resulted in a statistically higher unweighted-frequency acceleration RMS value compared to the combination of type 4 and tungsten bar (10.7 m/s^2), type 3 and steel bar (9.55 m/s^2), type 2 and steel bar (9.03 m/s^2), type 1 and tungsten bar (8.51m/s^2), and the combination of all rivet guns with the spring dampener and tungsten combined bucking bar.

Table 45. Connecting Letter Report Bucking Bar (Bar Acc X) (levels not connected by the same letter are significantly different)

Level		Least Sq Mean	Std Error	Std Deviation
Steel (1lb)	A	12.23	1.13	6.19
Tungsten (2.7lbs)	A	11.87	1.15	7.93
Spring Dampener (5lbs)	B	4.17	1.16	1.02

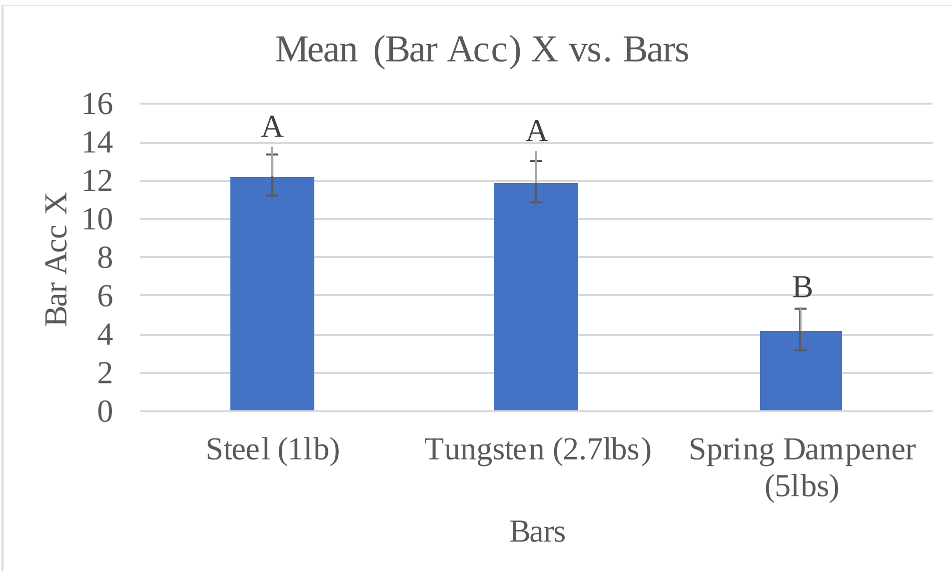


Figure 41. Mean Bar Acc X vs. Bucking Bar

The use of any rivet gun with the spring dampener and tungsten combined bucking bar resulted in the least acceleration RMS value ranging between (4.03-4.31 m/s^2) (see table 46 and figure 42).

Table 46. Connecting Letter Report Two-way Interaction Between Bucking Bar and Rivet Gun (Bar Acc X) (levels not connected by the same letter are significantly different)

Level		Least Sq Mean
Type 1,Steel (1lb)	A	18.88
Type 2,Tungsten (2.7lbs)	A B	15.79
Type 3,Tungsten (2.7lbs)	A B C	12.47
Type 4,Steel (1lb)	A B C D	11.46

Table cont'd

Level		Least Sq Mean
Type 4,Tungsten (2.7lbs)	B C D	10.70
Type 3,Steel (1lb)	B C D	9.55
Type 2,Steel (1lb)	B C D	9.03
Type 1,Tungsten (2.7lbs)	B C D	8.51
Type 1,Spring Dampener (5lbs)	C D	4.31
Type 3,Spring Dampener (5lbs)	D	4.19
Type 2,Spring Dampener (5lbs)	D	4.15
Type 4,Spring Dampener (5lbs)	D	4.03

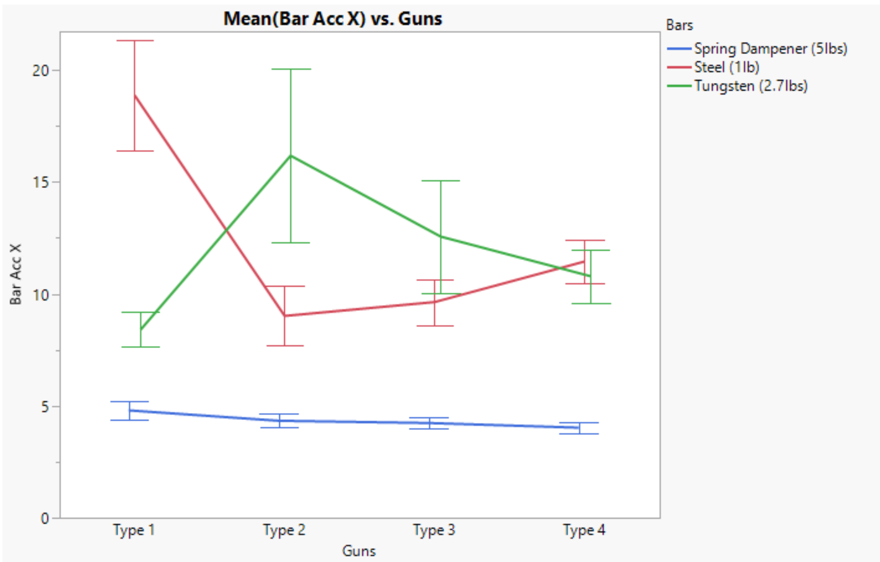


Figure 42. Mean Bar Acc X vs. Two-way Interaction between Bucking Bar and Rivet Gun Type

5.3.1.2 . Unweighted-frequency acceleration Root Mean Square (RMS) at the bucking bar coupling Y-Axis

The statistical analysis performed on the y-axis reveals that both the bar ($p<0.0001$) and two-way interaction ($p=0.0007$) between the bar and the gun were significant (see table 47).

Table 47. Fixed Effect Test (Bar Coupling Acc Y-axis)

Source	DF	F Ratio	Prob > F
Bars	2	32.5763	<.0001*
Guns*Bars	6	4.2874	0.0007*
Guns*Bars*Gun Handle	6	1.2582	0.2845
Guns*Gun Handle	3	1.0456	0.3763

Table cont’d

Guns	3	0.6315	0.5965
Bars*Gun Handle	2	0.0528	0.9486
Gun Handle	1	0.0008	0.9776

The Turkey post hoc analysis performed on the bar for the y-axis also reveals that the spring dampener bucking bar led to the least mean acceleration RMS value (2.95 m/s^2) compared to the steel and tungsten bucking bar 10.62 m/s^2 and 10.67 m/s^2 respectively, around 72.26% difference (see table 48 and figure 43).

Table 48. Connecting Letter Report Bucking Bar (Bar Acc Y) (levels not connected by the same letter are significantly different)

Level		Least Sq Mean	Std Error	Std Deviation
Tungsten (2.7lbs)	A	10.67	1.18	7.38
Steel (1lb)	A	10.62	1.17	5.53
Spring Dampener (5lbs)	B	2.96	1.18	1.24

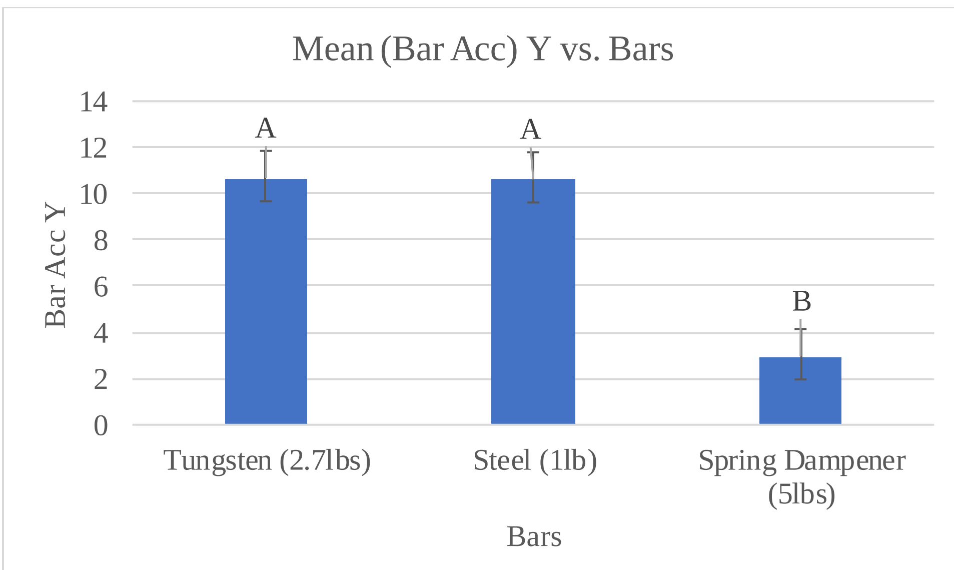


Figure 43. Mean Bar Acc Y vs. Bucking Bar

The Turkey post hoc analysis results for the two-way interaction on the y-axis are similar to the results found on the x-axis with the combination of gun type 1 and the steel bucking bar resulting in the highest unweighted-frequency acceleration RMS value (16.52 m/s^2). Also, the combination of any rivet gun type with the spring dampener and tungsten combined bucking bar led to the least acceleration values ranging from (2.81 – 3.17 m/s^2) (see table 49 and figure 44).

Table 49. Connecting Letter Report Two-way Interaction Between Bucking Bar and Rivet Gun (Bar Acc Y) (levels not connected by the same letter are significantly different)

Level				**Least Sq Mean**
Type 1,Steel (1lb)	A			16.52
Type 2,Tungsten (2.7lbs)	A	B		13.44
Type 3,Tungsten (2.7lbs)	A	B		11.55
Type 4,Steel (1lb)	A	B	C	9.81
Type 4,Tungsten (2.7lbs)	A	B	C	9.79
Type 3,Steel (1lb)		B	C	8.12
Type 2,Steel (1lb)		B	C	8.03
Type 1,Tungsten (2.7lbs)		B	C	7.89
Type 3,Spring Dampener (5lbs)			C	3.17
Type 4,Spring Dampener (5lbs)			C	3.00
Type 2,Spring Dampener (5lbs)			C	2.85
Type 1,Spring Dampener (5lbs)			C	2.81

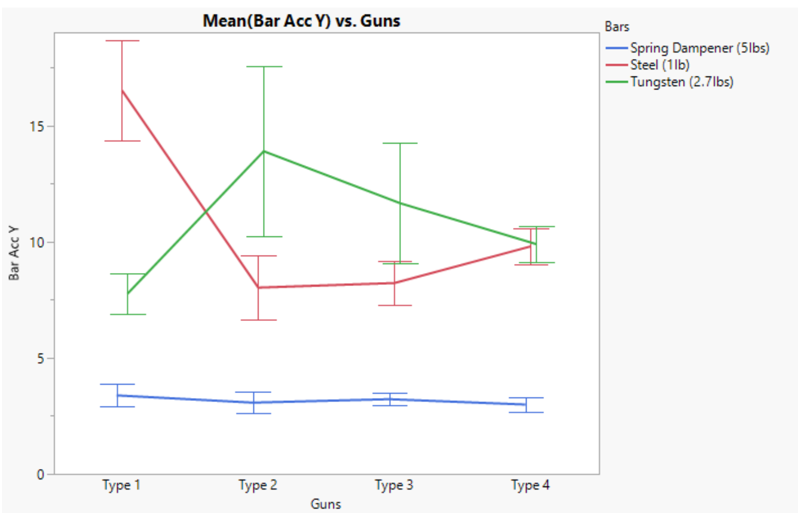


Figure 44. Mean Bar Acc Y vs. Two-way Interaction between Bucking Bar and Rivet Gun Type

5.3.1.3 . *Unweighted-frequency acceleration Root Mean Square (RMS) at the bucking bar coupling Z-Axis*

The results found in the z-direction are similar to the results observed on the x and y-axis with both the bar (p<0.0001) and two-way interaction between the bar and rivet gun (p<0.0001) being significant (see table below).

Table 50. Fixed Effect Test (Bar Coupling Acc Z-axis)

Source	DF	F Ratio	Prob > F
Bars	2	46.5733	<.0001 *
Guns*Bars	6	6.0231	<.0001 *
Guns	3	1.1075	0.3502
Guns*Bars*Gun Handle	6	1.0702	0.3863
Guns*Gun Handle	3	0.7718	0.5127
Gun Handle	1	0.0262	0.8717
Bars*Gun Handle	2	0.0913	0.9129

The Turkey post hoc analysis shows that the spring dampener bucking bar resulted in approximately 69.13 % less unweighted-frequency acceleration RMS compared to the tungsten and steel bucking bar (see table 51 and figure 45).

Table 51. Connecting Letter Report Bucking Bar (Bar Acc Z) (levels not connected by the same letter are significantly different)

Level			Least Sq Mean	Std Error	Std Deviation
Steel (1lb)	A		15.55	1.49	8.07
Tungsten (2.7lbs)	A		14.49	1.50	7.31
Spring Dampener (5lbs)		B	4.80	1.50	1.68

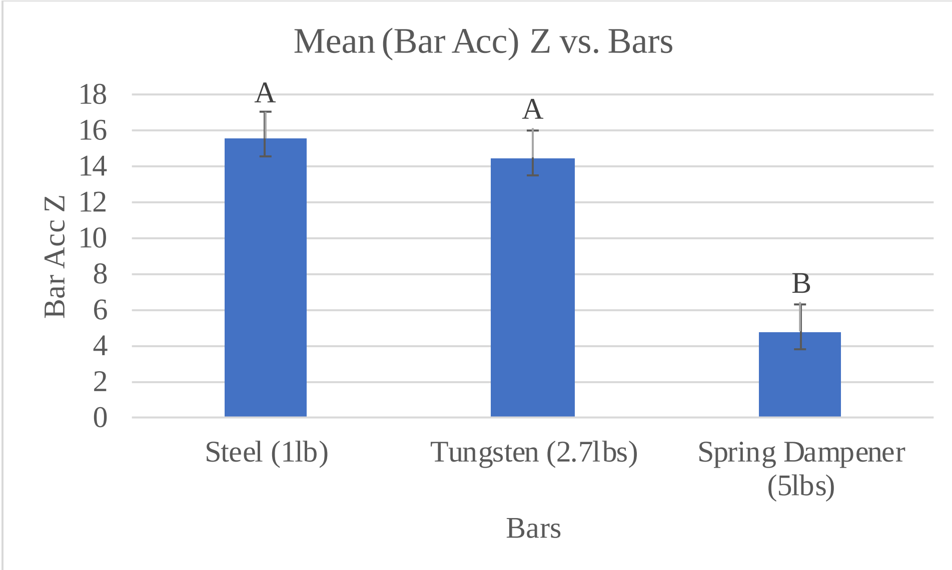


Figure 45. Mean Bar Acc Z vs. Bucking Bar

The Turkey post hoc analysis results for the two-way interaction between the bar and rivet gun on the z-axis are similar to the x and y-axis with the combination of type 1 rivet gun and steel bucking bar resulting in the highest unweighted-frequency acceleration RMS value (23.68 m/s^2) compared to the other combinations (see table 52 and figure 46).

Table 52. Connecting Letter Report Two-way Interaction Between Bucking Bar and Rivet Gun (Bar Acc Z) (levels not connected by the same letter are significantly different)

Level				**Least Sq Mean**
Type 1,Steel (1lb)	A			23.68
Type 2,Tungsten (2.7lbs)	A	B		17.98
Type 3,Tungsten (2.7lbs)		B		15.07
Type 4,Tungsten (2.7lbs)		B		14.00
Type 4,Steel (1lb)		B		13.98
Type 3,Steel (1lb)		B	C	12.54
Type 2,Steel (1lb)		B	C	11.98
Type 1,Tungsten (2.7lbs)		B	C	10.89
Type 3,Spring Dampener (5lbs)			C	4.98
Type 4,Spring Dampener (5lbs)			C	4.96
Type 1,Spring Dampener (5lbs)			C	4.80
Type 2,Spring Dampener (5lbs)			C	4.47

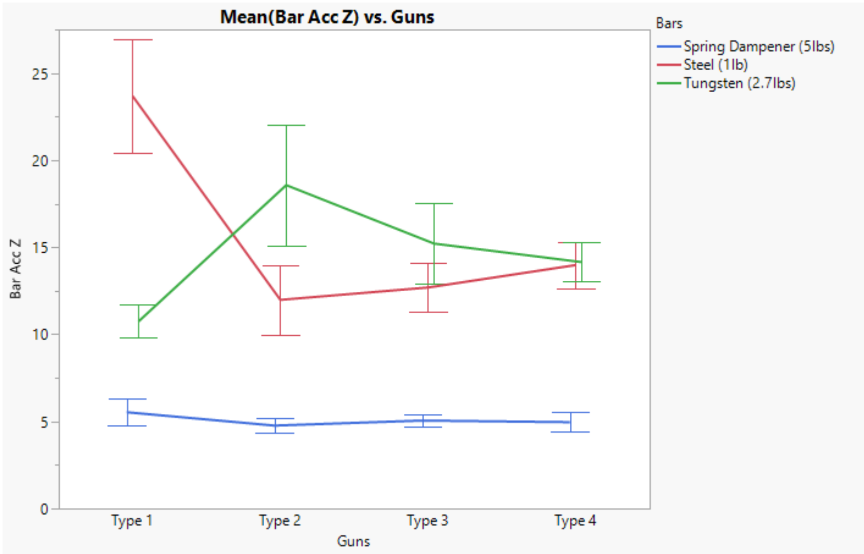


Figure 46. Mean Bar Acc Z vs. Two-way Interaction between Bucking Bar and Rivet Gun Type

5.3.1.4 . Unweighted-frequency acceleration Root Mean Square (RMS) at the bucking bar coupling resultant

Since the results on the individual axis are consistent, the results for the resultant of the 3 axes are also found to be consistent with each axis. Both the bar ($p<0.0001$) and two-way interaction between the bar and gun ($p=0.0001$) were significant (see table below).

Table 53. Fixed Effect Test (Bar Coupling Acc Resultant)

Source	**DF**	**F Ratio**	**Prob > F**
Bars	2	37.4054	<.0001*
Guns*Bars	6	5.2948	0.0001*
Guns*Bars*Gun Handle	6	1.1359	0.3480
Guns*Gun Handle	3	0.8869	0.4511
Guns	3	0.8695	0.4600
Bars*Gun Handle	2	0.0885	0.9154
Gun Handle	1	0.0012	0.9723

Similar to the individual axis, the spring dampener bucking bar resulted in the least unweighted-frequency acceleration RMS value (7.04 m/s^2) compared to the steel (22.50 m/s^2) and tungsten

(21.63 m/s^2) bucking bars, around 68.7% difference (see table 54 and figure 47).

Table 54. Connecting Letter Report Bucking Bar (Bar Acc Resultant) (levels not connected by the same letter are significantly different)

Level		Least Sq Mean	Std Error	Std Deviation
Steel (1lb)	A	22.50	2.18	11.48
Tungsten (2.7lbs)	A	21.63	2.20	12.92
Spring Dampener (5lbs)	B	7.04	2.21	2.20

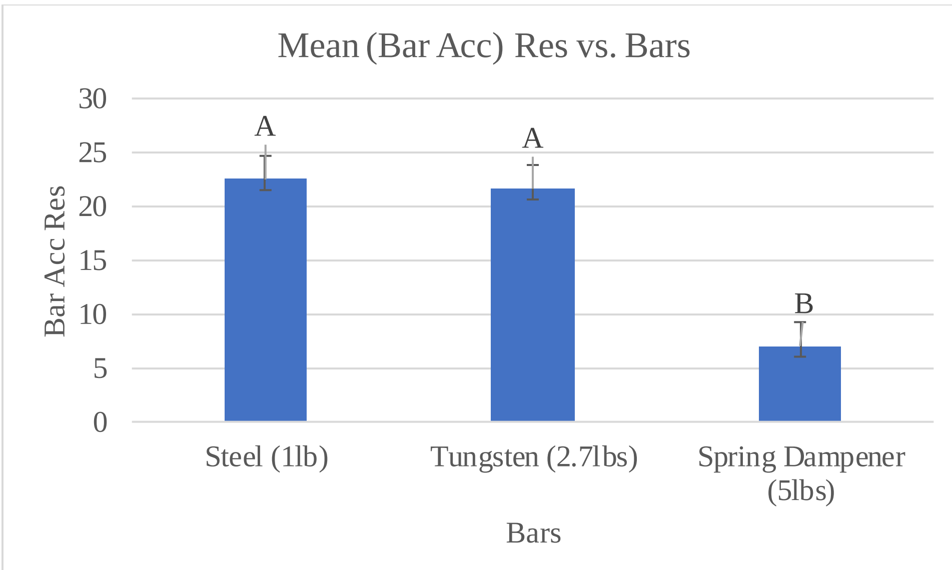


Figure 47. Mean Bar Acc Resultant vs. Bucking Bar

Unsurprisingly, the Turkey post hoc results for the resultant also show that the combination of type 1 rivet gun with the steel bucking bar was the most hazardous combination with the highest acceleration value (34.56 m/s^2) compared to the other combinations (see table 55 and figure 48).

