VIBRATION TRANSMISSION CHARACTERISTICS AND GRIP STRENGTH PRESERVATION OF ANTI-VIBRATION GLOVES

Karim Hamouda

A Thesis
in
The Department
of
Mechanical and Industrial Engineering

Presented in Partial Fulfillment of the Requirements
for The Degree of Masters of Applied Science at
Concordia University
Montreal, Quebec, Canada

April 2016

© Karim Hamouda, 2016

CONCORDIA UNIVERSITY
SCHOOL OF GRADUATE STUDIES

This is to certify that the Thesis prepared,

By: **Karim Hamouda**

Entitled: "**Vibration Transmission Characteristics and Grip Strength Preservation of Anti-vibration Gloves**"

and submitted in partial fulfillment of the requirements for the Degree of

Master of Applied Science (Mechanical Engineering)

complies with the regulations of this University and meets the accepted standards with respect to originality and quality.

Signed by the Final Examining Committee:

______________________________ Chair
Dr. Gerard Gouw MIE

______________________________ Examiner
Dr. Ramin Sedaghati MIE

______________________________ Examiner
Dr. Pragasen Pillay External
Electrical and Computer Engineering

______________________________ Supervisor
Dr. Subhash Rakheja MIE

______________________________ Co-Supervisor
Dr. Pierre Marcotte IRSST

Approved by: ______________________________
Dr. S. Narayanswamy, MASc Program Director
Department of Mechanical and Industrial Engineering

____
Dr. Amir Asif, Dean
Faculty of Engineering & Computer Science

Date: ______________________

ABSTRACT

VIBRATION TRANSMISSION CHARACTERISTICS AND GRIP STRENGTH PRESERVATION OF ANTI-VIBRATION GLOVES

Karim Hamouda, Master of Applied Science
Concordia University, 2016

Exposure to hand-transmitted vibration (HTV) arising from operating hand-held power tools has been associated with various health consequences such as vascular, neurological and musculoskeletal disorders of the hand-arm system, which are collectively termed as hand-arm vibration syndrome (HAVS). In order to decrease the effects of HTV, substantial efforts have been made to protect the operator from the vibrating tools and decrease the vibration exposure. One of the convenient means to isolate the hand from the vibrating tool handle is the anti-vibration (AV) glove. These gloves are constructed from different isolation materials, which are capable of reducing the vibration transmitted to the hands. Vibration isolation performance of AV gloves has been widely evaluated based on measurements of vibration transmitted to the palm of the hand following the method recommended in ISO 10819 (2013). The standard does not require the measurement of transmitted vibration at the fingers side, and consider similar vibration isolation performance of the gloves at the palm and the fingers. The standard also does not address the effect of AV gloves on the hand grip strength, which can be a reason for not wearing these gloves by tool operators. This dissertation seeks to develop a finger adapter capable of measuring the transmitted vibration to fingers and assess the AV gloves based on the integrated performance of vibration isolation at palm and fingers as well as the grip strength preservation.

Three different finger adapters (a steel ring, a split ring and a Velcro adapter), each instrumented with a tri-axial accelerometer, were developed and assessed to measure the vibration transmitted to the index and the middle fingers. The assessment of the three adapters showed that the Velcro adapter exhibit relatively lower inter-subject variability and yields resonably good agreements with the data reported in a recent study that measured fingers vibration using laser vibrometer. The effectiveness of the Velcro finger adapters was further explored through their ability of generating repeatable and reproducible vibration measurements. Good repeatability was observed from the vibration transmissibility measured during three trials perfromed with bare hand fingers. In the reproducibility tests, the subjects were asked to remove and reinstall the finger

adapters between the trials. The assessment results showed that the obtained vibration transmissibility measurements were reproducible within each subject.

In order to enhance the understanding of fingers vibration, an investigation was conducted through measurements of vibration transmissibility of four different vibration reducing (VR) gloves at the middle phalanges of index and middle fingers using two Velcro finger adapters. Four male subjects participated in the measurements, which were conducted under the standardized vibration spectrum and the spectra of three different hand tools. Vibration transmissibility of the gloves were also measured at the palm using the standardized palm adapter. The frequency response functions (FRFs) of gloves at the index and middle fingers were utilized to estimate the vibration transmissibility of the gloves under different tool spectra. Only two gloves would be considered as AV gloves, although these showed fingers vibration amplification. The FRF method of estimating fingers vibration responses resulted in reliable prediction of the perfromance for different tools.

Furthermore, 12 male subjects participated for assessment of integrated performance of 12 different VR gloves in terms of vibration transmission performance at the palm and fingers, as well as the effect of gloves on the grip strength preservation. The grip strength magnitude was measured using the cylindrical handle utilized in the vibration transmissibility measurements. The overall vibration transmissibility of the gloves at the fingers were obtained using the frequency weighting recommended in the standard and the reported fingers weighting. All the gloves attenuated fingers vibration in the 10–200 Hz frequency range, with exception of only two gloves. At greater frequencies (>200Hz), majority of the gloves amplified the middle finger transmitted vibration, while only a few gloves showed vibration amplification at the index finger. The effect of different frequency weightings on the vibration isolation performance of gloves at the fingers was only evident in the high frequency range (200–1250Hz). Only four gloves passed the standardized screening criteria despite their vibration amplification at the fingers. All the gloves resulted in reduced hand grip strength with only one exception.

ACKNOWLEDGMENT

{In the Name of Allah, the Beneficent, the Merciful}

First praise to Allah, the almighty God, on whom ultimately we depend for sustenance and guidance. I thank Allah for making it possible to successfully complete my master degree. Second, my sincere appreciation goes to my supervisors, Dr. Subhash Rakheja (Concordia University) and Dr. Pierre Marcotte (IRSST), for their professional guidance, financial and moral supports during my degree. Appreciation also goes to Dr. Krishna Dewangan from the Department of Agricultural Engineering, NERIST, Nirjuli, India for his assistance in my research.

I am also grateful to the experienced professors who fortified my knowledge while accomplishing my course work, Dr. Rama Bhat (Summer 2013); Dr. Ramin Sedaghati (Fall 2013); Dr. Gerard Gouw (Fall 2013); Dr. Ahmed Waizuddin (Winter 2014). The department of Mechanical and Industrial Engineering are also appreciated and acknowledged.

I would like to thank my great friends who truthfully supported me during all the tough time, and shared the cheerful moments with me in Canada.

Finally, I thank and appreciate my extraordinary parents and my great brother for their usual care, support, patience and love which helped me to be strong. I appreciate everything you all did for me.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION AND LITERATURE REVIEW

1.1 Problem statement

Workers exposed to long periods of hand transmitted vibration (HTV) arising from operation of power tools may experience disorders in the vascular, neurological and musculoskeletal structures of the hand-arm system, often referred as hand-arm vibration syndrome (HAVS) [1]. It has been reported that 4.6% to 10.9% of the workers population is exposed to HTV in the European countries, while the greatest exposure occurred in the construction (63%), manufacturing and mining (44%), and agricultural and fishing (38 %) sectors [2, 3]. The effects of long-term occupational exposure to HTV have been the focus of many epidemiological and clinical investigations [4, 5]. These suggest that the neural effect could cause numbness and pain in the arms, hands and fingers, and disturbance to operators' sleep rhythm. The early signs of this symptom is fingertip blanching, which may lead to white fingers with the continued exposure. Numbness that occurs with blanching of fingers may persist with decreased tactile and temperature sensitivity [6]. The muscular effects of HTV exposure have been related to muscles weakness, joints pains, and loss of grip strength and manipulation ability [7-9]. The exposure to HTV has also been associated with bones injuries such as cysts, vacuoles and an over-representation of carpal bone vacuoles, scaphoid fracture non-union and wrist joint arthrosis due to prolonged exposure to vibration [10, 11].

Owing to large magnitudes of HTV and its effects on operators' health, considerable efforts have been made towards decreasing the exposure through design of low vibration power tools, isolation of tool handles from the vibration source [12-16], isolation of the hand from the handle [17-20] and designs of tool supports [21-23]. Among these, the exposure reduction via isolation of the hand from the vibrating tool handle using anti-vibration (AV) gloves is considered as most convenient. The AV gloves are designed with vibration isolation materials such as air bladder, gel and gel-foam, which could provide attenuation of handle vibration transmitted to the hand and hand-arm structure. The isolation effectiveness of AV gloves is, invariably, evaluated through measurements in the laboratory using the method defined in ISO 10819 (2013) [24]. The standardized test involves measurement of the transmitted vibration at the glove-palm interface using a palm adapter equipped with a three-axis accelerometer. The standard also defines screening criteria for gloves to be classified as anti-vibration in the medium (25–200 Hz) and high (200–

1250 Hz) frequency ranges. The standardized method requires measurements of vibration only at the palm of the hand, assuming similar characteristics of vibration transmitted to the fingers of the hand. The measurements of vibration at the fingers, however, poses complex challenges. Three recent studies have employed a finger adapter, laser vibrometer and wooden disc to capture the fingers vibration [20, 25, 26]. These have shown that characteristics of fingers vibration differ substantially from that of the palm. A glove considered anti-vibration on the basis of the palm-transmitted vibration alone thus may or may not provide attenuation of vibration transmitted to the fingers. The effectiveness of AV gloves in limiting the vibration transmission to fingers, however, has not yet been attempted except in two recent studies [20, 25].

Moreover, the AV gloves generally employ relatively thick isolation materials to achieve greater damping and thus vibration isolation performance. The gloves thus adversely affect the grip strength and hand dexterity of the workers [18, 27]. The standardized method, however, does not address these aspects, although it requires same isolation materials at both the palm and fingers, while the material thickness at the fingers must be at least 60% of that at the palm. The loss of dexterity may encourage workers to function without the gloves and thereby increase the exposure and the risk of HAVS. The performance of different AV gloves have been reported in many studies, which are invariably based on vibration transmitted to the palm alone. It is vital that the performance of gloves be assessed considering not only the vibration transmitted to the palm but also the fingers, and preservation of grip strength and manual dexterity.

This dissertation research is aimed at developing methodologies for assessing integrated performance of AV gloves including the vibration transmission to the palm and fingers of the hand, and preservation of grip strength. An adapter is developed for measuring vibration transmitted to the index and middle fingers of the hand. Experiments were designed and performed to measure the grip strength reduction, and palm and finger vibration transmission performance of 12 different gloves under the standardized broadband random vibration excitation and fixed hand grip and push forces. The study included gloves made of gel, gel-foam, and air pockets. A total of 12 adult male subjects participated in the study involving 13 different hand treatments, including the bare hand. The data were analyzed to quantify the degree of grip force reduction, and palm and fingers vibration transmissibility. The applications of the standardized W_h and a reported fingers frequency-weightings are further discussed, and the results are used to provide guidance on designs and screening criteria for AV gloves.

1.2 Nature of tool vibration

Protecting workers from HTV requires good understanding of the nature of vibration caused by different hand-held power tools. The reported longitudinal and cross-sectional epidemiologic studies have mostly concentrated on two classes of power tools, namely, pneumatic tools and electrically operated tools [28]. As examples, Tables 1.1 and 1.2 respectively, summarize the ranges of vibration measured at different tools' handles in terms of rms acceleration, and the frequency ranges and directions of dominant handle vibration. The directions of vibration (X_h, Y_h, Z_h) refer to the hand coordinate system defined in the international standard ISO – 5349-1 (2001) [29] (Fig. 1.1). From the reported data, it is evident that the dominant handle vibration generally range from 25–150 Hz, although vibration at frequencies as high as 2000 Hz have been widely reported, especially for percussion tools. The reported data further show that the magnitudes of handle vibration arising from different tools could vary widely among different tools and could be as high as 2014 m/s^2 for impact type of tools.

Table 1.1: Acceleration levels measured on different tools reported in different studies [28]

Type of Tool	**Un-weighted Acceleration (m/s^2)**
Chipping hammer [30-33]	251-2014
Riveter [34]	1183
Pedestal grinder [35-37]	122-382
Jack-leg drill [38-40]	121-362
Grinders [41, 42]	20-205
Pavement breaker [43]	195
Chain saws[39]	75

Table 1.2: Frequency ranges and directions of dominant vibration caused by different hand-held power tools.

Type of Tool	Frequency range (Hz)	Directions of vibration
Heavy duty sander[44]	70-150	X_h, Y_h, Z_h
Orbital sander [44, 45]	60-125	X_h, Y_h, Z_h
Vertical polishers [44]	70-125	X_h, Y_h, Z_h
Chain saws [19, 46-49]	63-125	X_h, Y_h, Z_h

Pneumatic hammers [49, 50]	40-80	Z_h
Chipping hammers [41, 46, 51]	25-125	X_h, Y_h, Z_h
Electrical impact drills [19]	>500	X_h, Y_h, Z_h
Vertical grinders [41, 46]	40-80	X_h, Y_h, Z_h

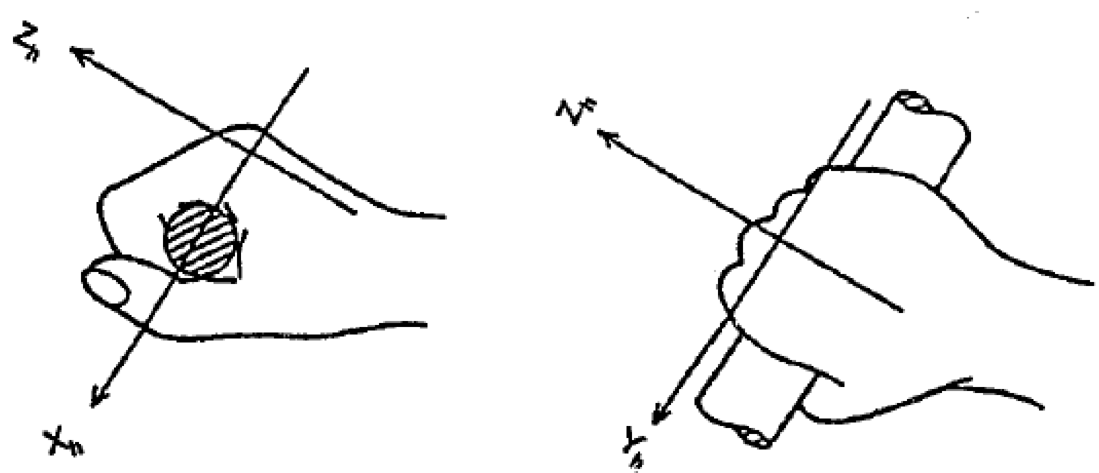


Figure 1.1: Coordinate systems for the human hand [29]

1.3 Vibration exposure Guidelines

The exposure of the hand to handle vibration is generally expressed in terms of rms acceleration in the one-third octave bands ranging from 6.3 Hz and 1250 Hz. A number of organizations, namely, the British standards Institute (BSI) [52], American National Standard Institute (ANSI) [53] and American conference of Government Industrial Hygienists (ACGIH) [54], have defined hand-transmitted vibration exposure limits in terms of rms acceleration up to 1000 Hz, as shown in Figure 1.2. These were intended for providing guidance for protecting a majority of workers from serious impairment due to HTV [28]. Although, the symptoms of the hand-arm vibration have been widely documented in many occupations, only a few studies have proposed dose-response relationships [55, 56].

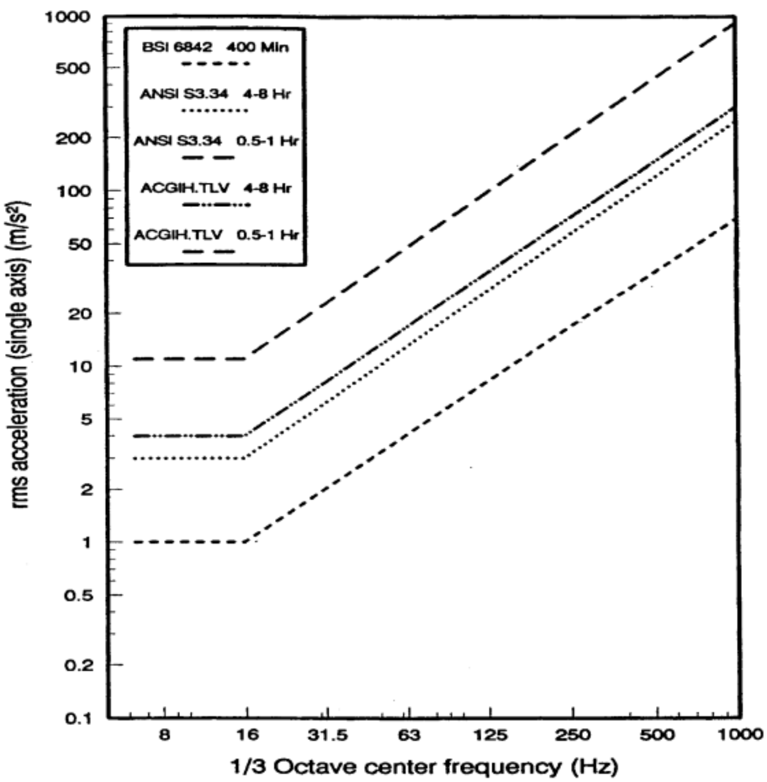
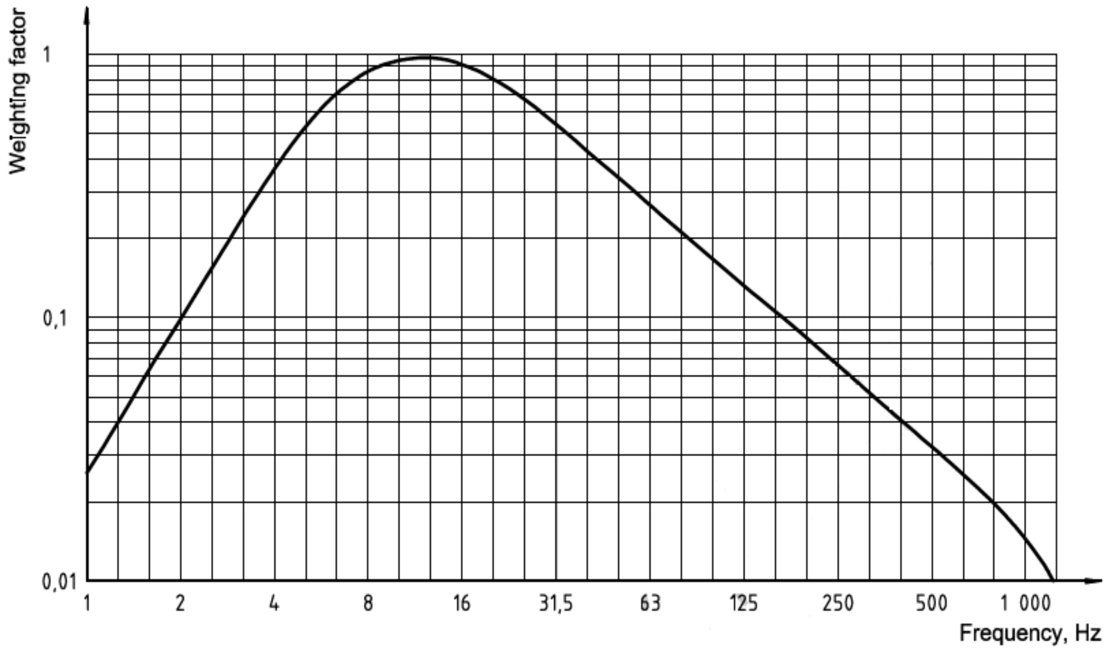
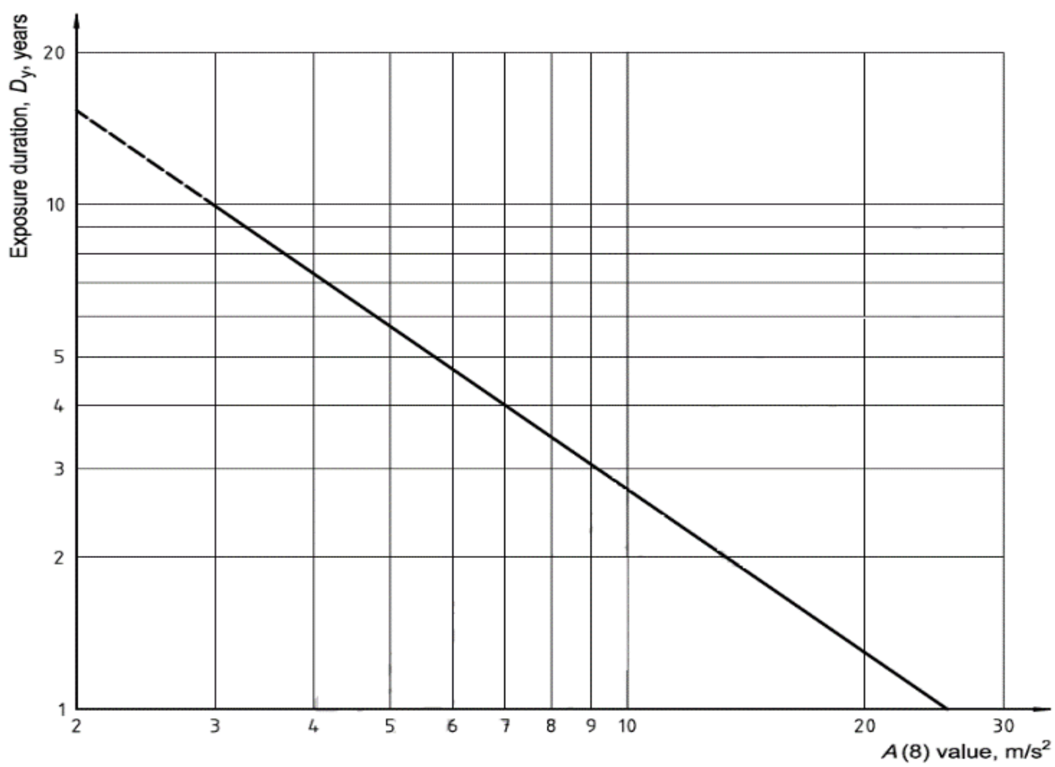


Figure1.2: Hand-Arm vibration exposure limits recommended by different organizations [28]

The exposure to HTV is mostly assessed using the guidelines and methods recommended in the international standard, ISO–5349-1 (2001) [29]. The standard defines the W_h-frequency weighting, shown in Figure 1.3(a), for estimating the HTV exposure in terms of frequency weighted rms acceleration, and a dose-response relation for predicting the onset of VWF on the basis of 8-hour equivalent exposure A(8), shown in Figure 1.3(b). The frequency-weighted HTV exposure is obtained from the handle vibration measured along the three translational directions (X_h, Y_h, and Z_h), as shown in Figure 1.1. The dose-response relation in the standard provides the probable exposure duration in terms of number of years (Dy) likely to produce white fingers among 10% of the exposed population.



(a)



(b)

Figure1.3: (a) W_h-frequency weighting; and (b) dose-response relation described in ISO–5349-1 (2001) [29]

1.4 Control of hand Transmitted Vibration (HTV)

Owing to the severe health effects of HTV among the hand tools operators, considerable efforts have been made towards protecting operators from HAVS. These include the efforts in assessment of potential risks and those aimed at reducing the magnitudes of HTV exposure. Only limited efforts, however, have been made in isolating the handle from the vibrating source or reducing the tool vibration due to the compact design of hand-held power tools, complexities in implementing different isolation mechanisms within the tool, additional cost of these mechanisms, reduced efficiency and robustness of the tool, and lack of customer interest [13, 57]. As an example, Ko et al. (2011) [58] evaluated the vibration attenuation performance of four different suspended anti-vibration handles installed on a petrol-driven grass trimmer. The study included a commercially available polymer material handle and three steel and aluminum handles mounted on a grass trimmer through two rubber mounts. The study also evaluated the effect of spacing between the two rubber mounts. The results revealed that not all the rubber mounts can effectively reduce HTV and the mild steel handle with closely spaced rubber isolators revealed the best vibration isolation along all the three axes. Golycheva et al. (2004) [14] developed an experimental rig and proposed the use of vibration isolator between the vibrating casing and the tool handle to reduce the high-frequency components of acceleration transmitted to an operator. The study also proposed a dynamic absorber attached to the handle that suppresses the dominant harmonics of tool operating speed. The results suggested that the vibration absorber and isolator could significantly reduce the HTV without significant increase in the mass of the tool. The isolator and the absorber, however, could limit the maneuverability of the tool by the operator.

Lindell (2011) [13], proposed the design of a tuned vibration absorber and isolation system between the tool impact mechanism and the casing (tool handles) for a pneumatic percussion tool. The proposed design showed substantial potential for reducing transmitted vibration from 20 m/s^2 to 2.7 m/s^2 (weighted hand-arm vector sum acceleration). Practical use of the tuned vibration absorber in the hand-held power machines, however, may be limited because it is tuned to one particular frequency and it is only effective over a narrow band of frequencies. It can also cause an undesirable increase in weight of the tool [13, 14, 59]. Lindell et al. (2015) [15], hence, introduced a nonlinear tuned vibration absorber (NTVA) for use in the pneumatic percussion tools. The study compared the vibration reduction performance of a tool with a NTVA and with a linear tuned vibration absorber. The results showed that the NTVA could yield 95% in the transmitted vibration, while the linear vibration absorber showed about 60% reduction. The NTVA also revealed relatively broader effective frequency range as compared to the linear absorber.

The variations in tool load and operating conditions could also affect the tool operating frequency range, which also may reduce effectiveness of the NTVA. Another study by Moschioni et al. (2011) [12] proposed two different designs of anti-vibration handles to reduce the HTV due to an impact wrench. It was concluded that the handles could reduce the transmitted vibration from 12.4 m/s^2 to 5.3 m/s^2 and 8.2 m/s^2. The vibration reduction effectiveness of these handles, however, showed dependence on the forces exerted by the operators. Furthermore, McDowell et al. (2015) [21] assessed the performance of mechanical arms designed to support horizontal and vertical pneumatic grinders employed in surface grinding tasks. The assessments were conducted by measuring the tool handle vibration with and without the supporting arms. The study concluded that the supports do not offer notable reductions in HTV for most of the tested grinders. The study further reported increase in the grinding task time due to use of the mechanical arms system, which would increase the daily-time weighted HTV exposures.

Alternatively, anti-vibration (AV) gloves made of vibration isolation materials have been widely recommended for limiting the HTV exposure, while providing protection against cuts and bruises. Such gloves, however, tend to limit the manual dexterity of the operator, and adversely affect the grip strength [18, 27, 60]. Moreover, the reported studies show either limited or negligible vibration attenuation by most of the anti-vibration gloves. Studies on recent designs of AV gloves, however, show notable vibration attenuation performance of gloves at the palm, especially in the high frequency ranges [19, 61]. The assessments of vibration attenuation performance of AV gloves, however, is challenging. The method of assessment and the associated challenges are discussed in the following section.

1.5 Performance measurements of AV gloves

1.5.1 Vibration isolation measurements

The vibration isolation effectiveness of AV gloves have been widely assessed in the laboratory using a standardized methodology defined in ISO 10819 (2013) [24]. Many studies have investigated the vibration isolation effectiveness of AV gloves at the palm using the standardized method [1, 18, 61-66]. Briefly, the method requires three subjects to perform the glove vibration transmissibility tests. As illustrated in Figure 1.4, the test utilizes an instrumented handle mounted on an electrodynamic vibration exciter. The handle is capable of generating band-limited random vibration in the 25–1600 Hz frequency range along the forearm (Z_h-axis), and measurements of the hand push and grip forces. Each subject is required to place a light weight palm adapter equipped with a tri-axial accelerometer (Figure 1.5) between the palm and the glove, while applying 30 N grip and 50 N push forces to the handle. Bare-adapter acceleration transmissibility measurement is also required to establish a reference transmissibility of the palm adapter. The standardized methodology requires the evaluation of glove vibration isolation effectiveness in the medium (M: 25–200 Hz) and high (H: 200–1250 Hz) frequency ranges. The frequency-weighted acceleration (rms) measured at the handle and the palm held adapter are computed using the W_h-weighting function defined in ISO–5349-1 (2013) [24] and shown in Figure 1.3(a). The vibration transmissibility of a glove is subsequently calculated as a ratio of the weighted rms acceleration measured at the palm of the hand with the glove to that of the handle. The obtained vibration transmissibility is then normalized with respect to that of the bare hand (adapter). The vibration transmissibility is computed using total vibration method (vector sum of the three-axis vibration) to compensate for the errors due to misalignments of the adapter with respect to the axis of vibration [65]. The standard also provides a screening criteria for the glove to be considered as an AV glove. A glove is concluded as an AV glove, when the frequency weighted palm acceleration transmissibility values in the M- and H-frequency ranges do not exceed 0.9 and 0.6, respectively. The standard also requires that the glove must employ identical vibration isolation material at the palm and the fingers regions, while the material thickness around the fingers must be at least 60% of that at the palm.

