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Lab and Field Based Approach for the Selection of Tool-Specific Vibration-Reducing Gloves

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Hand-arm vibration syndrome (HAVS) has been a well-recognized occupational disease for many decades. In order to protect the workers from harmful vibration exposures originating from an excessive amount of power tool vibration, vibration-reducing (VR), or antivibration (AV), gloves have been considered as beneficial personal protective equipment (PPE); however, commercially available gloves provide limited vibration protection to the hand-arm system. In addition, the use of VR PPE is not covered in the OSHA standards and regulations and vibration exposure control to the hand-arm system has not been effectively considered in the U.S. In order to protect the workers from excessive vibration exposures, a methodology of proper glove selection based on actual tool vibrations is needed that will realistically decrease the chance of these unwanted exposures. The evaluation method of VR gloves defined in ISO 10819 has been widely implemented internationally but the process is based on limited vibration exposure conditions that are conducted and assessed in controlled laboratory environments. Although a small number of VR gloves exist that have passed an ISO 10819 evaluation, they may not reduce actual vibration exposure levels and risks in the workplace. In order to fill the gap between laboratory and worksite vibration exposure assessment and to use this information to develop practical PPE technology, this dissertation: 1) conducted extensive ISO 5349 based vibration measurements on tools at worksites including health risk assessments, 2) used the ISO 10819 vibration spectrum and the actual tool vibration spectra obtained in the field to evaluate existing and newly developed VR gloves and materials, and 3) selected tool-specific VR gloves for use at

worksites that were identified visiting the Linear Time-Invariant (LTI) system theory along with power tool vibration spectra and VR glove transmissibility spectra.

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Dedicate to my family in Sapporo.

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1. Introduction

1.1 Background and Significance

The invention of power tools during the industrial revolution has contributed greatly to the quality of work and production efficiency in manufacturing; however, industrial workers have been suffering from vibration-induced symptoms, which are now recognized as Hand-Arm Vibration Syndrome or HAVS. HAVS is known to be induced from the use of vibratory power tools, holding vibrating workpieces, and/or other vibrating objects (ISO 5349-1, 2001; DHHS 89-106, 1989). The impact of Hand-Transmitted Vibration (HTV) on human health is categorized into four parts by ISO 5349-1: 1) vascular disorders, 2) neurological disorders, 3) musculoskeletal disorders, and 4) other disorders (ISO 5349-1, 2001). Depending on the level, type, duration, and/or area of the vibration exposure, these symptoms may appear alone or in combination with other symptoms (e.g. combination of vascular and musculoskeletal disorders) (Griffin, 1997).

In recent years, our society has been facing a global economic recession, which has a direct impact on our life styles, for example, employment. According to the U.S. Bureau of Labor Statistics, the U.S. unemployment rate was approximately 9 % in 2011 (Bureau of Labor Statistics, 2014) with about 142 million workers employed in the U.S. work force (US Census Bureau, 2013). Approximately 35 million people are working in the primary and secondary sectors of economy such as agriculture, forestry, fishing and hunting, mining, construction, manufacturing, transportation and warehousing. Among those, over 8 million people uses power tools regularly. Although not all of the power tool users are exposed to severe vibrations, it is estimated that 1.7 million workers could be experiencing HAVS in the U.S. Although the rate of

work-related injury has been slowly declining in recent years, the health risks associated with the vibration exposure still need significant attention.

In 1989, the National Institute for Occupational Safety and Health (NIOSH) reviewed the fundamental manner in which vibration exposures occur in U.S. industries. Although NIOSH has not established any specific standards and regulations, it recommends "to include engineering controls, good work practice, use of protective clothing and equipment, worker training programs, administrative controls, and medical monitoring and surveillance (DHHS 89-106, 1989)." Here, the occupational origin of vibration exposure was highlighted for concern but a standard for protection was not legally enforced within the industrial health and safety communities.

The International Labor Organization identifies the diseases caused by vibration, such as disorders of the muscles, tendons, bones, and/or joints, the peripheral blood vessels or peripheral nerves, etc., but there are no data that clearly demonstrate the presence of HTV-related injuries, illnesses, fatalities, or other reported occupational disease within the U.S. workforce (ILO, 2010; US Bureau of Labor Statistics, 2013; NASI, 2010). It is possible that HAVS is not fully understood and accepted as a health hazard within the U.S., especially since HAVS has not been considered as an occupational medical disease in the U.S. Statistics indicate that there are large numbers of occupational related musculoskeletal and neurological disorders but the correlation between the disorders and the vibration exposure has not been clearly defined (US Bureau of Labor Statistics, 2013; NASI, 2010).

The Occupational Safety and Health Administration (OSHA) regulates the use of personal protective equipment (PPE) in industries, which can be seen in their Occupational Safety and Health Standard (1910.138) (OSHA, 1994) and in the Occupational Safety and Health

Standard for Shipyard Employment (1915.157) (OSHA, 1996). In almost every industry around the world, PPE has been widely accepted and mandated. PPE is an effective and straightforward method to protect workers from accidents and unexpected injuries, which may potentially save on the high costs of medical expenses. In order to choose appropriate PPEs, it is recommended the hazardous sources be understood and how their motion may be reduced. For example, a pair of ear plugs will be selected not only by their fit but also on the level and frequency content of unwanted sound, the index number of the noise reduction rating (NRR) or the single number rating (SNR), which provide the customer simpler PPE decision making.

According to OSHA, regarding PPE for hand protection "there is no ANSI standard for gloves but OSHA recommends that selection be based upon the tasks to be performed and the performance and construction characteristics of the glove material" (OSHA 3151, 2003). There are many kinds of PPE gloves available for maintaining warmth, protecting against injuries and lacerations, blocking exposures to hazardous substances, and adding gripping friction; however, there is no mention of protection against vibration in any of these OSHA documents. Because there is no strong enforcement of vibration exposure and hand exposure protection, the importance of antivibration (AV) or vibration-reducing (VR) gloves has been severely overlooked.

Vibration exposure may be equivalent to chemical substance exposure, where both may potentially impact human health and quality of life. The OSHA PPE document states that, "for protection against chemicals, glove selection must be based on the chemicals encountered, the chemical resistance and the physical properties of the glove material" (OSHA 3151, 2003). This guideline could be applied for the use of VR gloves, where gloves are selected based on the vibration characteristics of tools. VR gloves are considered to be PPE but are not currently

enforced by OSHA. OSHA is known to cite and/or penalize a worksite if PPE methods are not applied during chemical exposures; however, this is not the case for vibration exposure.

In recent studies, the attenuation capabilities of VR gloves have been analyzed based on ISO 5349 (ISO 5349-1, 2001; ISO 5349-2, 2001) and ISO 10819 (ISO 10819, 1996; 2011; 2013), and the effectiveness of the VR gloves has been reported (Dong et al., 2002a; Dong et al., 2003; Shibata and Maeda, 2008; Wimer et al., 2010; Cabeças and Milho, 2011; Milosevic and McConville, 2012; Welcome et al., 2012). In the reported studies, results indicate that the methodology of ISO 5349 and 10819 could quantify the attenuation capabilities of VR gloves, even though there is some measurement variability among them (Boileau et al., 2002; Smutz et al., 2002). In addition, ISO 10819 mentions that "gloves with vibration reducing materials that meet the requirements of this International Standard to be classified as an antivibration glove can be expected to reduce hand-transmitted vibration at frequencies above 150 Hz. These gloves can reduce but not eliminate health risks associated with hand-transmitted vibration exposure" (ISO 10819, 1996; 2011; 2013).

This dissertation presents research and development on a major study to investigate intervention methods for gloves and tools, in order to reduce HAV. Nine different VR gloves and more than 35 different power tools were studied and gloves and tools were categorized by their attenuation materials and power tool vibration characteristics. In addition, all methodologies to successfully conduct, complete, and analyze the study were developed and are presented in this dissertation.

1.2 Objectives

In order to improve production time, many industries demand power tools with higher torque and/or higher rotational speeds. As a consequence, modern power tools can emit vibration with much higher frequency content than their older counterparts. It is important to note that the hand-arm frequency weighting measurement following ISO 5349 suppresses these high-frequency levels of vibration exposures. Theoretically, many commercially available ISO-certified antivibration gloves should attenuate frequencies above 150 Hz; however, these antivibration gloves are still expensive and their attenuation characteristic have not been adequately defined, which can negatively impact the proper design and use of antivibration gloves.

In order to protect workers from excessive vibration exposure caused by various power tools, properly selected PPE could be an effective method to minimize the exposure risk. In order to discover tool-specific antivibration gloves for specific working conditions, analysis of the design and implementation of new vibration-protective gloves is warranted, where gloves and/or materials (i.e., materials with vibration damping qualities suitable for use in new glove designs) are evaluated and selected using the spectra specified in ISO 10819 as well as tool-specific vibration spectra collected at actual worksites. This information would then be incorporated into glove selection criteria and/or applied in the development of new gloves.

In this study, vibration-reducing gloves are paired with power tools based on the most effective combination of tool vibration and/or matched glove attenuation characteristics. This methodology could be applied to the design new PPE gloves and to the design of power tools. Furthermore, matching characteristics between gloves and power tools would potentially create an easy method for the proper glove selection.

1.3 Phase 1: Tool Assessment

When power tool vibration becomes a health issue at work sites, Annex D of ISO 5349-1 (ISO 5349, 2001) specifies some influential factors of the HTV in working conditions that need to be considered and evaluated carefully. In order to determine a causal relationship between power tool vibrations and health issues, vibration assessments are conducted using either ISO 5349 or ANSI S2.70. Since HAVS originate from the tool vibration, previous studies have reported the vibration characteristics including the tool vibration levels and frequency content, as well as the condition of the tools (Hunt, 1936; Agate and Druett, 1947; Bovenzi, 1994; Burström et al., 1998; Ikeda et al., 1998; Wasserman et al., 2002; Bovenzi, 2010a; 2010b).

The characteristics of power tool vibrations in the field need to be assessed before identifying glove-tool relationships or designing new vibration-reducing gloves. In this dissertation, tool vibration signatures were captured at actual worksites and vibration exposure levels were analyzed using the methods defined in ISO 5349/ANSI S2.40 and ISO 8041 (ISO 5349, 2001; ANSI 2006; ISO 8041, 2005). The HTV health risk of power tools can be assessed using these international standards, which also specify measurement and assessment protocols in detail. According to the standards, pneumatic and electric power tool vibrations were directly measured by suitably positioning orthogonally configured accelerometers and a newly developed accelerometer adapter was used to measure vibrations from bucking bars, which are used in the riveting process and are not listed in the ISO 5349-2 standard.

Previous studies introduced several different HAV frequency-weighting profiles based on knowledge of the biodynamic response of the hand, the vibration energy absorption in the hand, or the ISO 5349 W_h band-pass filter (Pitts et al., 2012; Pitts and Brammer, 2012; Brammer and Pitts. 2012; Bovenzi et al., 2011); however, this dissertation only uses the current ISO 5349

frequency weighting W_h for determining weighted vibration levels and assessing health risk (ISO 5349-1, 2001). Even with the differences between the HAV frequency weighting published in these studies, ISO 5349 and ANSI S2.70 continue to be recognized as the standard guidelines in the U.S. Results from previous studies show power tool vibration levels in both weighted and unweighted levels and when power tools are compared by tool name among there studies, the results are widely diverse. Therefore, this dissertation does not consider any variation of the frequency weighting and assumes that tool vibration measurement conditions are different.

Although previous studies and manufacturers provide tool vibration characteristics, actual vibration patterns could be different in real working conditions. There are many influential factors involved in power tool vibration assessment that may cause inconsistency in the results between studies. Therefore, it is critical to take exact measurements of power tool vibrations during the actual work processes, since tool vibration signatures may be unique.

Measured power tool vibration could be influenced: 1) by different operating conditions such as manufacturers, models, supply air pressure, duration of tool use, or frequency of maintenance, 2) by subjects, such as anthropometric data, posture, or loading, and 3) by different measurement conditions, such as instruments, sensors, or frequency ranges. For these reasons and in order to appropriately match power tools and VR gloves, it was necessary to establish the actual vibration characteristics of the power tools at the work sites. By mounting orthogonally configured accelerometers following the coordinate system recommendation in ISO 5349-1, tool vibration signatures were measured in accordance with ISO 5349-2. Worksite vibration measurements were conducted at Sikorsky Aircraft Corporation (Bridgeport, CT) and Whirlpool Corporation (Amana, IA), where more than 25 different types of regularly used power tools were selected and tested. At the time of capturing the tool vibration signatures, grip force levels in the

hand were simultaneously recorded and surrogate grip and push force levels were also captured before and after the vibration measurement, for use in future analyses of dynamic grip coupling and vibration transmission. After obtaining tool vibration signatures, the data were post-processed by filtering and the ISO 5349 hand-arm frequency weighting (W_h) was applied for further evaluation. Tool vibration data sets were also processed through a one-third-octave analysis protocol and converted into Power Spectral Density (PSD) values.

Using the captured tool vibration signatures, vibration exposure assessments based on ANSI S2.70/ISO 5349-1 were performed. As specified in ANSI S2.70, the r.m.s. magnitude ($a_{hw(rms)}$), r.m.s. one-third-octave vibration spectrum ($a_{hi(rms)}$), direction of vibration, daily exposure, and cumulative exposure ($a_{hv(rms)}$, A(8)) were also determined.

1.3.1 Non-Power Tool Vibration

The U.S. has a world-class aerospace industry for both civilian and military use. Because aerospace industries involve different manufacturing processes, diverse engineering companies and factories exist all over the U.S., including in the state of Connecticut. There are wide varieties of engineering and manufacturing processes in the aerospace industry such as riveting, which is an essential process used to effectively and semi-permanently fasten curved aircraft frames and exterior walls. Several thousands of workers are engaged in the riveting process, and the details of the vibration exposure conditions in the aerospace industry are still poorly understood.

Riveting can be divided into two processes: 1) a riveter creates a large impulsive vibration to punch in a rivet and 2) a bucking bar receives large vibration and forms the other side of the rivet for closing. Two workers are needed to carry out the riveting process, where one

operates the rivet gun while the other positions and secures the bucking bar in place on the opposite side of the aircraft wall. Each aircraft contains millions of rivets and it could be estimated that aircraft assemblers are potentially exposed to hundreds of thousands of riveting vibrations. Previously mentioned studies (Dart, 1946; Engström and Dandanell, 1986; Dandanell and Engström, 1986; Burdorf and Monster, 1991; Jorgensen and Viswanathan, 2005; McDowell et al., 2012) emphasize that the riveting process needs to be investigated further and careful attention needs to be given to the high level of harmful vibration exposures to the human hand and/or body. Although numerous vibration measurements have been performed on the riveting process, less emphasis has been placed on the bucking bar primarily because of the difficulties associated with tri-axial accelerometer placement on irregular bar shapes and the significant levels of shock vibration. These instantaneous vibration levels associated with the bucking bar can be extremely high and, depending on the riveting direction and/or shape of the riveting section, the worker can select from a variety of different bucking bar shapes. It should be noted that if the bucking bar vibration is difficult to assess, then it is nearly impossible to make occupational health judgments or to implement bucking bar use guidelines. In order to conduct precise bucking bar vibration measurements, a novel type of accelerometer adapter, which is highly adaptable to any bucking bar shape and operation, was designed, verified, and used in actual manufacturing processes. The verification of the design of the adapter was also developed using information gathered from interviews with bucking bar users and field trials of previously reported bucking bar measurement methods.

Vibration exposure assessments based on ANSI S2.70/ISO 5349-1 were also performed for the case of the bucking bar, where the magnitude ($a_{hw(rms)}$), frequency spectrum ($a_{hi(rms)}$), direction of vibration, daily exposure, and cumulative exposure ($a_{hv(rms)}$, A(8)) were determined.

1.4 Phase 2: VR Glove Assessment

In order to minimize the risk of HTV, three concepts have been discussed since HAVS was recognized in the early 20th century: 1) shortening the duration of vibration exposure, 2) isolating the hand from the vibration source, and 3) reducing the vibration transmission to the hand. Variations of these three concepts lead to many different vibration control approaches, such as defining standards, regulating power tool use, or education on proper power tool use, which have been implemented in our society but have not yet obtained ideal solutions for occupational vibration exposure problems.

Although standards or regulations are enforced, workers and their employers can either follow the regulations perfectly or misunderstand the statements completely. On the other hand, reduction in the vibration transmission could be achieved by engineering controls, such as either improving power tool designs or using VR gloves, eliminating the misunderstanding of the standards and regulations. Although the engineering control methods of HTV are clearly more effective than enforcing the standards, redesigning tools or assessing VR gloves have to be accomplished in a careful and accurate manner. It has to be noted that, in order to standardize the VR glove effectiveness evaluations, it was necessary to develop a standard (i.e., ISO 10819) and even the standard recommends that the previously mentioned concepts need to be considered simultaneously.

ISO 10819-based evaluation tests were conducted to examine the attenuation capabilities of vibration-protective gloves. Because the testing methodologies followed the international standard, the evaluation results of gloves were comparable with those from different testing institutions in different countries. This testing was conducted under laboratory-controlled conditions and the results provided basic information about the characteristics of the VR gloves.

Although excess levels of vibration exposure to the hand-arm system have been studied, the usefulness of the VR gloves has not been well ascertained. ISO 10819 (ISO 10819, 1996; 2011; 2013) provides a standardized VR glove test procedure and expects gloves to be covered with continuous resilient material, of no more than 8 mm thick, on the palm but does not make any distinction between transmissibility on the palm and finger. Here, a VR glove could possibly achieve large reductions in vibration exposures by increasing the thickness of the resilient material but this may severely limit the usability and dexterity of the fingers.

Previous studies (Asaki and Peterson, 2014a; 2014b) have stated that the biodynamic responses of the fingers are different from the palm, which strongly suggests that VR gloves need to be assessed more carefully and precisely. Since ISO 10819 does not specify transmissibility measurement at the fingers, a new methodology and protocol for the vibration exposure and glove effectiveness at the fingers were required. In addition to the ISO specified palm adapter, a novel ring adapter for finger vibration measurement was developed and incorporated into the ISO 10819 tests. Finger transmissibility was measured using the newly developed finger adapter, where the finger transmissibility constraints and measurements were kept exactly to those of the palm in ISO 10819.

In this dissertation, an ISO 10819 based VR glove assessment system was developed that incorporated novel finger transmissibility measurements, in order to better select commercially available VR and non-VR gloves for tool use. Following the testing procedures of ISO 10819 (ISO 10819, 2011), nine commercially available gloves were evaluated. These VR gloves were selected and categorized according to their vibration attenuation materials. Each pair of gloves was tested for transmissibility characteristics using three subjects as they applied 30 N of grip and 50 N of push forces to an instrumented vibrating handle. Transmissibility calculations and

statistical data analysis were performed and the overall transmissibility values of the M and H spectra were obtained. In order to determine vibration transmissibility and exposures at the fingers, a novel ring adapter was also designed and verified for use in the ISO 10819 protocols. Once ISO 10819 testing was completed, the 10819-specific vibration spectrum was replaced with tool-specific vibration PSD spectra from the two worksites that are currently part of the study and one subject was used to determine if stimulus signals played a significant role in the transmissibility measurement.

In addition, several damping materials (e.g. rubber, foam, silicone, gel, etc.) were evaluated using simple dynamic material tests and the ISO 10819 methods, in order to characterize the vibration attenuation of materials for use in vibration-protective gloves. This was essential to understand the vibration attenuation characteristics of AV gloves and AV materials suitable for use in glove design. Selected materials were then further tested following ISO 10819 for eventual incorporation into a novel glove design for use in the field.

1.5 Phase 3: VR Glove Selection

When the hand-transmitted vibration (HTV) from power tools becomes an issue in the work place, tool vibration measurements and health risk assessments can be carefully conducted according to ISO 5349-1, 5349-2, and ISO 8041, where ISO 5349-1 defines the current guideline for HAV exposures and recommends durations of power tool operations that are measured using methods introduced in ISO 5349-2 and the measurement instrumentation defined in ISO 8041. From these tool vibration measurements, appropriate VR gloves could then be chosen from a wide variety of commercially available gloves. However, it would be better to consider ISO

10819-verified VR gloves, since ISO 10819 utilizes the ISO 5349-defined frequency weighting factors (W_h) for its transmissibility calculations and glove evaluation.

It is important to note that ISO 5349 and ISO 10819 measurement data are independently determined and not usually correlated, even although these standards are fundamentally related. One simple example of incompatibility is that the ISO 5349 specifies a target frequency range from 6.3 Hz to 1,250 Hz, while the frequency range of ISO 10819 is from 25 Hz to 1,250 Hz with total transmissibility values from 25 to 200 Hz for frequency range M and from 200 to 1,250 Hz for frequency range H. This removes a total of 6 one-third-octave bands (f_c = 6.3, 8, 10, 12.5, 16, and 20 Hz), which are the most critical frequency bands in ISO 5349 HAV assessment. It has been recognized that, below 150 Hz, VR gloves are not expected to attenuate the HTV, which may be the reason why ISO 10819 focuses on the middle (M) and high (H) frequency ranges and not the low frequency range. It is important to note that the frequency ranges, M and H, have no relationship to the actual tool vibration or operation as they just reflect the frequency range of interest as middle or high.

Current ISO 10819 VR glove assessment generates the obtained transmissibility values of less than, or equal to, 0.9 or 0.6 for the frequency ranges M and H, respectively. A VR glove cannot be categorized as an AV glove if its results are above these values. This classification could be a powerful tool for the glove manufactures, in order to simply compare VR effectiveness and to set the target transmissibility values for designing the VR gloves. However, from a consumer's viewpoint, ISO 10819 provides a decision as to whether the glove is AV or VR but this could mislead consumers, especially if the consumer does not understand the nature, and data, of the tests. Even though the AV and VR gloves are not appropriate for the specific power tool use, the consumers will purchase the AV gloves.

It has to be realized that if gloves do not pass the ISO 10819 guidelines, then their results do not mean that the gloves are useless or ineffective products. If a glove is designed and developed as a VR or AV glove, then it should have some level of vibration reducing characteristics. For appropriate VR glove selection, it is necessary to consider not only the power tool vibrations and the VR glove transmissibility, but also the condition of the power tool operations. Depending on the type of power tool use and operations, a thick and bulky AV glove that dramatically reduces finger dexterity dramatically may not be suitable for certain working conditions, while a less-effective knitted VR glove might be the most practical choice for those certain working conditions.

Many glove evaluation methodologies have been previously proposed beyond the ISO 10819 VR glove effectiveness assessments (Griffin, 1998; Dong et al., 2002; Rakheja et al., 2002). However, while many glove evaluation methods, including ISO 10819, are beneficial for characterizing VR glove effectiveness and comparing within a group of VR gloves, these are for "evaluation" purpose of the gloves and not for user-friendly information for the practical selection of VR gloves for specific power tool operations. Consumers obtain protective gloves based on the description of the product as an antivibration glove (i.e., passing ISO 10819 M- and H-range criteria) or vibration-reducing glove. Descriptions are unclear for consumers whether a particular AV/VR glove is effective for specific power tool operations, which strongly suggests the need for a simple and effective AV/VR selection methodology that is a useful tool for actual consumers.

Previous reports (Asaki and Peterson, 2014a) showed that the VR glove transmissibility does not change linearly with vibration excitation conditions but assuming that vibration transmissibility behaves as a Linear Time-Invariant system, the vibration exposure

characteristics of the hand and finger, while wearing any VR gloves, could be predicted from known frequency-dependent power tool vibration characteristics (as an input) and transmissibilities (as a factor). Power tool vibration information based on the measurement protocols of ISO 5349 and VR glove transmissibility information based on the measurement protocols of ISO 10819 are widely available from manufacturers or from previously published studies.

For example, this dissertation has data from more than 25 power tool vibration spectra from actual worksites and nine commonly used VR and non-VR gloves. Assessments of the power tool vibration and VR glove transmissibilities generate one-third-octave vibration and glove transmissibility spectra as a by-product that can be used in the LTI system. Moreover, the reduction percentage between the total values of input (i.e., tool vibration) and output (i.e., estimation of vibration exposure of gloved hand) can also be determined. The LTI operation could lead to quick and easy pairing of VR gloves with specific power tools. In this dissertation, this concept is used to independently connect ISO 5349 tool assessments with ISO 10819 VR glove evaluations and a simple intuitive computer program was developed that could quickly simulate VR glove effectiveness for any power tool vibration spectrum.

2. Methods

The methodologies of three phases are discussed in this section, where Phase 1 focuses on field power tool vibration measurements at two worksites and their health assessments, Phase 2 focuses on vibration-reducing (VR) glove assessments following the ISO 10819 standard, and Phases 3 focuses on a series of small experiments and discusses the methodology for VR glove selection based on LTI system theory.

2.1 Phase 1: Tool Vibration Assessment

In order to conduct ISO 5349-based power tool vibration measurements at a worksite, a measurement system, including adaptors for sensor mounting and the respective sensor mounting considerations, are discussed in this section.

2.1.1 Field Measurement System

A vibration measurement cart was designed and constructed to provide portability around a factory floor for direct tool vibration measurement during actual use. The cart was able to hold enough measurement instrumentation and accessories and to operate like a high-quality mobile laboratory in the field environment.

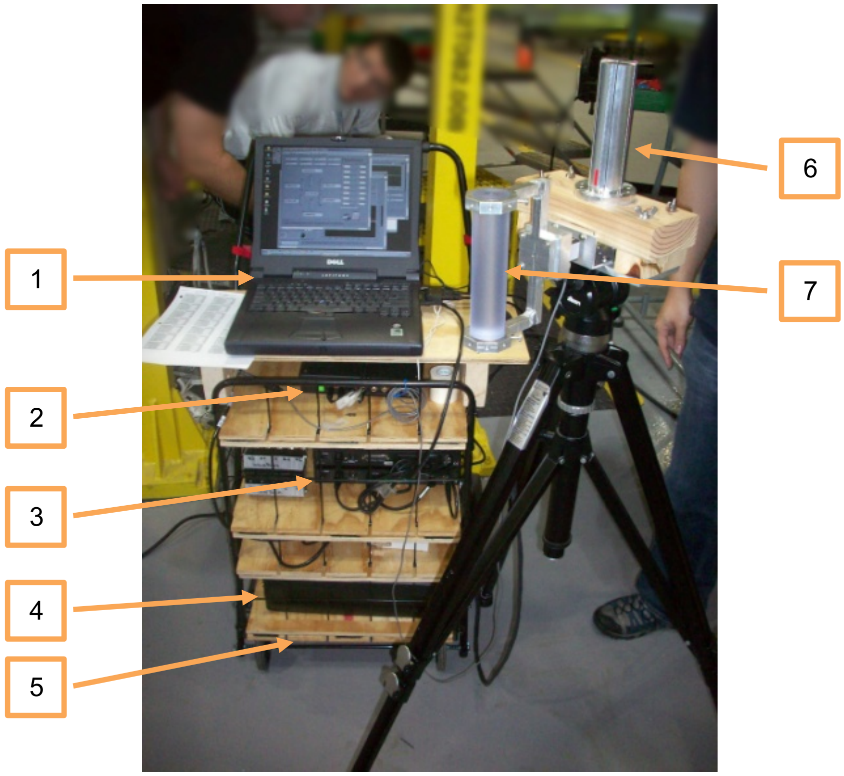


Figure 1: Vibration Measurement Cart for Actual Field Use:
(1) Laptop Computer with LabVIEW-based Measurement System and Data Storage,
(2) Signal Conditioning Box for Thin-Film Force Sensors,
(3) Data Acquisition Units, (4) Uninterrupted Power Supply, (5) Mobile Measurement Cart, and
(6) Grip, and (7) Push Force Handles

The bottom of the measurement cart housed an uninterrupted power supply (UPS, Back-UPS Pro 1000, APC, West Kingston, RI) and a surge-protected power extension (Isobar, Tripp Lite, Chicago, IL). The power supply was the heaviest instrument so it was placed at the bottom to stabilize the cart during mobility. In case of power outage or the existence of noisy AC power source, the UPS maintains field vibration measurements without the need for electric power accessibility. The top of the measurement cart contained the data acquisition systems (IO-Tech WAVABOOKs, NI USB-DAQ, LabJack U12) and the signal conditioning box for the thin-film force sensors. The space between the UPS and the instruments was designated for cable organization, in order to minimize the influence of electromagnetic noise on the measurement system.

Custom-made LabVIEW programs controlled all of the measurement instrumentation on a laptop computer that ran several different LabVIEW programs simultaneously. Due to technical difficulties, such as controlling sampling frequencies and conflict between DAQ systems, the LabVIEW programs for vibration and force measurements were developed as separate programs in order to avoid mis-operation.

Once the accelerometer was placed on the power tools, the tool vibration was captured at a sampling frequency of 9,000 Hz.

2.1.2 Accelerometer Mounting

An aluminum accelerometer adapter with a metal hose clump was used for regular power tool measurements based on ISO 5349-2 (ISO, 2001), as seen in Figure 2. The aluminum cube could accommodate shock type accelerometers (PCB Model 350B23, Buffalo, NY, USA), to measure high impact tool vibrations in the field. Due to the use of adjustable metal hose clamp, it was able to accommodate a wide variety of tool handle diameters and rigidly hold the accelerometer adapter in position during harsh power tool operations in the field.