Table 55. Connecting Letter Report Two-way Interaction Between Bucking Bar and Rivet Gun (Bar Acc Resultant) (levels not connected by the same letter are significantly different)

Level				Least Sq Mean
Type 1,Steel (1lb)	A			34.56
Type 2,Tungsten (2.7lbs)	A	B		27.56
Type 3,Tungsten (2.7lbs)	A	B		22.83
Type 4,Steel (1lb)		B	C	20.62
Type 4,Tungsten (2.7lbs)		B	C D	20.20

Table cont'd

Level					Least Sq Mean
Type 3,Steel (1lb)	B	C	D	E	17.78
Type 2,Steel (1lb)	B	C	D	E	17.06
Type 1,Tungsten (2.7lbs)	B	C	D	E	15.94
Type 3,Spring Dampener (5lbs)			D	E	7.27
Type 4,Spring Dampener (5lbs)			D	E	7.10
Type 1,Spring Dampener (5lbs)		C	D	E	7.03
Type 2,Spring Dampener (5lbs)				E	6.76

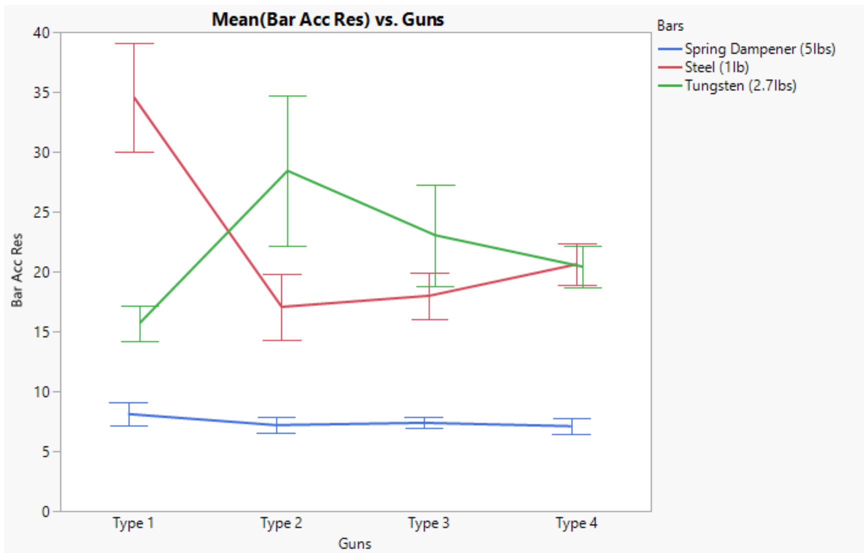


Figure 48. Mean Bar Acc Resultant vs. Two-way Interaction between Bucking Bar and Rivet Gun Type

5.2.2. PERCENTAGE MAXIMUM VOLUNTARY CONTRACTION (MVC) OF ELECTROMYOGRAPHY (EMG)

The objective of part 2 was to not only measure the vibrations transmitted to the bucker’s hand when using different riveting tools, but also to determine the effect of these vibrations on muscle fatigue. Electromyography was used to measure the activity of three different buckers’ arm muscles which are the extensor carpi radialis, the palmaris longus, and the biceps brachii muscles during each experimental trial. The results were reported as the % Maximum Voluntary Contraction (MVC) for each muscle. The following table summarizes the different sources of significance.

Table 56. Statistical Sources of Significance (Bucker's Muscle Fatigue)

	%MVC ECR B	%MVC PL B	% MVC Bi R	Borg Scale
Guns	0.5807	* <0.0001	0.089	0.3547
Bars	* 0.0110	* <0.0001	* <0.0001	* <0.0001
Gun Handle Position	0.5313	0.1767	* <0.0001	0.5768
Guns * Bars	0.5281	* 0.0296	0.764	* 0.0017
Gun * Gun Handle Position	0.9419	0.9671	0.6595	0.5468
Bars * Gun Handle Position	0.1014	0.4528	0.1254	0.9386
Guns * Bars * Gun Handle Position	0.9236	0.9891	0.7127	0.9332
Block & Random	0.2352	0.2313	0.1852	
Days & Random	0.5848	0.4565	0.0585	

The variables "pair of participants" and "day of experiment" were also not significant after performing a generalized linear model on the bucker EMG response. Blocking these two variables in our model is therefore justified.

5.2.2.1 . Percentage Maximum Voluntary Contraction (MVC) of the extensor carpi radialis muscle (Extensor muscle group)

The results of the generalized linear model performed on this response variable show that only the bar factor was significant with a p-value of 0.0110 (see table below).

Table 57. Fixed Effect Test (% MVC ECR B)

Source	**DF**	**F Ratio**	**Prob > F**
Bars	2	4.7391	0.0110 *
Bars*Gun Handle	2	2.3470	0.1014
Guns*Bars	6	0.8592	0.5281
Gun Handle	1	0.3950	0.5313
Guns	3	0.6568	0.5807
Guns*Bars*Gun Handle	6	0.3226	0.9236
Guns*Gun Handle	3	0.1302	0.9419

The Turkey post hoc test reveals that the spring dampener bucking bar resulted in the least mean % MVC for the extensor radialis muscle (34.31%) compared to the tungsten (91.52%) and steel (77.76%) bucking bars. The steel bucking bar was not statistically different from the spring dampener and tungsten combined bucking bar. However, the tungsten bucking bar led to a statistically higher % MVC, around 62.5 % compared to the spring dampener bucking bar (see table 58 and figure 49).

Table 58. Connecting Letter Report Bucking Bar (%MVC ECR B) (levels not connected by the same letter are significantly different)

Level			**Least Sq Mean**	**Std Error**	**Std Deviation**
Tungsten (2.7lbs)	A		91.52	28.54	135.76
Steel (1lb)	A	B	77.76	28.40	82.00
Spring Dampener (5lbs)		B	34.32	28.42	27.16

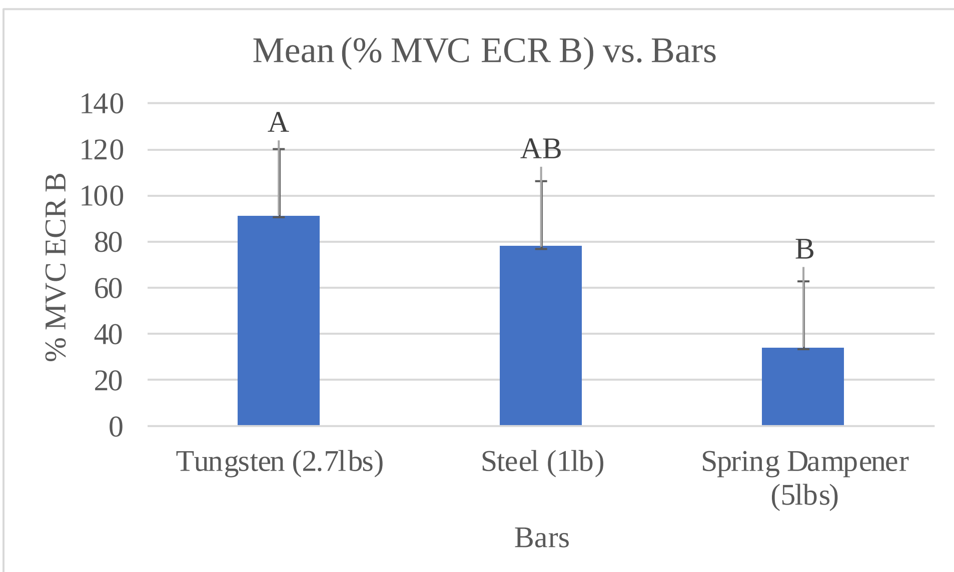


Figure 49. Mean %MVC ECR B vs. Bucking Bar

5.2.2.2 . *Percentage Maximum Voluntary Contraction (MVC) of EMG for the palmaris longus muscle (Flexor muscle group)*

The results of the statistical analysis performed on the palmaris longus muscle activity show that the gun, the bar, and the two-way interaction between the gun and the bar were all significant with p-values of <0.0001, <0.0001, and 0.0296 respectively (see table 59).

Table 59. Fixed Effect Test (% MVC PL B)

Source	**DF**	**F Ratio**	**Prob > F**
Guns	3	13.4962	<.0001*
Bars	2	16.4593	<.0001*
Guns*Bars	6	2.4657	0.0296*
Gun Handle	1	1.8541	0.1767
Bars*Gun Handle	2	0.7992	0.4528
Guns*Gun Handle	3	0.0869	0.9671
Guns*Bars*Gun Handle	6	0.1476	0.9891

The Turkey post hoc analysis performed on the first source of significance, the gun, shows that type 3 rivet gun resulted in the highest mean % MVC (152.26%) for the palmaris longus muscle compared to types 1, 2, and 4 rivet guns with mean % MVC of 56.32%, 68.19%, and 72.24% respectively. The highest difference was observed between type 3 and 1 rivet guns, with type 3 gun generating 55.2% higher mean percentage EMG of the palmaris longus muscle than type 1 rivet gun. Nevertheless, rivet gun types 1, 2, & 4 were not statistically different from one another (see table 60 and figure 50).

Table 60. Connecting Letter Report Gun Type (%MVC PL B) (levels not connected by the same letter are significantly different)

Level			**Least Sq Mean**	**Std Error**	**Std Deviation**
Type 3	A		152.26	27.49	130.22
Type 4		B	72.24	28.07	59.92
Type 2		B	68.19	28.22	57.37
Type 1		B	56.32	28.13	49.4

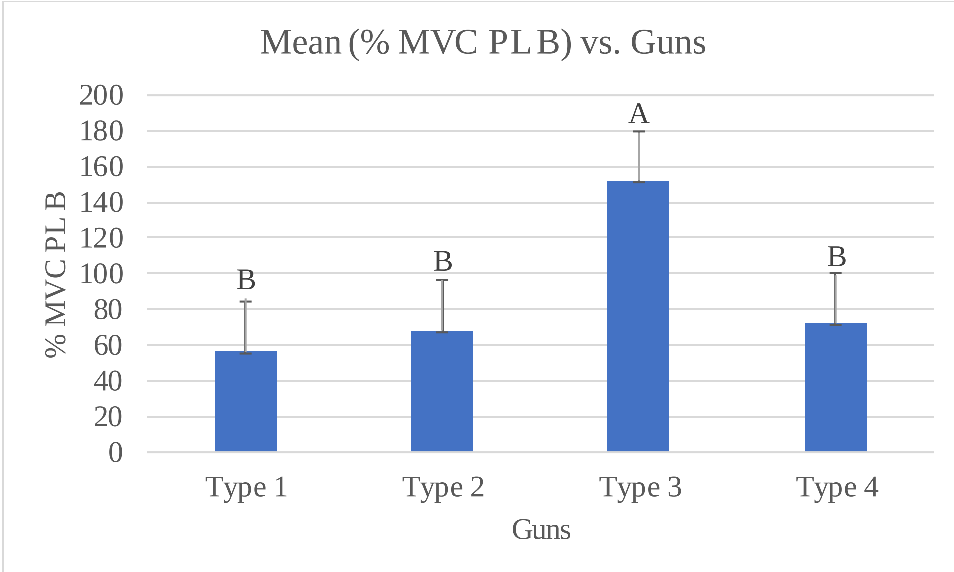


Figure 50. Mean %MVC PL B vs. Rivet Gun Type

The post hoc analysis performed on the bar reveals that the spring dampener bucking bar resulted in the least % MVC (42.18%) compared to the steel (94.38%) and tungsten (125.21%) bucking bars. The spring dampener bucking bar was 66.3% lower than the tungsten bucking bar acceleration in terms of mean % MVC of the palmaris longus muscle. The tungsten bucking bar was not statistically different from the steel bucking bar (see table 61 and figure 51).

Table 61. Connecting Letter Report Bucking Bar (%MVC PL B) (levels not connected by the same letter are significantly different)

Level			Least Sq Mean	Std Error	Std Deviation
Tungsten (2.7lbs)	A		125.21	27.49	114.41
Steel (1lb)	A		94.38	27.43	73.86
Spring Dampener (5lbs)		B	42.18	27.10	44.01

A more detailed post hoc analysis on the two-way interaction between the gun and bar reveals that the combination of rivet gun type 3 with the tungsten bucking bar resulted in a significantly higher mean % MVC (245.34%) value of the palmaris longus muscle compared to all other rivet gun and bucking bar combinations (see table 62 and figure 52).

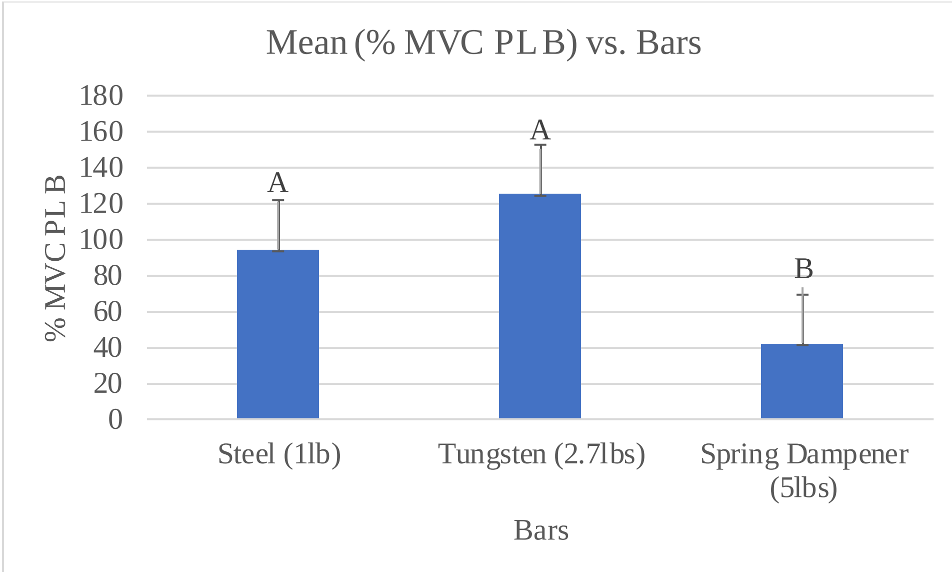


Figure 51. Mean %MVC PL B vs. Bucking Bar

Table 62. Connecting Letter Report Two-way Interaction between Gun Type and Bar (%MVC PL B) (levels not connected by the same letter are significantly different)

Level				**Least Sq Mean**
Type 3,Tungsten (2.7lbs)	A			245.34
Type 3,Steel (1lb)		B		130.60
Type 4,Steel (1lb)		B	C	92.60
Type 2,Steel (1lb)		B	C	88.45
Type 4,Tungsten (2.7lbs)		B	C	86.22
Type 1,Tungsten (2.7lbs)		B	C	84.73
Type 2,Tungsten (2.7lbs)		B	C	84.54
Type 3,Spring Dampener (5lbs)		B	C	80.83
Type 1,Steel (1lb)		B	C	65.85
Type 4,Spring Dampener (5lbs)		B	C	37.90
Type 2,Spring Dampener (5lbs)			C	31.60
Type 1,Spring Dampener (5lbs)			C	18.38

5.2.2.3 . Percentage Maximum Voluntary Contraction (MVC) of EMG for the biceps brachii muscle (Upper-arm muscle group)

The results of the generalized linear model performed on the biceps brachii emg activity show that both the bar and gun handle were significant with p-values<0.0001 and explained a large variation in the response variable (see table 63).

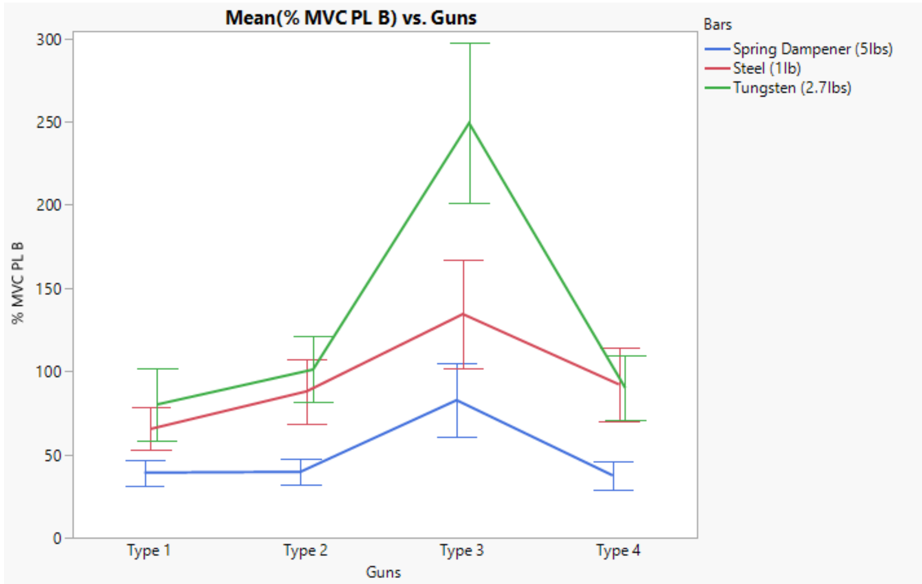


Figure 52. Mean %MVC PL B vs. Two-way Interaction between Bucking Bar and Rivet Gun Type

Table 63. Fixed Effect Test (% MVC Bi B)

Source	**DF**	**F Ratio**	**Prob > F**
Bars	2	10.6692	<.0001*
Gun Handle	1	17.3854	<.0001*
Guns	3	2.2441	0.0890
Bars*Gun Handle	2	2.1240	0.1254
Guns*Gun Handle	3	0.5349	0.6595
Guns*Bars*Gun Handle	6	0.6214	0.7127
Guns*Bars	6	0.5526	0.7640

The Turkey post hoc analysis performed on the bar shows that the spring dampener bucking bar resulted in the lowest mean % MVC of the biceps brachii muscle (22.03%) compared to the tungsten (50.3%) and steel (65.6%) bucking bars, around 65.42% difference. The tungsten and steel bucking bar were again not statistically different in terms of mean % MVC of the biceps brachii muscle (see table 64 and figure 53 below).

The post hoc analysis performed on the rivet gun handle position shows that the riveter operating the gun in a vertical handle position resulted in the highest mean % MVC of the bucker's biceps brachii muscle (61.11%) compared to the riveter using the gun in a horizontal handle position (30.84%), around 49.53% difference (see table 65 and figure 54 below).

Table 64. Connecting Letter Report Bucking Bar (%MVC Bi B) (levels not connected by the same letter are significantly different)

Level		Least Sq Mean	Std Error	Std Deviation
Steel (1lb)	A	65.60	14.47	65.20
Tungsten (2.7lbs)	A	50.30	14.88	52.41
Spring Dampener (5lbs)	B	22.03	15.42	1.24

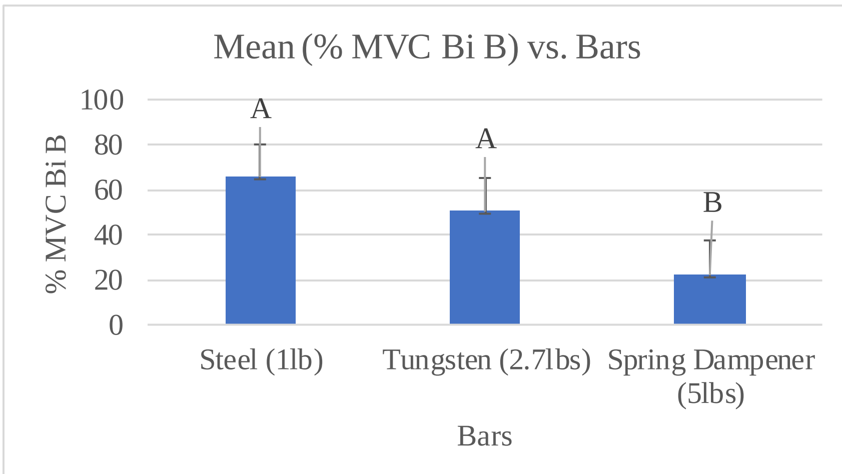


Figure 53. Mean %MVC Bi B vs. Bucking Bar

Table 65. Connecting Letter Report Gun Handle Position (%MVC Bi B) (levels not connected by the same letter are significantly different)

Level		Least Sq Mean	Std Error	Std Deviation
Vertical	A	61.11	14.20	64.67
Horizontal	B	30.84	14.66	28.77

5.2.3. Perceived Level of Exertion (Borg Scale)

After performing each experimental trial, the bucker was asked to rate the exertion he felt of a scale of 0-10. The results of the generalized linear model show that both the bar and the two-way interaction between the bar and the gun were significant with a p-value of <0.0001 and 0.0017 respectively (see table 66).

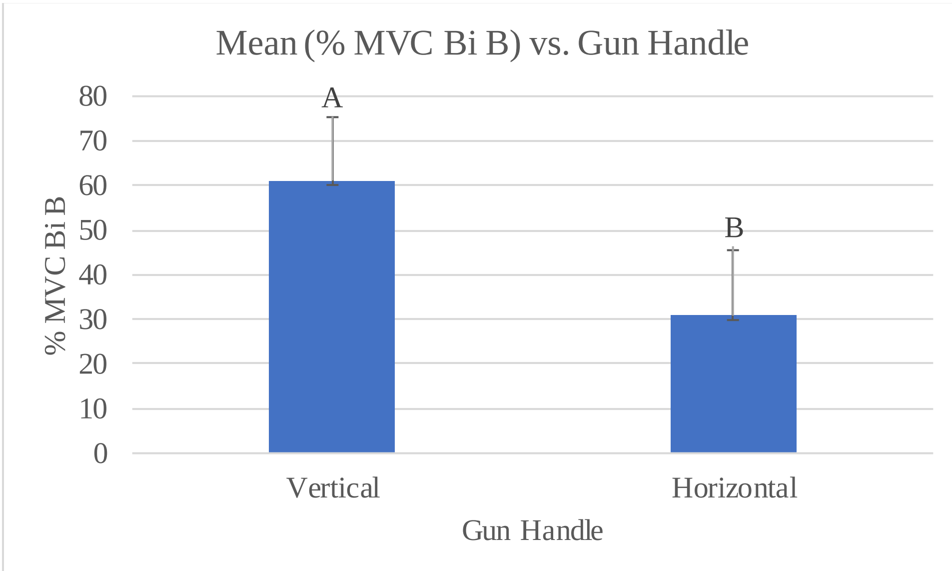


Figure 54. Mean %MVC Bi B vs. Gun Handle Position

Table 66. Effect Test (Perceived Level of Exertion B)

Source	**DF**	**L-R ChiSquare**	**Prob>Chi Sq**
Guns	3	3.2499382	0.3547
Bars	2	122.37689	<.0001*
Gun Handle	1	0.3114862	0.5768
Guns*Gun Handle	3	2.1253172	0.5468
Bars*Gun Handle	2	0.1266388	0.9386
Guns*Bars	6	21.133916	0.0017*
Guns*Bars*Gun Handle	6	1.8473063	0.9332

The side by side bar graph below shows that the participants felt less exertion when using the spring dampener and tungsten combined bucking bar compared to the steel and tungsten bucking bar. Their mean ratings for the steel (SD = 1.54) and tungsten (SD = 1.64) bucking bars were 77.7% and 71.8% higher than their mean rating for the spring dampener and tungsten combined bucking bar (SD = 1.24).