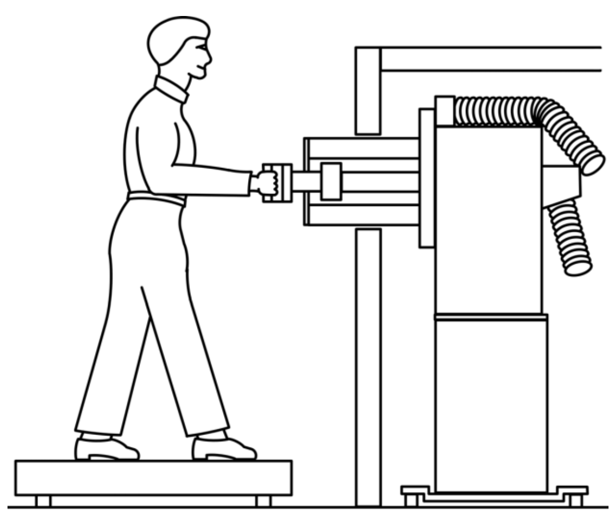


Figure 1.4: Schematic diagram of standard method setup – (ISO 10819) [24]

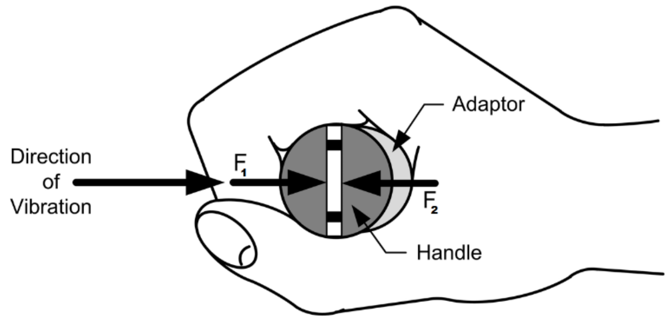


Figure 1.5: Palm adapter aligned with the direction of vibration (ISO 10819) [24]

1.5.2 Limitations of the standardized method

The test method recommended in ISO 10819 (2013) [24] for the screening of AV gloves may be considered effective, however, with some limitations. As example, the standardized method requires three subjects to participate in measurements of the glove transmissibility, which may lead to large inter-subject variability. Different studies have reported large variability in the glove transmissibility associated with different subjects [18, 67-71]. A glove certified as an AV glove by one laboratory may fail on the basis of experiments conducted in another laboratories, depending on the physical attributes of the selected subjects. The earlier version of the standard (ISO 10819, 1996) [72] required three trials per each subject, while the revised version (ISO 10819, 2013) [24] requires five trials. Increasing the number of trials may improve the reliability of the standardized test, while increasing the cost and time of the assessments. The reliability of the measurements could be enhanced by increasing the number of subjects.

Furthermore, the glove is only considered as an AV glove if the fingers section of glove employs same vibration reducing (VR) material at that of the palm. Considering similar VR material shows that the standard (ISO 10819, 2013) [24] may have assumed similar glove vibration isolation performance at the palm and the fingers. However, the reported studies have shown considerable differences in the vibration transmissibility characteristics of fingers as compared to that of the palm [17, 19, 26]. The studies also reported that the gloves exhibit different vibration isolation performance at the palm as compared to that at the fingers, irrespective of the VR material used. Moreover, it is recommended by the standard that the thickness of the VR material at the fingers section should be equal to or greater than 60% of that at the palm. This could make the glove bulky and increase the required grip strength as well as deteriorate the hand dexterity [18, 19, 27, 60]. Hence, it is believed that the standard should also address the effectiveness of the gloves at the fingers in addition to the effect of VR materials thickness on the manual dexterity and grip strength.

It has been suggested that the vibration isolation effectiveness of AV gloves is tool-specific considering wide variations in the magnitudes and frequency ranges of vibration of different tools. Rakheja et al. (2002) [64] compared different tools vibration spectra with the standardized frequency spectrum recommended for the glove test (ISO 10819, 2013) [24]. The study concluded that the standardized spectrum does not characterize the vibration characteristics of most of the tools considered. Consequently, the vibration isolation effectiveness of a glove for specific tools cannot be evaluated using the standardized criteria in the M- and H-frequency ranges. A recent study reported the tool-specific isolation performance of an AV glove at the palm and fingers [19]. The study showed that the AV glove cannot reduce the vibration transmitted to the palm and fingers for most of the low-frequency hand power tools considered, such as rammers and vibrating forks (Dominant frequencies ≤ 25Hz). However, when considering majority of the hand power tools (e.g., chipping hammers, rock drills, and sanders) the AV glove considerably reduced the transmitted vibration to the palm, with only slight vibration reduction at the fingers. The AV glove considered in that study marginally reduced the vibrations at the fingers with tools that generate high frequency vibration (>250 Hz).

1.5.3 AV glove design

Various types of gloves have been developed for use in the hand power tools and machines, in order to protect the workers from HTV apart from cuts, abrasion, and cold/hot environments. Different VR materials have been employed in gloves such as gel, air bladder (interconnected air pockets with pump or independent air pockets), gel-foam and rubber. The vibration isolation effectiveness of different gloves have been extensively studied through laboratory experiments [1, 17, 18, 20, 64-66, 68, 70, 73, 74]. As an example, Rakheja et al. (2002) [64]; Dong et al. (2002) [65]; Welcome et al. (2012) [18] reported the vibration isolation performance of two types of gloves (air and gel) at the palm under standardized spectrum. Both gloves showed comparable performance in the M-frequency range, while the air glove exhibited relatively greater vibration attenuation in the H-range as compared to the gel glove. Similarly, McDowell et al. (2013) [61] reported comparable performance of air and gel gloves at the palm in the M-frequency range, while the gel glove showed superior vibration attenuation performance in the H-frequency range when compared to that of the air gloves considered in the study. The results contradicted the findings reported by Rakheja et al. (2002) [64], Dong et al. (2002) [65], and Welcome et al. (2012) [18].

When testing the gloves with different hand power tools the air glove showed either comparable (road breaker and nutrunner) or relatively better (chain saw, orbital sander, chipping hammer and riveter) vibration isolation performance than that of gel glove [64]. Only a few studies have attempted measurements of vibration transmitted to the fingers of a gloved hand. Welcome et al, (2014) [20] reported that both air and gel gloves exhibit unity vibration transmissibility in the 10-80 Hz frequency range, with slight vibration amplification in the 80–400 Hz frequency range. The study also reported that the gel glove is more effective for reducing the high frequency vibration than the air glove. Hence it can be concluded that the isolation performance of AV gloves depends on the type of the VR material employed in the glove.

1.5.4 Vibration transmission characteristics of AV gloves

AV gloves amplify the palm transmitted vibration in the low frequency range (10–40 Hz) and attenuate the vibration at frequencies greater than 25–30 Hz [17, 18, 61, 75, 76], which is believed to be the palm fundamental resonant frequency [17]. Different from the palm, fingers possess relatively smaller effective mass with fundamental resonant frequencies lies in the 100–200 Hz frequency range [17, 20]. A recent study concluded that AV gloves slightly reduce fingers' vibration at frequencies <80 Hz, while they amplifies the transmitted vibration in 80–400 Hz frequency range [20].

Isolation effectiveness of AV gloves is tool-specific and does not seem to depend on the magnitude of vibration. It, however, strongly depends on the dominant frequency of the vibrating tool [64]. Generally, AV gloves isolation performance at the palm is better with tools that possess dominant frequencies >25 Hz such as chipping hammers or riveting hammers, when compared to the road breakers, vibrating forks or rammers [19, 64, 74]. Similarly for fingers, the AV gloves may reduce the fingers transmitted vibration only at high frequencies >400 Hz, which is produced from tools with dominant frequencies in very high frequency ranges such as electric impact drill [19, 20].

1.5.5 Grip strength preservation

As stated earlier, a glove that is classified as AV glove and satisfies the isolation material thickness criteria, could be bulky. Such a glove may thus require higher grip strength (force) than that required by the bare hand. Generally, increasing the grip effort could increase the risk of hand-arm musculoskeletal disorders (MSDs) [77-79]. In order to comprehend the effect of different gloves on grip strength, jamar dynamometer handles have been mostly used for the measurement of grip strength [27, 80, 81]. Grip strength is the total contact force measured when an individual applies a power grip to a handle with maximum voluntary contraction (MVC) [27], and it is the scalar sum of fingers and palm forces minus the push force (Figure 1.6) [82]. Jamar dynamometers, however, possess different handle geometry, which may provide underestimates of the palm and fingers contact force. It has been suggested that grip strength measured with such handles may not be fully representative of grip forces applied to tools' handles [27].

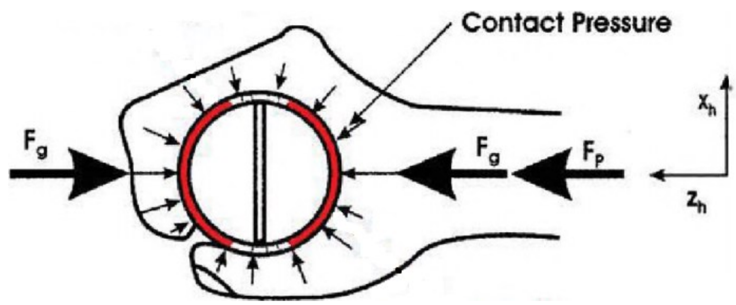


Figure 1.6: Schematic of push and grip forces [82]

Cylindrical handles were alternatively employed in different studies in order to overcome the deficiencies of the jamar dynamometer [18, 27, 82-84]. Grip strength reduction is generally affected by glove thickness. As the glove thickness increases the grip strength reduction increases when comparing same type of gloves employing different thickness [81], however, this is not the case when considering gloves with different VR materials [27]. The grip strength reduction by a glove is also reported to the glove material properties (stiffness). Welcome et al. (2012) [18] reported that gel gloves exhibit higher grip strength reduction compared to air glove, while Wimer et al. (2010) [27], reported comparable or higher reduction of gel glove when compared to air gloves. Furthermore, the grip strength reduction of an AV glove is also affected by the handle diameter. Smaller diameter handles revealed relatively smaller grip percentage reduction [27], which also permit greater hand grip strength [85]. Reducing the stiffness of the glove by choosing softer materials could improve grip strength reduction performance.

1.5.6 Hand dexterity

Another drawback could result from a thick AV glove, is the deterioration of the manual dexterity of the hand. Generally, gloves increase the task time when compared to the bare hand [83, 86-89]. Bensel (1993) [90] and Muralidhar et al. (1999) [91] conducted two different studies in order to study the effect of different gloves thickness on the hand dexterity. Both studies reported that thicker gloves took longer completion time compared to less thick ones. Dianat et al. (2010) [92], investigated hand performance capabilities (muscle activity, dexterity, touch sensitivity, finger pinch and forearm torque strength) when performing a light assembly task with bare hands and while wearing cotton, nylon or nitrile gloves. Participants worked with a screwdriver to fit two components together using screws. The study concluded that wearing gloves significantly increased the muscle activity, pinch strength and discomfort but reduced the dexterity and touch sensitivity. Different dexterity tests and assessments of gloves have been critically reviewed in the literature [60, 93]. The reported studies, invariably, considered only protective gloves, while the studies on dexterity performance of AV gloves could not be found. The process of choosing an appropriate dexterity assessment test that reflects an actual industrial task could be difficult. AV gloves are expected to possess poor dexterity performance due to large thickness compared to that reported in the literature. Assessments of AV gloves should take in account the effect of glove on preservation of grip strength as well as hand dexterity.

1.6 Objectives of the study

The overall objective of this dissertation research is to contribute towards developments in methods for assessing integrated performance of AV gloves in terms of vibration isolation at the palm and the fingers as well as grip strength preservation. The specific objectives of the study included:

a. Design and develop a finger adapter for measurement of vibration transmitted to the index and middle fingers of a gloved hand;
b. Develop a methodology for assessing fingers' vibration transmission performance of VR gloves;
c. Assess integrated performance of 12 different VR gloves through measurements of vibration transmitted vibration to the palm and the fingers of the hand, together with grip strength preservation;

d. Explore effectiveness of transfer function method for predicting vibration transmission performance of the VR gloves at the fingers under the vibration spectra of selected hand tools.

The study was conducted in three stages. During the initial stage, the reliability of three different finger adapters (a steel ring, a split ring and a Velcro adapter) was assessed through the measurements of vibration transmitted to mid-phalanges of the index and middle fingers of bare hand. The measurements were performed using the method similar to that described in ISO 10819 (2013) [24] for measurement of vibration transmitted to the palm of the hand. During the second stage, Velcro finger adapters were used to measure the vibration transmission characteristics of 4 different VR gloves (air, gel, hybrid and leather) at the middle phalanges of the index and middle fingers using a sample of 4 subjects (hand sizes: 8-9). Standardized palm adapter was also used to measure the vibration transmissibility of the gloves at the palm. Fingers and palm vibration transmissibility characteristics of 4 gloves were also measured under three different tool spectra (road breaker, nutrunner and orbital sander). The measured frequency response functions (FRFs) of the 4 gloves were used to estimate the vibration transmission performance of the gloves at the fingers under the selected hand tools vibration spectra. In the third stage of the study, 12 VR gloves (air, gel, hybrid, gel-foam and leather) were assessed based on their integrated performance of vibration isolation effectiveness at the palm and the fingers, and the grip strength preservation. The vibration transmissibility measurements of the gloves were performed under the standardized spectrum, however, that of grip strength were conducted under static grip conditions. The 40 mm cylindrical handle utilized in the vibration transmissibility tests was also used to measure the grip strength preservation performance of the gloves. 12 subjects with different hand sizes (7-10) participated in the experiments. Two groups of subjects (each group included three randomly chosen subjects) were also used to evaluate the repeatability and reproducibility of the fingers vibration measurements by the Velcro adapters. The vibration isolation effectiveness of the VR gloves were evaluated using two different frequency weightings including the standardized W_h-weighting and a finger weighting, W_f.

1.7 Organization of the thesis

This dissertation is organized in a "Manuscript" format consisting of four chapters. Chapter two briefly presents the development and reliability assessment of different designs of finger adapters that were utilized for characterizing fingers vibration. In this chapter, the vibration transmission characteristics of four different gloves were measured at the palm and fingers under the standardized broad-band vibration spectrum and vibration spectrum of selected hand power tools. The vibration transmissibility magnitudes at the mid-phalanges of the fingers of the gloved hand were obtained using standardized hand weighting (W_h) and a finger weighting (W_f) proposed in [94]. The validity of frequency response function (FRF) method to predict fingers vibration transmission characteristics of VR gloves for a few selected tools was also assessed. The measurement methods and the results have been presented in the following manuscript:

Hamouda, K., Rakheja, S., Marcotte, P., Dewangan, K.N., "Fingers vibration transmission performance of vibration reducing gloves". Under review, Int. J. of Industrial Ergonomics (Submitted: January 2016)

This paper describes the design of three different finger adapters (a steel ring, a split ring and a Velcro adapter). Each finger adapter integrated a miniature tri-axial accelerometer, weighting 1 gram, for measuring the vibration transmitted to mid-phalanges of the fingers. The effectiveness of the adapters were assessed in terms of repeatability and reproducibility of measurements. The vibration measurements were conducted following a method similar to that described in ISO 10819 (2013) [24]. The instrumented handle was subjected to standardized vibration spectrum, while each subject was advised to apply 30±5N grip force and 50±8N push force with the bare hand. The measured vibration transmissibility responses showed that the split ring and the Velcro finger adapters revealed measured responses comparable to those in a recent reported study [20]. The measurements with the Velcro adapter, however, revealed relatively lower inter-subject variability compared to the split ring adapter. Furthermore, the subjects reported relatively greater comfort with Velcro adapter. The Velcro finger adapters were thus used for measurements of index and middle fingers vibration responses. The vibration transmission characteristics of four different gloves (air, gel, hybrid and leather) were subsequently measured at the palm and middle phalanges of the index and middle fingers of the gloved hands of 4 subjects. The hybrid glove was constructed from air bladder in the palm region and gel pad at the fingers side. The vibration measurements were performed under the standardized vibration spectrum using same posture and hand forces as recommended in ISO 10819 (2013) [24]. The overall vibration transmissibility magnitudes of the gloves for the fingers were obtained in both M- and H-frequency ranges using the standardized hand-weighting (W_h) as well as the fingers-weighting (W_f) that was proposed in [94]. The vibration transmission characteristics of the gloves were also measured at both fingers under the spectra of three different power-hand tools (road breaker, nutrunner and orbital sander). The FRF of each glove measured under the standardized spectrum was used to estimate the fingers vibration responses under these selected tools vibration spectra. The estimated vibration responses at the fingers using the FRF method under the vibration spectra of the selected tools showed good agreements (-11%–13%) with the measured responses for all the gloves. The results showed that only the air and hybrid gloves could provide slight vibration attenuation at the index finger when compared to the measurements obtained with the bare hand. All the gloves showed middle finger vibration amplification. At the palm, the vibration attenuation was evident for the air and hybrid gloves above 40 Hz, while the gel and leather gloves revealed nearly unity transmissibility in most of the frequency range. Following the AV gloves screening criteria defined in ISO 10819 (2013) [24], only the hybrid glove could be designated as an anti-vibration (AV) glove, although it exhibited middle finger vibration amplification in the H-frequency range (200–1250 Hz).

Chapter three presents the following article highlighting the assessment of integrated performance of the VR gloves in terms of vibration isolation at the palm and the fingers as well as the grip strength preservation:

Hamouda, K., Rakheja, S., Marcotte, P., Dewangan, K.N., "Fingers' vibration transmission and grip strength preservation performance of vibration reducing gloves". To be submitted in J. of Applied Ergonomics (April 2016)

The paper describes the method to assess ability of the Velcro fingers adapters to generate repeatable and reproducible vibration measurements. Two groups (each involving three subjects) participated in these experiments. In the repeatability measurements, the first group of subjects were asked to install the Velcro finger adapters on the middle phalanges of the index and middle fingers. Following same method recommended in ISO 10819 (2013) [24], the vibration transmissibility characteristics of the bare hand were measured and repeated three times. Same procedures were followed for the reproducibility of measurements, where the subjects were asked to remove and re-install the finger adapters between the successive trials. The results showed the ability of Velcro finger adapters to yield repeatable and reproducible measurements.

The second phase of experiments involved the integrated performance assessments of the VR gloves based on the vibration transmissibility at the fingers and the palm, along with the grip strength preservation. 12 different VR gloves were used including three air bladder, three gel, three hybrid, two gel-foam gloves and a leather glove. Following the test methodology described in the first article (Chapter 2), the vibration transmission characteristics of the 12 VR gloves at the palm and the fingers were measured under standardized vibration spectrum using a sample of 12 subjects. The instrumented cylindrical handle (40 mm diameter) was further utilized to measure the grip strength magnitude of the 12 subjects with and without the VR gloves under static power grip condition. The vibration transmissibility results showed that all the gloves attenuate the vibration transmitted to the fingers in the 10–200 Hz frequency range, except for one of the air and gel gloves considered in the study. At frequencies greater than 200 Hz, majority of the VR gloves started to amplify middle finger vibration, while a few gloves followed this trend for the index finger also. Following the standardized screening criteria recommended in ISO 10819 (2013) [24], only four gloves (namely: air 1, gel 2, hybrid 1, hybrid 3) could be designated as VR gloves, despite their amplification of vibration at the fingers. The two weightings, W_h and W_f were subsequently used in obtaining fingers vibration transmissibility, which showed important significance of the weighting when assessing finger vibration performance of the VR gloves. Gel 2 glove marginally reduced the fingers vibration in the H-frequency range, irrespective of the weighting method used. In the M-range, air 1 glove exhibited the best performance at the index finger considering W_h-weighting and at the middle finger when W_f-weighting was considered. The results further showed that the air 1 glove yielded the highest grip strength reduction (41%), although it does not possess the greatest thickness. Comparable grip strength reduction among the gloves 27-33% were observed, with exception of the leather glove (16%).

Chapter four summarizes the major contributions and conclusions together with some recommendations for possible future works.

2. FINGERS VIBRATION TRANSMISSION PERFORMANCE OF VIBRATION REDUCING GLOVES

2.1 Introduction

Operators of hand-held power tools are exposed to comprehensive levels of hand-transmitted vibration (HTV) arising from tool-hand interactions. Occupational exposure to such vibration has been related to an array of disorders in the vascular, sensorineural and musculoskeletal structures of the hand-arm system, collectively defined as the hand-arm vibration syndrome (HAVS) [95]. The most serious among the diseases is perhaps the vascular disorder, which has been denoted by several different terms, such as Raynaud's phenomenon of occupational origin, traumatic vasospastic disease and vibration-induced white finger (VWF) [37]. The first symptoms of VWF disease are related to intermittent tingling and numbness of the fingers. Under continued exposure, these are followed by an attack of finger blanching confined, in the first instance, to the fingertips, which subsequently propagates to base of the fingers. The cold also acts as the provocative agent.

A number of studies have suggested that health risks imposed by HTV could be reduced by considering two factors, namely control of HTV and ergonomic interventions. Several technical solutions have been proposed over the years to reduce the vibration exposure levels of vibratory hand tools, but the success to reduce HTV have been limited to only a few hand tools, primarily due to the compact designs of hand tools, the associated cost and possibly the reduced working efficiency. Gloves are the most commonly used protective devices for the human hand in the workplace for protection against mechanical trauma, thermal extremities and vibration. In order to protect workers, different types of vibration reducing (VR) gloves have been developed, assessed and utilized to attenuate the HTV generated by tools [62, 63, 96, 97].

The International Organization for Standardization (ISO) has described a measurement procedure for assessing vibration transmission performance of a glove using a palm adapter equipped with a miniature accelerometer (ISO 10819, 2013)[24]. The standardized method assesses the effectiveness of VR gloves solely on the basis of vibration transmitted to the palm. Vibration transmissibility of different gloves to the palm of the hand have been investigated in many studies [1, 18, 61, 64, 65, 73, 76, 98]. The ISO 10819 (2013) standard [24] also defines the screening criteria for a glove to be classified as an anti-vibration (AV) glove. According to this standard, an AV glove must have a frequency-weighted palm acceleration transmissibility ≤ 0.9 in the medium frequency range (25–200 Hz) and ≤ 0.6 in the high frequency range (200–1250 Hz). The standard also requires that an AV glove employ the same vibration reducing materials in the palm and fingers regions, while the thickness of the vibration reducing material placed in the fingers and the thumb regions shall be ≥ 60% of the thickness of the material placed in the palm region. However, the reasoning for using the same vibration reducing materials at the palm and fingers is not sufficiently justified. The standard likely assumes similar vibration transmission performance of the glove material at the palm and the fingers, although the dynamic responses of the fingers differ greatly from that of the palm of the hand [99]. The vibration isolation effectiveness of a glove depends not only on the mechanical properties of the vibration reducing materials, but also on the masses and dynamics of the fingers and the palm. The tissues of the fingers and the palm absorb vibration, while the effective fingers tissue mass is considerably small as compared to the palm tissue mass. Furthermore, the resonant frequencies and the hand-handle contact force distributed at the fingers are substantially different from those of the palm of the hand [100, 101]. The nature of vibration transmitted through the glove material to the palm and the fingers are thus expected to differ. Glove is theoretically more effective to attenuate HTV at the palm along the forearm direction as compared to the fingers [99]. A number of studies have reported doubts on the methodology evaluating VR gloves at the palm only (ISO 10819, 1996) [72] and on the usefulness of VR gloves for attenuating finger vibration [17, 68, 102, 103].

The measurement of vibration transmitted to the fingers of a gloved hand, however, poses complex challenges. Only a few studies have thus attempted to measure the effectiveness of VR gloves in reducing vibration transmitted to the fingers [20, 97, 103]. Welcome et al. (2014) [20] used a 3-D scanning laser vibrometer to measure vibration transmitted to the fingers with and without wearing VR gloves (gel and air bladder). The study reported that the gloves yield only little vibration reduction at the fingers at frequencies below 80 Hz (less than 3%) with notable amplification in the 80–400 Hz range. The gel glove was found to be more effective in reducing vibration at the fingers at higher frequencies as compared with the air bladder glove.

The assessments of the vibration reduction performance of VR gloves as specified by the standardized method (ISO 10819, 2013) [24] are conducted under an idealized vibration spectrum in the 25-1250 Hz frequency range. The vibration spectra of hand held power tools, however, invariably differ from the standardized spectra. Griffin et al. (1998) [68] measured vibration transmissibility of 10 different gloves for predicting the isolation effectiveness of gloves under vibration spectra of 20 different hand tools. The study concluded that the standardized tool spectra cannot predict the vibration isolation performance of VR gloves coupled with different tools. On the basis of the frequency response characteristics of the gloves, Rakheja et al. (2002) [64] proposed a methodology to estimate the vibration isolation effectiveness of AV gloves as a function of handle vibration of specific tools. The effectiveness of the method was demonstrated through comparisons of estimated vibration transmissibility of 2 different gloves with the mean measured responses obtained for different tools' spectra. Dong et al. (2014) [104] estimated tool specific vibration reduction characteristics of four different VR gloves to the palm of the hand in three orthogonal directions (3-D), based on the frequency-weighted vibrations transmitted to the palm of the hand. The study concluded that the VR gloves offer only minimal vibration reduction (<5%) at low frequencies (<25 Hz) or may even marginally amplify vibration (<10%) at low frequencies. The VR gloves, however, revealed 5-58% reduction in the handle vibration transmitted to the palm of the hand, depending upon the vibration spectra of the different tools.

The present study focuses on the assessment of the effectiveness of VR gloves in view of vibration transmitted to both the palm and the fingers under the standardized as well as different tools' vibration spectra. Different designs of adapters were assessed for repeatable and reliable measurements of finger vibration. Vibration transmission characteristics of 4 different VR gloves were measured at the middle phalanges of the index and middle fingers using the finger adapters under the standardized and 3 different hand tools (road breaker, nutrunner and orbital sander) vibration spectra. Vibration transmission characteristics of the VR gloves were also measured at the palm using the standardized palm adapter. The frequency response functions (FRF) for both the fingers and the palm were used to assess the performance of the VR gloves in reducing vibration transmitted to the palm and the fingers. The FRFs were also used to estimate the vibration transmission performance of the VR gloves under the selected tools vibration spectra.

2.2 Methods

2.2.1 Experimental setup

Figure 2.1 illustrates the experimental setup for the measurement of the vibration transmissibility characteristics of VR gloves, which has been reported in many studies (e.g., Dong et al., 2002; Hewitt, 1998) [1, 65]. Briefly, the setup consists of a 40 mm diameter and 140 mm long cylindrical handle mounted on an electrodynamic vibration exciter capable of generating vibration along the forearm (Z_h-axis). The handle is instrumented with two single-axis force sensors (Kistler 9212) to measure the grip force and with a tri-axial accelerometer (PCB 356A01) to measure the handle acceleration, as described in ISO 10819 (2013) [24]. Another two force sensors (Kistler 9317b) were placed between the handle and the exciter for the measurement of the push force. The accelerometer also served as the feedback sensor for the control and synthesis of the handle vibration via a vibration controller (VR 9500, Vibration Research Corp., Jenison, MI, USA). The applied grip and push forces, sampled at a rate of 4 Hz, were displayed on a computer screen mounted near the exciter at the eye level of the subject, in order for the subject to control the hand grip and push forces.