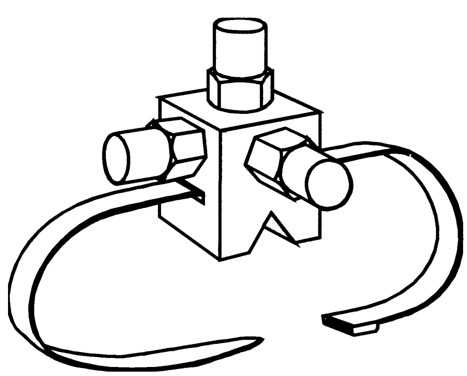


Figure 2: ISO 5349-2 Recommended Mounting Accelerometer
with Nylon Strap (ISO 5349-2, 2002)

The size, weight, and mounting of the accelerometer adapter were carefully considered, especially to accurately measure bucking bar vibration during the riveting process. In this dissertation work, bucking bars represent the most difficult tool assessed as there is a wide variety of bucking bars that are commonly used during actual aircraft manufacturing and each of them may have different vibration performances. Initially, five bucking bar shapes, including user interviews, were selected to assist in the development of the adapter to determine the actual frequency of use for each shape. In addition, the number of bucking bars was determined by comparing the shape characteristics of several bars used at a helicopter manufacturing worksite. The five bucking bars are shown in Figure 3.

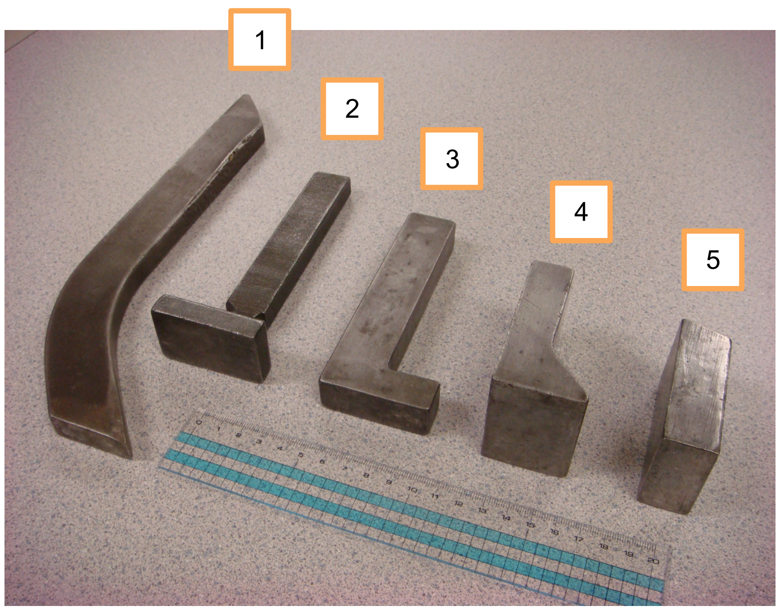


Figure 3: Shape and Size of Five Commonly-Used Bucking Bars in a Helicopter Factory (Asaki and Peterson, 2012): (1) Banana Shape (968.1 gram), (2) Duck-Foot (473.8 gram), (3) L-Shape (547.8 gram), (4) Foot Shape (676.2 gram), and (5) Trapezoidal (512.6 gram) Bucking Bars

A novel accelerometer adapter was designed for mounting to hand tools that do not allow for traditional mounting techniques to be used as is the case for the bucking bar, where the novel adapter is shown in Figure 4(a). During the riveting process, the bucking bar may experience

instantaneous vibration levels beyond 1,000 m/s^2, which is higher than that of previously reported levels of frequency-weighted vibration (Asaki and Peterson, 2012). To protect the accelerometer from excessive vibration, a shock-type accelerometer containing a mechanical filter (PCB Model 350B23, Buffalo, NY, USA) was selected for use with the adapter. It is important to note that the accelerometer adapter was designed to be used in a uni-axial or tri-axial configuration with specifications and mounting options that are compliant with Annex D of ISO 5349-2 (2001) and Annex E of ISO 8041 (2005).

Figure 4 shows the new accelerometer adapter used for bucking bar vibration measurements. The performance of the accelerometer adapter was verified by laboratory tests (i.e., hammer striking and shaker testing), where it was secured to the bucking bar surface with double-side adhesive tape, or cyanoacrylate glue, and tied with two plastic cable ties. In addition, the transmissibility of the adapter cube was verified by the vibration shaker system.

a) b)

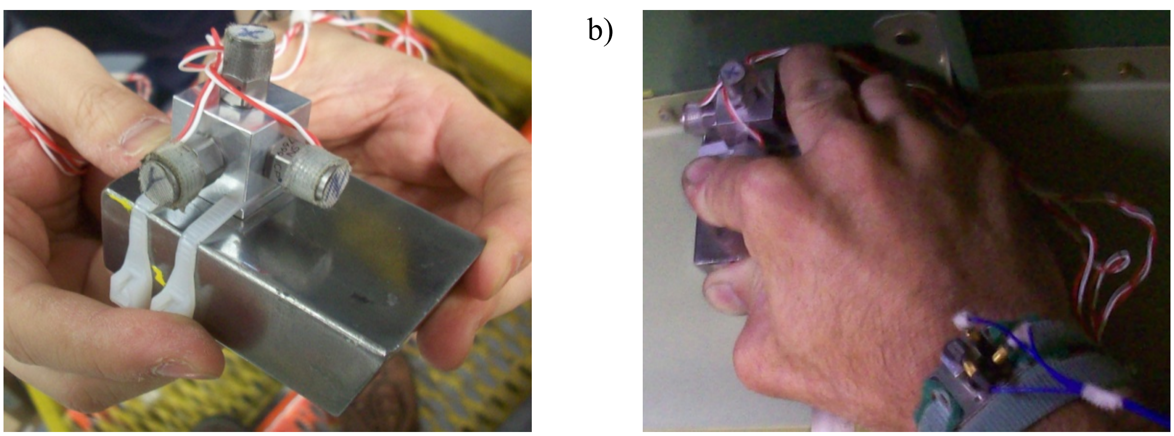


Figure 4: New Bucking Bar Adapter (Asaki and Peterson, 2012):
(a) Adapter Mounted on Bucking Bar and (b) Actual Use in a Helicopter Factory

2.1.3 Power Tool Vibration Measurement in the Field

Surveillance of vibration exposure at a worksite was a fundamental step in this glove research or in any type of occupational vibration exposure study. Occupational exposure research can be categorized in two ways: laboratory-based measurement or field-based measurement, both of which serve as powerful methods to understand and model vibration exposures. The advantage of laboratory-based measurement and research is that a wide variety of testing parameters can be controlled (e.g., operation of tools, laboratory environment, or measurement techniques). Because of the controlled and simulated nature, this aspect of vibration exposure research may be categorized as a virtual vibration exposure study. In contrast, field-based vibration measurement has the capability to determine practical vibration exposure levels, including the exact duration of vibration exposure of specific tool use per day.

When compared to field measurements, laboratory-based vibration measurements have fewer limitations, such as sensor placement, availability of electric power, and/or portability of measurement instrumentation. In the field, several limitations need to be considered and instantaneous on-site adjustments need to be made, especially for the experimenter who conducts measurements and needs to be flexible in their ability to solve measurement problems instantaneously. Even if vibration measurements in the field are well planned in advance, one should prepare for unpredicted incidents that could impact the whole measurement strategy. For example, measurement instrumentation and accelerometers could pick up electro-magnetic noise from various machineries that could be high enough to influence the reliability of the measurements. In the case of an incident, the power line to the measurement instrumentation may need to be connected to a different power outlet at the worksite and/or the entire

measurement instrumentation may need to be disconnected and reconnected, in order to reset the entire electrical and mechanical system.

Following the ISO 5349-1 hand-arm coordinate system (Figure 5) and the recommended accelerometer-mounting locations of ISO 5349-2, accelerometers were to be placed on each tool under investigation. Figure 4 introduces the coordinate system concept of ISO 5349-1, while Figure 6, 7, and 8 show examples of suggested mounting locations following ISO 5349-2 and some of the mounting locations from the field measurements. ISO strongly recommends the accelerometer-mounting locations, but if factors such as tool size, worker hand size, and/or task constraints directly impact the ideal mounting location, then modifications and adjustment will need to be applied. For example, as seen in Figure 6(a), the accelerometer is recommended to be placed on the middle part of the handle, which directly conflicted with worker's fingers; therefore, the mounting of the accelerometers was placed on the far bottom of the tool handle.

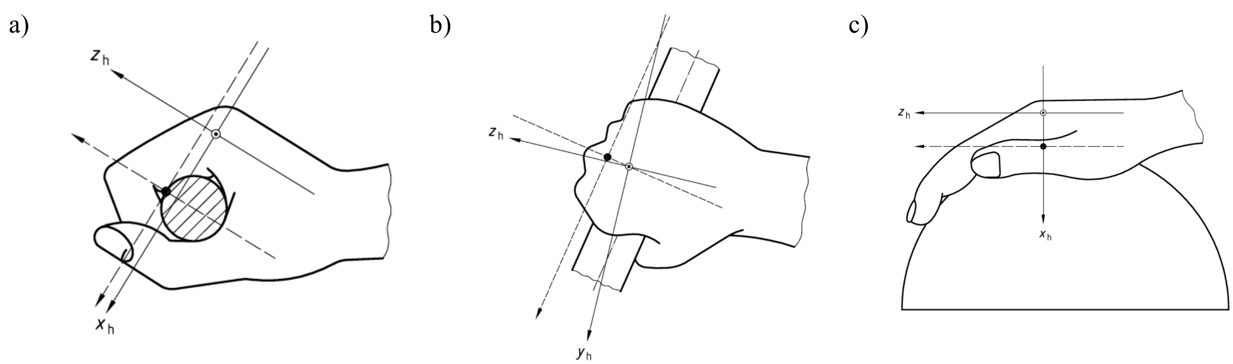
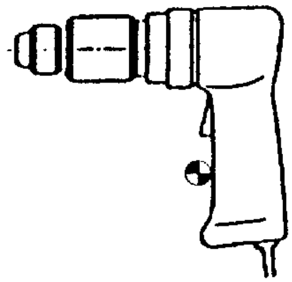


Figure 5: Coordinate System for the Hand (ISO 5349-1, 2001) for
Biodynamic (Solid Line) and Basicentric (Dash Line) Coordinate Systems:
(a) Handgrip, (b) Handgrip, and (c) Flat Palm Positions

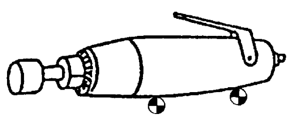
a)



b)

Figure 6: Accelerometer Mounting on Drill Gun:
(a) ISO Recommended Placement and (b) Actual Sensor Placement

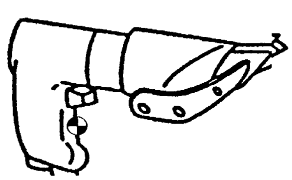
a)



b)

Figure 7: Accelerometer Mounting on Straight Die Grinder:
(a) ISO Recommended Placement and (b) Actual Sensor Placement

a)



b)

Figure 8: Accelerometer Mounting on Shear Gun:
(a) ISO recommended placement and (b) Actual Sensor Placement

2.1.4 Tool Assessments at Two Worksites

Field power tool vibration measurements were conducted at the helicopter manufacturing facility (Sikorsky Aircraft Corporation, Bridgeport, CT) and refrigerator manufacturing facility (Whirlpool Corporation, Amana, IA), where more than 25 different types of regularly used power tools were selected and tested. The working environments of these two sites were significantly different and the measurement system needed to be flexible based on the factory environment.

At the helicopter facility, because the sizes of the helicopter components are, at times, larger than a human, helicopters are assembled on a spacious floor allowing workers to freely move around. In contrast, space inside the helicopter body is very tight and can be almost the same size as a worker's arm and their reach. Generally, helicopter body assembly occurs in one designated location, where workers come to operate their tasks at their own pace.

On the other hand, at the refrigerator facility, because the factory is designed to operate several assembly lines simultaneously, workers areas are limited for space, which could be tight and higher than the work piece on a belt conveyer or lower than the work piece below a belt conveyor. Because of the line assembly processes, workers cannot need to around and are required to complete their task at their location in a quick and time-sensitive fashion. In this condition, the tool vibration measurements needed to be completed without disrupting the assembly processes. In order to perform these measurements, an extra worker (i.e., a floater) substituted for the subject worker so that the subject and their tools could be instrumented with the sensors. After mounting accelerometers and thin-film force sensors, the subject and the floater switched back and the subject performed the work task while the tool vibration measurement was made.

2.1.5 List of Assessed Tools

Table 1 shows the list of power tools that were measured and assessed in this dissertation. Although there is some redundancy in tool names, the tools were operated under different conditions (i.e., different work tasks, operators, etc.); therefore, the tools listed in Table 1 were measured and assessed as independently. These tools were selected from majority of common tools at the worksites, which was determined through communication with employers and workers.

Table 1: List of Assessed Tools from the Helicopter and Refrigerator Manufacturing Facilities

Helicopter Factory Tools	Refrigerator Factory Tools
Tool 01, Drill	Tool 01, Straight Nut Runner
Tool 02, Rivet Gun	Tool 02, Skid Bolt
Tool 03, Trapezoidal Bucking Bar	Tool 03, Nut Runner Lower Hinge
Tool 04, L Shape Bucking Bar	Tool 04, Nut Runner Center Hinge
Tool 05, Cherry Max Gun	Tool 05, ARO Gun
Tool 06, Cherry Gun	Tool 06, Pistol Screw Gun
Tool 07, Hilock Gun	Tool 07, Air Hammer
Tool 08, Terry Motor	Tool 08, Screw Gun
Tool 09, Rivet Gun	Tool 09, Angle Nut Runner
Tool 10, Duck Foot Bucking Bar	Tool 10, Damper Gun
Tool 12, Rivet Gun	Tool 12, Palm Hammer
Tool 13, Angle Grinder	
Tool 14, Pencil Grinder	
Tool 15, Die Grinder	
Tool 18, Shear Gun	
Tool 19, Rivet Gun	
Tool 20, Foot Bucking Bar	
Tool 21, Clunky Hook Bucking Bar	
Tool 22, Tungsten Trapezoidal Bucking Bar	
Tool 23a, Bucking Bar	
Tool 23b, Riveter	

2.1.6 Tool Assessment Calculations

To obtain the unweighted and weighted r.m.s. acceleration values for each axis, the following equations were used based on ISO 5349 (2001).

$$a_{\mathrm{hUW}} = \sqrt{\sum_{i} (a_{\mathrm{h}i})^2} \tag{2.1}$$

and

$$a_{\mathrm{hW}} = \sqrt{\sum_{i} (W_{\mathrm{h}i} a_{\mathrm{h}i})^2}\,, \tag{2.2}$$

where a_{hUW} is the r.m.s. single-axis acceleration value of the frequency-unweighted hand-transmitted vibration in meters per second squared (m/s^2), a_{hW} is the r.m.s. single-axis acceleration value of the frequency-weighted hand-transmitted vibration in meters per second squared (m/s^2), $W_{\mathrm{h}i}$ is the weighting factor for the *i* th one-third-octave bands, and $a_{\mathrm{h}i}$ is the r.m.s. acceleration measured in the *i* th one-third-octave band, in meters per second squared (m/s^2).

In this study, a tri-axial accelerometer was used to measure power tool vibrations and the following equations were used to combine all three axes.

$$a_{\mathrm{hv(UW)}} = \sqrt{a_{\mathrm{hUW}x}^2 + a_{\mathrm{hUW}y}^2 + a_{\mathrm{hUW}z}^2} \tag{2.3}$$

and

$$a_{\mathrm{hv}} = \sqrt{a_{\mathrm{hW}x}^2 + a_{\mathrm{hW}y}^2 + a_{\mathrm{hW}z}^2}\,, \tag{2.4}$$

where $a_{\mathrm{hv(UW)}}$ is the vibration total value of frequency-unweighted r.m.s. acceleration in meters per second squared (m/s^2) and a_{hv} is the vibration total value of frequency-weighted r.m.s. acceleration, in meters per second squared (m/s^2).

According to the ANSI S2.70-2006, the actual tool vibration exposure time, T_{v}, in hours was determined Equation (2.5) to see the relationship between the vibration exposure and health risk assessments.

$$T_{\mathrm{v}} = \frac{(1\ Tool\ Use\ Operation\ in\ sec)\times(No.of\ Tool\ Operations\ per\ Day)}{3600} \qquad (2.5)$$

The Equations (2.6) and (2.7) were used to determine the expected action and limit vibration exposure times in hours based on the daily exposure action value (DEAV, A(8) = 2.5 m/s^2) and the daily exposure limit value (DELV, A(8) = 5.0 m/s^2) using the tool a_{hv} values.

$$T_{\mathrm{v(DEAV)}} = \frac{50}{a_{\mathrm{hv}}^2} \qquad (2.6)$$

$$T_{\mathrm{v(DELV)}} = \frac{200}{a_{\mathrm{hv}}^2} \qquad (2.7)$$

2.1.7 Converting Tool Vibration Spectra into PSDs

The post-processing of the waveform tool vibration data (in the time domain) began with the application of both lowpass (fc = 4,450 Hz, 4th order) and highpass (fc = 3 Hz, 6th order) filters in Matlab (MathWorks, Natick, MA). After filtering, the lengthy waveform data were broken down to one cycle of tool operation, which varied depending on the working conditions.

Segmented waveforms were then selected by looking for large, medium, and low magnitude segments. At the same time, the durations in seconds of the three different sections were recorded for the time duration of one cycle of tool operation. All of the time domain segmented data files including all xyz directions were analyzed by a one-third-octave analysis program in LabVIEW that computed the frequency range from 1 to 3,150 Hz. After obtaining the r.m.s. one-third-octave tool vibration spectra, the rest of the numerical manipulations were done by in Excel spreadsheets. In order to convert the r.m.s. one-third-octave spectra to PSD spectra, the bandwidth of each frequency band was determined separately. In Excel, the r.m.s. one-third-octave values were squared (powered) and then divided by the corresponding bandwidth, which was directly exportable to the electrodynamic shaker controller.

2.2 Phase 2: ISO 10819 Glove Assessment

For glove evaluations, ISO 10819-based assessments were conducted carefully and is discussed in this section, including the details of testing system specifications as well as the glove assessment calculations.

2.2.1 ISO 10819-Based VR Glove Assessment System

ISO 10819 1996 edition was previously used to determine the vibration attenuation capabilities of commercially available gloves (Dong et al., 2002; Dong et al., 2003; Shibata and Maeda, 2008; Wimer et al., 2010; Cabeças and Milho, 2011; Milosevic and McConville, 2012; Welcome et al., 2012). A newly revised ISO 10819 2013 edition was published, which simplifies the testing methodologies further from the previous version. The Biodynamics Laboratory at the University of Connecticut Health Center purchased an electrodynamic vibration shaker system (Unholtz-Dickie, Wallingford, CT) for vibration-protective glove testing and evaluation and was prepared to perform various types of glove and material tests following the testing recommendations of both editions of ISO 10819.

The ISO 10819 standard requires the use of a specific handle with incorporated accelerometer and force sensors, a force plate for push force measurements, and a palm adapter for transmissibility measurements. In this dissertation, a ring adapter design was used, which was previously developed the laboratory (Kudernatsch and Peterson, 2014a). Although the palm adapter design has slight inconsistencies and a ring adapter are not discussed in ISO 10819, both adapters were successfully fabricated from PLA plastic by a 3D printing machine (Kudernatsch and Peterson, 2014a; 2014b). All accelerometer measurement systems used were verified extensively before testing operations.

The ISO 10819 handle that was used in the laboratory tests was designed and constructed by NIOSH and targeted no first resonance frequency below 1,600 Hz (ISO 10819, 2011; 2013). Figure 9 shows a schematic of the ISO 10819 recommended instrumented handle design and incorporates a tri-axial accelerometer (4 in Figure 9(a)) and two piezoelectric force sensors (3 and 5 in Figure 9(a)), where the vibration signal from the tri-axial accelerometer was used as the reference (or handle) vibration value. As seen in Figure 9(b), the tri-axial accelerometer (356A12, PCB Piezotronics, Depew, NY) was mounted in a 30-degree rotation orientation with respect to the centerline of the long axis of the handle. Preferably, it should not be mounted with any offset angle but the accelerometer cable interfered with the force sensors, so it was necessary to mount the accelerometer in this orientation inside the handle. An angle compensation routine was incorporated into the measurement control system using LabVIEW. The program also incorporated the grip force and push force measurements and a secondary monitor that was placed beside the shaker to provide a feedback control readout of push and grip force levels to the subjects, as well as the tilt of the palm and ring adapters. Figure 10 shows a schematic of the setup and the actual setup in the laboratory.

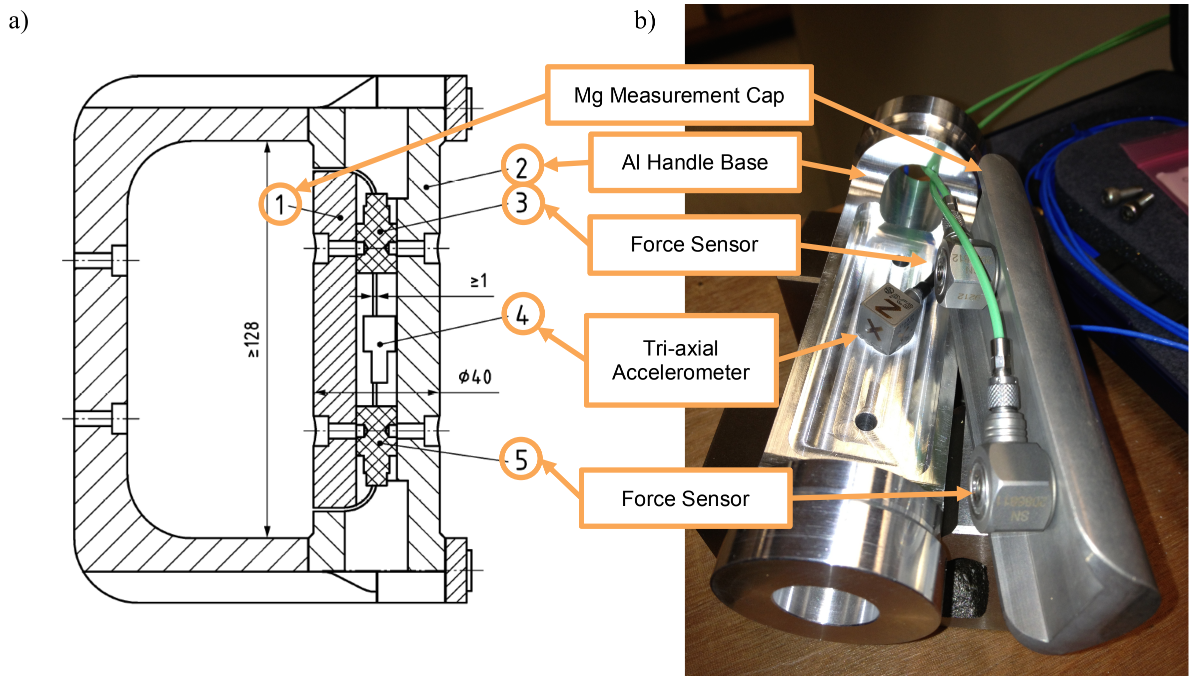


Figure 9: Instrumented Handle for Glove Assessment:
(a) ISO 10819 Recommended Handle Design (ISO 10819, 2011; 2013) and
(b) Actual Handle Inside

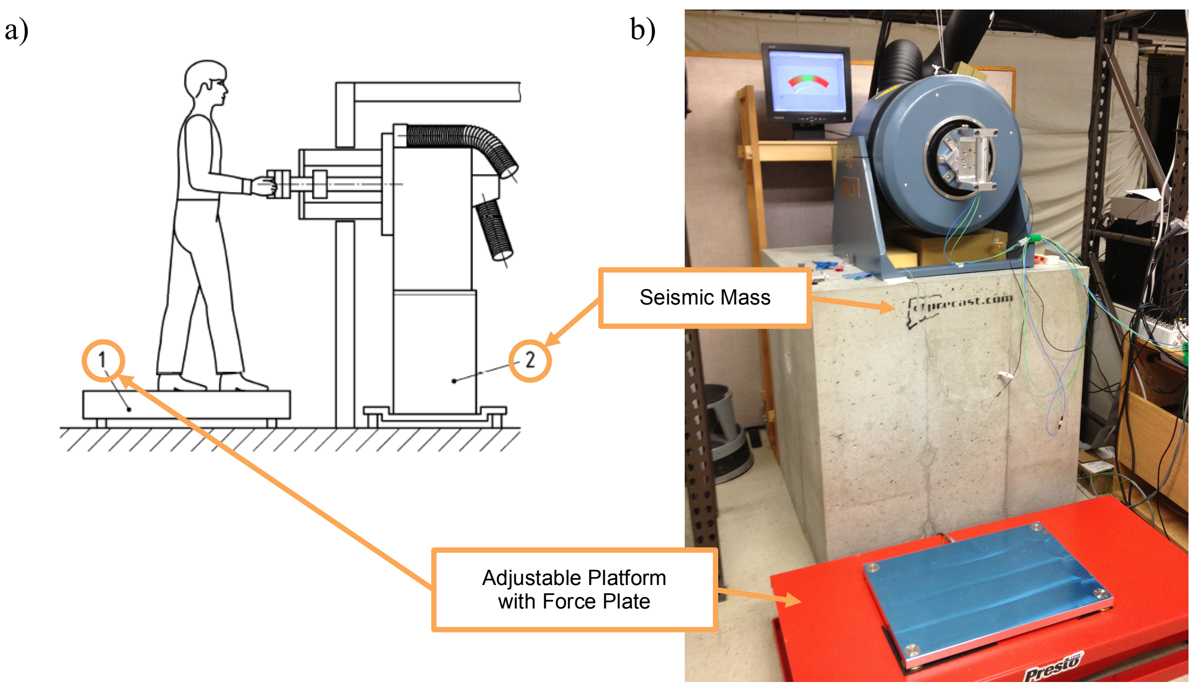


Figure 10: Schematic of Testing Condition:
(a) ISO 10819 Recommended Condition (ISO 10819, 2011; 2013) and (b) Actual Setup

2.2.2 ISO 10819-Based Excitation Spectrum

Once the setup of the entire test system was completed, the testing spectra from both versions of 10819 (ISO 10819, 1996; 2011) were prepared. The previous version of ISO 10819 identified M and H in two different vibration spectra, while the new version uses a single vibration spectrum and mathematically obtains the M and H transmissibility values following the tests. It is important to note that the vibration shaker controller software from the Unholtz-Dickie Corporation (VwinII) supported the direct input of ISO specified power spectrum density (PSD) values. The ISO 10819 specified spectra can be seen in Tables 2 and 3.

Table 2: Required ISO 10819 One-Third-Octave Acceleration Value Spectra in 1996 and 2011 Edition (ISO 10819, 1996; 2011; 2013): UW and W referes frequency unweighted and weighted, respectively

ISO 10819 1/3 Oct. Cent. Freq. fc [Hz]	1996 Ed. Spectrum M [r.m.s. m/s^2]	1996 Ed. Spectrum H [r.m.s. m/s^2]	2011/2013 Ed. [r.m.s. m/s^2]
16	0.18		
20	0.40		
25	0.90		1.98
31.5	2.36		2.45
40	3.18		3.22
50	3.88		4.10
63	4.54		4.85
80	5.16		6.38
100	5.71	3.77	8.20
125	6.14	6.29	9.81
160	6.28	10.47	12.53
200	5.89	15.24	16.00
250	5.04	20.20	20.14
315	3.94	24.86	23.79
400	2.89	29.07	28.19
500		32.48	31.59
630		35.15	33.96
800		35.95	35.19
1000		33.79	33.35
1250		28.91	28.37
1600		22.40	19.58
Total UW Acceleration	16.51	91.26	90.18
Total W Acceleration	3.15	3.27	4.82

Table 3: Required ISO 10819 Acceleration PSD Values in 1996 and 2011 Edition (ISO 10819, 1996; 2011; 2013)

ISO 10819 1/3 Oct. Cent. Freq. fc [Hz]	1996 Ed. Spectrum M $[(m/s^2)^2/Hz]$	1996 Ed. Spectrum H $[(m/s^2)^2/Hz]$	2011/2013 Ed. $[(m/s^2)^2/Hz]$
16	0.009		
20	0.035		
25	0.141		0.709
31.5	0.770		0.893
40	1.109		1.134
50	1.311		1.417
63	1.424		1.786
80	1.460		2.268
100	1.419	0.619	2.835
125	1.302	1.367	3.543
160	1.081	3.006	4.535
200	0.755	5.055	5.669
250	0.439	7.048	7.087
315	0.213	8.473	8.521
400	0.091	9.196	9.179
500		9.112	9.179
630		8.470	8.555
800		7.032	7.069
1000		4.931	4.994
1250		2.865	2.905
1600		1.365	1.324

2.2.3 Verification of Handle Output

In order to verify the excitation output at the handle, as well as the shaker controller system, the overall shaker system was verified using a laser Doppler vibrometer (LDV, PSV-300, Polytec, Irvine, CA). Because the LDV system was highly reliable, it was a very useful tool to independently determine the output reading of the shaker handle. This verification was essential and showed that the shaker controller properly generated the ISO 10819 specified excitation spectrum. Here, the LDV system was placed in front of the shaker head, which was nearly perpendicular to the shaker and experiment handle. Because the external handle was convex and light reflected from the aluminum surface, the laser was aimed carefully at the center point of the handle and directly behind the internal accelerometer location. Once in position, the LDV system displayed the waveform at the point and the one-third-octave vibration spectrum,

with user-specified averaging duration. Although the LDV system was nearly a turnkey system, at least some measurement conditions (i.e., target frequency range, appropriate sensitivity setting, and the laser reflection gauge) needed to be checked and adjusted accordingly.

