THE EFFECTS OF A VISCO-ELASTIC POLYMER GLOVE ON HAND-ARM VIBRATION, MUSCLE ACTIVITY, AND COMFORT DURING SIMULATED POWER TOOL USE

by

Ryan Alexander Shivpaul, BHSc

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of

Master of Health Sciences in Kinesiology

University of Ontario Institute of Technology

July 2017

TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER 2: LITERATURE REVIEW

CHAPTER 3: MANUSCRIPT

THE EFFECTS OF A VISCO-ELASTIC POLYMER GLOVE ON HAND-ARM VIBRATION, MUSCLE ACTIVITY AND COMFORT DURING SIMULATED POWER TOOL USE

Ryan Alexander Shivpaul

Committee Chairperson:

ABSTRACT

Prolonged exposure to hand-transmitted vibration (HTV) as a result of power tools can lead to hand-arm vibration syndrome (HAVS). The effectiveness of anti-vibration (AV) gloves for the reduction of hand arm vibration remains unclear. The ability of a glove to attenuate vibration is largely influenced by the material properties and forearm muscle activity during tool use. Visco-elastic polymer (gel-based) and air-bladder AV gloves are the most common options, however the material properties of gel based options have seen little attention. The purpose of this study is to investigate vibration transmissibility, forearm muscle activity and subjective grip dexterity using a variety of gel-based compositions and designs. Participants completed six simulated hand-held power tool tasks. RMS vibration, grip force, muscle activity, and perceived levels of comfort, dexterity, onset of forearm muscle fatigue and impairment of tactile sensation were collected. Vibration attenuation was most effective along the Z axis, with properties such as decreased contact stiffness, as well as increased mass, elasticity and viscosity performing better. Further investigation of visco-elastic polymers using the ISO standardized protocol is needed.

Keywords: Hand-Transmitted Vibration, Hand-Arm Vibration Syndrome, Muscle Activity, Grip Force, Visco-elastic Polymer, Anti-Vibration Gloves

DECLARATION

I, Ryan Alexander Shivpaul, declare that this thesis represents my own work except as acknowledged in the text, and that none of this material has been previously submitted for a degree at the University of Ontario Institute Of Technology, or any other University. The contribution of supervisors and others to this work was consistent with the UOIT regulations and policies. Research for this thesis has been conducted in accordance to UOIT's Research Ethics Committee.

ACKNOWLEDGMENTS

I would like to sincerely thank Dr. Michael Holmes. Your unwavering guidance, unrelenting patience, and persistent encouragement made this possible. You have my utmost respect, and I have gained an immeasurable appreciation for the world of research because of you.

I would also like to thank Ryan Foley and Bob MacMillan for their aid in the development of the prototypes involved in this study.

Furthermore, I would like to express my appreciation to the Nokes family for their assistance in the creation of the steel apparatus. Though our paths crossed briefly, I am sincerely glad to have had the pleasure of your company in this chapter of my life.

Of course, none of this would have been possible without my loving family. Thank you for your understanding, undying devotion, and continued support.

Lastly, but absolutely not in the least, I would like to thank my mother, Shanti. You have guided me through the greatest journey that is life and have stuck with me through every single step of the way. Your kind heart and unconditional encouragement, as well as the sacrifices you have made for me gave me the strength I needed to face challenges head-on, and keep moving forward every day.

Pursuing my Master's degree was an experience I will cherish forever. The past two years have not only helped me to learn about research, but, about my own potential to push beyond limits as well. In the words of the illustrious Michael Jordan, "*Limits, like fears, are often just an illusion*".

ABBREVIATIONS

ACGIH: American Conference of Governmental Industrial Hygienists

AV: Anti-Vibration

ECR: Extensor Carpi Radialis

ECU: Extensor Carpi Ulnaris

EDS: Extensor Digitorum Superficialis

EEG: Electroencephalogram

EMG: Electromyography

FCR: Flexor Carpi Radialis

FCU: Flexor Carpi Ulnaris

FDS: Flexor Digitorum Superficialis

g: Unit of acceleration derived from the Earth's gravitational pull; valued at 9.8 m/s^2

HAVS: Hand-Arm Vibration Syndrome

HTV: Hand-Transmitted Vibration

Hz: Hertz

ISO: International Standardization Organization

MEMS: Micro-electro mechanical systems

MVC: Maximal Voluntary Contraction

MVE: Maximal Voluntary Exertion

m/s^2: Metres per second squared

N: Newtons

NIOSH: National Institute for Occupational Safety and Health

VWF: Vibration Induced White Finger

DEFINITIONS

Anti-Vibration Gloves: Gloves capable of reducing hand-transmitted vibration

Accelerometer: An instrument used to quantify acceleration

Crest Factor: Ratio of peak value to RMS value of acceleration

Damping: Degree of resistance to rapid changes in displacement

Hand-Transmitted Vibration: Vibration reaching the fingers and hand from an external source

Hand-Arm Vibration: Vibration transmitted to the fingers, hand, forearm, upper arm, and shoulders

Hand-Arm Vibration Syndrome: An umbrella term used to the describe physiological complications which may arise as a result of repeated exposure to hand-transmitted vibration

Root Mean Square Acceleration: The square root of each raw value of acceleration

Stiffness: Degree of resistance to deformation

Vibration-Induced White Finger: Condition induced by hand-transmitted vibration in which fingers appear white accompanied by numbness

Vibration Transmissibility: The ratio of acceleration seen on the hand compared to at the tool handle

1/3 Octave Band Frequencies: Spectra of frequencies measured in hertz divided into thirds; lower, middle and upper

CHAPTER 1: INTRODUCTION

INTRODUCTION

The use of powered hand tools such as drills, saws, and sanders is common among many occupations such as construction workers, automotive technicians, orthopedic technologists, and dentists. The use of these tools will often demand prolonged exposure to hand-transmitted vibration (HTV), which has been associated with a debilitating disorder concerning the upper-extremity known as Hand-Arm Vibration Syndrome (HAVS) (Dong et al., 2009). HAVS is an umbrella term used to describe the damage that occur in the fingers, hand, and wrist as a result of repeated exposure to vibrating tools (Sauni et al., 2015). If left untreated, the damage can become severe and potentially irreversible; leading to gangrene as well as neurological and muscular disorders. The onset of tissue damage due to HAVS can vary among individuals due to differences in energy transfer and physiological responses to the vibration mechanism, tissue recovery and fatigue onset (Pelmear & Leong, 2000). As a result, the damage may develop insidiously; some individuals will feel symptoms within a year, while others may remain asymptomatic for decades (Pelmear & Leong, 2000). The damage associated with HAVS can include sensorineural, vascular and musculoskeletal complications (Sauni et al., 2015).

The plight of HAVS requires immediate attention, as there are an estimated 72,000 to 144,000 cases of individuals suffering from HAVS in Canada alone (Shen & House, 2017). Furthermore, approximately 80-90% of individuals exposed to hand-arm vibration in the workplace currently suffer from, or will acquire a form of HAVS at some instance during their career (Devine, 2016). The time necessary for symptoms to manifest can range from 1 month to 30 years of exposure (Pelmear & Leong, 2000).   Overall, HAVS can lead to a decrease in work ability and quality of life of many individuals (Sauni et al., 2015). At the present time, British

Columbia and New Brunswick are the only two Canadian provinces implementing legislation

limiting occupational exposure to HTV; despite this, the degree to which this legislation is

enforced is unknown (Shen & House, 2017). Under the present circumstances, methods of HTV

reduction, alterations in power tool design, as well as awareness appear to be the most viable

solutions to the overall problem HAVS presents.

Suggested approaches of reducing hand-transmitted vibration include, shorter exposure

times to hand held tool use, increasing rest periods and task automation (Hewitt et al., 2016).

However, these solutions may not be feasible in all situations, as the nature of some occupations

may not grant flexibility with regard to rest times. In addition, automation is costly, could

replace individuals in the workplace resulting in job loss and is not always a viable solution to all

types of tool use and manual labour. Therefore, a method that enables individuals to continue

working while being exposed to less, or reduced magnitudes of vibration would help immensely.

In addition to improved engineering and tool design, current research suggests that anti-

vibration (AV) gloves are able to reduce the amount of tool vibration that is transferred from the

tool to the user; known as vibration transmissibility (Dong et al., 2014). This would imply that

AV gloves serve as an effective means of vibration reduction and if so, could be a low-cost

solution to a medical problem that can have huge financial implications. The International

Standardization Organization (ISO) has outlined standards that must be met in order for a glove

to be considered a true "anti-vibration" glove. Despite some gloves successfully reducing the

amount of hand transmitted vibration, most commercially available AV gloves do not meet the

standards/requirements set forth by ISO-10819 (Griffin & Bovenzi, 2002). This illuminates the

research question of this thesis: What aspects of AV glove fabrication besides thickness can be

manipulated to meet ISO standards, providing adequate vibration attenuation to the hand-arm

system? In addition, a compromise between glove thickness, user comfort, dexterity, grip force decrements and forearm muscle activity must be considered for an optimal solution in the workplace.

PURPOSE AND HYPOTHESES

The purpose of this study was to engineer a glove with a visco-elastic polymer composition that reduces hand-arm vibration during simulated power tool use. In particular, the aims were: to determine an optimal visco-elastic polymer composition and design for the greatest attenuation of HTV, to evaluate the effects of glove design on HTV, and to evaluate the effects of a visco-elastic polymer and glove design on forearm muscle activity, grip force, and subjective comfort. This information will provide valuable insight into the fabrication of an AV glove that meets ISO standards and significantly attenuates HTV. Working closely with an industry partner that custom produces a visco-elastic polymer material, different gel material properties were tested. Specific hypotheses include:

H1: Thicker, more stiff gel inserts will attenuate the most vibration.

H2: Thicker, more dense gel inserts will illicit the most forearm muscle activity.

H3: Thicker, more dense gel inserts will offer more comfort during tool use.

H4: Thicker, more dense gel inserts will require more grip force for tool use.

CHAPTER 2: LITERATURE REVIEW

SECTION 1: VIBRATION

In order to fabricate an AV glove that significantly attenuates vibration transmissibility while adhering to the standards outlined by ISO, it is necessary to understand what comprises vibration. Vibration occurs when matter undergoes oscillatory motion and can be described using two variables, amplitude, and frequency. The amplitude of a vibration signal refers to the extent of the amount that the signal deviates from an equilibrium of zero; quantified in accordance with acceleration due to gravity (g). It is worth noting 1g is equivalent to 9.81 m/s^2. While vibration frequency refers to the rate at which vibration occurs within a specified period, usually pertaining to seconds, expressed in Hertz (Hz). Vibration is classified as a unit of acceleration. Consequently, vibration is measured by a category of electronic devices known as accelerometers. It is also worth noting that vibration in the workplace is stochastic; fluctuating in amplitude and frequency.

1.1   Accelerometers

Accelerometers generate signals by sensing the changes in magnitude of the forces acting upon the accelerometer itself. These devices accomplish this by incorporating Micro-electro mechanical systems (MEMS). These are comb-like structures built within the capacitors of an accelerometer (Figure 1). The structures in the comb itself are extremely close in proximity, but do not fully make contact with each other. Most often, movements such as vibration will cause a small mass to move in opposition of the combs, which will generate a change in voltage. The change in voltage is proportional to acceleration. These signals are amplified and processed by an A/D converter, which is typically processed by software. The more combs built in to an accelerometer, the more surface area it has; therefore, increasing its sensitivity to acceleration.

Accelerometer can be designed to measure acceleration along multiple axes. This can vary between two-dimensional (2-D) accelerometers, which measure acceleration in the X, and Y axes, as well as triaxial accelerometers which feature a third, Z axis in addition for the purposes of three-dimensional (3-D) positioning. Accelerometers measurement is typically displayed in metres per second (m/s^2).
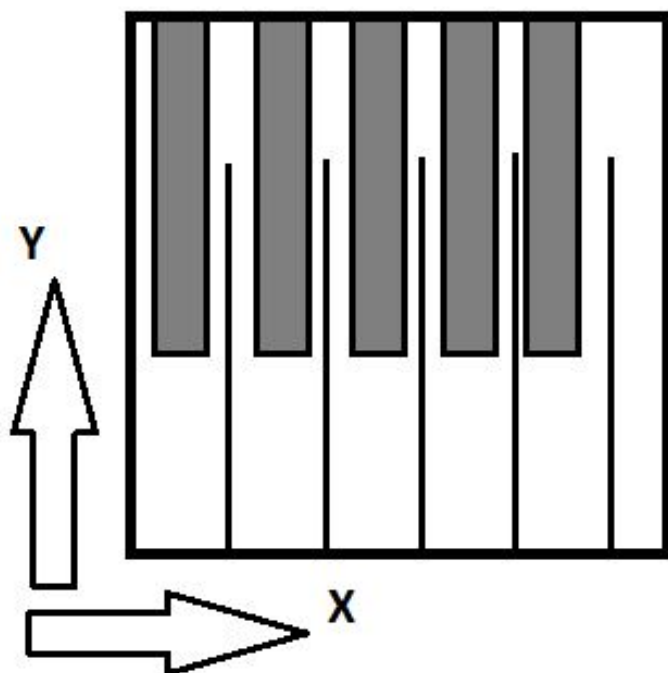
Figure 1. Comb-like structures within an accelerometer

1.2   Accelerometers in Research

Vibration has been frequently examined and applied within research; particularly in the fields of engineering and biomechanics. With regard to biomechanics, vibration has been analyzed within the context of a human body in motion, as well as examining phenomena such as body vibration as a response to an external stimulus. An example of vibration-based research applications can be observed in the study conducted by Welcome et al., (2014); wherein

accelerometers were used to collect data pertaining to the amount of vibration occurring at the hand during power tool use in order to formulate exposure guidelines with various power tools. For example, accelerometers offer the ability to collect vibration data, as vibration is expressed as acceleration. When executing a study regarding hand-arm vibration, it is necessary to measure vibration in three axes, rendering accelerometers highly applicable. As briefed, vibration is expressed as acceleration, suggesting that studies such as the one conducted by Griffin, (1998) support the utilization of accelerometers when examining hand-transmitted vibration.

SECTION 2: HAND-TRASMITTED VIBRATION

2.1 Hand-Arm Vibration Syndrome

The consistent use of hand-held power tools often entail prolonged exposure to hand-transmitted vibration which has been associated with a debilitating disorder concerning the upper-extremity known as Hand-Arm Vibration Syndrome (HAVS) (Dong et al., 2009). Moreover, a dose-response relationship has been exhibited between HTV exposure and the manifestation of HAVS symptoms (Rezali et al., 2017). As duration of HTV exposure increases the likelihood of the symptoms of HAVS manifesting increases as well. HAVS is an umbrella term used to describe the damages that occur in the fingers, hand, and wrist as a result of repeated exposure to vibrating tools (Sauni et al., 2015). If left untreated, the hand-transmitted vibration (HTV) may cause damage that can become worse and potentially irreversible; leading to gangrene as well as other vascular, sensorineural and musculoskeletal disorders (Figure 2). The onset of damage that occurs in HAVS varies among individuals due to the differences in energy transfer and physiological responses of tissues in each individual's upper extremity; as a

result, the damages may develop insidiously; some individuals will feel symptoms within a year, while others may remain asymptomatic for decades (Pelmear & Leong, 2000). Furthermore, symptoms may develop in as little as 2000 hours of tool use (Devine, 2016).

2.2 Prevalence of HAVS

There are thousands of new cases of HAVS reported each year globally (Hewitt et al., 2016). The prevalence of HAVS can range from 2.5% to 82.8% of the working population depending on the country (Azmir et al., 2017). Globally ubiquitous professions such as construction workers, automotive mechanics, miners, and forestry workers constitute a large portion of the individuals likely to develop HAVS (Mahbub et al., 2016). Moreover, 20-50% of individuals in the U.S. who use power tools in the workplace suffer from HAVS (Shen, 2017). Determining factors are duration, magnitude of vibration exposure as well as the temperature of the work environment. Furthermore, colder climates increase the likelihood of HAVS affliction (Azmir et al., 2017).

2.3 Musculoskeletal Impact

Contrary to the nature of hand-held power tool utilization, which entails physical labour, there are seldom musculoskeletal complications that arise as a result of repeated exposure to HTV (Matoba, 2015). The most common problem HTV presents with regard to the musculoskeletal system is mechanical hyperalgesia as well as an increased inflammatory response within the skeletal muscles of the hand-arm system (Chen et al., 2010). Moreover, pain and discomfort are also factors that are reported, however these variables are more often the result of poor ergonomic conditions (Pelmear & Leong, 2005). Motor function impairment of skeletal muscle within the hand-arm system as a result of HTV appears to entail the loss of

strength without atrophy or long-term damage to the skeletal muscle tissue itself. Realistically, most complications in this regard are neurological (Pelmear & Leong, 2005). However, as with many manual labour jobs that involve the upper extremity, poor working postures, high forces, as well as repetition each contribute to musculoskeletal disorders. It may not be the vibration that causes these musculoskeletal disorders, but these issues of tool use can.

2.4 Vascular Impact

Vascular complications may develop as a result of HTV largely due to a reduction in blood flow, which occurs as a result of the constriction of blood vessels within the digits of the upper extremities (Palmer, 2000). The most apparent vascular complication associated with HAVS is known as Vibration induced white finger (VWF), and is characterized by blanching of the fingers (Ye et al, 2015). Perhaps the reason for the prevalence of VWF is that it develops insidiously, with symptoms manifesting suddenly after years of exposure to hand-arm vibration, which impedes prevention (Matoba, 2015). Moreover, HAVS presents an additional concern, in that numerous instances of the development of VWF have been observed in the hand that is not exposed to vibration (in the case of one-handed power tools) (Ye et al, 2015). Vascular complications such as thrombosis, particularly pertaining to the ulnar artery, are also a major concern regarding HAVS (Poole & Cleveland, 2016). Lastly, Walus (1987), suggests that HTV occurring at approximately 8Hz may elicit an increase in ejection fraction as well as stroke volume, due to this frequency being identical to the resonant frequency of the heart itself.

2.5 Sensorineural Impact

The sensorineural damages due to repeated exposure of HTV are likely the most debilitating with regard to functionality and quality of life (Poole & Mason, 2005). The stress on

neurological tissues within the hand-arm system with repeated exposure to HTV are akin to repetitive traumatic injuries, which produce an array of sensory neuropathies (Pelmear & Leong, 2005). From a superficial stand point, the neurological damage done to the hand-arm system results in reduced precision and fine motor skills (Sauni et al, 2015). Examining the sensorineural complications of HAVS further, one of the most frequently discussed phenomenon is the sensation of numbness and paresthesia, which occurs in the digits of the upper extremities (Matoba, 2015). This phenomenon is suggested to be the result of increased vibrotactile and thermal perception thresholds (Gerhardsson & Hagberg, 2014). The increase of such thresholds impairs an individual's ability to gauge how strenuous or potentially damaging a particular hand-held power tool may be. In addition, individuals who are frequently exposed to HTV exhibit decreased nociceptor sensitivity (Chen et al., 2010). This presents an additional challenge, impairing an individual's ability to perceive pain over time; potentially leading to more damage. Lastly, it has been suggested that repeated exposure to HTV may alter the central sympathetic vasomotor reflexes, which account for the occurrence of VWF in non-vibrating exposed hands (in the case of one-handed power tools) (Bovenzi et al, 2006).
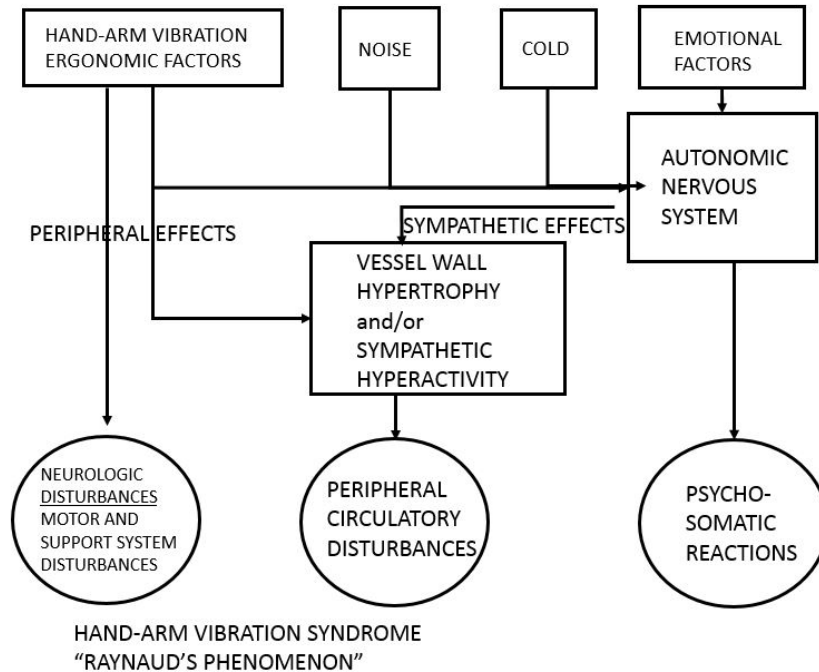
Figure 2. Mechanism of VWF as proposed by Murray (1983)

2.6 Financial Impact of HAVS Related Injury

The nature of HAVS prevalence involves individuals across many professions, and as such, it presents financial challenges for businesses as well as the healthcare system. Thomson et al. (2011) investigated the number of claims pertaining to HAVS during a five-year period (2003-2008), and found there were a total of 1190 claims from Ontario, Quebec and British Columbia alone, with 79% of these claims arising from Ontario. Thompson et al. (2011) go on to suggest the majority of claims may arise from Ontario due to the province being the most populous of the aforementioned group. With regard to the categories of occupations most claims are submitted from, the most common were loggers, with automotive mechanics following closely behind (Devine, 2016). Despite the number of insurance claims submitted, it is difficult to assess the financial impact of HAVS on healthcare systems due to the lack of proper diagnosis.