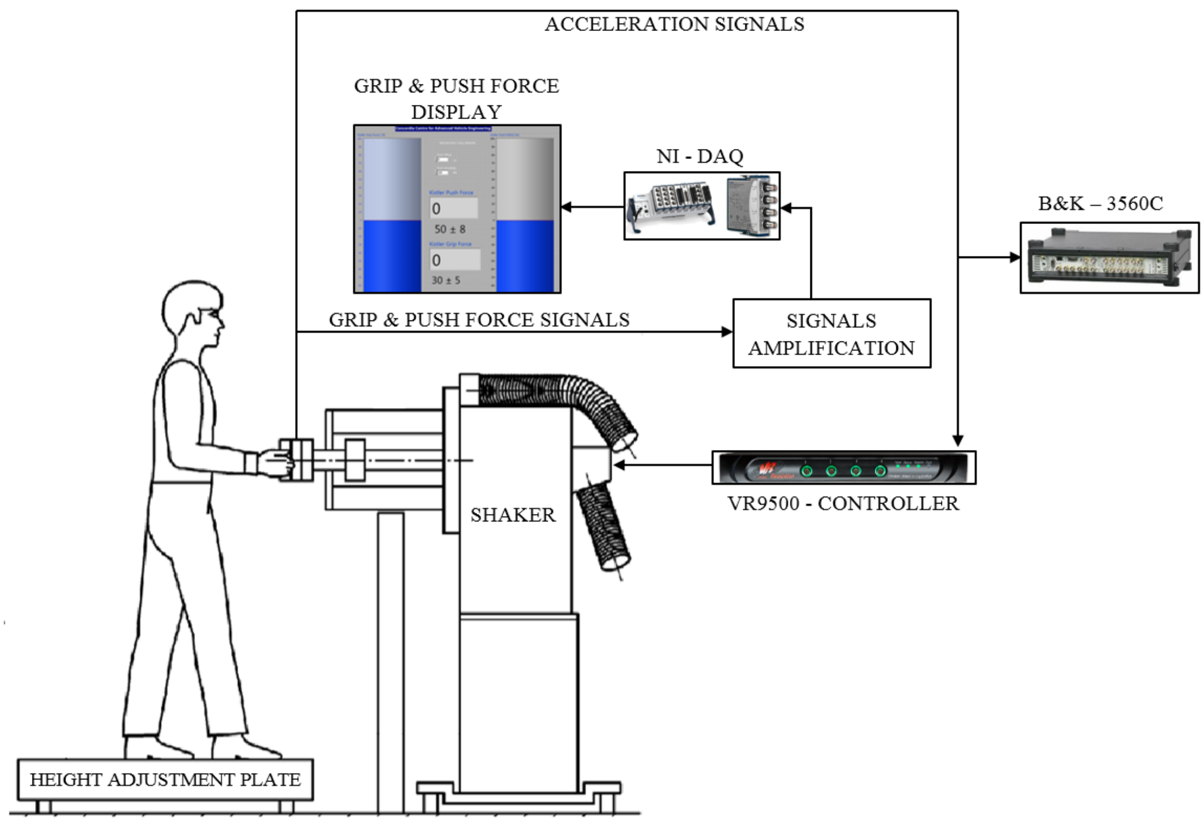


Figure 2.1: Experimental setup for the measurement of vibration transmissibility of vibration reducing gloves.

The vibration transmissibility characteristics of the gloves were measured at the palm and fingers of the subjects. A miniature palm adapter consisting of a tri-axial accelerometer (PCB 356A01) was used to measure vibration transmitted to the subjects' palm, in accordance with the ISO 10819 (2013) standard [24]. The measurement of the vibration transmitted to the fingers was attempted via three different designs of the finger adapters, each comprising a miniature tri-axial accelerometer (PCB 356A01) weighing only 1 gram, namely a stainless steel ring, a stainless steel split ring and Velcro (Fig. 2.2). A data acquisition and analysis system (B&K Type 3560C, PULSE v11.0) was used to record and process the acceleration signals from the handle, palm adapter and finger adapters.

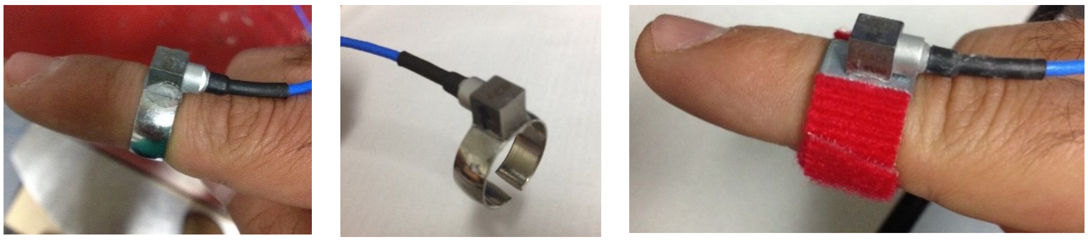


Figure 2.2: Finger adapters with miniature 3-axis accelerometer: (a) stainless steel ring; (b) stainless steel split ring; and (c) Velcro.

2.2.2 Subjects and VR gloves

The vibration transmission characteristics of the VR gloves were measured with four adult male subjects. The experimental protocol was approved by the ethical committee of Concordia University. Anthropometric body dimensions like hand length, hand width, index finger length and middle finger length of each subject were measured and are summarized in Table 2.1. The mean and standard deviation of these parameters and hand size of the subjects, according to EN 420 (1994) [105], are also presented in Table 2.1. The hand size was 9 for three of the subjects, and 8 for the other one. The experiments were performed with four different types of gloves, including 3 VR gloves (air bladder, gel, hybrid) and a leather glove. The hybrid glove was fabricated with air bladder material in the palm region and gel pad on the fingers side. Table 2.2 summarizes the type and thickness of the vibration attenuation materials used in the selected gloves.

Table 2.1: Hand anthropometric dimensions and hand size of subjects.

Subjects	Hand length (mm)	Hand width (mm)	Index finger length (mm)	Middle finger length (mm)	Hand size
1	190	83	66.5	73.4	9
2	185	84	67.8	76.0	8
3	193	85	72.2	77.6	9
4	195	88	77.6	77.5	9
Mean	190.8	85.0	71.0	76.1	-
SD	3.8	1.9	4.3	1.7	-

Table 2.2: Vibration isolation materials used in the selected gloves

Glove	Vibration reducing material		Material thickness (mm)	
	Palm	Fingers	Palm	Fingers
Air	Air	Air	9.2	7.4
Gel	Gel	Gel	4.3	4.3
Hybrid	Air	Gel	7.7	4.3
Leather	Leather	Leather	3.7	1.0

2.2.3 Measurement methods and data analysis

The experiments were performed in two stages consisting in the assessment of the finger adapters for the measurements of fingers' vibration, and in the evaluations of the vibration transmission characteristics of the VR gloves at the palm and middle phalanges of the index and middle fingers. The second stage included three series of experiments involving measurements with: (i) bare hand under standardized vibration spectrum; (ii) gloved-hand under standardized vibration spectrum; and (iii) gloved hands under vibration spectra of the 3 different hand tools. The hand tools considered in the study were a road breaker (dominant vibration frequency ≈ 16 Hz), a nutrunner (dominant vibration frequency ≈ 30 Hz) and an orbital sander (dominant vibration frequency ≈ 100 Hz) [64].

2.2.3.1 Assessments of finger adapters

The first stage of the experiments was performed to assess the reliability of three different designs of finger adapter (a steel ring, a split ring and a Velcro adapter) through measurement of the vibration transmissibility at the index finger without wearing a glove. Each adapter was positioned on the mid-phalange. The experiments were performed using the method described in the ISO 10819 (2013) [24] for the measurement of vibration transmitted to the palm. The subject was advised to apply, on the instrumented handle, a grip force of 30±5N and a push force of 50±8N. Each subject was given training in gripping and pushing the handle prior to the experiments. The instrumented handle was subjected to band-limited random vibration in the 25–1600 Hz frequency range. The overall root-mean-square of the frequency-unweighted acceleration was 90.2 m/s^2. The subjects adopted an upright standing posture on a platform facing the hand forces display monitor (Fig. 2.1). The platform height was adjusted so as to achieve horizontal forearm with an elbow angle of $90^o \pm 10^o$ and a wrist angle between 0^o (neutral) and 40^o. The signals from the handle and finger adapter accelerometers were subsequently acquired for a duration of 30 s, and analyzed to obtain one-third octave frequency band rms spectra of the handle and finger acceleration responses along the three orthogonal axes. Each measurement was repeated 3 times. The effective acceleration transmissibility (TEAT) of finger vibration at each of the one-third octave frequency band was obtained from the vector sums of the handle and the finger adapter acceleration signals, such that:

$$TEAT(\omega_j) = \frac{\sqrt{{A_x}^2(\omega_j) + {A_y}^2(\omega_j) + {A_z}^2(\omega_j)}}{\sqrt{{H_x}^2(\omega_j) + {H_y}^2(\omega_j) + {H_z}^2(\omega_j)}} \qquad (2.1)$$

Where $TEAT(\omega_j)$ is the effective finger vibration transmissibility at the center angular frequency ω_j of the one-third octave band j. H_x, H_y and H_z are the mean rms accelerations measured at the handle, while A_x, A_y and A_Z are the mean rms accelerations measured at the finger adapter in the same frequency band along the X_h-, Y_h- and Z_h-axis, respectively.

The acquired data were analyzed to obtain the mean TEAT values for each finger adapter. As an example, Figure 2.3 compares the mean finger transmissibility of one of the subjects using the three adapters. The responses measured with other subjects were also similar, although considerable inter-subject variability was evident, which is discussed in subsequent sections. The steel ring adapter resulted in multiple peaks of lower magnitudes in the frequency range considered in the experiments. This was attributed to oscillations of the ring with respect to the soft skin tissues. Both the stainless steel split ring and Velcro adapters resulted in distinct peaks of comparable magnitudes near 80 Hz, which is close to the reported resonant frequencies of the fingers. The peak finger transmissibility measured with the stainless-steel split ring adapter is relatively higher than that obtained with the Velcro adapter. The measurements also showed increase in the peak transmissibility with tightening of the split ring adapter. Since the subjects selected different tightness of the split ring, it resulted in substantially higher inter-subject variability of the peak transmissibility compared to the Velcro adapter. Subjects reported relatively greater comfort with the Velcro adapter compared to the steel rings. Furthermore, the Velcro adapter could be conveniently attached to the fingers with desired tightness to ensure minimal relative motion between the adapter and the finger. The mean measured responses were further compared with the finger vibration transmissibility reported by Welcome et al. (2014) [20] using a laser vibrometer. Comparison showed slightly higher peak vibration transmissibility with the

Velcro adapter (~3) and stainless steel split ring adapter (~3.4) compared to the reported value near 2.5. The frequency corresponding to the peak response, considered as the resonance frequency of the finger, occurred in the 80 Hz band, which is slightly lower than the 100–125 Hz frequency bands reported by Welcome et al. (2014) [20]. On the basis of the comparisons together with the convenience, the Velcro adapter was considered adequate for the accurate and repeatable measurement of finger vibration transmissibility.

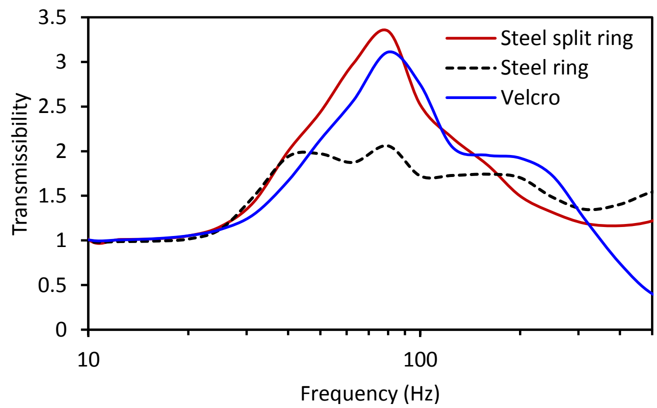


Figure 2.3: Mean total effective acceleration transmissibility responses of the finger measured with the stainless steel ring, the split ring, and the Velcro finger adapters.

2.2.3.2 Measurements of vibration transmissibility of the VR gloves

The first series of experiments were performed to measure the vibration transmissibility characteristics of the bare hand using both the standardized palm adapter and the Velcro finger adapters. The Velcro adapters were fixed at the intermediate phalanges of the index and middle fingers for characterizing the fingers vibration responses. The subject was advised to align the palm adapter on the handle along the Z_h-axis, while the experimenter ensured the tightness of the Velcro adapters. The positions of the adapters on the fingers were marked for each subject, which was used in the subsequent trials. The instrumented handle was excited using the vibration spectrum, posture and hand forces defined in the ISO 10819 (2013) [24]. The signals from the accelerometers (instrumented handle, index and middle fingers adapters and palm adapter) were subsequently acquired in a multi-channel data acquisition and analysis system for a duration of 30s. Each measurement was repeated three times, while the participants were asked to relax for about 2 min between the successive measurements. A measurement was rejected if the variation between two of the trials was more than 10%.

In the second series of experiments, the measurements were repeated with the VR gloves under the standardized vibration spectrum. Portions of the top covering of the gloves in the vicinity of the intermediate phalanges of the index and middle fingers were cut so as to install the finger adapters for measurements of vibration transmitted to the fingers, as shown in Figure. 2.4. Each subject was asked to wear the selected VR glove and the experimenter placed the Velcro adapters at mid-phalanges of the index and middle fingers. The subjects were also asked to position the palm adapter inside the glove and grip the handle with the desired forces, while maintaining the posture according to the ISO 10819 (2013) [24]. When the grip and push force on the handle was stabilized, the signals from the accelerometers (instrumented handle, palm, and index and middle fingers adapters) were acquired. The experiments were repeated with the other VR gloves, while the sequence of the measurements was randomized among the subjects and the gloves.

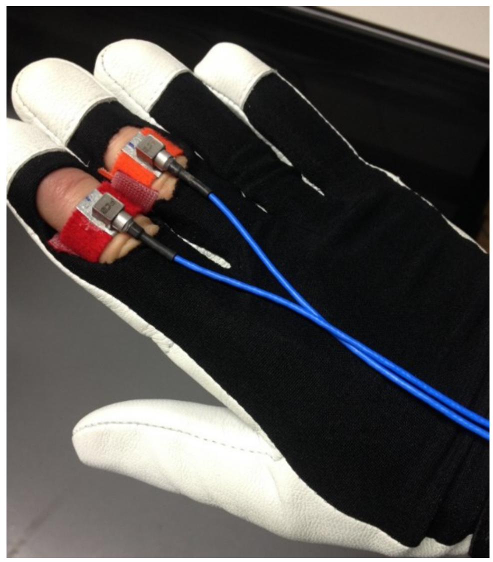


Figure 2.4: Gloved hand with fingers adaptors mounted at the mid-phalanges of the index and middle fingers.

In the third series of measurements, the palm and fingers' vibration transmissibility characteristics of gloved hands were measured under vibration spectra of the selected tools. The spectra of three different tools, reported in (Rakheja et al., 2002) [64] were reproduced in the laboratory using the vibration controller. The acceleration PSDs of the tools vibration are presented in Figure 2.5, together with the standardized vibration spectrum (ISO 10819, 2013). The fingers and palm vibration transmissibility of both the bare and gloved hands were measured for each glove-subject combination using the same procedure as outlined previously.

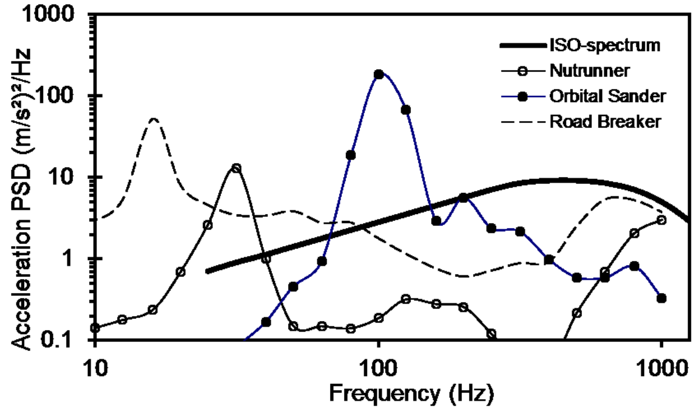


Figure 2.5: Acceleration power spectral density (PSD) of the standardized (ISO 10819, 2013) and selected tools' vibration.

The measured data were analyzed to obtain the frequency-weighted vibration transmission ratio of the VR gloves ($TEAT_w$) for each subject, using Eq. (2.1) together with the frequency-weighting as per the ISO 5349-1 (2001) standard (W_h-weighting) [29]. The mean overall unweighted and frequency-weighted vibration transmissibility of the VR gloves were obtained in the medium frequency (M: 25 to 200 Hz) and high frequency (H: 200 to 1250 Hz) spectra, as per the ISO 10819 (2013). In this study, an alternate frequency-weighting, W_f, proposed by Dong et al. (2008) [94] for the fingers was also employed for assessing the vibration isolation effectiveness of the VR gloves at the fingers. As recommended by the ISO 10819 (2013) [24], the frequency-weighted vibration transmissibility values of the VR gloves were normalized by that obtained for the bare-hand.

Rakheja et al. (2002) [64] proposed a frequency response method for estimating the vibration transmission of VR gloves at the palm of the hand, considering the glove as a single-input single-output dynamic system. In this study, the proposed method was used for estimating the vibration responses at the fingers, from the multiplication of the measured transfer function under the standardized excitation, $TEAT(\omega_j)$ and the rms acceleration of the specific tool in each of the one-third octave frequency band, such that:

$$A(\omega_j) = TEAT(\omega_j)H(\omega_j) \tag{2.2}$$

Where, $H(\omega_j)$ is the rms acceleration of the tool and the $A(\omega_j)$ is estimated rms acceleration of the fingers at the center frequency of band j.

2.2.3.3 Statistical analysis

One-way analysis of variance (ANOVA) was used to determine the significance level of the influence of the gloves on the palm and fingers' peak vibration transmissibility and the corresponding frequency, as well as the overall mean unweighted and frequency-weighted vibration transmissibility magnitudes in the M and H spectra. Statistical analysis was performed using the SPSS software (version 20), while a statistical significant difference among the data was considered at $p<0.05$.

2.3 Results

2.3.1 Vibration transmissibility at the palm

Figure 2.6 compares the mean vibration transmissibility characteristics of the 4 VR gloves measured at the palm of each subject. The results show considerable inter-subject variability, specifically for the hybrid and air gloves. The gel and leather gloves, however, show very small inter-subject variability. The coefficients of variation (CoV) for the gel and leather gloves ranged from 1–4% and 2–8% in the M (25–200 Hz) and H (200–1250 Hz) spectra, respectively. The CoV of the transmissibility was relatively high for the air and hybrid gloves, which ranged from 3–32% and 6–37% for respectively the M and H spectra. The mean palm vibration transmissibility characteristics obtained from all the 4 subjects' data are compared in Figure 2.7. The figure also shows the palm vibration transmissibility measured with the bare hand. The results show notable vibration reduction at the palm in the 40–1000 Hz frequency range for the air and hybrid gloves. Both the gloves, however, amplified vibration in the lower frequency range. Both the gel and leather gloves showed comparable vibration transmissibility; nearly unity in the entire frequency range, suggesting none or negligible vibration attenuation. The leather glove exhibited a slight reduction (2–9%) in vibration transmissibility in the 31.5–315 Hz frequency range and vibration amplification (1–8%) at frequencies above 315 Hz.

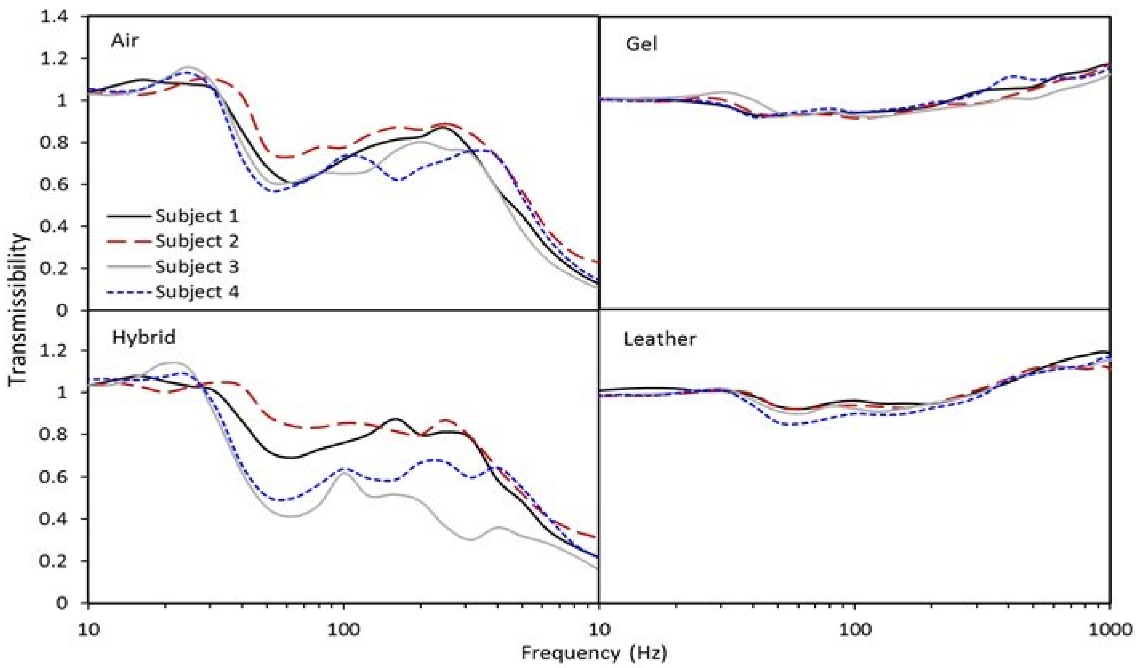


Figure 2.6: Comparisons of mean palm vibration transmissibility of subjects with different vibration reducing gloves: air; gel; hybrid; and leather.

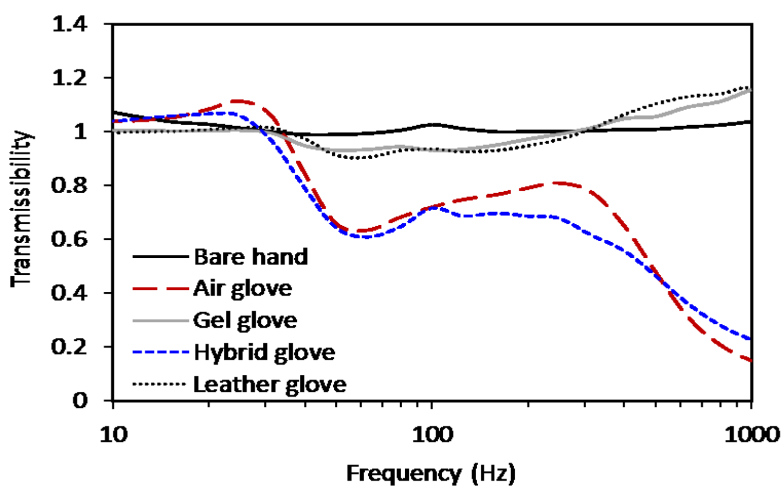


Figure 2.7: Comparisons of mean vibration transmissibility of the bare and gloved hand measured at the palm.

Table 2.3 summarizes the peak palm vibration transmissibility of the VR gloves and the corresponding frequency (referred to as the primary resonant frequency) together with the mean values and the subjective variations in terms of CoV of the mean. Mean peak vibration transmissibility of the air and hybrid gloves were relatively higher than the gel and leather gloves, while the mean resonance frequencies of all the gloves occurred in a narrow range, approximately

25–29 Hz range. The variability in the resonance frequency was substantially higher than that in the peak magnitude, irrespective of the glove. The measurements with subject #1 consistently showed lower resonant frequencies, while those with subject#2 generally showed higher resonant frequencies. The results attained through ANOVA suggest that the peak vibration transmissibility is significantly different among the gloves (p<0.001), while the primary resonance frequency is not significantly different (Table 2.4).

Table 2.3: Peak vibration transmissibility of the gloves measured at the palm and corresponding frequency

Gloves	Subject 1	Subject 2	Subject 3	Subject 4	Mean	CoV
	Peak transmissibility					
Air	1.10	1.11	1.17	1.13	1.13	0.03
Gel	1.01	1.02	1.04	1.00	1.02	0.02
Hybrid	1.08	1.06	1.16	1.10	1.10	0.04
Leather	1.03	1.02	1.03	1.02	1.02	<0.01
	Resonance frequency (Hz)					
Air	17.50	36.25	26.25	26.25	26.56	0.29
Gel	17.50	26.25	35.00	20.00	24.69	0.32
Hybrid	16.25	37.50	22.50	23.75	25.00	0.36
Leather	17.50	37.50	32.50	30.00	29.38	0.29

CoV: coefficient of variation

Table 2.4: p-Values obtained from one-way analysis of variance (ANOVA) for the effect of glove on the peak palm vibration transmissibility.

Measures	Gloves
Peak vibration transmissibility	**<0.001**
Primary resonance frequency	0.677
Frequency-weighted vibration transmissibility	
M spectrum (25-200 Hz)	**0.003**
H spectrum (200-1250 Hz)	**<0.001**

Figure 2.8 shows the mean frequency-weighted vibration transmissibility of the VR gloves at the palm for the M and H spectra normalized with respect to that of the palm of the bare hand. The results show greater vibration attenuation performance of the hybrid and air gloves than the gel and leather gloves for both the spectra. The gel and leather gloves reduced the vibration for the M spectrum only slightly, but resulted in slight amplification for the H spectrum. A VR glove can be classified as an AV glove, when the mean transmissibility values in the M and H spectra do not exceed 0.90 and 0.60, respectively. As per this criterion, only the hybrid glove could be designated as an AV glove. The air glove satisfied the criterion only for the M spectrum, while the gel and leather gloves failed the criterion for both spectra. All the gloves, with the exception of the hybrid glove, showed relatively low CoV values. The hybrid glove data revealed substantially higher variability compared to the other gloves with CoV values of 16% and 27%, for the M and H spectra, respectively. The results of the ANOVA suggested that the normalized frequency-weighted vibration transmissibility of the gloves for the M (p<0.01) and H spectra (p<0.001) were significantly different (Table 2.4).

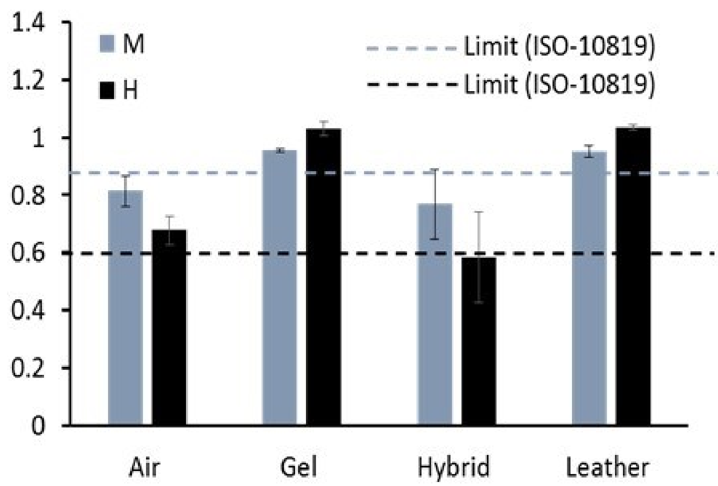


Figure 2.8: Frequency-weighted vibration transmissibility at the palm.

2.3.2 Vibration transmissibility at the fingers

Figures 2.9 and 2.10 show the inter-subject variability of the vibration transmissibility of the VR gloves measured at respectively the index and middle fingers. Relatively lower inter-subject variability was evident for the M spectrum as compared to the H spectrum, irrespective of the fingers. The CoV for the index finger varied from 9–13% and 18–21% in the M and H spectra, respectively. The CoV for the middle finger (6–9%) is slightly lower than the index finger for the M spectrum, while it is considerably higher (15–27%) for the H spectrum.