2.2.4 ISO 10819-Based Data Acquisition System

Based on the ISO 10819 measurement processes shown in Figure 11, the data acquisition system was formed by a laptop computer with a USB data acquisition system. The laptop computer (Precision M4300, Dell, Round Rock, TX) was selected because of its computational power, memory spaces, and capability to utilize a second monitor for the indication of the force reading. For the data acquisition system, the NI USB-6363 (National Instruments, Austin, TX) was used, which had more than enough analog inputs (up to 32 inputs) and A-to-D sampling capability (1 MSamples/sec/multichannel) for this study. In addition, all required ISO 10819 measurement and transmissibility calculation procedures were developed in LabVIEW 2012 and its additional tool kits (e.g., Sound and Vibration Measurement Suite). The developed program could capture not only the vibration transmissibility spectra, but could also record all channel waveforms (i.e., push and grip forces, handle XYZ accelerations, palm adapter xyz accelerations, and ring acceleration) for future analysis. Figure 12 shows the LabVIEW screens that were specifically developed for the operator and subject screens, respectively. For observation purposes, the operator screen showed more information than the subject screen; however, the subject screen displayed a two-colored large needle meter for maintaining grip and push (feed) forces via subject visual feedback.

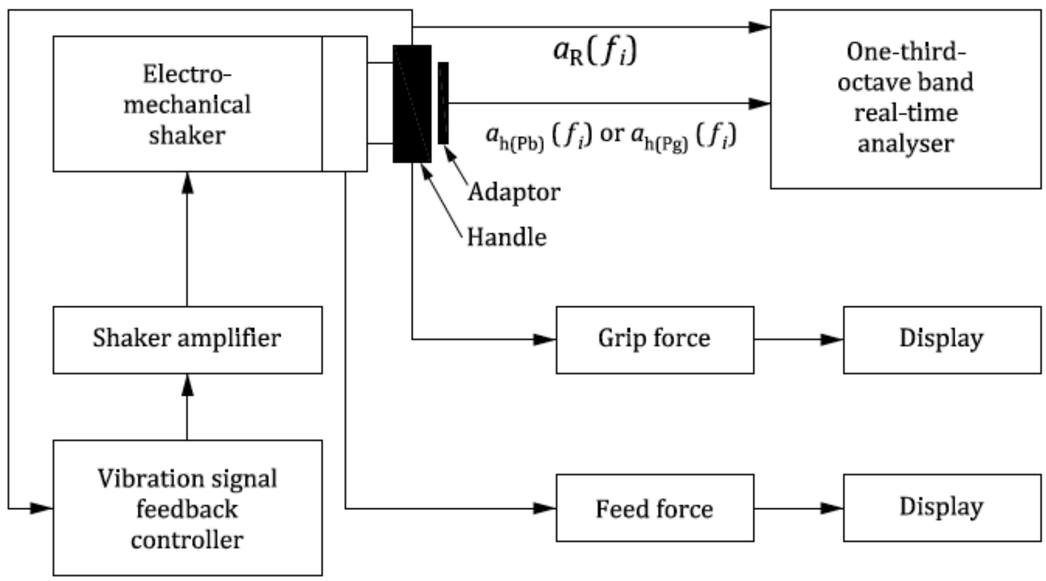
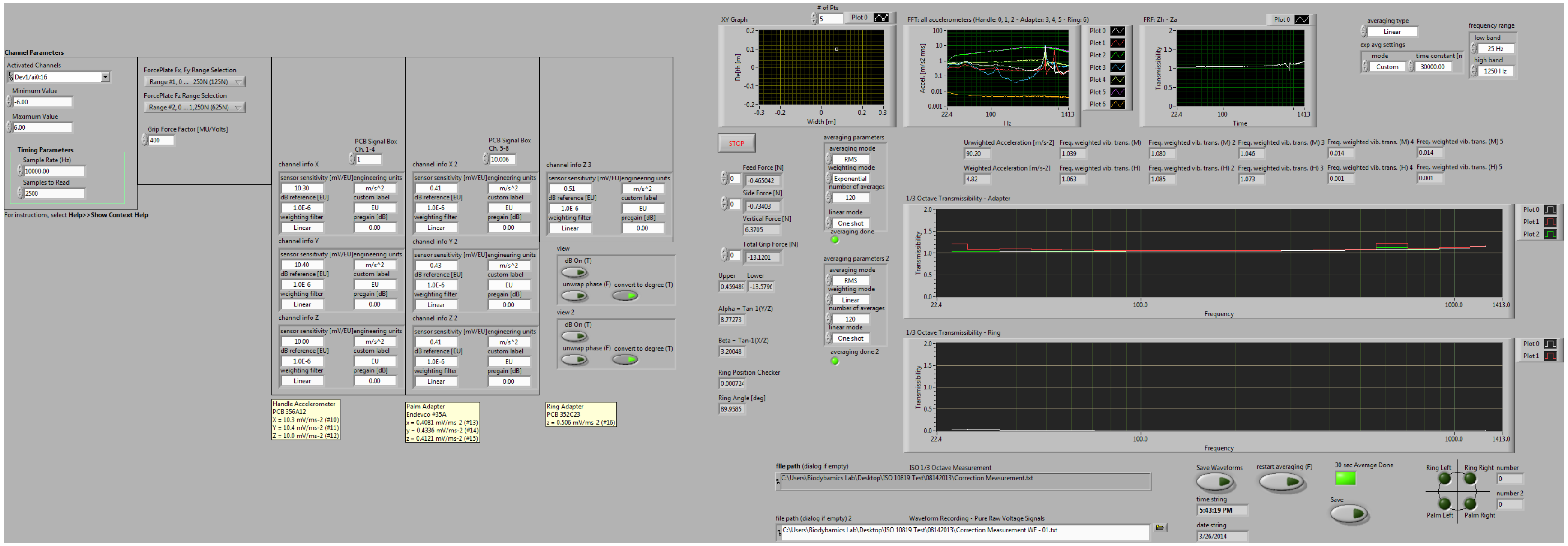


Figure 11: Schematic Diagram for Measurement of Glove Vibration Transmissibility (ISO 10819, 2011)

a)



b)

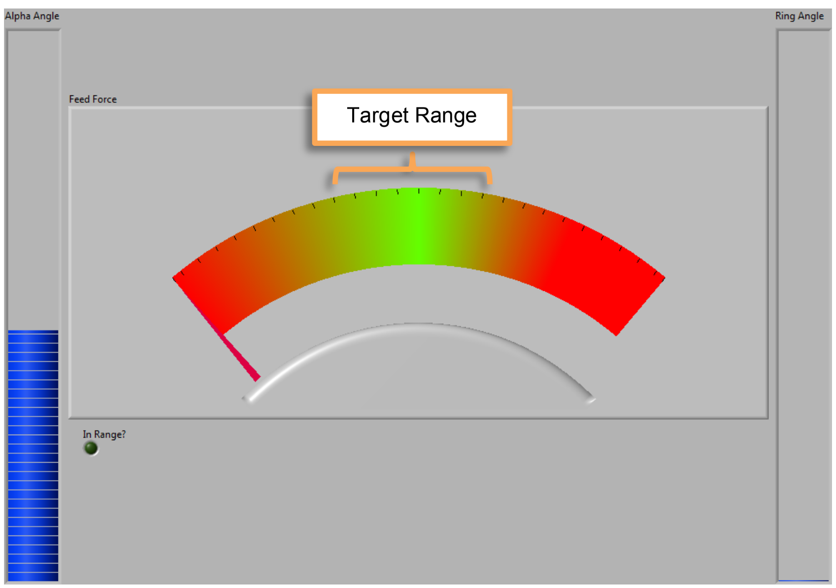


Figure 12: Screen Capture of ISO 10819 Measurement LabVIEW Program: (a) Operator and (b) Subject GUI Screens
(Subject were directed to hold center green part for appropriately maintain force levels in (b).)

Because ICP/IEPE accelerometers were used for the vibration measurements in the laboratory, certain voltage and current levels were needed to operate these sensors properly. The current data acquisition system, as well as a shaker controller, did not have any capability to support ICP/IEPE accelerometers; therefore, an ICP/IEPE signal conditioner (Model 483C15, PCB, Dopew, NY) was used that has selectable gain (x1, x10, x100) and frequency range from 0.05 to 17kHz.

2.2.5 Palm Adapter and Ring Adapter for ISO 10819 Test

Vibration measurements performed at specific locations are very critical for glove assessments; however, this is not easily achieved, especially with a gloved hand. ISO 10819 recommends using an accelerometer contained within a palm adapter, as seen in Figure 13, which specifies the adapter material as wood or hard plastic with the overall adapter weight not exceeding 15 gram (ISO 10819, 2011; 2013).

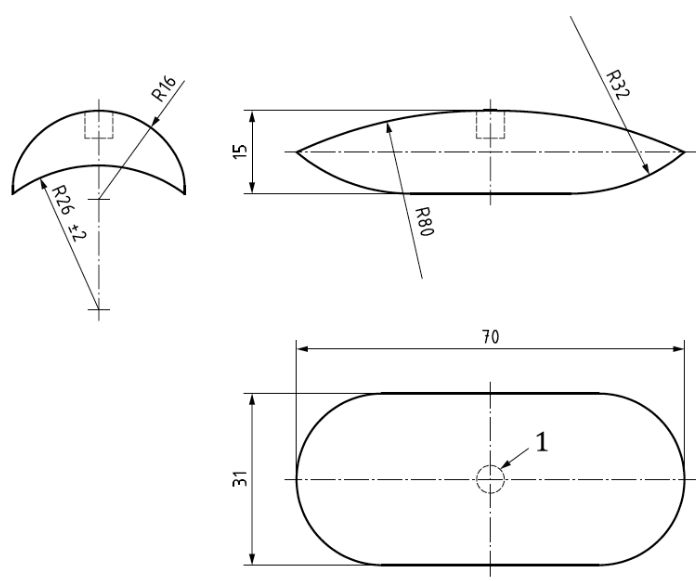


Figure 13: Adaptor for Holding the Accelerometer in the Palm of the Hand (ISO 10819, 2011; 2013)

The transmissibility measured at the palm using the palm adapter is a commonly used procedure, as illustrated in ISO 10819:1996. Because many HAVS are occurring at the fingertip, finger vibration exposure assessment is preferred; however, ISO 10819 does not include glove assessments at the fingers. A novel finger adapter was designed by our laboratory and used in this study. In order to accurately observe the palm and finger vibration exposure, it was necessary to develop extremely light adapters. To achieve this, both palm and finger adapters were manufactured from polylactic acid (PLA) using fused deposition modeling (FDM), or 3D printing. As seen in Figure 14, the finger adapter was positioned on the pad of the middle phalange of the third digit, which has been shown to be a common contact point of the fingers when gripping cylindrical style handles (Tornifoglio, 2012; Tornifoglio and Peterson, 2012). With these adapters, vibration transmissibility was determined based on the ISO 10819 bare adapter test procedure as well as the simple excitation-transmissibility test.

Figure 14: 3D-Printed Palm and Finger Adapters

2.2.6 ISO 10819 Glove Transmissibility Tests and Calculations

Once all of the settings for the ISO 10819 glove assessments were completed, six commercially available VR gloves, three of which are commonly used working gloves, and bare hand transmissibility assessments were performed by following the ISO/DIS 10819:2011 protocol. Briefly, ISO/DIS 10819:2011 recommends that assessing a pair of gloves needs three subjects with five repetitions of 30 seconds of vibration measurement. The major testing conditions (ISO 10819, 2011) are as follows:

a) Grip force – The test subject maintains the grip force at 30 ± 5 N throughout the test.
b) Push force – The test subject maintains the push force at 50 ± 8 N throughout the test.
c) Conditioning of gloves – The test subject wears the gloves at least 3 minutes before the test starts.
d) Posture – As shown in Figure 9a, standing upright on the force plate.
e) Posture – The elbow angle needs to be 90° ± 15° and not touching the body.
f) Posture – The wrist could be bent between 0° (neutral) and 40° (dorsal bending).
g) Adapter – The palm adapter needed to be aligned with the motion of the handle, ± 15°.
h) Adapter – The finger adapter needed to be aligned with the motion of the handle as much as possible.

In order to obtain the mean corrected glove transmissibility values, the measurements and calculations followed the methods specified in ISO/DIS 10819: 201. Figure 15 summarizes the processes from measurement to the transmissibility values. Measurement starts from a bare adapter test, where these values were used to compensate for the influence of the instrumented

handle and to confirm the transmissibility was within the range of 0.95 to 1.05 from 25 to 1,250 Hz. It has to be noted that, although the total number of tests for each glove is the same, this dissertation followed the ISO/DIS 10819:2011 recommendation, where three subjects and five separate tests are the target; however, it is important to note that the newly introduced ISO 10819:2013 requires five subjects and three separate tests.

The transmissibility values could be obtained by a variety of input and output combinations. For example, ISO 10819 specified the transmissibility between the forearm direction (i.e., Z_h direction, assumed dominant direction of vibration tool exposure or electrodynamic shaker excitation direction) and perpendicular direction to the palm (i.e., z_a direction) as Method 1 (ISO 10819, 2011; 2013). Method 1 focuses on the use of a single axis accelerometer, while Method 2 focuses on the use of triaxial accelerometer in the palm adapter, where palm vibration levels were measured in all of the orthogonal directions (i.e., x_a, y_a, and z_a), and were combined using the root-sum-squared (ISO 10819, 2011; 2013). Moreover, researchers from NIOSH (Dong et al., 2002) suggested using the root-sum-square of three orthogonal directions for both handle and palm adapter triaxial accelerometer measurements, which were incorporated in this dissertation as Method 3.

This dissertation also incorporates finger transmissibility measurements along with ISO 10819-based palm transmissibility measurements. Finger transmissibility evaluations followed ISO 10819 as defined for the palm adapter; however, the transmissibility values were determined between instrumented handle vibration signals and uniaxial finger adapter vibration signals. Because finger and palm could slip along the tool handle surface, the direction of vibration exposure at the finger may not be same as the palm, which could wobble less in the axial direction. An additional finger transmissibility measurement involved the radial direction of

handle vibrations was categorized as Method 4. All of the palm and finger transmissibility assessments are summarized in Table 4.

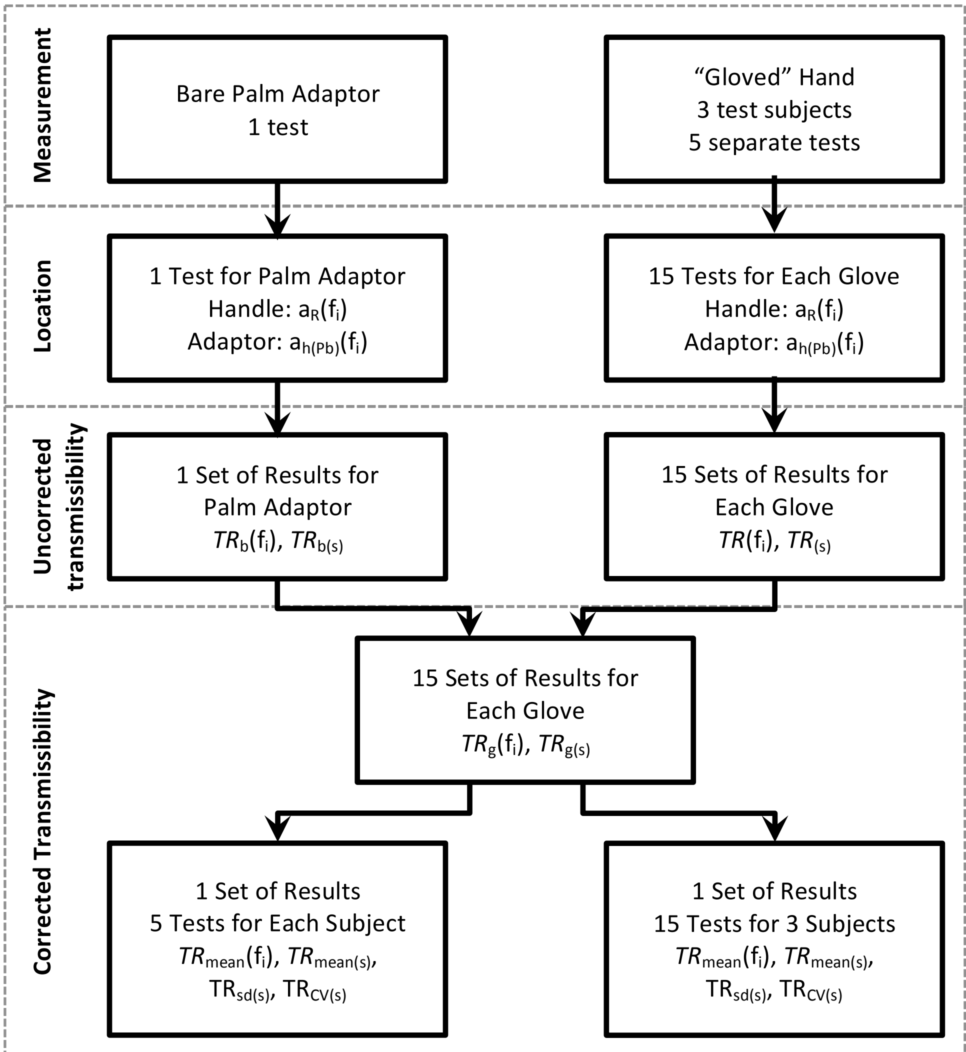


Figure 15: Flow chart for ISO 10819 Glove Tests (ISO 10819, 2011)

Table 4: Organization of Transmissibility Measurements

	PALM	FINGER
Method 1	ISO 10819: Single-axis accelerometer Z_{handle} and Z_{palm}	UCHC: Single-axis vibration Z_{handle} and A_{finger}
Method 2	ISO 10819: Tri-axial accelerometer Z_{handle} and Total-XYZ_{palm}	
Method 3	Dong et al. (2002): Total vibration Total-XYZ_{handle} and Total-XYZ_{palm}	
Method 4		UCHC: Radial Direction vibration YZ_{handle} and A_{finger}

2.2.7 Subjects - Human

Because this dissertation follows the ISO 10819 2011 edition, the hands of three healthy male subjects were measured and evaluated. All the subjects were informed of the health risks of being a subject in this study and signed informed consents (UConn Health Center, IRB #09-227-2). All subjects were instructed in the ISO 10819 testing postures and conditions. Because evaluation of each glove required an average of five measurements with 10 different glove types, each subject was asked to perform 50 tests, so the glove evaluation order was randomized and split into two separate days (25 times per day) to minimize vibration exposure stress and fatigue.

2.2.8 Subjects – VR Gloves

A total of nine gloves was used in this study, where six were commercially available AV/VR gloves and three were commonly used working gloves, as described in Table 5. Bare hand transmissibility was also evaluated following the ISO 10819:2011. Because all of the subject hands were measured as large in size, all of the evaluated gloves were large size glove in this dissertation.

Table 5. Evaluated Glove Information

Test ID	Manufacture and Model	Color	Material Information
Glove 1	Impacto, BG413A	White	Air bladder
Glove 2	Impacto, BG650A	Yellow	Air bladder
Glove 3	Impacto, Blackmaxx Pro	Black	Chloroprene rubber coated
Glove 4	Camelbak, Impact CT	Black	Eva foam
Glove 5	Ansel, HyFlex 11-500	Yellow	Kevlar liner, Nitrile foam coated
Glove 6	Ansel, HyFlex 11-511	Green	Kevlar liner,Nitrile foam coated
Glove 7	Ansel, HyFlex 11-624	Silver	Dyneema and Lycra liner, Polyurethane coated
Glove 8	Ergodyne, Proflex 9002	Black	Nu^2O_2 Polymer
Glove 9	Ergodyne, Proflex 900	Black	Half finger glove, Visco-elastic gel polymer
Hand 1	NO Glove		

2.3 Phase 3: Additional Experiments and Glove Selection

Using results from Phases 1 and 2, additional glove and resilient material experiments were considered, especially to support the application of the LTI system theory for VR glove selection.

2.3.1 Replace Excitation Spectrum by Tool Spectra

After the ISO 10819 glove assessment, the excitation spectrum was replaced by several different vibration spectra, such as a flat spectrum, averaged riveter spectrum, ISO 5349 profile spectrum, air hammer spectrum, and palm hammer spectrum. Figure 16 shows screen captures of experimental spectra from the shaker controller computer. Although it is practical to test the time-domain tool vibration waveform in addition to the frequency-domain random vibration, the shaker controller is not capable of accepting arbitrary time-domain waveforms.

The shaker controller (VwinII, Unholts-Dickie, Wallingford, CT) only accepts an arbitrary frequency-domain PSD spectrum, which was limited to a bandwidth from 3 to 2,500 Hz. Because previously obtained tool vibration spectra were converted from r.m.s. to PSD spectra, it was fairly easy to carry out the glove transmissibility assessment for different power-tool originated vibration excitations. The shaker controller was capable of maintaining the excitation spectrum profile and could change the total vibration output levels in m/s^2 r.m.s., as shown in Figure 15. This functionality was very powerful in that some tool vibration in the PSD spectrum exceeded the maximum acceleration levels of the shaker system, which could be adjusted by modifying the total acceleration values.

Utilizing the above mentioned spectra, especially flat and averaged riveter spectra, glove assessments were performed. This test still followed the ISO 10819 testing conditions, where same loading conditions, subject postures, and mathematical calculations were maintained.

2.3.2 Material Damping Tests using Electodynamic Shaker

In order to understand the mechanism of VR gloves, material damping tests were considered and performed. Several different resilient materials were sampled from different manufacturers. Some of them were pure rubber, silicone, or gel-form, and the others were foam rubber or urethane materials. It was assumed that the material needed to have a fair amount of thickness and stiffness because, if the material were perfectly compressed by applying either static or dynamic loads, then it would not function as damping material anymore. Therefore, especially when considering VR glove use, the damping materials needed to be tested under both static load and dynamic load (i.e., vibration) conditions.

For the ISO 10819 glove assessment, it was required to obtain the bare adapter transmissibility by securing the palm adapter using a rubber strip (i.e., tourniquet, about 80 N equivalent to grip force) to the instrumented handle. Using the same principle, the resilient material was wrapped around the instrumented handle and the palm adapter was positioned and secured by the rubber strip with approximately 80 N of load. Because the measurement system was designed to capture the handle and palm adapter accelerometer signals simultaneously, it was easy to obtain the material transmissibility. The results of the previously evaluated VR gloves were also compared between a subject’s hand holding the handle and the tourniquet wrapped around the handle.

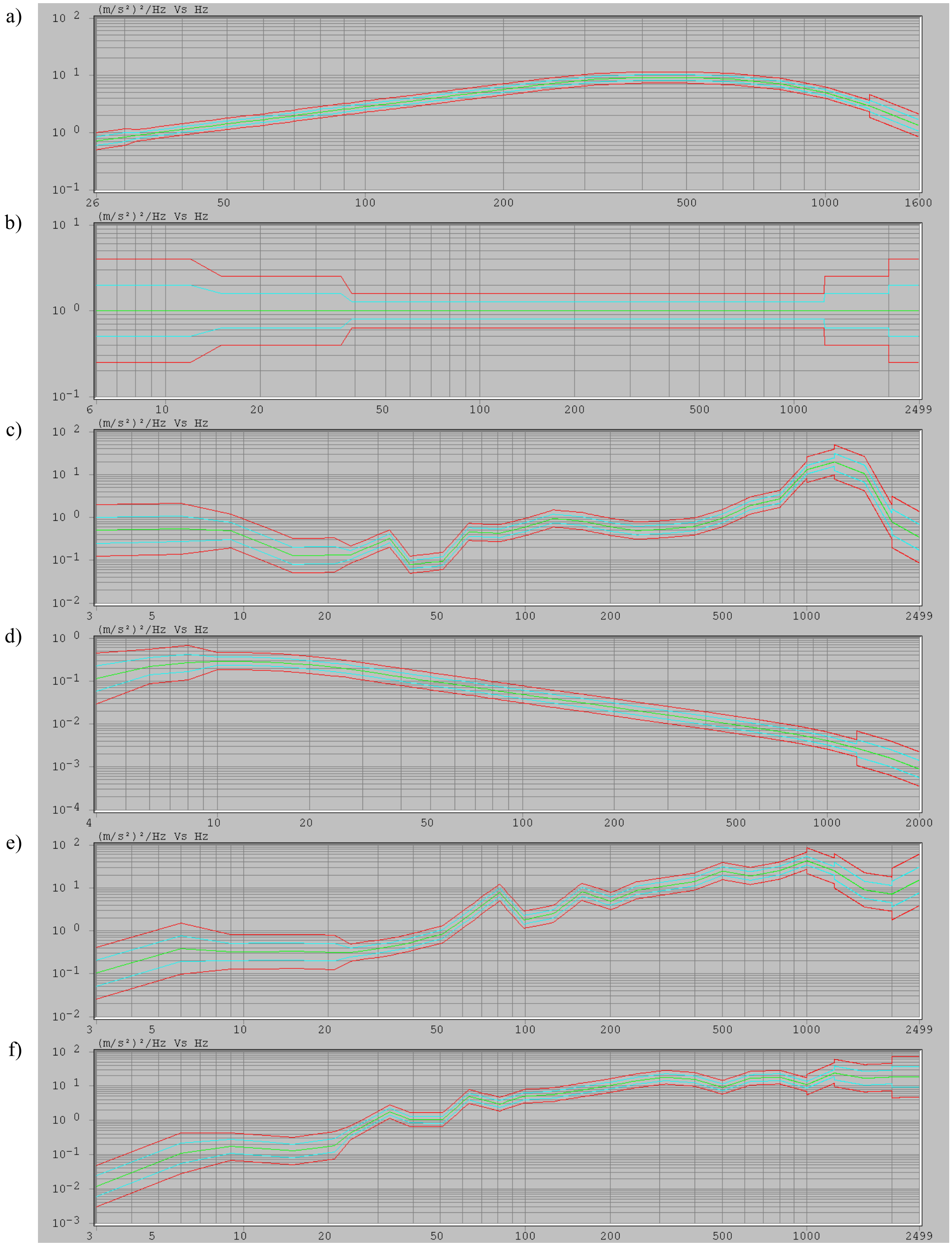


Figure 16: Examples of Different Excitation Spectra (Captured from the Shaker Controller) (a) ISO 10819:2011, Total 91.428 m/s^2 r.m.s., (b) Flat Spectrum, Total 50 m/s^2 r.m.s., (c) Average Riveter, Total 113.873 m/s^2 r.m.s., (d) ISO 5349 Profile, Total 5 m/s^2 r.m.s. (e) Air Hammer, Total 200 m/s^2 r.m.s., and (f) Palm Hammer, Total 200 m/s^2 r.m.s.

2.3.3 LTI System Based Glove Reduction Assessment

Power tool vibration spectra were obtained from ISO 5349- and ISO 8041-based vibration measurements of several power tool operations. All glove transmissibility assessments were conducted using an ISO 10819-based hand-arm excitation system, where vibration at the handle, palm, and finger were measured. In order to directly overlap the frequency range between ISO 5349 and ISO 10819, the six low-frequency one-third-octave band frequencies (fc = 6.3, 8, 10, 12.5, 16, and 20 Hz, from ISO 5349) in the tool spectra were excluded. The tool vibration spectrum was multiplied by the glove transmissibility spectrum, for both palm and finger, to yield an estimated vibration exposure spectrum to the hand-arm system while a glove is worn.

In addition, the overall percent reduction in vibration exposure for each glove was calculated using the total unweighted (UW) and weighted (W) accelerations determined from the tool and estimated vibration exposure spectra. The following Equation (2.8) was used to obtain the percent reduction of gloved hand vibration exposures, which yields positive values as reduction or negative values as amplification due to the glove transmissibility.

$$Reduction\ \% = \left(1 - \frac{Estimated\ Vibration\ Exposure\ Level\ of\ Gloved\ Hand}{Tool\ Vibration\ Level}\right) \times 100 \qquad (2.8)$$

2.3.4 Creation of Glove Selection Tool

Based on the previously discussed methods, a simple and intuitive LabVIEW program was developed, where arbitrary one-third-octave power tool vibration and glove transmissibility spectra are inputted into the program, to assist in glove selection. Because this program was capable to display the expected reduction percentage of a gloved hand quickly, the program could be used as a decision generator for glove selections. For example, the program could be used to compare the percent reduction between two gloves over one specific power tool spectrum to determine which glove would be appropriate for that specific tool, where the higher reduction percentage is chosen. Moreover, selecting one VR glove and the changing different power tool spectra, the program would display several different percentage reductions based on input tool spectra, which would allow one to be able to consider a hypothesis of which tool should be appropriate for the glove.