SECTION 3: INTERNATIONAL STANDARDIZATION ORGANIZATION

3.1 ISO Hand-Arm Vibration Testing Criteria

The International Standardization Organization has produced specifications that must be met when collecting hand-transmitted vibration signals; initially outlined by ISO-2631(1997) and revised by ISO-5349-1 (2001). The principles of these specifications are based on obtaining the magnitude of vibration and the duration of exposure with frequency weighting to produce a daily vibration dose. ISO-5349-1 (2001) specifies when testing, subjects must be standing, gripping the tool handle with the forearm parallel to the floor, with the elbow angled between 90° and 120°. Subjects must also exert 30N ± 5N grip force and 50N ± 8N push force respectively, as these are considered the average hand forces administered in the operation of many tools. Moreover, the vibration measured is weighted against the frequency weightings defined by ISO-5349-1 (2001). As the range of frequencies given by power tools is vast, the spectrum is divided into thirds, known as 1/3 octave band frequencies. In the case of HTV, the frequency range with the most relevance is between 6.3 and 25Hz (Figure 3). It is important to note that ISO-5349-1 (2001) should be used when examining hand-transmitted vibration, as ISO-5349 (1997) pertains to whole-body vibration. Numerous researchers mention these specifications when formulating the methodology for their studies and the ISO standards have helped standardize methodology for the HAV literature. The first major specification addressed frequently by the literature in relation to the ISO standards is the measurement of hand-transmitted vibration signals in three

orthogonal directions. The X axis should run perpendicular to the other axis, the Y axis should run along the tool handle, and the Z axis should run in the direction of the forearm (Figure 5). Gomes et al., (2014) support this ideology by stating tri-axial measurement of vibration should be performed in order to obtain a proper value of frequency weighted root means-squared (RMS) vibration for each axis. Hewitt et al., (2015), extrapolate upon this statement by reasoning that the RMS values obtained for each axis should be combined in order to achieve a vector sum; ideally producing the total weighted vibration. The strength of basing the methodology of a study on these specifications is addressed by Dong et al., (2013). Dong et al., (2013) agree with the aforementioned researchers by stating that this procedure essentially develops a uniform method for differentiating vibration attenuation within studies.

With regard to other specifications outlined by the ISO standards, assessment of vibration isolation effectiveness is another factor that must meet the standards. The ISO specifications dictate that the vibration isolation effectiveness should be assessed by examining frequency-weighted acceleration; which is further outlined by ISO-10819 (2013). ISO-10819 also details the requirements for analyzing hand-transmitted vibration when involving vibration attenuating objects such as gloves. According to the specifications outlined by ISO-10819 (2013), vibration transmissibility occurring between the frequencies of 6.3Hz to 25Hz should be given the most weighting with respect to contribution towards frequency-weighted vibration; as it is closest to the resonant frequency of the fingers and hand. Essentially, transmissibility can be determined by dividing the amount of frequency weighted acceleration at the hand, by the frequency weighted acceleration on the tool handle (Figure 4). Hewitt et al., (2015) validated this specification and produced a frequency-weighting

curve that reflected the specifications outlined by ISO-10819. In addition, as per the testing

protocol outlined by ISO, a minimum of three participants are required to test AV gloves.
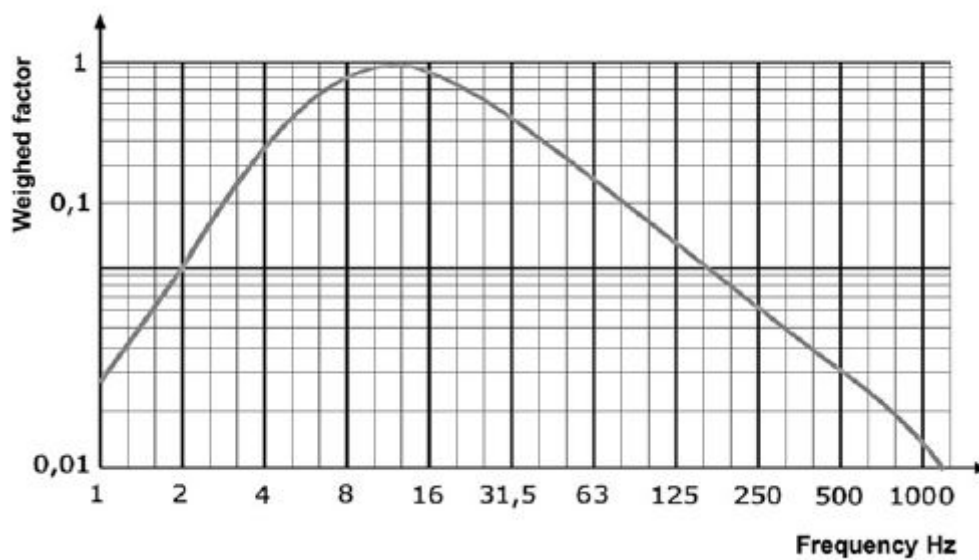
Figure 3. Weighting of frequencies for hand-arm vibration (ISO 5349-1, 2001).

$$\text{Transmissibility} = \frac{Frequency\ weighted\ acceleration\ at\ hand}{Frequency\ weighted\ acceleration\ on\ tool\ handle}$$

Figure 4. Equation for transmissibility derived from ISO-10819 standards.
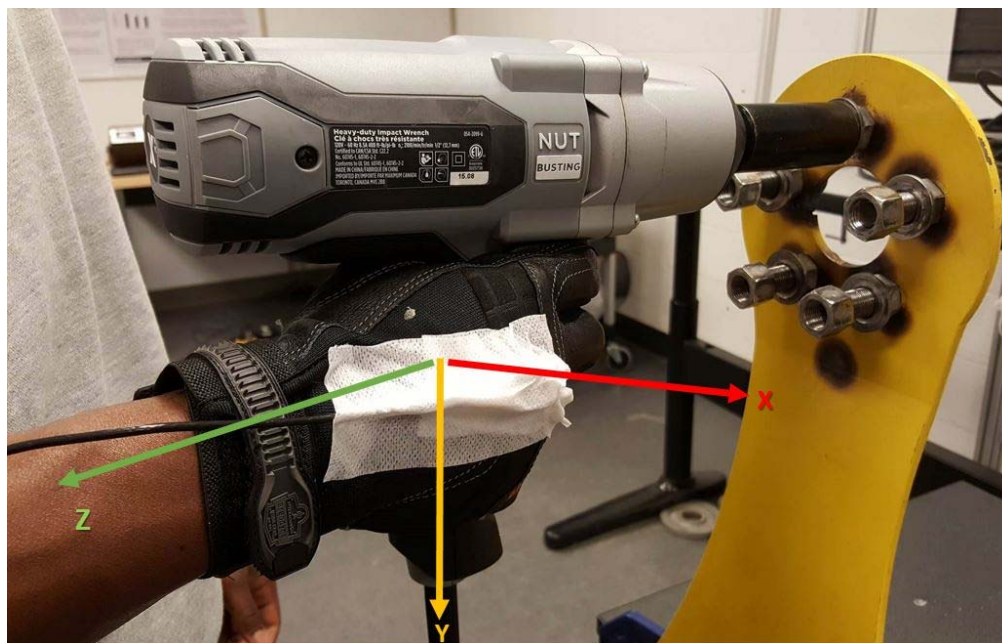
Figure 5. Direction of each axis for the measurement of on-hand three-dimensional hand-arm vibration.

3.2 ISO Signal Processing

There are a few different approaches for filtering of hand-arm vibration data and the literature is not always consistent in the best approach. NIOSH (1989) recommended the use of an electric low-pass filter with a cut-off frequency above 5000Hz placed between the accelerometer voltage and the recording device. NIOSH suggested that this is best due to the frequency of vibration produced from tools falling between 1Hz-5000Hz; therefore, a low-pass filter would ensure that all signals above 5000Hz are blocked. In addition, NIOSH (1989) suggested that a mechanical low-pass filter with a linear transfer function between 5Hz and 500Hz be utilized. Conversely, Dong et al., (2003) argued that it is difficult to fully attenuate the signal shift with a mechanical filter without sacrificing the accuracy of the raw signal measurement in high frequency ranges such as 5000Hz. Pelmear & Long (2000) stated that the

pathophysiological effects of hand-transmitted vibration are proportional to the acceleration experienced during tool use. As a result, Pelmear et al., (2000) recommended the use of band-limiting filters from 6.3Hz to 1250Hz.

Furthermore, the characterization of vibration signals is an additional factor that must be taken into consideration. With regard to ISO 5349 (2001) standards, RMS acceleration is the standardized variable concerning hand-transmitted vibration. Gomes et al., (2014) stated that the RMS acceleration should be weighted with respect to the ISO frequency domains and passed through a narrow-band filter; producing a final value defined as a weighted frequency RMS vibration. Furthermore, the guidelines set forth by ISO-5349 (2001), mandate the determination of a crest factor with respect to each of the three axis involved.

3.3 ISO Anti-Vibration Glove Criteria

In order for a glove to be classified as 'anti-vibrational', gloves must meet three classification criteria outlined by ISO. The first of these criteria is that the AV gloves must exhibit a transmissibility value in the middle frequency range (25-200Hz) less than or equal to 0.90Hz. Second, the AV glove must exhibit a transmissibility value in the high frequency range (200-1250Hz) less than or equal to 0.60Hz. Lastly, the AV glove must be full-fingered, consisting of uniform materials from the glove fingers to the palm; with glove finger and thumb thickness at least 0.55 times that of the palm.

3.4 ISO Standards Controversy

Despite support for the specifications outlined by ISO-5349-1 (2001), many researchers have scrutinized the methodology. Hewitt et al., (2015) argued that the ISO standards serve more as an affordable screening process for anti-vibration gloves rather than to assess vibration

transmissibility directly. Wimer et al., (2012) had a similar opinion on the ISO-5349-1(2001)

standards and the methodology may produce generalized and flawed results. Wimer et al.,

(2012) mentioned that vibration signals obtained in accordance with this methodology may

suggest that an attenuating object such as a glove should be classified as "anti-vibrational" when

it actually provides no significant attenuation within the frequencies that are weighted the

heaviest. Dong et al., (2013) added to the opposition of the ISO standards by arguing that these

methods employ generalized test handles and input vibration spectra that are not representative

by most tools from which hand-transmitted vibration should be assessed. Jetzer et al., (2003)

also noted that the specifications pertaining to gloves produced by ISO 10819 do not address the

methodology of future studies at all; rather this series of specifications focuses on results

interpretations. Finally, the amount of transmissibility for HTV has shown to vary by up to 20%

based on an individual's anthropometrics, even under the controlled conditions outlined by the

ISO protocol (Hewitt et al., 2016).

3.5 Exposure Limits

With regard to exposure limits within Canada, British Columbia and New Brunswick are the

only provinces that have implemented legislation for occupational exposure to HTV (Shen &

House, 2017). The limitations within these provinces are based on the current guidelines for

hand-arm vibration outlined by the American Conference of Governmental Industrial Hygienists

(ACGIH). The current ACGIH recommendations dictate daily hand-arm vibration exposure

should not exceed eight hours to vibrations equal or more than 5 m/s^2.   These guidelines were

based on the recommendations outlined by ISO; as this is the daily vibration exposure limit

which most workers are able to be exposed to repeated doses of vibration without progressing

beyond Stage 1 VWF. Moreover, when assessing occupations involving hand-arm vibration, the

Workers' Compensation Board of British Columbia requires employees to receive a diagnostic check-up for HAVS symptoms from a specialist physician for every 1000 hours of exposure (Youakim, 2012).

SECTION 4: ANTI-VIBRATION GLOVES

4.1   Vibration Attenuation

There are a vast array of powered hand-tools used across many occupations. As a result, the range of vibration frequencies individuals are exposed to varies considerably. When formulating an ergonomic anti-vibration glove which reduces the most vibration transmissibility, it is imperative to know which frequencies of vibration the glove will be combatting. Additionally, it is extremely difficult to manufacture a glove that is capable of covering all frequencies effectively (Griffin, 1998). Among the literature, numerous studies concur on the theory that anti-vibration gloves are considerably better at reducing vibration transmissibility at higher frequencies than lower frequencies. Gurram et al., (1994) demonstrated that when concerning vibration transmissibility at frequencies above 500Hz, only 1% of vibration is transmitted to the hand. Moreover, at frequencies lower than 100Hz, anti-vibration gloves actually amplify finger vibration. Dong et al., (2009), continued to identify trends concerning specific ranges in vibration frequencies. Dong et al. (2009) stated that a strong correlation exists between the isolation effectiveness of a typical anti-vibration glove and the characteristics of the human hand in a broad frequency range of 40-200Hz. Reynolds and Wolf (2005) expand upon this. The authors stated that the stressors in human tissues which contribute to the development of HAVS occur near the fingers' own resonant frequency of 100-300Hz'; with changes in sensorineural facets occurring most at this frequency. In addition, Krajnak et al., (2015) confirm

100-300Hz as the frequency range to focus on by finding that this is also the resonant frequency of most current anti-vibration glove materials. It is interesting to note that while a more specific range of vibration frequency (100-300Hz) has been illuminated, other studies continue to discuss the relationship between anti-vibration gloves and vibration frequencies at lower ends of the frequency spectrum. Similarly, Rahkeja et al., (2002) stated that vibration near or at 9Hz will cause minimal damage, if at all, to the fingers as it is far enough away from their resonant frequency.

4.2   Glove Characteristics

Most experts agree that there are certain characteristics which dictate whether or not an anti-vibration glove will be successful in attenuating vibration transmissibility. Krajnak et al., (2015) elaborated upon this idea by stating that characteristics such as vibration frequency, grip/push force involved, glove fit, and glove material are important to consider for anti-vibration glove effectiveness. Welcome et al., (2014), has suggested similar information. The authors stated that the thickness of anti-vibration gloves is often the first major adjustment made during the fabrication of a new pair. These authors suggested that while increasing glove thickness beyond the standard may aid vibration transmission, it could likely yield an uncomfortable glove fit; leading to a quicker increase in hand fatigue during tool use. Similarly, Wu et al., (2012) stated that the thickness of glove materials can potentially modify cutaneous sensation and influence grip force regulation. Wu et al., (2012) also noted that material stiffness should be considered a primary design characteristic in addition to glove thickness during the fabrication of an ergonomically correct anti-vibration glove. While the reasoning presented in both studies are biomechanically sound, the methodology in which anti-vibration gloves were assessed is not applicable under all circumstances as vibration transmissibility was mainly

assessed in the fingers and not in the palm of the hand. Despite this, Cabecas, and Milho (2011) seem to validate the aforementioned findings due to their study involving the entire hand; confirming that glove condition as well as the type of hand grip will have an effect on physiological fatigue. In additon to the physical characteristics of an anti-vibration glove, direction specificity is also an important factor to consider when assessing vibration transmissibility; as there are three axes which vibration can travel along; X, Y, and Z. Hewitt et al., (2014) stated that anti-vibration gloves seem to be the most effective in the Z-direction (along the forearm), and least effective in the Y-direction (horizontally).

4.3   Grip Force

The development of HAVS in workers is often accelerated by increased amounts of fatigue occurring in the muscles within the hand-arm system. As a result, the effect that AV gloves have on grip force should be investigated in order to fully understand vibration transmissibility and injury risk. Griffin (1998) evaluated 10 different gloves during the use of 20 power tools adhering to the ISO protocol for testing AV gloves. The author stated that an AV glove that allowed for the most control over grip force exertion would result in the best overall attenuation in vibration transmissibility. Furthermore, the design on an AV glove should focus on the minimization of grip force during use. Welcome et al., (2011) suggested that reducing grip force could also decrease the resonant frequency of the fingers, therefore reducing overall vibration transmissibility. In addition, Dong et al., (2014) stated that forces applied to the tool by the worker (to manipulate the tool) will affect tool vibration. Therefore, applying less force to the tool equals less overall amplification of the vibration at hand.

Wearing any form of gloves will result in a reduction in grip strength (Willms et al., 2009). More specifically, wearing gloves will result in a 5-30% decrease in grip strength which

may be too much to risk during tool use (Cabecas et al., 2011).   During tasks involving gripping powered hand-tools, the wrist extensors, particularly extensor carpi ulnaris is activated the most, even more than any of the wrist flexors (Cabecas et al., 2011). Interestingly, Cabecas et al., (2011) stated that grip strength reduction should be a major parameter in selecting an appropriate glove design, as gloves may alter the muscle recruitment and force output of forearm musculature during tool usage. This is problematic, considering some AV gloves are likely to result in increased grip force and forearm muscle fatigue during use. This, along with repetitive motions from the workplace task (i.e. a power tool), can be associated with an increased risk of upper extremity musculoskeletal disorders.

4.4   Glove Impact on Forearm EMG

With regard to the effects of AV gloves on forearm muscle activity, there has been minimal research conducted on this matter. Cabecas et al. (2011), examined four muscles of the forearm during simulated tool use; extensor carpi ulnaris (ECU), extensor carpi radialis (ECR), flexor digitorum superficialis (FDS) and flexor carpi ulnaris (FCU). Cabecas et al. (2011) reported ECU exhibited the largest increase in activity, which may be influenced the most by AV gloves. In addition it was noted that FDS exhibited a decrease in activity during gloved tasks. Furthermore, ECR was the muscle with the lowest amount of activation throughout all gloved tasks compared to bare hand tasks. Overall, Cabecas et al. (2011) reported no significant differences in muscle activity across each of the four muscles during barehand, and gloved tool usage; imploring more research to be conducted on this subject with special attention given to ECU during tool use in future studies.

4.5   Air Bladder Inserts

Most of the work concerning the efficiency of AV gloves examines the effectiveness of air-bladder inserts rather than their gel-filled counterparts. According to Jetzer et al. (2003), the mechanism behind the air bladder in these gloves is that it increases the contact surface area of the AV glove, therefore absorbing more vibration before it reaches the hand. The effectiveness of air-bladder inserts within AV gloves is elaborated upon by Welcome et al. (2011) due to the fact that these authors demonstrated that air-bladder insert AV gloves are very proficient at reducing vibration transmissibility along the forearm direction. In addition, after initial praise of air-bladder insert AV gloves it appears that other studies contribute more opinions concerning air-bladder gloves that were previously unmentioned. Sauni et al. (2015) mention that air-bladder insets are essentially massless, which can potentially decrease any excess strain on the structures of the hand. Similarly, Wu et al. (2012) stated that air-bladder insert AV gloves are light weight, and low cost. Although the aforementioned studies praise air-bladder gloves, there is no comparison between any other glove types within the studies themselves, making the conclusions seem premature. A study conducted by Reynolds et al., (2005), concluded that air-bladder insert AV gloves may pose further problems with tools that require fine movements such as those found in dental hygiene. These authors argue that air-bladder units impede dexterity, leaving a more malleable material to be desired within the structure of an AV glove.