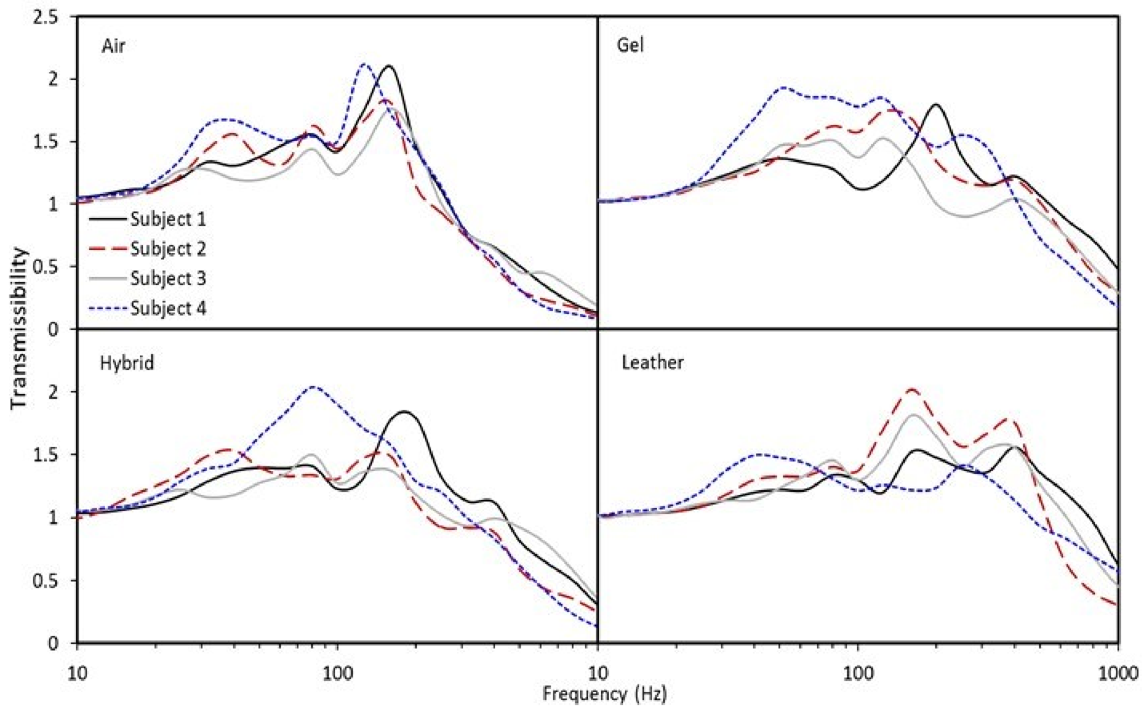


Figure 2.9: Inter-subject variability of the vibration transmissibility of the gloves measured at the index finger: air; gel; hybrid; and leather.

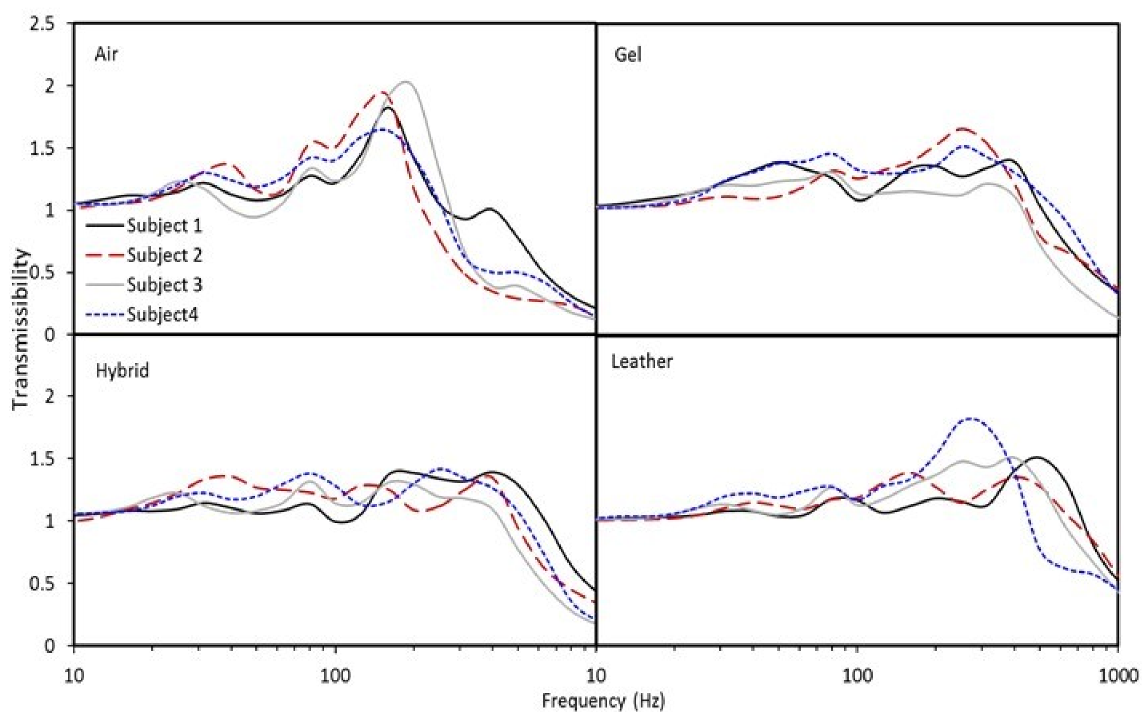


Figure 2.10: Inter-subject variability of the vibration transmissibility of the gloves measured at the middle finger: air; gel; hybrid; and leather.

Figure 2.11 compares the mean vibration transmissibility of the index and middle fingers of the hand without and with different gloves. The results show that all the gloves yield lower vibration at the index and middle fingers in the M spectrum, when compared to the bare hand. For the bare hand, the peak vibration transmissibility measured at the index finger (1.92) was slightly higher than the middle finger (1.63). All the gloves, with the exception of the air glove, yield lower peak index finger vibration transmissibility compared to the bare hand. The air glove, however, yields superior vibration reduction performance at frequencies above 200 Hz. The variations in fingers vibration transmissibility among different gloves is relatively lower in the lower frequency range compared to that at higher frequencies (above 200 Hz). The leather glove reveals relatively lower finger vibration transmissibility in the 10–150 Hz frequency range, while it provided largest amplification of vibration at frequencies above 200 Hz. The gel and hybrid gloves also show middle finger vibration transmission performance similar to the leather glove in the high frequency range. The Gel glove, however, yields only slight amplification of index finger vibration compared to the bare hand at frequencies above 400 Hz. With bare hand, the resonance frequency of the index finger (≈125 Hz) was slightly lower than that of the middle finger (≈150 Hz). The primary resonance frequencies of the index and middle fingers of the gloved hand are relatively higher compared with the bare hand, although this tendency is not clearly evident for the index finger.

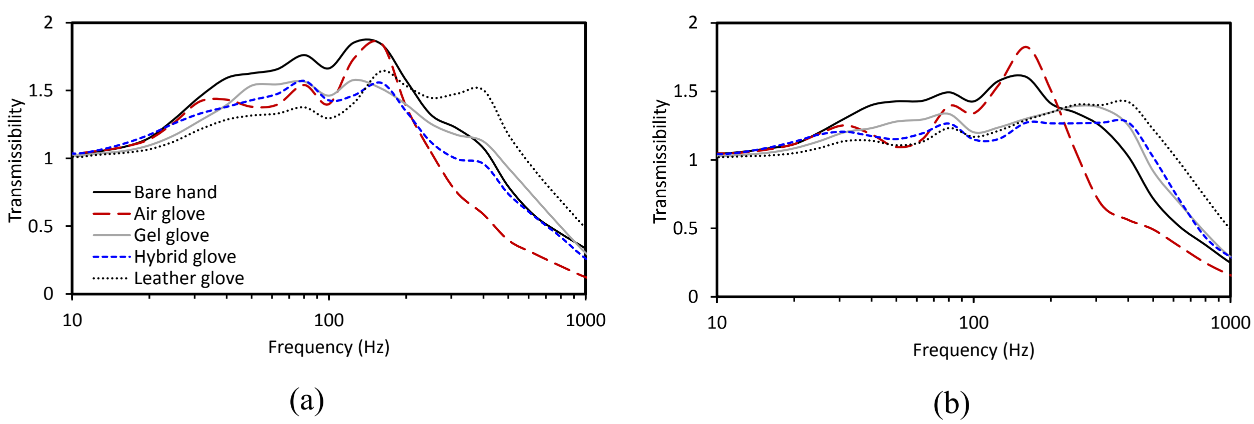


Figure 2.11: Mean vibration transmissibility of the fingers of the bare and gloved hands: (a) index finger; and (b) middle finger.

Table 2.5 summarizes the variations in the peak fingers vibration transmissibility magnitudes and the corresponding frequencies together with the mean and CoV. The results suggest that the gloves, with the exception of the air glove, reduce the peak vibration magnitude transmitted to both the fingers. The peak vibration transmissibility magnitudes of the gel, hybrid and leather gloves are also quite similar for both the fingers. The mean vibration transmissibility magnitude is slightly higher at the index finger as compared with the middle finger, irrespective of the gloves. Inter-subject variabilities on the peak vibration transmissibility at the index and middle fingers are generally high for the bare (12–14%) as well as gloved hand fingers (7–17%). The mean frequencies corresponding to the peak magnitude for the index finger, denoted as the primary resonance frequency, is observed near 128 Hz for the bare hand, which is lower than that with the gloves (145–158 Hz). The gloves thus tend to shift the primary resonance frequency towards a higher value. Similarly, the primary resonance frequency of the middle finger shifted from 117 Hz without the glove to 164, 226, 218 and 231 Hz with the air, gel, hybrid and leather gloves, respectively. The CoV of the primary resonance frequency was considerably lower with the air glove (9% and 7% for the index and middle fingers, respectively) as compared with the gel, hybrid and leather gloves (15–28% for the index finger and 17–21% for the middle finger). Relatively higher CoV for the index (21%) and middle (17%) fingers' frequencies was obtained without the glove. The results attained through one-way ANOVA suggest that the peak vibration transmissibility is significantly ($p<0.05$) different at the middle fingers only, while the primary resonance frequency is not significantly different at the index and middle fingers among the gloves (Table 2.6).

Table 2.5: The peak index and middle fingers vibration transmissibility and the corresponding frequencies obtained from the individual subjects' data.

Gloves	Subject 1	Subject 2	Subject 3	Subject 4	Mean	CoV	Subject 1	Subject 2	Subject 3	Subject 4	Mean	CoV
	Peak transmissibility						Corresponding frequency (Hz)					
	Index finger											
Bare hand	2.30	2.09	2.15	1.72	2.07	0.12	164	125	125	98	128	0.21
Air	2.23	1.94	1.81	2.44	2.11	0.13	155	161	163	133	153	0.09
Gel	1.86	1.91	1.69	2.08	1.89	0.08	211	144	124	124	151	0.28
Hybrid	1.90	1.88	1.54	2.24	1.89	0.15	185	135	136	123	145	0.19
Leather	1.69	2.07	1.87	1.45	1.77	0.15	178	159	168	125	158	0.15
	Middle finger											
Bare hand	1.96	1.51	1.96	1.54	1.74	0.14	140	127	101	100	117	0.17
Air	1.90	2.06	2.12	1.80	1.97	0.07	163	155	180	158	164	0.07
Gel	1.43	1.65	1.19	1.51	1.44	0.13	192	264	193	255	226	0.17
Hybrid	1.45	1.64	1.41	1.45	1.49	0.07	179	250	188	253	218	0.18
Leather	1.23	1.46	1.48	1.86	1.51	0.17	235	163	250	274	231	0.21

CoV: coefficient of variation

Table 2.6: *p*-Values obtained from one-way ANOVA on the effect of gloves on index and middle fingers' peak vibration transmissibility magnitude and the corresponding frequency.

Measures	Index finger	Middle finger
Peak vibration transmissibility	0.346	**0.004**
Primary resonance frequency	0.623	0.052
Unweighted vibration transmissibility – M spectrum	0.938	**0.019**
– H spectrum	**0.021**	0.206
Wh-weighted vibration transmissibility – M spectrum	0.958	0.409
– H spectrum	0.022	0.549
Wf-weighted vibration transmissibility – M spectrum	0.922	**0.014**
– H spectrum	**0.010**	0.456

Table 2.7 summarizes the normalized unweighted vibration transmissibility of the gloves at the index and middle fingers in the M and H spectra. The results show that the gel and leather gloves amplify vibration at the index and middle fingers for the H spectrum. The air and gel gloves amplify middle finger vibration in the M and H spectra. The gel, hybrid and leather gloves, however, attenuate both the index and middle fingers vibration for the M spectrum. While the air glove provides index finger vibration attenuation comparable to the other gloves for the M spectrum, it also shows notable attenuation of vibration for the H spectrum for both fingers. The results attained from one-way ANOVA show that the unweighted vibration transmissibility values at the middle finger for the M spectrum and index finger for the H spectrum are significantly different ($p<0.05$) among the gloves (Table 2.6). Furthermore, the CoV of the unweighted vibration transmissibility is relatively lower for the index finger for the M spectrum as compared with the H spectrum. Similar general trend is also observed for the middle finger.

Table 2.7: Normalized unweighted, hand weighted (Wh) and finger weighted (Wf) vibration transmissibility at the index and middle fingers under M and H spectra.

Excitation	M spectrum (25-200 Hz)				H spectrum (200-1250 Hz)			
Glove	Air	Gel	Hybrid	Leather	Air	Gel	Hybrid	Leather
Index finger, Mean (CoV)								
Unweighted	0.93 *(0.15)*	0.89 *(0.22)*	0.86 *(0.19)*	0.88 *(0.16)*	0.67 *(0.31)*	1.06 *(0.15)*	0.92 *(0.31)*	1.37 *(0.27)*
W_h- weighted	0.91 *(0.17)*	0.90 *(0.21)*	0.87 *(0.19)*	0.85 *(0.13)*	0.68 *(0.25)*	1.03 *(0.12)*	0.89 *(0.25)*	1.31 *(0.28)*
W_f- weighted	0.94 *(0.15)*	0.88 *(0.22)*	0.86 *(0.19)*	0.89 *(0.17)*	0.73 *(0.20)*	0.98 *(0.05)*	0.87 *(0.16)*	1.22 *(0.23)*
Middle finger- Mean (CoV)								
Unweighted	1.04 *(0.03)*	0.87 *(0.14)*	0.83 *(0.06)*	0.85 *(0.12)*	0.80 *(0.50)*	1.21 *(0.25)*	1.22 *(0.29)*	1.52 *(0.42)*
W_h- weighted	0.96 *(0.13)*	0.89 *(0.13)*	0.85 *(0.13)*	0.84 *(0.13)*	0.88 *(0.47)*	1.10 *(0.16)*	1.06 *(0.24)*	1.22 *(0.33)*
W_f- weighted	1.05 *(0.03)*	0.87 *(0.14)*	0.83 *(0.06)*	0.86 *(0.12)*	0.86 *(0.49)*	1.13 *(0.19)*	1.10 *(0.26)*	1.28 *(0.36)*

(CoV): coefficient of variation

Table 2.7 further presents the mean normalized frequency-weighted vibration transmissibility of the fingers together with the CoV of the mean. The normalized frequency-weighted vibration transmissibility magnitudes are obtained using the hand (W_h) and finger (W_f) frequency weightings. The results show that vibration is generally attenuated at the index and middle fingers for all the gloves for the M spectrum, irrespective of the frequency weighting. The air glove also attenuates vibration at the index and middle fingers for the H spectrum, while the leather glove amplifies the high frequency vibration at the index and middle fingers, irrespective of the frequency weighting used. The gel and hybrid gloves also amplify vibration at the middle finger for the H spectrum, but generally attenuate the medium frequency vibration at the index finger, irrespective of the frequency weighting. Hand- and finger-weighted middle finger vibration transmissibility values are not significantly different among the gloves for the H spectrum, while only the W_f-weighted magnitudes are significantly different for the M spectrum ($p<0.05$). Both the hand- and finger-weighted index finger transmissibility magnitudes are significantly different only for the H spectrum ($p<0.05$). The CoV of the means of the frequency-weighted (W_h or W_f) vibration transmissibility are relatively lower for both fingers for the M spectrum as compared with those for the H spectrum. The CoVs of the vibration transmissibility of the air and leather gloves are relatively higher, irrespective of the frequency-weighting method used.

2.3.3 Measured and estimated vibration acceleration at the fingers

Figures 2.12 and 2.13 present the measured and estimated acceleration responses of respectively the index and middle fingers when subjected to the vibration spectra of the selected hand tools (road breaker, nutrunner and orbital sander). The results are presented for all the 4 gloves together with the tools' acceleration spectra. The estimated acceleration responses are obtained using Eq. (2.2). The results show reasonable good agreements between the measured and estimated acceleration responses at the fingers for all the glove-tool combinations. Notable deviations, however, are also evident, especially for the road breaker, irrespective of the glove. The overall rms values of the measured and estimated acceleration responses of the fingers with different tool-glove combinations are further computed and compared in Table 2.8. The results show good agreements between the estimated and measured overall rms acceleration values. The peak error between the estimated and measured index finger responses is 11%, which occurred for the air and hybrid gloves coupled with the orbital sander and nutrunner, respectively. The peak error in the middle finger responses ranged from 6–13% for the glove-tool combinations considered in the study.

The results further show that the finger resonances, in-general, cause relatively higher vibration of both the fingers in most of the frequency range (up to 500 Hz) compared to the handle vibrations of all the tools considered in the study. The fingers vibration reduction performance of the gloves, however, could not be deduced from the data due to absence of bare hand finger vibration responses. The amplifications of handle vibrations are more pronounced near the dominant frequencies of tools, particularly for the nutrunner and the orbital sander. Relatively higher fingers' vibrations are also generally seen near the resonant frequencies of the fingers, which is more evident for the orbital sander near the fingers' resonance frequency. This is attributed to dominant sander vibration (around 100 Hz) near the fingers' resonant frequencies.

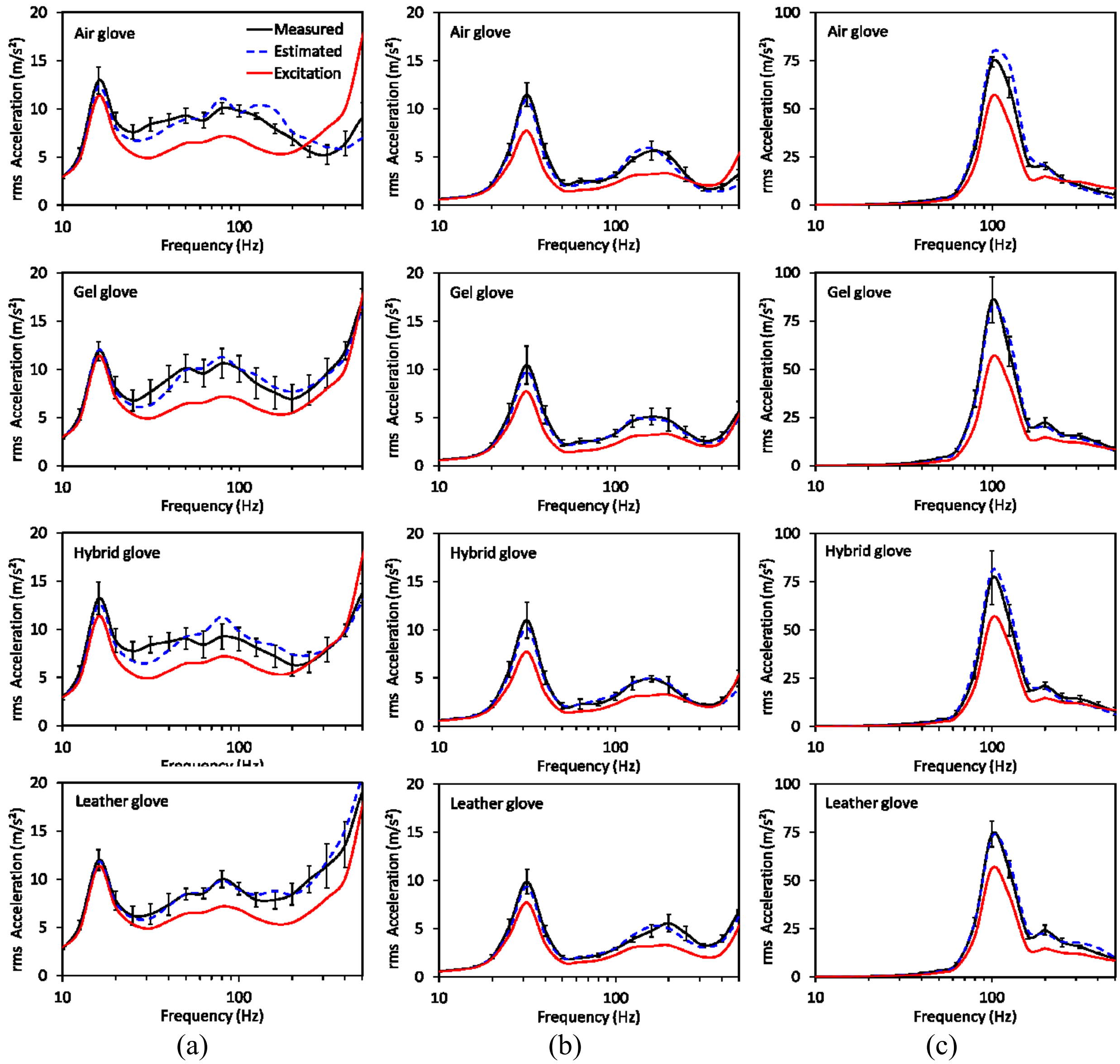
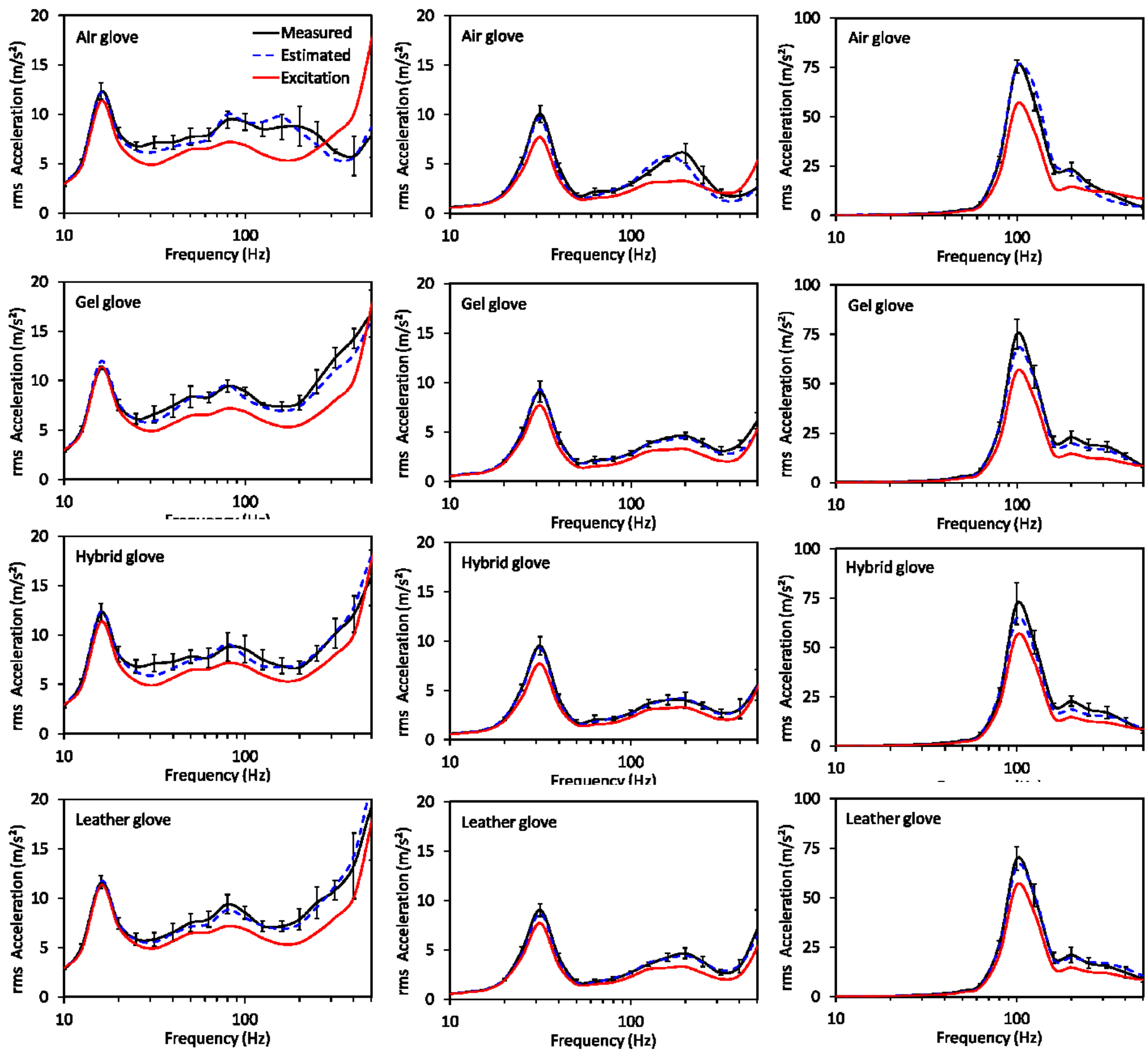


Figure 2.12: Effect of the hand tools spectra on the measured and estimated vibration acceleration response at the index finger for the VR gloves: (a) Road breaker; (b) nutrunner; and (c) Orbital sander.



(a) (b) (c)

Figure 2.13: Effect of hand tools spectra on the measured and estimated vibration acceleration response at the middle finger for the VR gloves: (a) Road breaker; (b) nutrunner; and (c) Orbital sander.

Table 2.8: Effect of tool spectra at the index and middle fingers on the mean measured and estimated frequency-unweighted vibration acceleration (m/s^2) and variation (%) between the measured and estimated vibration accelerations for the 4 VR gloves.

Tool spectrum	Air glove			Gel glove			Hybrid glove			Leather		
	Measured	Estimated	Variation	Measured	Estimated	Variation	Measured	Estimated	Variation	Measured	Estimated	Variation
Index finger												
Road breaker	37.21	36.80	-1	47.77	47.94	<1	42.54	43.48	2	51.91	56.01	8
Nutrunner	19.50	18.41	-6	23.11	21.76	-6	22.88	20.32	-11	26.36	25.42	-4
Orbital sander	107.23	119.35	11	117.87	118.73	1	106.78	113.80	7	106.93	109.67	3
Middle finger												
Road breaker	18.72	17.60	6	23.59	20.49	13	23.00	20.22	12	26.58	25.28	5
Nutrunner	106.98	111.49	4	106.64	99.11	7	102.94	94.02	9	99.52	97.61	2
Orbital sander	35.39	35.94	2	47.99	45.86	4	44.85	45.77	2	52.01	55.87	7

2.4 Discussions

2.4.1 Vibration transmissibility at the palm and effectiveness of gloves

The results showed considerable inter-subject variability in the vibration transmissibility for the hybrid glove (CoV: 16–27%), while the inter-subject variability was low for the air, gel and leather gloves (CoV: 1–6%) (Fig. 2.8). All the gloves showed comparable peak palm vibration transmissibility with large variation in the primary resonance frequency (CoV: 29–36%), as seen in Table 2.3. Griffin et al. (1998) [68], Hewitt (1998) [1], Boileau et al. (2002) [70], Dong et al. (2002a) [65], Laszlo and Griffin (2011) [69] and Welcome et al. (2012) [18] also reported high inter-subject variability. Owing to such high inter-subject variability, the standardized method (ISO 10819, 2013) for assessing vibration reduction performance of a glove with only 3 subjects raises some concerns. Welcome et al. (2012) [18] suggested that the hand size of the subjects could possibly play a role on the inter-subject variability. Although the hand sizes of the subjects used in the study ranged between 8 and 9 (Table 2.1), the inter-subject variability was quite high. Since the experiments involved repeated trials, the large inter-subject variability may be due to vibration reducing materials and intrinsic variations of the human hand affecting the contact force on the palm adapter and dynamic properties of the hand-arm system. A study involving more subjects and more gloves with different materials may yield more insight to understand the effect of vibration reducing materials and hand size on the inter-subject variability.