3. Results

This section is divided into three subsections based on the three phases presented in the Methods section. Phase 1 presents the results and health risk assessments of tool vibrations from two worksites, as well as their converted power spectral density (PSD) tool spectra. Phase 2 presents the validation of the ISO 10819-based testing apparatus and the transmissibility results of nine commonly used gloves tested using three subjects. Phase 3 presents the results of series of small experiments to investigate the usefulness of the Linear Time-Invariant (LTI) system theory on vibration-reducing (VR) glove selection.

3.1 Phase 1: Tool Vibration Assessment

In this section, field power tool vibration measurements were conducted at two worksites about 35 tools. Initially, the frequency response of a newly developed accelerometer adapter is presented followed by detailed tool vibration measurements and health risk assessments conducted based on ISO 5349 with tool vibration data sets converted from r.m.s. acceleration to PSD values.

3.1.1 Bucking Bar Adapter Verification

The transmissibility of the adapter cube for the bucking bar was verified by the vibration shaker system. Figure 17 shows a typical response of the developed accelerometer adapter, where it was observed to be nearly flat up to about 2,000 Hz.

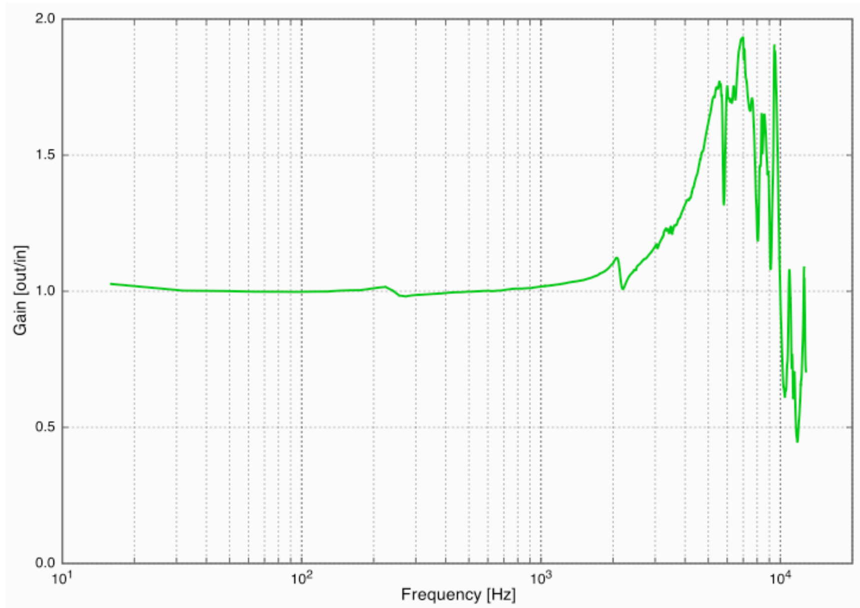


Figure 17: Typical Frequency Response of Accelerometer Adapter (Asaki and Peterson, 2012)

3.1.2 Power Tool Vibration Measurement in the Field

Utilizing the vibration measurement cart and the bucking bar adapter, power tool vibration measurements were conducted in the helicopter facility in Connecticut and the refrigerator facility in Iowa. About 35 different tool vibrations were captured, based on the ISO 5349 and ANSI S2.70, and converted into one-third-octave PSD spectra. All of the tool spectra information is in Appendix A. Figures 18 through 29 show a selection of the total tool vibration spectra in PSD and corresponding tool pictures. There were no electric power vibration tools captured in this study.

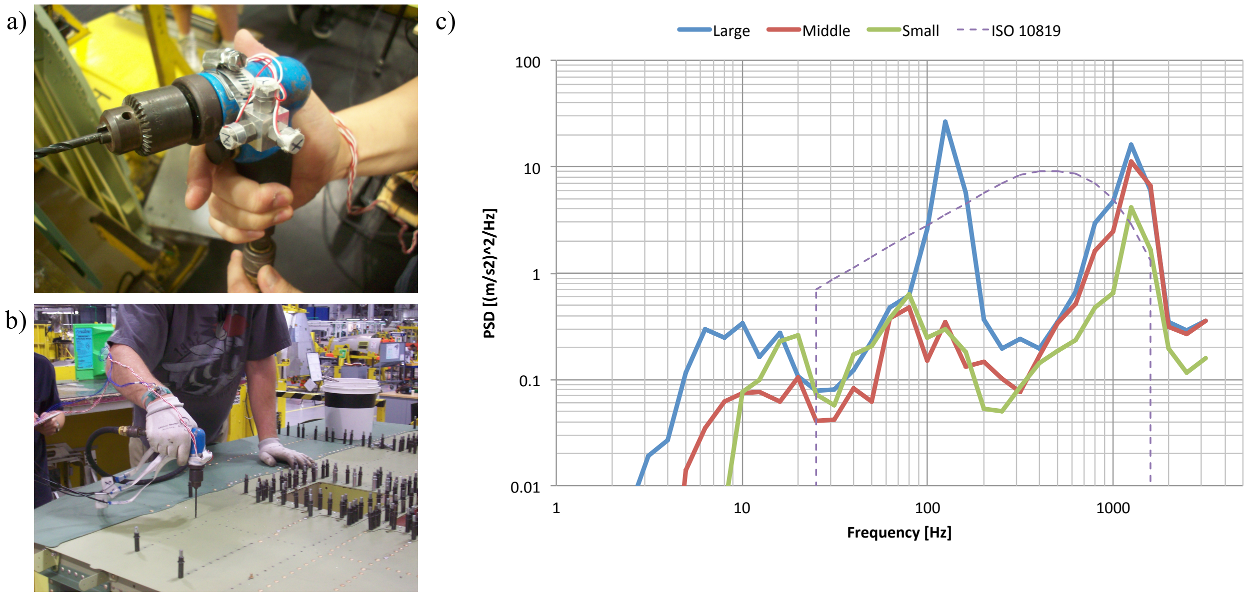


Figure 18: Examples of Drill Vibration Measurement and Its PSD Spectrum:
(a) Sensor Mounting, (b) Tool Operation, and (c) 1/3 Octave PSD Spectrum

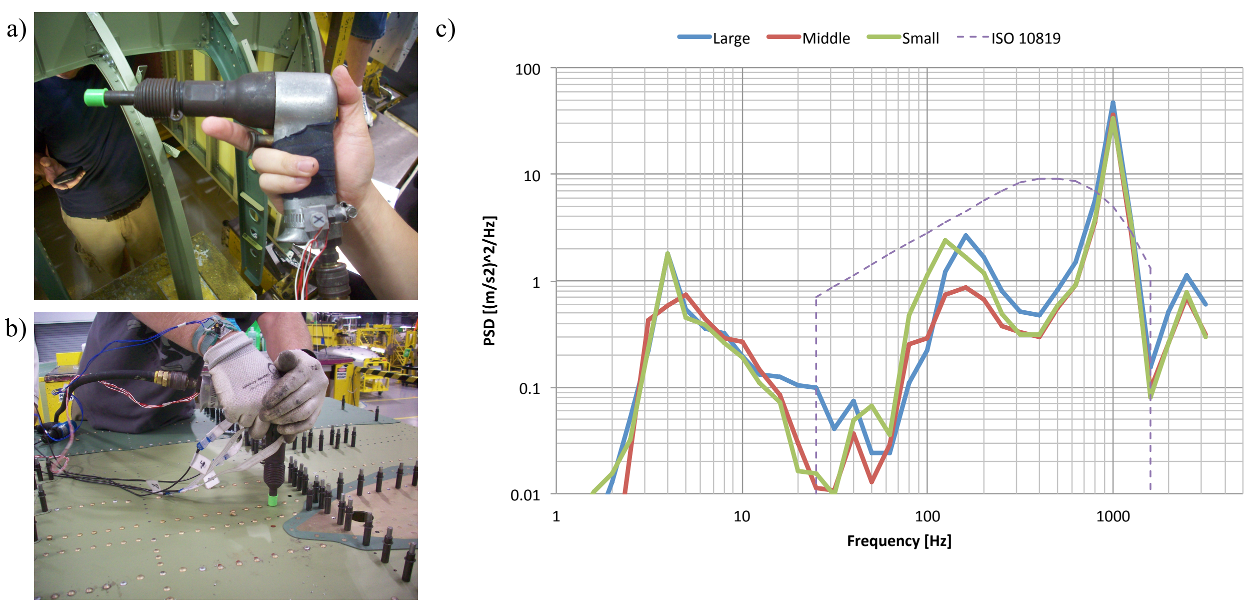


Figure 19: Examples of Riveter Vibration Measurement and Its PSD Spectrum:
(a) Sensor Mounting, (b) Tool Operation, and (c) 1/3 Octave PSD Spectrum

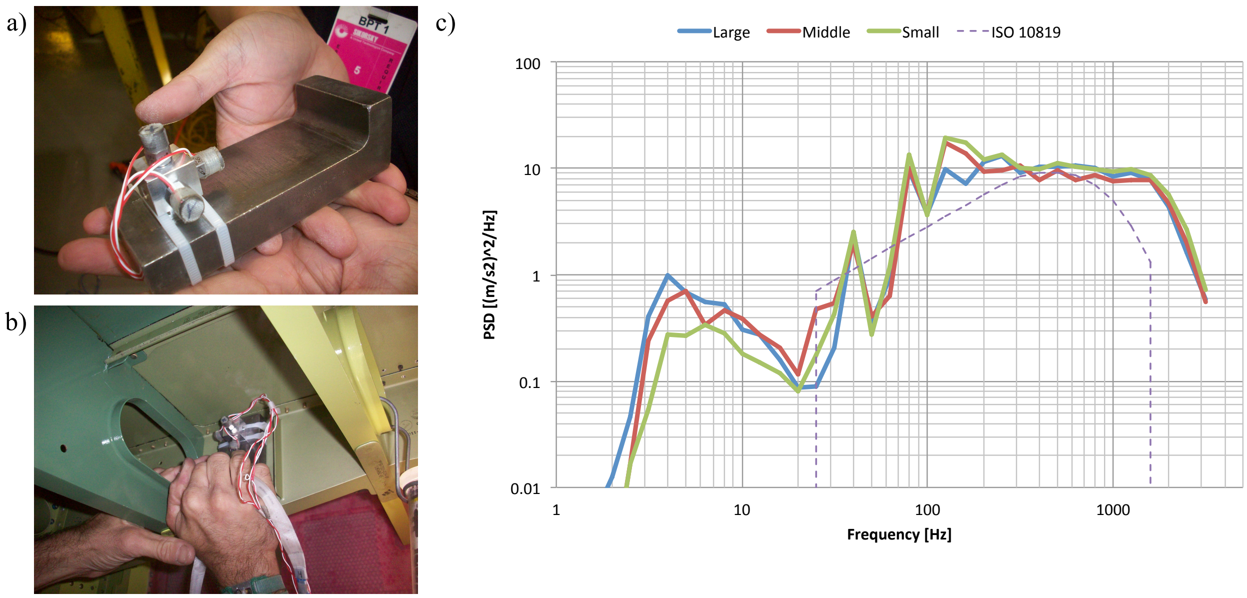


Figure 20: Examples of Bucking Bar Vibration Measurement and Its PSD Spectrum:
(a) Sensor Mounting, (b) Tool Operation, and (c) 1/3 Octave PSD Spectrum

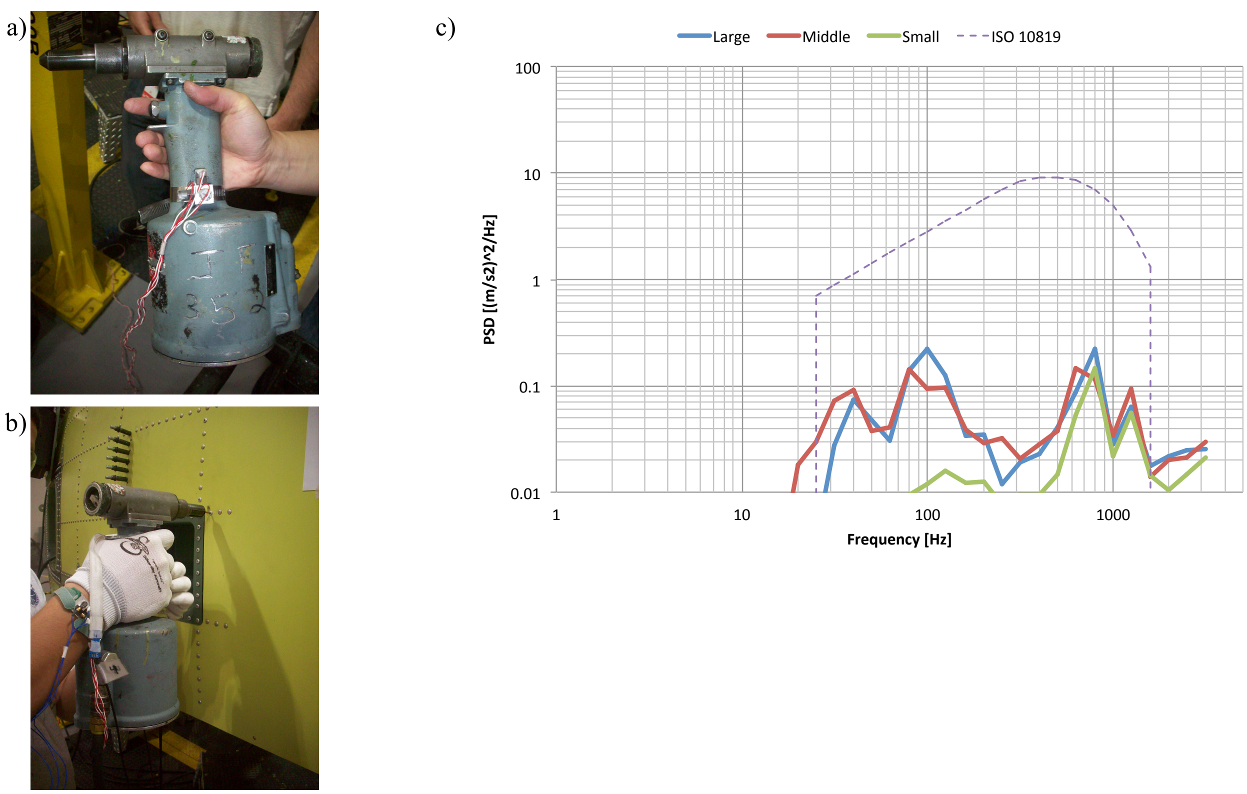


Figure 21: Examples of Cherry Gun Vibration Measurement and Its PSD Spectrum:
(a) Sensor Mounting, (b) Tool Operation, and (c) 1/3 Octave PSD Spectrum

a) 

b) 

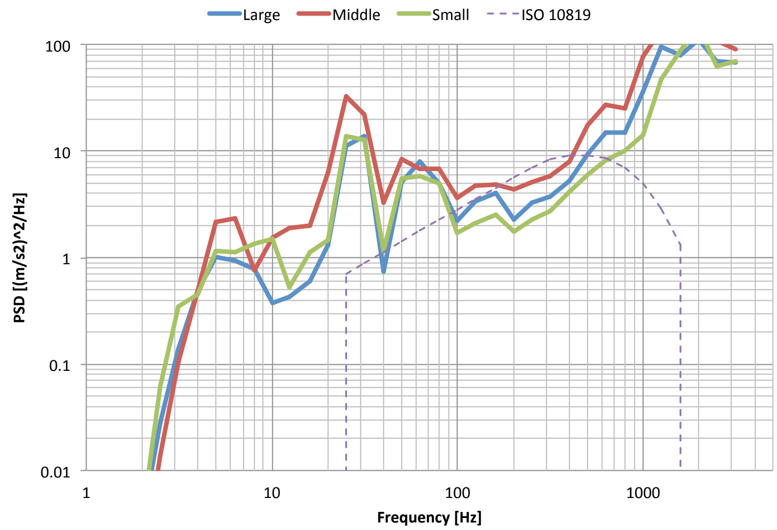
c) 

Figure 22: Examples of Bucking Bar Vibration Measurement and Its PSD Spectrum: (a) Sensor Mounting, (b) Tool Operation, and (c) 1/3 Octave PSD Spectrum

a) 

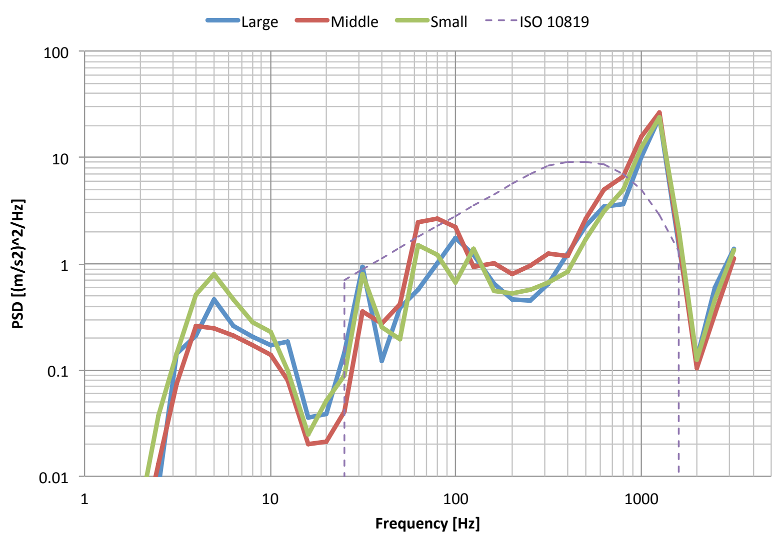
b) 

Figure 23: Examples of Bucking Bar Vibration Measurement and Its PSD Spectrum: (a) Tool Operation and (c) 1/3 Octave PSD Spectrum

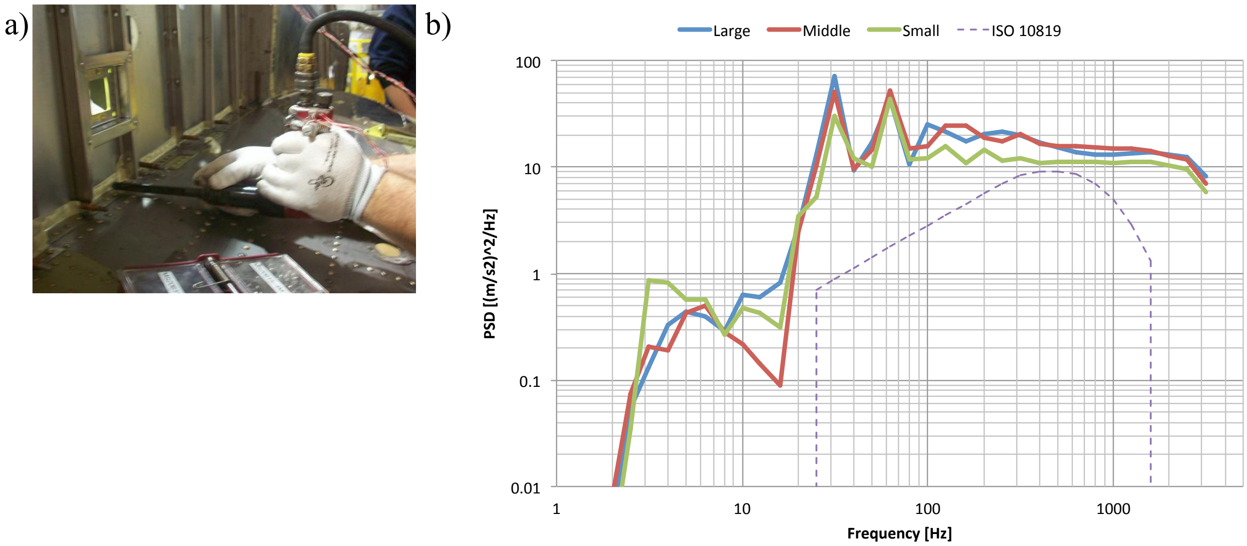


Figure 24: Examples of Riveter Vibration Measurement and Its PSD Spectrum:
(a) Tool Operation and (c) 1/3 Octave PSD Spectrum

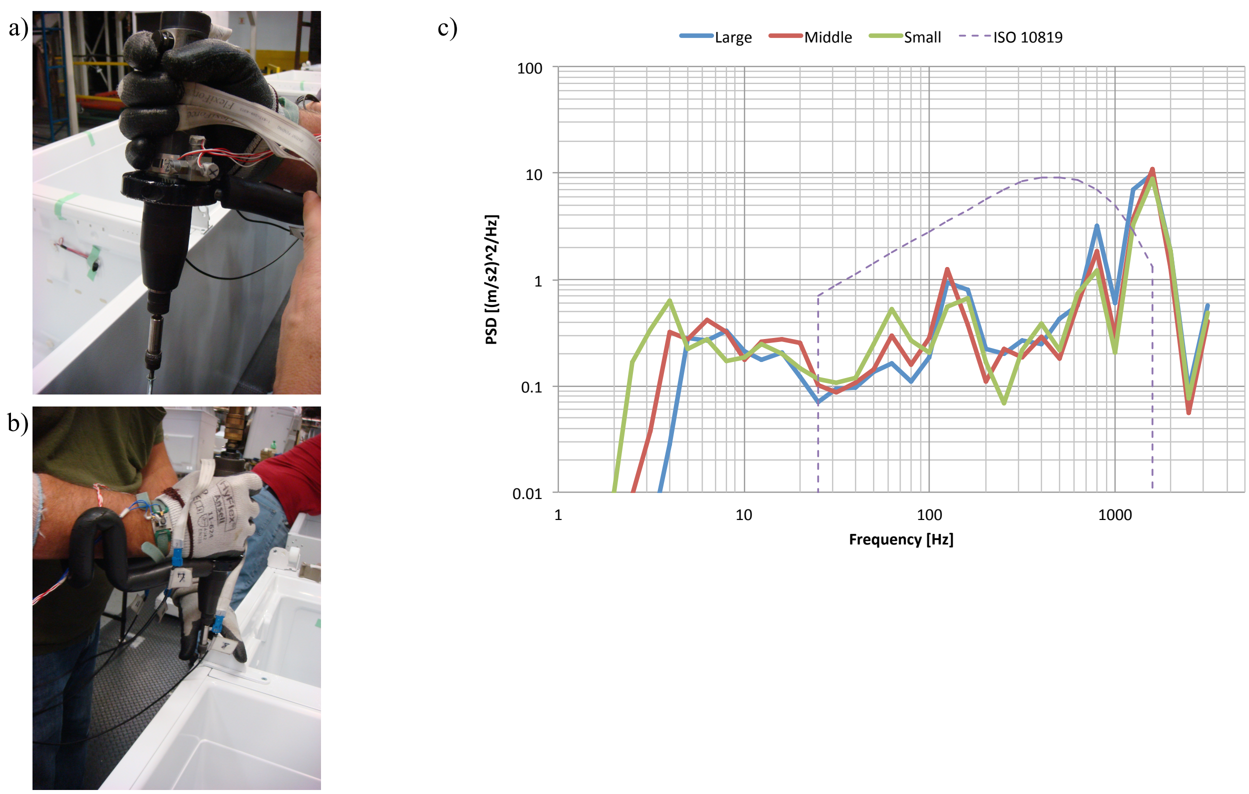


Figure 25: Examples of Nut Runner Vibration Measurement and Its PSD Spectrum:
(a) Sensor Mounting, (b) Tool Operation, and (c) 1/3 Octave PSD Spectrum

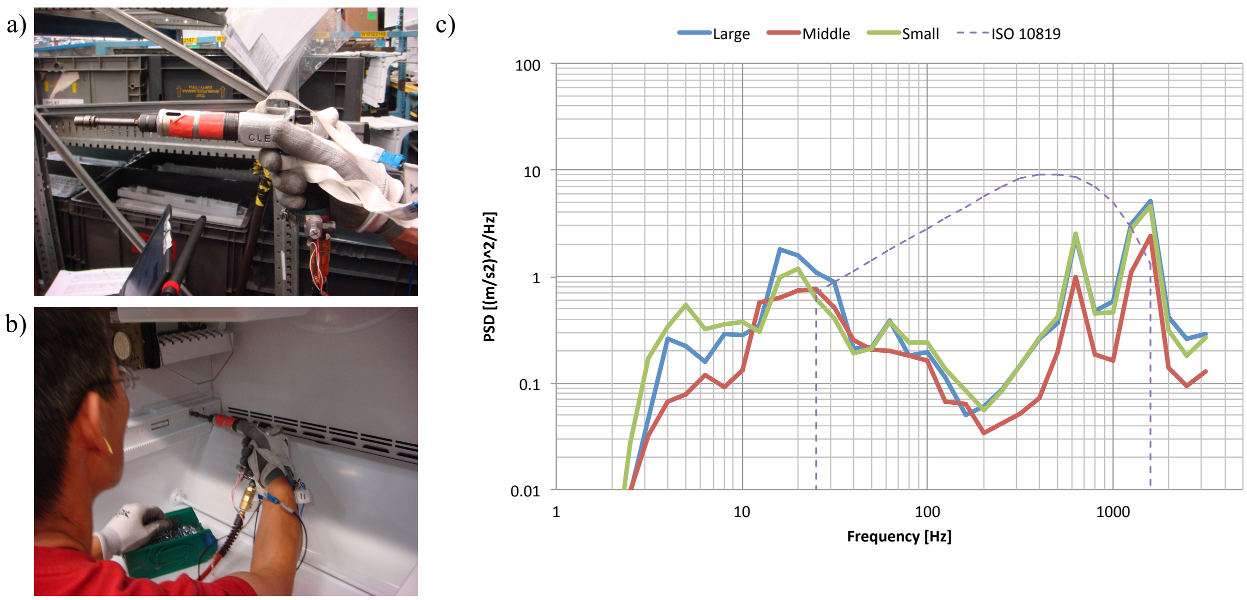


Figure 26: Examples of Screw Gun Vibration Measurement and Its PSD Spectrum:
(a) Sensor Mounting, (b) Tool Operation, and (c) 1/3 Octave PSD Spectrum

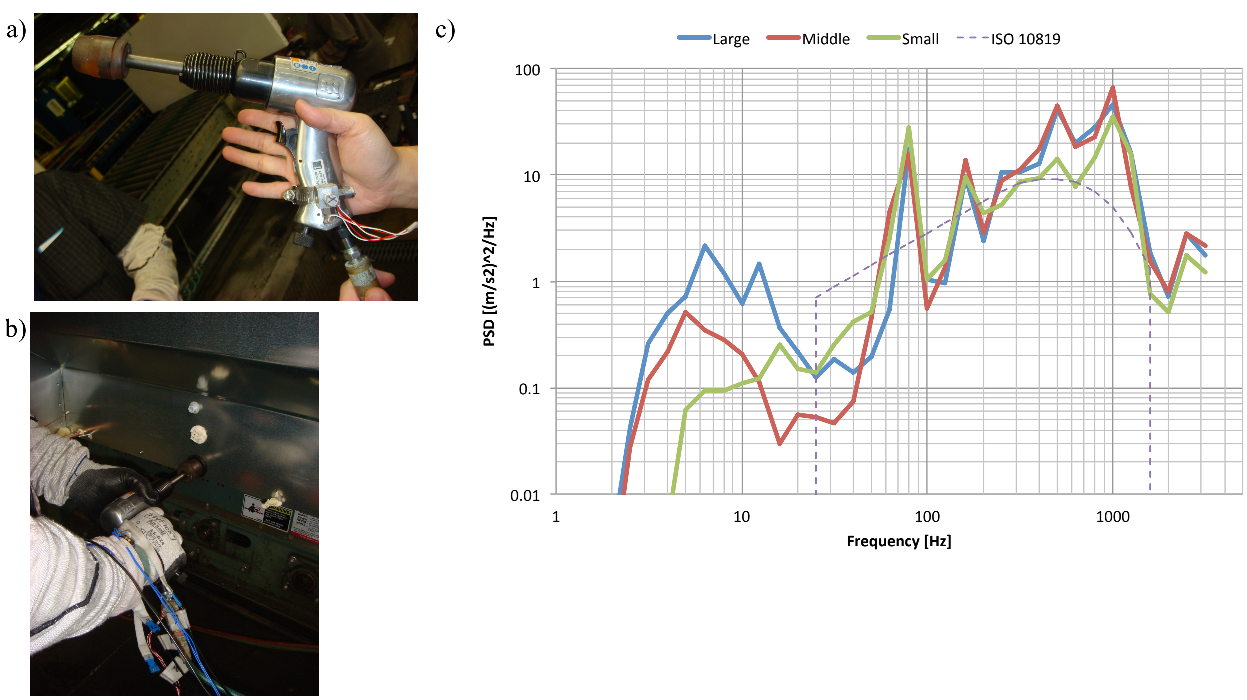


Figure 27: Examples of Air Hammer Vibration Measurement and Its PSD Spectrum:
(a) Sensor Mounting, (b) Tool Operation, and (c) 1/3 Octave PSD Spectrum