4.6   Gel-based Inserts

Gel-based insert AV gloves consist of an outer lining, which can be made from any material used for clothing, as well as a gel-filled casing located at the palm and fingers of the glove. Despite the malleability of the gel in these gloves, only one study in the existing literature conducted by Dong et al. (2014), comments on the specific properties regarding gel-filled gloves.

Furthermore, it appears as though a very minute amount of gel-based insert AV gloves utilized in previous research actually met ISO standards in order to be considered a true AV glove. This is alarming, as a noticeable amount of other studies utilize gel-based insert AV gloves during data collection. Even though Dong et al. (2014) discuss the properties of gel-based insert AV gloves; their findings are exploratory. Essentially, all that was stated was that ISO standards dictate that a gel must have a vibration transmissibility rating of less than 60%. Welcome et al. (2014) have attempted to investigate factors such as gel density in relation to vibration transmissibility in the past, however due to the investigation of many other glove properties such as material, and stiffness; minimal information was obtained on this aspect.   Virtually no other article in the literature discusses properties of gel-based insert AV gloves that may have a significant effect on vibration transmissibility. It is apparent that the characteristics of gel inserts such as gel composition, and gel density contribute to one of the largest gaps in the literature concerning the effectiveness of AV gloves and vibration transmissibility, as well as a gel-filled casing located at the palm and fingers of the glove. It stands to reason that the characteristics of gel-based insert AV gloves such as gel composition, and gel density contribute to one of the largest gaps in the literature concerning the effectiveness of AV gloves and vibration transmissibility.

4.7   Factors Affecting Transmissibility Of AV Gloves

There are many characteristics which influence transmissibility of HTV, however, such factors are not yet well understood (Khairil et al., 2017). Primarily, the stiffness and dampening properties of a gel-based insert are the two variables considered to be most important when determining transmissibility (Dong et al., 2013). A reduction in stiffness most likely yields a reduction in transmissibility as well; suggesting softer materials may attenuate HTV better. Despite this, softer materials may decrease overall physical protection from other forms of injury

such as lacerations and abrasions (Khairil et al., 2016). Dong et al. (2014) also suggest the effectiveness of these inserts is also specific to tool type and direction in which the tool's driving-point is located.

Contact area is also a factor influencing transmissibility of gel-based inserts (Khairil et al., 2016). When the amount of contact area is changed, a change in stiffness and dampening properties of the AV glove is reflected as well (Khairil et al., 2016).

The influence of varying thickness of gel-based inserts within AV gloves has recently begun to be explored as well. Thicker gel-based inserts will require more grip force in order to grasp and properly control tools; which increases potential for injury (Hewit et al., 2016). While research on the aforementioned factors and their effects is receiving attention, there remain quite a few unknowns; especially how each factor interacts with a variable such as muscle activity.

Differences in AV glove materials influence the vibration attenuation capabilities. Yun et al., (2011), stated that the external fabric of the glove has demonstrated variability with regard to vibration attenuation. The authors implemented ISO-5359 standards to assess the vibration attenuating abilities of leather, rubber-coated, sponge, and cotton gloves. The materials were found to be most effective in the order of leather, fabrics, rubber-coated, and sponge. Sponge is most effective below 10 Hz, while rubber most effective at 100 Hz or greater. The authors stated the most effective material is a combination of gel, sponge, and rubber with regard to the testing frequency range outlined by ISO 10819. Rezali et al., (2014) compared the effects of foam and gel materials within AV gloves. Participants were instructed to exert 10N of push force downwards onto the material while vibration ranging from 5 to 500Hz was transmitted into the material. Rezali et al., (2014) found both the foam and gel materials attenuated vibration at the palm at frequencies greater than 20Hz, but amplified vibration at the fingers.

REFERENCES

Almagirby, A., Carré, M. J., & Rongong, J. A. (2017). A new methodology for measuring the vibration transmission from handle to finger whilst gripping. International Journal of Industrial Ergonomics, 58, 55-61. doi:10.1016/j.ergon.2017.02.011

Azmir, N. A., & Yahya, M. N. (2017). Prevalence of Hand-transmitted Vibration Exposure among Grass-cutting Workers using Objective and Subjective Measures. IOP Conference Series: Materials Science and Engineering, 165, 012026. doi:10.1088/1757-899x/165/1/012026

Bovenzi, M. (2006). Acute effects of force and vibration on finger blood flow. Occupational and Environmental Medicine, 63(2), 84-91. doi:10.1136/oem.2004.019703

Cabeças, J., & Milho, R. (2011). The efforts in the forearm during the use of anti-vibration gloves in simulated work tasks. International Journal of Industrial Ergonomics, 41, 289-297.

Chen, X., Green, P. G., & Levine, J. D. (2010). Neuropathic pain-like alterations in muscle nociceptor function associated with vibration-induced muscle pain. Pain, 151(2), 460-466. doi:10.1016/j.pain.2010.08.004

De Luca, C. J. (1997). The use of surface electromyography in biomechanics. Journal of Biomechanics, 13(2), 135-163. doi:10.1016/0021-9290(94)91124-x

Dong, R., Mcdowell, T., Welcome, D., Warren, C., Wu, J., & Rakheja, S. (2009). Analysis of anti-vibration gloves mechanism and evaluation methods. Journal of Sound and Vibration, 435-453.

Dong, R., Wu, J., & Welcome, D. (2005). Recent Advances in Biodynamics of Human Hand-Arm System. Industrial Health Ind Health, 43, 449-471.

Dong, R., Welcome, D., Peterson, D., Xu, X., Mcdowell, T., Warren, C., . . . Brammer, A. (2014). Tool-specific performance of vibration-reducing gloves for attenuating palm-transmitted vibrations in three orthogonal directions. International Journal of Industrial Ergonomics, 44, 827-839.

Gerhardsson, L., & Hagberg, M. (2014). Work ability in vibration-exposed workers. Occupational Medicine, 64(8), 629-634. doi:10.1093/occmed/kqu121

Griffin, M. (1998). Evaluating the effectiveness of gloves in reducing the hazards of hand-transmitted vibration. Occupational and Environmental Medicine, 55, 340-348.

Gurram, R., Rakheja, S., & Gouw, G. (1994). Vibration transmission characteristics of the human hand-arm and gloves. International Journal of Industrial Ergonomics, 13, 217-234.

Hewitt, S., Dong, R., Welcome, D., & Mcdowell, T. (2014). Anti-Vibration Gloves? Annals of Occupational Hygiene, 59(2), 127-141. doi:10.1093/annhyg/meu089

Hewitt, S., Dong, R., Mcdowell, T., & Welcome, D. (2016). The Efficacy of Anti-vibration Gloves. Acoustics Australia, 44(1), 121-127. doi:10.1007/s40857-015-0040-5

Holmes, M. W., Tat, J., & Keir, P. J. (2015). Neuromechanical control of the forearm muscles during gripping with sudden flexion and extension wrist perturbations. Computer Methods in Biomechanics and Biomedical Engineering, 18(16), 1826-1834. doi:10.1080/10255842.2014.976811

Hua, Y., Lemerle, P., & Ganghoffer, J. (2017). A two scale modeling and computational framework for vibration-induced Raynaud syndrome. Journal of the Mechanical Behavior of Biomedical Materials, 71, 320-328. doi:10.1016/j.jmbbm.2017.03.019

Idzior-Waluś, B. (1987). Coronary risk factors in men occupationally exposed to vibration and noise. European Heart Journal, 8(10), 1040-1046. doi:10.1093/oxfordjournals.eurheartj.a062168

Jetzer, T., Haydon, P., & Reynolds, D. (2003). Effective Intervention with Ergonomics, Antivibration Gloves, and Medical Surveillance to Minimize Hand–Arm Vibration Hazards in the Workplace. Journal of Occupational and Environmental Medicine, 45(12), 1312-1317.

Khairil Anas Md Rezali & Michael J. Griffin (2017) Transmission of vibration through gloves: effects of contact area, Ergonomics, 60:1, 69-81, DOI:10.1080/00140139.2016.1170210

Khairil Anas Md Rezali & Michael J. Griffin (2016) Transmission of vibration through gloves: effects of material thickness, Ergonomics, 59:8, 1026-1037,DOI:10.1080/00140139.2015.1102334

Krajnak, K., Waugh, S., Johnson, C., Miller, R., Welcome, D., Xu, X., Dong, R. (2015). Antivibration Gloves: Effects on Vascular and Sensorineural Function, an Animal Model. Journal of Toxicology and Environmental Health, Part A, 78, 571-582. doi:10.1080/15287394.2015.1014079

Larivière, C., Tremblay, G., Nadeau, S., Harrabi, L., Dolez, P., Vu-Khanh, T., Lara, J., 2010. Do mechanical tests of glove stiffness provide relevant information relative to their effects on the musculoskeletal system? A comparison with surface electromyography and psychophysical methods. Applied Ergonomics 41, 326e334.

Mahbub, M., Kurozawa, Y., Ishitake, T., Kume, Y., Miyashita, K., Sakakibara, H., Harada, N. (2015). A systematic review of diagnostic performance of quantitative tests to assess musculoskeletal disorders in hand-arm vibration syndrome. Industrial Health INDUSTRIAL HEALTH, 53(5), 391-397. doi:10.2486/indhealth.2014-0221

Matoba, T. (2015). Human response to vibration stress in Japanese workers: lessons from our 35-year studies A narrative review. Industrial Health INDUSTRIAL HEALTH, 53(6), 522-532. doi:10.2486/indhealth.2015-0040

McDowell, T.W., Dong, R.G., Welcome, D.E., Warren, C., Xu, X.S., 2013a. Vibration reducing gloves: transmissibility at the palm of the hand in three orthogonal directions. Ergonomics 56 (12), 1823e1840.

Mogk, J. P., & Keir, P. J. (2007). Prediction of forearm muscle activity during gripping. Ergonomics, 49(11), 1121-1130. doi:10.1080/00140130600777433

National Institute for Occupational Safety and Health. (1989). Criteria for a recommended standard: occupational exposure to hand-arm vibration. U.S. department of health and human services, 18-26.

Palmer, K. T. (2000). Prevalence of Raynaud's phenomenon in Great Britain and its relation to hand transmitted vibration: a national postal survey. Occupational and Environmental Medicine, 57(7), 448-452. doi:10.1136/oem.57.7.448

Pelmear, P., & Leong, D. (2000). Review of occupational standards and guidelines for hand-arm (segmental) vibration syndrome (HAVS). Applied Occupational and Environmental Hygiene, 15(3), 291-302.

Perotto, A. O. (2005). Anatomical Guide for Electromyographer: the Limbs and Trunk. Springfield: Charles C Thomas Publisher, LTD.

Poole, C. J., & Cleveland, T. J. (2015). Vascular hand–arm vibration syndrome—magnetic resonance angiography. Occupational Medicine, 66(1), 75-78. doi:10.1093/occmed/kqv151

Poole, K., & Mason, H. (2005). Disability in the Upper Extremity and Quality of Life in hand-arm vibration syndrome. Disability and Rehabilitation, 27(22), 1373-1380. doi:10.1080/09638280500164610

Rakheja, S., Dong, R., Welcome, D., & Schopper, A. (2002). Estimation of tool-specific isolation performance of antivibration gloves. International Journal of Industrial Ergonomics, 30, 71-87.

Rezali, K. A., & Griffin, M. J. (2017). Transmission of vibration through gloves: effects of contact area. Ergonomics, 60(1), 69-81. doi:10.1080/00140139.2016.1170210

Rezali, K. A., & Griffin, M. J. (2014). The Transmission of Vibration through Gloves to the Hand and to the Fingers: Effects of Material Dynamic Stiffness. Applied Mechanics and Materials, 564, 149-154. doi:10.4028/www.scientific.net/amm.564.149

Reynolds, D. (2001). Design of antivibration gloves. Canadian Acoustics, 29(3), 15-17.

Reynolds, D., & Wolf, E. (2005). Evaluation of antivibration glove test protocols associated with the revision of ISO 10819. Industrial Health, 43, 556-565.

Sauni, R., Toivio, P., Pääkkönen, R., Malmström, J., & Uitti, J. (2015). Work disability after diagnosis of hand-arm vibration syndrome. Int Arch Occup Environ Health International Archives of Occupational and Environmental Health, 88, 1061-1068. doi:10.1007/s00420-015-1034-1

Shen, S., & House, R. (2017). Hand-arm vibration syndrome what family physicians should know. Canadian Family Physician, 63(3), 206-210. doi:PMC5349719

Waugh, S., Kashon, M. L., Li, S., Miller, G. R., Johnson, C., & Krajnak, K. (2016). Transcriptional Pathways Altered in Response to Vibration in a Model of Hand-Arm Vibration Syndrome. Journal of Occupational and Environmental Medicine, 58(4), 344-350. doi:10.1097/jom.0000000000000705

Welcome, D., Dong, R., Xu, X., Warren, C., & Mcdowell, T. (2014). The effects of vibration-reducing gloves on finger vibration. International Journal of Industrial Ergonomics, 44, 45-59.

Wells, R., Hunt, S., Hurley, K., Rosati, P. (2010). Laboratory assessment of the effect of heavy rubber glove thickness and sizing on effort, performance and comfort.International Journal of Industrial Ergonomics 40, 386e391.

Willms, K., Wells, R., & Carnahan, H. (2009). Glove Attributes and Their Contribution to Force Decrement and Increased Effort in Power Grip. Human Factors, 51(6), 797-812. doi:10.1177/0018720809357560

Wimer, B., Welcome, D., & Dong, R. (2012). An analysis of contact stiffness between a finger and an object when wearing an air-cushioned glove: The effects of the air pressure. Medical Engineering & Physics, 34, 386-393.

Wu, J., Wimer, B., Welcome, D., & Dong, R. (2012). An analysis of contact stiffness between a finger and an object when wearing an air-cushioned glove: The effects of the air pressure. Medical Engineering & Physics, 34, 386-393.

Ye, Y., Mauro, M., Bovenzi, M., & Griffin, M. J. (2015). Reduction in finger blood flow induced by hand-transmitted vibration: effect of hand elevation. International Archives of Occupational and Environmental Health, 88(7), 981-992. doi:10.1007/s00420-015-1027-0

Youakim, S. (2012). The compensation experience of hand-arm vibration syndrome in British Columbia. Occupational Medicine, 62(6), 444-447. doi:10.1093/occmed/kqs033

Yun, H., Jang, S., Seo, C., & Lee, J. (2011). The Effect of Vibration Reduction on the Anti-vibration Gloves Made of Different Materials. Epidemiology, 22. doi:10.1097/01.ede.0000392492.28537.69

CHAPTER 3: MANUSCRIPT

THE EFFECTS OF A VISCO-ELASTIC POLYMER GLOVE ON HAND-ARM VIBRATION, MUSCLE ACTIVITY AND COMFORT DURING SIMULATED POWER TOOL USE

AUTHOR: RYAN ALEXANDER SHIVPAUL

INSTITUTION: THE UNIVERSITY OF ONTARIO INSTITUTE OF TECHNOLOGY

FACULTY OF HEALTH SCIENCES

OSHAWA, ON CANADA

L1H7K4

CONTACT: ryan.shivpaul@uoit.ca

1.0 ABSTRACT

Prolonged exposure to hand-transmitted vibration (HTV) as a result of power tools can lead to hand-arm vibration syndrome (HAVS). The effectiveness of anti-vibration (AV) gloves for the reduction of hand arm vibration remains unclear. The ability of a glove to attenuate vibration is largely influenced by the material properties and forearm muscle activity during tool use. Visco-elastic polymer (gel-based) and air-bladder AV gloves are the most common options, however the material properties of gel based options have seen little attention. The purpose of this study is to investigate vibration transmissibility, forearm muscle activity and subjective grip dexterity using a variety of gel-based compositions and designs. Participants completed six simulated hand-held power tool tasks. RMS vibration, grip force, muscle activity, and perceived levels of comfort, dexterity, onset of forearm muscle fatigue and impairment of tactile sensation were collected. Vibration attenuation was most effective along the Z axis, particularly with inserts which possessed properties such as decreased contact stiffness, as well as increased mass, elasticity and viscosity performing better. Further investigation of visco-elastic polymers using the ISO standardized protocol is needed.

Keywords: Hand-Transmitted Vibration, Hand-Arm Vibration Syndrome, Muscle Activity, Grip Force, Visco-elastic Polymer, Anti-Vibration Gloves

2.0 INTRODUCTION

Many professional occupations involve the use of powered hand-tools. As such, the use of powered hand-tools involves repetitive physical labour, wherein an individual may be exposed to large quantities of hand transmitted vibration (HTV) over the course of a single work day. Large exposures of HTV can lead to numerous types of injuries including musculoskeletal, sensorineural, and vascular, with each falling under the condition known has hand arm vibration syndrome (HAVS) (Pelmear & Leong, 2000). More specifically, musculoskeletal complications can include hand-arm musculature atrophy, mechanical hyperalgesia, swelling and discomfort as well as motor function impairment (Chen et al., 2010). Vascular complications can include Raynaud's phenomenon, ulnar artery thrombosis and the most prominent vascular complication associated with HAVS, vibration induced white-finger (VWF) (Ye et al, 2015). Sensorineural challenges are perhaps the most detrimental, including complications such as numbness, paresthesia, compressive neuropathies of the median and ulnar nerves, digital sensory neuropathies, decreased nociceptor sensitivity, VWF, and carpal tunnel syndrome (Gerhardsson & Hagberg, 2014). With regard to long-term challenges, individuals who are afflicted with HAVS may eventually suffer the loss of the entire hand-arm system functionally, and in the literal sense if amputation is necessitated by the presence of gangrene (Pelmear & Leong, 2000). HAVS is an issue which requires immediate attention, as it is estimated there are 72,000 to 144,000 cases of individuals suffering from HAVS in Canada alone (Shen & House, 2017). Furthermore, approximately 50% of individuals exposed to hand-arm vibration in the workplace currently have, or will acquire HAVS at some point in their career (House, 2012). Further complicating the issue is the fact that acute diagnosis and mechanism of injury is never apparent, with the time necessary for symptoms to manifest ranging from 1 month to 30 years of exposure

(Pelmear & Leong, 2000). Overall, HAVS can lead to a decrease in the work ability and quality of life of many individuals (Sauni et al., 2015).

In order to significantly address the issues presented by HAVS, a suitable method of HTV reduction may be the best approach. Anti-vibration (AV) gloves have been widely accepted as a proposed method of attenuating HTV exposure during the use of power tools (Griffin, 1998).   AV gloves are advantageous due to the protection they offer from abrasions and lacerations, hot or cold environments, as well as their potential to reduce the amount of HTV by approximately 5-58% (Dong et al., 2014). Numerous designs of AV gloves have been conceptualized and implemented, however, most do not provide adequate HTV attenuation, or fail to meet ISO standards to be considered certified AV gloves (Dong et al., 2009), thus additional research is needed into the efficacy of AV glove use.

While the existing literature has examined specific vibration frequencies and their relationship with AV gloves, there are controversies around which glove material accommodates the widest range of frequencies, or what glove characteristics should be manipulated for best results when attempting to attenuate HTV. The two main types of AV glove inserts currently in existence include: an air-bladder insole AV glove, and a gel-based insole AV glove. Previous research has consisted of limited examination of the effectiveness of such AV gloves, specifically concerning how properties such as overall glove stiffness, thickness, mass, and external glove design affect vibration transmissibility (Dong et al., 2009). Air-bladder insert AV gloves significantly reduce vibration transmissibility; however, impede dexterity (Wimer et al., 2012). On the other hand, gel-based insole AV gloves offer increased comfort and dexterity; however, the vast majority of current designs do not attenuate HTV between 25-200Hz for medium frequencies, and 200-1250Hz for high frequencies while meeting ISO standards (Dong

et al., 2009). Increasing the thickness of a gel insole to the point where it attenuates HTV across all frequencies is not a viable option as a thick gel has disadvantages such as reducing manual dexterity, the ability to grasp, and can reduce the amount of sensory input during tool use; increasing handgrip fatigue rates (Wells et al., 2010). Moreover, if the gel insole is too thin, it will attenuate little HTV. When designing an appropriate AV glove, reducing any amount of superfluous grip force required during tool usage is ideal. However, the question of what characteristics within a visco-elastic composition of gel insoles would accomplish this best within an AV glove remains unknown.