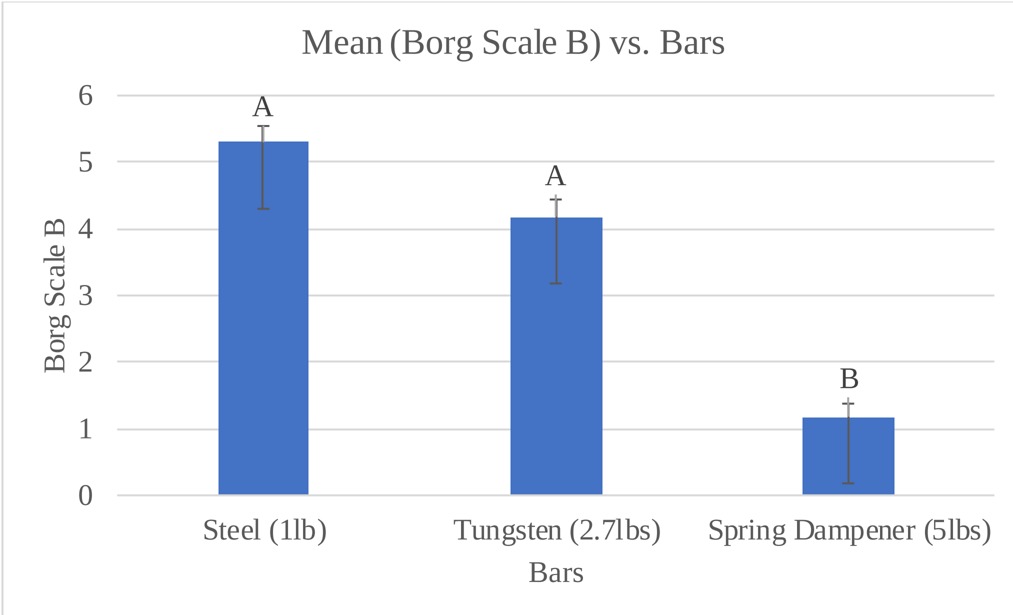


Figure 55. Mean Buckers' Perceived Level of Exertion vs. Bucking Bar

The results also show that the two-way interaction between the rivet gun and bucking bar was significant. The corresponding side by side bar graph below shows that the buckers felt the least exertion when using the spring dampener and tungsten combined bucking bar with the riveter using rivet gun type 1 or 2 on the other side (see figure 56).

5.2.4. Summary of Generalized linear model Results for all Response Variables

The generalized linear model results reported above are summarized in the table below per response variable. According to the table below, the spring dampener bucking bar resulted in the least acceleration RMS at the bar coupling, the least extensor, flexor and upper arm muscle activity represented by the %MVC of the extensor carpi radialis, the palmaris longus muscle, and the biceps brachii muscles respectively compared to the tungsten and steel bucking bar. The participants also found that using the spring dampener and tungsten combined bucking bar was less strenuous compared to using the tungsten or steel bucking bar.

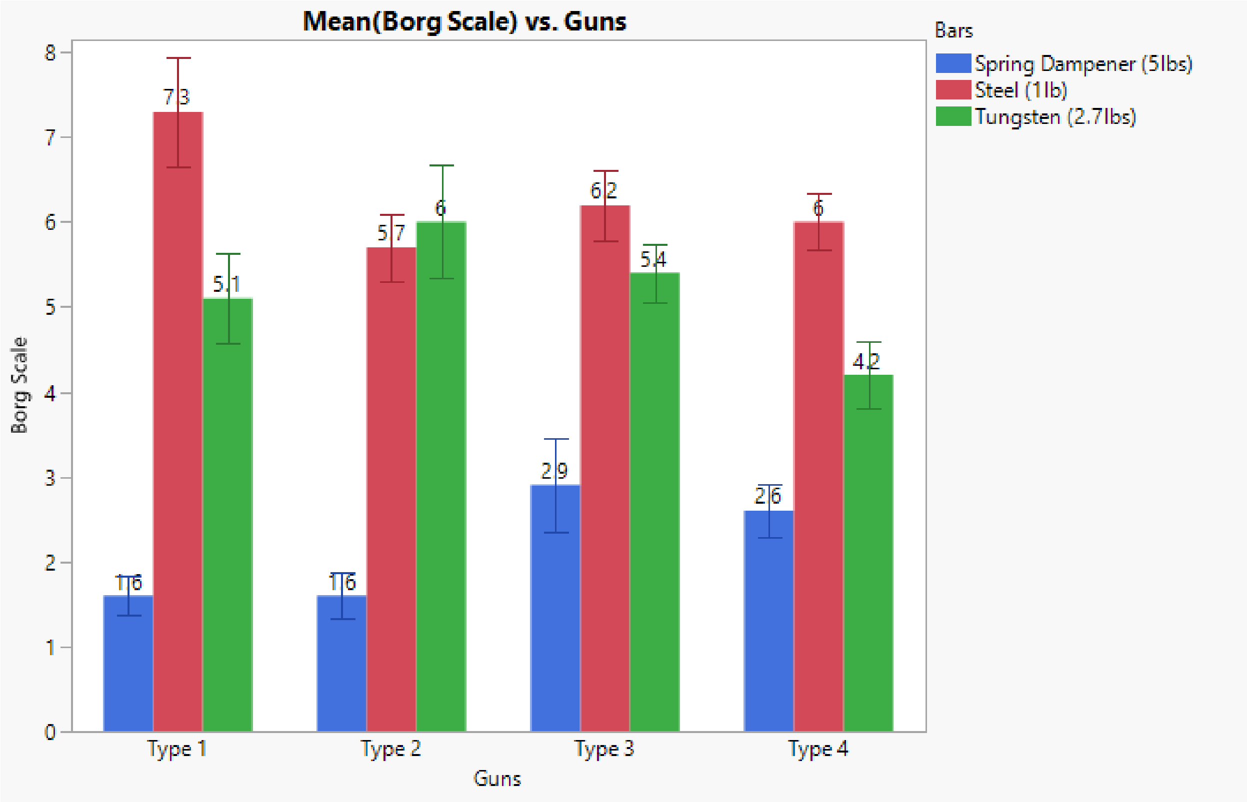


Figure 56. Mean Buckers' Perceived Level of Exertion vs. Two-way Interaction between Bucking Bar and Rivet Gun Type

Table 67. Summary Generalized Linear Model (Bucking Bar)
(levels not connected by the same letter are significantly different)

	Spring Dampener and Tungsten Combined	Tungsten	Steel
Bar Acc Res	(a) 7.04	(b) 21.63	(b) 22.50
%MVC ECR	(a) 34.32	(b) 91.52	(ab) 77.76
%MVC PL	(a) 42.18	(b) 125.21	(b) 94.38
%MVC BI	(a) 22.03	(b) 50.3	(b) 65.6
Borg Scale	(a) 1.18	(b) 4.18	(b) 5.3

The rivet gun handle orientation was also of interest in our generalized linear model. The results reported in the section above are summarized in the table below.

Table 68. Summary Generalized Linear Model (Gun Handle Position)
(levels not connected by the same letter are significantly different)

	Horizontal Rivet Gun Handle Position	Vertical Rivet Gun Handle Position
Bar Acc Res	(a) 17.03	(a) 17.09
%MVC ECR	(a) 62.9	(a) 72.83
%MVC PL	(a) 95.38	(a) 79.12
%MVC BI	(a) 30.84	(b) 61.11
Borg Scale	(a) 3.62	(a) 3.48

The rivet gun handle position was only significant for the %MVC of the biceps muscle (upper-arm muscle group) response variable with the horizontal handle position resulting in 49.5% less mean % MVC of the biceps muscle compared to the vertical handle direction.

The table below summarized the results found for the effect of using different rivet guns on all response variables.

Table 69. Summary Generalized Linear Model (Rivet Gun Type)
(levels not connected by the same letter are significantly different)

	Type 3	Type 4	Type 1	Type 2
Bar Acc Res	(a) 15.96	(a) 15.97	(a) 19.18	(a) 17.13
%MVC ECR	(a) 57.58	(a) 76.34	(a) 81.21	(a) 56.33
%MVC PL	(a) 152.26	(b) 72.24	(b) 56.32	(b) 68.19
%MVC BI	(a) 60.25	(a) 47.61	(a) 35.53	(a) 40.53
Borg Scale	(a) 4.83	(a) 4.27	(a) 4.67	(a) 4.43

The table shows that the gun type was significant only for the %MVC of the buckers' palmaris longus with rivet gun types 1, 2, & 4 resulting in significantly less mean % MVC of the buckers' palmaris longus muscle compared to rivet gun type 3. Although the gun type factor was not significant in terms of acceleration measure at the bar, rivet gun type 4 resulted in the second least mean acceleration RMS (15.97) following the rivet gun type 3 (15.96).

5.4. DISCUSSION

The objective of this study was to determine the effect of using different bucking bars, different rivet guns, and gun handle position on the buckers' vibration exposure and muscle fatigue. The vibration exposure was measured in terms of unweighted-frequency acceleration Root Mean Square (RMS) at the bucking bar coupling, and the muscle fatigue was measured in terms of Maximum Voluntary Contraction (MVC) of the extensor carpi radialis (extensor muscle group), palmaris longus (flexor muscle group), and biceps brachii (upper-arm muscle group), and the perceived level of exertion (Borg Scale). Also, the grip strength of the buckers was measured prior and after the experimental trials of the day as a way to determine the overtime fatigue.

The different hypotheses of this study are listed based on the bucking bars, rivet guns, and rivet gun handle positions as independent variables and the unweighted-frequency acceleration RMS, the % MVC of the three muscle of interest listed above as dependent variables. The outcomes of this study are discussed per dependent variables in the subsections below.

5.4.1. EFFECT OF USING DIFFERENT RIVETING TOOLS ON THE VIBRATION TRANSMITTED TO THE BUCKER'S HAND AND FINGERS

The results of the generalized linear model show that both the bucking bar and the two-way interaction between the gun and the bar were significant on the x, y, z-axis as well as the resultant of the three axes. The significance of the two-way interaction suggests that the use of the gun on the other side significantly affects the bucker exposure to vibration. In other words, selecting the right combination of tools can reduce the vibration exposure experienced by the buckers.

The steel bucking bar resulted in the highest mean unweighted-frequency acceleration RMS resultant value compared to the spring dampener bucking bar (68.7 % difference) and tungsten bucking bar (3.9% difference). This observation is consistent with earlier studies which found that steel bucking bar resulted in the highest unweighted and weighted-frequency acceleration RMS compared to other new technologies bucking bars including tungsten alloy, spring dampener, and spring recoilless bucking bars (Jorgensen and Viswanathan, 2005; Hull, 2007; McDowell et al, 2015, 2018). Although the spring dampener bucking bar was significantly different from the steel and tungsten bucking bars, the steel bucking bar was not statistically different from the tungsten bucking bar. A study by Jorgensen and Viswanathan (2015) found different results when comparing the weighted-frequency acceleration RMS resulting from the use of four different bucking bars of the same shape (2.4×0.8×0.4"; L×H×W) around 0.77 in^2 of volume but different material and mass characteristics 90% tungsten (1.78 lbs.), >90% tungsten (1.99 lbs.), cold rolled (0.86 lbs.) and stainless steel (0.85 lbs.). They found that both tungsten bars led to significantly less mean resultant weighted acceleration (>90% tungsten, 3.4 m/s^2; 90% tungsten, 3.6 m/s^2) than either the cold-rolled (5.3 m/s^2) or stainless steel (5.6 m/s^2) bar of similar size. This difference in results might be explained by the use of smaller rivets in that study compared to the present study. Setting larger rivets size might require bucking bars of higher volume and weight. The volumes and weights of bucking bar used in the present study, 4.13 in^2 (2.8 lbs.) for the tungsten bucking bar and 3.72 in2 (1 lb.) for the steel bucking bar, might be too small to set level 6 rivets, leading to the loss of some high-frequency acceleration that could have explained the difference between the steel and tungsten bucking bars. This might explain the fact that the tungsten and steel bucking bars were not statistically significant in our study. The magnitude of the unweighted-frequency acceleration RMS refers to how fast the bucking bar is bouncing or shifting from its original position Widia and Dawal, 2011). Thus, the bucking bar which resulted in the highest mean acceleration RMS would require the bucker to exert a stronger grip force to stabilize the bucking bar. This might result in an increase in the bucker major arm muscle activity. The results of the electromyography response to the different vibration levels from different bucking bars are discussed in the section below.

5.4.2. EFFECT OF USING DIFFERENT RIVETING TOOLS ON THE PERCENTAGE MAXIMUM VOLUNTARY CONTRACTION OF THE BUCKER'S MAJOR ARM MUSCLES (EMG)

Three different bucker's arm muscles were tested in this study, the extensor carpi radialis (extensor group), the palmaris longus (flexor group), and the biceps brachii (upper-arm group) muscles. The results of the generalized linear model on EMG data reveal that the spring dampener bucking bar resulted in a significantly less mean % MVC of all three muscles tested compared to the steel and tungsten bucking bars. This finding indicates that the least vibrating bucking bar requires a lighter gripping force and thereby a less intense major arm muscle activity to stabilize the tool compared to highly vibrating bucking bars. A research by Widia and Dawal (2011) confirmed this observation by studying the effect of a bench drill and an electric drill, on muscle activities and grip strength Level of vibration. They found that as the vibration exposure increases, the arm muscle activity and grip strength increase as well. The additional weight of the spring dampener bucking bar which is around five times the weight of the steel bucking bar, and three times the weight of the tungsten bucking bar does not seem to cause more exertion in the bucker's major arm muscles. The steel and the tungsten bucking bars were not statistically different for all three muscle groups. This observation is not a surprise since the two bucking bars were not significantly different in terms of mean unweighted-frequency acceleration RMS, and the difference in their weights (2.8 lbs. for the tungsten bar and 1 lb. for the steel bucking bar) was not large enough to create a difference in the bucker's major arm muscles activity.

The results of the generalized linear model also show that the gun and the two-way interaction between the gun and the bar were statically significant for the palmaris longus muscle (flexor muscle group). This observation suggests that the type of rivet gun used on one side of the riveting platform impacts the muscle activity of the bucker on the other side. The Turkey post hoc test shows that the riveter's use of rivet gun type 3 led to the significantly highest mean % MVC value of the bucker's palmaris longus muscle. This observation might be explained by the higher Blow Per Minute (BPM) of gun type 3 (2100) compared to other rivet gun types (1740). Having a higher BPM suggests that rivet gun type 3 hammers faster than the other rivet guns, which might lead to the bucker exerting more grip force and flexor muscle activity to stabilize the bucking bar on the other side of the riveting platform. The two-way interaction between rivet gun type 3 and the tungsten bucking bar resulted in a significantly higher mean % MVC value of the bucker's palmaris longus muscle compared to the other combinations of rivet guns and bucking bars.

The results also show that the riveter operating the gun with a vertical handle position resulted in the highest mean % MVC of the bucker's biceps brachii muscle (61.11%) compared to the riveter using the gun in the horizontal handle position (30.84%), around 49.53% difference. In summary, in order to reduce the vibration exposure and muscle fatigue experienced by the buckers, it is necessary to consider the type of guns and the position in which the rivet gun operator is performing the task.

5.4.3. EFFECT OF USING DIFFERENT RIVETING TOOLS ON THE BUCKERS PERCEIVED LEVEL OF EXERTION (BORG SCALE)

The results of the generalized linear model show that the buckers felt less exertion when using the spring dampener and tungsten combined bucking bar instead of the tungsten and steel bucking bar around 22.1 % difference. Hull (2007) also studied the perceived level of exertion of buckers when using a tungsten bucking bar, a steel bucking bar, and other interventions such as a Viscolas® rubber wrap adhered to a steel bucking bar, anti-vibration glove, a detachable handle. He found that the tungsten bucking bar resulted in a significantly less mean perceived level of exertion compared to a steel bucking bar of similar size.

The two-way interaction between the gun and the bar was also significant when considering the ratings of the buckers for different tools. In other words, the bucker's perceived level of exertion was not only influenced by the bar he was using, but also by the type of gun that was used on the other side. Thus, the buckers felt the least exertion using the spring dampener bucking bar in combination with rivet gun types 1 and 2 in comparison to all other combinations of tools. They also felt less exertion using gun type 4 with either the tungsten or steel bucking bar compared to the combination of other types of guns with the same bars.

5.5. CONCLUSION

The objective of this study was to study the effect of using different types of rivet guns, different rivet gun handle positions, and different bucking bars on the buckers' vibration exposure and muscle fatigue. The vibration exposure was measured in terms of unweighted-frequency acceleration Root Mean Square (RMS) at the bar coupling, and the muscle fatigue was measured in terms of Maximum Voluntary Contraction (MVC) of the extensor carpi radialis, palmaris longus, and biceps brachii muscle, and perceived level of exertion (Borg Scale). Also, the grip strength was measured before and after the experimental trials of the day as a way to determine the overtime fatigue.

The results show that the spring dampener bucking bar resulted in the least acceleration RMS at the bar coupling, the least extensor, flexor and upper arm muscle activity represented by the %MVC of the extensor carpi radialis, the palmaris longus muscle, and the biceps brachii muscles respectively, compared to the tungsten and steel bucking bar. The participants also found that using the spring dampener and tungsten combined bucking bar was less strenuous compared to using the tungsten or steel bucking bar. The combination of tungsten material with a spring dampener was found to successfully reduce the buckers' exposure to vibration. The additional weight of the spring dampener and tungsten combined bucking bar did not constitute an overexertion factor on the buckers' major arm muscle. Actually, the spring dampener and tungsten combined bucking bar resulted in the least extensor carpi radialis, palmaris longus, and biceps brachii muscle activity.

The rivet gun handle position was only significant for the %MVC of the biceps muscle (upper-arm muscle group) response variable with the horizontal handle position resulting in 49.5% less mean % MVC of the biceps muscle compared to the vertical handle direction. Although the rivet gun handle position was not significant for the acceleration RMS resultant at the bucking bar and the % MVC of the extensor carpi radialis muscle, the horizontal rivet gun handle position used by the rivet gun operator led to less mean acceleration RMS resultant bucking bar value, and to less mean % MVC value of the extensor carpi radialis muscle compared to the vertical rivet gun handle position used by the riveter. This observation partially supports the hypothesis that the horizontal rivet gun handle position employed by the riveter led to less buckers' vibration exposure and less buckers' biceps brachii and extensor carpi radialis muscle activity.

The results show that the gun type was significant only for the %MVC of the buckers' palmaris longus with rivet gun types 1, 2, & 4 resulting in significantly less mean % MVC of the buckers' palmaris longus muscle compared to rivet gun type 3. Although the gun type factor was not significant in terms of acceleration measure at the bar, rivet gun type 4 resulted in the second least mean acceleration RMS (15.97) following the rivet gun type 3 (15.96). Thus, there is evidence that the type of rivet gun used by the riveter affects the % MVC of the buckers' palmaris muscle (flexor group). This observation is further justified with the interaction results.

The interaction between gun and bar was significant in terms of the resultant unweighted-frequency acceleration RMS at the bar coupling, and the % MVC of the buckers' palmaris longus with the combination of rivet gun type 3 and tungsten bucking bar resulting in the significantly highest buckers' vibration exposure and palmaris longus muscle activity compared to all other combinations. The other combinations were not statistically different in terms of bucking bar acceleration RMS resultant value and % MVC of the bucker's palmaris longus.

Since the interaction between the type of gun and bar were significant factors when considering the acceleration RMS at the bucking bar, we can conclude that the type of rivet gun used by the riveter in combination with the type of bucking bar affects the buckers' exposure to vibration. Besides, the fact that the gun and two-way interaction between the bar and the gun were significant for the % MVC of the bucker's palmaris longus muscle suggests that the type of rivet gun and certain combinations of rivet gun and bucking bar have a higher impact on the buckers' palmaris muscle activity compared to other combination of tools. In this study, the combination of rivet gun type 3 and tungsten bucking bar led the highest mean value of %MVC of the buckers' palmaris longus muscle compared to other combinations.

In summary, when in order to reduce the vibration exposure and muscle fatigue experienced by the buckers, it is necessary to consider the type of guns and the position in which the rivet gun operator is performing the task.

Overall, when considering the buckers, the flexor muscle group (Palmaris longus) seemed to be the most affected by the bar vibration with the highest % MVC values followed by the extensor muscle group (Extensor carpi radialis) and the upper arm muscle group (Biceps brachii) (see table 67). This might be due to the fact that the palmaris longus is the most activated and the most sensitive to the vibration transmitted to the buckers' hand and fingers.