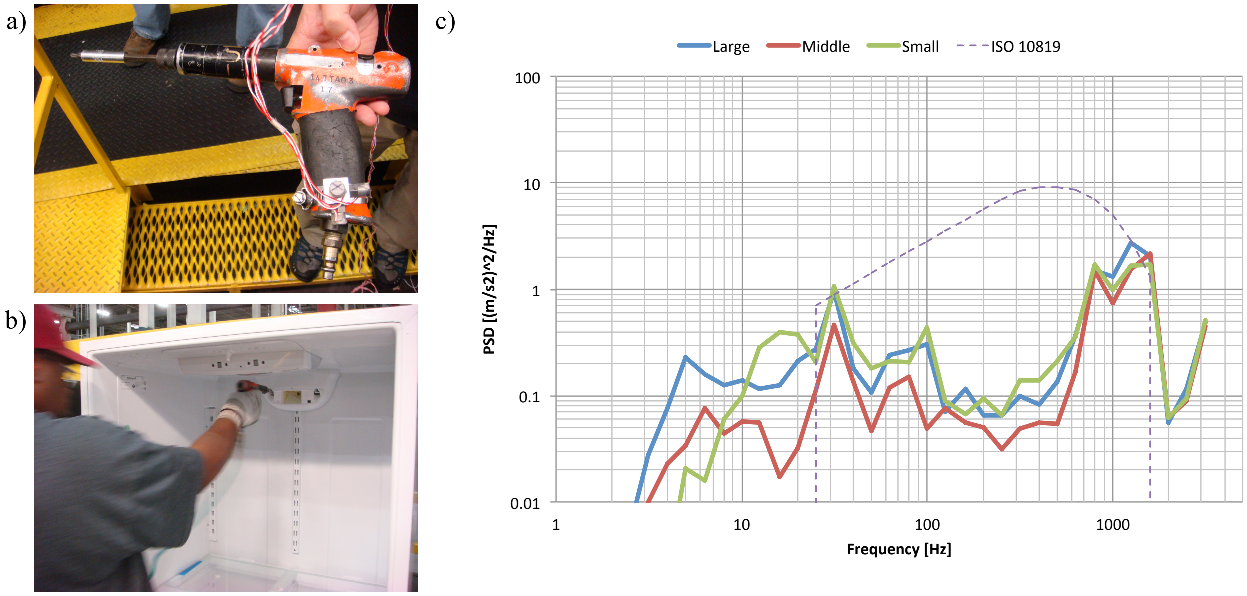


Figure 28: Examples of Screw Gun Vibration Measurement and Its PSD Spectrum:
(a) Sensor Mounting, (b) Tool Operation, and (c) 1/3 Octave PSD Spectrum

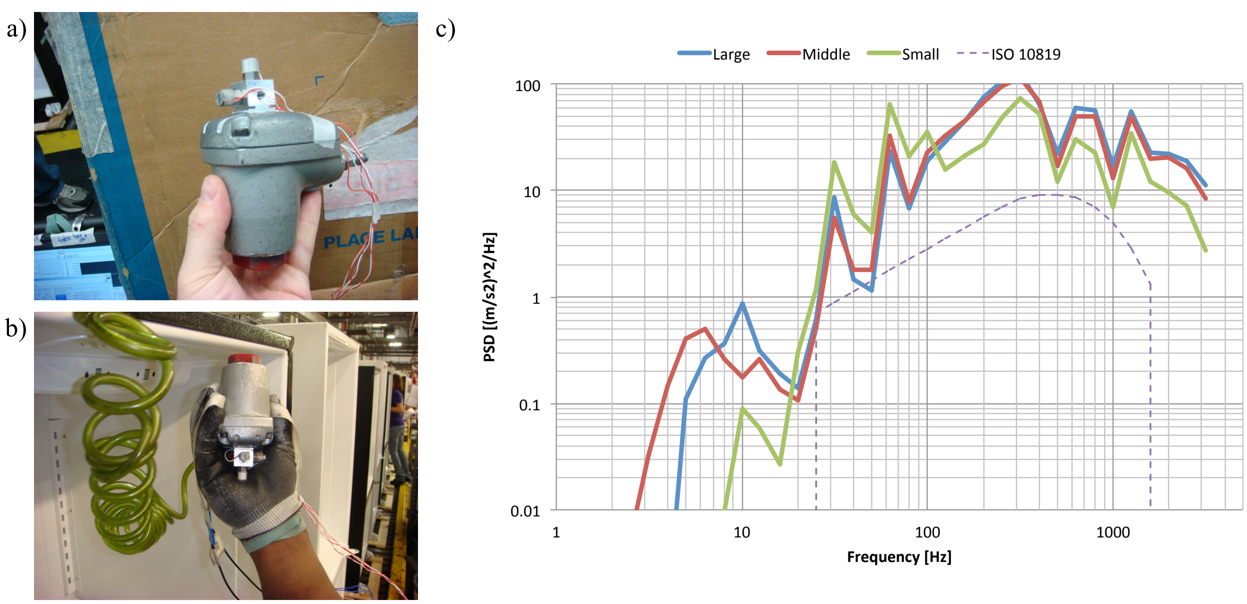


Figure 29: Examples of Palm Hammer Vibration Measurement and Its PSD Spectrum:
(a) Sensor Mounting, (b) Tool Operation, and (c) 1/3 Octave PSD Spectrum

Because the PSD spectra in Figures 18 through 29 were square-root-sum (total) vibrations, the unique directional vibration characteristics were eliminated. Some tools showed very large vibration in a dominant direction (i.e., forearm or Z_h), and noticeably smaller or different vibration characteristics in other directions, which can be see in Appendix A.

The frequency-weighted (W) and un-weighted (UW) vibration values for each axis were also obtained. It is important to note that the UW vibration values were obtained for the frequency range from 1 to 3,150 Hz, which could be a proper representation of the total vibration exposure in this specific frequency range; however, if the total unweighted vibration values were for the same frequency range as ISO 5349 specifies (i.e., 6.3 to 1,250 Hz), then the UW values would be different from these reported values. Table 6 and 7 shows total tool vibration values corresponding with the tools mentioned in Figure 18 and 29.

Table 6. Total Tool Vibration Values Corresponding with Tools in Figures 18 through 24: (for both unweighted and weighted values in the frequency range from 1 to 3,150 Hz)

		Unweighted [m/s^2 r.m.s]				Weighted [m/s^2 r.m.s.]			
		X	Y	Z	Total	Wx	Wy	Wz	Wtot
(a) Drill	Large	28.5	66.9	71.5	102.0	1.6	1.7	4.0	4.7
	Middle	24.4	54.6	61.6	85.9	0.7	1.0	1.2	1.8
	Small	16.6	28.9	36.7	49.5	0.8	0.9	1.6	2.0
(b) Riveter	Large	17.6	54.2	108.4	122.4	1.0	1.4	2.3	2.9
	Middle	15.4	46.2	93.6	105.5	1.0	1.2	1.9	2.4
	Small	13.5	45.7	92.6	104.1	1.0	1.3	2.2	2.7
(c) Bucking Bar	Large	23.5	86.2	106.2	138.8	1.8	3.0	5.2	6.3
	Middle	43.2	31.0	124.3	135.2	3.1	1.7	5.6	6.7
	Small	52.0	27.1	136.5	148.5	2.8	1.5	6.3	7.1
(d) Cherry Gun	Large	5.1	6.7	9.1	12.4	0.1	0.4	0.7	0.8
	Middle	5.5	5.3	9.5	12.3	0.2	0.5	0.7	0.9
	Small	4.2	6.9	5.5	9.8	0.1	0.2	0.2	0.3
(d) Bucking Bar	Large	402.3	127.6	190.7	463.1	3.8	7.4	5.5	9.9
	Middle	495.9	147.3	194.3	552.6	7.3	11.8	4.6	14.6
	Small	398.9	125.0	186.1	457.6	4.3	8.0	4.5	10.1
(e) Bucking Bar	Large	24.3	27.2	108.6	114.5	0.9	1.6	2.6	3.2
	Middle	23.3	29.5	119.8	125.5	0.8	1.5	3.1	3.6
	Small	23.2	28.3	111.7	117.5	1.0	1.5	2.7	3.2
(f) Riveter	Large	87.7	19.8	195.9	215.5	12.3	3.1	12.9	18.1
	Middle	81.4	37.0	196.1	215.5	11.3	4.5	11.5	16.7
	Small	62.4	21.4	175.7	187.7	7.9	2.6	11.5	14.2

Table 7. Total Tool Vibration Values Corresponding with Tools in Figures 25 through 29:
(for both unweighted and weighted values in the frequency range from 1 to 3,150 Hz)

		Unweighted [m/s^2 r.m.s]				Weighted [m/s^2 r.m.s.]			
		X	Y	Z	Total	Wx	Wy	Wz	Wtot
(a) Nut Runner	Large	20.4	47.6	72.7	89.3	1.0	1.2	1.7	2.3
	Middle	17.4	35.0	71.7	81.6	0.9	1.6	1.7	2.5
	Small	19.2	32.3	67.7	77.5	1.0	1.6	1.4	2.3
(b) Screw Gun	Large	14.6	22.8	57.5	63.5	2.7	1.8	2.7	4.3
	Middle	9.4	14.0	37.7	41.3	2.1	1.4	1.9	3.2
	Small	11.9	22.5	54.7	60.4	2.5	1.6	2.0	3.6
(c) Air Hammer	Large	39.3	75.2	168.9	189.0	1.5	3.3	5.9	6.9
	Middle	46.9	74.8	173.3	194.5	1.3	3.6	5.4	6.6
	Small	31.0	46.8	143.8	154.3	1.0	3.3	5.6	6.6
(d) Screw Gun	Large	13.9	17.8	46.8	52.0	0.9	1.1	2.0	2.4
	Middle	13.7	17.9	40.6	46.4	0.7	0.7	1.3	1.6
	Small	13.9	18.2	41.9	47.7	0.8	1.1	2.4	2.8
(e) Palm Hammer	Large	322.2	18.5	66.0	329.4	12.7	3.7	3.7	13.8
	Middle	302.8	18.7	59.5	309.2	12.9	2.8	3.8	13.7
	Small	227.5	24.5	47.1	233.6	13.6	3.8	4.2	14.7

All of the tool vibration waveforms were segmented into one-cycle waveforms, which was a great advantage for determining the tool vibration exposure time, T_v, for specific tool operations. Because it was unclear how many times workers actually operate the power tools over the course of one day, it was assumed that the tool was triggered 500 or 1,000 times per day. The assumed tool exposure times were obtained by Equation (2.5) and are shown in Table 8 and 9, respectively, for the previous tools examples.

The obtained frequency-weighted vibration values, and assumed vibration exposure time, were plotted with DEAV (blue) and DELV (red) lines as shown in Figures 30 and 31. The figures provide health risk assessment information for the helicopter (Figure 30) and refrigerator factories (Figure 31).

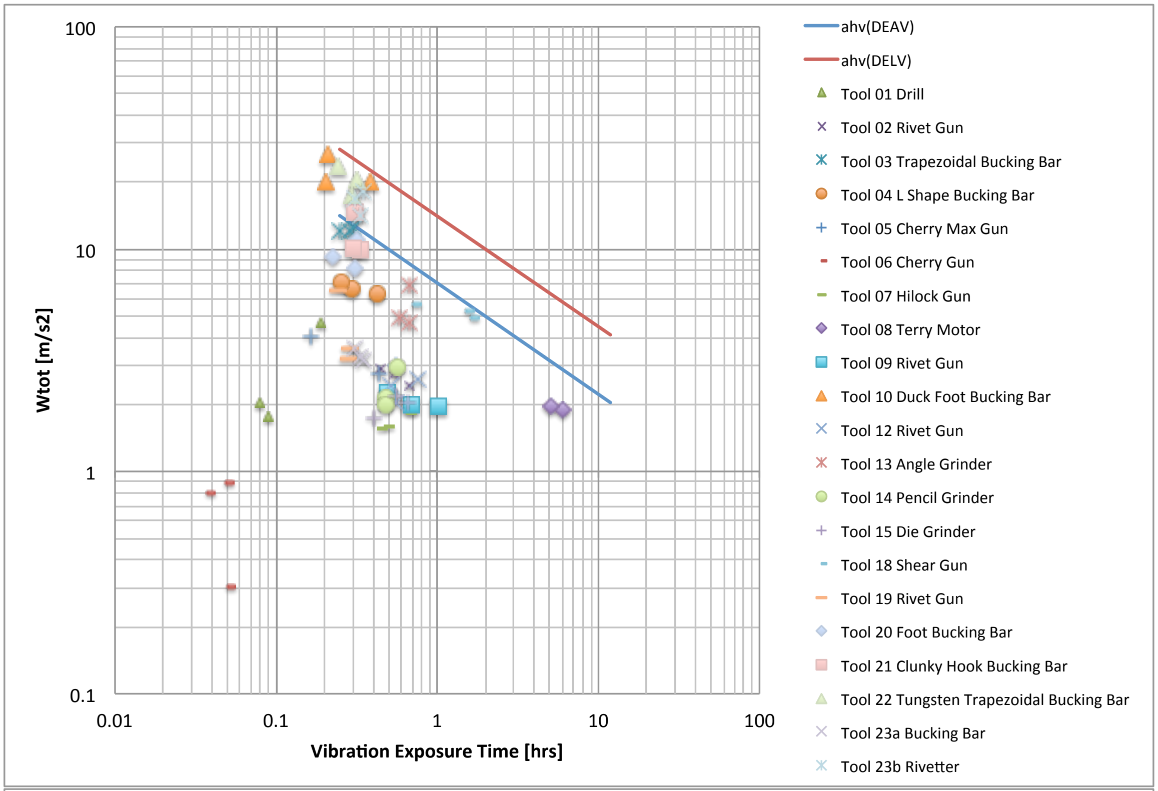
Table 8. One-cycle Tool Operation Time and Assumed Total Exposure Time per Day

		One-cycle Time [sec]	Assumed 500 Tv [hrs]	Assumed 1000 Tv [hrs]
(a) Drill	Large	1.383	0.192	0.384
	Middle	0.651	0.090	0.181
	Small	0.566	0.079	0.157
(b) Riveter	Large	3.239	0.450	0.900
	Middle	4.888	0.679	1.358
	Small	3.878	0.539	1.077
(c) Bucking Bar	Large	3.035	0.421	0.843
	Middle	2.140	0.297	0.595
	Small	1.841	0.256	0.511
(d) Cherry Gun	Large	0.270	0.037	0.075
	Middle	0.355	0.049	0.099
	Small	0.359	0.050	0.100
(e) Bucking Bar	Large	2.401	0.334	0.667
	Middle	2.244	0.312	0.623
	Small	2.179	0.303	0.605
(f) Bucking Bar	Large	2.489	0.346	0.691
	Middle	2.208	0.307	0.613
	Small	2.422	0.336	0.673
(g) Riveter	Large	2.489	0.346	0.691
	Middle	2.208	0.307	0.613
	Small	2.422	0.336	0.673

Table 9. One-cycle Tool Operation Time and Assumed Total Exposure Time per Day

		One-cycle Time [sec]	Assumed 500 Tv [hrs]	Assumed 1000 Tv [hrs]
(a) Nut Runner	Large	1.512	0.210	0.420
	Middle	1.973	0.274	0.548
	Small	2.336	0.324	0.649
(b) Screw Gun	Large	1.763	0.245	0.490
	Middle	1.730	0.240	0.481
	Small	2.132	0.296	0.592
(c) Air Hammer	Large	2.187	0.304	0.608
	Middle	2.226	0.309	0.618
	Small	1.003	0.139	0.279
(d) Screw Gun	Large	1.235	0.172	0.343
	Middle	1.283	0.178	0.356
	Small	1.231	0.171	0.342
(e) Palm Hammer	Large	0.779	0.108	0.216
	Middle	1.360	0.189	0.378
	Small	0.490	0.068	0.136

a)



b)

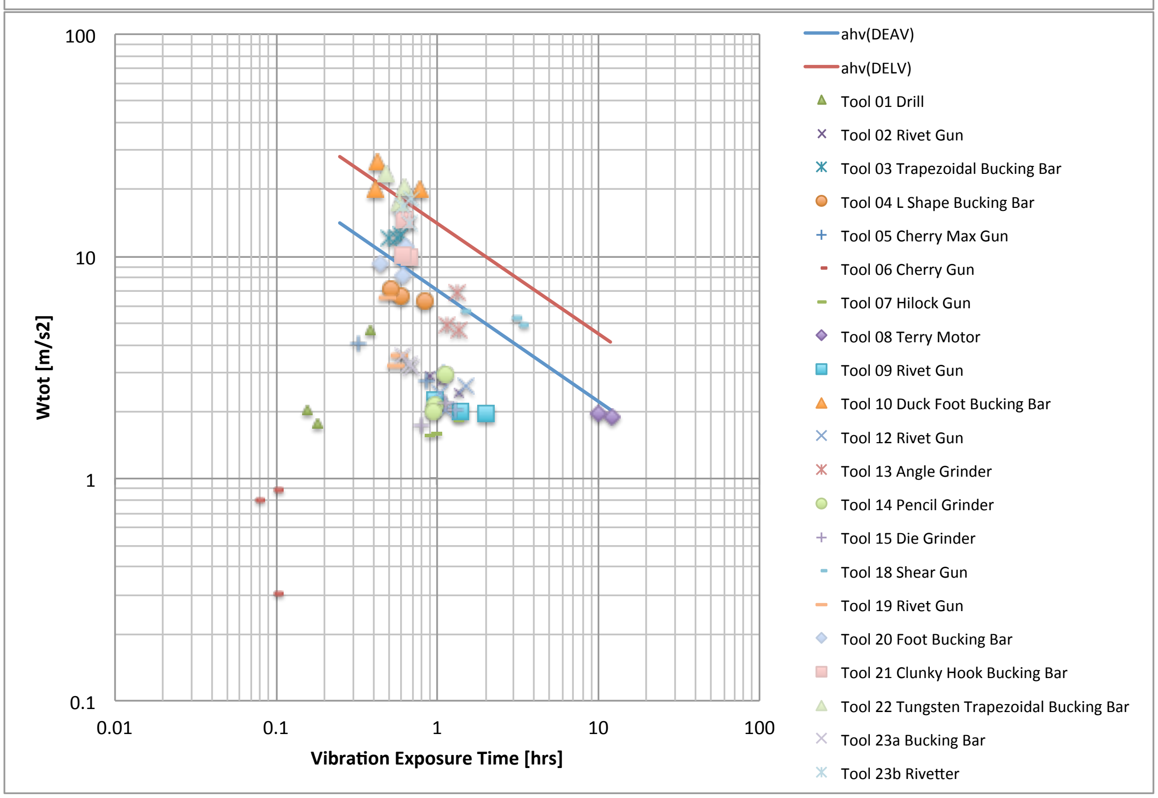
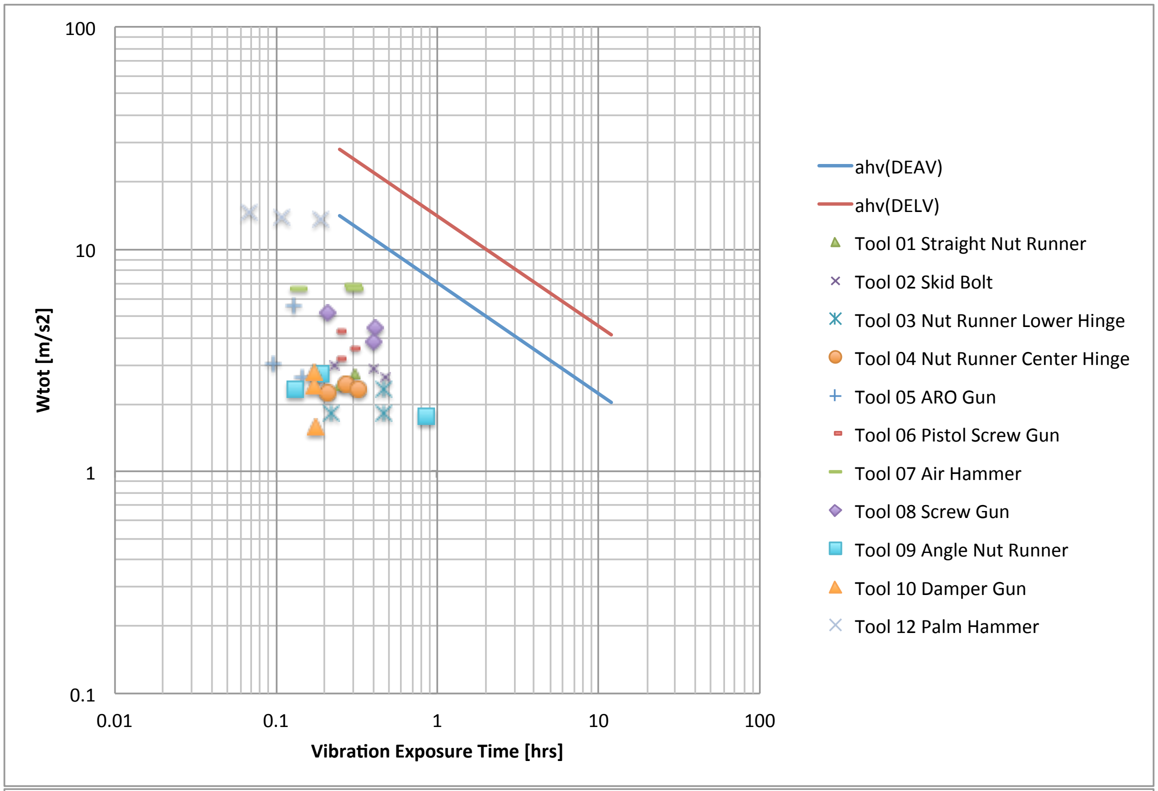


Figure 30: Total Weighted Acceleration Values and Assumed Tool Exposure Time in Hours Helicopter Factory: (a) Case of 500 and (b) Case of 1,000 Times of Tool Operations per Day

a)



b)

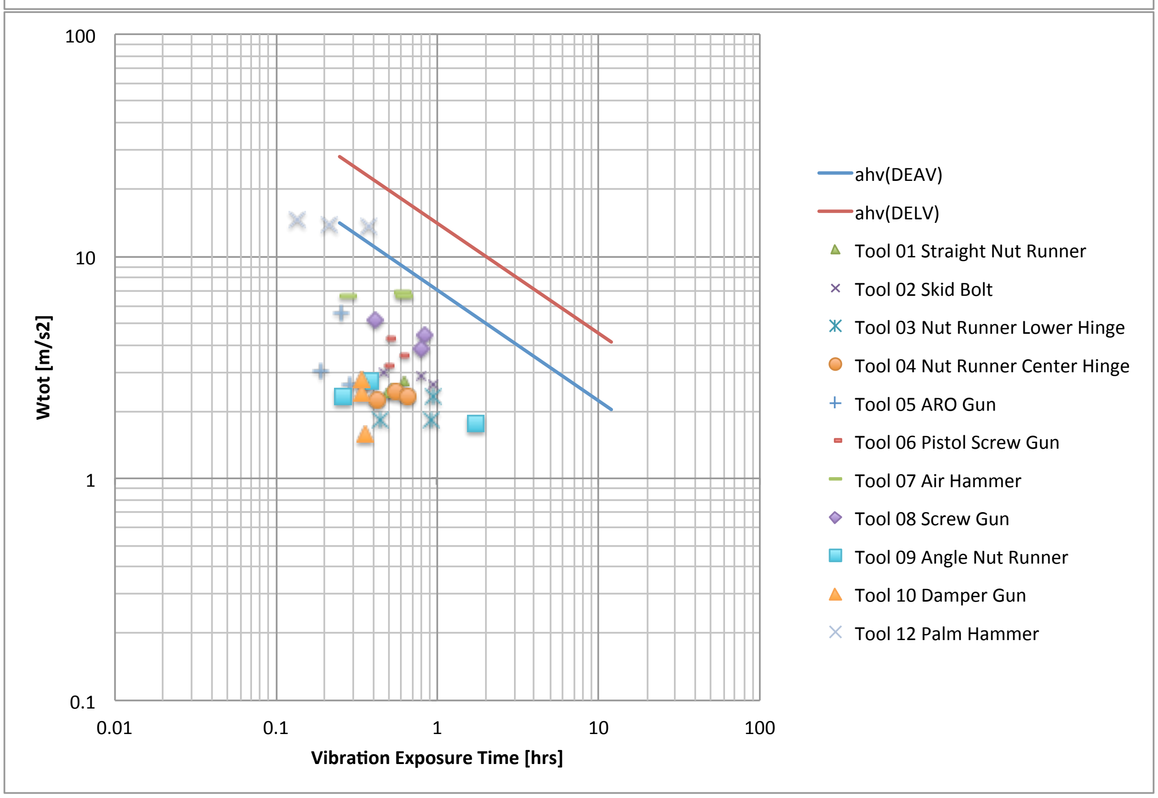


Figure 31: Total Weighted Acceleration Values and Estimated Tool Exposure Time in Hours Refrigerator Factory: (a) Case of 500 and (b) Case of 1,000 Times of Tool Operations per Day

3.2 Phase 2: ISO 10819 Glove Assessment

The verifications and results of the developed ISO 10819-based glove test system and adapters, as well as the VR characteristics of nine commercially available gloves, are presented in this section.

3.2.1 Test System Verification

Figure 32 shows the verification of the test system. The green line represents an expected output, while the other lines represent the measurements using the LDV. There were slight variations at the low frequency end (around 32 Hz) but, overall, the handle followed the ISO 10819 spectrum. This proved that the shaker controller and measurement system were functioning adequately.

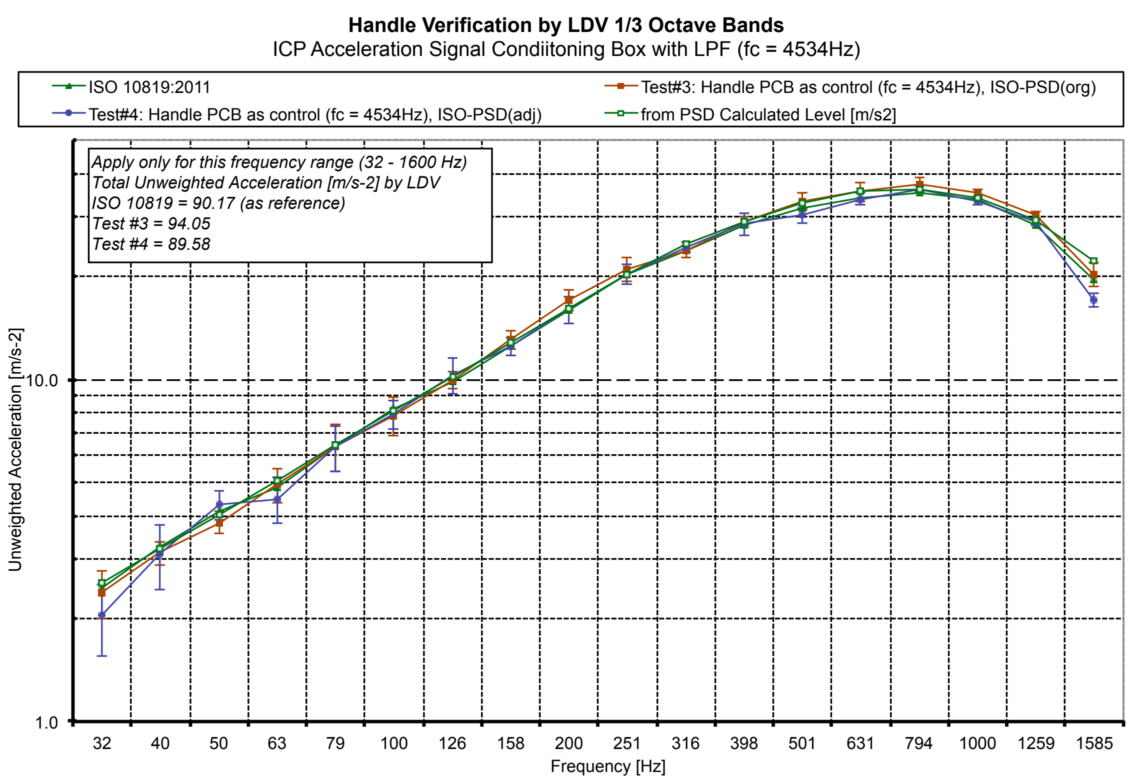


Figure 32: Handle Verification by LDV and Checking of ISO-PSD Values

3.2.2 Palm and Finger Adapter Evaluation

The newly developed 3D-printed ISO 10819 palm and finger adapters were evaluated in preliminary tests and were shown to meet the ISO 10819 specified criteria (i.e., TR between 0.95 and 1.05). They were also shown to meet the ISO 10819 criteria in the actual subject tests. Figure 33 shows the typical transmissibilities of the palm and finger adapter, which were obtained independently from the ISO 10819 bare adapter test method.