The response to fatigue that is imposed on the skeletal muscle of the hand-arm system is a variable that is also in need of further investigation. Limited research has been conducted regarding forearm EMG, as well as forearm muscle fatigue during AV glove usage. Of the research which has attempted to examine forearm muscle activity and fatigue during tool use with AV gloves, the main conclusions are that thicker AV gloves will produce forearm muscle fatigue more quickly and impede grip (Cabecas et al., 2011). Moreover, whether or not one muscle group, or a single muscle in particular is more active during tool usage with AV gloves is in need of a more explicit answer. In addition, how different gel material properties and designs affect forearm musculature during hand-held power tool usage is in need of investigation.

The material composition of visco-elastic polymers can be altered during the manufacturing process and working with a custom producer of gel will allow for unique properties to be tested, rather than the unknown gel composition used in most gel based AV gloves today. Gel material properties, coupled with a glove palm insert design could be an improved solution to current gel based options. The purpose of this study was to investigate vibration attenuation, forearm muscle activity, grip force and subjective perception of comfort,

gripping ability, dexterity, and tactile sensation using a variety of gel-based compositions and designs during a simulated power tool task.

3.0 METHODS

3.1   Participants

Twelve right-hand dominant individuals (six males, six females) participated (Table 1). All individuals were free from injuries to the upper extremity in the past 12 months. Prior to participation, participants signed Informed Consent and the study was approved by the University of Ontario Institute of Technology Research Ethics Board (REB # 14-046).

Table 1. Mean (±SD) participant demographics

	Female	**Male**
Age (years)	26 ± 10.3	26.3 ± 8.2
Height (cm)	163.3 ± 12.5	180.0 ± 9.2
Weight (kg)	54.4 ± 6.3	85.2 ± 8.1

3.2 Glove Development

The prototype AV gloves used in this study were developed with three principal concepts in mind: 1) vibration attenuation, 2) reducing forearm muscle activity, and 3) maintaining grip force and comfort. To begin the process, three-dimensional (3-D) drawings were rendered using AutoCAD (Autodesk Inc.). See figure 1 for AutoCAD drawings development. These designs included supplementary layers of gel across the 2nd to 5th palmar metacarpal surfaces, as well as the hypothenar and thenar eminences for added comfort and grip. Moreover, one glove was

designed with a similar layout to some current air bladder gloves on the market with gel-based

layers instead of sealed air bladder pockets (figure 1, middle). Next, the AutoCAD renderings

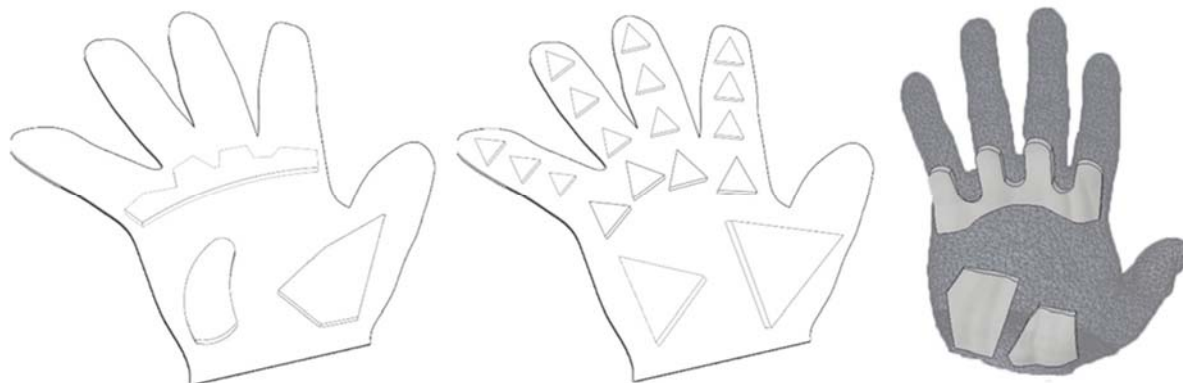were used to produce 3-D printed prototypes of the designs (Figure 2).

Figure 1: Left/Middle, two examples of AutoCAD designs and Right, a 3-D hand perspective of another design. Each design included a base layer (difficult to see in the perspective shown) and additional thick layers strategically placed.

Figure 2: Sample of 3-D printed prototypes. Left, base layer. Middle/right, base layers plus additional layers.

We specifically worked with a custom producer of visco-elastic polymers (gel) for the glove development (Hexyoo Scientific Inc, Scarborough, ON). The manufacturing process for the gel allowed us to manipulate the gel composition, resulting in a variety of material properties that could be manipulated. Thus, gel was produced for the design with various viscoelastic properties. The 3D prints served as templates to be traced onto sheets of gel which were then cut. Finally, the gloves which required additional layers were adhered to the base layer using Gorilla Glue. An existing AV glove manufactured by Ergodyne (ProFlex® 9002 Cert. AV Glove w/Dorsal Protection, Ergodyne, Saint Paul, Minnesota, USA) was also tested in this study (Figure 3). The Ergodyne gloves contained a patented Nu202® gel polymer palm pad, and is an ANSI S2.73/ISO 10819-certified glove, typically referred to as a foam padding. Additional Ergodyne Proflex gloves were used to produce the gel prototypes for testing. The inserts were removed from the Ergodyne gloves and replaced with the newly fabricated gel inserts. Each gel-insert had similarities and was comprised of a base layer that spanned from the finger tips to the base of the palm. However, each gel-insert varied with regard to thickness, material properties (gel composition), and the overall placement of additional gel pieces attached to the base layer for added thickness. Glove 1 was the default Ergodyne glove and was not altered in any way. Glove 2 had a base layer of gel that was 7mm thick. Glove 3 had a base layer of gel that was 4mm thick, and had 7mm thick supplementary palmer layers (the additional pieces were a more viscous gel material than the base layer). Glove 4 had a base layer of gel that was 5mm thick and had 4mm supplementary palmer layers. Lastly, Glove 5 had a base layer of gel that was 4mm thick, and had 4mm thick triangular supplementary layers adhered to the base layer from each fingertip to the base of the palm. See figure 3 for gel glove prototypes used in this study.

Figure 3: AV gloves tested. Glove 1: Standard Ergodyne 5mm Foam Glove (Proflex 9002 by Ergodyne Saint Paul, Minnesota, USA); Glove 2: 7mm gel-insert; Glove 3: 4mm gel-insert with 7mm palm inserts; Glove 4: 5mm gel-insert with 4mm palm inserts; Glove 5: 4mm gel-inssert with 4mm triangular finger-to-palm inserts. Note: Gloves 2, 3 and 5 had the same gel composition as the base layer (but thickness varied). The thicker inserts on Glove 3 had a gel with different material properties than the base layer. Glove 4 consisted of a gel base and thicker insert pieces that had different material properties from Gloves 2, 3 and 5.

3.3   Experimental Setup

In order to investigate the HTV attenuating properties of the prototype gel-based gloves, a modality of vibration production, as well as a method of assessment was required. Vibration was induced by a MAXIMUM™ ½-inch impact wrench (Figure 4) and a custom steel apparatus (Figure 4). The apparatus was a 0.5 cm thick piece of steel, which stands approximately 62 cm tall, 17 cm wide, with a 12cm x 26cm base, and a steel support rod welded from the base to the top of the apparatus for support. Five bolts threaded with five lug nuts welded onto the front face of the apparatus in a star-shape formation, allowed lug nuts to be fastened and removed similar to a mechanic performing the task. This apparatus was secured to the top of a height adjustable table using industrial C-clamps. 0.24cm lug nuts were used along with the corresponding sized socket for the impact wrench.

Figure 4: MAXIMUM™ ½-inch impact wrench used to adjust bolts on custom steel apparatus.

Figure 5: Experimental setup involving a custom steel apparatus designed to emulate the position of lug nut bolts on an automobile.

3.3   Protocol

Each participant was provided with a pair of safety glasses and earplugs. In addition, each participant received instruction regarding power tool operation, as well as several opportunities at trial runs for the safety purposes prior to data collection. Prior to performing the impact wrench task, participants were instructed to complete a series of randomized maximal grip trials

involving the five gloves (Figure 3) as well as a barehand trial. Participants were instructed to

hold a grip dynamometer, standing, with the elbow flexed to 90 degrees. Peak grip force

(newtons), was recorded and two minutes of rest was given between each trial to minimize the

effects of muscle fatigue prior to the hand-arm vibration simulation. Following a five-minute

rest period, muscle specific maximal voluntary contractions (MVCs) were performed for each

muscle unilaterally including; flexor digitorum superficialis (FDS), flexor carpi ulnaris (FCU),

flexor carpi radialis (FCR), extensor carpi ulnaris (ECU), extensor carpi radialis longus (ECRL),

and extensor digitorum longus (EDL). This was performed to obtain maximal voluntary

excitation (MVE) for each muscle and was used for the purpose of normalizing muscle activity

during the vibration protocol. For the forearm extensors, manual resistance of wrist extension

was applied, along with ulnar, or radial deviation as necessary for ECU and ECR. In the case of

the forearm flexors, manual resistance of wrist flexion was applied along with ulnar, or radial

deviation as necessary for FCU and FCR. Moreover, manual resistance opposing finger flexion

and extension were also applied in the case of FDS and EDS.

Following MVC's, an accelerometer (detailed below) was strapped to the back of the

participant's hand approximately at the head of the third metacarpal, as recommended by ISO

5349 standards (Figure 6). A combination of 3M adhesive tape, as well as Hypafix (BSM

Medical, Canada) dressing tape was used to rigidly secure the accelerometer. Participants were

instructed to stand in front of the apparatus, starting each trial with the elbow flexed to 90

degrees, and a neutral wrist. Participants were then asked to grip the impact wrench with their

right hand on the base, using the left hand as a stabilizer around the barrel of the impact wrench.

This posture was strictly enforced throughout the trials. Participants were then instructed to

tighten the bolts on the apparatus in a star-shaped pattern (Figure 7), followed by loosening the

bolts in the reverse order. Following this, participants completed the same task with each glove, in a randomized order. Each trial lasted approximately 1 minute. Five-minute rest intervals were allotted in between each trial to allow for any residual fatigue of soft tissues to dissipate. Following the completion of the task with each glove, a subjective questionnaire was given to each participant The questionnaire sought to obtain an understanding of each participant's perception of each AV glove with regard to comfort, usability, and grip impediment. The questionnaire took the form of Likert scales ranging from one to five for each question, one representing an opinion of "Strongly Disagree", three representing a neutral stance, and five being "Strongly Agree".

Figure 6: Position of accelerometer on the back of the hand.

Figure 7: Experimental procedure, participants would tighten bolts in the order indicated, followed by loosening the bolts in the reverse order.

3.4 Instrumentation

3.4.1   Vibration

For the purpose of assessing vibration, a Series 2 10G tri-axial accelerometer (NexGen Ergonomics, Montreal, QC) was used to collect HTV during simulated tool use (Figure 8). In addition, vibration signals collected were expressed in m/s^2 as a root-mean-square (RMS) value to produce a final value in accordance with the weighted frequencies outlined by ISO. Data was collected at a sampling rate of 1000Hz and the DataLOG MWX8 (Biometrics, United Kingdom, 1.2V, 129g, 104 x 62 x 22mm) analogue to digital converter stored the files for processing.

Figure 8: Series 2 10G tri-axial accelerometer (NexGen Ergonomics, Montreal, QC) used to quantify HTV during simulated tool use.

3.4.2 Electromyography

A Trigno^{TM} Wireless EMG system with two parallel-bar surface electrodes and a 10mm inter-electrode distance was used to collect activity from six forearm muscles (20-450Hz, CMRRN 80 dB, input impedance 1015 Ω, Delsys Inc., Boston, USA). Electrodes were placed unilaterally over each muscle belly in line with muscle fiber orientation and included: flexor digitorum superficialis (FDS), flexor carpi ulnaris (FCU), flexor carpi radialis (FCR), extensor carpi ulnaris (ECU), extensor carpi radialis longus (ECRL), and extensor digitorum longus (EDL). Prior to electrode placement, each site was shaved using a disposable razor, and disinfected with alcohol-based wipes. Hypafix tape^{TM} was applied over each electrode in an attempt to reduce electrode movement artifact. EMG data were collected using EMG works 4.0 (Delsys Inc., Boston, USA), sampled at 1926Hz (Figure 6). Muscle placements were confirmed with manual resistance and palpation, following guidelines recommended by Perotto (2005) and was similar to previous work (Holmes et al., 2015).

Figure 9: Trigno Delsys wireless EMG system.

3.4.3   Grip Force Measurement

A hand-grip dynamometer (MIE Medical Research Ltd., Leeds, UK) was used to assess each participant's maximum grip force. The hand-grip dynamometer was zeroed before each trial, and each participant's maximum grip force was recorded in Newtons in a posture described earlier. Each grip force trial for each glove was randomized with approximately two minutes of rest between trials to avoid altered results from forearm muscle fatigue.

Figure 10: Hand-grip dynamometer (MIE Medical Research Ltd., Leeds, UK) used to measure grip strength in Newtons.

3.5   Questionnaire

A subjective questionnaire on the experiences each participant had regarding aspects of each glove such as comfort, grip, dexterity, fatigue, and tactile sensation was also implemented

in this study. Each of the five questions allowed participants to respond on a Likert scale with responses ranging from: strongly disagree, disagree, neither, agree, and strongly agree (see appendix).

3.6   Data Analysis

Vibration data was analyzed using the VATS software (NexGen Ergonomics Inc, Pointe Claire, Quebec, Canada) and following the ISO 5349 standard for hand-arm vibration. First, the data range average was used to remove offset from the RMS data using the VATS software. The VATS software calculates the RMS for each of the frequency-weight accelerations in each direction based on the formula presented in ISO 10819 (Figure 11). In this formula, W_h is the frequency weighting factor pertaining to hand-arm vibration exposure outlined by ISO 5349-1, while w_i is the circular frequency in radians corresponding with the ith frequency in the $1/3^{rd}$ octave bands ranging from 6.3 to 1250Hz. The RMS values for total hand-arm vibration were calculated using the formula outlined by ISO 5349-1 (Figure 12). A fast fourier analysis (FFT) was also performed on the vibration data coupled with a Butterworth filter (low cutoff 0.1 Hz, High cutoff 500 Hz and a 2nd order filter). A hanning filtering window was applied to reduce spectral leakage with an average window size of 1024 Hz. Lastly, each of the windows were averaged to produce one result by using an average FTT.

$$T_{w-n} = \sqrt{\overline{\sum_i [T_n(\omega_i) \cdot a_n(\omega_i) \cdot W_h(\omega_i)]^2}}$$

Figure 11: RMS value of frequency-weighted acceleration equation.

$$T_{w-total} = \sqrt{\sum_i \left\{ [T_x(\omega_i) \cdot a_x(\omega_i)]^2 + [T_y(\omega_i) \cdot a_y(\omega_i)]^2 + [T_z(\omega_i) \cdot a_z(\omega_i)]^2 \right\} \cdot W_h^2(\omega_i)}$$

Figure 12: RMS value of total vibration equation.

EMG data had the bias removed (offset) from each EMG channel. Next, a linear envelope (3 Hz cutoff, second order, dual pass Butterworth filter) was applied and all EMG signals were then normalized to the MVC for each muscle. Average and peak muscle activity for each muscle was determined for the entire vibration trial for each glove condition.

3.7   Statistical Analysis

A repeated measures ANOVA was used to compare the vibration attenuation abilities (RMS acceleration), grip force, and muscle activity for each glove during the vibration task. Significant effects were compared using Bonferroni's correction. An alpha level of 0.05 was used within all analyses (SPSS v24.0, IBM Corporation, Somers, NY, USA).

4.0   RESULTS

4.1   Vibration

There were no significant main effects for the amount of attenuation of average RMS ($F_{4,44} = 7.968$, p= 0.17) and peak RMS ($F_{4,44}$ =9.353, p= 0.11) across the different glove designs. Moreover, all gel glove prototypes had average and peak RMS vibration that was not significantly different than the Ergodyne glove (Figure 13). While not significantly different, overall, RMS vibration appeared to be reduced in most gloved trials compared to the bare-hand trial; attenuating a range of 37.5% to 78.3% of HTV during power tool usage. The use of AV gloves in this study exhibited various levels of peak vibration reduction compared to the bare-hand trials. Glove 1, (the unaltered Ergodyne glove), which did not contain a substituted visco-elastic polymer, reduced peak vibration by 42.0%, 37.5% and 51.5% along the X, Y, and Z axis respectively. Despite possessing the thickest gel-based insert, glove 2 amplified vibration, increasing peak vibration up to 11.3%, 14.0%, and 12.5% along the X, Y and Z axis respectively compared to the bare-hand trials. In contrast, glove 3 was the most effective, reducing peak vibration by 57.4%, 56.7%, and 78.3% along the X, Y, and Z axis respectively. Glove 4 reduced peak vibration by 62.3%, 56.6%, and 58% along the X, Y, and Z axis respectively. Lastly, glove 5 reduced peak vibration by 42%, 57.5%, and 51.6% along the X, Y, and Z axis respectively, when compared to the bare-hand trials. Figures 13, 14 and 15 demonstrate the X, Y and Z axis vibration, respectively for all glove and bare-hand trials.

While each glove (except glove 2) demonstrated attenuation compared to the bare-hand trials, the amount of attenuation varied in accordance with each of the three orthogonal axis (Table 2). With regard to the X axis (perpendicular to the tool handle), glove 4, reduced

approximately 62.3% of HTV. The glove which performed best along the Y axis (parallel to the tool handle) was glove 5, which reduced approximately 57.5% of HTV. Lastly, the glove which performed best along the Z axis (along the forearm) was glove 3, which reduced approximately 78.3% of HTV.
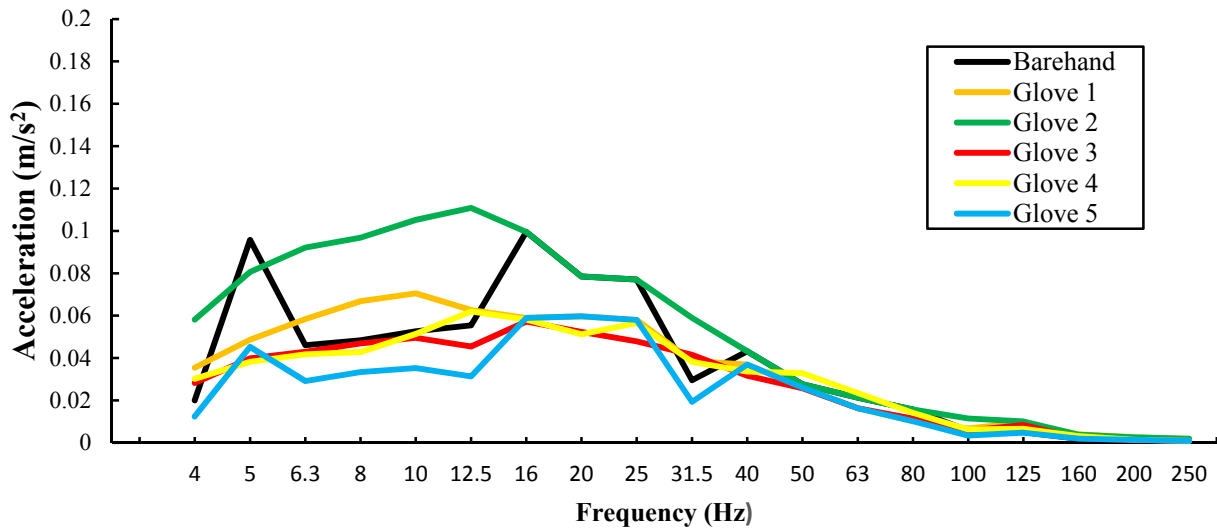