The buckers' heart rate was monitored throughout the experimental trials, and their grip strength was measured prior and after the experimental trials each day as a way to determine the overtime fatigue. The results were inconclusive with no statistical significance. This outcome is understandable since the buckers were exposed to vibration for only 6 min per day with resting periods every 30 s. The time of exposure and intensity of the task were not high enough to cause a significant difference in heart rate or grip strength for the buckers.

CHAPTER 6. PART 3-THE EFFECT OF USING DIFFERENT RIVETING TOOLS ON THE JOINT VIBRATION EXPOSURE OF RIVETERS AND BUCKERS, AND THEIR MUSCLE FATIGUE

6.1. INTRODUCTION

Past researches have either focused on the riveter side by comparing different types of rivet guns varying by size, piston material (Tungsten vs. Steel), design (Dampener vs Regular), or on the bucker side by comparing different material of bucking bars (Tungsten vs Steel), different design (Spring dampener vs Regular), and other alternatives such as adding a handle or using antivibration gloves (Hull, 2007; Jorgensen, Khan, & Polsani; Jorgensen & Viswanathan, 2005; Kattel & Fernandez, 1999; T. W. McDowell, Warren, Xu, Welcome, & Dong, 2015; T. W. McDowell, Xu, Warren, Welcome, & Dong, 2018). However, no studies have considered both sides simultaneously and determined how the tools on each side affect the workers on the other side.

Part 3 was a combination of the two previous parts by studying the effect of using different rivet guns, different gun handle positions, and different bucking bars on the joint vibration exposure of the riveters and buckers, and their respective muscle fatigue when subjected to these different vibration levels. To attain this objective, we collected acceleration, EMG, Heart rate, grip strength, and perceived level of exertion data simultaneously from both riveters and buckers, and later averaged the vibration exposure of the riveters and buckers as well as their perceived level of exertion (Borg Scale) in order to identify the tools that lessen the joint vibration exposure of riveters and buckers and lessen their joint perceived level of exertion. The outcome of this part was to find a combination of riveting tools that simultaneously lessen the exposure of both the riveter and bucker.

6.2. DEPENDENT AND INDEPENDENT VARIABLES

Three independent variables were tested in part 3, which are 4 types of rivet guns, 3 bucking bars, as well as two rivet gun handle positions. The comparisons were based on the following dependent variables: the average value of the bucking bar and rivet gun unweighted-frequency acceleration RMS resultant, the percentage Maximum Voluntary Contraction (MVC) of the riveters' extensor digitorium, brachioradialis, and biceps brachii muscles, the % MVC of the buckers' extensor carpi radialis, palmaris longus, and biceps brachii muscles, and the average value of the riveters and buckers perceived level of exertion (Borg Scale) of as a measure of muscle fatigue. Heart rate and grip strength percentage change were used to estimate the overtime fatigue of buckers and riveters. The data collection was achieved following the protocol on page 46 of this document.

6.3. RESULTS

Part 3 main objective was to investigate how the tools used on one side of the metallic sheet affect the operator on the other side. Having this understanding would help us identify a combination of tools which results in the minimum vibration exposure and muscle fatigue on both sides. To attain this objective, we studied the riveter and bucker side simultaneously. We came up with 2 new response variables which are the average value of the bucking bar and rivet gun unweighted-frequency acceleration RMS resultant, and the average value of the riveters and buckers perceived level of exertion (Borg Scale). Finding an average value of the rivet gun and bucking bar acceleration RMS would help us find the combination of tools that jointly lessen the exposure of both the riveter and bucker. The same calculation was performed on the perceived level of exertion (Borg Scale) data in order to find the combination of tools that resulted in the least rating when considering the bucker and riveter simultaneously. The percentage Maximum

Voluntary Contraction (EMG) of the riveter's three major arm muscles (Extensor Digitorium, Brachioradialis, and Biceps Brachii), as well as that of the bucker (Extensor Carpi Radialis, Palmaris Longus, and Biceps Brachii), was also of interest in determining the optimum combination of riveting tools. The subsections below display the results found after performing a generalized linear model on the two new response variables.

6.3.1. AVERAGE OF THE BUCKING BAR WITH THE RIVET GUN UNWEIGHTED-FREQUENCY ACCELERATION RMS RESULTANT

The results of the generalized linear model show that the gun, bar, and gun handle direction were all significant with p-values of <0.0001, 0.0002, and 0.0182 respectively (see table below). The interaction between the different factors were removed from the model because adding them in the model did not give any statistical results (p-value).

Table 70. Fixed Effect Test Average Rivet Gun and Bucking Bar Acc Resultant)

Source	DF	F Ratio	Prob > F
Guns	3	22.2541	<.0001*
Bars	2	9.1501	0.0002*
Gun Handle	1	5.7515	0.0182*

When performing a turkey post hoc test on the gun, we found that rivet gun type 3 and type 4 resulted in around 43.27% less vibration exposure for both riveter and bucker compared to gun types 1 and 2. Rivet gun types 1 & 2 and 3 & 4 were not statistically different from one another (see table 71 and figure 57).

Table 71. Connecting Letter Report Gun Type (Gun and Bar Average Acc Resultant) (levels not connected by the same letter are significantly different)

Level			Least Sq Mean	Std Error	Std Deviation
Type 1	A		32.68	1.64	10.61
Type 2	A		29.12	1.76	9.63
Type 4		B	20.55	1.55	6.02
Type 3		B	18.54	1.59	6.92

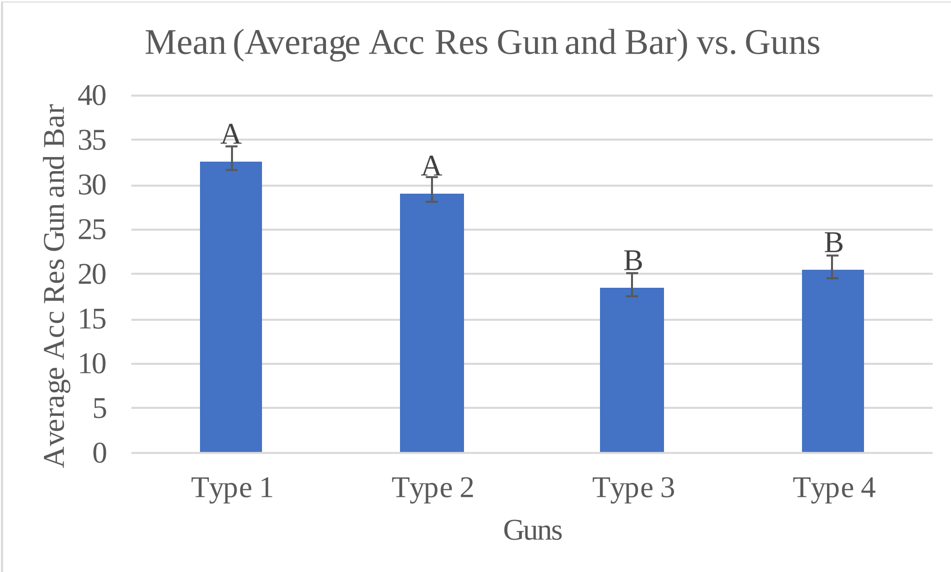


Figure 57. Mean Gun and Bar Average Acc Resultant vs. Rivet Gun Type

The bar was also a significant factor in the generalized linear model. The results of the Turkey post hoc analysis show that the spring dampener and tungsten combined bucking bar led to 24.46% less vibration on both the riveter and bucker side compared to the use of the tungsten or steel bucking bar (see table 72 and figure 58). The connecting letter report below shows that there is no significant difference between the tungsten and steel bucking bar.

Table 72. Connecting Letter Report Bucking Bar (Gun and Bar Average Acc Resultant) (levels not connected by the same letter are significantly different)

Level			**Least Sq Mean**	**Std Error**	**Std Deviation**
Steel (1lb)	A		27.57	1.38	10.89
Tungsten (2.7lbs)	A		27.28	1.48	9.32
Spring Dampener (5lbs)		B	20.82	1.60	9.06

The results of the Turkey post hoc analysis performed on the gun handle position show that the horizontal gun handle position resulted in 12.66 % less vibration on both the riveter and bucker side compared to the vertical handle position (see table 73 and figure 59).

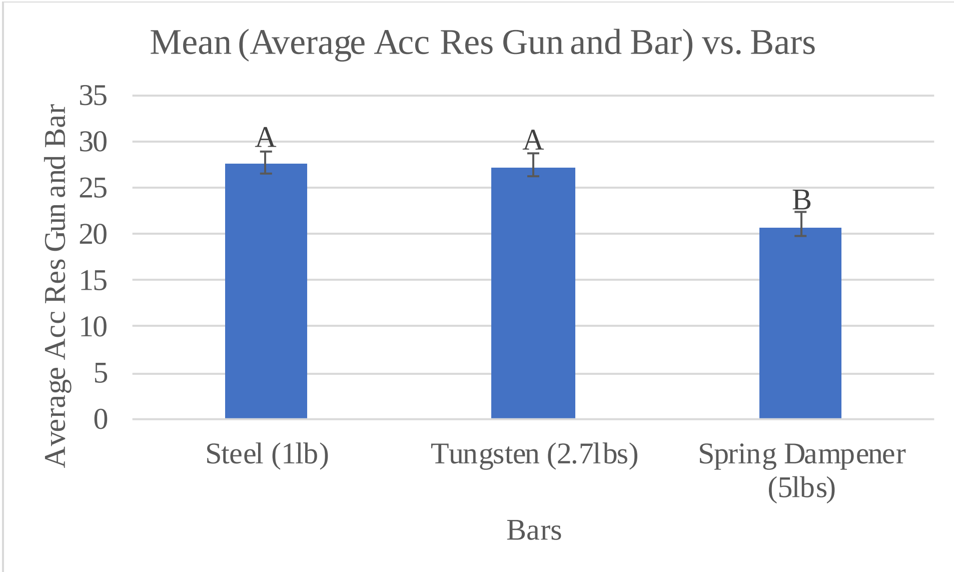


Figure 58. Mean Gun and Bar Average Acc Resultant vs. Bucking Bar

Table 73. Connecting Letter Report Gun Handle Position (Gun and Bar Average Acc Resultant) (levels not connected by the same letter are significantly different)

Level			**Least Sq Mean**	**Std Error**	**Std Deviation**
Vertical	A		26.93	1.24	10.52
Horizontal		B	23.52	1.35	9.69

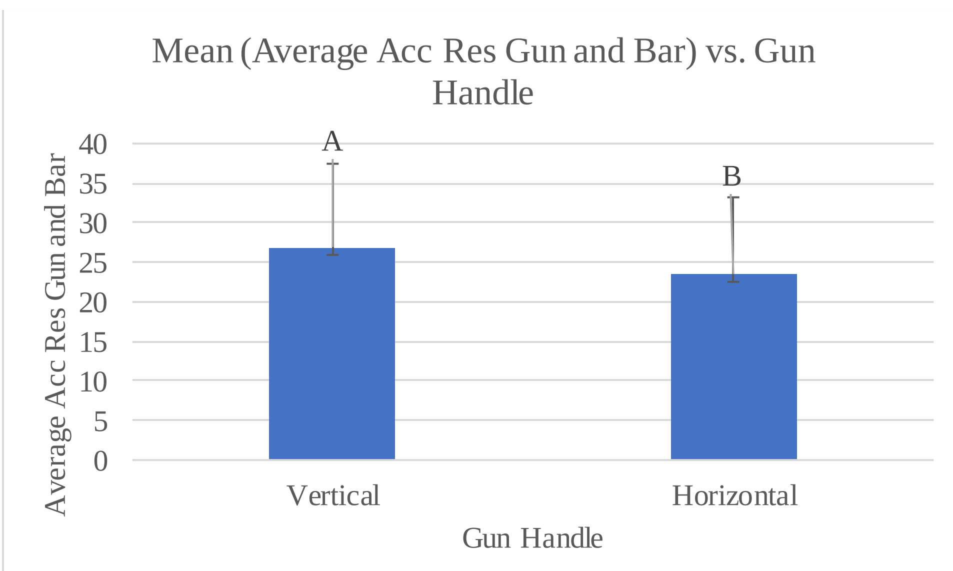


Figure 59. Mean Gun and Bar Average Acc Resultant vs. Rivet Gun Handle Position

6.3.2. AVERAGE OF THE BUCKERS AND RIVETER PERCEIVED LEVEL OF EXERTION (BORG SCALE)

The goal of this section was to find a combination of tools that would result in the least average rating of the bucker and the riveter perceived level of exertion (Borg Scale). The results of the generalized linear model show that the bar, gun handle position, and two-way interaction between the gun and the bar were all significant with p-values of <0.0001, 0.0180, 0.0114 respectively (see table below).

Table 74. Effect Test (Average Rivet Gun and Bucking Bar Perceived Level of Exertion)

Source	**DF**	**L-R ChiSquare**	**Prob>Chi Sq**
Guns	3	4.8217111	0.1853
Bars	2	90.686041	<.0001*
Gun Handle	1	5.5978673	0.0180*
Guns*Gun Handle	3	1.258448	0.7390
Bars*Gun Handle	2	0.144266	0.9304
Guns*Bars	6	16.47837	0.0114*
Guns*Bars*Gun Handle	6	0.6533577	0.9954

The Turkey post hoc test performed on the bar reveals that the mean average rating of the riveter

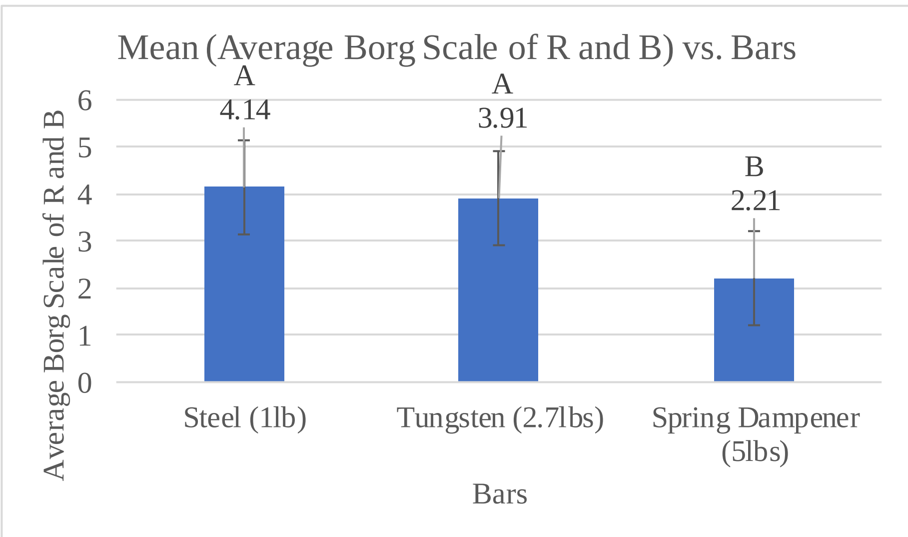


Figure 60. Mean Riveters and Buckers Average Perceived Level of Exertion vs. Bucking Bar

and bucker was the minimum for the spring dampener bucking bar (2.21) (STD = 0.79) compared to the tungsten (3.91) (STD = 1.03) and steel (4.14) (STD = 0.92) bucking bars (see figure 60) . The results of the generalized linear model also show that the gun handle position was a significant factor. A more detailed analysis reveals that the bucker and riveter average rating was 10% lower for the vertical handle position (STD = 1.26) compared to the horizontal handle position (STD = 1.23) (see figure 61).

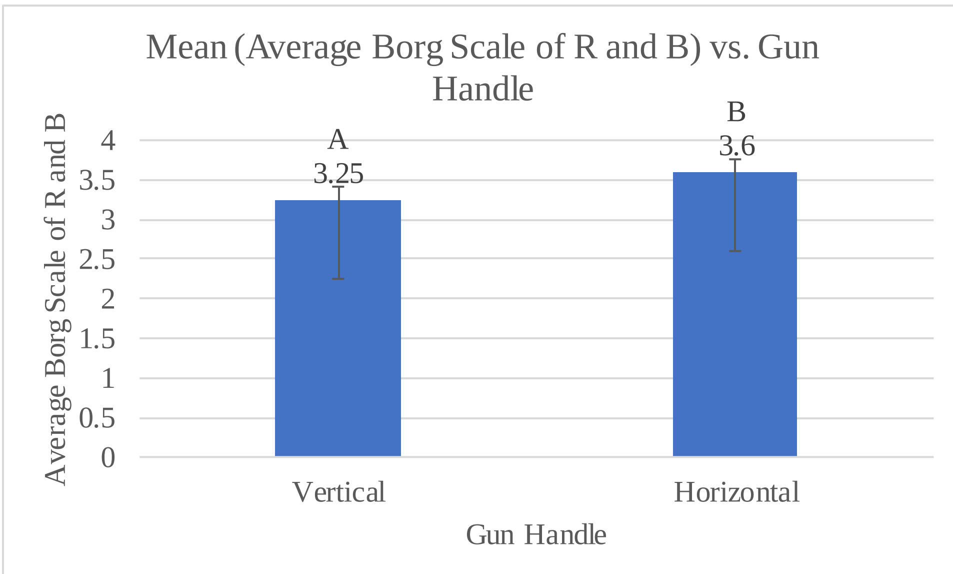


Figure 61. Mean Riveters and Buckers Average Perceived Level of Exertion vs. Rivet Gun Handle Position

The results of the Turkey post hoc analysis performed on the two-way interaction between the rivet gun and bucking bar show that the bucker and riveter average rating was the smallest for the combination of type 2 rivet gun and the spring dampener and tungsten combined bucking bar closely followed by the combination of the spring dampener and tungsten combined bucking bar with type 1, 4, and 3 rivet guns (see figure 62 below).

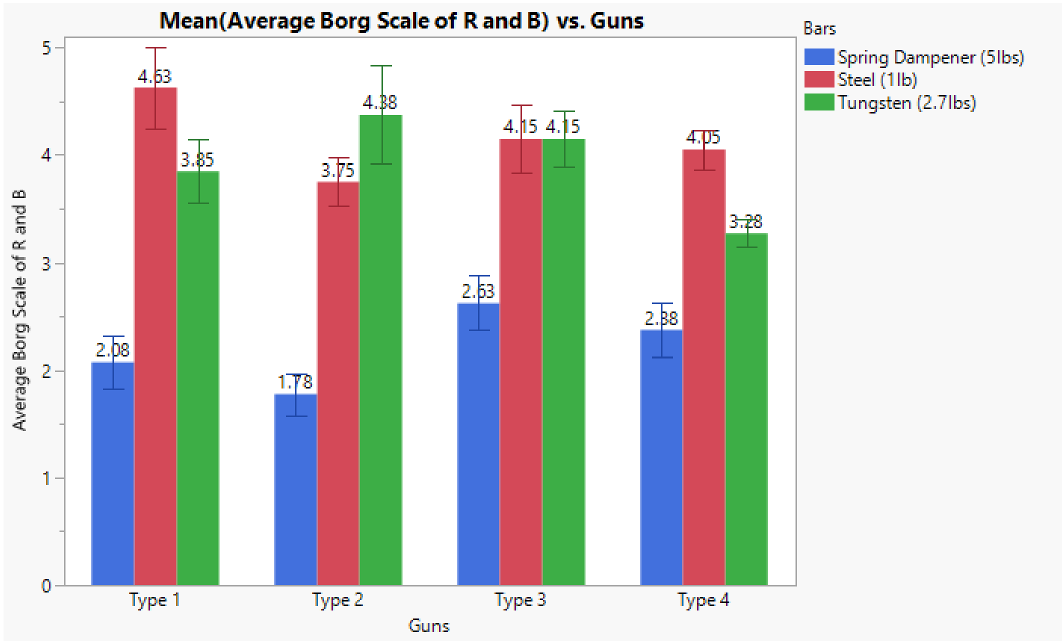


Figure 62. Mean Riveters and Buckers Average Perceived Level of Exertion vs. Two-way Interaction between Rivet Gun Type and Bucking Bar

Table 75. Summary Generalized Linear Model (Rivet Gun Type)
(levels not connected by the same letter are significantly different)

	Type 3	Type 4	Type 1	Type 2
Wrist Acc Res	(a) 16.52	(a) 16.77	(a) 17.04	(b) 18.64
Ave Acc Res Gun and Bar	(a) 18.54	(a) 20.55	(b) 32.68	(b) 29.12
%MVC ED (R)	(a) 72.35	(a) 60.46	(a) 66.62	(a) 66.122
%MVC BR (R)	(a) 61.832	(b) 26.79	(ab) 30.87	(ab) 33.55
%MVC BI (R)	(a) 25.32	(a) 18.29	(a) 19.97	(a) 19.6
%MVC ECR (B)	(a) 57.58	(a) 76.34	(a) 81.21	(a) 56.33
%MVC PL (B)	(a) 152.26	(b) 72.24	(b) 56.32	(b) 68.19
%MVC BI (B)	(a) 60.25	(a) 47.61	(a) 35.53	(a) 40.53
Average Borg Scale	(a) 3.64	(a) 3.23	(a) 3.52	(a) 3.3

The table above suggests that the rivet gun type 4 resulted in the least wrist acceleration, in the least gun and bar average resultant acceleration, the least riveter flexor muscle activity (brachioradialis), and the least bucker flexor muscle activity (palmaris longus). Although the gun factor on all other response variables was not statistically significant, gun type 4 resulted in the least riveters' extensor digitorium and biceps brachii muscle, the third least buckers' extensor carpi radialis (76.34 %) following gun type 2 (56.33 %) and type 3 (57.58 %), and the third least mean % MVC of the buckers' biceps brachii muscle (47.61 %) following type 1 (35.53%) and type 2 (40.53%). Also, the average perceived level of exertion of riveters and buckers suggest that they felt the least exertion on each side when the riveter was using rivet gun type 4 (3.23) compared to gun type 2 (3.3), gun type 1 (3.52), and gun type 3 (3.64). Nevertheless, the difference between the guns were not statistically significant in terms of average buckers and riveters' perceived level of exertion.