The mean vibration transmissibility of the gel and leather gloves was close to unity in most of the frequency range (Fig. 2.7), which is due to higher stiffness of the glove material. McDowell et al. (2013) [61] also reported close to unity vibration transmissibility for an ordinary synthetic leather glove. The air bladder in the air and hybrid gloves reduces the effective stiffness at the palm. These gloves revealed comparable vibration transmissibility, with amplification in the 10–40 Hz frequency range and attenuation of vibration above 40 Hz. These gloves revealed relatively higher peak transmissibility compared to the gel and leather gloves, which is attributed to low damping of the air bladder. The mean vibration transmissibility magnitudes of the hybrid glove for the M and H spectra were respectively 0.77 and 0.58 (Fig. 2.8), which satisfied the screening criterion of an AV glove according to the ISO 10819 (2013) [24]. All the other gloves considered in this study did not satisfy this criterion and thereby cannot be designated as AV gloves.

2.4.2 Vibration transmissibility at the fingers and effectiveness of gloves

The results showed comparable inter-subject variability of the fingers' vibration transmissibility for all the gloves (Figs. 2.9 and 2.10). The CoV of the mean vibration transmissibility for the index finger varied from 9–13% and 18–21% for the M and H spectra, respectively, while the CoV for the middle finger varied in the 6–9% range for the M spectrum and 15–27% range for the H spectrum. Variations in the peak vibration transmissibility magnitude (7–17%) and the corresponding frequency (7–28%) were considerable among the subjects (Table 2.5). The results suggested relatively small effect of the vibration reducing materials on the fingers vibration and on the inter-subject variability.

The mean primary resonance frequencies of the index and middle fingers of the bare hand were respectively around 128 and 117 Hz (Table 2.5). The primary resonance frequencies and the peak magnitudes seen in Figure 2.11 and Table 2.5 differed slightly, which was due to averaging. Moreover, the results in Figure 2.11 are presented in the one-third octave bands, while those in Table 2.5 are extracted from the constant bandwidth spectrum. Welcome et al. (2014) [20] reported slightly lower primary resonance frequency with bare hand as compared with the present study. This difference in the primary resonance frequency may be due to the characteristics of the subjects, the measurement system and the experimental setup. In this study, the VR gloves increased the resonant frequency of the index and middle fingers (Table 2.5), however the study by Welcome et al. (2014) [20] reported either same (air glove) or lower (gel glove) resonant frequency of the fingers of the gloved-hand as compared with the bare hand for similar experimental conditions, i.e. 30 N grip and 50 N push force and measurements at the mid-phalanges. This is likely caused by the different gloves used in both studies. A glove reduces the maximum grip strength of a subject grasping a handle [27]. The hand grip force is proportional to the scalar sum of the palm and finger forces minus the push force [82]. Thus, in order to maintain the required grip force (30 N) in the present study, the subject might have exerted more finger force. Higher finger force increases stiffness of the finger tissues and thus produces a higher resonant frequency. The reduction in grip strength is strongly dependent on the stiffness of the glove materials, which could alter the resonant frequencies of the fingers.

For the bare hand, the primary resonance frequency of the index finger was slightly higher than the middle finger (Table 2.5), which is likely due to the higher force imparted by the index finger and thus the higher stiffness as compared with the middle finger. Gurram et al. (1995) [106]

and Aldien et al. (2005) [107] reported that the distal and middle phalanges of the index finger exert higher dynamic force compared with the middle finger. Rossi et al. (2012) [108] also reported higher percentage of mean grip strength of the index finger without glove on 38 and 43 mm cylindrical handles. Unlike the bare hand, the primary resonance frequency of the middle finger was considerably higher than the index finger with gloves suggesting higher middle finger stiffness. Studies have also reported that wearing a glove changes the dynamics of the hand. Furthermore, the primary resonance frequency of the index finger varied form 145–158 Hz, suggesting relatively small effect of gloves on the index finger. The primary resonance frequency of the middle finger varied in the 164–234 Hz range (air glove: 164 Hz; gel glove: 226 Hz; hybrid glove: 218 Hz; leather glove: 234 Hz) (Table 2.5). Welcome et al. (2014) [20] also reported higher primary resonance frequency for the air glove as compared with the gel glove at the index finger, however similar primary resonance frequencies were reported at the middle finger for both gloves. The results suggest that vibration reducing material has more effect on the middle finger primary resonance frequencies (Table 2.5), while the stiffness of gel is more than that of air bladder. Xu et al. (2011) [109] also reported the effect of vibration reducing materials on the primary resonance frequency. The study, however, showed higher primary resonance frequency of the air glove as compared to the gel glove. The differences in the two studies may be due to the glove type. The present study used an air bubble glove, while the glove used by Xu et al. (2011) [109] employed an air filled bladder. In the air bladder design, the air volume may shift from the finger area to the palm area, which may cause higher primary resonance frequency. Similarly, the gels used in different glove designs may exhibit somewhat different static and dynamic properties. A future study to evaluate the vibration transmission characteristics at the fingers for gloves fabricated with different materials may yield more insights.

The peak vibration transmissibility at the index finger was higher than that at the middle finger, irrespective of the gloves considered in the study. The peak vibration transmissibility of the air glove is higher than that obtained with the bare hand, while the other gloves (gel, hybrid and leather) reduced the peak vibration transmissibility as compared with the bare hand (Table 2.5). This is attributable to low damping of the air bubbles compared to the gel. Welcome et al. (2014) [20] reported slightly higher peak fingers' vibration transmissibility with gel glove, however, slightly lower with air glove as compared with bare hand.

The effectiveness of a VR glove depends on the primary resonance frequency, peak vibration transmissibility and frequency weighting. Dong et al. (2008) [94] reported that the standardized W_h weighting overestimates the low frequency effects but greatly underestimate high-frequency effects on the development of finger disorders. Normalized frequency-weighted vibration transmissibility of the VR gloves at the fingers were also obtained using the hand (W_h) and finger (W_f) weightings. In the medium frequency (25–200 Hz), the performances of all the gloves were comparable at the index and middle fingers. Furthermore, all the gloves generally attenuated vibration (Table 2.7). The VR gloves thus can be considered suitable for reducing vibration exposure of the fingers, especially for the powered hand tools with dominant vibration in this frequency range. However, Welcome et al. (2014) [20] reported that the air bladder and gel gloves are not suitable for frequencies <400 Hz. The difference between the two studies may be due to the different types of VR gloves utilized. In the high frequency range (200–1250 Hz), the frequency-weighting has a larger effect on the mean vibration transmissibility (Table 2.7). While the normalized unweighted values suggested improved performance of the air glove (vibration transmissibility of 0.67 and 0.80 at the index and middle fingers, respectively) as compared with the gel glove (vibration transmissibility of 1.06 and 1.21 at the index and middle fingers, respectively) and the hybrid glove (vibration transmissibility of 0.92 and 1.22 at the index and middle fingers, respectively). The air glove also performed better than the other gloves when the hand (W_h) and finger (W_f) weighting were used for the calculation of vibration transmissibility.

2.4.3 Measured and estimated vibration acceleration at the fingers

The results showed reasonably good agreements between the measured and estimated acceleration responses at the index and middle fingers for all the gloves and tools combinations. The computed and estimated values were very close for all the gloves coupled with the nutrunner and orbital sander spectrum considered in the study (Figs. 2.12 and 2.13). Variations between the measured and estimated vibration acceleration were relatively higher in the mid-frequency range for the road breaker (Fig. 2.12), due to dominance of its vibration at very low frequencies. The results also showed slightly larger difference between the estimated and measured values for the hybrid glove coupled with the nutrunner and the air glove with the orbital sander (Table 2.8). The results suggest that a tool vibration spectrum has a strong influence on the acceleration responses of the fingers, and thereby further efforts would be desirable for the design of tool-specific AV gloves. Rakheja et al. (2002) [64] also suggested the need for tool specific AV gloves for reducing the risk of HAVS among the operators of power tools.

2.4.4 ISO 10819 and effectiveness of VR gloves

Based on the vibration transmissibility measurement at the palm, the hybrid glove passed the screening criterion defined in the ISO 10819 (2013) [24] and thus could be designated as an AV glove. The vibration transmissibility measurements, however, showed amplification of middle finger vibration by the hybrid glove at frequencies greater than 300 Hz (Fig. 2.11). Furthermore, the performance of the hybrid glove in terms of the mean normalized unweighted and frequency-weighted (W_h and W_f) vibration transmissibility magnitudes was inferior to those of the air glove, particularly for the H spectrum (200–1250 Hz) (Table 2.7). The results also suggest that the requirements of same material in the palm and fingers regions of the glove (ISO 10819, 2013) may not be beneficial for enhancing the performance of a glove. Considering the vast differences between the dynamic responses of the fingers and of the hand, the use of different vibration isolation materials at the palm and fingers could yield improved performance. Furthermore, additional efforts would be worthy towards standardizing the method for measuring vibration transmissibility at the fingers.

2.5 Conclusions

Velcro adapters with miniature tri-axial accelerometers can be used to measure the vibration transmitted to the fingers of a gloved hand. The vibration reducing material of a VR glove plays an important role in the vibration transmitted to the palm and fingers. VR gloves amplify vibration at the palm in the 10–40 Hz frequency range, while at the fingers, the vibration is amplified in the 125–200 Hz frequency range for the air glove and to frequencies above 200 Hz for the gel, hybrid and leather gloves. The peak vibration transmissibility was slightly higher for the index finger as compared with the middle finger, however the opposite for the primary resonance frequency was observed, irrespective of the type of the glove considered in this study. The air glove revealed better performance in terms of vibration attenuation at the fingers for the H spectrum (200–1250 Hz), while the hybrid glove (made of air bubbles in the palm area and gel in the fingers area) performed better for the M spectrum (25–200 Hz), irrespective of the frequency weighting used. Only the hybrid glove passed the criteria of the ISO 10819 (2013) to be designated as AV glove. Considering the very high inter-subject variability for the palm vibration transmissibility for the gloved hand and amplification of vibration by the fingers, testing of gloves according to ISO 10819 (2013) cannot reliably measure the effectiveness of the glove to reduce the risk of HAVS. The FRF method could be effectively used to estimate the fingers vibration transmissibility characteristics of gloves under vibration spectra of the tools.

3. FINGERS' VIBRATION TRANSMISSION AND GRIP STRENGTH PRESERVATION PERFORMANCE OF VIBRATION REDUCING GLOVES

3.1 Introduction

Workers operating hand-held power tools are occupationally exposed to comprehensive levels of hand transmitted-vibration (HTV), which has been associated with various disorders of hand and arm [95, 102, 110]. Anti-vibration (AV) gloves are commonly viewed as simple and convenient mean to limit the HTV levels [63, 97, 111]. International Organization for Standardization (ISO) has set forth a screening criterion for classifications of a glove as an AV glove on the basis of measurement of vibration transmitted to the palm of the gloved hand (ISO 10819, 2013) [24], while the measurements of vibration transmitted to the fingers is not required. A glove is considered as an AV glove when the frequency-weighted palm acceleration transmissibility magnitudes in the medium (M: 25–200 Hz) and high (H: 200–1250 Hz) frequency ranges are ≤0.9 and ≤0.6, respectively. Moreover, the standard requires that fingers section of the glove should employ same vibration isolation material as the palm, while its thickness must be at least 60% of that in the palm region. This suggests that the standard likely assumes similar vibration transmission to both the palm and the fingers. A few recent studies have invariably shown that VR gloves yield widely different vibration responses at the palm and fingers [20, 25, 112]. This is likely due to widely different vibration characteristics of the fingers compared to those of the palm and the hand arm system [17, 113, 114] . Moreover, the effective mass of the fingers is substantially lower than that of the palm-arm system, which may contribute to differences in the isolation effectiveness of VR gloves at the palm and the fingers

A recent study has experimentally characterized the fingers' vibration response and measured the effectiveness of VR gloves at different segments of the fingers [20]. Hewitt et al. (2015) [19] used the data reported by Welcome et al. (2014) [20] to estimate the finger vibration transmissibility of the gloves under vibration of different tools using the frequency response function. Both the studies showed none or minimal attenuation of handle vibration transmitted to the fingers. Md Rezali and Griffin (2015) [26] evaluated the effect of glove material (foam and gel) thickness by measuring the vibration transmitted to the palm and distal phalange of the index finger (tip). It was shown that the glove material reduced vibration at the palm in the 20 to 350 Hz frequency range but increased the vibration at the fingertip. Hamouda et al. (2015) [112] measured the handle vibration transmitted to mid-phalanges of the index and middle fingers, which exhibit the highest vibration transmissibility compared to the proximal and distal phalanges of the fingers of the hand coupled with four different types of VR gloves (air, gel, hybrid, and leather). The results showed that the VR gloves generally reduce fingers vibration in the 10–200 Hz frequency range and amplify vibration in the 200–600 Hz range, except for the air glove. Welcome et al. (2014) [20] concluded that the gel glove was more effective in reducing fingers vibration at higher frequencies (>400 Hz) as compared with the air bladder glove, while Hamouda et al. (2015) [112] concluded that air glove was more effective at higher frequencies (>200 Hz). Furthermore, Welcome et al. (2014) [20] reported that the resonance frequencies of the fingers of the gloved hand were similar to those of the bare hand, although the gel glove resulted in relatively lower index finger resonant frequency. Hamouda et al. (2015) [112], on the other hand, reported relatively higher resonant frequencies of the index and middle fingers when coupled with the gloves.

The spectra of vibration measured at the palm of the gloved hand, reported in different studies (e.g., Welcome et al., 2012; McDowell et al., 2013) [18, 61], generally show resonant peaks in the 20–30 Hz range suggesting amplification of handle vibration transmitted to the palm in this frequency range. The frequency weighting, W_h, (ISO 5349-1, 2001) [29] used for evaluating vibration transmission performance of the gloves also emphasizes the palm vibration up to about 25 Hz. Different from the palm, the spectra of finger-transmitted vibration generally exhibit resonant peaks in the 80–200 Hz frequency range depending on the type of VR gloves or the vibration isolation material [20, 112]. Studies reporting biodynamic responses of the hand and arm system have also suggested substantially higher resonant frequencies of the fingers compared to the palm and the hand-arm structure [17, 113, 114]. Considering that the W_h weighting substantially attenuates vibration in this frequency range, its application for assessing effectiveness of gloves in view of fingers vibration transmissibility may be questionable. On the basis of the measured biodynamic response distributed at the palm and the fingers, Dong et al. (2008) [94] proposed an alternate finger weighting (W_f), which provides greater emphasis on fingers vibration up to 500 Hz frequency considering the fingers resonances at higher frequencies.

It has been suggested that reducing the glove material stiffness and optimizing its damping could help enhance isolation effectiveness of the VR gloves [17, 19]. The use of low stiffness materials such as air pockets, foam or gel-foam combinations, however, would yield greater thickness of the glove. Thick and bulky gloves are known to limit the manual hand dexterity, which may discourage the use of gloves by the operators [60]. It has been further shown that gloves in general require increased grip effort of the workers [115, 116], and thereby limit the effective hand grip strength [27]. Usually workers tackle the reduced hand grip strength by applying higher hand grip force and thus the increased effort. The increased grip effort may increase the risk of hand-arm disorders such as carpal tunnel syndrome [77, 117]. Many studies have investigated the grip strength reduction due to gloves [18, 27, 81, 83, 91, 118]. The majority of these studies have employed Jamar dynamometer for measuring the grip strength reduction due to VR gloves, although the dynamometer handle is not representative of the tool handle, which is cylindrical in many vibrating tools [27, 119]. Instrumented cylindrical handles have been employed in a few studies for measurement of the grip strength in a power grip condition corresponding to maximum voluntary contraction effort [27]. The study employed six different gloves including two conventional gloves and four VR gloves with different isolation materials (air bladder, air pump bladder, leather, and gel) and concluded that all of the VR gloves reduced the grip strength by more than 29%, while one of the conventional glove resulted in less than 10% deterioration in the grip strength. Welcome et al. (2012) [18] measured the grip strength due to 15 different VR gloves (air bladder, gel pad, and air bladder with pump), and showed comparable grip strength reduction of all the gloves (30–42%). Greatest reduction was obtained with the gel glove.

The current standard for screening of VR gloves is based solely on the magnitude of handle vibration transmitted to the palm of the gloved hand. The vibration transmitted to the fingers of the gloved hand, and reductions in grip strength and manual dexterity also constitute important factors in describing the performance of VR gloves. The preservations of the grip strength and hand dexterity are particularly vital for promoting the use of VR gloves among the vibrating hand tools operators. An integrated performance measure addressing the aforementioned factors thus needs to be defined so as to seek improved designs of VR gloves.

This study explores the performance of VR gloves on the basis of the handle vibration transmitted to the palm and fingers of the gloved hand, and the grip strength reduction. The validity of a Velcro adapter developed for measurement of finger vibration was assessed in terms of repeatability and reproducibility of the measurements. The vibration transmission characteristics of 12 VR gloves were measured in the laboratory using the standardized method, which included the palm vibration using the standardized palm adapter and the index and middle fingers vibration near the mid-phalanges using the Velcro adapters. The instrumented cylindrical handle was also used to measure the grip strength of the subjects with the bare hand, and while wearing the selected the VR gloves. The measured data were analyzed and discussed to highlight different performance measures of the gloves. The significance of the proposed finger-weighting is further discussed.

3.2 Methods

3.2.1 Experimental setup

Figure 3.1 shows the experimental setup recommended in ISO 10819 (2013) [24] for characterizing the vibration transmission effectiveness of VR gloves, which has been described in a number of reported studies [18, 64, 69]. The setup involves a single axis electrodynamic exciter that generates vibration along the forearm direction (Z_h-axis) by means of an instrumented split-handle (40 mm diameter and 140 mm long) mounted on the exciter. The handle integrates two single-axis force sensors (Kistler 9212) to measure grip force and a tri-axial accelerometer (PCB 356A01) to measure handle vibration. Two additional force sensors (Kistler 9317b) were installed between the handle and the exciter for measurement of the push force. Handle vibration is synthesized and controlled via a vibration controller (VR 9500, Vibration Research Corp., Jenison, MI, USA). In order to facilitate the control of applied forces, the subjects were able to monitor the grip and push force magnitudes via a computer screen installed near the exciter, as described in earlier studies [18, 64]. The displayed forces were sampled at a rate of 4 Hz. The instrumented handle was also used to measure the hand grip strength of each subject under static condition, with and without the gloves.

The vibration transmitted to the palm was measured using a light weight palm adapter integrating a tri-axial accelerometer (PCB 356A01). The vibration transmitted to the index and middle fingers was measured using the Velcro finger adapters developed by the authors (Hamouda et al., 2015) [112]. Each finger adapter contained a miniature tri-axial accelerometer (PCB 356A01) weighing only 1 gram. The vibration measurements at the mid-phalanges of the index and middle fingers were considered in the current study, since the vibration at this location has been reported to be higher than those measured at the distal and proximal phalanges [20].

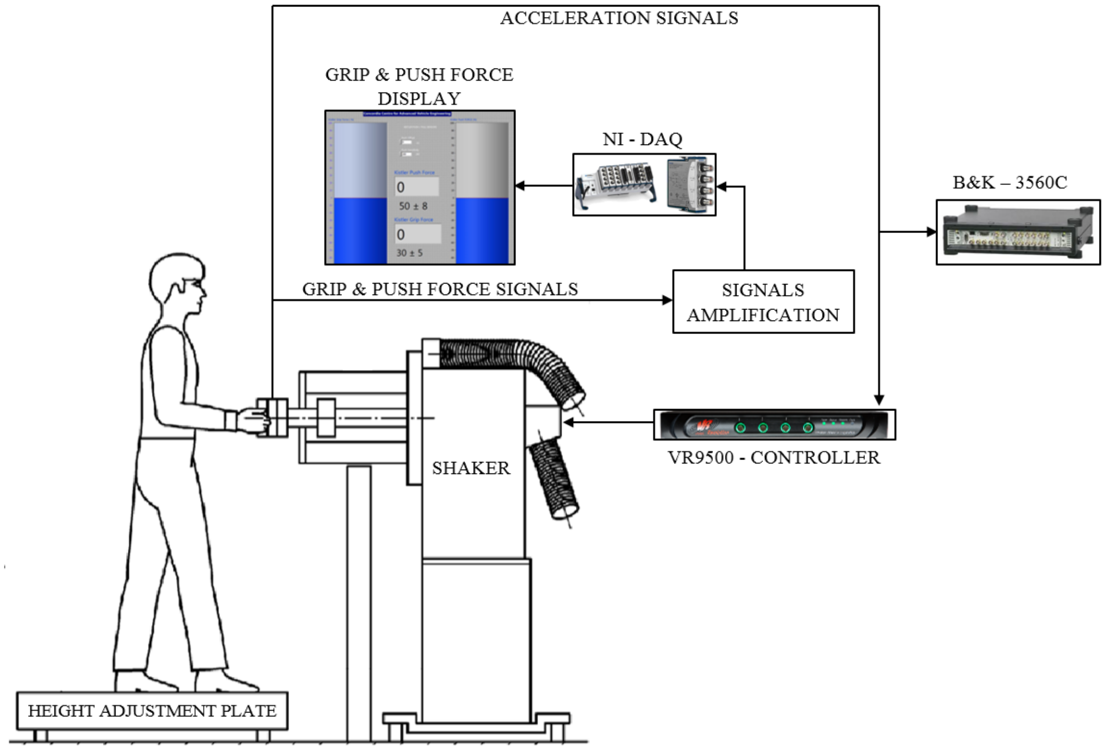


Figure 3.1: Experimental setup for the measurement of vibration transmissibility and grip strength performance of vibration reducing gloves (Hamouda et al., 2015) [112].

3.2.2 Subjects and VR gloves

12 healthy male subjects participated in the current study. The experimental protocol was approved by the ethical committee of Concordia University. Anthropometric hand dimensions of each subject are summarized in Table 3.1. The hand sizes were evaluated in accordance with EN 420 (1994) [105], which ranged from 8 to 10, with only 1 subject with hand size of 7. Experiments were conducted using 13 hand treatments, including the bare hand and 12 VR gloves. The VR gloves included three different air bladder gloves, three different hybrid gloves, three different gel gloves, two gel-foam gloves and a leather glove. The leather glove was more like a conventional glove, although it was specified as a VR glove by the manufacturer. The three hybrid gloves were constructed with air bladder/pockets in the palm region and gel or gel-foam pad in the fingers region. The overall thickness of the undeformed gloves in the palm and fingers regions were measured, which are summarized in Table 3.2 together with the isolation materials used. The selected gloves are also classified in 4 groups on the basis of their construction (vibration reducing material), as seen in Table 3.2. For instance: gloves denoted as air 1, air 2 and air 3 are constructed of air pockets in the palm and fingers regions, and classified as “air” gloves. Similarly, the gloves

classified as 'hybrid' comprise air in the palm region and either gel or gel-foam in the fingers region. The gloves within each class, however, differed in the isolation material coating, which included different types of polyurethane foams, and the covering such as, fabric, leather and PVC. These accounted for differences in overall thickness of the gloves.

Table 3.1: Hand anthropometric dimensions and hand size of subjects.

Subjects	Hand length (mm)	Hand width (mm)	Index finger length (mm)	Middle finger length (mm)	Hand size
1	18.0	84.0	71.7	72.7	8
2	18.5	84.0	68.7	78.0	8
3	20.0	84.0	70.7	76.5	10
4	17.0	78.0	66.8	72.0	7
5	19.0	83.0	66.5	73.4	9
6	19.7	86.0	74.8	82.7	10
7	18.5	84.0	67.8	76.0	8
8	20.5	91.5	77.5	84.9	10
9	19.3	85.0	72.2	77.6	9
10	19.5	88.0	75.6	77.5	9
11	18.0	78.6	69.1	77.7	8
12	19.0	86.2	74.7	76.0	9
Mean	19.08	85.0	70.53	76.13	-
SD	0.38	1.87	3.61	1.70	-

Table 3.2: Specifications of the vibration reducing gloves considered in the study.

Glove	Vibration reducing materials		Material thickness	Material thickness
	Palm	Fingers	Palm (mm)	Fingers (mm)
Air 1	Air	Air	7.7	6.50
Air 2	Air	Air	9.2	7.35
Air 3	Air	Air	9.1	7.70
Gel 1	Gel	Gel	4.3	4.30
Gel 2	Gel	Gel	7.0	6.80
Gel 3	Gel	Gel	8.5	7.70
Hybrid 1	Air	Gel	7.7	4.30
Hybrid 2	Air	Gel-Foam	7.7	5.87
Hybrid 3	Air	Gel	7.7	4.60
Gel-Foam 1	Gel-Foam	Gel-Foam	6.3	5.87
Gel-Foam 2	Gel-Foam	Gel-Foam	9.8	9.00
Leather	Leather	Leather	3.7	1.00

3.2.3 Measurement methods and data analysis

The experiments were conducted in three stages. The first stage involved the assessment of the finger adapters in terms of repeatability and reproducibility of the measurements obtained under broad-band random vibration spectrum defined in (ISO 10819, 2013) [24]. In the second stage, measurements were performed to evaluate vibration transmission characteristics of the bare hand and the 12 VR gloves. Vibration was measured at the palm, and middle phalanges of the index and middle fingers under the standardized vibration spectrum. In the third stage, the static grip strength of each subject was acquired using the instrumented handle with the bare hand as well as the gloved hand.

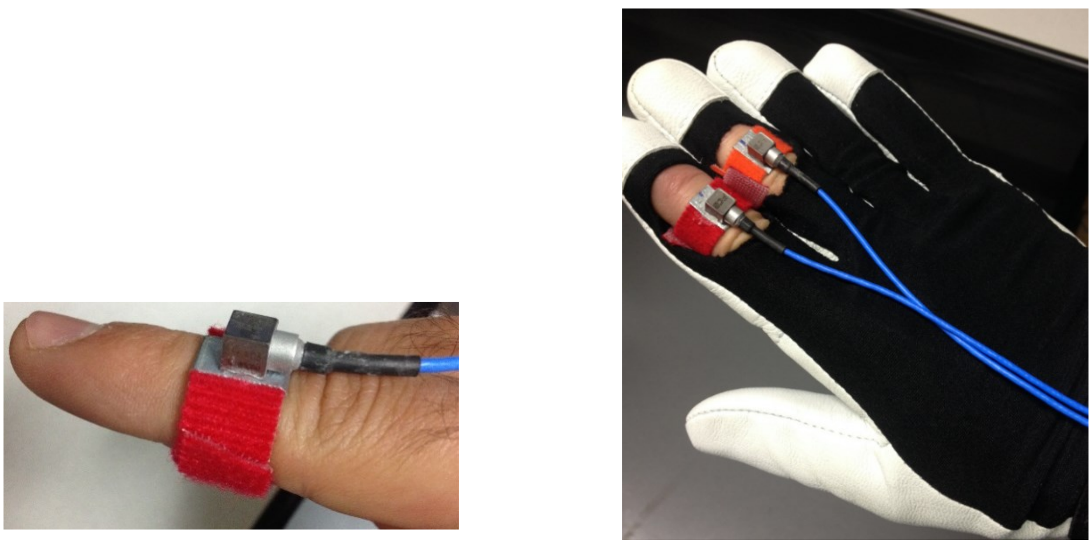
3.2.3.1 Finger adapters repeatability and reproducibility

The first series of experiments were conducted to assess the repeatability and reproducibility of the finger adapters. Three subject were randomly chosen from the 12 subjects, who participated in the study. The subjects were asked to install the finger adapters at the middle phalanges of the index and middle fingers (Fig. 3.2a), while the tightness and orientation of the adapter was examined by the experimenter. Each subject was asked to grasp the instrumented handle with the bare hand and apply 30±5 N grip and 50±8 N push force. Each subject stood on base plate, whose height could be adjusted to achieve the desired posture with horizontal forearm, elbow angle of 90°±10°, wrist angle between 0° (neutral) and 40° of extension, and 0°shoulder abduction, as recommended in ISO 10819 (2013) [24]. The handle was subject to the recommended broadband vibration and the signals from the handle and the two fingers adapters were acquired in a multi-channel data acquisition and analysis system (B&K Type 3560C, PULSE v18.0) to derive the fingers vibration response properties. The measurements were repeated three times. Subsequently, another three different subjects were chosen for evaluating reproducibility of the measurements. Similar to the repeatability tests, each subject performed three trials, while they were asked to remove and re-install the finger adapters after each trial. The position of each adapter was marked on each finger. The repeatability and reproducibility of the measurements were assessed in terms of intra-subject variability of the measured frequency response characteristics.