Figure 13. Frequency weighted RMS vibration along the X Axis for each glove and bare-hand trial.
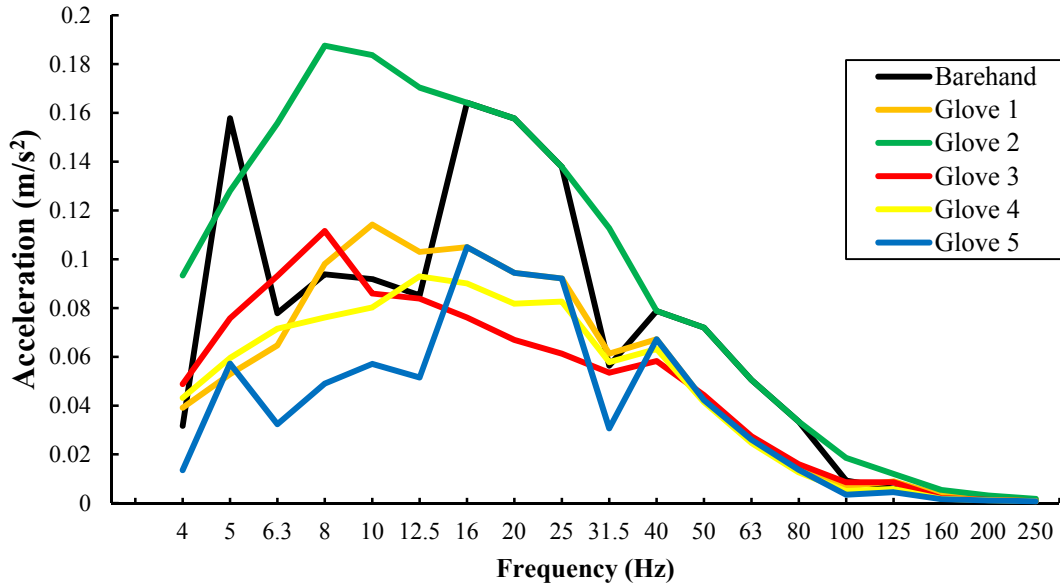
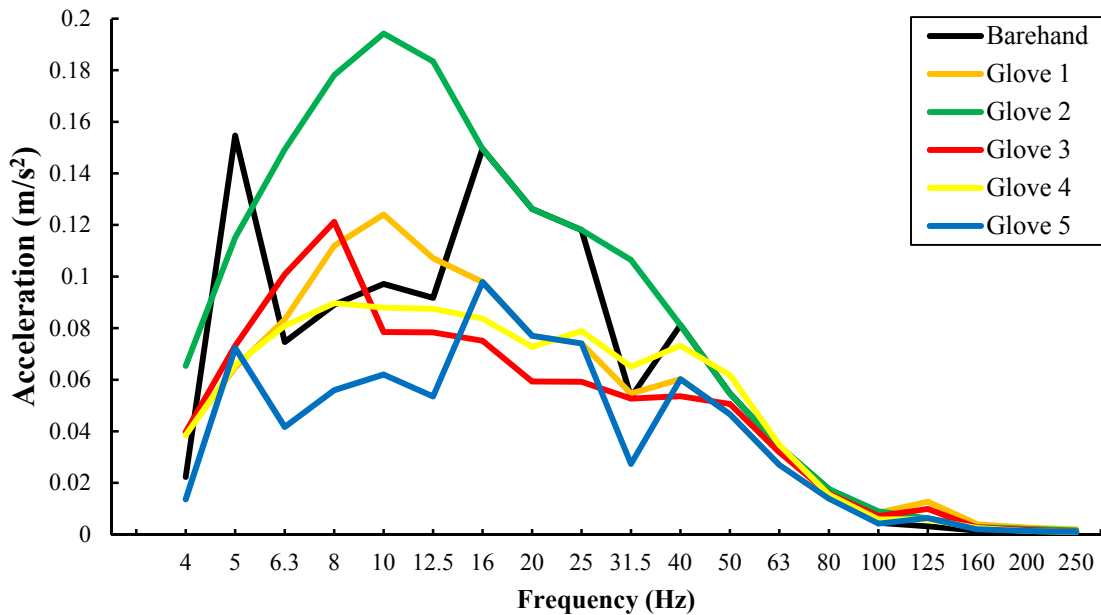**Figure 14.** Frequency Weighted RMS vibration along the Y Axis for each glove and bare-hand trial

Figure 15. Frequency Weighted RMS vibration along the Z Axis for each glove and bare-hand trial.

Table 2. Percentage of vibration reduction for each glove condition as compared to the bare-hand trails for each axis.

Axis	Glove 1 (% Reduction)	Glove 2 (% Reduction)	Glove 3 (% Reduction)	Glove 4 (% Reduction)	Glove 5 (% Reduction)
X	42.0	+ 11.3	57.4	62.3	42.0
Y	37.5	+ 14.0	56.7	56.6	57.5
Z	51.5	+ 12.5	78.3	58.0	51.6

Table 3. Overall Frequency Weighted RMS vibration for the bare hand trials.

	aRMS (m/s²)	Peak (m/s²)	Crest Factor (ratio)
X-axis:	1.45 ± 2.58	78.86 ± 142.47	22.48 ± 20.46
Y-axis:	0.51 ± 1.64	6.78 ± 20.92	18.28 ± 5.39
Z-axis:	0.66 ± 2.13	9.31 ± 29.55	18.23 ± 5.80
Sum:	1.90 ± 3.60	81.62 ± 145.85	25.39 ± 16.55

Table 4. Overall Weighted RMS vibration for Glove 1.

	aRMS (m/s²)	Peak (m/s²)	Crest Factor (ratio)
X-axis:	1.26 ± 2.29	77.82 ± 140.70	24.39 ± 24.89
Y-axis:	0.49 ± 1.60	8.76 ± 28.45	18.12 ± 12.12
Z-axis:	0.51 ± 1.65	8.26 ± 27.14	14.67 ± 8.20
Sum:	1.66 ± 3.13	80.71 ± 144.91	24.08 ± 21.99

Table 5. Overall Weighted RMS vibration for Glove 2.

	aRMS (m/s²)	Peak (m/s²)	Crest Factor (ratio)
X-axis:	1.60 ± 2.37	98.20 ± 146.28	30.55 ± 26.00
Y-axis:	1.45 ± 3.56	48.28 ± 141.24	20.85 ± 12.21
Z-axis:	1.18 ± 2.70	12.86 ± 29.56	13.07 ± 5.48
Sum:	2.81 ± 4.85	126.33 ± 195.07	27.31 ± 23.80

Table 6. Overall Weighted RMS vibration for Glove 3.

	aRMS (m/s²)	Peak (m/s²)	Crest Factor (ratio)
X-axis:	2.47 ± 2.61	155.13 ± 163.58	38.26 ± 29.92
Y-axis:	0.74 ± 2.47	23.55 ± 79.48	20.87 ± 11.95
Z-axis:	0.70 ± 2.34	27.79 ± 95.08	13.96 ± 8.68
Sum:	3.10 ± 3.96	176.44 ± 189.36	37.92 ± 29.86

Table 7. Overall Weighted RMS vibration for Glove 4.

	aRMS (m/s^2)	Peak (m/s^2)	Crest Factor (ratio)
X-axis:	1.70 ± 2.50	101.30 ± 150.93	27.86 ± 26.46
Y-axis:	0.77 ± 2.57	23.96 ± 81.12	19.56 ± 12.52
Z-axis:	0.75 ± 2.50	5.67 ± 18.47	10.97 ± 3.94
Sum:	2.37 ± 4.17	112.79 ± 166.37	27.40 ± 25.85

Table 8. Overall Weighted RMS vibration for Glove 5.

	aRMS (m/s^2)	Peak (m/s^2)	Crest Factor (ratio)
X-axis:	2.13 ± 2.62	128.60 ± 160.31	32.51 ± 26.18
Y-axis:	0.67 ± 2.19	23.58 ± 79.29	20.99 ± 13.34
Z-axis:	0.71 ± 2.36	27.07 ± 92.69	13.16 ± 9.77
Sum:	2.74 ± 3.88	149.31 ± 188.96	32.23 ± 25.66

Table 9. Frequency at which greatest RMS vibration occurred during tool use.

	Glove 1	**Glove 2**	**Glove 3**	**Glove 4**	**Glove 5**
X Axis (Hz)	8	12.5	16	12.5	16
Y Axis (Hz)	8	8	8	8	16
Z Axis (Hz)	8	10	8	8	8

Glove 1 attenuated the least vibration along the X and Y axis out of all gloves that successfully reduced vibration, however, glove 1 performed within a 5% margin of glove 4 and glove 5 along the Z axis. On the other hand, glove 3 attenuated more vibration than all other gloves that reduced vibration along the Z axis, but performed within a 1% margin of glove 4 and glove 5 along the X and Y axis. Glove 4 attenuated more vibration than all other gloves along

the X axis, within a 1% margin of glove 3 and glove 5, and within a 7% margin of glove 1 and glove 5.

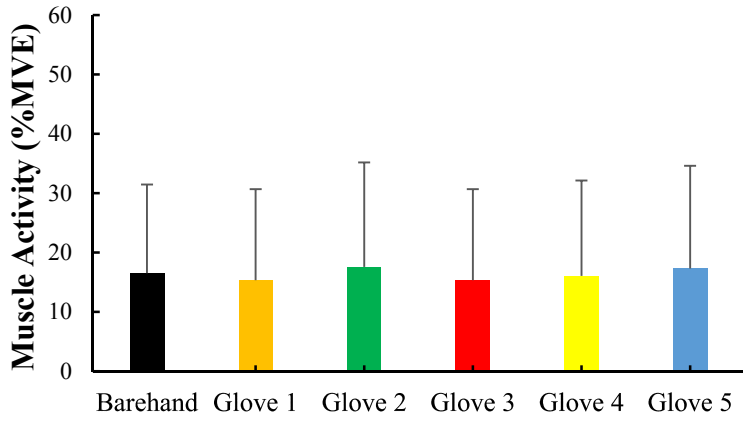## 4.4   Muscle Activity

4.4.1 Average Muscle Activity

There were no significant differences in average muscle activity for FDS, FCR, FCU, ECU, ECR or EDS across the glove conditions. For glove 1, FDS produced the lowest average activity (15.34 ±13 %MVE), with FCR producing the highest activity (85.74 ± 5.4 %MVE). For glove 2, FCU produced the lowest average activity (14.83 ± 8.2%MVE), with EDS produced the highest activity (33 ± 15.2 %MVE). For glove 3, FCU produced the lowest average activity (15.03 ± 9.3%MVE), with FCR produced the highest average activity (31.23 ± 22%MVE). Glove 4 exhibited the lowest average activity for FDS (16.68 ± 27.2%MVE), while the highest activity was found for FCR (34.16 ± 33.1%MVE). Lastly, with respect to glove 5, the lowest average activity was FCU (15 ± 12.8%MVE); while the highest average activity was EDS (31.82 ± 16.6%MVE). See figure 16 for average muscle activity data.

4.4.2   Peak Muscle Activity

There were significant main effects of glove condition for peak muscle activity for ECR ($F_{5,55}$=7.034, p=0.00). Pairwise comparisons determined muscle activity for glove 2 was greater than glove 3 ($F_{5,55}$=7.034, p=0.01), and glove 5 ($F_{5,55}$=7.034, p=0.02). Significant main effects were also found for EDS ($F_{5,55}$=3.612, p=0.012). Pairwise comparisons determined muscle activity for glove 2 was greater than glove 4 ($F_{5, 55}$=3.612, p=0.02). No other significant differences for peak muscle activity were found between gloved conditions.

FDS was found to produce the lowest peak activity for glove 1 (51.59 ±23.6 %MVC) and the highest peak activity was found for ECR (30.89 ± 23.1%MVC). With regard to glove 2, the lowest peak activity was found for FCR (63.95 ± 38.5%MVC) and the highest peak activity was found for ECR (93.19 ± 5.4%MVC). Concerning glove 3, the lowest peak activity was found for FDS (49.2 ± 21.7%MVC), in contrast, the highest peak activity was found for ECR (87.91 ± 34.7%MVC). With respect to glove 4, the lowest peak activity was found for FCU (57.25 ± 14.6%MVC) and the highest peak activity was found for ECR (85.05 ± 30.2%MVC). Lastly, glove 5 demonstrated the lowest peak activity for FCR (44.97 ± 24.2%MVC) and the highest peak activity was found for ECR (79.65 ± 25.2%MVC). See figure 17 for peak muscle activity data.
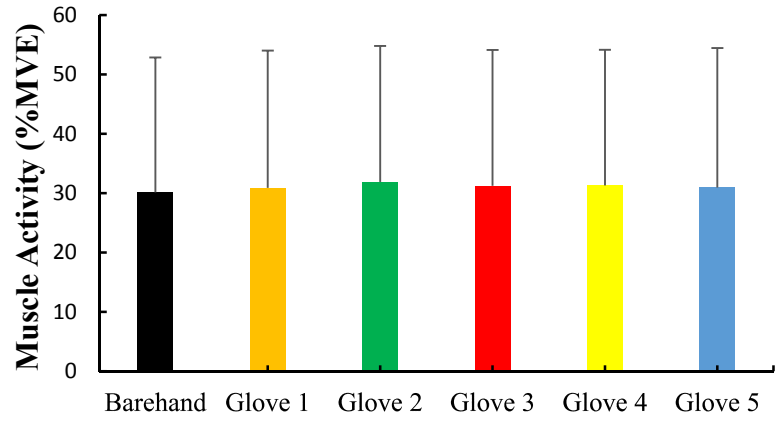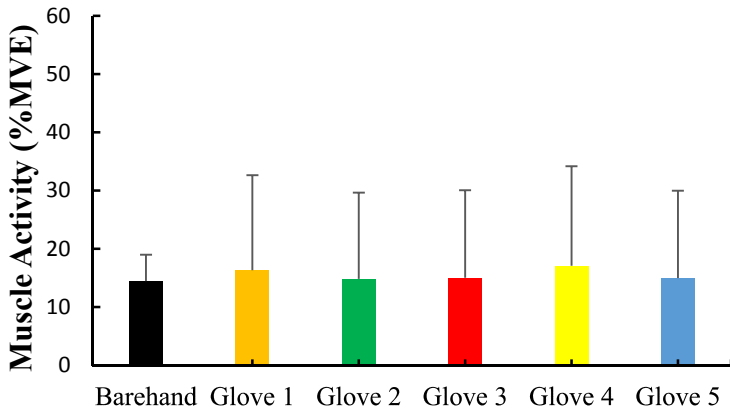
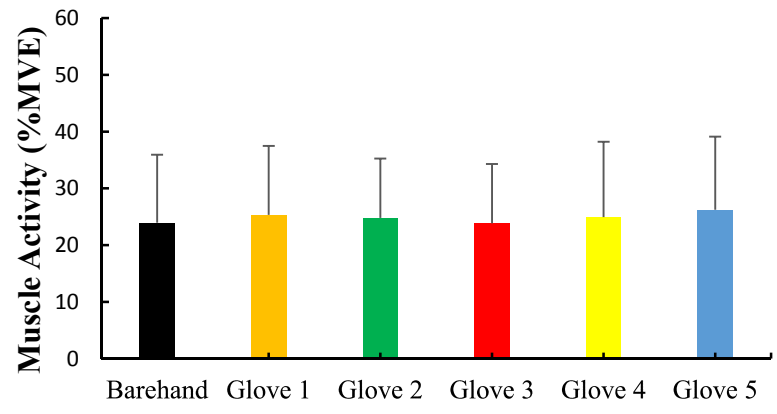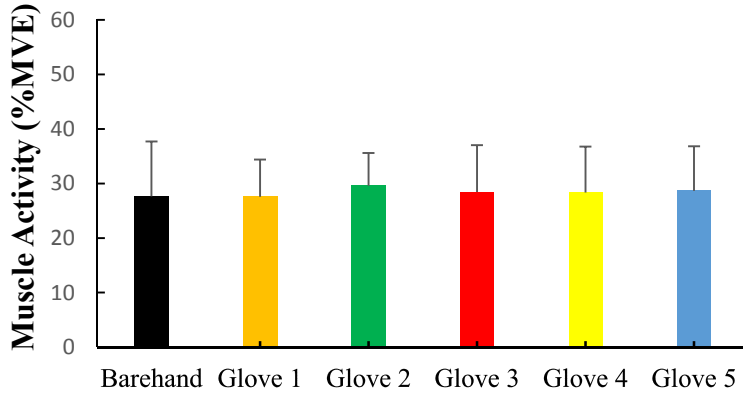**Figure 16.** Average muscle activity (%MVE) for the flexor digitorum superficialis, flexor carpi radialis, and flexor carpi ulnaris, extensor carpi ulnaris, extensor carpi radialis and extensor digitorum superficialis for each condition.
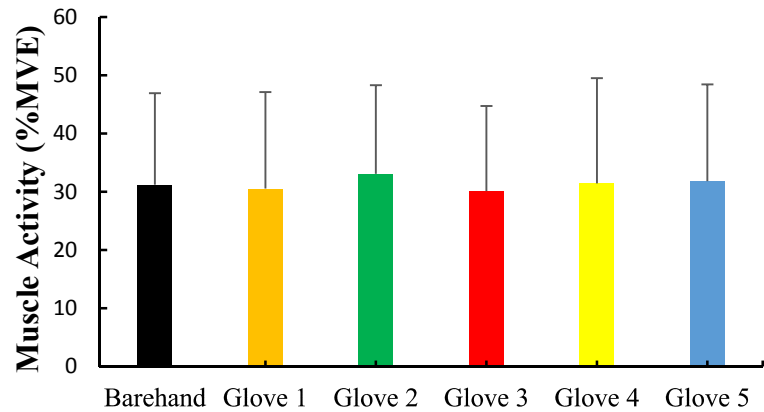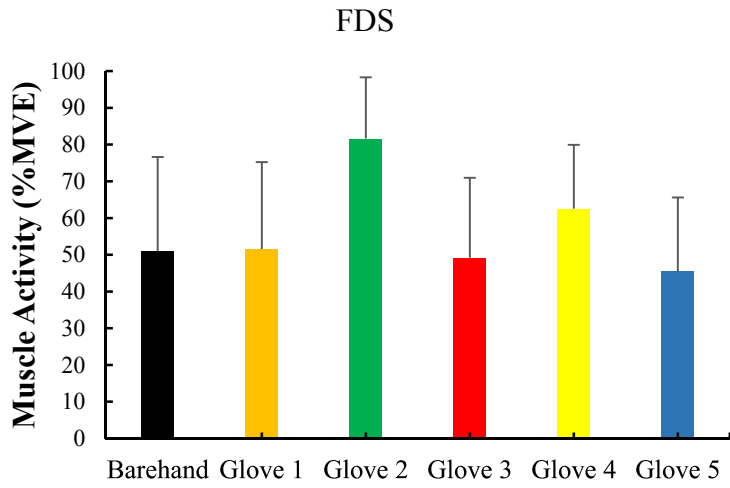
Figure 17. Peak muscle activity (%MVE) for the flexor digitorum superficialis, flexor carpi radialis, flexor carpi ulnaris, extensor carpi ulnaris, extensor carpi radialis, and extensor digitorum superficialis for each condition.
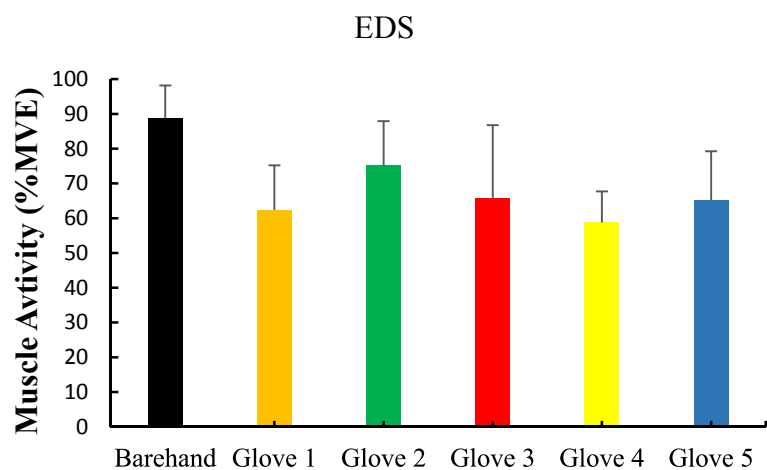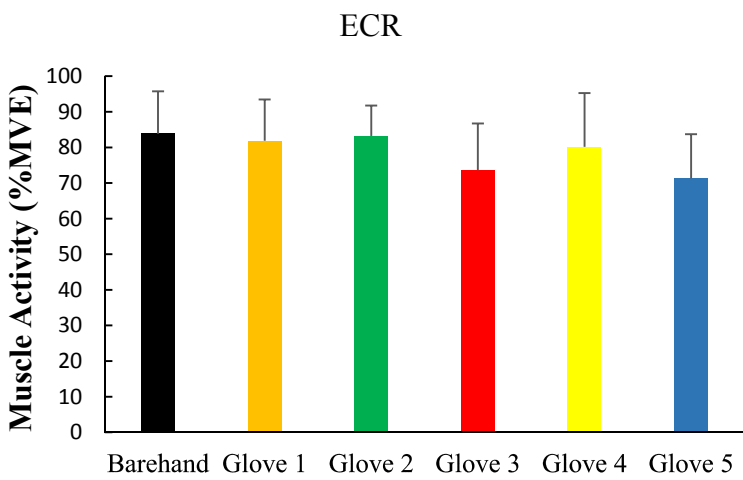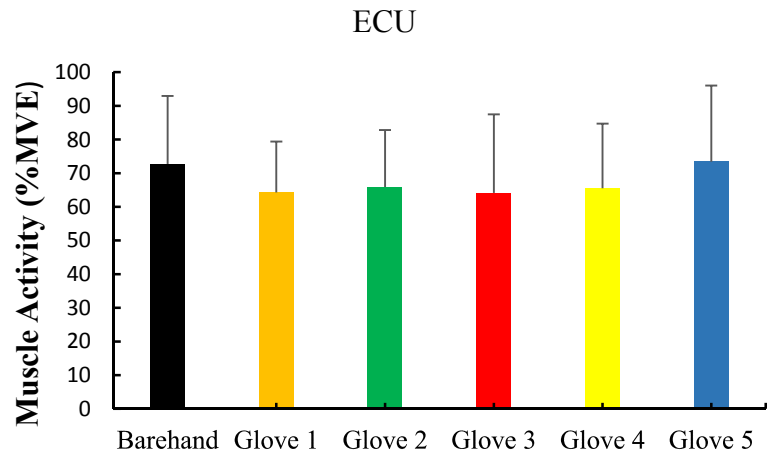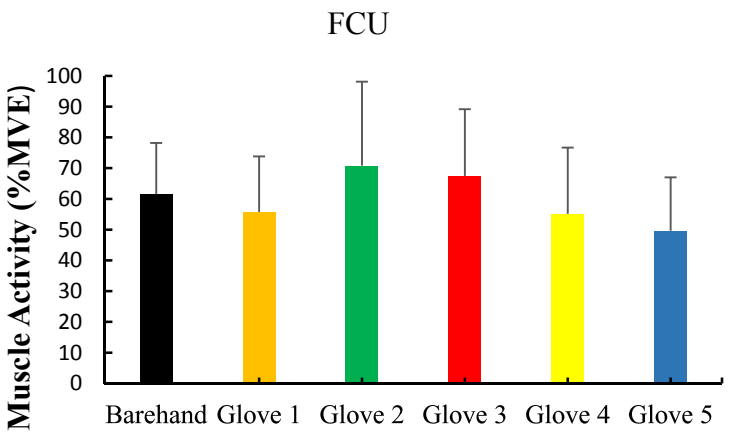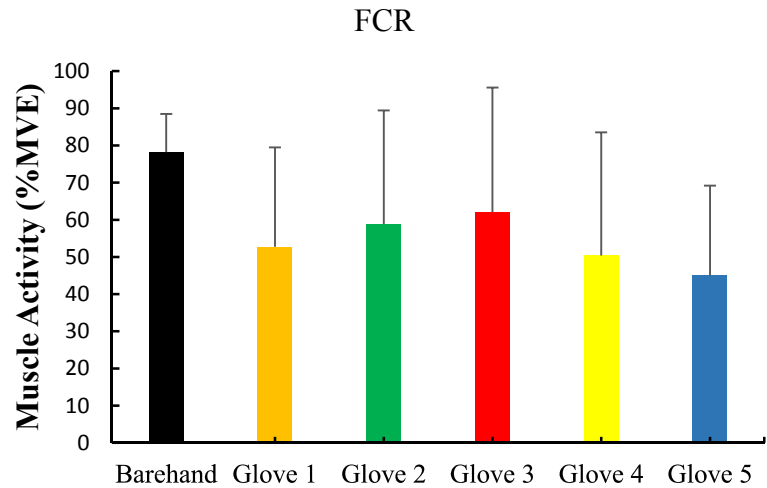
4.5 Grip Force