Table 76. Summary Generalized Linear Model (Bucking Bar)
(levels not connected by the same letter are significantly different)

	Spring Dampener and Tungsten Combined	Tungsten	Steel
Wrist Acc	(a) 17.11	(a) 17.37	(a) 17.24
Ave Acc Res Gun and Bar	(a) 20.82	(b) 27.28	(b) 27.56
%MVC ED	(a) 65.74	(a) 61.46	(a) 71.96
%MVC BR	(a) 32.36	(a) 47.76	(a) 34.65
%MVC BI	(a) 18.25	(a) 20.62	(a) 23.52
%MVC ECR	(a) 34.32	(b) 91.52	(ab) 77.76
%MVC PL	(a) 42.18	(b) 125.21	(b) 94.38
%MVC BI	(a) 22.03	(b) 50.3	(b) 65.6
Average Borg Scale	(a) 4.98	(b) 11.4	(b) 12.3

The table above shows that the spring dampener and tungsten combined bucking bar resulted in the least rivet gun and bucking bar average acceleration resultant, the least buckers' extensor (extensor carpi radialis), flexor (palmaris longus), and upper-arm (biceps brachii) muscle activity. Although, the bucking bar factor was not significant for any of the riveters' muscle group, the spring dampener and tungsten combined bucking bar resulted in the least mean % MVC of the riveters' extensor digitorium, brachioradialis and biceps brachii muscles. Also, the average exertion rating of the bucker with that of the riveter was the least for the spring dampener and tungsten combined bucking bar. The use of different bucking bars does not seem to have an impact on the riveter side since the factor bar was not significant on all the response variables related to the riveter (wrist acceleration and riveter muscle activity).

The table below summarizes the generalized linear model related to the gun handle position. The table indicates that the horizontal rivet gun position resulted in significantly less mean wrist acceleration resultant, less mean rivet gun and bucking bar average acceleration resultant, less % MVC of the riveters' brachioradialis and biceps brachii muscle, less % MVC of the buckers' extensor carpi radialis, palmaris longus and biceps brachii muscle. However, the horizontal rivet gun handle position resulted in a significantly higher %MVC of the riveters' extensor digitorium muscle compared to the vertical handle position.

Table 77. Summary Generalized Linear Model (Gun Handle Position)
(levels not connected by the same letter are significantly different)

	Horizontal Rivet Gun Handle Position	Vertical Rivet Gun Handle Position
Wrist Acc Res	(a) 5.67	(b) 8.33
Ave Acc Res Gun and Bar	(a) 23.52	(b) 26.93
%MVC ED	(a) 82.09	(b) 50.68
%MVC BR	(a) 27.20	(b) 49.32
%MVC BI	(a) 7.11	(b) 34.49
%MVC ECR	(a) 62.9	(a) 72.83
%MVC PL	(a) 95.38	(a) 79.12

Table cont'd

	Horizontal Rivet Gun Handle Position	Vertical Rivet Gun Handle Position
%MVC BI	(a) 30.84	(b) 61.11
Average Borg Scale	(a) 10.2	(b) 8.9

6.4. DISCUSSION

The objective of this study was to study the effect of using different rivet guns, different gun handle positions, and different bucking bars on the joint vibration exposure of the riveters and buckers, and their respective muscle fatigue when subjected to these different vibration levels. The comparison was based on the gun and bar average resultant unweighted-frequency acceleration RMS, the riveter's wrist resultant unweighted-frequency acceleration RMS, the Percentage Maximum Voluntary Contraction (MVC) of the riveter's extensor digitorium, brachioradialis, and biceps brachii muscle, and the Percentage Maximum Voluntary Contraction (MVC) of the bucker's extensor carpi radialis, palmaris longus, biceps brachii muscles, as well as the average perceived level of exertion (Borg scale) of the riveters and buckers. Also, the grip strength was measured before and after the experimental trials of the day as a way to determine the overtime fatigue experienced by riveters and buckers. The outcomes of this part are discussed per dependent variables in the subsection below.

6.4.1. UNWEIGHTED-FREQUENCY ACCELERATION ROOT MEAN SQUARE (RMS) AT THE WRIST RESULTANT

The results found when the acceleration was measured from the wrist of the riveter show that the gun and gun handle position were both significant on the resultant of the three axes. The rivet gun type 2 resulted in a statistically significant higher mean acceleration RMS value compared to gun types 1, 3 & 4 (8.58%, 11.37%, and 10.03% respectively). Rivet gun types 1, 3,

& 4 were not statistically different from each other. Thus, gun types 3 & 4, which difference resides in the piston material (tungsten vs. steel respectively), were not significantly different. The difference between gun types 3 and 4 primarily resides in the piston material (Tungsten and Steel respectively). A study by HumanTech (2010) on the effect of using different guns varying by manufacturer and piston material, also reports no significant difference between similar tungsten vs. steel piston material rivet guns. However, Jorgensen et al. (2006) after studying the effect of using different types of rivet guns on Hand-Arm Vibration (HAV) found that tungsten piston rivet guns significantly decreases the vibration experienced by riveter compared to steel piston guns. This might be due to some other factors involved in the comparison such as rivet gun size and/or manufacturer.

Besides, the horizontal rivet gun handle position resulted in a statistically smaller mean wrist resultant acceleration RMS value compared to the vertical gun handle position, around 52% difference. Changing the rivet gun handle position from vertical to horizontal involves some changes in the wrist and shoulder position. A study by Kattel and Fernandez (1999) on the effect of using different riveting wrist postures which are neutral referring to the vertical gun handle position, 1/3 max. flexion, and 1/3 max. ulnar deviation from the neutral position, found similar results with the neutral wrist position leading to the second-highest frequency-unweighted acceleration RMS value following the 1/3 max. flexion wrist posture which led to the highest RMS value on both the x and y-axis.

6.4.2. Average of the Bucking Bar and Rivet gun Unweighted-Frequency acceleration RMS resultant

The results of the generalized linear model performed on the gun and bar average resultant unweighted-frequency acceleration RMS show that the gun handle position, gun, and bar were all statistically significant.

After performing a turkey post hoc test on the gun, we found that rivet gun type 3 and type 4 resulted in around 43.27% less vibration exposure for both riveter and bucker compared to gun types 1 and 2. In other words, gun types 3 and 4 led to the least joint vibration exposure of the riveters and buckers. Rivet gun types 1 & 2 as well as rivet gun types 3 & 4 were not statistically different from each other.

The turkey post hoc test performed on the bucking bar reveals that the spring dampener and tungsten combined bucking bar led to 24.46 % less vibration when considering both the riveter and bucker side compared to the use of the tungsten or steel bucking bar. This result is consistent with previous studies that found that the use of new technology bucking bars including tungsten, spring dampener, and spring recoilless bucking bar reduce the vibration exposure of buckers (Hull, 2007; Jorgensen & Viswanathan, 2005; Jorgensen et al., 2006; McDowell et al., 2015, 2018).

The results of the post hoc analysis performed on the gun handle position reveal that the horizontal rivet gun handle position led to a significantly less mean bar and gun average acceleration RMS resultant value compared to the vertical handle position, around 12.66 % difference. In other words, when considering both the riveter and bucker in terms of vibration exposure, the horizontal rivet gun handle position resulted in significantly less acceleration value compared to the vertical handle position. The acceleration RMS indicates how fast an object or tool is moving from its original position. Since the horizontal gun handle position was found to have the least mean acceleration RMS value, this position offers more stability to the gun, thereby preventing it from fluctuating too much from its original position. Nevertheless, changing the rivet gun handle position from horizontal to vertical might involve additional stresses on the riveter arm muscle activity, especially the shoulder. The results related to the effect of changing the rivet gun handle position on the major riveters and buckers' arm muscle will be discussed in the following section.

6.4.3. Effect of using different riveting tools on the percentage maximum voluntary contraction of the riveters and buckers' major arm muscles (EMG)

Three different riveter's arm muscles were tested in this study, the extensor digitorium (extensor group), the brachioradialis (flexor group), and the biceps brachii (upper-arm group) muscles. The results of the generalized linear model on EMG data reveal that the gun handle position was significant for all three muscles tested. Changing the rivet gun handle orientation from vertical to horizontal significantly decreases the mean % MVC of the brachioradialis and biceps brachii muscle, but increases the mean % MVC of the extensor digitorium muscle. The extensor digitorium muscle extends through all the fingers except the thumb and help moving them. This muscle also helps in the movement of the wrist and elbows. Since changing the gun handle orientation from vertical to horizontal involves changes in the wrist, elbow, shoulder, and possibly fingers, we expect to see an increase in this muscle activity when changing gun handle orientation from vertical to horizontal (https://www.healthline.com/human-body-maps/extensor-digitorum-muscle#1). The gun was only significant for the brachioradialis muscle. The brachioradialis is located in the lateral part of the posterior forearm and its fiber orientation helps flex the forearm, especially when the forearm is semi pronated. The riveter standard position involving the flexion of the forearm at a (90-degree elbow position) with the palm in half pronation activates the brachioradialis muscle making it sensitive to the change in vibration levels from the different rivet guns. This might be the reason why the gun factor was only significant for the brachioradialis muscle.

The two-way interaction between the gun and bar as well as the three-way interaction between the gun, bar, and gun handle position were significant only considering the riveters' biceps muscle activity. Overall, when considering the riveter, the extensor muscle group (Extensor digitorium) seemed to be the most affected by the gun vibration with the highest mean % MVC values followed by the flexor muscle group (Brachioradialis) and the upper-arm muscle group (Biceps brachii) (see table 75). The same observation applied for the gun handle position (see table 77). Radwin et al (1987) found that an increase in tension inside a muscle results in an increase in myoelectric activity. Thus, the highest %MVC value indicates the muscle that is most affected by the vibration, and that experience the most muscle fatigue (Widia and Dawal, 2011).

Three different bucker's arm muscles were tested in this study, the extensor carpi radialis (extensor group), the palmaris longus (flexor group), and the biceps brachii (upper-arm group) muscles. The results of the generalized linear model on EMG data reveal that the spring dampener bucking bar resulted in significantly less mean % MVC for all three muscles tested. This finding indicates that the least vibrating bucking bar requires a lighter gripping force and thereby a less intense major arm muscle activity to stabilize the tool compared to a highly vibrating bucking bar. This observation is consistent with a study by Radwin et al (1987), who found that gripping a handle without vibration resulted in a 32% EMG decrease for the lower arm extensors muscles compared to gripping one with vibration. The additional weight of the spring dampener bucking bar which is around five times the weight of the steel bucking bar, and three times the weight of the tungsten bucking bar does not seem to cause more exertion in the bucker's major arm muscles. The steel and the tungsten bucking bars were not statistically different for all three muscle groups. This observation is not a surprise since the two bucking bars were not significantly different in terms of mean unweighted-frequency acceleration RMS, and the difference in their weights (2.8 lbs. for tungsten bar and 1 lb. for steel bucking bar) was not large enough to create a difference in the bucker's major arm muscles.

The results of the generalized linear model also show that the gun and the two-way interaction between the gun and the bar were statically significant for the palmaris longus muscle (flexor muscle group). This observation suggests that the type of rivet gun used on one side of the riveting platform impacts the muscle activity of the bucker on the other side. The Turkey post hoc test shows that the riveter's use of rivet gun type 3 (Honsa 12T) led to the significantly highest mean % MVC of the bucker's palmaris longus muscle. This observation might be explained by the higher Blow Per Minute (BPM) of gun type 3 (2100) compared to other rivet gun types (1740). Having a higher BPM suggests that rivet gun type 3 hammers faster and required more blows to set rivets compared to larger rivet guns which have a smaller BPM value and hit hard enough to minimize the number blows to set rivets. Thus, the use of rivet gun type 3 by the riveter might lead to the bucker exerting more grip force and flexor muscle activity to set the rivets.

The two-way interaction between rivet gun type 3 and the tungsten bucking bar resulted in the significantly highest mean % MVC of the bucker's palmaris longus muscle compared to the other combinations of rivet guns and bucking bars.

The results also show that the riveter operating the gun with a vertical handle position resulted in the highest mean % MVC of the bucker's biceps brachii muscle (61.11%) compared to the riveter using the gun in the horizontal handle position (30.84%), around 49.53% difference. In summary, in order to reduce the vibration exposure and muscle fatigue experienced by the buckers, it is necessary to consider the type of guns and the position in which the rivet gun operator is performing the task.

Overall, when considering the buckers, the flexor muscle group (Palmaris longus) seemed to be the most affected by the bar vibration with the highest % MVC values followed by the extensor muscle group (Extensor carpi radialis) and the upper arm muscle group (Biceps brachii) (see table 76). The palmaris muscle is a muscle located in the anterior forearm, extending from the distal humerus to the root of the hand. This muscle not only intervenes in the flexion of the wrist but also plays an important function in the anatomy of the grip (https://www.kenhub.com/en/library/anatomy/palmaris-longus-muscle). The bucker task involving the solid gripping of the bucking bar activates the palmaris longus muscle and leaves it under tension. This might explain the fact that the palmaris muscle was the muscle with the highest % MVC. We can, therefore, conclude that the palmaris longus muscle is most affected by the vibration, and experience the most fatigue.

6.4.4. AVERAGE OF THE RIVETERS AND BUCKERS PERCEIVED LEVEL OF EXERTION (BORG SCALE)

The results of the generalized linear model show that the bar, gun handle orientation, and two-way interaction between the gun and the bar were all significant factors.

The Turkey post hoc test performed on the bar reveals that the mean average rating of the riveter and bucker was the minimum for the spring dampener and tungsten combined bucking bar (2.21) compared to the tungsten (3.91) and steel bucking bar (4.14). The average rating of the bucker and riveter was 5.56% lower when using the tungsten bucking compared to the steel bucking bar. However, the tungsten and steel bucking bar were not statistically different in terms of bucker and riveter average perceived level of exertion. Hull (2007) also study the perceived level of exertion of participants when using a tungsten bucking bar, a steel bucking bar, and other interventions such as a Viscolas® rubber wrap adhered to a steel bucking bar, anti-vibration glove, a detachable handle. He found that the tungsten bucking bar resulted in a significantly less perceived level of exertion compared to the steel bucking bar of a similar size.

The results of the generalized linear model also show that the gun handle direction was a significant factor. A more detailed analysis reveals that the bucker and riveter average rating was 10 % lower for the vertical handle position compared to the horizontal handle position. In other words, using the gun in a vertical handle position resulted in the least exertion when considering both the riveter and bucker. Nevertheless, the Electromyography (EMG) results show that only the % MVC of riveter's extensor digitorium muscle increases when changing the rivet gun handle position from vertical to horizontal. It is possible that the exertion felt by the riveter when using the gun in a horizontal handle position comes from the extensor digitorium muscle, or other muscles not studied in this paper such as the shoulder or trapezius muscle, or might simply be due to some discomfort felt in using the gun in this position. A more detailed study on the exertion felt per body segment during a riveting activity is required to draw any pertinent conclusion.

The results of the Turkey post hoc analysis performed on the two-way interaction between the rivet gun and bucking bar show that the bucker and riveter average rating was the smallest for the combination of type 2 rivet gun and the spring dampener and tungsten combined bucking bar closely followed by the combination of the spring dampener and tungsten combined bucking bar with type 1, 4, and 3 rivet guns.

6.5. CONCLUSION

The objective of this study was to study the effect of using different rivet guns, different gun handle positions, and different bucking bars on the joint vibration exposure of the riveters and buckers, and their respective muscle fatigue when subjected to these different vibration levels. The comparison was based on the gun and bar average resultant unweighted-frequency acceleration RMS, the riveter's wrist resultant unweighted-frequency acceleration RMS, the Percentage Maximum Voluntary Contraction (MVC) of the riveter's extensor digitorium, brachioradialis, and biceps brachii muscle, and the Percentage Maximum Voluntary Contraction (MVC) of the bucker's extensor carpi radialis, palmaris longus, biceps brachii muscles, as well as the average perceived level of exertion (Borg scale) of the riveters and buckers. Also, the grip strength was measured before and after the experimental trials of the day as a way to determine the overtime fatigue experienced by riveters and buckers.

The results show that the spring dampener and tungsten combined bucking bar resulted in the least average rivet gun and bucking bar acceleration resultant value, the least buckers' extensor (extensor carpi radialis), flexor (palmaris longus), and upper-arm (biceps brachii) muscle activity. Although, the bucking bar factor was not significant for any of the riveters' muscle group, the spring dampener and tungsten combined bucking bar resulted in the least mean % MVC of the riveters' extensor digitorium, brachioradialis and biceps brachii muscles. Also, the average exertion rating of the bucker and riveter was the least for the spring dampener and tungsten combined bucking bar. The use of different bucking bars does not seem to have an impact on the riveter side since the factor bar was not significant on all the response variables related to the riveter (wrist acceleration and riveter muscle activity). Therefore, we recommend the use of the spring dampener and tungsten combined bucking bar as a way to primarily and significantly lessen the bucker's vibration exposure and muscle fatigue and keep the vibration level and muscle fatigue experienced by the riveters at a minimum.

The results also show that the rivet gun type 4 resulted in the least wrist acceleration, in the least gun and bar average resultant acceleration, the least riveter flexor muscle activity (brachioradialis), the least bucker flexor muscle activity (palmaris longus), and the least average riveters and buckers perceived level of exertion. Although rivet gun types 1 and 2 resulted in less bucker's extensor carpi radialis and biceps brachii muscle activity compared to gun type 4, the difference between the gun was not statistically significant. The use of different rivet gun seems to affect the buckers' major arm muscle activity, especially the palmaris longus muscle. It is therefore necessary to consider the type of rivet gun in minimizing the muscle fatigue experienced by buckers. Thus, we recommend the use of rivet gun type 4 as a way to significantly lessen the buckers and riveters' joint vibration exposure and muscle fatigue.

The results also indicate that the horizontal rivet gun handle position resulted in significantly less mean wrist acceleration resultant, less mean rivet gun and bucking bar average acceleration resultant, less % MVC of the riveters' brachioradialis and biceps brachii muscle, less % MVC of the buckers' extensor carpi radialis, palmaris longus and biceps brachii muscle. However, the horizontal rivet gun handle position resulted in a significantly higher %MVC of the riveters' extensor digitorium muscle compared to the vertical handle position. Although, the horizontal rivet gun handle position led to significantly less buckers and riveters vibration exposure, and muscle activity, there is still a need to conduct more experiment on the effect of changing the gun handle position on riveters' shoulder, trapezius and neck muscle in order to draw any pertinent conclusion and make any recommendations.

In summary, in order to reduce the vibration exposure and muscle fatigue experienced simultaneously by buckers and riveters, it is necessary to consider the type of guns and the position in which the rivet gun operator is performing the task.

The buckers and riveters' heart rate were monitored throughout the experimental trials, and their grip strength was measured prior and after the experimental trials each day as a way to determine the overtime fatigue. The results were inconclusive with no statistical significance for both riveters and buckers. This outcome is understandable since the participants were exposed to vibration for only 6 min per day with resting periods every 30 s. The time of exposure and intensity of the task were not high enough to cause a significant difference in heart rate or grip strength.

CHAPTER 7. CONCLUSION

The overall objective of this research was to compare different rivet guns, rivet gun handle positions, and bucking bars based on their impact on hand-arm vibrations and the effect of these vibration levels on muscle fatigue. This objective was achieved by studying first the impact of these factors on riveters' vibration exposure and muscle fatigue in part 1, second at the impact of these factors on buckers' vibration exposure in part 2, and finally at the impact of these tools on the joint vibration exposure of riveters and buckers in part 3. The outcome of these different studies was to recommend a combination of tools that keeps the workers at the lowest risk of vibration exposure and muscle fatigue.

From part 1, we found that the rivet gun type 4 resulted in the least riveter wrist acceleration RMS, least gun coupling acceleration RMS, and least % MVC of the riveters' brachioradialis muscle, extensor digitorium, and biceps brachii muscle. Also, the horizontal rivet gun handle position led to the least wrist acceleration resultant, least gun acceleration, least % MVC of the brachioradialis muscle (flexor group), and biceps brachii muscle (upper arm group). However, the horizontal handle position caused 38.26 % more exertion on the extensor digitorium muscle (extensor group) compared to the vertical handle position. It was also found that the type of bucking bar used by the bucker does not affect the riveter exposure to vibration, but impact the riveter's biceps brachii muscle activity.

From part 2, we found that the spring dampener bucking bar resulted in the least acceleration RMS at the bar coupling, the least buckers' extensor, flexor and upper arm muscle activity represented by the %MVC of the extensor carpi radialis, the palmaris longus muscle, and the biceps brachii muscles respectively, compared to the tungsten and steel bucking bars. The participants also found that using the spring dampener and tungsten combined bucking bar was less strenuous compared to using the tungsten or steel bucking bar. The rivet gun handle position was only significant for the %MVC of the biceps muscle (upper-arm muscle group) response variable with the horizontal handle position resulting in 49.5% less mean % MVC of the biceps muscle compared to the vertical handle direction. The gun type was significant only for the %MVC of the buckers' palmaris longus with rivet gun types 1, 2, & 4 resulting in significantly less mean % MVC of the buckers' palmaris longus muscle compared to rivet gun type 3. Since the interaction between the type of gun and bars and the gun were significant factors when considering the acceleration RMS at the bucking bar and the buckers' muscle activity, we can conclude that the type of rivet gun used by the riveter in combination with the type of bucking bar affects the bucker exposure to vibration and muscle activity, especially the palmaris longus muscle activity. In summary, we found that in order to reduce the vibration exposure and muscle fatigue experienced by the buckers, it is necessary to consider the type of guns and the position in which the rivet gun operator is performing the task.