3.2.3.2 Measurement of vibration transmissibility of the VR gloves

The second stage involved measurements of vibration transmissibility characteristics of the VR gloves as well as the bare hand of each subject. Vibration was measured at the palm using standardized palm adapter, and at the middle phalanges of the index and middle fingers using the

Velcro adapters. The Velcro adapters were tightly secured to middle phalanges of the index and middle fingers, while position of the adapters on the fingers were marked to facilitate consistency during subsequent trials. The subject assumed the posture, as described above, while grasping the handle with 30±5 N grip and 50±8 N push force with the bare hand using the display of forces on the monitor, while aligning the palm adapter along the axis of the shaker (Z_h-axis). The handle was subject to broad-band random vibration in the 25–1600 Hz frequency range (ISO 10819, 2013). The signals from the handle, palm and fingers' accelerometers were acquired in a mutli-channel data acquisition and analysis system for a duration of 30 s. Each subject performed three trials of bare hand measurements, while ensuring a 2 minutes break between the consecutive trials. The measured data acquired during different trials were compared and the subject was asked to repeat a trial, if the variability between two trials was more than 10%.



(a) (b)

Figure 3.2: (a) Velcro finger adapters instrumented with 3-axis accelerometer; (b) Gloved hand with fingers adaptors installed at the mid-phalanges of the index and middle fingers.

The experiments were repeated with the selected VR glove, which were available in two sizes (medium and large). Each subject chose the size which provided appropriate fitting, which was ensured by the experimenter. The top covering of the glove was cut around the middle phalanges of the index and middle fingers in order to install the finger adapters on the respective fingers (Fig. 3.2b). The Velcro adapters were installed at both the fingers, while the experimenter ensured the correct location and tightness of the adapters. The subject was also asked to place the palm adapter inside the glove and align it along the axis of the vibration exciter. Similar to the bare hand, the measurements were repeated three times (3 trials) with each glove under the same handle excitation. Posture and hand force combination (push and grip) were kept the same in all the trials. The sequence of measurements was randomized among the subjects and the gloves

The acquired acceleration signals from the adapters (palm and fingers) and the instrumented handle were analyzed to obtain 1/3-octave frequency band rms spectra of the palm, fingers and handle acceleration responses in the three orthogonal axes (X_h, Y_h and Z_h). The total effective acceleration transmissibility (TEAT) of the palm and fingers vibration at each 1/3-octave frequency band was obtained from vector sums of the handle and the palm or fingers adapters acceleration signals, such that (Dong et al., 2002) [65]:

$$TEAT(\omega_j) = \frac{\sqrt{{A_x}^2(\omega_j) + {A_y}^2(\omega_j) + {A_z}^2(\omega_j)}}{\sqrt{{H_x}^2(\omega_j) + {H_y}^2(\omega_j) + {H_z}^2(\omega_j)}} \tag{3.1}$$

$TEAT(\omega_j)$ is the total effective palm or finger vibration transmissibility at the center angular frequency ω_j of the 1/3-octave band j. A_x, A_y and A_Z are the mean rms accelerations measured at palm or finger adapters, and H_x, H_y and H_z are the mean rms accelerations measured at the handle corresponding to the same frequency band along the X_h-, Y_h- and Z_h-axis, respectively.

The overall frequency-weighted vibration transmissibility of the VR gloves ($TEAT_w$) was further obtained for every subject-glove combination using W_h-weighting defined in ISO 5349-1 (2001) [29]. The palm and fingers' vibration transmissibility values were obtained in the medium (M: 25-200 Hz) and high (H: 200-1250 Hz) frequency ranges following the standardized method described in ISO 10819 (2013) [24]. The fingers' weighted vibration transmissibility of each glove was also obtained using fingers weighting (W_f) propose by Dong et al. (2008) [94]. The overall transmissibility magnitudes were also computed from the unweighted responses. The overall frequency weighted vibration transmissibility magnitudes of the VR gloves at the palm and fingers were further normalized by those obtained from the bare hand measurements.

3.2.3.3 Grip strength measurement

The third stage of experiments were conducted to evaluate the grip strength reduction due to gloves. The grip strength magnitudes of the 12 subjects were measured with and without the gloves. The test methodology utilized was similar to that described by Jung and Hallbeck (2004) [118]. Briefly, the subjects were trained to grip the instrumented handle with their right hand while applying maximum voluntary contraction (MVC) without any push force. Subjects were required to build up the MVC in one second and comfortably maintain it for 4 seconds. Posture used in the test was identical to that used in the vibration measurements. The subjects were trained to use their left hand (free hand) to advise the experimenter to start recording the maintained grip strength for a period of 4 seconds. The signals from the grip force sensors were acquired in Labview and analyzed for mean grip strength during a trial.

Following the training, the bare hand grip strength was measured three times. Each subject was given 10 to 15 minutes rest between the trials. During the rest period, the experimenter evaluated the mean grip strength acquired during each trial during the first two seconds of the grip-maintained period, as recommended by Jung and Hallbeck (2004) [118]. Moreover, the fluctuation in the measured force around the mean (coefficient of variation, CoV) was also evaluated for each trial. A trial was repeated when the CoV value exceeded 10%. Subsequent measurements were performed with the subject wearing one of the VR gloves. Both the vibration and grip force measurements were performed during the same session, although measurements were limited to a maximum of two hand treatments per day, involving grip strength and vibration measurements for either two gloves or one glove in addition to the bare hand. Furthermore, each subject was asked to perform a bare hand grip strength test at the beginning of each session, which was compared with the mean grip strength acquired during the earlier sessions. The test session was cancelled, if there was more than 10 % difference in the mean values. The test session was also rescheduled, in the event the subject reported fatigue. Sequence of the measurements was randomized among the subjects and gloves.

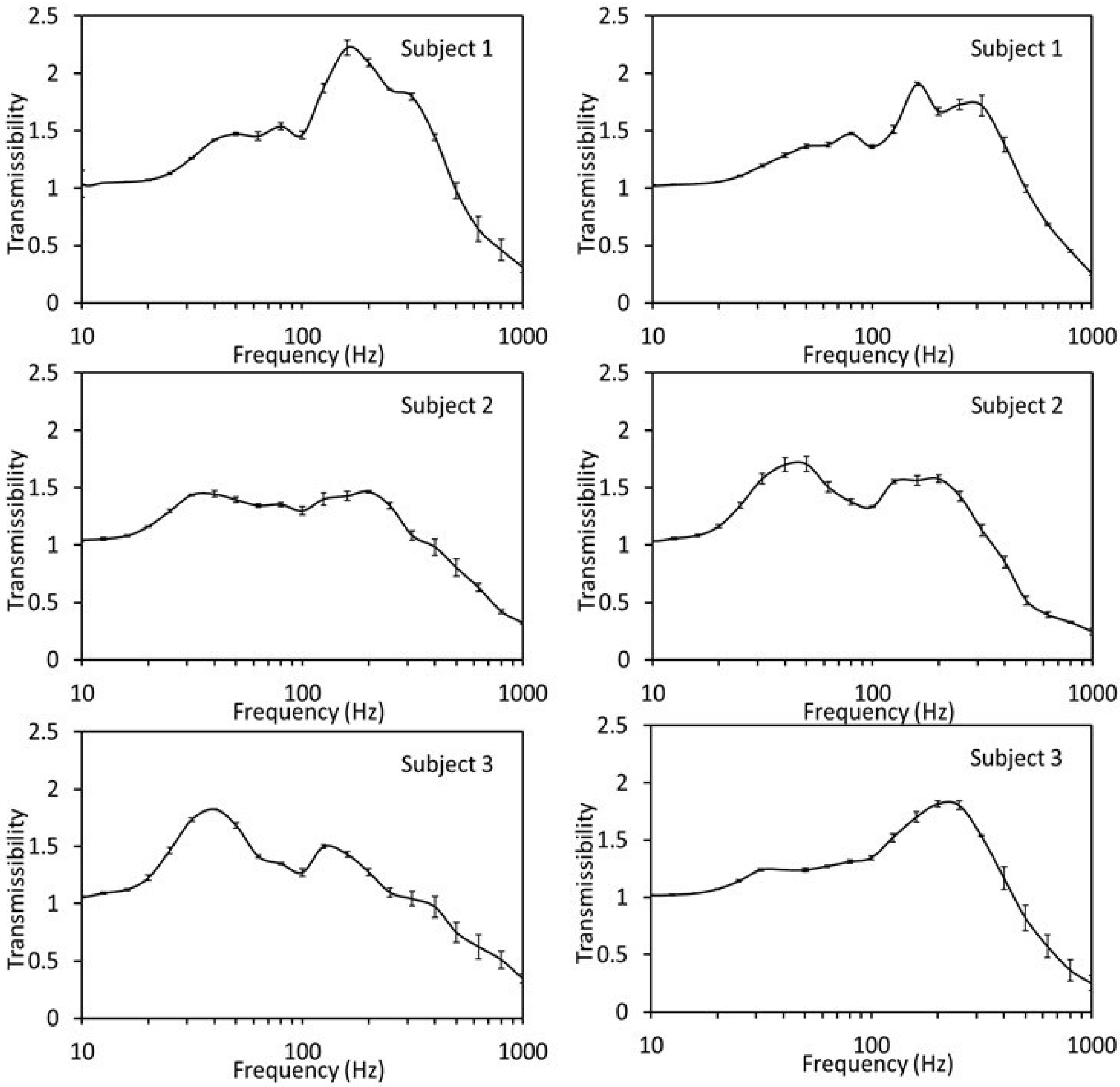
3.2.3.4 Statistical analysis

One-way analysis of variance (ANOVA) was performed to determine the significant influences of different hand treatments (12 gloves and bare hand) on the peak vibration transmissibility and the corresponding frequency, the overall mean unweighted and frequency-weighted (W_f *and* W_h) vibration transmissibility magnitudes in the M- and H- frequency ranges. The analyses were conducted for the palm, index and middle fingers. ANOVA also was used to identify the significance of the different hand treatments on the mean grip strength magnitudes and grip strength percentage reduction. Statistical analysis was performed using SPSS software (version 20), while a significant difference among the data was considered when $p < 0.05$.

3.3 Results

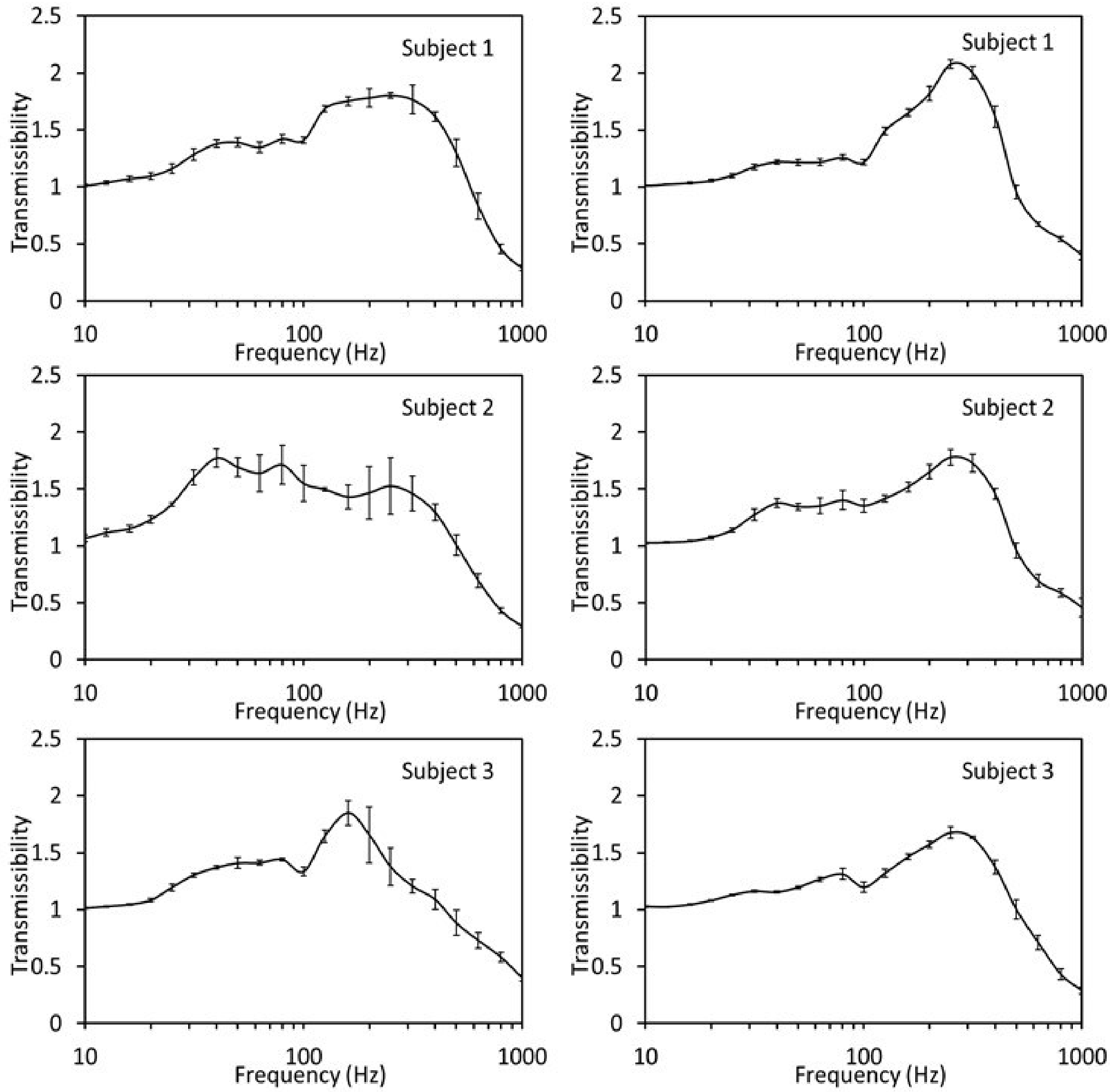
3.3.1 Finger adapter repeatability and reproducibility

Figure 3.3 shows the intra-subject variability of the middle and index fingers vibration transmissibility characteristics measured using the fingers adapters of the three randomly chosen subjects in terms of mean of three trials and the standard deviations. The results suggest good repeatability of the measurements. The coefficient of variation (CoV) is below 4% in the M-frequency range (25-200 Hz) across the subjects. Relatively higher variability, however, is evident in the H-frequency range (200-1250 Hz) for both the index and middle fingers with peak CoV of 20% at frequencies above 500 Hz, where the mean magnitudes are quite low. The measurements also show considerable differences in the peak magnitudes and corresponding frequencies between the subjects, which are attributed dynamic characteristics of the individuals' hand and fingers. Similarly, Figure 3.4 illustrates the mean and standard deviations of the mean measurements obtained from the reproducibility tests performed with three subjects. The results show relatively higher variability in the measurements compared to the repeatability tests. The variability, however, is low in the middle finger data, where the peak CoV values are 6% and 18% in the M- and H-frequency ranges, respectively. The index finger data show considerably higher variability with CoV up to 16% and 17% in the M- and H-frequency ranges, respectively.



(a) (b)

Figure 3.3: Mean and standard deviation of the index and middle fingers vibration transmissibility measured using Velcro adapters during three repeatability trials with three subjects: (a) Index finger; (b) Middle finger.



(a) (b)

Figure 3.4: Mean and standard deviation of the index and middle fingers vibration transmissibility measured using Velcro adapters during three reproducibility trials with three subjects: (a) Index finger; (b) Middle finger.

3.3.2 Vibration transmissibility at the palm

As an example, Figure 3.5 shows the inter-subject variability in mean palm vibration transmissibility data obtained for five different VR gloves, one from each class of gloves (air 1, gel 1, hybrid 1, gel-foam 1 and leather). Similar degree of variations were also observed with the other gloves. The data acquired for all the 12 gloves showed relatively small inter-subject variability for all the gel, gel-foam and the leather gloves with CoV ranging from 1–16% and 2–24% in the M- and H-frequency ranges, respectively. Relatively higher variability was evident for the air (3) and hybrid (3) gloves with CoV ranging from 4–22% and 8–47% in the M- and H-frequency ranges, respectively.

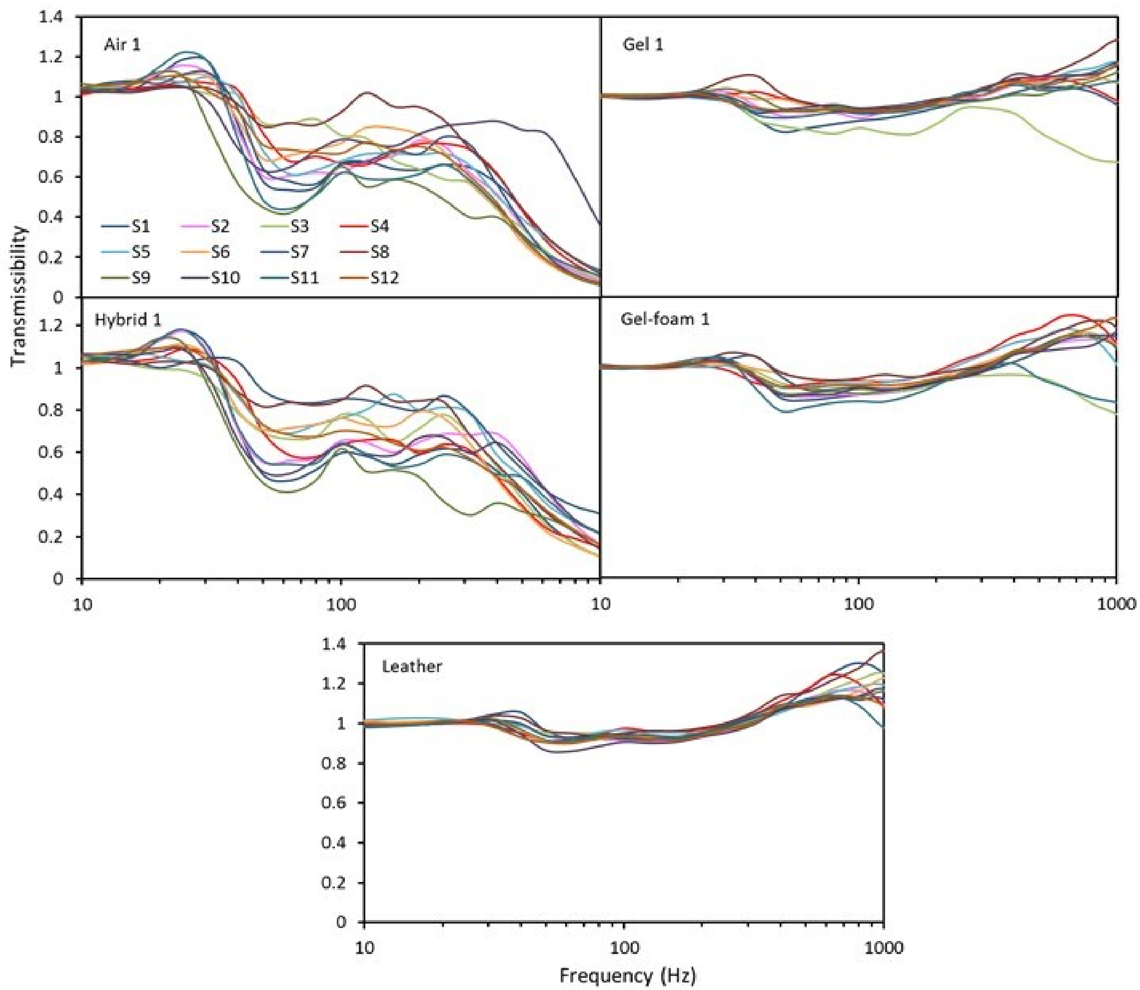
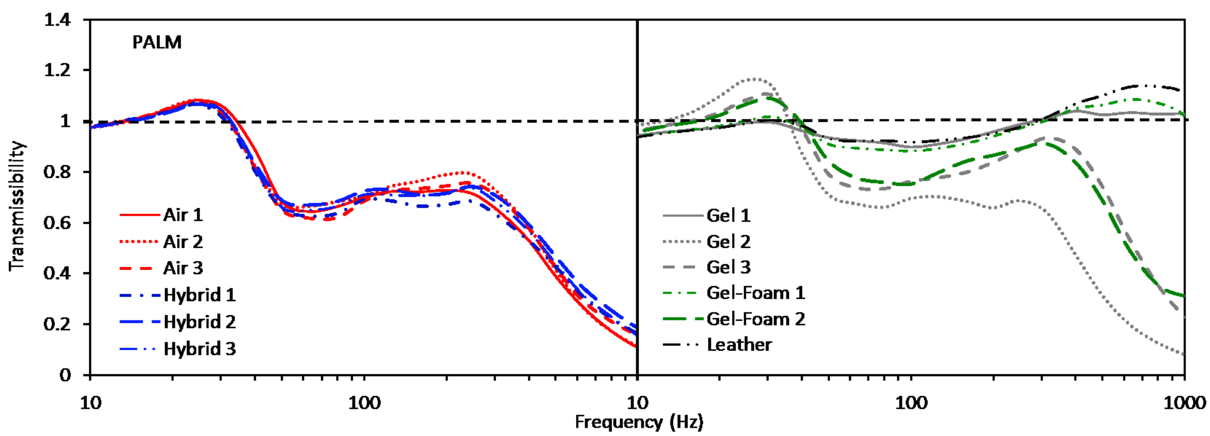


Figure 3.5: Comparisons of mean palm vibration transmissibility of subjects with different vibration reducing gloves (inter-subject variability): air 1; hybrid 1; gel 1; gel-foam 1 and leather.

Figure 3.6 presents the mean vibration transmissibility characteristics of different gloves measured at the palm of 12 subjects and normalized with respect to that measured with the bare hand. The air and hybrid gloves generally show notable attenuation of vibration compared to the gel gloves, which was also observed for the gel 2 glove. These showed 11–89% attenuation of handle vibration transmitted to the palm in the 40–1000 Hz frequency range, with only slight amplification in the vicinity of the fundamental resonant frequencies, which occurred below 30 Hz for all of the gloves. Similar trend was evident for gel 3 and gel-foam 2 gloves but with relatively less vibration attenuation at frequencies greater than 40 Hz. The palm vibration transmissibility of gel 1, gel–foam 1 and leather gloves were nearly unity in the entire frequency range suggesting minimal or no vibration attenuation. The leather glove, however, exhibited a slight reduction (2–8%) in vibration in the 10–315 Hz frequency range with notable amplification at frequencies above 315 Hz.



(a) (b)

Figure 3.6: Comparisons of mean vibration transmissibility of the gloved hand measured at the palm and normalized with that of bare hand palm: (a) air and hybrid gloves; (b) gel, gel-foam and leather gloves

The mean values of the peak vibration transmissibility at the palm and the corresponding mean frequencies (denoted as primary resonant frequency) of each VR gloves are summarized in Table 3.3. Variability between subjects are also presented in terms of CoV of the mean. Gel 2 glove exhibit the greatest mean peak vibration transmissibility among all the gloves. Higher peak magnitudes were generally evident for all air and hybrid gloves, as well as the gel-foam 2 and gel 3 gloves, while the leather glove revealed the smallest peak transmissibility. The peak vibration transmissibility of all the gloves occurred within a narrow frequency range (24–31 Hz). The inter-subject variability in the resonance frequency was considerably higher than that in the peak magnitude, irrespective of the type of glove. The stiffer gloves, in general, showed relatively lower variability in the primary resonance frequency as compared to the other VR gloves, as it is evident for the gel 3 and gel-foam 1 gloves. The results of ANOVA, however, showed that peak vibration transmissibility as well as the primary resonant frequency are significantly different among the gloves (p<0.001 and p<0.05, respectively).

Table 3.3: Peak vibration transmissibility and corresponding frequency of the VR gloves measured at the palm, and normalized overall frequency-weighted palm vibration transmissibility in the M- and H- frequency ranges.

Gloves	Mean	CoV	Mean	CoV	Mean		CoV	
	Peak transmissibility		Primary resonant frequency (Hz)		M-range	H-range	M-range	H- range
Air 1	1.16	0.10	26.42	0.15	0.80	0.58	0.09	0.18
Air 2	1.13	0.04	26.23	0.21	0.81	0.64	0.07	0.09
Air 3	1.13	0.04	25.52	0.18	0.78	0.62	0.07	0.11
Gel 1	1.04	0.03	29.00	0.24	0.94	1.01	0.03	0.05
Gel 2	1.22	0.08	27.81	0.14	0.82	0.54	0.06	0.09
Gel 3	1.15	0.06	30.98	0.09	0.87	0.81	0.05	0.05
Hybrid 1	1.11	0.06	24.98	0.20	0.77	0.57	0.10	0.16
Hybrid 2	1.11	0.05	25.06	0.20	0.80	0.62	0.08	0.10
Hybrid 3	1.11	0.04	24.92	0.15	0.79	0.60	0.05	0.12
Gel-Foam 1	1.03	0.02	31.29	0.09	0.93	1.01	0.02	0.04
Gel-Foam 2	1.13	0.04	29.83	0.17	0.88	0.80	0.06	0.13
Leather	1.02	0.02	31.67	0.20	0.95	1.03	0.02	0.02

CoV: coefficient of variation

The overall W_h-weighted palm vibration transmissibility magnitudes of the VR gloves in the M- and H-frequency ranges are also presented in Table 3.3 in terms of the mean and CoV of the mean. The magnitudes were obtained upon normalization with respect to that of the bare hand, as recommended in ISO 10819 (2013) [24]. Generally, the gloves revealed relatively lower CoV values in the M-frequency range (0.02 to 0.10) compared to that in the H-frequency range (0.02 to 0.18). All of the air and hybrid gloves exhibit superior vibration attenuation performance than rest of the gloves in both the M- and H-frequency ranges. The vibration attenuation performance of the gel 2 glove is also comparable with the air and hybrid groups of gloves in the M-frequency range, while it exhibits the greatest vibration attenuation amongst all gloves in the H-frequency range. All the gloves show some degree of attenuation of vibration in both the M- and H-range with the exception of gel 1, gel-foam 1 and leather gloves, which show slight amplification of the handle vibration transmitted to the palm of the gloved hand. All the gloves, with the exception of gel 1, gel-foam1 and leather gloves, satisfy the M-frequency range screening criteria of ISO 10819 (2013) [24], which requires the overall transmissibility to not to exceed 0.9. The standard also requires that the mean normalized frequency-weighted transmissibility value in the H-frequency range must not exceed 0.6 for the glove to be considered as an anti-vibration (AV) glove. From the results, it is evident that only air 1, gel 2 and hybrid 1&3 gloves satisfy the above screening criterion, and can be considered as AV gloves. The results from ANOVA also showed that the glove type has a significant influence on the frequency-weighted vibration transmissibility in the M- and H- frequency ranges (p<0.001).

Table 3.4: Dependence of the normalized frequency-weighted vibration transmissibility of VR gloves at the palm on different combinations of 3 subjects, under M- and H- frequency ranges.