There was a significant main effect of maximum grip force for glove condition (p=0.00). Pairwise comparisons determined that participants generated significantly less grip force for glove 2 ($F_{5,55}$ =22.664, p= 0.011) and glove 5 ($F_{5,55}$=22.664, p= 0.029) than glove 3 (Figure 18). Glove 3 produced 95.5N and 9.08N more grip force than gloves 2 and 5 respectively. The average maximum bare-hand grip force was 389.75 ± 152.8N (range: 223N to 640N). Maximum grip force for glove 1 was 264.44 ± 108.8N (range: 154N to 434N), resulting in a 67.7% reduction from the maximum bare-hand trials. Average maximum grip force for glove 2 was 176.41 ± 70.1N (range: 106N to 321N), or a 46.9% reduction from the bare-hand trials. With respect to glove 3, average maximum grip force was 263.58 ± 106.9N (range: 136N to 470N), or a 67.9% reduction from the bare-hand trials. Glove 4 produced an average maximum grip force of 265.66 ± 106.2N (range: of 141N to 454N), or a 68.6% reduction from the bare-hand trials. Lastly, the average maximum grip force for glove 5 was 262.83 ± 108.8N (range: 152N to 445N) or a 67.1% reduction from the bare-hand trials.
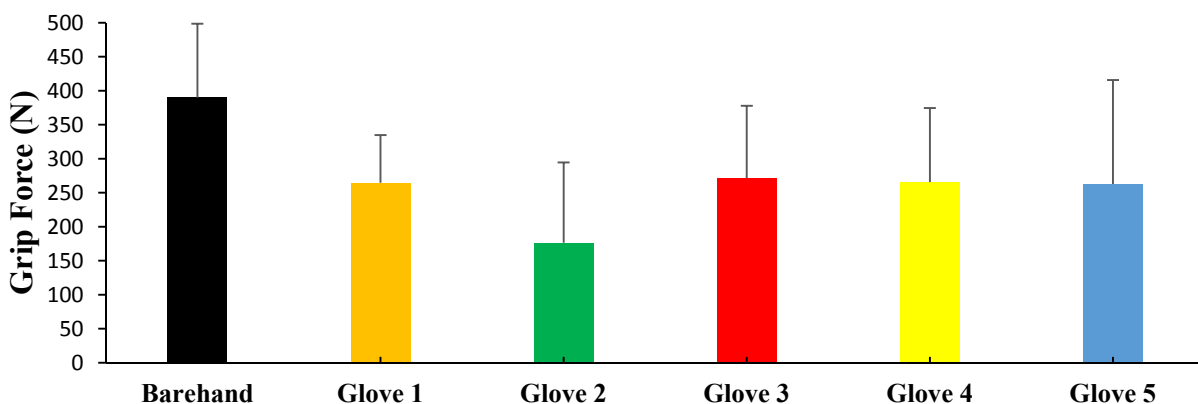
Figure 18. Average maximum grip force (N) for each glove condition.

4.6   Subjective Response to Glove Comfort During Tool Use

Glove 3 was shown to be significantly higher (4.08 $\pm$ 0.51) in satisfaction for comfort

($F_{4,44}$ = 6.710 p = 0.013) compared to glove 2 (2.33 $\pm$ 1.56) (Figure 19).
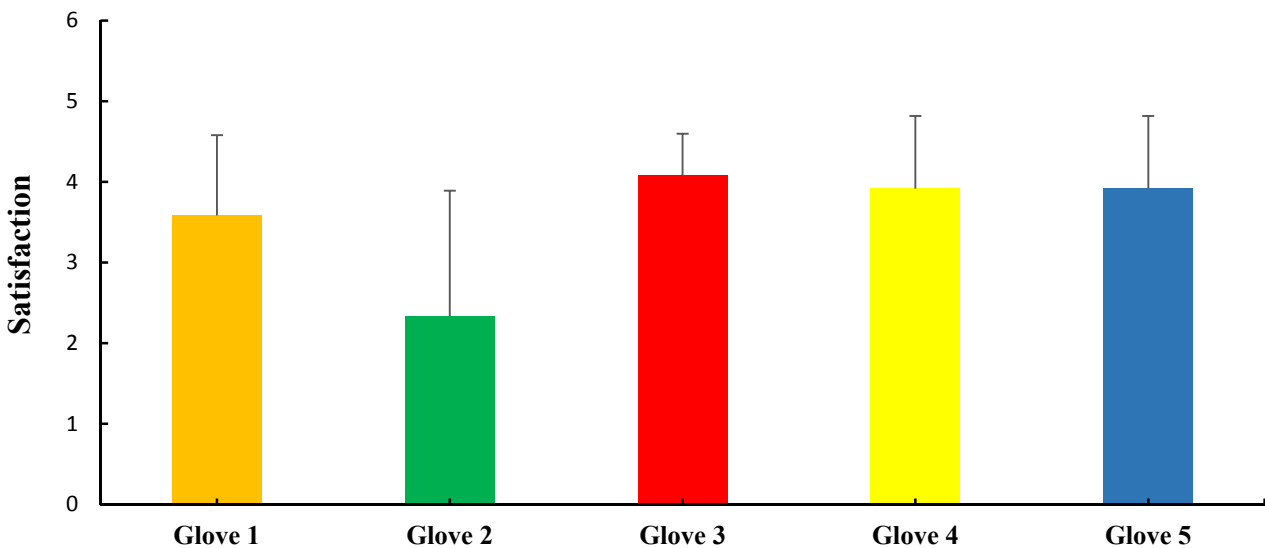
Figure 19. Average subjective satisfaction of comfort (scale of 1 to 5) during gloved tool use.

4.7   Subjective Response to Glove Conditions

4.7.1   Gripping Ability During Tool Use

There were significant main effects found with respect to gripping ability for each glove

($F_{4,44}$ = 9.604, p= 0.00). Pairwise comparisons found significant differences for Glove 1 (3.25 $\pm$

1.36*)* ($F_{4,44}$ =9.604, p= 0.043), glove 3 (3.33 $\pm$ 0.89) ($F_{4,44}$ =9.604, p= 0.002), glove 4 (3.00 $\pm$

1.21) ($F_{4,44}$ =9.604, p= 0.009), and glove 5 (3.50 $\pm$ 1.00) ($F_{4,44}$ =9.604, p= 0.001), each presented

higher subjective satisfaction pertaining to grip during gloved tool use than glove 2 (Figure 20).
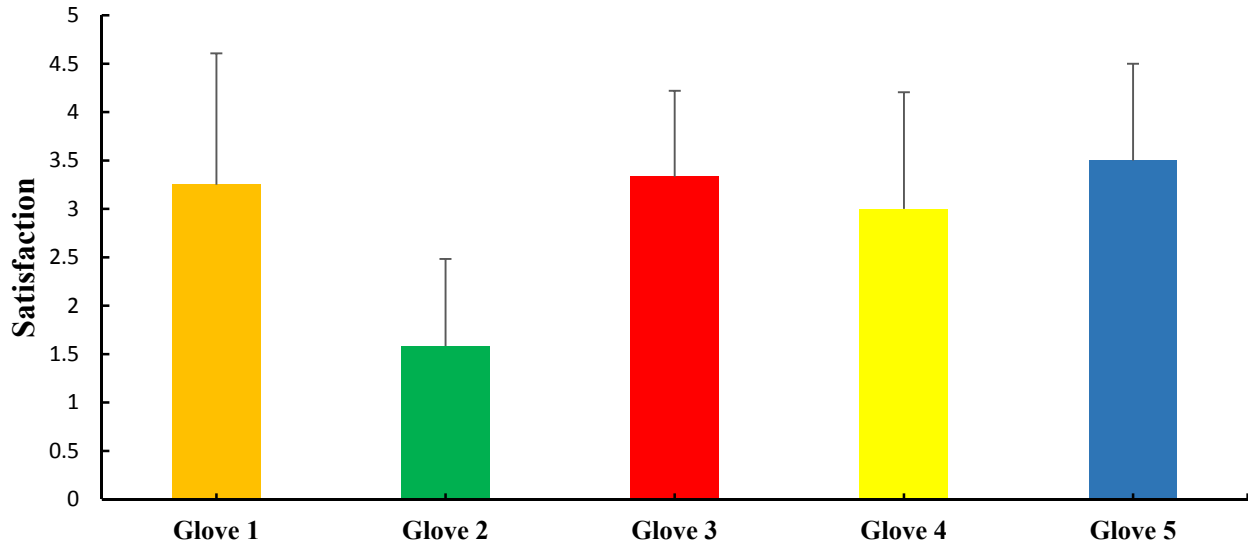
Figure 20. Average subjective satisfaction of grip (scale of 1 to 5) during gloved tool use.

4.7.2   Dexterity During Gloved Tool Use

There were significant main effects found for subjective satisfaction with dexterity during gloved tool use. Glove 3 (3.42 ± 1.24) ($F_{4,44}$=8.965, p= 0.004), glove 4 (3.75 ± 1.22) ($F_{4,44}$ =8.965, p= 0.001), and glove 5 (3.58 ± 1.16) ($F_{4,44}$ =8.965, p= 0.002) were each perceived to offer higher levels of subjective dexterous ability during gloved tool use than glove 2 (Figure 21).
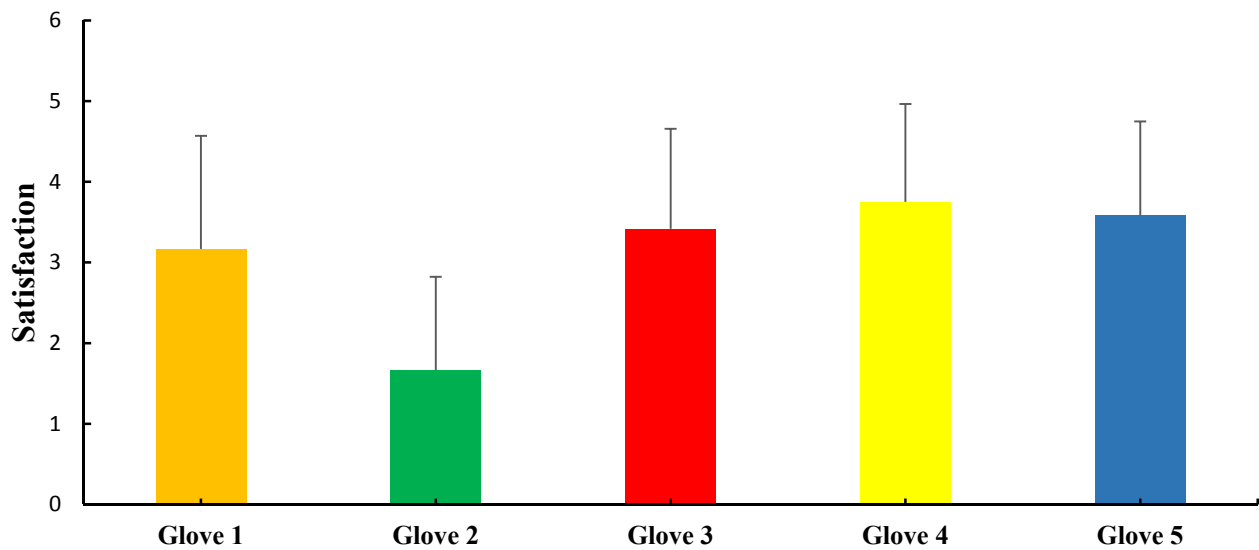
Figure 21. Average subjective satisfaction of dexterity (scale of 1 to 5) during gloved tool use.

4.7.3   Perceived Onset of Forearm Muscle Fatigue

There were no significant differences found regarding the perception of the onset of

forearm muscle fatigue (Figure 22).
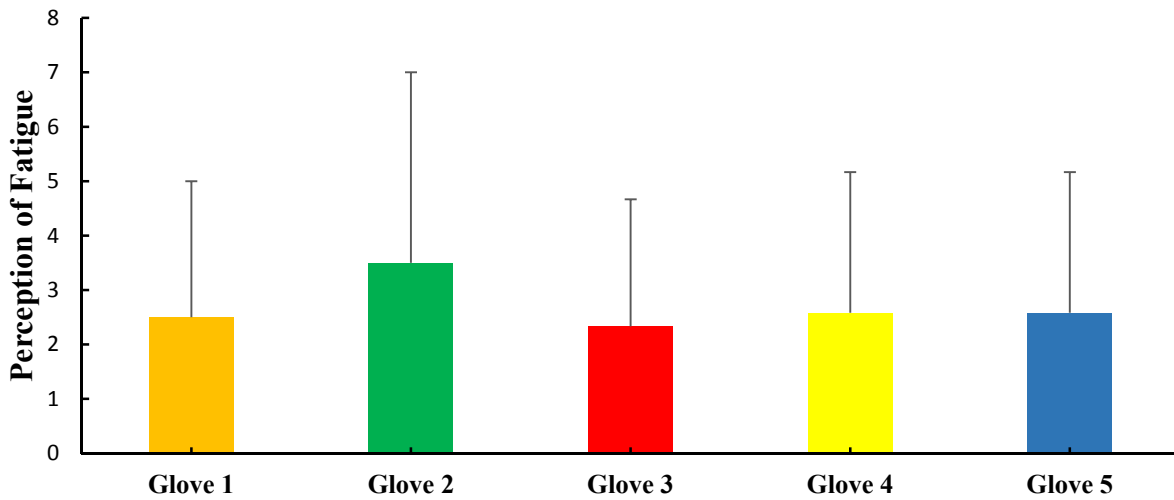
Figure 22. Average perception of glove-induced forearm fatigue (scale of 1 to 5) during tool use.

4.7.4   Tactile Sensation During Gloved Tool Use

There were no significant differences found pertaining to the perception of impairment of

tactile sensation during tool use (Figure 23).
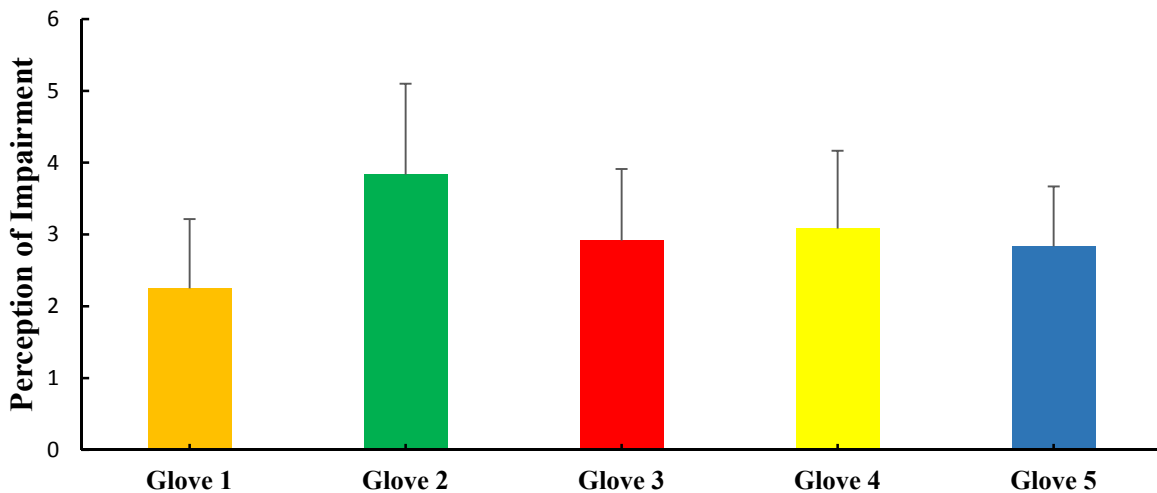
Figure 23. Average perception of tactile sensation impairment (scale of 1 to 5) during gloved tool use.