Part 3 results are consistent with the results from the two previous parts with the spring dampener and tungsten combined bucking bar resulting in the least average rivet gun and bucking bar acceleration resultant value, the least buckers' extensor (extensor carpi radialis), flexor (palmaris longus), and upper-arm (biceps brachii) muscle activity. Rivet gun type 4 resulted in the least wrist acceleration, in the least gun and bar average resultant acceleration, the least riveter flexor muscle activity (brachioradialis), the least bucker flexor muscle activity (palmaris longus), and the least average riveters and buckers perceived level of exertion. The results also indicate that the horizontal rivet gun handle position resulted in significantly less mean wrist acceleration resultant, less mean rivet gun and bucking bar average acceleration resultant, less % MVC of the riveters' brachioradialis and biceps brachii muscle, less % MVC of the buckers' extensor carpi radialis, palmaris longus and biceps brachii muscle.

In summary, since the factor bar was not significant for all the response variables related to the riveter (wrist acceleration and riveters' extensor digitorium and brachioradialis), we recommend the use of the spring dampener and tungsten combined bucking bar as a way to primarily and significantly lessen the buckers' vibration exposure and muscle fatigue and keep the vibration level and muscle fatigue experienced by the riveters at a minimum. During data collection, all participants preferred the use of the spring dampener and tungsten combined bucking bar because of its efficiency in setting rivets faster compared to other bucking bars. They also felt the minimum vibration level using that bucking bar compared to the steel and tungsten bucking bars.

Also, since the use of different rivet guns and rivet gun handle positions seems to affect the buckers' exposure to vibration and major arm muscle activity, especially the palmaris longus muscle, it is necessary to consider the type of rivet gun in minimizing the vibration exposure and muscle fatigue experienced by buckers. Thus, we recommend the use of rivet gun type 4 as a way to significantly lessen the buckers and riveters' joint vibration exposure and muscle fatigue.

Since the blocking variables ("pair of participants" and "day of experiment") were not statistically significant (p-value > 0.05) for any of the response variables, we can conclude that there was not a significant difference between the pair of professionals and the different pairs of students in the acceleration and muscle fatigue results. In other words, having experience or not in riveting activities did not make a difference in the results found in this study. The difference between the days of experiment did not affect the results as well.

In this study, type 1 rivet gun refers to the AERO US Industrial Aircraft (4X), type 2 rivet gun refers to the model CP4444-RUTAB manufactured by Chicago Pneumatic, type 3 and 4 rivet guns refer to the models HTOP38 12T and HTOP38 4X respectively manufactured by Honsa Ergonomic Technologies (see table 1 in the method and procedure section of this document for more details related to the different rivet guns tested in this study).

The spring dampener and tungsten combined bucking bar model HVRBB-670A as well as the tungsten bucking bar model JBBT4545T were also manufactured by Honsa Ergonomic Technologies (see table 2 in the method and procedure section of this document for more details concerning the different bucking bars tested in this study).

CHAPTER 8. LIMITATIONS AND FUTURE RESEARCH

The current research has several limitations, one of which is that participants were recruited from a student population. Many of the student participants did not have previous experience in riveting activities. Although, two experienced riveters trained them to properly drive rivets, the technique and riveting quality may have differed from that of experienced riveters. However, the benefit of using inexperienced participants can inform on the vibration exposure and muscle fatigue risk of newly employed riveters.

The data collection in this study was performed without replications because of time restriction and in order to minimize the effect of fatigue.

The number of observations (120) in this study is too small for a factorial design which requires at least 10 times the number of factorial combinations (minimum 240 observations in this study) to have a more accurate and powerful model. Increasing the number of participants and/or the number of replications in future studies might solve this problem.

The present study does not consider the effect of changing the gun handle position (Vertical vs. Horizontal) on the shoulder muscle activity. This would be an important study since changing the rivet gun handle position from vertical to horizontal may add some additional stresses in the shoulder of the riveter.

Another limitation of this study is the use of a generalized linear model in the analysis of the perceived level of exertion data (Borg Scale). Indeed, this type of data is not continuous, but ordinal. Therefore, performing a generalized linear model on such data violates one of the assumptions of performing a generalized linear model which is that the data must be continuous. Besides, the subjective nature of this data makes the perceived level exertion the least preferred and reliable way to compare riveting tools. Nevertheless, combining these results with more objective results from electromyography and accelerometers can help justify our results.

The assumption of normality of the generalized linear model was violated. The Shapiro Wilk test was performed on each response variable with H0 = the data follow a normal distribution, and H1= the data do not follow a normal distribution. The p-values for all response variables were smaller than the alpha value (0.05), therefore we rejected the null hypothesis, and concluded that the data did not follow a normal distribution (see appendix A for a detailed analysis). After analyzing the results, we found that the presence of one outlier in the data shifted the graphs to the left making it not normal. This problem can be easily solved by increasing the number of participants.

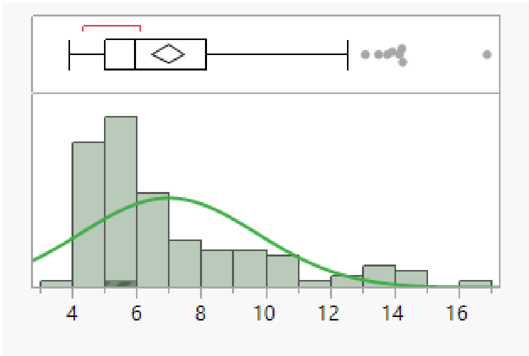
This study used rivets size 6, bucking bar weights ranging between 1 lb. and 5 lbs., as well as 4X rivet guns with 1740 BPM and 2100 BPM. Nevertheless, future researches may investigate on larger rivet guns or heavier bucking bars and their effect on vibration transmission and muscle fatigue as well as the study of other factors such as force exerted, repetitive motion, and posture.

This study only investigated the effect of using different riveting tools on hand-arm vibration and the effect of these vibration levels on muscle fatigue. However, the study of additional factors such as riveting quality, productivity, efficiency can help to make more informed riveting tools decisions.

APPENDIX A. TEST OF NORMALITY

Part 1

Wrist Acc X



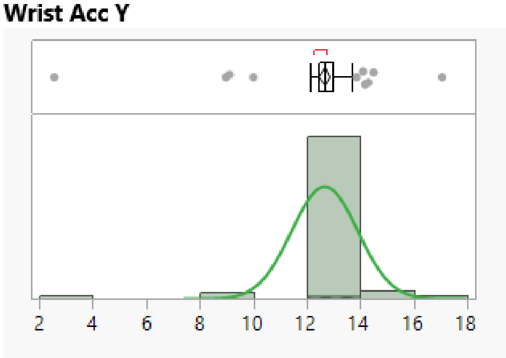
Goodness-of-Fit Test

	W	Prob<W
Shapiro-Wilk	0.8420521	<.0001*

	A2	Prob > A2
Anderson-Darling	6.1999518	<.0001*

H_0= Data follow a normal distribution
H_1= Data does not follow a normal distribution

Wrist Acc Y



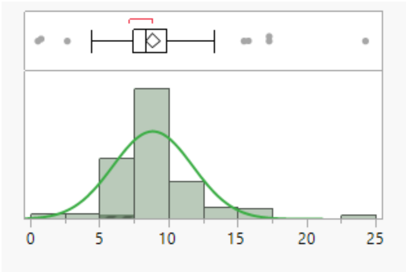
Goodness-of-Fit Test

	W	Prob<W
Shapiro-Wilk	0.5262484	<.0001*

	A2	Prob > A2
Anderson-Darling	15.088408	<.0001*

H_0= Data follow a normal distribution
H_1= Data does not follow a normal distribution

Wrist Acc Z



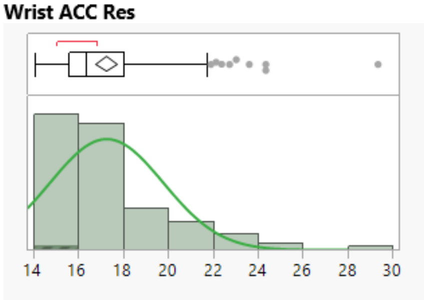
Goodness-of-Fit Test

	W	Prob<W
Shapiro-Wilk	0.8481955	<.0001*

	A2	Prob > A2
Anderson-Darling	5.1993326	<.0001*

H_0= Data follow a normal distribution
H_1= Data does not follow a normal distribution

Wrist ACC Res



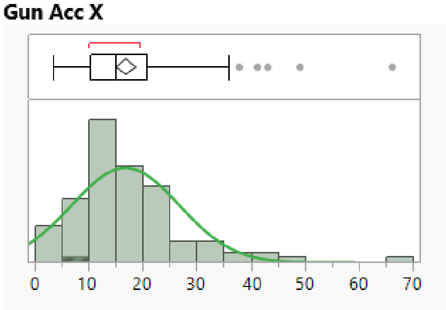
Goodness-of-Fit Test

	W	Prob<W
Shapiro-Wilk	0.8295122	<.0001*

	A2	Prob > A2
Anderson-Darling	5.9890309	<.0001*

H_0= Data follow a normal distribution
H_1= Data does not follow a normal distribution

Gun Acc X



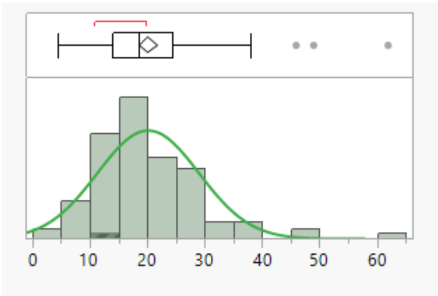
Goodness-of-Fit Test

	W	Prob<W
Shapiro-Wilk	0.8763791	<.0001*

	A2	Prob > A2
Anderson-Darling	2.9561763	<.0001*

H_0= Data follow a normal distribution
H_1= Data does not follow a normal distribution

Gun Acc Z



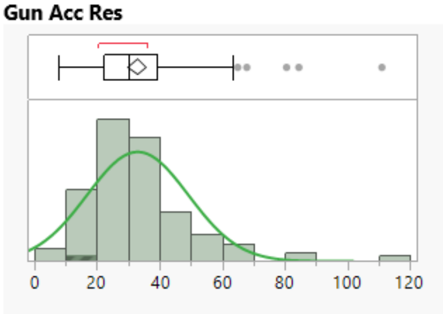
Goodness-of-Fit Test

	W	Prob<W
Shapiro-Wilk	0.9157636	<.0001*

	A2	Prob > A2
Anderson-Darling	1.6830868	<.0001*

H_0= Data follow a normal distribution
H_1= Data does not follow a normal distribution

Gun Acc Res



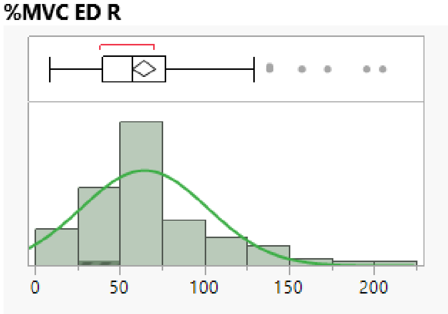
Goodness-of-Fit Test

	W	Prob<W
Shapiro-Wilk	0.8995802	<.0001*

	A2	Prob > A2
Anderson-Darling	2.2832443	<.0001*

H_0= Data follow a normal distribution
H_1= Data does not follow a normal distribution

%MVC ED R



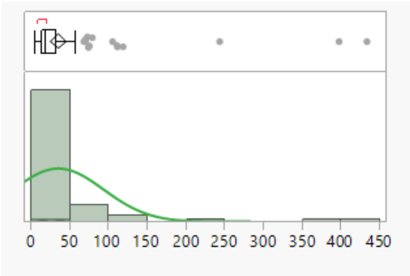
Goodness-of-Fit Test

	W	Prob<W
Shapiro-Wilk	0.9040286	<.0001*

	A2	Prob > A2
Anderson-Darling	3.1628049	<.0001*

H_0= Data follow a normal distribution
H_1= Data does not follow a normal distribution

% MVC Br R



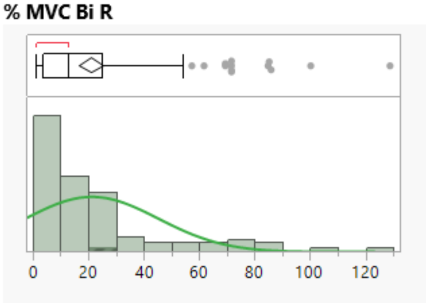
Goodness-of-Fit Test

	W	Prob<W
Shapiro-Wilk	0.415664	<.0001*

	A2	Prob > A2
Anderson-Darling	20.974529	<.0001*

H_0= Data follow a normal distribution
H_1= Data does not follow a normal distribution

% MVC Bi R



Goodness-of-Fit Test

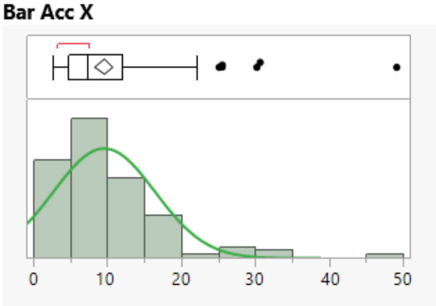
	W	Prob<W
Shapiro-Wilk	0.7588404	<.0001*

	A2	Prob > A2
Anderson-Darling	9.3278488	<.0001*

H_0= Data follow a normal distribution
H_1= Data does not follow a normal distribution

Part 2

Bar Acc X



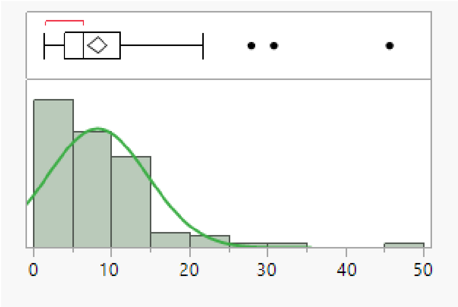
Goodness-of-Fit Test

	W	Prob<W
Shapiro-Wilk	0.7790612	<.0001*

	A2	Prob > A2
Anderson-Darling	5.9602482	<.0001*

H_0= Data follow a normal distribution
H_1= Data does not follow a normal distribution

Bar Acc Y



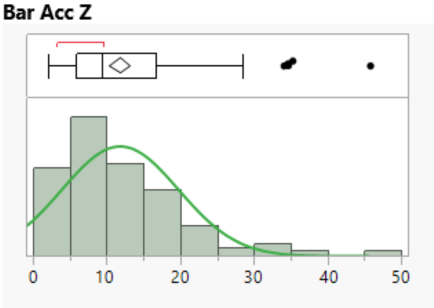
Goodness-of-Fit Test

	W	Prob<W
Shapiro-Wilk	0.7946899	<.0001*

	A2	Prob > A2
Anderson-Darling	4.5888977	<.0001*

H_0= Data follow a normal distribution
H_1= Data does not follow a normal distribution

Bar Acc Z



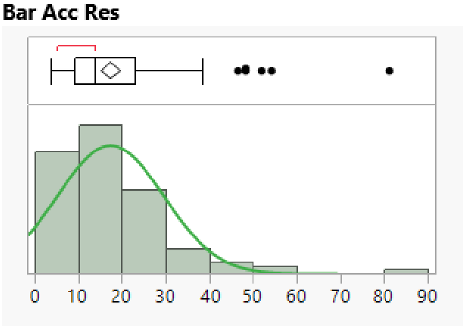
Goodness-of-Fit Test

	W	Prob<W
Shapiro-Wilk	0.8637005	<.0001*

	A2	Prob > A2
Anderson-Darling	3.8666373	<.0001*

H_0= Data follow a normal distribution
H_1= Data does not follow a normal distribution

Bar Acc Res



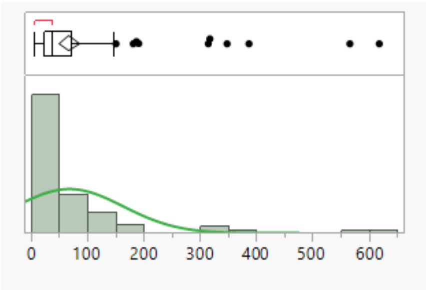
Goodness-of-Fit Test

	W	Prob<W
Shapiro-Wilk	0.8235145	<.0001*

	A2	Prob > A2
Anderson-Darling	4.6289793	<.0001*

H_0= Data follow a normal distribution
H_1= Data does not follow a normal distribution

%MVC ECR B



Goodness-of-Fit Test

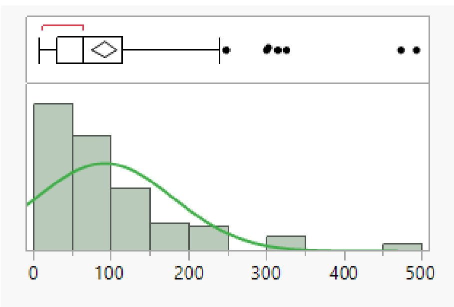
	W	Prob<W
Shapiro-Wilk	0.5647982	<.0001*

	A2	Prob > A2
Anderson-Darling	15.82496	<.0001*

H_0= Data follow a normal distribution

H_1= Data does not follow a normal distribution

% MVC PL B



Goodness-of-Fit Test

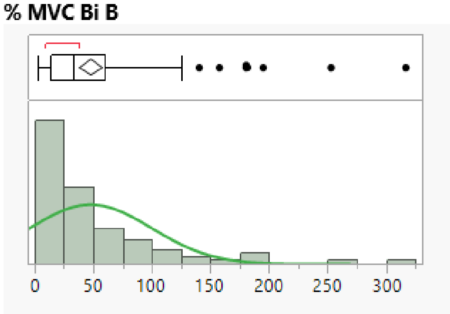
	W	Prob<W
Shapiro-Wilk	0.7834128	<.0001*

	A2	Prob > A2
Anderson-Darling	7.021361	<.0001*

H_0= Data follow a normal distribution

H_1= Data does not follow a normal distribution

% MVC Bi B



Goodness-of-Fit Test

	W	Prob<W
Shapiro-Wilk	0.7295273	<.0001*

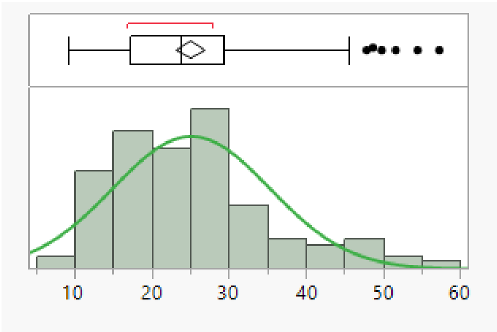
	A2	Prob > A2
Anderson-Darling	9.3387662	<.0001*

H_0= Data follow a normal distribution

H_1= Data does not follow a normal distribution

Part 3

Average Acc Res Gun and Bar



Goodness-of-Fit Test

	W	Prob<W
Shapiro-Wilk	0.9318229	<.0001*

	A2	Prob > A2
Anderson-Darling	2.1446261	<.0001*

H_0= Data follow a normal distribution

H_1= Data does not follow a normal distribution

APPENDIX B. IRB CONSENT FORM

1. **Study Title**

The Effect of Aircraft Manufacturing Riveting Tools on Hand-Arm Vibrations and Muscle Fatigue**.**

2. **Site:**

Mechanical Engineering shop in the Engineering Lab Annex Building (ELAB) room # 185, Louisiana State University, Baton Rouge, LA 70803.

3. **Contacts**

Name: Dr. Fereydoun Aghazadeh
Title: Professor Department of Mechanical and Industrial Engineering
Office: 3250A Patrick F Taylor Hall, Louisiana State University, Baton Rouge, LA 70803
Tel. No.: (225) 578-5367
Email: aghazadeh@lsu.edu
Hours available: M-F, 8 AM-5 PM

Name: Lou Toua Vi
Title: Graduate Student Department of Mechanical and Industrial Engineering
Office: 1354 Patrick F Taylor Hall, Louisiana State University, Baton Rouge, LA 70803
Tel. No.: (713) 632-5483
Email: lvi2@lsu.edu
Hours Available: M, W, F, 12-5 PM / T, Th, 9-1 PM, 3-5 PM

4. **Purpose the study**

Assessing the effect of riveting tools vibration on workers by measuring acceleration, muscle activity, heart rate, blood pressure, and the perceived rate of exertion (Borg Scale).

5. **Participants**

There will be a total of 10 male participants with two of them being experienced riveters and the rest being students. The two experienced riveters will train the other participants to properly drive rivets.

6. **Number of participants**

Ten (10).

7. **Study Procedures**

One day will be allowed to train all the participants and prepare them for data collection. Two riveting professionals will train the participants on how to drive rivets (the proper way to hold the tools, proper posture, etc.). Participants will also be allowed to familiarize themselves with the different tools by driving a couple of rivets.

These participants will be randomly paired to perform the experimental trials. Since 4 rivet guns, 3 bucking bars, and 2 wrist positions are tested, there will be a total of 24 experimental trials. Each pair of participants will perform all experimental trials in random orders in three days. In other words, each pair of participants will perform 8 experimental trials per day. The experimental trial consists of setting at least five single rivets in 30 s. During each task, acceleration data will be collected simultaneously in the x, y, z-axis from the bucking bar, rivet gun, and riveter wrist, as well as EMG data from the riveter and bucker muscles. Heart rate data will also be monitored throughout each task. After each task, each participant will be asked to rate the level of exertion they felt on a scale of 0 to 10 (Borg Scale).