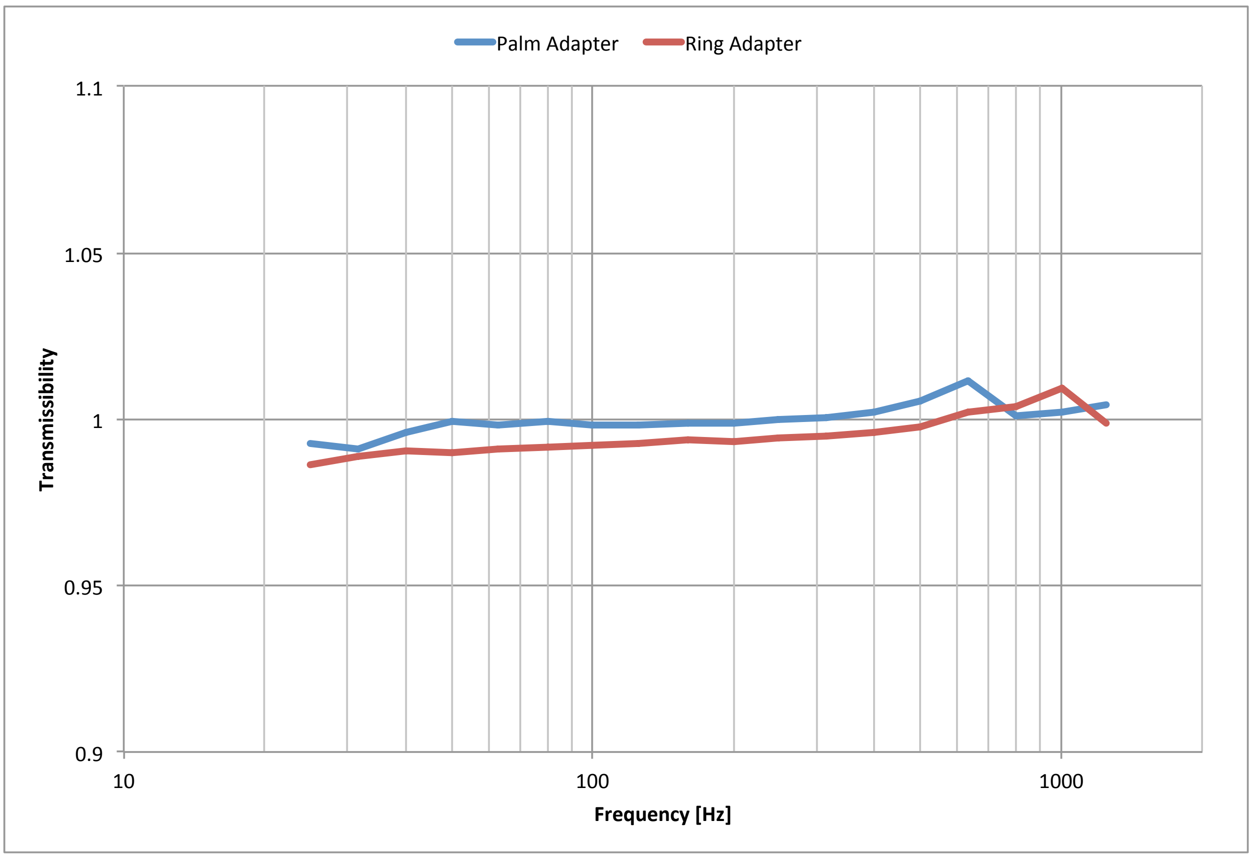


Figure 33: Typical Transmissibility Spectra of Both Palm and Finger Adapters

3.2.3 ISO 10819 Glove Assessment

Table 10a and 10b show overall results of the ISO 10819 glove evaluations and the additional finger transmissibility evaluations, where the blue (pass) and red (fail) colored cells indicate the pass-fail conditions based on the ISO 10819 guidelines. There is no assessment of finger transmissibility in ISO 10819 and so no pass-fail condition was applied to the results in Table 10b. Figure 34 shows both palm and finger transmissibility spectra of all tested gloves using Method 1 (i.e., transmissibility between Z_{handle} and Z_{palm} or a_{finger}) and the detailed glove transmissibility spectra, as well as the standard deviation and coefficient of variation, are presented in Appendix B.

As seen in Figure 34(a), most of VR gloves (Gloves 1, 2, 3, and 8) showed vibration attenuation characteristics of lower than a transmissibility of 1.00 in palm, while the rubber-coated working gloves (Gloves 5, 6, and 7) showed slight vibration amplification in higher frequency range above 500 Hz. On the other hand, several gloves (Glove 2, 3, and 8) showed that the finger transmissibility results indicated large amplification around 100 Hz in Figure 34(b). Figures 35 and 36 show individual VR glove (Glove 1 and 3) results, where, for the palm transmissibilities as seen in the Figures 35(a) and 36(a), the transmissibility profiles show that these two gloves attenuated the entire frequency range and especially more so in higher frequency range. In addition, especially as seen in Figures 35(b) and 36(b), finger transmissibility results showed some variations within the subjects.

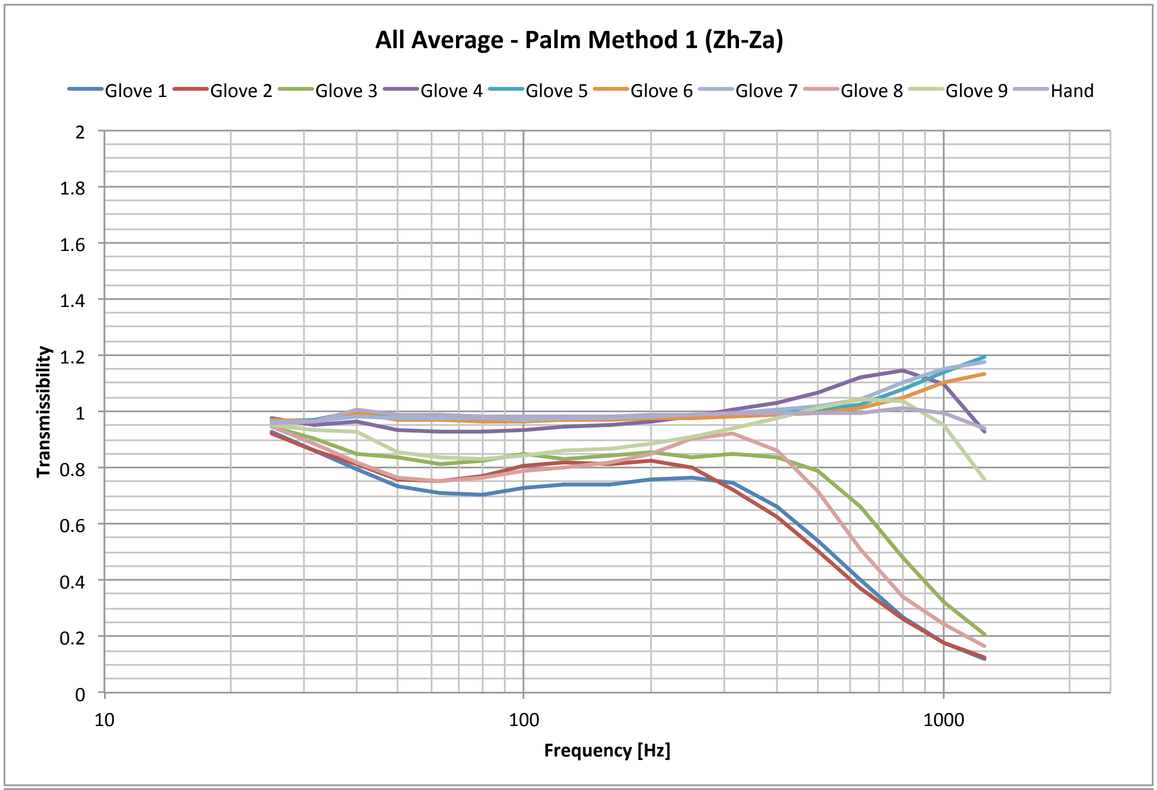
Table 10a. Overall Results for Palm Transmissibility of Gloves in ISO 10819:2011-Specified M and H Ranges (blue color indicates pass the ISO 10819:2011 and red color indicates fail; PA is Palm and M1 is Method 1)

	M (25 - 200 Hz), Pass: ≤ 0.90					H (200 - 1250 Hz), Pass: ≤ 0.60				
PA-M1	Max	Min	Mean	S.D.	C.V.	Max	Min	Mean	S.D.	C.V.
Glove 1	0.850	0.683	0.764	0.059	0.077	0.744	0.527	0.664	0.062	0.094
Glove 2	0.885	0.744	0.810	0.044	0.055	0.893	0.562	0.670	0.081	0.121
Glove 3	0.948	0.715	0.851	0.077	0.090	0.995	0.502	0.797	0.162	0.203
Glove 4	0.972	0.897	0.947	0.020	0.021	1.121	0.979	1.028	0.041	0.040
Glove 5	0.987	0.959	0.977	0.008	0.008	1.028	0.973	1.004	0.014	0.014
Glove 6	0.982	0.939	0.971	0.010	0.011	1.011	0.969	0.993	0.011	0.011
Glove 7	0.990	0.949	0.976	0.010	0.010	1.047	0.994	1.012	0.015	0.015
Glove 8	0.881	0.529	0.813	0.083	0.102	0.967	0.488	0.805	0.102	0.126
Glove 9	0.938	0.794	0.876	0.042	0.048	1.033	0.818	0.954	0.056	0.059
Hand	1.010	0.945	0.984	0.015	0.015	1.071	0.933	0.992	0.030	0.030
PA-M2	Max	Min	Mean	S.D.	C.V.	Max	Min	Mean	S.D.	C.V.
Glove 1	0.913	0.747	0.832	0.057	0.068	0.831	0.577	0.744	0.067	0.090
Glove 2	0.943	0.781	0.871	0.042	0.049	1.014	0.642	0.767	0.109	0.142
Glove 3	0.981	0.806	0.905	0.059	0.065	0.999	0.635	0.840	0.122	0.145
Glove 4	1.035	0.974	0.994	0.017	0.017	1.121	1.003	1.058	0.033	0.031
Glove 5	1.062	1.011	1.022	0.013	0.012	1.032	0.993	1.004	0.010	0.010
Glove 6	1.039	1.000	1.019	0.011	0.011	1.012	0.987	0.996	0.007	0.007
Glove 7	1.062	1.003	1.025	0.017	0.016	1.075	0.987	1.017	0.023	0.022
Glove 8	0.936	0.678	0.882	0.062	0.070	1.021	0.660	0.873	0.086	0.098
Glove 9	0.976	0.887	0.944	0.024	0.025	1.067	0.917	1.009	0.040	0.040
Hand	1.081	1.018	1.038	0.020	0.019	1.101	0.980	1.002	0.031	0.031
PA-M3	Max	Min	Mean	S.D.	C.V.	Max	Min	Mean	S.D.	C.V.
Glove 1	0.866	0.720	0.798	0.049	0.061	0.835	0.579	0.748	0.067	0.090
Glove 2	0.897	0.755	0.840	0.039	0.046	1.020	0.645	0.771	0.110	0.143
Glove 3	0.941	0.783	0.869	0.055	0.063	1.003	0.638	0.844	0.123	0.145
Glove 4	0.973	0.936	0.955	0.012	0.013	1.127	1.008	1.062	0.033	0.031
Glove 5	0.992	0.975	0.983	0.006	0.006	1.035	0.998	1.009	0.010	0.010
Glove 6	0.989	0.972	0.979	0.005	0.005	1.016	0.992	1.001	0.007	0.007
Glove 7	0.992	0.969	0.979	0.008	0.008	1.079	0.991	1.021	0.022	0.022
Glove 8	0.899	0.660	0.853	0.058	0.068	1.027	0.663	0.878	0.087	0.099
Glove 9	0.947	0.878	0.921	0.020	0.021	1.073	0.922	1.016	0.040	0.040
Hand	1.030	0.998	1.009	0.007	0.007	1.108	0.984	1.007	0.031	0.031

Table 10b. Overall Results for Finger Transmissibility of Gloves in ISO 10819:2011-Specified M and H Ranges (FA is Finger and M1 is Method 1)

	M (25 - 200 Hz)					H (200 - 1250 Hz)				
FA-M1	Max	Min	Mean	S.D.	C.V.	Max	Min	Mean	S.D.	C.V.
Glove 1	1.100	0.846	0.982	0.086	0.087	0.976	0.574	0.775	0.125	0.162
Glove 2	1.266	0.851	1.070	0.130	0.121	0.840	0.477	0.673	0.103	0.153
Glove 3	1.367	0.891	1.136	0.151	0.133	0.844	0.457	0.653	0.115	0.177
Glove 4	1.025	0.976	1.006	0.015	0.015	1.010	0.879	0.955	0.044	0.046
Glove 5	1.122	0.977	1.025	0.033	0.033	1.003	0.725	0.918	0.082	0.090
Glove 6	1.113	0.964	1.020	0.038	0.037	0.967	0.742	0.897	0.074	0.082
Glove 7	1.068	0.949	1.015	0.030	0.029	1.023	0.830	0.945	0.068	0.071
Glove 8	1.353	0.894	1.131	0.164	0.145	0.672	0.320	0.526	0.106	0.202
Glove 9	1.015	0.927	0.967	0.030	0.031	1.017	0.779	0.947	0.062	0.066
Hand	1.028	0.800	0.966	0.056	0.058	1.001	0.735	0.943	0.068	0.072
FA-M4	Max	Min	Mean	S.D.	C.V.	Max	Min	Mean	S.D.	C.V.
Glove 1	1.080	0.821	0.963	0.089	0.092	0.977	0.574	0.776	0.125	0.162
Glove 2	1.241	0.832	1.051	0.128	0.122	0.841	0.477	0.674	0.103	0.153
Glove 3	1.331	0.876	1.119	0.150	0.134	0.845	0.457	0.654	0.115	0.177
Glove 4	1.004	0.932	0.985	0.022	0.022	1.010	0.880	0.956	0.044	0.046
Glove 5	1.096	0.916	1.006	0.038	0.037	1.004	0.726	0.920	0.083	0.090
Glove 6	1.099	0.930	1.001	0.044	0.044	0.968	0.743	0.899	0.074	0.082
Glove 7	1.041	0.887	0.993	0.043	0.044	1.024	0.831	0.946	0.068	0.072
Glove 8	1.324	0.878	1.115	0.159	0.143	0.672	0.321	0.527	0.106	0.202
Glove 9	1.001	0.898	0.950	0.031	0.033	1.018	0.780	0.948	0.063	0.066
Hand	1.015	0.763	0.956	0.062	0.065	1.003	0.736	0.944	0.068	0.072

a)



b)

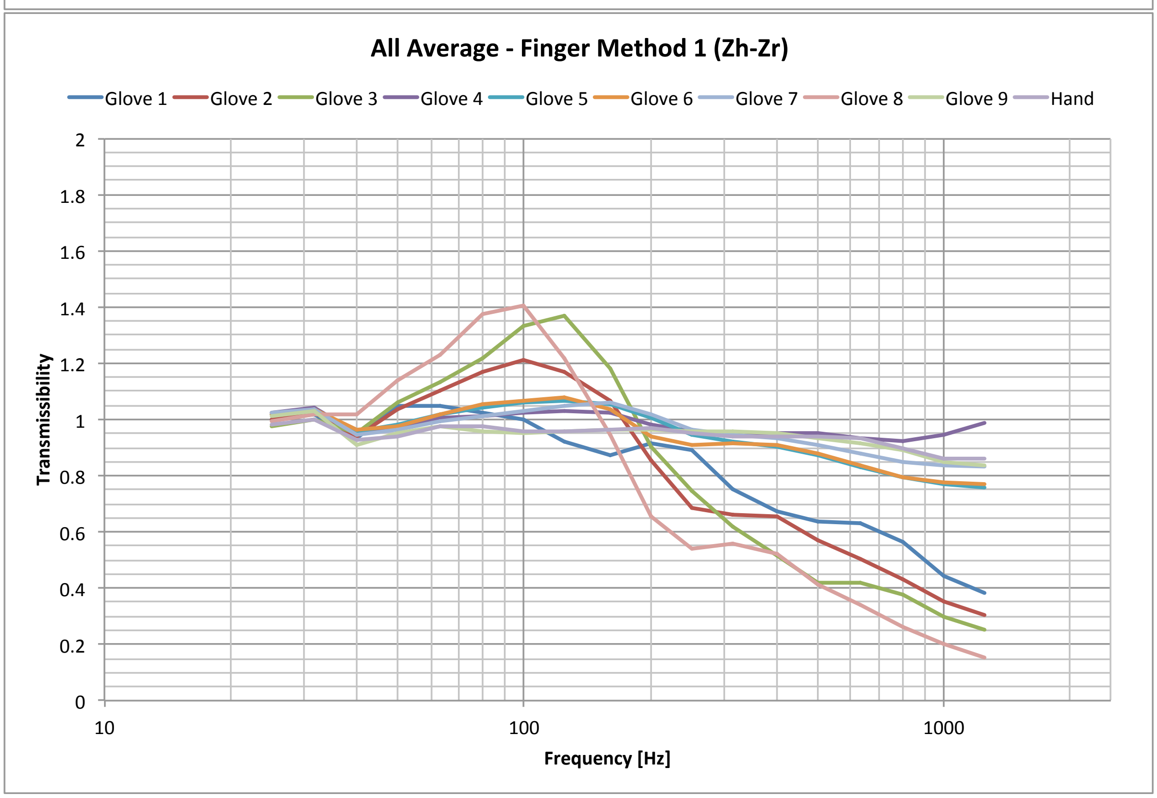


Figure 34: All Average Evaluated Glove Transmissibility Spectra (Method 1): (a) Palm Transmissibility and (b) Finger Transmissibility

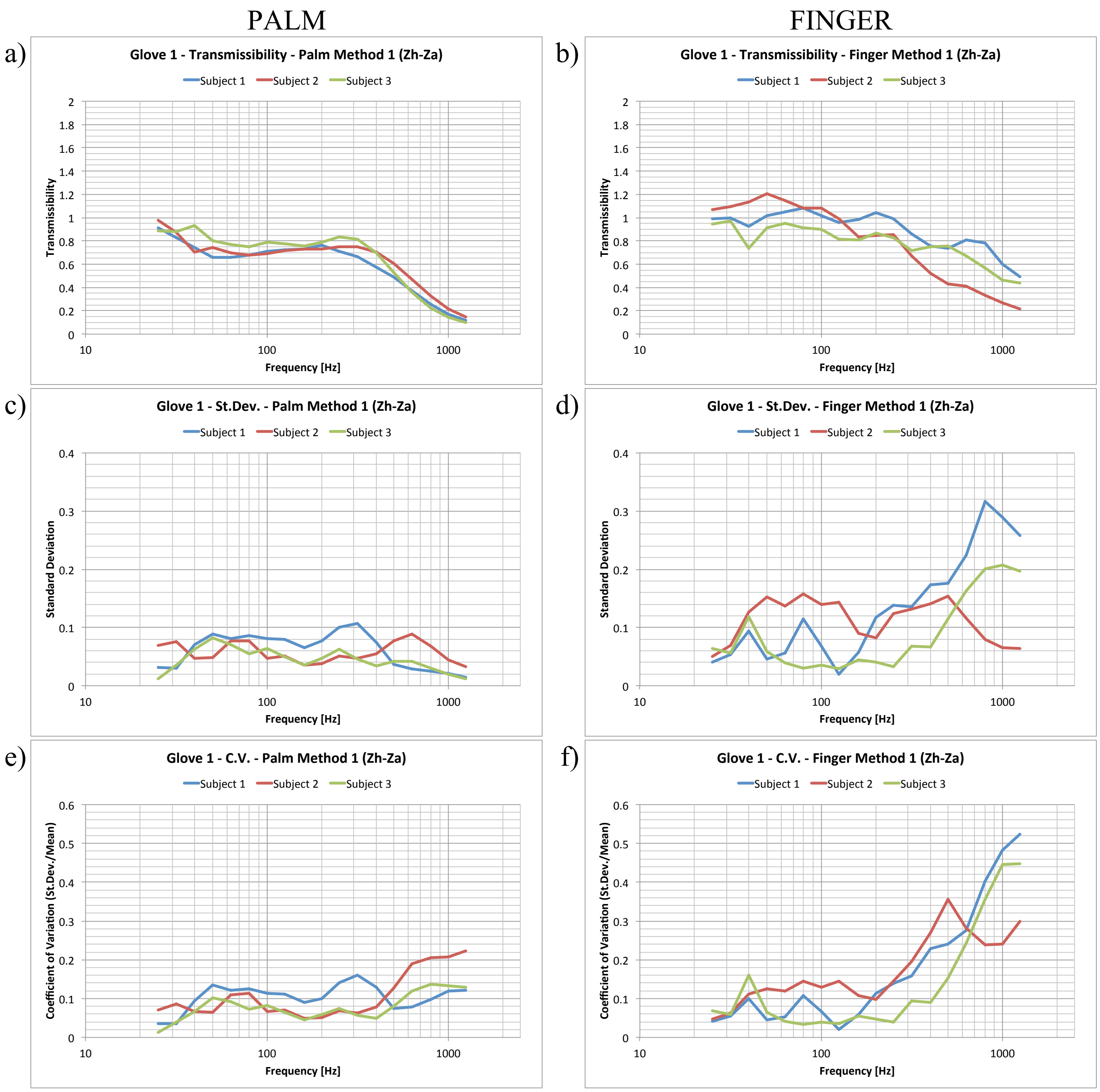


Figure 35: Example Glove 1 Transmissibility Spectra (Method 1):
Average of (a) Palm Transmissibility and (b) Finger Transmissibility
Standard Deviation of (c) Palm and (d) Finger Transmissibilities
Coefficient of Variation of (e) Palm and (f) Transmissibilities

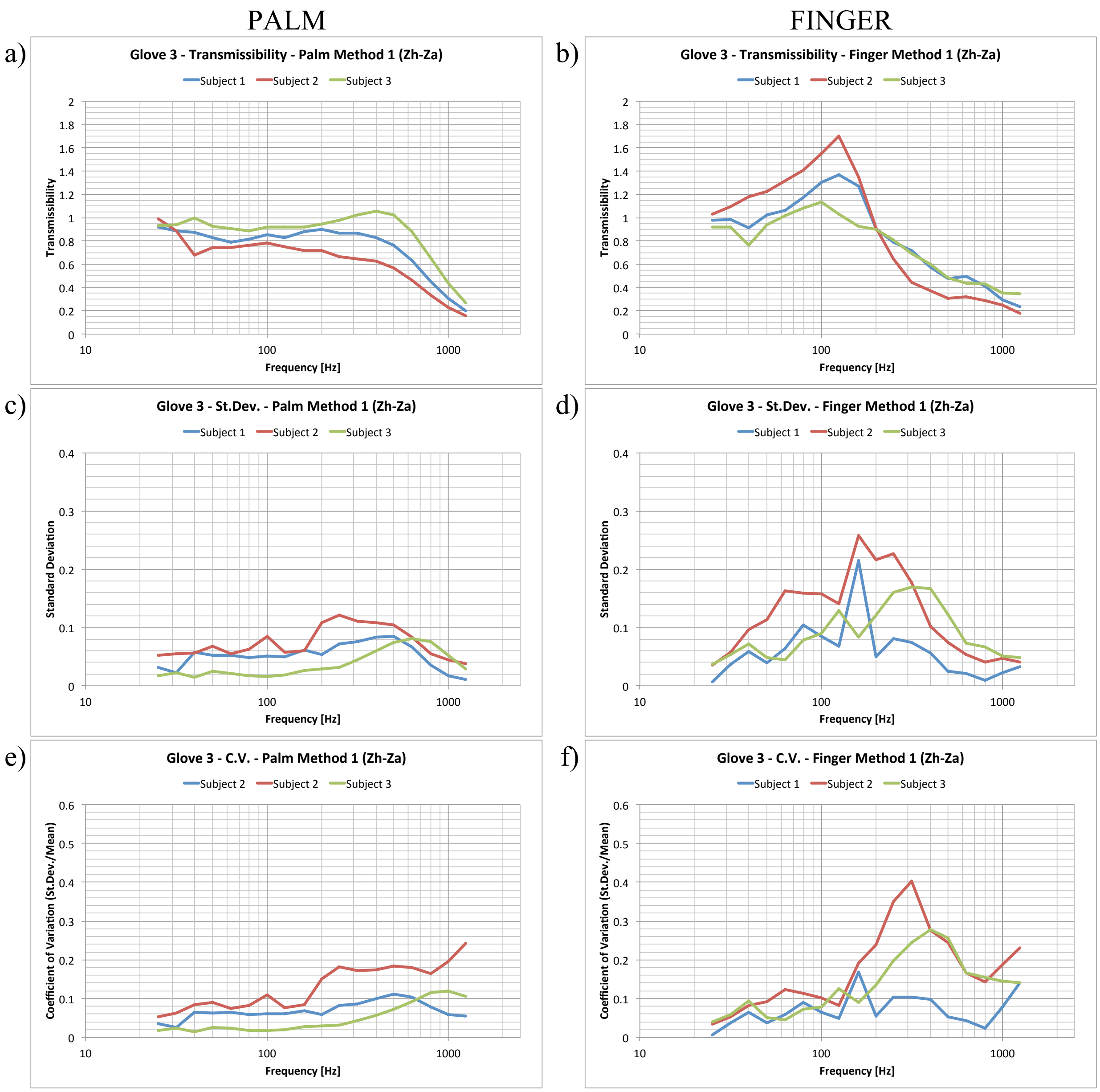


Figure 36: Example Glove 3 Transmissibility Spectra (Method 1):
Average of (a) Palm Transmissibility and (b) Finger Transmissibility
Standard Deviation of (c) Palm and (d) Finger Transmissibilities
Coefficient of Variation of (e) Palm and (f) Transmissibilities

3.3 Phase 3: Additional Experiments and Glove Selection

In order to consider the selection of a tool-specific VR glove, additional experiments were conducted and the results of which are presented in this section. In addition, newly introduced percent reductions of expected vibration exposures of gloved hands using previously obtained power tool vibrations (from Phase 1) and VR glove transmissibility (from Phase 2) spectra are also presented in this section.

3.3.1 Replace Excitation Spectrum and Glove Transmissibility

Glove transmissibility was also obtained by changing the vibration excitation spectra without modifying the ISO 10819 calculation protocols, where the ISO 10819, flat, and averaged riveter PSD spectra were used as shown in Figure 37. The glove transmissibility assessments were conducted on one subject and two gloves (Glove 1 and Glove 3) in this study and each glove was tested only once. There were also no repetitions in there measurements.