5.0   DISCUSSION

This study evaluated the effects of an industry standard AV glove and custom fabricated visco-elastic polymer glove inserts on hand-transmitted RMS vibration, forearm muscle activity, grip strength, and subjective responses during simulated power tool use. The results of this study can be used as a first step in determining the most appropriate material properties for a visco-elastic (gel based) insert during hand-held power tool usage. Gel based polymer gloves have shown promise over traditional foam AV gloves for vibration attenuation (Xu et al., 2011), and can be superior to air based gloves for dexterity (Welcome et al., 2014). Despite the apparent potential for gel AV gloves, little attention has been given, to date, on the specific material properties that provide the most optimal benefits. This work provides insight into the selection of the most appropriate visco-elastic polymer to attenuate HTV, while also taking into consideration the effects on forearm muscle activity, grip strength and user comfort. Glove 3 was found to elicit the lowest levels of average and peak muscle activity, onset of forearm muscle fatigue, and tactile sensation impairment, as well as the highest levels of perceived comfort, grip, and dexterity. Glove 2 was found to perform the worst; raising HTV above bare-hand levels, eliciting higher levels of average and peak muscle activity and leading to the highest perceived onset of forearm muscle fatigue. Furthermore, glove 2 was found to impair grip, dexterity, tactile sensation more than any other glove in this study. This highlights the importance of the tradeoff between gel palm thickness and performance metrics when designing the optimal AV glove. Our study elaborates on the interaction between vibration and visco-elastic polymers so that a gel insert can be manufactured without sacrificing workers' comfort, dexterity and safety.

5.1   Comparison of Glove Hand-Transmitted Vibration

We found variation in vibration attenuation along the X, Y, and Z axis, which reaffirms the conclusions made by Dong et al., (2014), that the effectiveness of an AV glove is direction-specific. We also found that glove 3 was the most effective in attenuating vibration along the Z axis (vibration transmitted along the forearm), and this is likely due to the combined thickness of the base and supplementary layers, which increases the mass of the hand. The gel based inserts used in this study were visco-elastic polymers which means that the material properties exhibit both viscous and elastic characteristics when undergoing deformation. The supplementary layers of gel in this glove included a gel that is a soft, highly viscous, flexible material with high shock absorbing properties compared to the base layer and it is likely that these properties are important for optimal gel based glove design.

McDowell et al. (2013) evaluated AV gloves with various material properties (gel, air, etc.) using a 3D vibration set up similar to the ISO standards. The authors found that vibration attenuation was most effective along the X axis, which contradicts our power tool simulation study where overall vibration attenuation was most effective along the Z axis. In addition to the most contact area of our AV gloves aligning with the Z axis, this may be attributed to the tissues of the hand-arm system aligning with the Z axis, aiding in the attenuation of vibration. Forearm posture, hand and general upper extremity posture was different than how participants held the handle from McDowell and colleagues. In addition to postural differences, this could possibly be due to less glove contact area interacting with the tool handle attributed to the width of the hand being less than the length of the hand, as well as potential gaps between fingers in an individual's grasp. In addition, the impact wrench utilized in our study produced a torqueing motion to the right when tightening bolts. This resulted in superior translation of the impact

wrench to the surface of the hand; leading to increased muscular efforts to support the tool. Our tool produced different vibration characteristics than the McDowell et al., (2014) study, which can make direct comparisons difficult. Furthermore, the degree of AV glove vibration attenuation may also depend on tool-orientation, and this implemented postural differences across the studies. Further work should be conducted on this area using visco-elastic polymers in gel-based inserts of AV gloves.

In our work, the only glove that did not attenuate vibration compared to bare-hand trials and actually amplified vibration was glove 2. Glove 2 possessed the thickest layer of our visco-elastic polymer base layers, which increased the overall mass of the hand compared to all other gloves. According to Dong et al., (2009), increasing the mass of the hand should theoretically aid in vibration attenuation. Although glove 2 was the heaviest of the gloves used in this study, its thick layer of visco-elastic polymer greatly increased its contact stiffness; likely decreasing its vibration attenuating properties. Moreover, our subjective questionnaires suggested that participants had an inability to grip the tool effectively with glove 2. Grip force was reduced by 66.6% and the design of this glove potentially altered the area of contact between the participant's hand and the tool handle; creating a larger distance between the hand and tool handle and a decreased likelihood of vibration attenuation as reported by Almagirby et al., (2017).

As exhibited by Table 3, all gloves were ineffective at attenuating vibration at a frequency of 8Hz along the Y axis, with the exception of glove 5, which proved ineffective at 16Hz. This may have been due to the triangular shapes implemented into the supplementary layer which created more friction, and finger contact stiffness as suggested by Welcome et al., (2014). Moreover, all gloves were ineffective along the Z axis at 8Hz, with the exception of

glove 2, exhibiting lack of effectiveness at 10Hz; potentially due to increased contact stiffness from the thick base layer of the glove. The results of this study support the suggestion by Khairil & Griffin (2016) that AV gloves prove to be less effective during lower frequencies, between 8-16Hz along the forearm (Z axis). Welcome et al., (2014) suggested that failure to attenuate vibration at lower frequencies can be attributed to a problem at the fingers, rather than the palm. ISO standards require that a frequency range of 6.3 to 25Hz be weighted most heavily with regard to assessing vibration attenuation properties of an AV glove. Considering that range, all gloves in this study performed weakest in vibration attenuation on the lower end of that frequency range, specifically at 8Hz. This is likely due to EMG-EEG coherence that occurred during trials as well as Schumann's resonance. Furthermore, this suggests that our glove design could have an issue with the area of the fingers and this could be a potential area of redesign. Khairil et al., (2017), investigated HTV with a gel insert and reported decreased levels of vibration attention at low frequencies as well. Furthermore, Welcome et al., (2014) found gel gloves fail to attenuate vibration at frequencies lower than 25Hz. This suggests that future AV gloves be fabricated with visco-elastic polymers that increase the mass of the hand, have a large amount of contact area with the tool (to promote dexterous functionality), and reduce contact stiffness; particularly in the area of the fingers to re-distribute finger contact pressure; decreasing likelihood of low frequency vibration transmissibility.

The introduction of supplementary gel-based layers in the form of shapes (Figure 1) may have also influenced the attenuation capabilities of our AV gloves. These supplementary layers had different material properties (i.e. elasticity and stiffness) and differed in thickness.   The supplementary layers were chosen for specific locations, such as, the ventral surface of the 2nd to 5th metacarpal heads, as well the hypothenar and thenar eminences; where more cushion to the

palmer surface would be provided but would not get in the way of gripping the tool handle.

Glove 3 and glove 4 both featured these designs, with the supplementary layer of glove 3

exhibiting more thickness, elasticity, and was less stiffness than glove 4. Glove 5 incorporated

several triangular supplementary pieces spanning from the fingertips to the base of the palm,

using a gel layer that was different in material properties (less elastic, and stiffer) than the

supplementary layers found in gloves 3 and 4. This design was created theorizing that triangles

would serve as a means of funneling HTV into the broader portions of the hand where more

tissue could dampen vibration more efficiently than at the fingers (Hua et al., 2017). The

inclusion of these supplementary layers featured in gloves 3, 4 and 5 did not appear to attenuate

vibration as effectively along the X axis as glove 1 did (which did not feature a gel-based layer at

all). Despite this, gloves 3 and 4 appeared to attenuate more vibration than a base layer on its

own (glove 1); exhibiting most vibration attenuation along the Z axis. Furthermore, glove 5 was

weakest in attenuating vibration at 16 Hz for the X and Y axis respectively; which represents a

higher frequency than all other gloves evaluated. This may be the result of the decrease in

contact area between the glove and tool handle due to the multiple triangular supplementary

layers. Despite this, it may be worth revisiting triangular supplementary layers spanning the

surface of the hand for future AV gloves if the layers were elongated to cover more surface area.

5.2 Gloved Forearm Muscle Activity during Simulated Task

This study demonstrated that forearm muscle activity in the extensors was consistently

greater than in the flexors, which has been demonstrated previously during gripping tasks (Mogk

& Keir, 2007). With regard to peak muscle activity, ECR and EDS were most affected by glove

condition; with glove 2 producing the highest activity for both muscles. EDS has been

documented as a wrist stabilizer (Holmes et al., 2015), and EDS activity may have been the

result of force feedback of the tool, as the forearm extensors may be required to counter forces from the impact wrench. The barrel of the impact wrench was heavier and extended past participant's grasp, which could force extension of the fingers to support the tool during use. This is likely due to the thickness and stiffness of the glove's base layer which would require more force when attempting to grip objects (Hewitt et al., 2014). Cabecas et al., (2011), is, to our knowledge, the only other EMG study involving HAV. Our muscle activity findings contradict the findings put forth by Cabecas et al., (2011), who reported that ECR was the least active muscle throughout all gloved tasks. Moreover, Cabecas et al., (2011) reported the largest increase in activity was exhibited by ECU, and suggested this is due to a neutral wrist position. Muscle activity differences in our study, compared to Cabecas et al., 2011, may be attributed to the differences in stiffness and thickness of visco-elastic polymers used our study compared to the gel, leather, and neoprene inserts used by Cabecas. In addition, tool position may influence the activation of forearm muscles even when the wrist is in a neutral position. An impact wrench oriented horizontally will illicit different perturbations to the hand-arm system than an impact wrench positioned vertically with its barrel facing the ground (as was the case in the Cabecas et al. study) and may have contributed to the reported high ECU activity. In addition, Cabecas et al., (2011) performed submaximal reference contractions for normalization of muscle activity. We performed isometric maximal contractions. Given the differences in cross sectional area and overall muscle size of the flexors relative to the extensors (Holmes et al., 2014), we expected greater extensor muscle activity, like demonstrated. Furthermore, in a study involving the effects of glove stiffness on forearm muscle activity during gripping tasks, Larivière et al. (2010) suggested that activity of the extensors and flexors of the forearm are comparable. In our work, we demonstrated more activity from the extensor muscles of the forearm than the flexors. We did

however, find comparable results for FDS as Cabecas et al., (2011) also exhibited minimal FDS activity during gloved conditions. This study also confirms the conclusions of Wells et al., (2010); that forearm EMG increases as glove thickness increases. Wells et al., (2010) conducted a series of gripping tasks with rubber insulation gloves while analyzing forearm muscle activity and reported similar results to our study; increases in EMG amplitude and perceived effort, as well as decreased perceived comfort and dexterity as glove thickness increased.

5.3 Grip Force Changes with Glove Design

Not surprisingly, the bare-hand condition produced the highest grip force exertion among all conditions in this study. This was expected, due to the cushioning effect produced by the gloves (Wells et al., 2010). Glove 1, which contained a foam insert produced average maximal grip force that was not significantly different than gloves 3, 4, and 5 (Table 10). This suggests that, in terms of grip force production, the visco-elastic polymers used in this study was similar to the industry standard glove that was tested (glove 1). Significant reductions in maximal grip force were found for glove 2. This was likely due to glove 2 possessing the thickest, stiffest visco-elastic polymer; which required more force than the other gloves, to simply bend and grip objects. Glove 4 allowed a higher average maximal grip force than glove 3 and glove 5 (i.e. less of a reduction from the bare-hand trials); allowing participants to grip the tool handle more effectively. While glove 4 elicited grip forces closer to bare-hand trials, forearm EMG was comparable to the other gloves (no significant differences). Moreover, glove 5 was not able to attenuate vibration as well as gloves 3 and 4 (Table 2). These results support Welcome et al., (2014), who demonstrated that an increase in grip force impedes glove suspension; decreasing its vibration attenuation abilities. The results of our study also confirm that an increase in grip force will translate to increased finger contact pressure and increased stiffness (Welcome et al., 2014).

Moreover, reductions in grip force due to glove thickness greater than 25% have been reported

(Wimer et al., 2012). Both glove 4 and glove 5 shared similar thickness regarding their base

layers, however differences in the supplementary layers caused the overall thickness of both

gloves to differ. The multiple triangular supplementary layers of glove 5 resulted in an increased

thickness at the fingers in addition to the palm, which likely reduced the amount of grip force

participants were able to exert compared to glove 4. While not significant, this may explain why

glove 5 attenuated more vibration than glove 4 even though it enabled less grip force. Based on

the results of this study, an AV glove that is less stiff may allow for less bowing of the palmar

surface and proper grip without altering grip force on tool handles while still attenuating

vibration, however the ideal thickness of a visco-elastic gel insert needs to be determined.

Table 10. Average Percentage of Maximum Bare-hand Grip Force Achieved According to Glove Condition.

Glove 1 (%)	Glove 2 (%)	Glove 3 (%)	Glove 4 (%)	Glove 5 (%)
67.7	46.9	67.9	68.6	67.1

5.4 Comparisons of Subjective Responses to Comfort

With regard to participants' perception of comfort, glove 3 yielded significantly higher

satisfaction of comfort than glove 2, despite its thicker insert. This may be due to the

reduced stiffness and placement of the supplementary layers across the palmar surface.

Moreover, the results of this study suggest similar levels of perceived comfort for glove 3,

glove 4 and glove 5. This is likely explained by the decreased stiffness of their gel inserts in

comparison to glove 1 and glove 2. Glove 2 exhibited the lowest perceived satisfaction of

comfort. This is likely due to the difficulty encountered during gripping tasks.

5.5 Comparisons of Subjective Responses to Grip

All gloves in this study were found to have higher satisfaction of gripping ability than glove 2. This suggests that material properties such as stiffness do not impact grip as much as the thickness of an insert; as the foam insert was rated similarly to the gel inserts. Moreover, between the gel inserts (gloves 3-5), glove 5 exhibited the highest satisfaction of gripping ability. This may be explained by the multiple supplementary layers spanning from the fingertips to the base of the palm. These supplementary layers would increase contact area with the tool handle, thus increasing the amount of contact pressure at the fingers; aiding to maintain grip.

5.6 Comparisons of Subjective Responses to Dexterity

With respect to dexterity, glove 3, glove 4, and glove 5 each exhibited higher levels of satisfaction for dexterity over glove 2. This may be attributed to the decreased stiffness of the inserts of gloves 3-5; decreasing the amount of excess material in between the thenar and hypothenar eminences upon bowing of the glove occurring during gripping tasks. There was less satisfaction of dexterity for glove 1 compared to gloves 3-5 as well; suggesting that the material properties of the visco-elastic polymers used in gloves 3-5 is favourable for dexterity than the foam found in glove 1.

5.7 Comparisons of Perception of Forearm Muscle Fatigue

Although there were no significant differences found for the perception of the onset of forearm muscle fatigue, glove 2 was rated the highest followed by glove 1, then gloves 3-5. This is likely due to the requirement of higher forces needed for gripping tasks with thicker

inserts. In addition, the gel inserts for gloves 3-5 are less stiff than the inserts of glove 1 and glove 2.

5.8 Comparisons of Tactile Sensation

With respect to perceived impairment of tactile sensation, there were no significant differences found between each of the gloves. Based on the results, glove 1 impaired perceived tactile sensation the least; suggesting foam inserts are superior than gel inserts in this regard. This may be due to material properties of the foam such as stiffness, resembling the bare-hand more closely than the visco-elastic polymers in this study.

6.0 Limitations

There were certain limitations imposed on this study. The cost of AV gloves is a barrier in this regard. While hand size varied very little across our male subjects, incorrect glove size for the participant would potentially influence muscle activity, grip force, and perceived comfort, grip, dexterity, onset of fatigue, and impairment of tactile sensation. It is likely that our female participants were more affected than males due to smaller hand sizes, overall. Additionally, proper engineering and testing of the material properties, as well as testing of the gel against a wider range of frequencies are needed in order to quantify and describe the gel in our study. Furthermore, investigation of the dampening and stiffness characteristics should be conducted. The magnitude of our RMS vibration was low in this simulation and our study involved only one hand-held power tool, so it is unclear if these findings extend to other power tools. While the tool-specific performance of each glove would aid in understanding the attenuation capabilities of each glove, power tools are costly. In addition, posture was strictly enforced during trials with the impact wrench, it is worth noting that

other power tools may require different postures during tool use. We evaluated average and peak vibration, future work should break down the specific frequencies further in order to evaluate the vibration attenuation properties of gel inserts. In addition, it is difficult to select an appropriate finger-adapter approach for measuring vibration at the fingers, the evaluation of transmissibility to the hand and fingers should be included in future work to fully understand the attenuation capabilities of each glove. Although the ISO standardized testing protocol was not implemented in this study, it is necessary for future evaluation of the gloves in order to certify them as "anti-vibration" gloves and to better understand how the gloves produced in our work perform in a broader frequency spectrum. Moreover, EMG frequencies range from 10-500Hz (De Luca, 1997), which shares the same range with some of the frequencies in our study. In order to reduce as much electrode noise with motion artifact as possible, we secured all electrodes with tape. Handedness is also a variable that must be taken into consideration, as all participants in our study were right-hand dominant. It may be necessary for future research to examine the effects of left-hand dominant individuals.

6.0 CONCLUSION

This study evaluated the effects of visco-elastic polymer glove inserts on hand-transmitted RMS vibration, forearm muscle activity, grip strength, and subjective responses during simulated power tool use. Our study found that the vibration attenuation capabilities of our fabricated gloves were most effective along the Z axis (along the forearm). Furthermore, decreasing contact stiffness while increasing mass, elasticity, and viscosity of visco-elastic polymer (gel) inserts likely results in an increase in vibration attenuation. Glove 3 performed best overall and was found to elicit the lowest levels of average and peak muscle activity, onset of forearm muscle fatigue, and tactile sensation impairment, as well as the highest levels of perceived comfort, grip, and dexterity. On the other hand, glove 2 was found to perform the worst; raising HTV above bare-hand levels, eliciting higher levels of average and peak muscle activity; leading to the highest perceived onset of forearm muscle fatigue. In addition, glove 2 was found to impair grip, dexterity, tactile sensation more than any other glove in this study. The results of this study suggest visco-elastic polymer inserts that possess increased viscosity, elasticity, and mass and decreased stiffness attenuate vibration more effectively. Moreover, supplementary layers which increase contact area with the tool handle likely increases vibration attenuation. Our results can be used as a first step in determining the most appropriate material properties for a visco-elastic, gel based, insert during hand-held power tool usage. This work can provide insight into the selection of the most appropriate visco-elastic polymer to attenuate HTV, while also taking into consideration the effects on forearm muscle activity, grip strength and user comfort.

REFERENCES

Almagirby, A., Carré, M. J., & Rongong, J. A. (2017). A new methodology for measuring the vibration transmission from handle to finger whilst gripping. International Journal of Industrial Ergonomics, 58, 55-61. doi:10.1016/j.ergon.2017.02.011

Azmir, N. A., & Yahya, M. N. (2017). Prevalence of Hand-transmitted Vibration Exposure among Grass-cutting Workers using Objective and Subjective Measures. IOP Conference Series: Materials Science and Engineering, 165, 012026. doi:10.1088/1757-899x/165/1/012026

Bovenzi, M. (2006). Acute effects of force and vibration on finger blood flow. Occupational and Environmental Medicine, 63(2), 84-91. doi:10.1136/oem.2004.019703

Cabeças, J., & Milho, R. (2011). The efforts in the forearm during the use of anti-vibration gloves in simulated work tasks. International Journal of Industrial Ergonomics, 41, 289-297.

Chen, X., Green, P. G., & Levine, J. D. (2010). Neuropathic pain-like alterations in muscle nociceptor function associated with vibration-induced muscle pain. Pain, 151(2), 460-466. doi:10.1016/j.pain.2010.08.004

De Luca, C. J. (1997). The use of surface electromyography in biomechanics. Journal of Biomechanics, 13(2), 135-163. doi:10.1016/0021-9290(94)91124-x

Dong, R., Mcdowell, T., Welcome, D., Warren, C., Wu, J., & Rakheja, S. (2009). Analysis of anti-vibration gloves mechanism and evaluation methods. Journal of Sound and Vibration, 435-453.

Dong, R., Wu, J., & Welcome, D. (2005). Recent Advances in Biodynamics of Human Hand-Arm System. Industrial Health Ind Health, 43, 449-471.

Dong, R., Welcome, D., Peterson, D., Xu, X., Mcdowell, T., Warren, C., Brammer, A. (2014). Tool-specific performance of vibration-reducing gloves for attenuating palm-transmitted vibrations in three orthogonal directions. International Journal of Industrial Ergonomics, 44, 827-839.

Gerhardsson, L., & Hagberg, M. (2014). Work ability in vibration-exposed workers. Occupational Medicine, 64(8), 629-634. doi:10.1093/occmed/kqu121

Griffin, M. (1998). Evaluating the effectiveness of gloves in reducing the hazards of hand-transmitted vibration. Occupational and Environmental Medicine, 55, 340-348.

Gurram, R., Rakheja, S., & Gouw, G. (1994). Vibration transmission characteristics of the human hand-arm and gloves. International Journal of Industrial Ergonomics, 13, 217-234.