8. Benefits

This research will also be beneficial to the industry as it would help to recommend a combination of riveting tools that gives the least exposure to vibrations, thereby offering a safer working environment to workers; recommend safe practices for the tools that generate the highest level of vibration as well as PPE's for the workers that are the most affected by vibration (Riveters or Buckers). This study would also recommend safe practices for the tools that are the most demanding on the workers' muscles.

9. Risks/Discomforts

Minimal discomfort can be experienced from the Electromyography electrode removal as they are taped directly to the skin without gel.

Minimal discomfort can also be experienced while removing the medical tape used to secure the accelerometer to the riveter wrist.

The riveting task can be very loud, but earplugs will be provided for each participant.

10. Right to refuse

At any time during this experiment, each participant may choose not to participate, especially if he feels discomfort with any part of the procedure.

11. Privacy

The identity of each test participant will remain confidential unless disclosure by law is required. All data will be stored in a secure location or password-protected computer. No personal information such as names will be used in this study.

Signature

The study has been discussed with me and all my questions have been answered. I may direct additional questions regarding study specifics to the investigators. If I have questions about participants' rights or other concerns, I can contact Dennis Landin, Chairman, LSU Institutional Review Board, (225) 578-8692, irb@lsu.edu, www.lsu.edu/irb. I agree to participate in the study described above and acknowledge the researchers' obligation to provide me with a copy of this consent form if signed by me.

Participant Signature: ___________________________________Date: ___________

APPENDIX C. PERCEIVED LEVEL OF EXERTION (BORG SCALE) FORM

Borg Scale Instruction

Please rate your perceived level of exertion according to how heavy or strenuous the activity feels to you (feeling of physical stress, strain, effort, pain and fatigue)

Borg CR10 Ratings of perceived Exertion	
10-point Scale	
Ratings	Definition
0	No Exertion at all
0.5	Extremely light
1	Very light
2	Light
3	Moderate
4	Somewhat hard
5	Hard
6	Very hard
7	
8	Extremely hard
9	
10	Maximal exertion

APPENDIX D. DATA

Part 1: Data Table

Pattern	Blocks	Days	Subjects	Guns	Bars	Gun Handle	Number of Rivets Set	Borg Scale	Average Borg Scale of R and B	Wrist Acc X	Wrist Acc Y	Wrist Acc Z	Wrist ACC ...	Gun Acc X	Gun Acc Y	Gun Acc Z	Gun Acc ...	Average Acc Res Gun and Bar	%MVC ED R	% MVC Br R	% MVC Bi R
111	1	Day 1	Riveter	Model 4	Steel (1lb)	Vertical	5	1	4	8.18...	12.60...	7.31...	16.709...	17.47...	17.69...	14.40...	28.73...	24.00	10.44...	20.512...	15.38...
231	1	Day 1	Riveter	Model 2	Spring Dam...	Vertical	5	1	2	11.4...	13.42...	9.74...	20.167...	34.89...	29.72...	37.91...	59.49...	33.04	11.94...	12.820...	19.23...
421	1	Day 2	Riveter	Model 3	Tungsten (2...	Vertical	6	1	3	5.81...	12.38...	7.51...	15.611...	4.089...	4.398...	4.717...	7.637...	16.82	80	75.675...	85
211	1	Day 1	Riveter	Model 2	Steel (1lb)	Vertical	6	1	3	10.1...	13.83...	17.2...	24.337...	20.07...	26.31...	18.49...	37.91...	25.04	32.83...	15.384...	61.53...
132	1	Day 2	Riveter	Model 4	Spring Dam...	Horizontal	6	2	3	4.79...	12.44...	7.36...	15.235...	10.28...	13.00...	12.22...	20.59...	13.46	83.33...	7.8947...	6.153...
221	1	Day 2	Riveter	Model 2	Tungsten (2...	Vertical	5	1	3	4.03...	12.42...	5.26...	14.085...	10.20...	10.10...	19.15...	23.94...	25.88	70	9.4594...	25
122	1	Day 1	Riveter	Model 4	Tungsten (2...	Horizontal	5	2	3.5	5.36...	12.67...	6.09...	15.049...	17.25...	13.61...	13.62...	25.85...	26.82	12.28...	26.923...	5.194...
332	1	Day 2	Riveter	Model 1	Spring Dam...	Horizontal	6	3	2	4.56...	12.69...	7.86...	15.619...	32.00...	32.34...	30.07...	54.53...	32.72	105.5...	12.280...	3.076...
212	1	Day 2	Riveter	Model 2	Steel (1lb)	Horizontal	5	1	4	4.87...	12.25...	6.97...	14.921...	20.07...	26.31...	18.49...	37.91...	25.04	105.5...	9.6491...	9.230...
412	1	Day 2	Riveter	Model 3	Steel (1lb)	Horizontal	5	2	5	4.91...	12.53...	9.85...	16.686...	10.94...	6.781...	9.835...	16.20...	20.63	94.44...	7.0175...	4.615...
431	1	Day2	Riveter	Model 3	Spring Dam...	Vertical	5	2	2.5	5.09...	12.36...	6.48...	14.866...	10.11...	7.718...	10.64...	16.58...	12.77	90	10.810...	20
131	1	Day 2	Riveter	Model 4	Spring Dam...	Vertical	7	2	3	5.72...	12.31...	6.41...	15.016...	14.61...	18.15...	13.35...	26.85...	16.93	75	12.162...	25
322	1	Day 1	Riveter	Model 1	Tungsten (2...	Horizontal	6	2	3.5	5.81...	13.12...	9.03...	16.966...	33.09...	39.45...	33.67...	61.52...	41.23	8.771...	23.076...	1.298...
311	1	Day 1	Riveter	Model 1	Steel (1lb)	Vertical	5	1	4	5.97...	12.93...	8.34...	16.510...	37.76...	37.60...	36.81...	64.77...	44.28	11.94...	17.948...	23.07...
222	1	Day 2	Riveter	Model 2	Tungsten (2...	Horizontal	5	1	3	3.88...	12.51...	5.70...	14.294...	11.36...	13.76...	21.40...	27.87...	28.31	122.2...	6.1403...	3.076...
312	1	Day 2	Riveter	Model 1	Steel (1lb)	Horizontal	5	1	2	7.40...	12.37...	6.74...	15.917...	22.08...	27.78...	24.12...	42.91...	45.54	172.2...	24.561...	26.15...
432	1	Day 2	Riveter	Model 3	Spring Dam...	Horizontal	6	2	4.5	4.51...	12.56...	7.19...	15.166...	9.303...	7.663...	8.675...	14.85...	12.19	77.77...	5.2631...	3.076...
112	1	Day 2	Riveter	Model 4	Steel (1lb)	Horizontal	4	2	4.5	4.73...	12.52...	6.98...	15.103...	16.29...	12.29...	13.76...	24.61...	21.94	111.1...	6.1403...	3.076...
321	1	Day 1	Riveter	Model 1	Tungsten (2...	Vertical	6	1	3	8.12...	13.26...	8.23...	17.598...	43.05...	50.07...	45.82...	80.37...	48.63	13.43...	17.948...	23.07...
422	1	Day 2	Riveter	Model 3	Tungsten (2...	Horizontal	5	3	4	4.70...	12.48...	7.03...	15.080...	4.626...	4.842...	4.528...	8.084...	16.79	127.7...	7.0175...	3.076...
232	1	Day 2	Riveter	Model 2	Spring Dam...	Horizontal	5	2	2.5	4.80...	12.46...	7.87...	15.510...	22.37...	26.74...	19.49...	39.94...	23.07	122.2...	11.403...	4.615...
331	1	Day 2	Riveter	Model 1	Spring Dam...	Vertical	7	2	2.5	6.40...	12.59...	7.02...	15.783...	30.21...	32.87...	31.89...	54.87...	33.12	75	12.162...	20
121	1	Day 1	Riveter	Model 4	Tungsten (2...	Vertical	7	2	3.5	5.65...	12.59...	5.15...	14.738...	22.22...	20.18...	19.45...	35.77...	33.40	11.94...	15.384...	15.38...

Part 1: Generalized Linear Model Output

Response Wrist Acc X

Summary of Fit

RSquare	0.58124
RSquare Adj	0.480913
Root Mean Square Error	2.009976
Mean of Response	6.983979
Observations (or Sum Wgts)	120

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	Std Error	95% Lower	95% Upper	Wald p-Value	Pct of Total
Blocks	0.3739997	1.5109599	1.1881835	-0.817837	3.8397568	0.2035	26.966
Days	0.0129293	0.0522343	0.1916669	-0.323426	0.4278944	0.7852	0.932
Residual		4.0400026	0.5992795	3.0816593	5.52946		72.102
Total		5.6031968	1.3301592	3.6956401	9.4945473		100.000

Response Bar Acc Y

Summary of Fit

RSquare	0.219557
RSquare Adj	0.032576
Root Mean Square Error	1.219803
Mean of Response	12.64177
Observations (or Sum Wgts)	120

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	Std Error	95% Lower	95% Upper	Wald p-Value	Pct of Total
Blocks	0.0317207	0.0471978	0.0779109	-0.105505	0.1999003	0.5447	3.075
Days	-0.009033	-0.01344	0.0254912	-0.063402	0.0365213	0.5980	0.000
Residual		1.4879206	0.2202218	1.1356027	2.0349492		96.925
Total		1.5351184	0.2253433	1.1740481	2.0936907		100.000

Response Wrist Acc Z

Summary of Fit

RSquare	0.455289
RSquare Adj	0.324785
Root Mean Square Error	2.387926
Mean of Response	8.829907
Observations (or Sum Wgts)	120

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	Std Error	95% Lower	95% Upper	Wald p-Value	Pct of Total
Blocks	0.2121829	1.2099068	1.0260561	-0.801126	3.2209397	0.2383	17.504
Days	-0.013984	-0.079741	0.0633884	-0.20398	0.0444982	0.2084	0.000
Residual		5.7021893	0.8440934	4.3518217	7.7989937		82.496
Total		6.9120961	1.310913	4.9212835	10.418781		100.000

Response Gun Acc X

Summary of Fit

RSquare	0.445881
RSquare Adj	0.313124
Root Mean Square Error	8.362807
Mean of Response	16.71883
Observations (or Sum Wgts)	120

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	Std Error	95% Lower	95% Upper	Wald p-Value	Pct of Total
Blocks	0.0648151	4.532943	5.2930789	-5.841301	14.907187	0.3918	6.044
Days	0.0075409	0.5273841	2.7827733	-4.926751	5.9815195	0.8497	0.703
Residual		69.936533	10.379771	53.339333	95.738171		93.253
Total		74.99686	11.425366	56.818812	103.59246		100.000

Response Gun Acc Y

Summary of Fit

RSquare	0.522159
RSquare Adj	0.407677
Root Mean Square Error	7.851219
Mean of Response	19.45708
Observations (or Sum Wgts)	120

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	Std Error	95% Lower	95% Upper	Wald p-Value	Pct of Total
Blocks	0.0442839	2.729734	3.8181788	-4.753759	10.213227	0.4747	4.237
Days	0.0008486	0.0523065	1.926425	-3.723417	3.8280301	0.9783	0.081
Residual		61.641642	9.1763562	46.977091	84.469685		95.682
Total		64.423682	9.5756722	49.116502	88.235575		100.000

Response Gun Acc Z

Summary of Fit

RSquare	0.628983
RSquare Adj	0.540093
Root Mean Square Error	6.104987
Mean of Response	20.05089
Observations (or Sum Wgts)	120

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	Std Error	95% Lower	95% Upper	Wald p-Value	Pct of Total
Blocks	0.1105827	4.1215128	4.0216887	-3.760852	12.003878	0.3054	9.879
Days	0.008766	0.3267158	1.5564814	-2.723932	3.3773633	0.8337	0.783
Residual		37.270862	5.5293752	28.428738	51.014127		89.338
Total		41.719091	6.7470574	31.110911	58.885961		100.000

Response Gun Acc Res

Summary of Fit

RSquare	0.550712
RSquare Adj	0.44307
Root Mean Square Error	12.25269
Mean of Response	32.82305
Observations (or Sum Wgts)	120

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	Std Error	95% Lower	95% Upper	Wald p-Value	Pct of Total
Blocks	0.0707964	10.628549	12.014696	-12.91982	34.176921	0.3764	6.563
Days	0.0078862	1.1839378	6.0841279	-10.74073	13.108609	0.8457	0.731
Residual		150.12829	22.294355	114.48359	205.55493		92.706
Total		161.94078	24.879433	122.42163	224.34968		100.000

Response %MVC ED R

Summary of Fit

RSquare	0.527834
RSquare Adj	0.41471
Root Mean Square Error	29.1946
Mean of Response	64.35996
Observations (or Sum Wgts)	120

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	Std Error	95% Lower	95% Upper	Wald p-Value	Pct of Total
Blocks	0.4634043	394.97081	304.44484	-201.7301	991.67172	0.1945	30.066
Days	0.0778959	66.392535	117.90516	-164.6973	297.4824	0.5734	5.054
Residual		852.3244	126.47215	650.08783	1166.6865		64.880
Total		1313.6877	346.84939	831.4208	2382.7927		100.000

Response % MVC Br R

Summary of Fit

RSquare	0.426326
RSquare Adj	0.288883
Root Mean Square Error	50.10982
Mean of Response	35.67969
Observations (or Sum Wgts)	120

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	Std Error	95% Lower	95% Upper	Wald p-Value	Pct of Total
Blocks	0.1636019	410.80352	364.86687	-304.3224	1125.9294	0.2602	12.862
Days	0.1083646	272.10301	412.47657	-536.3362	1080.5422	0.5095	8.519
Residual		2510.9943	372.26462	1915.6213	3436.0933		78.618
Total		3193.9008	653.86894	2218.9653	4992.1362		100.000

Response % MVC Bi R

Summary of Fit

RSquare	0.695017
RSquare Adj	0.621949
Root Mean Square Error	14.91241
Mean of Response	21.09859
Observations (or Sum Wgts)	120

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	Std Error	95% Lower	95% Upper	Wald p-Value	Pct of Total
Blocks	0.6853898	152.41687	114.92443	-72.83088	377.66462	0.1848	40.667
Days	-0.011642	-2.589032	3.2295163	-8.918768	3.7407032	0.4227	0.000
Residual		222.37984	33.063004	169.52985	304.60387		59.333
Total		374.7967	118.74783	219.18027	782.88043		100.000

Response Perceived Level of Exertion Riveters (Borg Scale)

Whole Model Test

Model	-LogLikelihood	L-R ChiSquare	DF	Prob>ChiSq
Difference	9.17972737	18.3595	23	0.7377
Full	188.426865			
Reduced	197.606592			

Goodness Of Fit Statistic	ChiSquare	DF	Prob>ChiSq	Overdispersion
Pearson	162.4000	96	<.0001*	1.3533
Deviance	162.4000	96	<.0001*	

Part 2: Data Table

Pattern	Blocks	Days	Subjects	Guns	Bars	Gun Handle	Number of Rivets Set	Borg Scale	Bar Acc X	Bar Acc Y	Bar Acc Z	Bar Acc Res	%MVC ECR B	% MVC PL B	% MVC Bi B
411	1	Day 2	Bucker	Model 3	Steel (1lb)	Neutral	4	4	12.13...	10.49...	13.23...	20.797...	186.27...	125.64...	120.83...
111	1	Day 1	Bucker	Model 4	Steel (1lb)	Neutral	5	7	12.02...	9.684...	11.50...	19.255...	386.11...	50.980...	45.945...
231	1	Day 1	Bucker	Model 2	Spring Dampener (5lbs)	Neutral	5	3	4.155...	2.848...	4.251...	6.5916...	38.888...	9.8039...	18.918...
421	1	Day 2	Bucker	Model 3	Tungsten (2.7lbs)	Neutral	6	5	13.50...	12.85...	18.13...	26.009...	72.549...	153.84...	87.5
211	1	Day 1	Bucker	Model 2	Steel (1lb)	Neutral	6	5	6.240...	5.977...	8.558...	12.162...	150	56.862...	40.540...
132	1	Day 2	Bucker	Model 4	Spring Dampener (5lbs)	Sidewise	6	4	3.513...	2.569...	4.586...	6.3228...	5.7692...	92.592...	11.764...
221	1	Day 2	Bucker	Model 2	Tungsten (2.7lbs)	Neutral	5	5	16.37...	13.12...	18.24...	27.808...	17.647...	51.282...	12.5
122	1	Day 1	Bucker	Model 4	Tungsten (2.7lbs)	Sidewise	5	5	16.40...	12.91...	18.34...	27.793...	617.39...	58.139...	32
332	1	Day 2	Bucker	Model 1	Spring Dampener (5lbs)	Sidewise	6	1	6.289...	5.111...	7.291...	10.901...	5.7692...	66.666...	8.8235...
212	1	Day 2	Bucker	Model 2	Steel (1lb)	Sidewise	5	7	6.240...	5.977...	8.558...	12.162...	7.6923...	218.51...	11.764...
412	1	Day 2	Bucker	Model 3	Steel (1lb)	Sidewise	5	8	13.56...	11.42...	17.70...	25.056...	7.6923...	55.555...	11.764...
431	1	Day2	Bucker	Model 3	Spring Dampener (5lbs)	Neutral	5	3	5.191...	4.362...	5.844...	8.9520...	19.607...	84.615...	25
131	1	Day 2	Bucker	Model 4	Spring Dampener (5lbs)	Neutral	7	4	3.803...	2.804...	5.177...	7.0097...	5.8823...	48.717...	12.5
322	1	Day 1	Bucker	Model 1	Tungsten (2.7lbs)	Sidewise	6	5	10.88...	10.43...	14.52...	20.940...	565.21...	218.60...	36
311	1	Day 1	Bucker	Model 1	Steel (1lb)	Neutral	5	7	12.76...	11.13...	16.70...	23.791...	347.22...	21.568...	75.675...
222	1	Day 2	Bucker	Model 2	Tungsten (2.7lbs)	Sidewise	5	5	17.37...	13.39...	18.56...	28.744...	9.6153...	85.185...	14.705...
312	1	Day 2	Bucker	Model 1	Steel (1lb)	Sidewise	5	3	25.47...	21.78...	34.58...	48.165...	59.615...	103.70...	50
432	1	Day 2	Bucker	Model 3	Spring Dampener (5lbs)	Sidewise	6	7	5.630...	4.107...	6.510...	9.5372...	17.307...	233.33...	17.647...
112	1	Day 2	Bucker	Model 4	Steel (1lb)	Sidewise	4	7	10.87...	8.355...	13.53...	19.262...	11.538...	100	11.764...
321	1	Day 1	Bucker	Model 1	Tungsten (2.7lbs)	Neutral	6	5	9.132...	8.180...	11.60...	16.883...	313.88...	13.725...	37.837...
422	1	Day 2	Bucker	Model 3	Tungsten (2.7lbs)	Sidewise	5	5	14.24...	12.35...	17.16...	25.498...	5.7692...	492.59...	11.764...
232	1	Day 2	Bucker	Model 2	Spring Dampener (5lbs)	Sidewise	5	3	3.400...	2.431...	4.572...	6.1953...	5.7692...	62.962...	14.705...
331	1	Day 2	Bucker	Model 1	Spring Dampener (5lbs)	Neutral	7	3	6.596...	5.378...	7.538...	11.369...	11.764...	87.179...	20.833...
121	1	Day 1	Bucker	Model 4	Tungsten (2.7lbs)	Neutral	7	5	18.39...	14.92...	20.02...	31.021...	316.66...	107.84...	56.756...