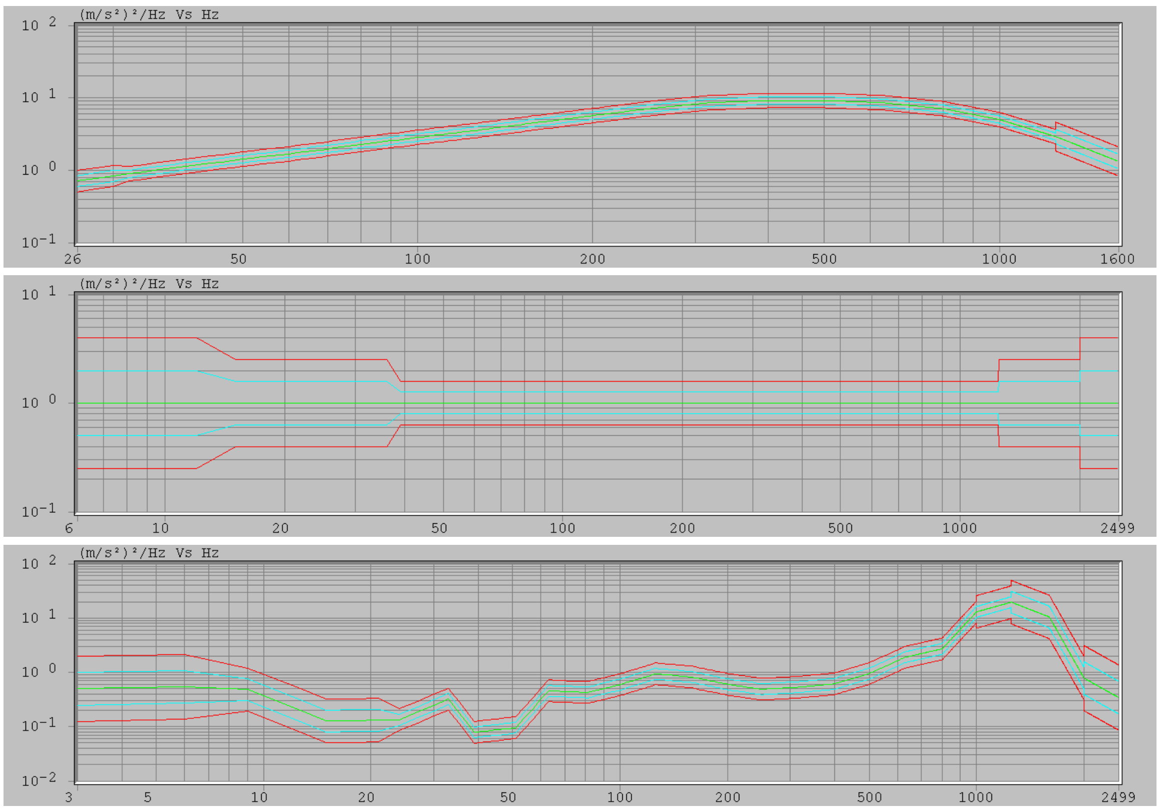
a)
b)
c)


Figure 37: Vibration Excitation Spectra:
(a) ISO 10819:2011, Total 91.428 m/s2 r.m.s., 25-1,600 Hz,
(b) Flat Spectrum, Total 50 m/s2 r.m.s., 6.5-2,000 Hz, and
(c) Average Riveter, 118.873 m/s2 r.m.s., 3-1600 Hz

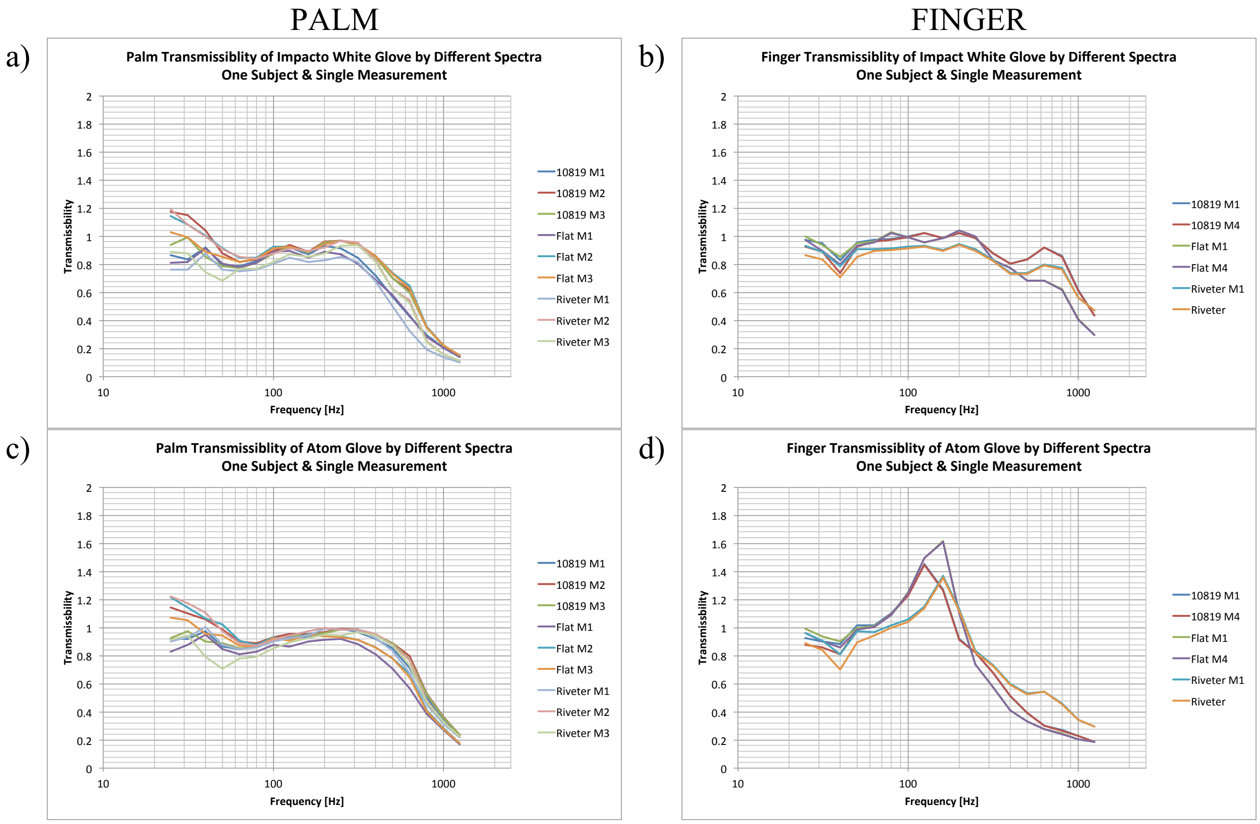


Figure 38: Transmissibility Spectra on Palm and Finger Under Different Excitations: (a) Palm and (b) Finger of Glove 1 Transmissibilities, (c) Palm and (d) Finger of Glove 3 Tranmissibility (M1 implies as Method 1)

The results are shown in Figures 38(a) and 38(c) and are reasonably consistent at the palm. The finger transmissibility of Glove 3 in Figure 38(d) displayed considerable variability between 100 and 200 Hz, even though the results show similar overall transmissibility profiles.

3.3.2 Material Damping Tests

In this section, several different testing combinations were examined. At first, the transmissibility of one of the VR gloves was obtained when the glove was held by a tourniquet at 80 N under the different vibration excitations (Figure 39). It has to be noted that the glove and palm adapter were held by the tourniquet without out changing any physical configurations during the experiment as the different vibration spectra were generated. Reference to Figure 39 shows that the transmissibility was only slightly dependent on the input excitation vibration spectrum, except at frequencies below 60 Hz.

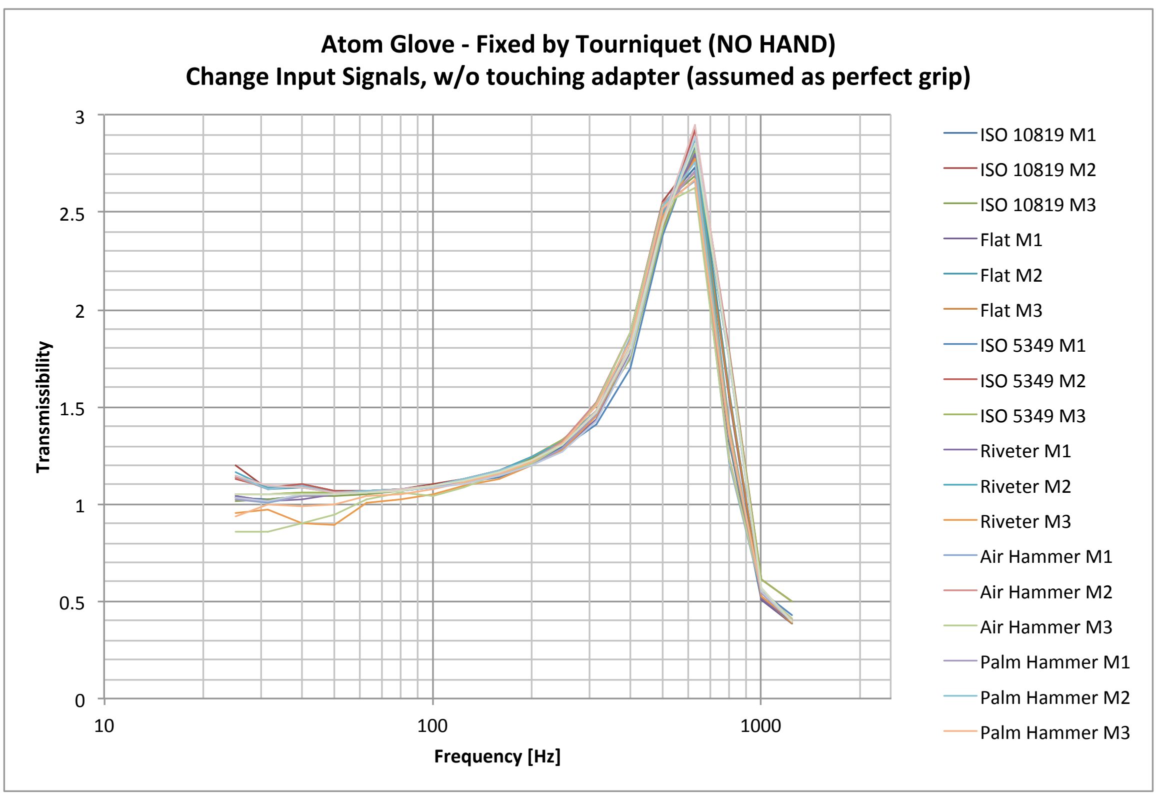


Figure 39: Held by Tourniquet with Different Excitations

Next, maintaining one vibration excitation (i.e., ISO 10819 spectrum), several gloves were held by tourniquet at various forces (i.e., 30N, 50N, and 80N) and the glove transmissibility

spectra were obtained (Figure 40). Although the measurement conditions of Figures 39 and 40(b) were technically the same for one glove with the application at 80 N of wrapping force and the same excitation spectrum, it should be noted that the transmissibility profiles in Figures 39 and 40(b) were different. Even though the experiments were conducted under highly controlled laboratory conditions, this was due to differences in the glove location on the instrumented handle and the wrapping of the tourniquet. It should also be noted that the maximum transmissibility depended significantly on the wrapping force for some gloves, as seen in Figures 40(a) and 40(d).

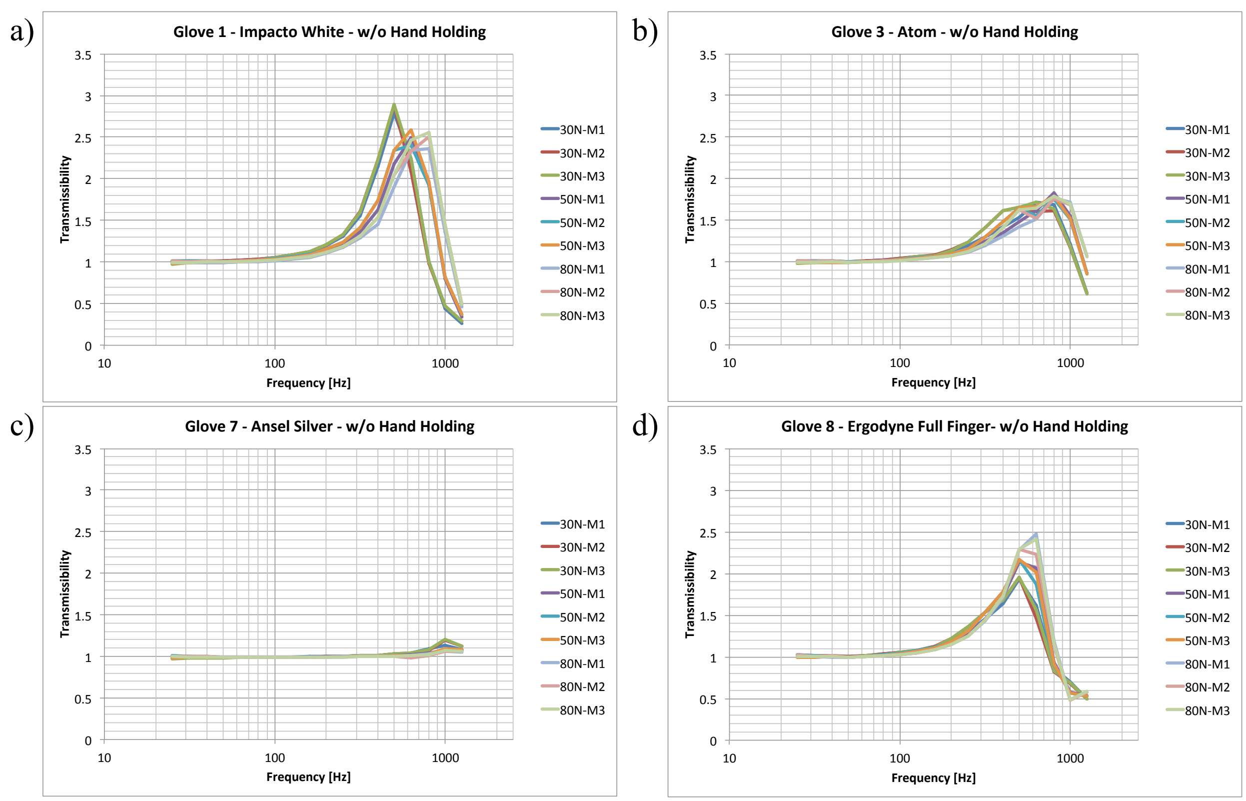


Figure 40: Maintaining Same Excitation with Changing Wrapping Force
(a) Glove 1, (b) Glove 3, (c) Glove 7, and (d) Glove 8

Lastly, one material, which was expected to demonstrate similar transmissibility behavior to Glove 1, was selected from a pool of several different damping materials and Figure 41 shows the material transmissibility under the different loading conditions.

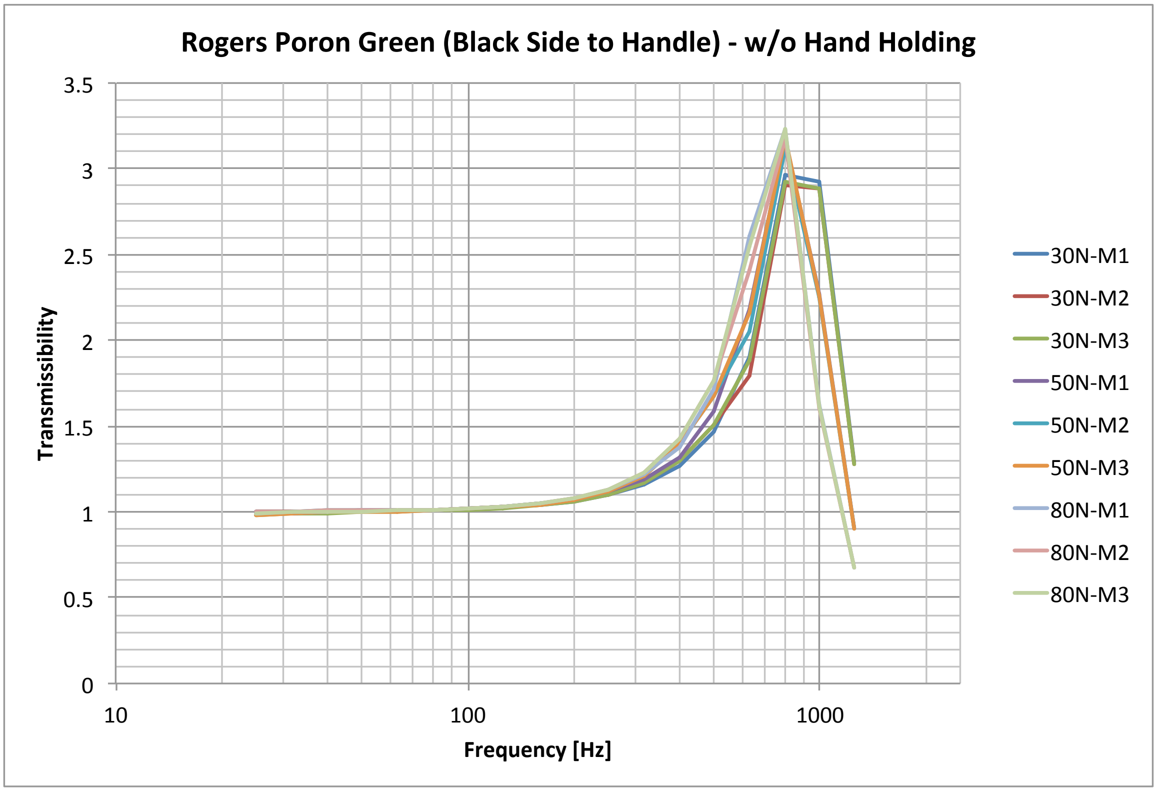


Figure 41: Damping Material Transmissibility under Different Loading Conditions Held by Tourniquet with 30 N, 50 N, and 80 N Forces

As expected, the results show a similar transmissibility profile to that of Glove 1 as can be seen by comparing Figures 40(a) and 41. The one-layer and double-layer materials were hand held and their transmissibility spectra are shown in Figure 42(a). In addition, this experiment was also conducted while wearing a regular working glove and gripping the material with resalts shown in Figure 42(b). The test conditions of ISO 10819 (i.e., grip 30 N, push 50 N, 30 seconds of averaging) were used here, since this test involved a human hand.

a) b)

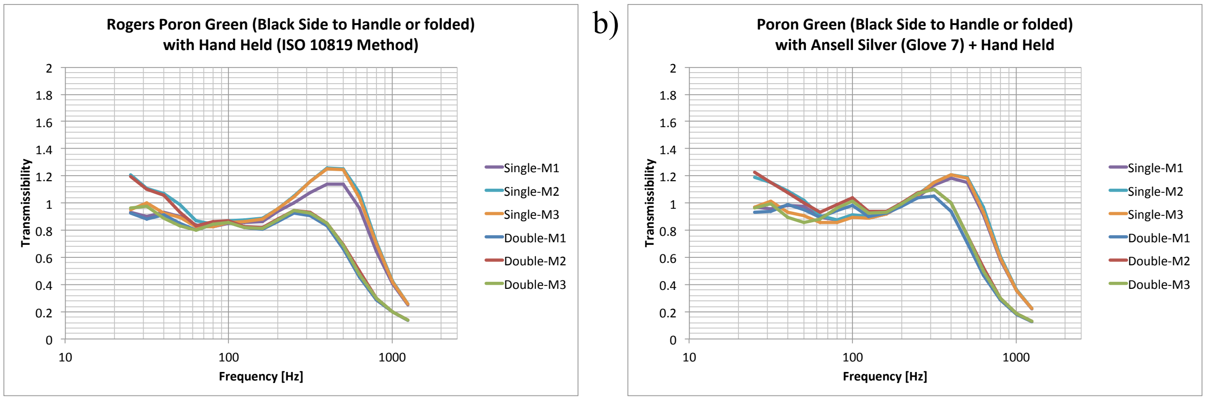


Figure 42: One- and Double-Layer Damping Material Transmissibility Spectra
(a) Held by Hand and (b) Held by Gloved Hand

3.3.3 LTI System Based Glove Reduction Assessment

Based on the results from the previous experiments, it is clear that the VR glove transmissibility behavior fairly complies with the concepts of a Linear Time-Invariant (LTI) system. Therefore, previously obtained ISO 5349-based tool vibration spectra could be combined with ISO 10819-based glove transmissibility spectra to estimate the vibration exposure of a gloved hand. An example of this new technique using UW and W reduction percentage of particular tools, is presented in Figure 41 and detailed results can be found in Appendix C. Using this new method developed in this dissertation, a LabVIEW program was created as seen in Figure 44.

The results presented in Figure 41 show the VR glove effectiveness of Glove 1 and Glove 3 for the helicopter tools presented in this dissertation. When blue and red bars extend to the positive side (i.e., the right hand side of 0 %), the glove is expected to better attenuate tool vibration exposures. On the other hand, when the bars extend to negative side (i.e., the left hand side of 0 %), the glove is expected to amplify tool vibration exposures. Figures 43(a) and 43(c) show that the VR glove attenuates any tool vibrations in both the palm and fingers for the

unweighted tool vibrations; however, Figures 43(b) and 43(d) show that, depending on the tools, the VR glove may attenuate vibration in the palm but not in the fingers.

3.3.4 Creation of Glove Selection Tool

The newly proposed percent reduction of vibration exposure with a gloved hand can be easily determined by multiplying by each frequency values; however, it involves repeated arithmetic. Therefore, an intuitive computer program was created and its graphical user interface (GUI) can be seen in Figure 44. Because the program was developed in the LabVIEW environment, all operations can be done in the intuitive GUI through simple mouse clicks and minimum keyboard operations. When the one-third-octave tool vibration spectrum and VR glove transmissibility are inputted, the program displays the total weighted and unweighted tool exposure values, as well as the expected W and UW exposure values for values for a gloved hand.

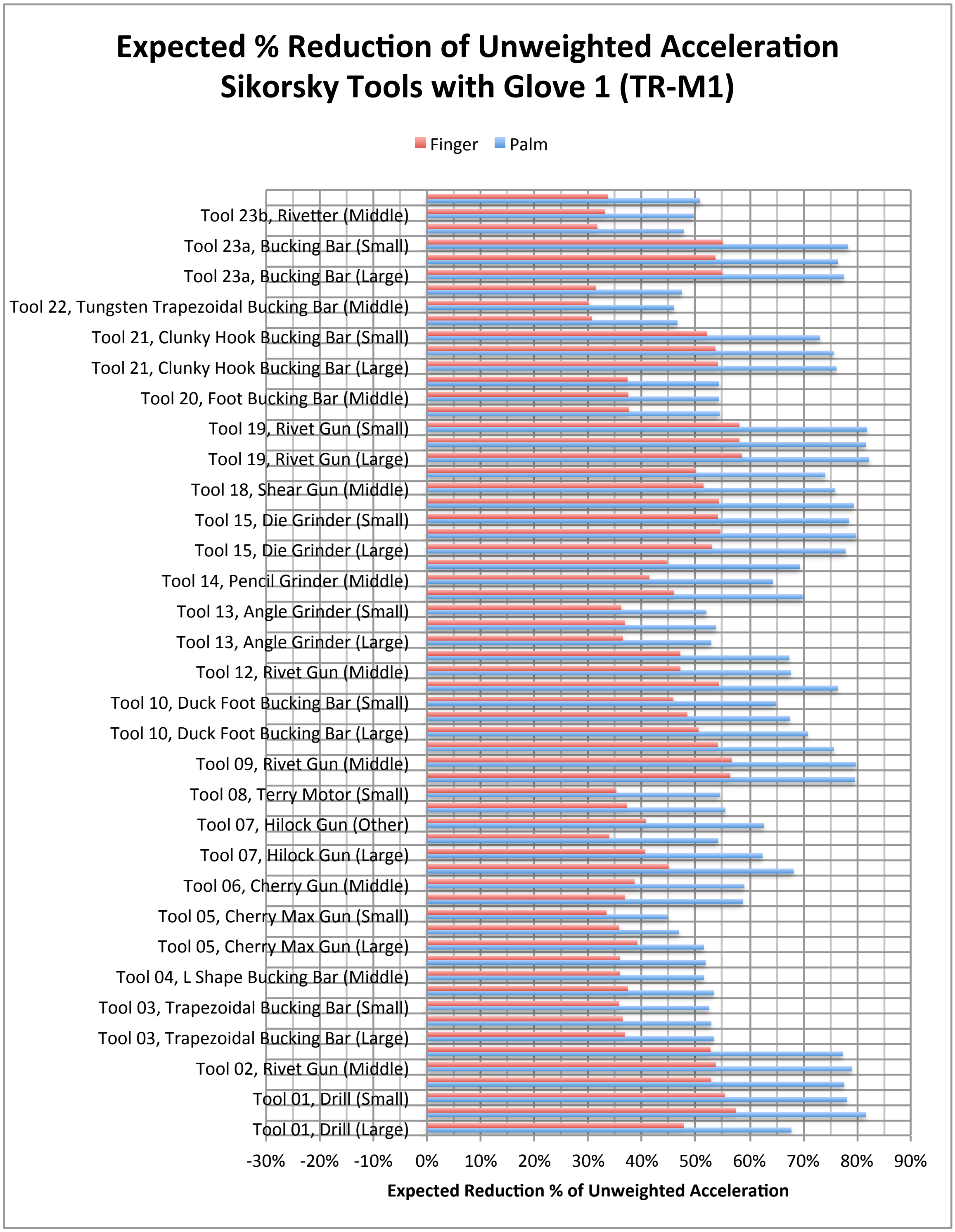


Figure 43(a): Expected Frequency-Unweighted Reduction Percentage of Glove 1 with Helicopter Factory Tools and Using ISO 10819-Based Method 1 Transmissibility

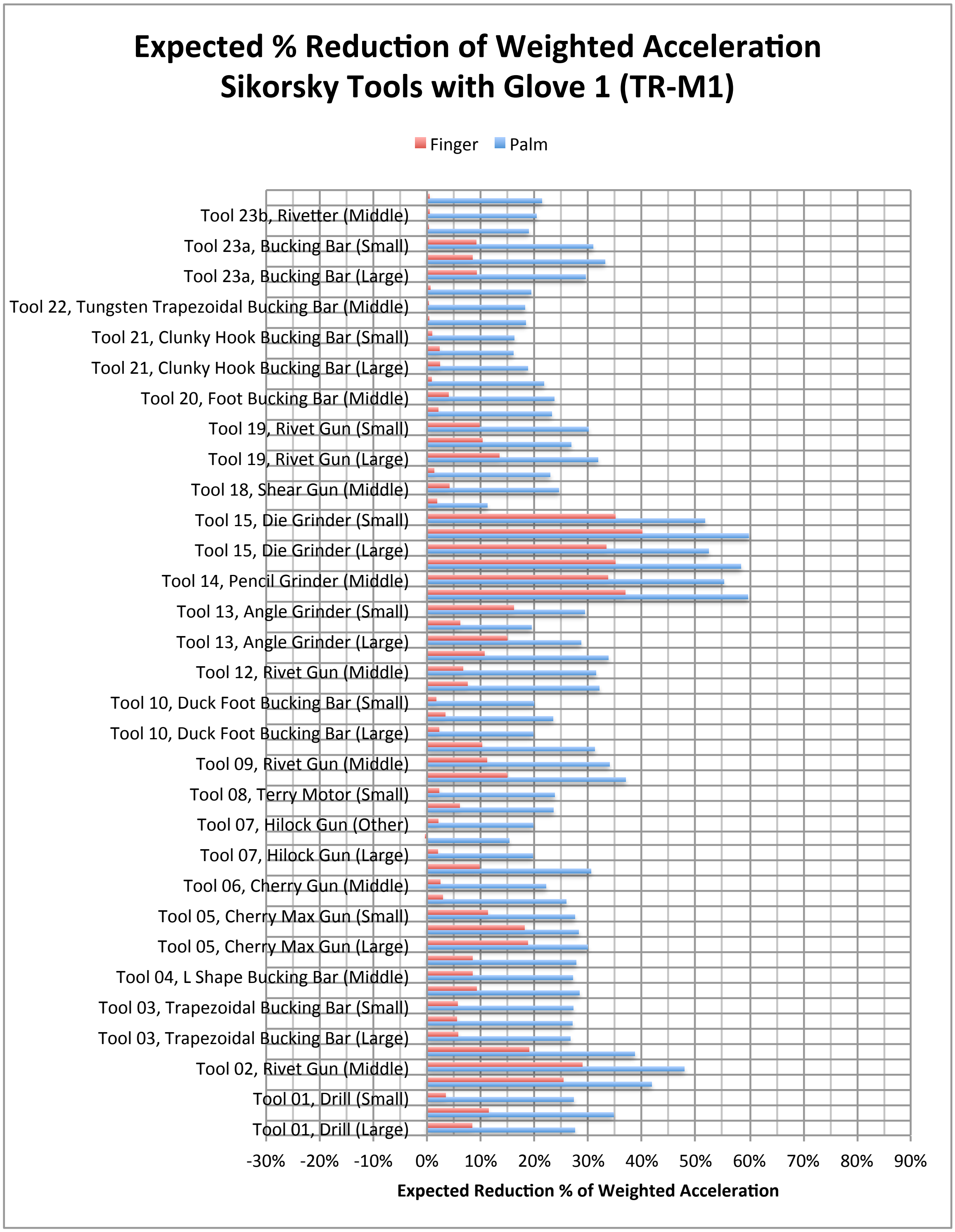


Figure 43(b): Expected Frequency-Weighted Reduction Percentage of Glove 1 with Helicopter Factory Tools and Using ISO 10819-Based Method 1 Transmissibility