Glove	Transmissibility M-range	Transmissibility H-range
Air 1	0.79-0.83	0.54-0.63
Air 2	0.76-0.87	0.59-0.67
Air 3	0.76-0.81	0.59-0.67
Gel 1	0.90-0.97	0.96-1.03
Gel 2	0.79-0.86	0.53-0.56
Gel 3	0.85-0.87	0.78-0.84
Hybrid 1	0.73-0.81	0.54-0.59
Hybrid 2	0.77-0.84	0.60-0.64
Hybrid 3	0.77-0.82	0.58-0.66
Gel-Foam 1	0.91-0.95	0.98-1.05
Gel-Foam 2	0.87-0.92	0.72-0.84
Leather	0.93-0.96	1.02-1.04

The acceptance or rejection of a glove on the basis of the above-stated screening criterion could also be affected by the inter-subject variability. The standardized method requires the assessments using only 3 subjects. The data were subsequently analyzed to obtain the overall vibration attenuation performance of gloves considering 4 groups of 3 subjects. Table 3.4 summarizes the ranges of the mean normalized frequency-weighted (W_h) palm vibration transmissibility of the VR gloves obtained from different combinations of 3 subjects. The results suggest that H-frequency range transmissibility values for air 1 and hybrid 3 gloves, considered acceptable on the basis of the 12 subjects' data, may exceed the 0.6 and thus may not satisfy the criterion depending on the chosen combination of 3 subjects. The lower limits of H-range values for the air 2, air 3 and hybrid 2 gloves, on the other hand, vary from 0.59 to 0.6 and thus satisfy the screening criterion depending on the different combinations of subjects. It should be noted that these gloves do not satisfy the criterion on the basis of the 12 subjects' data (Table 3.3). Similar discrepancies are also observed for gel 1 and gel-foam 2 gloves in their performance in the M-frequency range. Only gel 2 and hybrid 1 gloves seem to satisfy the criterion, irrespective of the chosen subjects' combination.

3.3.3 Vibration transmissibility at the fingers

Figures 3.7 and 3.8 illustrate variations in the mean index and middle fingers vibration transmissibility characteristics, respectively, of the selected VR gloves (air 1, gel 1, hybrid 1, gel-foam 1 and leather). The measurements obtained for all the 12 gloves showed relatively lower variability between subjects in the M-frequency range than that in the H-frequency range for both the fingers, irrespective of the glove, as observed in palm vibration transmissibility data. Both the index and middle fingers data showed comparable variability in the M-frequency range for all gloves with CoV ranging from 3 to 26%. The variability in the index finger responses in the H-range (CoV; 3–63%), however, was notably higher than the middle finger (8–47%), while the mean magnitudes are substantially smaller in this frequency range.

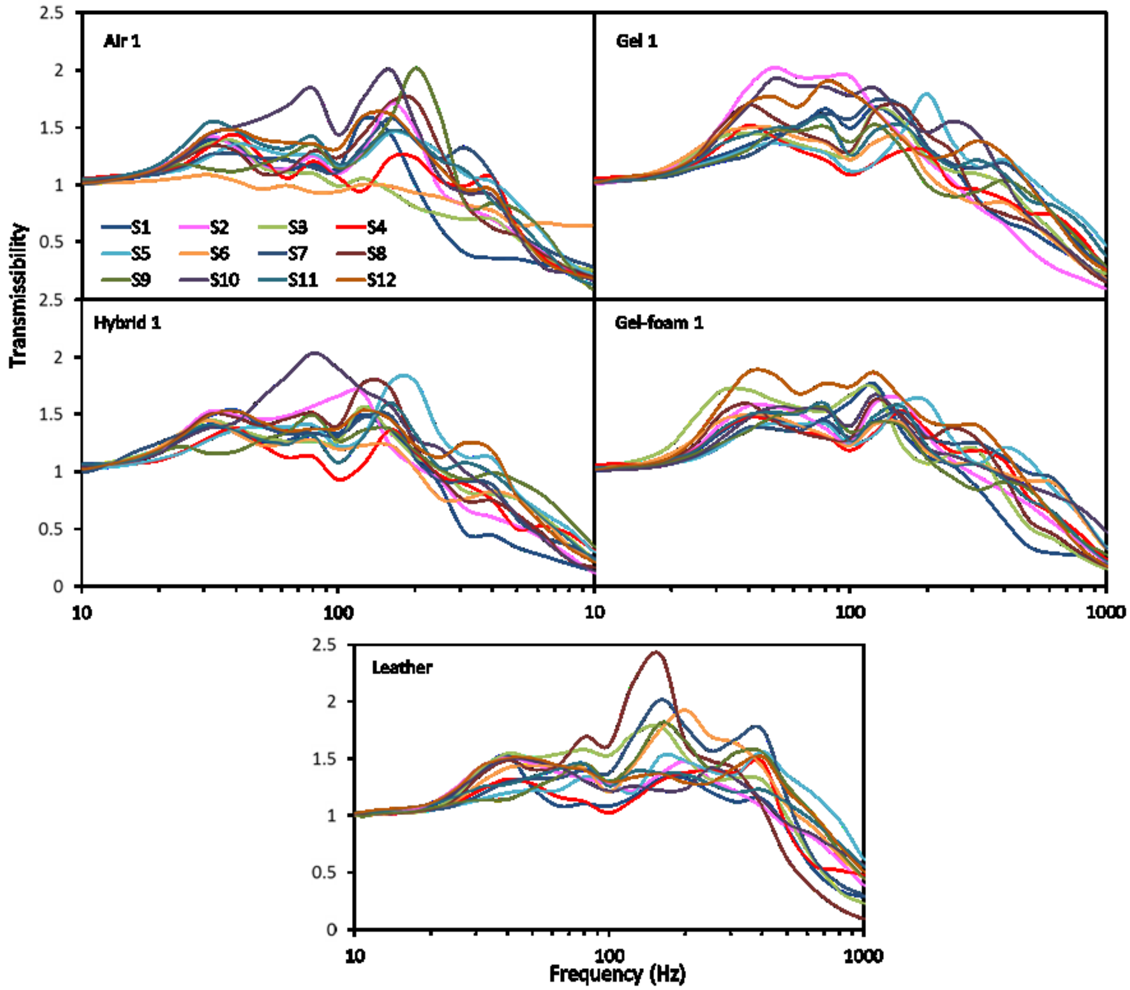


Figure 3.7: Comparisons of mean vibration transmissibility of subjects measured at the index finger with different vibration reducing gloves: air 1; hybrid 1; gel 1; gel-foam 1 and leather.

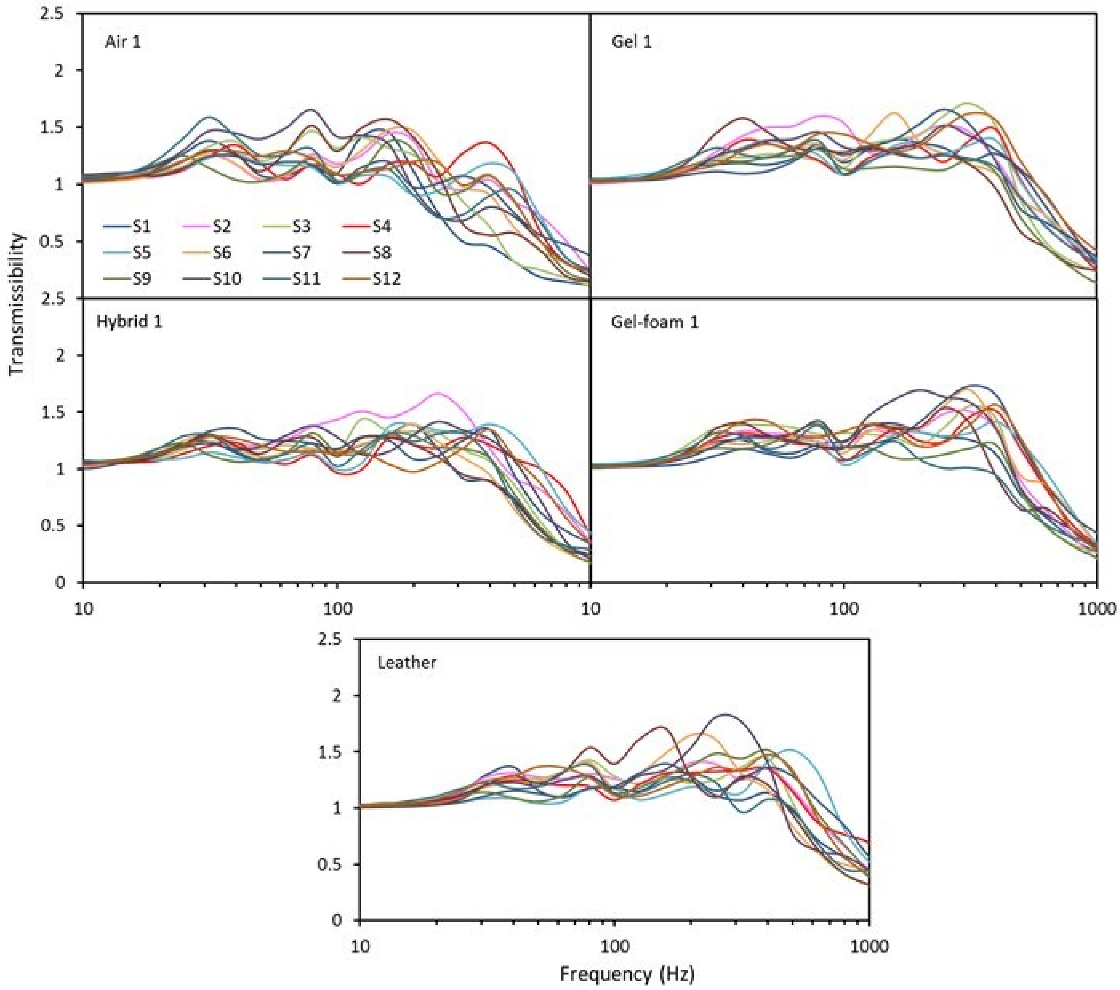


Figure 3.8: Comparisons of mean vibration transmissibility of subjects measured at the middle finger with different vibration reducing gloves: air 1; hybrid 1; gel 1; gel-foam 1 and leather.

The mean vibration transmissibility characteristics of the index and middle fingers gloved- as well as bare hand are compared in Figure 3.9. Results show amplification of the handle vibration transmitted to the fingers of the bare hand, especially in the M-frequency range. The bare hand index and the middle fingers exhibit comparable peak vibration transmissibility magnitudes (1.68 and 1.71, respectively). The frequencies corresponding to the peak magnitudes, denoted as resonant frequencies, are observed in the vicinity of 125 Hz and 160 Hz for the index and the middle fingers, respectively. The transmissibility peaks of the fingers with the gloves also occur around the same frequencies. The transmissibility magnitudes of the fingers of the gloved hand, normalized with respect to those of the bare hand fingers, are presented in Figure 3.10. The normalized magnitudes represent the relative vibration attenuation performance of the gloves at the fingers. The results generally show either very little attenuation or amplification of the handle vibration transmitted to both the fingers by the gloves. The majority of the gloves show slight reduction in the middle finger vibration in the 10–200 Hz; the air 2 and gel 2 gloves form the exception. The air 1 shows superior index finger vibration attenuation in the 30–160 Hz frequency range. Some of the gloves show reduction of fingers vibration at frequencies above 200 Hz. The gel 2 glove, in particular, shows greatest attenuation of the index and middle fingers at frequencies above 200 Hz and 250 Hz, respectively, while it amplifies the vibration at frequencies below 200 Hz. Furthermore, the leather glove revealed the greatest vibration amplification amongst the gloves at frequencies greater than 250 Hz and 315 Hz for the index and middle fingers, respectively. The all the hybrid, and gel 1 and gel-foam 1 gloves show middle finger vibration transmission performance comparable to that of leather glove in the high frequency range.

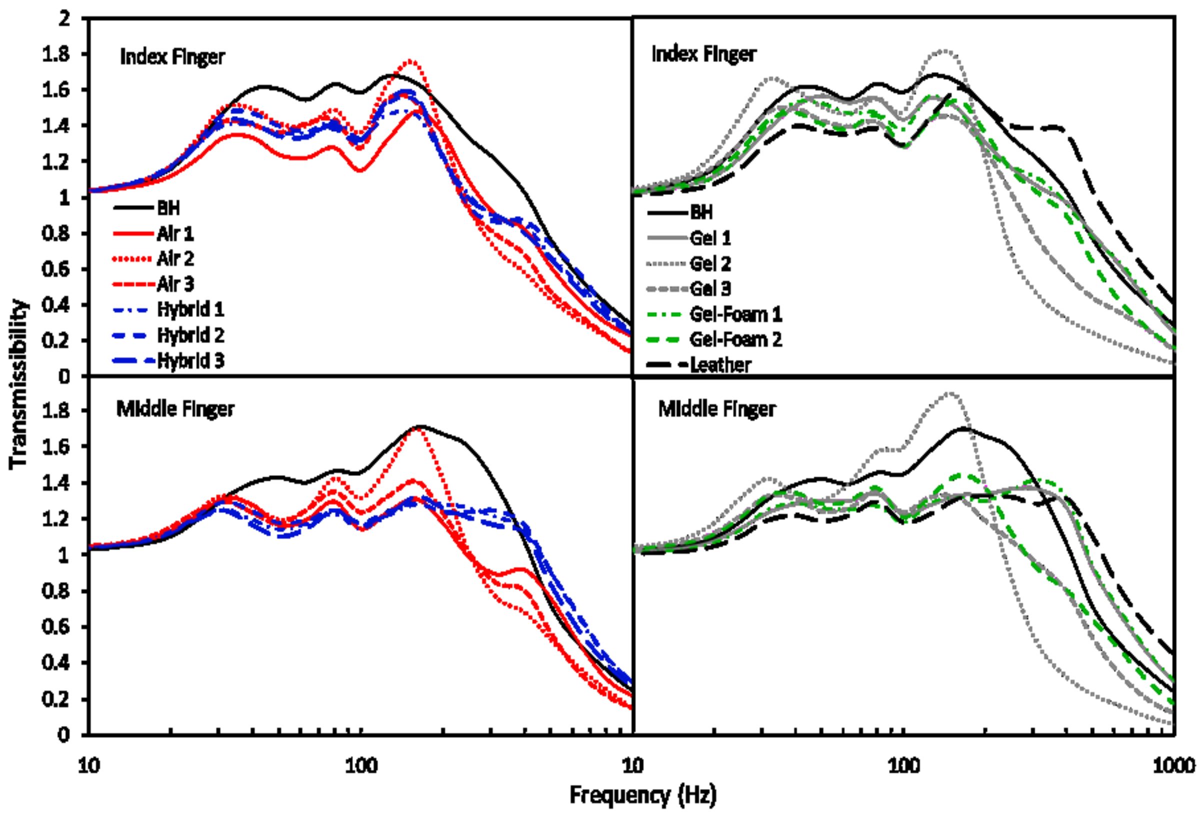


Figure 3.9: Comparisons of mean vibration transmissibility characteristics of index and middle fingers of the bare and gloved hand: (a) air and hybrid gloves; (b) gel, gel-foam and leather gloves

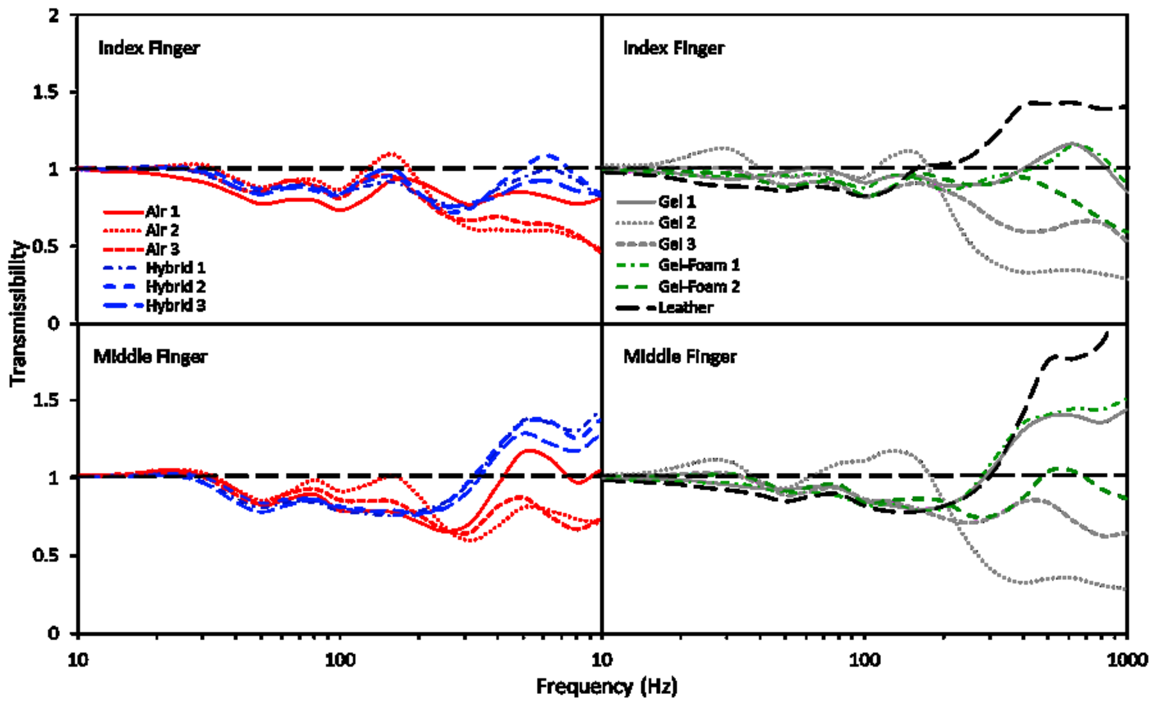


Figure 3.10: Comparisons of mean normalized vibration transmissibility characteristics of index and middle fingers of the gloved hand: (a) air and hybrid gloves; (b) gel, gel-foam and leather gloves

The mean peak vibration transmissibility magnitudes of the index and middle fingers and the corresponding frequencies are summarized in Table 3.5 for all the gloves and the bare hand. The table also lists the CoV of the means. The mean magnitudes and the corresponding frequencies of bare and gloved hand fingers were obtained from averaging of the data obtained for the 12 subjects. The results show that all the gloves, with the exception of gel 2, help in reducing the peak vibration transmitted to both the fingers, although the degree of reduction is small. All of the gloves, with the exception of air 2 and gel 2, exhibit comparable peak vibration transmissibility magnitudes for both the fingers, while the peak magnitudes of the index finger are greater than those of the middle finger. The results also show relatively large variability in the data for both the bare and the gloved hand fingers. Generally, the CoV of the peak vibration transmissibility for the bare and gloved hand index finger (11–21%) is slightly higher than that of the middle finger (7–19%). The mean primary resonant frequency of the index finger of the bare hand (122 Hz) is lower than that with the gloves (129–148 Hz), excluding the leather glove, which shows peak at 184 Hz. An opposite trend, however, is evident in the middle finger resonant frequencies. The resonant frequencies of middle finger of the gloved hand are generally lower than that of the bare hand, with the exception of gel 1, hybrid 3 and gel-foam 1 gloves. The gloves thus generally tend to increase the index finger primary resonant frequency, while decreasing the middle finger frequency. The inter-subject variabilities in the index finger primary resonance frequency were generally lower than those for the middle finger for both the bare and gloved hands. Air 1, gel 2 and gel 3 gloves, however, show higher variability in the index finger frequency compared with that of the middle finger. The results obtained from one-way ANOVA suggested that the peak vibration transmissibility and the primary resonance frequency are significantly different for both index (p<0.05) and middle (p<0.001) fingers among the gloves.

Table 3.5: The mean peak index and middle fingers vibration transmissibility and the corresponding frequencies obtained for the bare and gloved hand.

	Index finger				Middle finger			
	Peak transmissibility		Resonance frequency (Hz)		Peak transmissibility		Resonance frequency (Hz)	
Gloves	Mean	CoV	Mean	CoV	Mean	CoV	Mean	CoV
BH	1.95	0.13	122	0.22	1.90	0.12	174	0.39
Air 1	1.61	0.20	149	0.29	1.41	0.11	157	0.22
Air 2	1.90	0.14	145	0.15	1.82	0.13	173	0.17
Air 3	1.82	0.16	139	0.14	1.56	0.14	140	0.23
Gel 1	1.82	0.15	129	0.24	1.56	0.10	229	0.54
Gel 2	2.04	0.13	131	0.19	1.99	0.17	142	0.16
Gel 3	1.70	0.14	134	0.26	1.60	0.19	126	0.21
Hybrid 1	1.75	0.13	133	0.18	1.44	0.07	167	0.34
Hybrid 2	1.77	0.15	137	0.16	1.43	0.08	156	0.40
Hybrid 3	1.84	0.19	138	0.17	1.48	0.10	174	0.45
Gel-Foam 1	1.74	0.11	134	0.12	1.56	0.09	270	0.39
Gel-Foam 2	1.63	0.19	144	0.15	1.52	0.09	152	0.28
Leather	1.72	0.21	184	0.29	1.49	0.14	268	0.32

CoV: coefficient of variation

Table 3.6 presents the mean overall normalized unweighted and W_h-frequency weighted vibration transmissibility values of 12 gloves for both the fingers in the M- and H- frequency ranges together with the CoV of the means. The table also presents the weighted values obtained using the W_f-frequency weighting proposed by Dong et al. (2008) [94]. The results show that the gloves generally attenuate the index and middle finger transmitted vibration in the M-frequency range, irrespective of the frequency-weighting used. The degree of attenuation, however, is low for most of the gloves. The gel 2 glove appears to be the only exception, where the slight amplification is observed in the middle finger vibration transmissibility magnitude. Similar trend is also evident in the H-frequency range transmissibility for all the gloves. All the gloves, with the exception of the leather glove, show reduction in the overall vibration transmissibility of the index finger in the H-frequency range. The results for the leather glove consistently show amplification of the index finger transmitted vibration, irrespective of the frequency weighting used. For the middle finger, vibration amplification is evident with gel 1, hybrid 1, hybrid 2, gel-foam 1 and leather gloves, as seen from the unweighted and W_f-weighted values. The attenuation of middle finger vibration in the H-frequency range is observed for nearly half of the gloves (all air gloves, gel 2, gel 3, hybrid 3, and gel-foam 2). The degree of attenuation of finger vibration by the glove is strongly dependent on the type of glove. This was also evident from the one-way ANOVA, which showed that the unweighted vibration transmissibility at the middle finger is significantly different ($p<0.001$) among the gloves in both the frequency ranges, while it was only significant only for the index finger in the H-range ($p<0.001$). Air 1 glove provided superior vibration attenuation in the M-frequency range (index: 0.86; middle: 0.76), while the gel 2 glove revealed greatest attenuation in the H-frequency range (index: 0.47; middle: 0.51). Generally, the gloves in the M-frequency range revealed relatively lower CoV values of the unweighted vibration transmissibility for both the fingers when compared with those in the H-range. The middle finger transmissibility values for the air 1, air 2, gel 2, gel-foam 2 and leather gloves, in particular, show high variability (CoV: 32–36%).

Table 3.6: Mean normalized unweighted, hand weighted (W_h) and finger weighted (W_f) overall vibration transmissibility at the index and middle fingers in the M- and H-frequency ranges.

	Mean overall transmissibility (CoV)											
Glove	Air 1	Air 2	Air 3	Gel 1	Gel 2	Gel 3	Hyb-1	Hyb-2	Hyb-3	Gel-Foam 1	Gel-Foam 2	Leather
Index finger	M-frequency range (25-200Hz)											
Unweighted	0.86 *(0.19)*	0.97 *(0.15)*	0.89 *(0.14)*	0.93 *(0.17)*	0.97 *(0.14)*	0.87 *(0.16)*	0.87 *(0.15)*	0.89 *(0.17)*	0.90 *(0.22)*	0.90 *(0.13)*	0.91 *(0.19)*	0.94 *(0.18)*
W_h- weighted	0.66 *(0.13)*	0.93 *(0.11)*	0.88 *(0.12)*	0.93 *(0.14)*	0.96 *(0.10)*	0.88 *(0.13)*	0.87 *(0.12)*	0.88 *(0.11)*	0.88 *(0.16)*	0.91 *(0.10)*	0.90 *(0.15)*	0.90 *(0.13)*
W_f- weighted	0.90 *(0.20)*	0.94 *(0.15)*	0.91 *(0.18)*	0.88 *(0.22)*	0.95 *(0.14)*	0.87 *(0.22)*	0.86 *(0.19)*	0.85 *(0.11)*	0.86 *(0.27)*	0.83 *(0.14)*	0.93 *(0.25)*	0.89 *(0.17)*
Middle finger												
Unweighted	0.76 *(0.11)*	0.93 *(0.13)*	0.82 *(0.19)*	0.82 *(0.11)*	1.01 *(0.11)*	0.80 *(0.21)*	0.78 *(0.10)*	0.78 *(0.12)*	0.78 *(0.16)*	0.81 *(0.15)*	0.86 *(0.16)*	0.81 *(0.12)*
W_h- weighted	0.84 *(0.10)*	0.94 *(0.09)*	0.87 *(0.11)*	0.88 *(0.09)*	1.04 *(0.09)*	0.88 *(0.11)*	0.83 *(0.08)*	0.84 *(0.09)*	0.82 *(0.11)*	0.86 *(0.09)*	0.91 *(0.12)*	0.84 *(0.09)*
W_f- weighted	0.77 *(0.12)*	1.05 *(0.03)*	0.94 *(0.18)*	0.87 *(0.14)*	1.12 *(0.13)*	0.95 *(0.23)*	0.83 *(0.06)*	0.82 *(0.10)*	0.84 *(0.07)*	0.89 *(0.19)*	0.94 *(0.16)*	0.86 *(0.12)*
Index finger	H-frequency range (200-1250 Hz)											
Unweighted	0.84 *(0.25)*	0.67 *(0.24)*	0.69 *(0.14)*	0.96 *(0.19)*	0.47 *(0.24)*	0.69 *(0.23)*	0.84 *(0.24)*	0.86 *(0.22)*	0.82 *(0.22)*	0.96 *(0.15)*	0.88 *(0.27)*	1.26 *(0.20)*
W_h- weighted	0.84 *(0.31)*	0.65 *(0.23)*	0.68 *(0.17)*	0.94 *(0.19)*	0.43 *(0.23)*	0.70 *(0.25)*	0.81 *(0.23)*	0.80 *(0.22)*	0.79 *(0.23)*	0.94 *(0.29)*	0.90 *(0.29)*	1.22 *(0.21)*
W_f- weighted	0.96 *(0.26)*	0.73 *(0.20)*	0.82 *(0.05)*	0.98 *(0.05)*	0.57 *(0.12)*	0.79 *(0.24)*	0.87 *(0.16)*	0.89 *(0.17)*	0.84 *(0.15)*	0.93 *(0.10)*	0.90 *(0.07)*	1.22 *(0.23)*
Middle finger												
Unweighted	0.84 *(0.36)*	0.72 *(0.33)*	0.73 *(0.27)*	1.09 *(0.20)*	0.51 *(0.32)*	0.74 *(0.28)*	1.03 *(0.27)*	1.03 *(0.26)*	0.97 *(0.29)*	1.12 *(0.24)*	0.83 *(0.32)*	1.23 *(0.36)*
W_h- weighted	0.75 *(0.29)*	0.75 *(0.34)*	0.71 *(0.25)*	0.96 *(0.16)*	0.62 *(0.29)*	0.73 *(0.23)*	0.90 *(0.24)*	0.89 *(0.23)*	0.87 *(0.25)*	*0.98* *(0.21)*	*0.79* *(0.27)*	1.00 *(0.29)*
W_f- weighted	0.87 *(0.39)*	0.86 *(0.49)*	0.85 *(0.30)*	1.13 *(0.19)*	0.69 *(0.35)*	0.92 *(0.21)*	1.10 *(0.26)*	1.10 *(0.29)*	1.06 *(0.30)*	1.19 *(0.17)*	0.98 *(0.30)*	1.28 *(0.36)*

CoV: coefficient of variation

The overall M-frequency range index finger unweighted, and W_h- and W_f-weighted transmissibility magnitudes range from 0.86-0.97, 0.66-0.96 and 0.85-0.93, respectively. The W_f-weighted values are similar to the unweighted values, which is due to near unity magnitude of the W_f-frequency weighting in this frequency range. Similar tendency is also evident in the middle finger unweighted transmissibility values for all the gloves, except for the gel 2 glove. Application of W_f-weighting further emphasized the vibration amplification tendency of the gel 2 and air 2 gloves at the middle fingers. Excluding the data for these gloves, the overall middle finger unweighted, and W_h- and W_f-weighted transmissibility magnitudes in the M-frequency range from 0.76-0.86, 0.82-0.91 and 0.77-0.95, respectively. The application of W_f-frequency weighting in the H-frequency range, however, resulted in considerably higher transmissibility values for both the fingers when compared to the unweighted and W_h-weighted values. The W_h-weighted vibration transmissibility was significantly different among the gloves for both fingers and frequency ranges ($p<0.001$). Similarly, the W_f -weighted vibration transmissibility was significantly ($p<0.001$) different among the gloves for both fingers in the H-frequency range, while it was significantly different only for the middle finger in the M-range.