Part 2: Generalized Linear Model Output

Response Bar Acc X

Summary of Fit

RSquare	0.532697
RSquare Adj	0.420739
Root Mean Square Error	5.27872
Mean of Response	9.527353
Observations (or Sum Wgts)	120

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	Std Error	95% Lower	95% Upper	Wald p-Value	Pct of Total
Blocks	0.0250861	0.6990222	1.3423351	-1.931906	3.3299507	0.6025	2.380
Days	0.0287595	0.8013816	1.8772203	-2.877903	4.4806657	0.6695	2.729
Residual		27.864886	4.1219304	21.269811	38.102284		94.891
Total		29.36529	4.4869758	22.230511	40.604271		100.000

Response Bar Acc Y

Summary of Fit

RSquare	0.553352
RSquare Adj	0.446342
Root Mean Square Error	4.849032
Mean of Response	8.199927
Observations (or Sum Wgts)	120

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	Std Error	95% Lower	95% Upper	Wald p-Value	Pct of Total
Blocks	0.0512811	1.2057793	1.5633872	-1.858403	4.2699619	0.4406	4.694
Days	0.041191	0.968529	1.958548	-2.870155	4.8072126	0.6209	3.770
Residual		23.513113	3.4801426	17.945485	32.157784		91.536
Total		25.687421	4.0915958	19.234512	36.05319		100.000

Response Bar Acc Z

Summary of Fit

RSquare	0.637663
RSquare Adj	0.550853
Root Mean Square Error	5.406112
Mean of Response	11.77681
Observations (or Sum Wgts)	120

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	Std Error	95% Lower	95% Upper	Wald p-Value	Pct of Total
Blocks	0.1200908	3.5097782	3.3741103	-3.103356	10.122913	0.2982	10.268
Days	0.0494201	1.4443546	2.7406622	-3.927244	6.8159538	0.5982	4.226
Residual		29.226043	4.3261664	22.305062	39.972532		85.506
Total		34.180176	5.8690086	25.067202	49.379788		100.000

Response Bar Acc Res

Summary of Fit

RSquare	0.588057
RSquare Adj	0.489363
Root Mean Square Error	8.852063
Mean of Response	17.2908
Observations (or Sum Wgts)	120

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	Std Error	95% Lower	95% Upper	Wald p-Value	Pct of Total
Blocks	0.0623772	4.8878196	5.8415804	-6.561468	16.337107	0.4027	5.648
Days	0.0420987	3.2988135	6.6226106	-9.681265	16.278892	0.6184	3.812
Residual		78.359013	11.596018	59.806844	107.16237		90.541
Total		86.545646	13.889725	64.673269	121.80906		100.000

Response %MVC ECR B

Summary of Fit

RSquare	0.376789
RSquare Adj	0.227477
Root Mean Square Error	85.98989
Mean of Response	67.16594
Observations (or Sum Wgts)	120

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	Std Error	95% Lower	95% Upper	Wald p-Value	Pct of Total
Blocks	0.2194317	1622.5352	1366.7471	-1056.24	4301.3103	0.2352	16.997
Days	0.0715819	529.29548	968.83284	-1369.582	2428.1729	0.5848	5.545
Residual		7394.2618	1097.7749	5639.0285	10123.287		77.459
Total		9546.0924	1968.6131	6616.1485	14975.142		100.000

Response % MVC PL B

Summary of Fit

RSquare	0.583243
RSquare Adj	0.483395
Root Mean Square Error	65.02286
Mean of Response	91.54644
Observations (or Sum Wgts)	120

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	Std Error	95% Lower	95% Upper	Wald p-Value	Pct of Total
Blocks	0.230778	975.72276	815.05142	-621.7487	2573.1942	0.2313	16.171
Days	0.1963168	830.02177	1114.7242	-1354.798	3014.8411	0.4565	13.756
Residual		4227.9718	627.03265	3225.2077	5786.3245		70.072
Total		6033.7164	1509.1051	3901.4486	10559.108		100.000

Response % MVC Bi B

Summary of Fit

RSquare	0.572185
RSquare Adj	0.469688
Root Mean Square Error	38.02183
Mean of Response	47.36467
Observations (or Sum Wgts)	120

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	Std Error	95% Lower	95% Upper	Wald p-Value	Pct of Total
Blocks	0.6376682	921.851	695.75011	-441.7942	2285.4962	0.1852	38.938
Days	-0.016081	-23.24798	12.289856	-47.33566	0.8396936	0.0585	0.000
Residual		1445.6593	214.69148	1102.4084	1979.4152		61.062
Total		2367.5103	723.73725	1407.3628	4796.7938		100.000

Response Perceived Level of Exertion Buckers (Borg Scale)

Whole Model Test

Model	-LogLikelihood	L-R ChiSquare	DF	Prob>ChiSq
Difference	66.5083529	133.0167	23	<.0001*
Full	202.462226			
Reduced	268.970579			

Goodness Of Fit Statistic	ChiSquare	DF	Prob>ChiSq	Overdispersion
Pearson	205.2000	96	<.0001*	1.7100
Deviance	205.2000	96	<.0001*	

Part 3: Generalized Linear Model Output

Response Average Acc Res Gun and Bar

Summary of Fit

RSquare	0.482704
RSquare Adj	0.455237
Root Mean Square Error	7.582853
Mean of Response	25.05692
Observations (or Sum Wgts)	120

REML Variance Component Estimates

Random Effect	Var Ratio	Var Component	Std Error	95% Lower	95% Upper	Wald p-Value	Pct of Total
Blocks	0.0665609	3.8272279	4.497107	-4.98694	12.641396	0.3947	6.241
Days	-0.01074	-0.617541	0.6941934	-1.978135	0.7430533	0.3737	0.000
Residual		57.499661	7.7979543	44.824439	76.460379		93.759
Total		61.326889	8.7760842	47.198378	82.942323		100.000

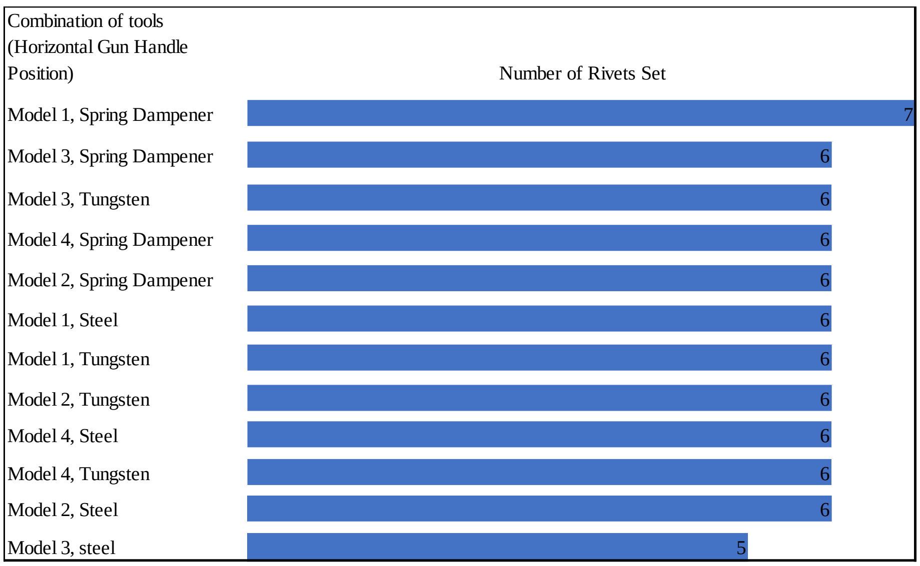
Response Average Perceived Level of Exertion Riveters and Buckers (Borg Scale)

Whole Model Test

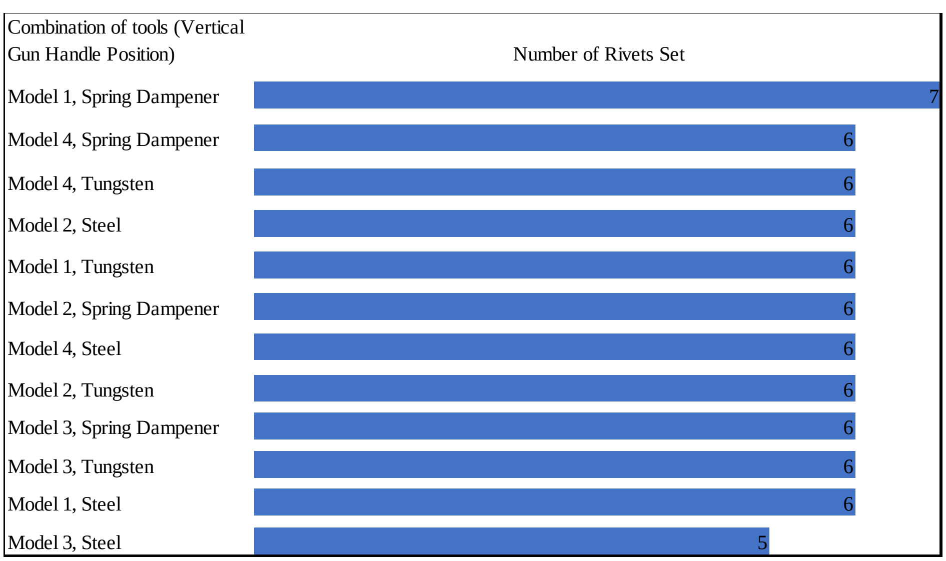
Model	-LogLikelihood	L-R ChiSquare	DF	Prob>ChiSq
Difference	52.0837413	104.1675	23	<.0001*
Full	145.037899			
Reduced	197.121641			

Goodness Of Fit Statistic	ChiSquare	DF	Prob>ChiSq	Overdispersion
Pearson	78.8000	96	0.8989	0.6567
Deviance	78.8000	96	0.8989	

Number of Rivet Sets per Combination of tools (Horizontal Gun Handle Position)



Number of Rivet Sets per Combination of tools (Vertical Gun Handle Position)



APPENDIX E. EXTRA TOOLS PICTURES

Guns Pictures

Honsa Model HTOP38 12T

AERO US Industrial Aircraft 4X

Honsa Model HTOP38 4X

Chicago Pneumatic Model CP4444-RUTAB

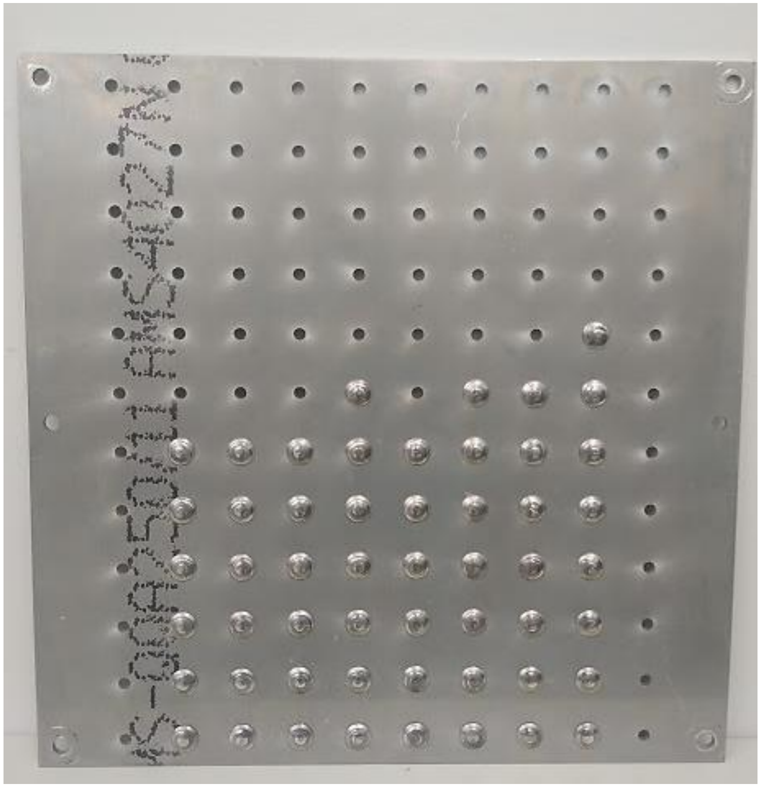
Bars Pictures

Honsa Bucking Bar Model HVRBB-670A

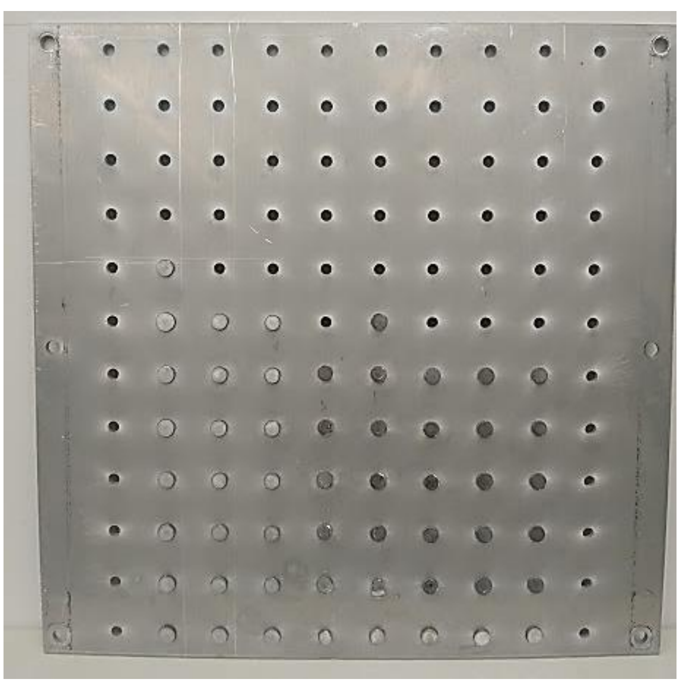
Honsa Tungsten Bucking Bar Model JBBT4545T

Steel Bucking Bar PN 15009

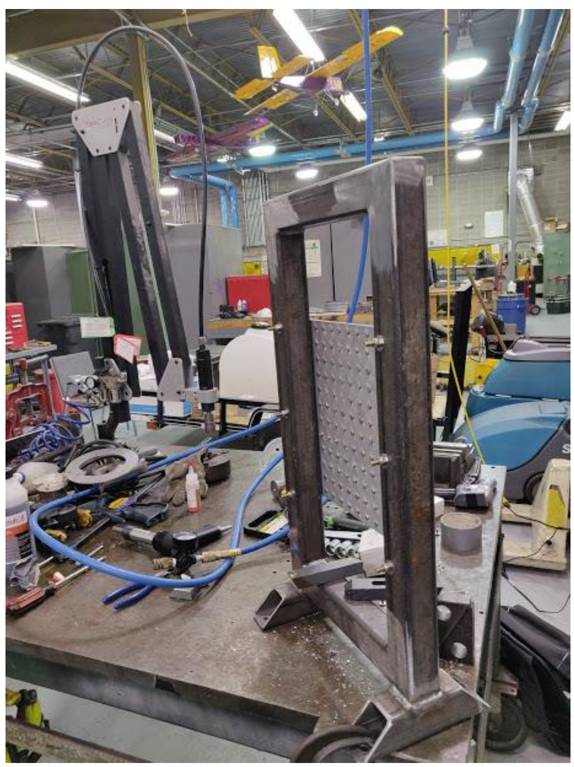
Riveting Aluminum Sheet Front



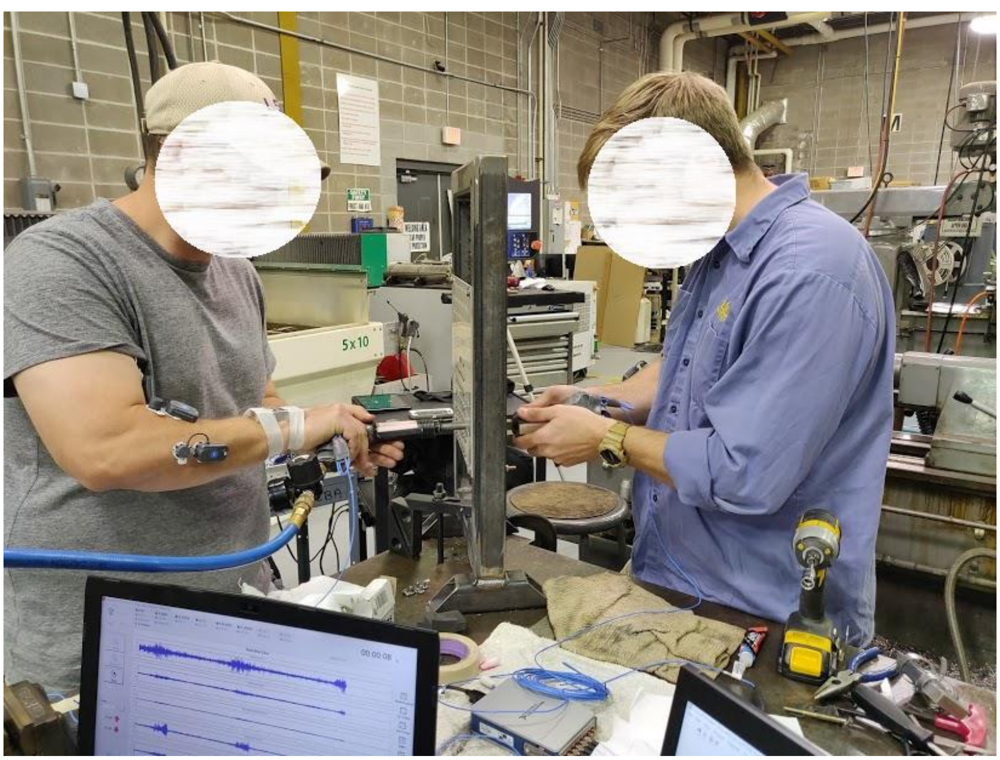
Riveting Aluminum Sheet Back



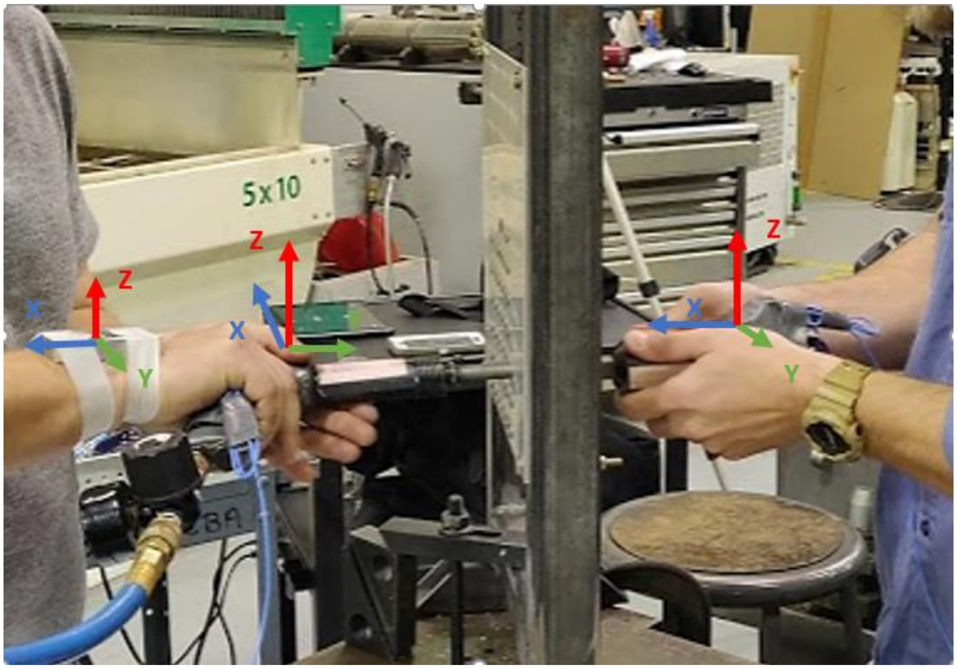
Riveting Platform with Training Aluminum Sheet

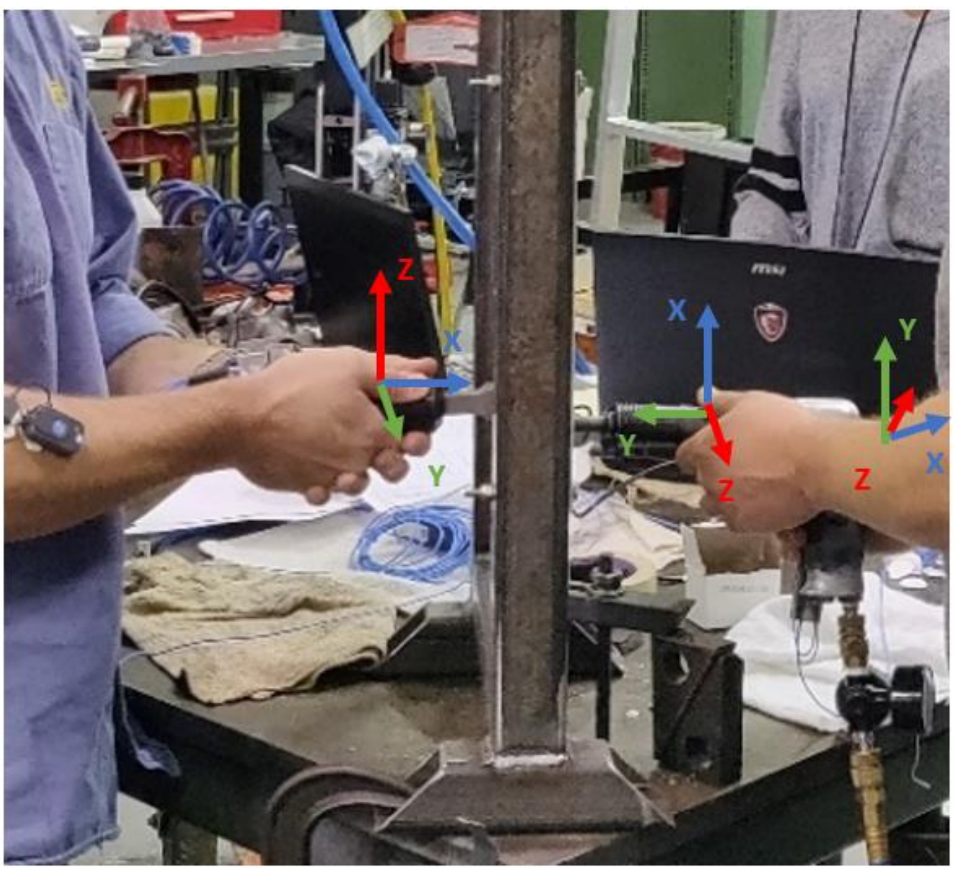


Equipment Set up



Accelerometers axes





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VITA

Lou Toua Vi was born in Abidjan, Ivory Coast in 1995. As a result of her outstanding grade in the Nationwide university entrance examination, she received a scholarship from the Ivory Coast Ministry of Hydrocarbons and Energy to pursue her study in the United States. She earned her undergraduate degree in Petroleum Engineering with a double minor in Mathematics and Geology from the University of Louisiana at Lafayette in May 2018.

Upon graduation, she joined the Industrial Engineering program at Louisiana State University (LSU) to pursue a Master in Industrial Engineering with a concentration in Human Factors. At LSU, she worked as a Research Assistant (RA) under Dr. Fereydoun Aghazadeh for 2 years. As a RA, she was responsible for writing two NIH (National Institute of Health) grant proposals among many other tasks. She expects to receive her Master’s degree with a minor in Experimental Statistics in August 2020.