Hewitt, S., Dong, R., Welcome, D., & Mcdowell, T. (2014). Anti-Vibration Gloves? Annals of Occupational Hygiene, 59(2), 127-141. doi:10.1093/annhyg/meu089

Hewitt, S., Dong, R., Mcdowell, T., & Welcome, D. (2016). The Efficacy of Anti-vibration Gloves. Acoustics Australia, 44(1), 121-127. doi:10.1007/s40857-015-0040-5

Holmes, M. W., Tat, J., & Keir, P. J. (2015). Neuromechanical control of the forearm muscles during gripping with sudden flexion and extension wrist perturbations. Computer Methods in Biomechanics and Biomedical Engineering, 18(16), 1826-1834. doi:10.1080/10255842.2014.976811

Holmes, M. W., Tat, J., & Keir, P. J. (2014). Neuromechanical control of the forearm muscles during gripping with sudden flexion and extension wrist perturbations. Computer

Methods in Biomechanics and Biomedical Engineering, 18(16), 1826-1834. doi:10.1080/10255842.2014.976811

Hua, Y., Lemerle, P., & Ganghoffer, J. (2017). A two scale modeling and computational framework for vibration-induced Raynaud syndrome. Journal of the Mechanical Behavior of Biomedical Materials, 71, 320-328. doi:10.1016/j.jmbbm.2017.03.019

Idzior-Waluś, B. (1987). Coronary risk factors in men occupationally exposed to vibration and noise. European Heart Journal, 8(10), 1040-1046. doi:10.1093/oxfordjournals.eurheartj.a062168

Jetzer, T., Haydon, P., & Reynolds, D. (2003). Effective Intervention with Ergonomics, Antivibration Gloves, and Medical Surveillance to Minimize Hand–Arm Vibration Hazards in the Workplace. Journal of Occupational and Environmental Medicine, 45(12), 1312-1317.

Khairil Anas Md Rezali & Michael J. Griffin (2017) Transmission of vibration through gloves: effects of contact area, Ergonomics, 60:1, 69-81, DOI:10.1080/00140139.2016.1170210

Khairil Anas Md Rezali & Michael J. Griffin (2016) Transmission of vibration through gloves: effects of material thickness, Ergonomics, 59:8, 1026-1037,DOI:10.1080/00140139.2015.1102334

Krajnak, K., Waugh, S., Johnson, C., Miller, R., Welcome, D., Xu, X., Dong, R. (2015). Antivibration Gloves: Effects on Vascular and Sensorineural Function, an Animal Model. Journal of Toxicology and Environmental Health, Part A, 78, 571-582. doi:10.1080/15287394.2015.1014079

Larivière, C., Tremblay, G., Nadeau, S., Harrabi, L., Dolez, P., Vu-Khanh, T., Lara, J., 2010. Do mechanical tests of glove stiffness provide relevant information relative to their effects on the musculoskeletal system? A comparison with surface electromyography and psychophysical methods. Applied Ergonomics 41, 326e334.

Mahbub, M., Kurozawa, Y., Ishitake, T., Kume, Y., Miyashita, K., Sakakibara, H., Harada, N. (2015). A systematic review of diagnostic performance of quantitative tests to assess musculoskeletal disorders in hand-arm vibration syndrome. Industrial Health INDUSTRIAL HEALTH, 53(5), 391-397. doi:10.2486/indhealth.2014-0221

Matoba, T. (2015). Human response to vibration stress in Japanese workers: lessons from our 35-year studies A narrative review. Industrial Health INDUSTRIAL HEALTH, 53(6), 522-532. doi:10.2486/indhealth.2015-0040

McDowell, T.W., Dong, R.G., Welcome, D.E., Warren, C., Xu, X.S., 2013a. Vibration reducing gloves: transmissibility at the palm of the hand in three orthogonal directions. Ergonomics 56 (12), 1823e1840.

Mogk, J. P., & Keir, P. J. (2007). Prediction of forearm muscle activity during gripping. Ergonomics, 49(11), 1121-1130. doi:10.1080/00140130600777433

National Institute for Occupational Safety and Health. (1989). Criteria for a recommended standard: occupational exposure to hand-arm vibration. U.S. department of health and human services, 18-26.

Palmer, K. T. (2000). Prevalence of Raynaud's phenomenon in Great Britain and its relation to hand transmitted vibration: a national postal survey. Occupational and Environmental Medicine, 57(7), 448-452. doi:10.1136/oem.57.7.448

Pelmear, P., & Leong, D. (2000). Review of occupational standards and guidelines for hand-arm (segmental) vibration syndrome (HAVS). Applied Occupational and Environmental Hygiene, 15(3), 291-302.

Perotto, A. O. (2005). Anatomical Guide for Electromyographer: the Limbs and Trunk. Springfield: Charles C Thomas Publisher, LTD.

Poole, C. J., & Cleveland, T. J. (2015). Vascular hand–arm vibration syndrome—magnetic resonance angiography. Occupational Medicine, 66(1), 75-78. doi:10.1093/occmed/kqv151

Poole, K., & Mason, H. (2005). Disability in the Upper Extremity and Quality of Life in hand-arm vibration syndrome. Disability and Rehabilitation, 27(22), 1373-1380. doi:10.1080/09638280500164610

Rakheja, S., Dong, R., Welcome, D., & Schopper, A. (2002). Estimation of tool-specific isolation performance of antivibration gloves. International Journal of Industrial Ergonomics, 30, 71-87.

Rezali, K. A., & Griffin, M. J. (2017). Transmission of vibration through gloves: effects of contact area. Ergonomics, 60(1), 69-81. doi:10.1080/00140139.2016.1170210

Rezali, K. A., & Griffin, M. J. (2014). The Transmission of Vibration through Gloves to the Hand and to the Fingers: Effects of Material Dynamic Stiffness. Applied Mechanics and Materials, 564, 149-154. doi:10.4028/www.scientific.net/amm.564.149

Reynolds, D. (2001). Design of antivibration gloves. Canadian Acoustics, 29(3), 15-17.

Reynolds, D., & Wolf, E. (2005). Evaluation of antivibration glove test protocols associated with the revision of ISO 10819. Industrial Health, 43, 556-565.

Sauni, R., Toivio, P., Pääkkönen, R., Malmström, J., & Uitti, J. (2015). Work disability after diagnosis of hand-arm vibration syndrome. Int Arch Occup Environ Health International Archives of Occupational and Environmental Health, 88, 1061-1068. doi:10.1007/s00420-015-1034-1

Shen, S., & House, R. (2017). Hand-arm vibration syndrome what family physicians should know. Canadian Family Physician, 63(3), 206-210. doi:PMC5349719

Waugh, S., Kashon, M. L., Li, S., Miller, G. R., Johnson, C., & Krajnak, K. (2016). Transcriptional Pathways Altered in Response to Vibration in a Model of Hand-Arm Vibration Syndrome. Journal of Occupational and Environmental Medicine, 58(4), 344-350. doi:10.1097/jom.0000000000000705

Welcome, D., Dong, R., Xu, X., Warren, C., & Mcdowell, T. (2014). The effects of vibration-reducing gloves on finger vibration. International Journal of Industrial Ergonomics, 44, 45-59.

Wells, R., Hunt, S., Hurley, K., Rosati, P., 2010. Laboratory assessment of the effect of heavy rubber glove thickness and sizing on effort, performance and comfort.International Journal of Industrial Ergonomics 40, 386e391.

Willms, K., Wells, R., & Carnahan, H. (2009). Glove Attributes and Their Contribution to Force Decrement and Increased Effort in Power Grip. Human Factors, 51(6), 797-812. doi:10.1177/0018720809357560

Wimer, B., Welcome, D., & Dong, R. (2012). An analysis of contact stiffness between a finger and an object when wearing an air-cushioned glove: The effects of the air pressure. Medical Engineering & Physics, 34, 386-393.

Wu, J., Wimer, B., Welcome, D., & Dong, R. (2012). An analysis of contact stiffness between a finger and an object when wearing an air-cushioned glove: The effects of the air pressure. Medical Engineering & Physics, 34, 386-393.

Xu, X. S., Riley, D. A., Persson, M., Welcome, D. E., Krajnak, K., Wu, J. Z., Raju, R. J., and Dong, R. G. (2011). Evaluation of anti-vibration effectiveness of glove materials using an animal model. Biomed. Mater. Eng. 21: 193–211.

Ye, Y., Mauro, M., Bovenzi, M., & Griffin, M. J. (2015). Reduction in finger blood flow induced by hand-transmitted vibration: effect of hand elevation. International Archives of Occupational and Environmental Health, 88(7), 981-992. doi:10.1007/s00420-015-1027-0

Youakim, S. (2012). The compensation experience of hand-arm vibration syndrome in British Columbia. Occupational Medicine, 62(6), 444-447. doi:10.1093/occmed/kqs033

Yun, H., Jang, S., Seo, C., & Lee, J. (2011). The Effect of Vibration Reduction on the Anti-vibration Gloves Made of Different Materials. Epidemiology, 22. doi:10.1097/01.ede.0000392492.28537.69

CHAPTER 4: APPENDICES

Example Data Collection Form

Name:
Age:

MVC Files Numbers (Right Forearm)

Extensor Carpi Ulnaris: _____ ___ _____

Flexor Carpi Ulnaris: _____

Extensor Carpi Radialis: _____

Flexor Carpi Radialis: _____

Extensor Digitorum: _____

Flexor Digitorum Superficialis: _____

Max Grip EMG

Condition	File #	Force	Condition	File #	Force	Condition	File #	Force
BareHand			**Glove __**			**Glove __**		
Glove __			**Glove __**			**Glove __**		

Condition Order

Condition	File #	Condition	File #	Condition	File #
BareHand		**Glove __**		**Glove __**	
Glove __		**Glove __**		**Glove __**	

Subjective Measures Questionnaire

	Strongly disagree	Disagree	Neither Agree or Disagree	Agree	Strongly Agree
1. This glove provides an adequate level of comfort during tool use.					
2. This glove does not interfere with my ability to grip objects naturally.					
3. This glove does not restrict movement of my fingers and thumbs.					
4. My forearm muscles feel fatigued more quickly when using this glove.					
5. This glove impedes my ability to feel external objects with my hands					

Michael Holmes
University of Ontario Institute of Technology
Faculty of Health Sciences
2000 Simcoe St. North
Oshawa, Ontario
CANADA L1H 7K4
Email: michael.holmes@uoit.ca

Letter of information and consent form

Title of Project: Defining muscle recruitment strategies and control of the upper limb

You are invited to participate in a research study entitled "Defining muscle recruitment strategies and control of the upper limb". This study (REB # 14-046) has been reviewed by the UOIT Research Ethics Board and has been approved as of December 2, 2014 (renewal November 25, 2016). Please read this form carefully, and feel free to ask any questions you might have. If you have any questions about your rights as a participant in this study, please contact the Compliance Officer at 905-721-8668 ext. 3693 or compliance@uoit.ca.

Researchers

Dr. Michael Holmes, Adjunct Professor, Faculty of Health Sciences, University of Ontario Institute of Technology, email: michael.holmes@uoit.ca.

Dr. Paul Yielder, Assistant Professor at the University of Ontario Institute of Technology, Faculty of Health Sciences, 2000 Simcoe St North, Oshawa, Ontario, L1H 7K4, email: paul.yielder@uoit.ca, Phone : 905-721-8668 ext. 2768.

Ryan Shivpaul, Graduate Student, email: ryan.shivpaul@uoit.ca

Purpose of the Study
The purpose of this study is to better understand how humans recruit forearm muscles during gripping and wrist flexion/extension activities and to determine if these recruitment strategies change with forearm muscle fatigue. In particular, the purpose is:
1. To understand how the brain controls upper limb movements and to define the role of forearm and shoulder muscles during upper extremity tasks (e.g. gripping, finger manipulation, pushing, and pulling).
2. To determine muscle recruitment and control strategies while establishing a theoretical framework for identifying co-contraction and synergist actions. Individual muscle parameters (force, length, velocity, and fatigue) will be modulated to replicate time-varying task exposures (repetition and loading).
3. To evaluate how hand arm vibration affects forearm muscle activity and to evaluate the effectiveness of custom made gloves for reducing hand arm vibration.

Potential Benefits to Participants and/or to Society
There are no known or anticipated direct benefits to you for your involvement in this project.

The scientific community will benefit from this research because these findings may lead to changes in the field of ergonomic design of hand gripping tasks during complex activities where gripping and wrist activities are required simultaneously. Examples include screw driving and other manual labour jobs.

Participation and Withdrawal
Your participation in this study is voluntary. You may withdraw from this study at any time without consequence. To do so, indicate this to one of the researchers listed at the top of this page by saying, "I no longer wish to participate in

this study". If you wish to withdrawal from this study your data will be permanently discarded and all paper copies (consent form, etc.) will be destroyed.

If you wish to withdraw consent after the study has ended, please contact one of the researchers on this project and they will remove you from the study.

We remind you that your participation is completely confidential and your data will be treated as such. You have the right to withdraw without consequence, and you are not being personally assessed in any way on your performance in our task. We encourage you to discuss any discomforts with the researcher immediately during collection and we will stop the session if you experience any irritation or discomfort.

Rights of Research Participants
You are free to ask any questions that you may have about your rights as a research participant. You may withdraw your consent at any time and discontinue participation without consequence. If any questions come up during or after the study, contact the study researchers listed on the first page.

Eligibility
Males and females are eligible to participate (age range, 20-40 years). We are seeking individuals who have not had upper extremity pain or injury in the past 12 months.

Procedures Involved in this Study and Time Commitment

Description
As humans, we continuously interact with tools and objects in our environment. Even trivial human-object interactions require the musculoskeletal system to instantaneously find a solution to coordinate movement successfully and safely for the task demands. During hand intensive tasks (like tool use), the forearm muscles control multi-joint limb movements, balance forces at the wrist, provide stability and neuromechanical control. A complex arrangement of muscles, with many degrees of freedom, combined with muscular redundancy, suggests that no unique solution for control of a task exists. Biomechanical characteristics partially dictate roles for each muscle, but mechanical output is ultimately a consequence of signals sent by the central nervous systems (CNS) to the muscle. These neuromechanical aspects need to be considered at the forearm and shoulder to fully understand the links between motor commands, neural activity, and limb mechanics.

Hypothesis:
1. The type of perturbation (vibration) will influence recruitment strategies as much as magnitude.
2. Fatigued Extensor carpi radialis (ECR) and Extensor carpi ulnaris (ECU) will result in CNS redistribution. Other forearm extensor muscles will have increased stabilizing roles. The forearm flexor muscles will produce the required grip force, but with lowered accuracy and have an increased stabilizing role.
3. The reduced capacity of ECR will result in a redistribution of extensor activity to provide added stability. The forearm flexors role will change to accommodate task completion.

Protocol:
Upon arrival to the lab, the investigators will explain and demonstrate all of the tasks to you. We will also familiarize you will the equipment being used and verbally explain and review the consent form.

You will be holding a vibrating tool during this workplace simulation. You will stand in front of the workstation and perform a drilling task. The task will last for approximately 2 minutes. After this, you will wear a variety of gloves (5) that are classified as having hand arm vibration reduction properties (6 conditions in total, 1 without gloves, 5 with gloves). You will perform the same 2-minute task with each glove and we will measure the amount of vibration transmitted to your hand and arm. You will be given 2 minutes' rest between each glove condition.

Metrics/Instrumentation: Once familiarized with all of the tasks, you will be instrumented for our biomechanical measures. Muscle activity will be recorded using surface electromyography (SEMG) and prior to electrode placement, standard preparations, including shaving the surface and cleansing the skin with alcohol will be performed. Parallel bar electrodes will be used to obtain SEMG data from each muscle and will be affixed to the skin surface with custom double-sided adhesives. Selected muscle groups will include:

1. The forearm muscles: Extensor carpi radialis, extensor carpi ulnaris, extensor digitorum, flexor carpi radialis, flexor carpi ulnaris, and flexor digitorum superficialis.
2. The elbow muscles: Biceps brachii, brachioradialis, and triceps brachii
3. The shoulder muscles: Anterior deltoid, middle deltoid, posterior deltoid, and trapezius

Following preparation, you will perform a series of maximal voluntary contractions to normalize the EMG signals. You will perform isometric maximal wrist flexion and extension contractions to normalize the EMG signals. You will also perform a maximal hand grip test using a hand grip dynamometer with your arm resting by your side and forearm and wrist in a neutral position. Two maximal trials will be recorded and the peak of both trials will be used as the maximum grip force. Maximal shoulder and elbow contractions will include a series of maximal shoulder exertions including flexion and abduction and maximal elbow flexion and extension trials. All SEMG data will be digitally recorded at a rate of 2048 Hz.

Next, a set of custom-molded rigid bodies consisting of infrared light emitting markers will be affixed to you so that three-dimensional positions and orientations of your body segments can be accurately measured with optoelectronic cameras. Specifically, these rigid bodies will be affixed to the pelvis, thorax, upper arms, forearms, hands and head.

A small accelerometer (same size as the EMG sensors) will be attached to both the tool and your dominant hand during the task. All accelerometer data will be digitally recorded at a rate of 2048 Hz.

Timeline
Including instrumentation and experimental setup, it is expected that you will be in the biomechanics laboratory for approximately 1.5 hours.

Risks and Discomforts
There may be minimal risk associated with this study. For instance, the use of electromyography may require tape to secure the electrodes to the skin. However, in the unlikely event there is irritation caused by surface electrodes, this will fade in 1-2 days. As a requirement for electromyography investigations, maximal voluntary exertions are required. You may experience some mild muscle soreness as a result of these maximal contractions. However, these maximal activities can be considered similar to activities of daily living often experienced at home.

All tasks being simulated for this study are considered to be minimal risk and simply involve gripping and wrist movements, like we do as part of our daily activities. In the very unlikely event of injury (for example, you may experience discomfort to the hand or forearm), we do not have funds in our grant to cover treatment expenses. We remind you that as a student, the student health insurance plan does cover chiropractic and physiotherapy care. We encourage any individuals with persistent irritation or discomfort to please visit the Campus Wellness Centre located in the Campus Recreation and Wellness Centre or your healthcare provider.

Compensation for Participation
You will receive a $5 Tim Horton's gift card for participating in this study (this means that you have completed the laboratory session).

Disclosure
Your identity will be kept confidential and only made available to the researchers. You will be identified only by a subject identification code during the data collection phase of this study. Only the researchers will have access to the actual identities of the participants, even during release of the study findings. All data will be stored in a secure area (UAB 355), locked in the principal investigator's filing cabinet or on a secured computer server.

Please read the following before signing the consent form and remember to keep a copy for your own records.

By signing this form, I agree that:
- The study has been explained to me. All my questions were answered to my satisfaction.
- The possible harms and discomforts and the possible benefits (if any) of this study have been explained to me.
- I know about the alternatives to taking part in this study. I understand that I have the right not to participate and the right to withdraw at any time.

- ▪ The data collected in this study will be kept in a locked filing cabinet, and/or stored on a password protected computer at UOIT, Oshawa, Ontario.
- ▪ I hereby consent to participate.

I, …………………………………………….................... agree to take part in this research.

- • I have read and I understand the information for volunteers taking part in the study "Defining muscle recruitment strategies and control of the upper limb". I have had the opportunity to discuss this study with the researchers and I am satisfied with the answers I have been given.

Signing this form gives us your consent to be in this study. It tells us that you understand the information about the research study. When you sign this form, you do not give up your legal rights. Researchers or agencies involved in this research study still have their own legal and professional responsibilities.

Thank you very much for your time and help in making this study possible. If you have any queries or wish to know more please contact Dr. Michael Holmes, an Adjunct Professor at the University of Ontario Institute of Technology, Faculty of Health Sciences, 2000 Simcoe St North, Oshawa, Ontario, L1H 7K4
email: michael.holmes@uoit.ca . Or Paul Yielder, Assistant Professor at the University of Ontario Institute of Technology, Faculty of Health Sciences, 2000 Simcoe St North, Oshawa, Ontario, L1H 7K4
email: paul.yielder@uoit.ca Phone : 905-721-8668 ext. 2768

For any other queries regarding this study, please contact the UOIT Research and Ethics Committee Compliance officer (compliance@uoit.ca and 905-721-8668 ext. 3693).

I, the undersigned, have fully explained the relevant details of this research study to the participant named above and believe that the participant has understood and has knowingly given their consent.

_____   _____
Printed Name and Signature   Date

_____
Signature

_____
Role in the Study (only authorized / qualified member of the research team)