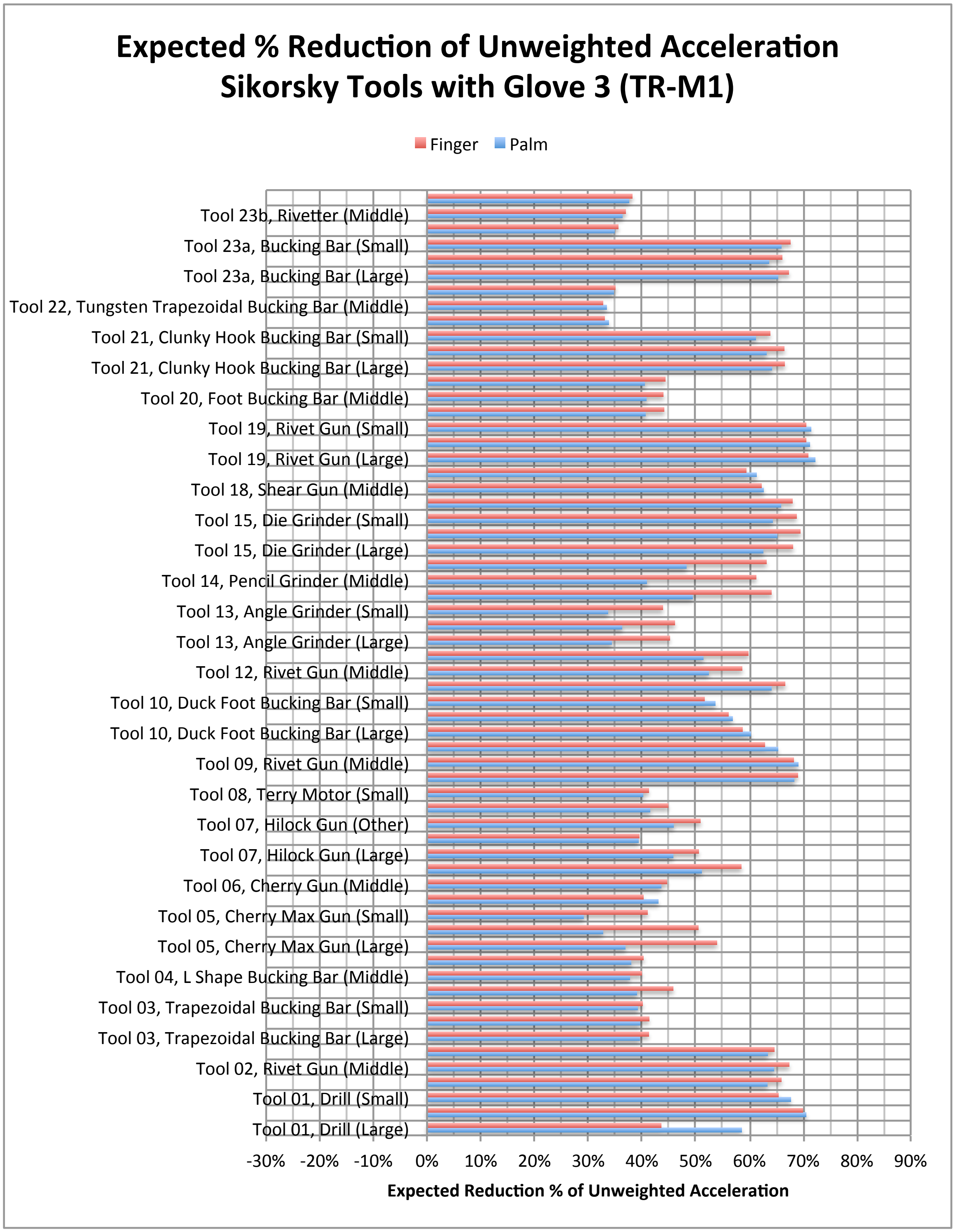


Figure 43(c): Expected Frequency-Unweighted Reduction Percentage of Glove 3 with Helicopter Factory Tools and Using ISO 10819-Based Method 1 Transmissibility

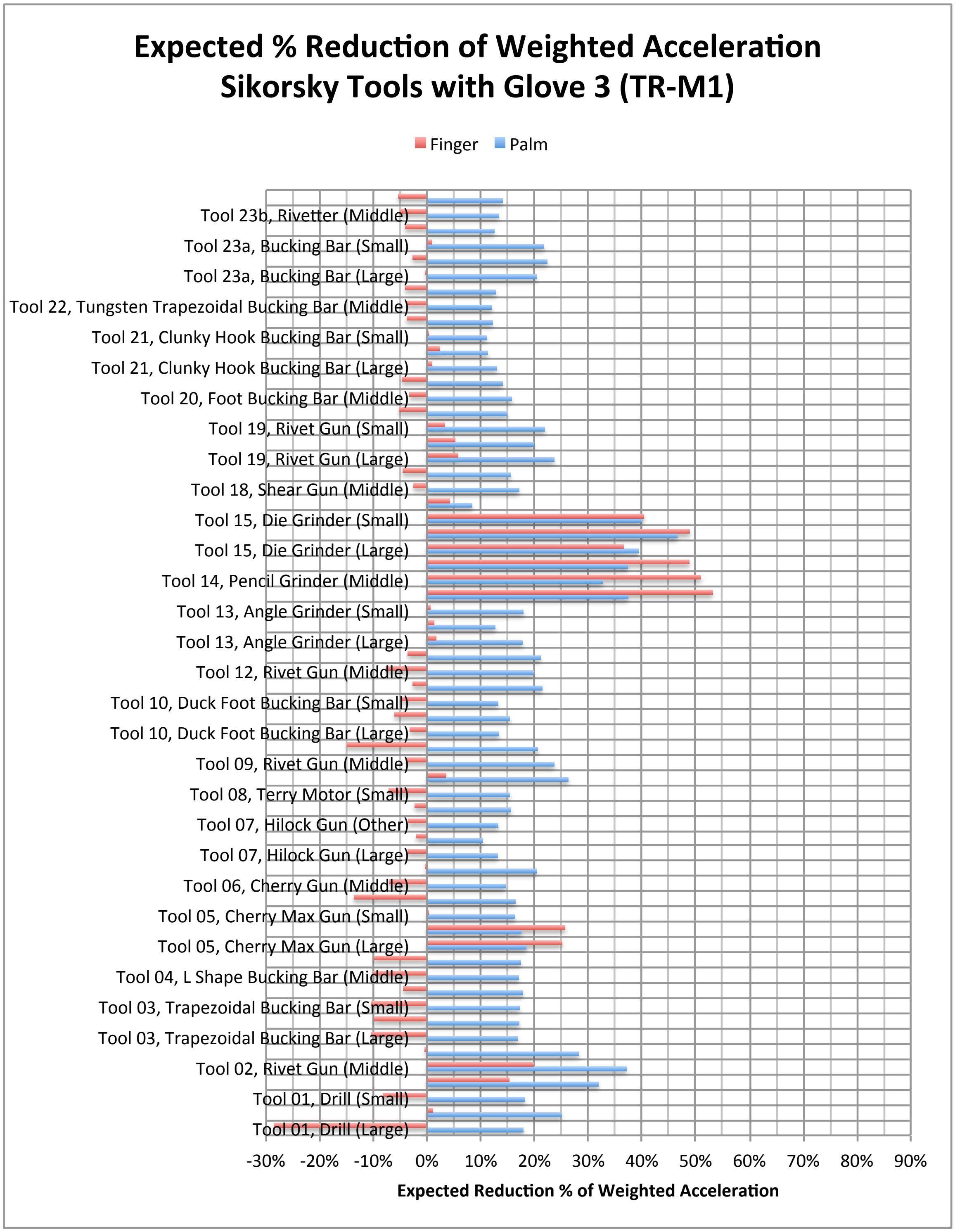


Figure 43(d): Expected Frequency-Weighted Reduction Percentage of Glove 3 with Helicopter Factory Tools and Using ISO 10819-Based Method 1 Transmissibility

4. Discussion

In brief, this section is the discussion of the three phases and is based on the previously presented results. It is important to note that the first two phases were analyzed based on the current ISO 5349 and 10819 standards, which are commonly assumed to be straightforward to a potential user. In these two phases, the field tool measurements and glove assessments involved many specifications and processes defined in the standards; however, the potential misreading of the ISO documents could easily cause the creation of incompatible data, especially when considering study results from different international research teams. Lastly, in order to determine tool-specific VR glove selections, the Linear Time-Invariant (LTI) system theory was used to calculate the reduction percent of vibration exposures of gloved hands and is discussed in this section. In this phase, the reduction percent is introduced as a tool to evaluate and identify tool-specific vibration-reducing (VR) glove at any given worksite and for any given work task.

4.1 Phase 1: Tool Vibration Assessment

Based on the power tool vibration measurements at two worksites, approximately 35 tool vibrations from different work tasks were assessed based on ISO 5349. All of the tool vibrations were translated from time-domain to frequency-domain information, which enables the determination of the power tool vibration characteristics, especially their frequency content and levels. In order to understand the hand-arm vibration (HAV) exposures more precisely, the tool vibration information in the frequency-domain is highly beneficial.

4.1.1 Accelerometer Adapter for Bucking Bar Vibration Measurement

As seen in Figure 17, the adapter response was nearly flat from 16.0 Hz to 2.0 kHz, and the response increased to reach a resonance peak between 5.0 and 9.0 kHz. A similar phenomenon was observed for all adapter faces (or axes) and, according to ISO 5349 (ISO, 2001), it was concluded that the adapter was suitable for ISO-based hand-arm vibration measurements, since the adapter had a resonance of approximately 7.0 kHz. The ISO 5349 frequency weighting curve, which suppresses higher frequency components, indicates that this adapter resonance will not influence the weighted acceleration values.

Bucking bar or riveter vibrations can be considered as "bursts of tool operation" in ISO 5349-2 Annex E.2.4 (ISO, 2001). Without recognizing such impulsive or percussive vibration patterns, vibration exposure times could be easily miscalculated. Therefore, depending on how the data is analyzed, bucking bar vibration exposure can be categorized from no risk to harmful health risk, which demonstrates that a misinterpretation of ISO 5349 could yield significantly different results. Thus, vibration exposure assessment needs to be analyzed carefully and thoughtfully.

4.1.2 Power Tool Vibration Characteristics

In this study, about 35 different tool vibrations were captured from two different manufacturing facilities and analyzed for their vibration characteristics. Because the measurement strictly followed ISO 5349 and ISO 8041, frequency-weighted total vibration values were expected to be generated; however, the overall frequency spectra, as well as each axial vibration spectrum, raised many different considerations.

In referencing Figures 6, 7, and 8 in the section 2.1.3 and Figures 18 through 29 in the section 3.1.2 and given that ISO 5349-2 recommends possible accelerometer mounting locations and provides HAV measurement specifications, it can be seen that power tool vibration measurements conducted at the two different facilities in this dissertation were very complex. For example, ISO 5349-2 recommends accelerometer placement to be generally at the middle part of the hand grip; however, some smaller-size pistol grip power tool (as seen in Figure 18(a)) had no space to place the shock-ready accelerometers in the middle of the grip surface. In addition, the hand size of the factory workers was generally larger than average and easily covered the tool handle surface. Therefore, the accelerometer was placed at the side of tool body, which might not represent the true HAV exposure levels even though it was still possible to characterize tool frequency content.

Some tool spectra showed noticeably higher frequency contents (e.g., see Figures 18(c) and 19(c)), which were assumed to be the tool operating frequencies. Furthermore, the spectrum of Figure 18(c) did not have a large peak in the lower frequency region when compared to the spectrum of Figure 19(c). It was speculated that one-handed or two-handed tool operations may be influencing the characteristics of the tool vibration. This highlights several considerations to be noted. Two-handed tool operation adds more biodynamic mass to the tools and may change tool resonance. In addition, two-handed tool operation induced a slower arm swing motion to the tool use, which may be captured as low frequency tool vibration. Similarly, the screw gun spectrum (Figure 26(c)) had a large peak in the low frequency range (around 20 Hz), which could have been introduced by an awkwardly extended arm swaying as the screw was set into position. Moreover, lower vibration components may originate from prolonged tool tip vibrations. Because this study recorded not only the vibration waveforms, but also pictures of

power tool use in actual working conditions, it was possible to obtain a further understanding of the power tool operations and its vibrations.

It is believed that as fundamental assumption of ISO 5349-2, if a tool has one-handle, then the operation is done by one-hand, while two-handled power tools are operated by two-hands. However, during power tool vibration measurements in the two facilities, it was observed that one-handed tool operations were done by either two hands or one hand, as seen in Figures 19(b), 21(b), 24(b), and 27(b). In particular, upside down tool operation was observed to be done with two-hands as can be seen in Figure 24(a). Adding secondary weight to the tool via the second hand could significantly change the vibration of the tool from its free run state, where more vibration is attenuated by both hands. Therefore, in order to properly consider tool vibration exposures, more attention should be paid to observing the use of the tool. During field measurements, taking pictures of tools, sensor location, actual posture of operations is, thus, highly encouraged. Beyond a field journal, these pictures could assist in understanding how the power tools are used and how the hands are involved in specific tool operations.

All of the vibration PSD spectra in Figures 18 through 29 show the ISO 10819 excitation spectrum as a dotted line. Some tool spectra exceeded this ISO profile, as seen in Figures 22(c), 24(b), 27(c), and 29(c), while others did not even reach the profile as seen in Figures 21(c) and 28(c). Further tool assessments may be required in order to revise the ISO 10819 excitation spectrum to reflect actual power tool vibrations.

Because the frequency-weighted acceleration values were adjusted by the weighting curve specified in ISO 5349 and ISO 8041, the values should not change dramatically as long as the target frequency range is wide (i.e., from 6.3 to 1,250 Hz). It was noted in a previous section that the target frequency range of the tool vibration assessments needed to be clearly identified,

especially since the unweighted acceleration values are specifically needed and the total unweighted acceleration values can be strongly influenced by the frequency range.

4.1.3 Health Risk Assessment

The health risk associated with the power tool vibration exposures in both facilities was determined based on one cycle of tool operation and an estimate of total exposure time. Because it was unclear how many time workers triggered the power tools, the number of trigger events was estimated as 500 or 1,000 times per day in order to yield an estimated total exposure time in hours per day. As shown in Figure 30 and 31, the majority of points were lower than the daily exposure action value (DEAV) line. Several tools were placed between the DEAV and daily exposure limit value (DELV) lines and the estimated exposure times were less than 1 hour. This suggested that a simple task rotation could be used for hand-arm vibration syndrome (HAVS) prevention in these two facilities. Some bucking bar vibration levels in the helicopter facility exceeded the DEAV and DELV lines, which indicates that the bucking bar operation needs to be paid serious attention for health risk management.

It is important to note that these health risk assessments were based on an assumed number of trigger events per day; therefore, the results may not indicate actual vibration exposures. In order to accurately determine the vibration exposure time, daylong data logging would be needed in order to demonstrate the true duration of vibration tool operations. Otherwise, a self-report tool survey can be performed; however, it has already been demonstrated that such a survey does not provide the actual duration of power tool operations (Peterson et al, 2008).

4.2 Phase 2: ISO 10819 Glove Assessment

Understanding the glove characteristics, especially VR capability, could directly impact PPE selection for the worker's hands. Since ISO 10819 is accepted as the glove evaluation standard, it has been widely utilize all over the world. In this dissertation, nine commercially available gloves were studies for their VR capabilities at the palm and the finger and is discussed in this section.

4.2.1 ISO 10819-Based Experiment Configuration

Utilizing an independent laser Doppler vibrometer (LDV) system, the vibration characteristics were observed at the experiment handle. It is important to note that the vibration testing spectrum specified in ISO 10819:2011 was observed to have a mismatch between the ISO-proposed PSD values and the corresponding acceleration values. Because of the tolerance values specified in ISO 10819, this not seen as a significant problem, since the total frequency unweighted values differed by only about 3 m/s^2. But it still should be noted that this difference could theoretically introduce measurement errors. As Figure 32 shows, there are slight mismatches between the ISO PSD and acceleration values; however, it was concluded that the instrumented handle output follows the specified spectrum fairly well.

Following ISO 10819 and its graphical descriptions, a testing system was developed that consisted of numerous components. ISO 10819 minimally describes the construction of the system and does not clearly state what or how the components should be prepared. For example, as seen in Figure 10(a), ISO 10819 simply states that the subject stands on the adjustable platform with a force plate, which should be adjustable in order to promote 90° of elbow flexion. This seems simple enough to understand but provides no solution to determine the right

adjustable platform for covering various subject anthropometries. Utilizing the available anthropometric databases for short to tall subjects, a scissors lift was selected that is capable of holding up to 2,000 lbs and can be adjusted in height and can be seen in Figure 10(b).

4.2.2 Palm and Finger Adapter Evaluation

Before using the 3D printing technology, several different palm adapter samples were manually manufactured from different kind of woods and plastics. Although a computer numerical control (CNC) milling machine and lathe were used, the shape of the ISO 10819 adapter was extremely difficult to clamp onto machine and the machine was difficult to program as it required the subsequent use of several different ball endmills. The adapter is a very simple design; however, its complex geometry truly requires the use of a multi-axis machine. In order to realistically meet the adaptor geometries and weight constraints (i.e., less than 15 gram), the process of precision plastic mold manufacturing was considered but was discarded because it could involve more manufacturing process time and cost.

Using a 3D printer (Makerbot, Brooklyn, NY) made the custom prototyping very simple and time-efficient. Manual adapter manufacturing required almost two full days of scraping and sanding, where, once the object was designed in 3D CAD software, the object data was transferred to the 3D printer and quickly printed. This technology dispelled the traditional bias against plastics, where plastics may not be strong enough to withstand tough working environments. In the end, the 3D printed plastic was selected based on its vibrational performance and durability.

As shown in Figure 33, both palm and finger adapters made with PLA well withstand the vibration environment. Their typical transmissibilities were nearly flat (i.e., around 1.00) and

were within the ISO 10819 adapter transmissibility requirements (i.e., between 0.95 and 1.05). These results showed enough evidence for their use in the evaluations for the ISO 10819 glove tests. The results of this dissertation demonstrate that 3D-printed components have significant potential to be applied to human vibration research.

4.2.3 ISO 10819 Based Glove Assessment

Based on the results of the ISO 10819 glove assessments, shown in Table 10a, none of the tested gloves passed the defined M and H requirements. This suggested that none of the tested gloves could be categorized as an antivibration (AV) glove but only recognized as a VR glove. It is important to note that these results were obtained from an average of three different subjects with five repeated measurements on each gloved condition and showed that a majority of the VR gloves possessed the minimum transmissibly values lower than the required M and H values. It is also interesting to note that the intra-measurement variability within a subject was smaller than the intra-subject variability and strong suggests that glove transmissibility is highly influenced by hand biodynamics.

The more recently released ISO/FDIS 10819:2013 recommends that five subjects be used and that three measurements are conducted per glove. When considering this study, the total measurement number is not different from that latest version. Given the change in the testing protocols between 2011 and 2013, it is suspected that the ISO committee members are well aware of the existence of this intra-subject variability and increased the number of subjects and decreased the number of measurements per subject. The subject variability observed in this study can be seen in Figures 35 and 36.

The overall glove transmissibility spectra in the palm and finger showed an interesting result (see Figure 34). It was observed that some gloves, especially those utilizing rubber materials, showed amplification in the finger transmissibility results, even though the palm side exhibited clean attenuation profiles. It is assumed that the biodynamic mass distribution of the hand varies with location and influences the material damping characteristics, which yields glove transmissibilities as either attenuation or amplification. In addition, the detailed observations between palm and finger transmissibilites could not have been achieved without utilizing the 3D-printed palm and finger adapters.

During glove testing, subjects were having difficulties using their fingers because of the thick and immobile resilient materials in some of the gloves. ISO 10819 does not involve any precise finger task for subjects and in real working environment, these gloves would make it difficult to pick up, for example, a dropped quarter-inch bolt on the floor. Therefore, future VR glove assessments should include finger dexterity measurements (i.e., peg board, mechanics test). Vibration reduction is an important functionality to consider in glove development but finger movement is equally as important for workers as well. Depending on the type of work task, a glove with minimal hand coverage, which still maintains breathability, cut protection, warmth, protection from chemical exposures, etc., and vibration attenuation capabilities could be appropriate, but these types of gloves do not typically meet the ISO 10819 standard. The VR glove is one possibility in the prevention of excess amount of vibration exposures to the hand; however, without combining reductions in tool use and tool use times, as well as using VR treated tools (i.e., incorporating counter balancer in handle and/or wrapping VR material over the handle), the VR glove alone is not enough to protect workers completely.

4.3 Phase 3: Additional Experiments and Glove Selection

Tool-specific VR gloves considered based on the ISO 10819 pass-fail criteria in the M or H frequency ranges; however, when the effectiveness of a glove is considered under different vibration stimulation conditions, it was previously believed that evaluation outcome do not match ISO 10819-based glove assessment outcomes. Based on a series of additional experiment in this research, the transmissibilities were observed to not be significant altered for gloves exposed to different vibration excitations. Additional experiments were conducted to further understand the characteristics of a VR glove, including the importance of these characteristics in the selection of tool-specific gloves.

4.3.1 Glove Transmissibility for Different Excitation Spectra

It was initially questioned whether glove transmissibility remained the same or differed if the vibration excitation spectrum was replaced with a different spectrum (i.e., tool-specific vibration or simple flat spectra). Historically, ISO 10819:1996 previously specified two different M- and H-range vibration excitation spectra, then ISO/DIS 10819:2011 and ISO/FDIS 100819:2013 introduced a single vibration excitation spectrum and mathematically obtained the glove transmissibility in M- and H-range. Hence, the ISO 10819 methodology changed from the 1996 to 2013 version, would not be an issue if the hypothesis is correct. In addition, it is easily questionable whether a tested glove would be effective for certain specific tool operations, if only the ISO spectra are used.

The three different vibration spectra used in this dissertation had noticeably different profiles and amplitudes (see Figure 37) and the measurements specifically followed ISO 10819 to determine glove transmissibilities, as shown in Figure 38. Although there were roughly ± 0.2

differences in transmissibility, all the transmissibilities showed nearly identical profiles. The lower end of the frequency axis showed slight variations but still demonstrated similar transmissibility spectra overall. Because the flat and average spectra contained larger low frequency vibrations (i.e., larger shaker displacement at low frequency vibrations), it was observed the 30 N grip and 50 N push combinations were disturbed by such large displacements.

Changing the excitation spectrum from the ISO 10819 testing conditions did not seem to influence the results, as the transmissibility characteristics of the gloves showed very similar responses with only slight differences observed between spectra. These results strongly suggest that consistent operation of an ISO 10819-based hand-arm excitation system, including the data acquisition system, should yield similar transmissibility measurements regardless of the excitation spectra.

Based on the results, shown in Figure 38 and that the testing conditions remained the same for all of the assessments, the vibration excitation differences did not change the glove transmissibility spectra, which supports the finding in previous studies (Rakheja et al., 2002; Dong et al., 2002b; Welcome et al., 2012). In addition, if the transmissibility measurements were observed to be dramatically different in a multi-subject study, then variations in subjects (e.g., gender, anthropometry, etc.) and/or applied forces (i.e., grip and push/pull) may be the major influences on transmissibility results rather then changes in the vibration excitation. As long as the testing conditions remain the same as ISO 10819 assessment, transmissibilities can show extremely similar patterns for a given glove. In other words, latest excitation spectrum from ISO 10819 is not a bad excitation for evaluating glove effectiveness although this excitation spectrum does not represent commonly used power tool vibrations.

During the vibration testing in the laboraotry, it was realized that the excitation spectrum should cover more than the frequency range of interest. The armature of electrodynamic shaker responded precisely to the input signals and, in this study, the excitation frequency range was limited to, at most, 3 to 5,000 Hz. Technically the shaker did not move at all above or below the set frequency range. However if the frequency range of an electrodynamic shaker is not carefully configured and monitored, where the measurement is conducted beyond the programmed frequency range, then the resulting data becomes chaotic and meaningless.

4.3.2 Series of Material Damping Tests

When the glove material was held to the instrumented handle by hand or by tourniquet, the transmissibility profiles were remarkably different, as can be seen in Figures 38(c) and 39. The transmissibility profile for holding by hand indicated the complex vibration models involved in the hand-glove relationship, while, for the glove held by tourniquet, the transmissibility profile indicated that the glove behaved almost the same as a 1-DOF vibration system. Additionally, the tourniquet wrapping force did not seem to influence the damping characteristics of the glove material. As seen in Figure 40(a), the transmissibility profiles show slight shifting, which was assumed to imply that the vibration damping material used in the glove was stiff enough to resist dynamically changing work loads but still compliant enough to reduce vibration energy transmissions. Depending on the applied load, the resonance of the damping material may shift, such as if the load were to increase, then the peak resonance would shift toward the lower frequencies. This is similar to a compressed spring with its mobility constrained, when the spring is fully compressed, the spring becomes a lumped mass of and its resonance where will shift towards the lower frequencies. Although most AV gloves are designed to be used in a

harsh environment, their vibration attenuation and control should also be sensitive enough to withstand various loading conditions.

As seen in Figures in 40(a) and 41, if the dynamic behavior of the arbitrarily selected damping materials was similar to the glove transmissibility profile when held by the tourniquet, then the selected material was expected to also attenuate the incoming vibration spectrum. Figure 42 shows the transmissibility profile of a selected material and, when compared to that of Glove 1 in Figure 34, shows similar response. This was a crude technique to determine the effectiveness of damping materials for use in VR glove design and could be applied to the development of effective VR gloves.

4.3.3. LTI System Theory and Glove Transmissibility

With an adjustment in the frequency range, the LTI-based method can be used to simply estimate the vibration exposure of a gloved hand using ISO 5349-based power tool vibration spectra and ISO 10819-based glove transmissibility spectra. While the mean transmissibility values for the M and H spectrums are beneficial for categorizing VR gloves for manufacturers, these values do not provide any simple practical instructions for glove users. Even with the recent changes in the ISO 10819 standard, glove manufacture should continue to satisfy the original M (≤ 0.9) and H (≤ 0.6) guidelines but look to provide the one-third-octave spectrum of the glove design for better understanding of the glove's vibration attenuation characteristics.

The frequency ranges between ISO 5349 (6.3 to 1,250 Hz) and ISO 10819 (25 to 1,250 Hz) do not match because ISO 10819 omits the frequency bands with center frequencies of 6.3, 8, 10, 12.5, 16, and 20 Hz. Although these frequencies are important for assessing and characterizing HTV exposures, ISO 10819 glove testing does not include them into its contents.

In addition, it is interesting to note that previously reported studies showed frequency-weighted and unweighted vibration levels in their glove testing but do not clearly mention their measurement frequency range. In actuality, the discrepancy between frequency ranges may not largely influence frequency-weighted vibration levels, simply because the frequency weighting, W_h, automatically focuses on certain frequencies of interest. On the other hand, the discrepancy largely influences unweighted vibration levels, where, for example, if one power tool vibration spectrum contains many high frequencies, then the tool vibration characteristics could easily be misinterpreted. Therefore, it is very important to consider the frequency range for the HAV exposure assessment.

Figures 43(a) through 43(d) display examples of estimated vibration exposures of the gloved hand with both unweighted and weighted reductions. Because Glove 1 was a VR glove, the unweighted reduction percentage was larger, which means the glove was very effective overall. In Figure 43(b), the weighted reduction percentages show some greater vibration reductions for some tools as opposed to other tools. As an example, these results suggest that Glove 1 is expected to better reduce both palm and finger vibration exposures for grinders rather than bucking bars, while Glove 3 is expected to reduce unweighted vibration exposures in both palm and finger over any power tools. However, because of the different palm and finger transmissibility profiles of Glove 3, as seen in Figures 36(a) and 36(b), and depending on the tool vibration spectra, the expected weighted percent reduction of Glove 3 in the finger indicates that some tool vibration exposure will be amplified. Therefore, this simple method could easily categorize which glove should be appropriate for specific tools and tool operations.

Based on this simple glove selection methodology, a LabVIEW program was created, as seen in Figure 44, that can use one-third-octave tool vibration spectra and VR glove

transmissibility spectra, calculate, and display all of the HAV information for a glove, tool and work process combination. More specifically, in order to use this program, three inputs are needed: 1) ISO 5349-based one-third-octave tool vibration spectrum, 2) ISO 10819-based glove transmissibility spectrum, and 3) an assumed, or known, tool operation time and number of operations. The program displays the estimated vibration exposure of a gloved hand and can be a powerful companion for tool assessments and VR glove selections.

All of the field and laboratory measurement programs were created in LabVIEW, so it would be possible to combine all programs into one master program that is able to perform real-time VR glove evaluations using actual power tool vibrations and specific operations in the field. Recent technological advancements have helped develop instruments with a wider dynamic measurement range, a better A-to-D resolution, and much higher sampling rates, that are inexpensive and smaller in size than their previous counterparts. In other words, quality laboratory instruments could be incorporated into a small brief case, transported, and used at any working site.

5. Conclusion

It has been reported that the number of patients with HAVS has decreased in recent years. Previous studies by the Biodynamics Laboratory at the University of Connecticut Health Center and others have analyzed problems regarding vibration-associated occupational hazards; however, further analyses are warranted in order to fully understand the complexity of hand-arm vibration exposures.

In this study, the vibration signatures from 35 power tools from actual worksites were measured following ISO 5349 and their vibration characteristics were analyzed and converted into one-third-octave PSD spectra. In order to measure the tool vibration in the field, a vibration measurement cart and a novel accelerometer adapter particularly, for bucking bar vibration, were designed and developed. The functionality of the adapter was verified and it was reliably used in the actual measurement situations.

Moreover, in a laboratory environment, an ISO 10819-based evaluation system was developed using a closed-loop electrodynamic shaker system and nine gloves were assessed for their vibration transmissibility capabilities. None of the gloves tested passed the ISO 10819:2011 criteria.

In addition to the tool vibration measurements and the glove evaluations, several small experiments were performed to understand the relationship between the vibration and the vibrational performance of various glove materials. Because the characteristics of the damping materials demonstrated that they followed the Linear Time-Invariant (LTI) system theory, with glove transmissibilities were shown to not differ if the vibration excitations that they were tested were changed.

Finally, tool-specific VR glove selection was determined using ISO 5349-based tool vibration measurements and ISO 10819-based glove assessments, while taking full advantage of the LTI system theory. Both tool vibration and VR glove transmissibility information are widely available today, so the selection of tool-specific VR gloves can be considered more practically. The proposed methodology integrated all of the available information in order to simplify the selection processes and provide easy and simpler glove selection to the end-users.

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