3.3.4 Grip strength reduction

Table 3.7 summarizes the mean grip strength obtained from the 12 subjects' data with the bare and gloved hand together with CoV of the mean. The table also presents percent reduction in the grip strength of the gloved hand, evaluated with reference to mean force measured with the bare hand. The results suggest that gloves, invariably, cause notable reductions in the grip strength. Moreover, all the gloves, with the exception of the leather and air 1 gloves, show comparable degree of reduction in the grip strength, which ranges from 27 to 33%. The leather glove resulted in substantially lower grip strength reduction (16%) compared to the other gloves, while the air 1 glove showed the highest grip strength reduction (41%). Comparable variability (CoV) between subjects is also evident for all gloves as well as the bare hand, ranging from 17 to 22%. The results of one-way ANOVA show that the grip strength magnitude and the grip strength percentage reduction were significantly ($p<0.05$ and $p<0.001$, respectively) different among the gloves.

Table 3.7: Mean grip strength magnitude and percentage reduction

Glove	Grip strength Magnitude (N)	CoV	% Reduction
BH	353	0.18	
Air 1	210	0.21	41%
Air 2	250	0.22	29%
Air 3	248	0.17	30%
Gel 1	252	0.19	29%
Gel 2	253	0.20	28%
Gel 3	238	0.19	32%
Hybrid 1	237	0.20	33%
Hybrid 2	253	0.21	28%
Hybrid 3	251	0.22	29%
Gel-Foam 1	259	0.21	27%
Gel-Foam 2	237	0.18	33%
Leather	295	0.17	16%

CoV: coefficient of variation

The mean percentage grip strength reduction due to four different groups of gloves (air, gel, hybrid and gel-foam) in addition to the leather glove are further illustrated in Figure 3.11. The figure also shows the standard deviation bars. The four groups of gloves show very comparable mean percentage reduction in the grip strength, ranging from 31–34%. Air gloves cause slightly higher reduction in the grip strength (34%), while the gloves within the gel, hybrid and gel-foam classes show similar reduction (≈31%).

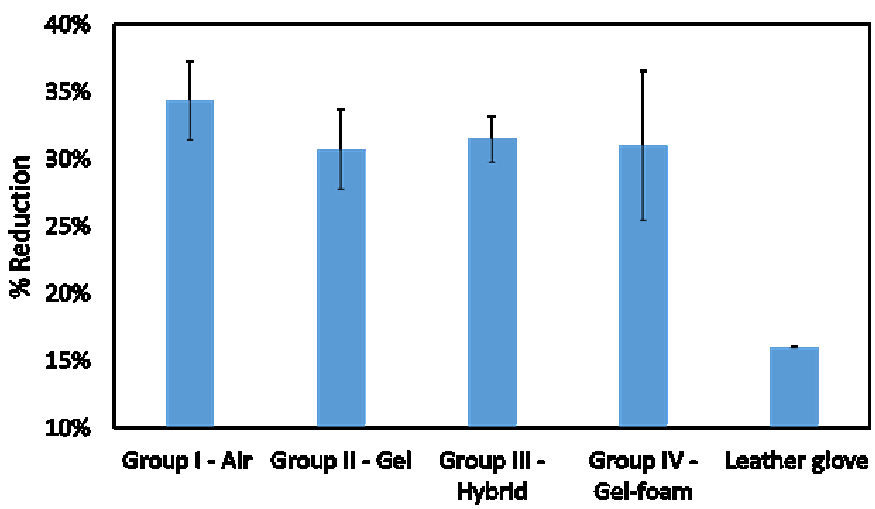


Figure 3.11: Comparison of mean grip strength percentage reduction of different groups of gloves that are constructed from same glove materials.

3.4 Discussions

3.4.1 Reliability of finger adapter

Comparison of bare hand index and middle fingers vibration transmissibility measured during three trials with each subject (Fig. 3.3) showed relatively small variability (0–3%) in the M-frequency range (25–200 Hz). In the high frequency range, the variability between trials increased slightly (0–12%) in the 200–500 Hz frequency range and to 2–20% above 500 Hz. Variability in vibration transmissibility at the palm also showed similar trend, although considerably lower as compared with the fingers. Lower variability at the palm may be due to high palm-handle contact force than the fingers force [100]. In order to obtain 30 N grip and 50 N push force, a subject exerts 30 N finger force and 80 N palm force [82]. The variability may also be due to differences in the mechanical impedance of the fingers and palm [99, 120]. Furthermore, intrinsic variations of the human hand may also be affecting the contact force on the Velcro adapter and dynamic properties of the fingers. Furthermore, finger acts as a curved beam hinged at palm while gripping a handle. Thus it is very difficult to ensure the same degree of contact between the fingers and the handle, as opposed to the palm within a subject. Increase in variability with increase in frequency of vibration for both fingers and palm maybe attributed to the dynamic characteristics of hand arm system. The high frequency vibration becomes more localized to the hand and fingers, while the low frequency vibration is transmitted to the fore-arms. The fingers vibration thus occurs at far greater frequencies. The large variability in transmissibility to the finger has also been reported by Md Rezali and Griffin (2015) [26].

Reproducibility tests showed relatively less variability (1–6%) in the vibration transmissibility in the M-frequency range, and relatively higher variability (1–18%) for the H-frequency range, irrespective of the fingers. Variability in the reproducibility test of vibration transmissibility is however higher than those obtained in the repeatability test (Figs 3.3 and 3.4). The effect of removing and re-installing of Velcro adapters on the subjects' finger might have slightly changed the tightness and orientation of the adaptor. It is thus deduced that the Velcro finger adapters could yield repeatable and reproducible measurements, despite the small variability found in the H-frequency range.

3.4.2 Palm vibration transmissibility characteristics and effectiveness of gloves

The CoV values of the mean normalized palm vibration transmissibility showed comparable variability among air and hybrid gloves for M- (air gloves: 7–9% and hybrid gloves: 5–10%) and H- (air gloves: 9–18% and hybrid gloves: 10–16%) frequency ranges (Table 3.3). Vibration reducing material used in the palm area of the hybrid gloves is the same as in the air gloves, which may be the possible reason for comparable variability in vibration transmissibility. Similarly gel used for construction of the gel-foam gloves in the palm area showed comparable variability between the gel and gel-foam groups of gloves in the entire frequency range (3–9% and 2–13% for the gel and gel-foam gloves, respectively). The CoV values of the gel and gel-foam gloves are lower than the air and hybrid gloves while the leather glove showed lowest variability (2%) in both the frequency ranges. Higher variability in the air gloves is likely due to dependence of effective air pocket/bladder stiffness on the contact area and thus the hand size. The results thus suggest the vibration reducing materials have strong influence in the inter-subject variability. Laszlo and Griffin, (2011) [69] also reported that vibration reducing materials affect inter-subject variability on vibration transmissibility. Relatively lower variability was observed in the peak vibration transmissibility (CoV: 2–10%) compared to that in the primary resonance frequency shows relatively higher variability (CoV: 9–24%). High inter-subject variability have also been reported in different studies [1, 26, 65, 68-71, 76]. Variation in the CoV values between different studies may be attributed to the subjects' size and their hand characteristics (hand size) apart from variations in anti-vibration gloves and the materials. Welcome et al. (2012) [18] reported that the use of large number of subjects with comparable hand size could help reduce the inter-subject variability.

The peak vibration transmissibility varied more in the gel (1.04–1.22) and gel-foam (1.03–1.13) gloves as compared with the air (1.13–1.16) and hybrid (1.11) gloves (Table 3.3). The gel 1, gel-foam 1 and leather gloves show relatively lower and comparable peak vibration transmissibility (1.02–1.04) than that of other gloves (1.11–1.22). The mean normalized vibration transmissibility of the gel 1, gel-foam 1 and leather gloves was unity in most of the frequency range (Fig. 3.6) which is attributable to higher damping. The gel-foam glove is constructed with a layer of thin and soft foam and gel. Same gel is used for construction of gel 1 glove and gel-foam 1 glove thus the performance of these two gloves is comparable in terms of the peak vibration transmissibility. Hamouda et al. (2015) [112] also reported relatively low peak vibration transmissibility for the gel and leather gloves (1.02) as compared with the air and hybrid gloves (1.10–1.13), and vibration transmissibility for the gel and leather gloves were close to unity in the 10–1000 Hz frequency range. Similar trend of vibration transmissibility of an ordinary leather glove has been reported in McDowell et al. (2013) [61]. Dong et al. (2009) [17] reported that gel gloves exhibit relatively higher damping property as compared with the air gloves. In the present study, the air and hybrid (air bladder in the palm) gloves showed consistent performance however the performance of gel gloves varied considerably in the M- and H-frequency range (Fig. 3.6, Table 3.3).

3.4.3 Fingers vibration transmissibility and effectiveness of gloves

The Index and middle fingers showed comparable variability at the M-frequency range (3–26%), however variability at the index finger (3–63%) was relatively higher than that of the middle (8–47%) in the H-range (Fig. 3.7 and 3.8). Studies generally reported high inter-subject variability at the fingers [26, 112, 121]. Hamouda et al. (2015) [112] reported relatively lower variability in the vibration transmissibility at the index and middle fingers as compared to the variability obtained in the present study for both frequency ranges. The variation in the variability in the two studies may be attributed to the difference in hand sizes, number of subjects and differences in the gloves. Hamouda et al. (2015) [112] also reported lower inter-subject variability in the M-frequency range as compared to the H- frequency range. Similar trend of inter-subject variability at the fingertip vibration transmissibility was reported in Md Rezali and Griffin (2015) [26].

The primary resonance frequencies and the corresponding peak magnitudes summarized in Table 3.5 are slightly different from that results presented in Figure 3.9. This difference is attributed to the averaging effect. Results in Figure. 3.9 is shown in the one-third octave bands, while those in Table 3.5 are based on the constant band width spectra. The mean primary resonance frequency (122 Hz) at the index finger with bare hand is lower than that obtained at the middle finger (174 Hz) (Table 3.5). Welcome et al. (2014) [20] and Hamouda et al. (2015) [112] reported lower values of the primary resonance frequency at the middle finger than that at the index finger with bare hand. The primary resonance frequency at the index finger with bare hand reported in Welcome et al. (2014) [20] and Hamouda et al. (2015) [112] is comparable with the present study, however, the primary resonance frequency at the middle finger in both the studies is lower than those obtained in the present study. Difference in the primary resonance frequencies between different studies may be due to variation in the subjects' characteristics. In the present study, hand size of the subjects was in the range of 7–10 (Table 3.1), however, hand size of the subjects in Hamouda et al. (2015) [112] and Welcome et al. (2014) [20] was in the range of 8–9 and 9–10, respectively. Seven subjects among 12 subjects in the present study showed either comparable or greater resonant frequency at the index finger than at the middle finger while the rest five subjects exhibited relatively higher resonant frequency at the middle finger (174 Hz) than those obtained at the index finger. The results thus indicate the effect of hand sizes and the number of subjects on the primary resonance frequency. Higher primary resonance frequency at the index finger may be due to more finger force and thus higher stiffness [112]. Rossi et al. (2012) [108] reported that higher percentage of mean grip force by the index finger with bare hand and higher finger force may cause higher finger stiffness. Similarly, Gurram et al. (1995) [106] and Aldien et al. (2005) [107] reported higher dynamic force (higher finger stiffness and resonant frequency) by the index finger than that of the middle finger at the distal and middle phalanges.

Wearing a glove increased the primary resonance frequency at the index finger however no trend is evident in the primary resonance frequency at the middle finger (Table 3.5). Higher primary resonance frequency of gloved hand at the index finger is in line with those reported in Hamouda et al. (2015) [112], however Hamouda et al. (2015) [112] reported higher primary resonance frequency with gloved hand as compared with the bare hand at the middle finger. Welcome et al. (2014) [20] reported negligible effect of the air and gel gloves on the middle finger resonant frequency for same grip and push force (30 N grip and 50 N push forces) used in the present study. Welcome et al. (2014) [20] also reported similar or lower index finger resonant frequency for the gloved hand as compared with bare hand. The differences between the present and reported studies are likely caused by variation in the gloves and subjects' characteristics. Glove reduces hand grip strength [18, 27], thus the subjects have to exert muscular force to obtain comparable grip strength of 30 N grip force and 50 N push force and thus higher finger force. Higher finger force may increase the stiffness of the fingers and the glove material, and thus increase the primary resonance frequency [112]. This trend is clearly evident at the index finger with all gloves (Table 3.5), however only gel 1, gel-foam 1 and leather gloves showed this trend at the middle finger. No clear trend on the change in the primary resonance frequency at the middle finger may be due to finger anthropometry of the subjects and uneven contribution of middle finger in grip force exertion. Proportion of grip force by index finger might have been more with some subjects while the other subjects might have used fairly large proportion of middle finger force. This is also evident from the higher inter-subject variability in the primary resonance frequency at the middle finger as compared with the index finger (Table 3.5). Furthermore, variation in the primary resonance frequencies of the gloved hand at the middle finger is considerably higher with CoV in the range of 16–54% than at the index finger in the range of 12–29% (Table 3.5). The results also show that the materials of the gloves have effect on the primary resonance frequencies at the middle finger. Gel is used for construction of gloves in the finger area for the gel, hybrid and gel-foam gloves and the gel material used for construction of gel 1 and gel-foam 1 gloves is same. The primary resonance frequency (229–270 Hz) of the gel 1 and gel-foam 1 gloves at the middle finger is considerably higher than the primary resonance frequency (126–174 Hz) of other gloves used in the study with exception of leather glove (primary resonance frequency–268 Hz). Furthermore, in general, the gel materials used in gloves revealed lower primary resonance frequency than the air gloves at the middle finger. Lower primary resonance frequencies of the gel gloves than the air gloves have been reported at the index finger in Welcome et al. (2014) [20]. Xu et al. (2011) [109] reported that the air glove revealed higher primary resonant frequency than the gel glove.

The peak vibration transmissibility at the index finger is greater than those obtained at the middle finger (Table 3.5), irrespective of the gloves. Similar trend has been reported in Hamouda et al. (2015) [112] and Welcome et al. (2014) [20]. Comparison of the peak vibration transmissibility with bare hand and gloved hand revealed that the peak vibration transmissibility is reduced with the gloved hand for both the fingers as compared with that of the bare hand with exception of gel 2 glove where the peak vibration transmissibility is higher than that obtained with bare hand for both fingers (Table 3.5). Gel 2 glove was constructed with perforated gel which may be reason for low damping property. Hamouda et al. (2015) [112] reported higher peak vibration transmissibility for the air glove than that of the bare hand for both fingers. Welcome et al. (2014) [20] reported comparable peak vibration transmissibility with the air glove and slightly lower peak vibration transmissibility with the gel glove finger as compared with the bare hand at the index under same experimental conditions however slightly higher peak values at the middle fingers for both gloves as compared with the bare hand.

Normalized vibration transmissibility shows generally good vibration attenuation characteristics of the gloved hand at the index (30–160 Hz) and middle (10–200 Hz) fingers (Fig. 3.10) and thus gloves are suitable for reducing vibration exposure of the fingers, especially for the hand-held power tools with dominant vibration in this frequency range. Some gloves however amplified fingers vibration at frequencies greater than 160 Hz for the index finger and greater than 200 Hz for the middle finger until the cut-off frequency. Welcome et al. (2014) [20] reported that the air and gel gloves are not suitable for frequencies between 80–400 Hz which agrees for gel 2 glove at the middle finger in the present study. Cut-off frequency of most of the gloves at the index finger is ≈160 Hz with exception of gel 1, gel-foam 1 and hybrid 2 gloves which showed cut-off frequency at ≈600 Hz. Cut-off frequency of most of the gloves at the middle finger is ≥ 600 Hz with exception of air 2, 3 and gel 2, 3 gloves with cut-off frequency ≤ 160 Hz. Leather glove exhibit cut-off frequency >1000 Hz for both fingers. Hamouda et al. (2015) [112] reported cut-off frequency ≈160 Hz for the air glove and ≈600 Hz for the gel and hybrid gloves at both fingers. The study also reported cut-off frequency ≈600 Hz at the index finger and >1000 Hz at the middle finger for the leather glove. Welcome et al. (2014) [20] reported 450 Hz and 400 Hz cut-off frequencies at the mid-phalanges of the index and middle fingers under 30 N grip and 50 N push force, irrespective of the air and gel gloves. The difference in the cut-off frequencies between different studies may be attributed to the types of gloves and subjects' characteristics.

One of the important factors affecting the vibration isolation performance of VR gloves is the frequency weighting [112]. Use of standardized hand weighting (W_h) to obtain vibration transmissibility at the fingers can overestimate low-frequency effects and greatly underestimates high-frequency effects on the development of finger disorders [94]. Hamouda et al. (2015) [112] presented the effect of finger (W_f) and hand (W_h) weighted vibration transmissibility at the mid-phalanges of index and middle fingers. The study reported comparable performance of the gloves with both frequency-weighting in the M-frequency range (25–200 Hz) however the weighting has a larger effect in the H-frequency range (200–1250 Hz). In the present study, the frequency-weighted vibration transmissibility of the majority of gloves were comparable with frequency-unweighted vibration transmissibility at both fingers under M-frequency range with exception of air 1 glove at the index finger (W_h-weighted transmissibility=0.66) and gel 2 glove at the middle (W_f-weighted transmissibility=1.12) (Table 3.6). Generally, the finger weighted (W_f)

transmissibility values are either comparable or greater than the frequency-unweighted values at the index finger except the leather glove and at the middle finger for all the gloves in the H-frequency range. Comparison of vibration transmissibility revealed comparable or better vibration attenuation with W_h-weighted than that obtained with W_f-weighted for all the gloves at both fingers in the H-frequency range. The W_f-weighting underestimates the high-frequency effects [94]. Thus, the performance of the gloves depends on the weighting factor.

3.4.4 Effect of VR gloves on grip strength

Studies have reported that glove reduces hand grip strength [18, 27, 81, 83, 91, 118]. The results of the present study also show same trend however reduction in the hand grip strength varied among different gloves. Reduction in the grip strength (29–41%) of air group of gloves in the present study (Table 3.7) is comparable to the 30.7–40.3% in Welcome et al. (2012) [18] and 29–34% and 33.1–36% for 30 and 40 mm handle, respectively in Wimer et al. (2010) [27] for air gloves. Gel group, hybrid group and gel-foam group of gloves exhibited comparable grip strength reduction ranging from 28–32%. Wimer et al. (2010) [27] obtained 29% and 35% reduction in hand grip strength for 30 and 40 mm handle, respectively with gel glove. Air 1 glove exhibited the greatest reduction (41%) while reduction was least (16%) with leather glove (Table 3.1). Thickness of the leather glove was lowest which may be the reason for very less reduction in the grip strength. The air 1 glove however was thinner than other air gloves but reduction in hand grip strength was highest. Though the gel-foam 2 glove has largest thickness but reduction in the grip strength was comparable with thinner gloves. It is thus deduced that reduction in the grip strength could not be established from thickness of the glove but stiffness of the glove may also play an important role in reduction of hand grip strength. Further study on gloves with different thickness and stiffness may provide more insights on reduction in hand grip strength.

3.4.5 ISO 10819 and effectiveness of VR gloves

Performance evaluation of a glove solely based on the vibration transmissibility characteristics at the palm using three subjects' data is questionable. Comparison of the mean normalized vibration transmissibility magnitudes in the M- and H- frequency ranges (Table 3.3) show that air 1, hybrid 1&3 and gel 2 gloves pass the criteria of anti-vibration glove according to ISO 10819 (2013) [24] and thus can be classified as anti-vibration (AV) gloves. However, ISO 10819 (2013) [24] requires 3 subjects for screening test to be classified as anti-vibration glove.

The present study was performed with 12 subjects and the vibration transmissibility obtained from 3 subjects of different combination shows that air (1, 2 and 3) and hybrid (2 and 3) gloves can pass the screening criteria by few combination of 3 subjects however it fail the screening criteria from another few combination of 3 subjects (Table 3.4). Thus 3 subjects in the ISO 10819 (2013) [24] are questionable. Furthermore, a glove can pass the screening test in one laboratory, however it may not pass in another with different subjects. Hewitt et al (2015) [19]; Hamouda et al. (2015) [112] also reported concern on the number of subjects required in the standardized screening test of AV gloves. Thus the number of subjects required for assessing anti-vibration glove should be more. Number of trials by a subject has been increased from 3 to 5 while revising ISO 10819 standard. The present study shows that intra-subject variability is less than the inter-subject variability. Thus increasing number of trials may not change the performance of the glove. However, it is suggested that number of subjects should be increased in the ISO 10819 standard.

Vibration attenuation characteristics of the glove at the finger and palm differs (Tables 3.3 and 3.6) which is attributed to the difference between the palm and fingers vibration transmission characteristics and hand anthropometry of subjects. Thus a glove designated as anti-vibration may be good for vibration attenuation at the palm but may amplify vibration at the fingers. For example, gel 2 glove shows vibration transmissibility in the M- and H-frequency ranges of 0.79–0.86 and 0.53–0.56, respectively (Table 3.4) and pass the anti-vibration criteria of ISO 10819 (2013) [24]. This glove however shows amplification of normalized frequency-weighted and frequency-unweighted vibration transmissibility at the middle finger in M-frequency range (Table 3.6) and normalized frequency-weighted and frequency-unweighted vibration transmissibility shows unity or amplification in the 10–200 Hz frequency range at both fingers (Fig. 3.9 and 3.10). Md Rezali and Griffin (2015) [26] suggested that measuring the vibration transmissibility at the palm of the hand is not sufficient to assess an 'anti-vibration' glove. Furthermore, glove pass the screening test of anti-vibration glove however reduces grip strength considerably and thus affecting dexterity. For example, however hand grip strength was reduced by 41% and the glove will be affecting finger motion and thus performance of the hand held power tools.

The vibration transmission characteristics of the fingers and palm are different. The results of vibration transmissibility in the present study show that different vibration reducing materials in the palm and fingers may be better for vibration attenuation. Hamouda et al. (2015) [112] suggested that the requirements of same material in the palm and fingers regions of the glove (ISO 10819, 2013) may not be beneficial for enhancing the performance of a glove.

3.5 Conclusions

Velcro finger adapters showed very good repeatable and reproducible data of vibration transmissibility at the index and middle fingers and thus Velcro adapter can be used for finger vibration measurement. VR materials have strong effect on the inter-subject variability at the palm and fingers. Generally, air bladder showed relatively higher variability in the vibration transmissibility than with the gel, gel-foam and leather. The vibration isolation performance of gloves also depends on the type of VR material. VR gloves amplified the low frequency vibration (10–40 Hz) at the palm, however vibration is generally attenuated >40 Hz. Vibration is attenuated in the 30–160 Hz frequency range at the index finger and 10–200 Hz at the middle finger. Most gloves showed cut-off frequency ≈160 Hz at the index finger while the cut-off frequency was generally >600 Hz at the middle finger. Only leather glove showed cut-off frequency greater than 1000 Hz. The VR gloves generally reduced the peak vibration transmissibility at both the fingers however the gloves showed higher primary resonant frequency at the index finger as compared with the bare hand. VR gloves showed comparable vibration transmissibility at both the fingers in the M-frequency range, irrespective of the frequency-weighting and frequency-unweighting while relatively higher effect of weighting was evident in the H-frequency range. The W_h weighting underestimated both fingers transmissibility magnitudes in the H-frequency range as compared with the unweighted values, however this was not evident in the M-frequency range. Results revealed that a glove may pass the screening criteria in ISO 10819 (2013) [24] with one group of 3 subjects while it may not pass the screening criteria with another group of 3 subjects. Air, gel, hybrid and gel foam gloves reduced nearly 30% hand grip strength.

4. CONCLUSIONS AND RECOMMENDATIONS OF FUTURE WORK

4.1 Major Contributions

This dissertation's main focus was the development of a finger adapter capable of characterizing fingers vibration transmission performance of VR gloves so as to build upon methods for assessing integrated performance in terms of vibration isolation effectiveness at the palm and fingers, and preservation of grip strength and manual dexterity. The dissertation research, however, was limited to assessments based on vibration transmission and grip strength reduction properties of VR gloves. The major contributions of the dissertation research are summarized below:

i. Design of a finger adapter (Velcro) capable of measuring the vibration transmitted to the fingers with and without the gloves with good repeatability and reproducibility.
ii. Vibration transmissibility measurements of different VR gloves at the index and middle fingers under the standardized vibration spectrum and spectra of three different hand power tools.
iii. Measurements of grip strength reductions due to VR gloves.
iv. A methodology for predicting fingers vibration characteristics of VR gloves under the vibration spectra of the selected tools so as to seek guidance on tool-specific gloves designs.
v. Assessment of the integrated performance of VR gloves based on the vibration isolation effectiveness at the palm and fingers, in addition to the effect of the gloves on the grip strength reduction.
vi. The relative significance of the standardized hand weighting and the proposed finger-weighting for assessing overall vibration transmissibility of gloves at the fingers.

4.2 Major Conclusions

Major conclusions drawn from the study are summarized below:

i. Velcro finger adapters offer a reliable and convenient mean for measurements of transmitted vibration at the fingers with and without the gloves. The adapters also exhibited repeatable and reproducible finger vibration measurements.

ii. The vibration responses measured at the fingers differ significantly from those at the palm. Vibration isolation performance of gloves at the palm and the fingers strongly depend on the properties of the VR materials employed, the number of subjects participating in the glove test, the different hand sizes and the vibration transmission characteristics of these subjects.

iii. VR gloves considered in this study, generally showed amplification of low frequency handle vibration (10–40 Hz) transmission at the palm and vibration attenuation at frequencies greater than 40 Hz. Some of the gloves, however, showed almost unity vibration transmissibility at the palm over the entire frequency range.

iv. Gloves that employ air bladder in the palm showed superior vibration isolation in the H-frequency range compared to those with gel, gel-foam or leather materials. Only one of the gel gloves showed better isolation performance than the air gloves.

v. VR gloves that are designated as AV gloves based on 12 subjects data, may not pass the standardized screening test when a particular group of only three subjects is considered as recommended in the standard. Increasing the number of subjects therefore is essential for enhancing performance assessment of VR gloves.

vi. Different from the palm, the VR gloves attenuated vibration transmitted to fingers in the 10–200 Hz frequency range, with exception of only two gloves, which showed some vibration amplification in this frequency range. At frequencies greater than 200 Hz, most of the gloves amplified vibration transmitted to the middle finger. This trend was also observed for a few gloves in the index finger vibration measurements.

vii. A glove can be considered as an AV glove according to the standard, although it amplifies vibration transmitted to the fingers. It would thus be important to include a screening criteria on the basis of fingers' responses measured at the fingers.

viii. The vibration isolation performance of VR gloves in the M-frequency range was not affected by the frequency weighting method utilized, while the effect of weighting was clearly evident in the H-frequency range. The application of the standardized W_h-weighting generally resulted in superior performance of gloves compared to that obtained with the proposed finger (W_f) weighting. The W_h-weighting is considered inadequate for assessing VR gloves performance in terms of vibration transmissibility at the fingers.

ix. The VR gloves comparably reduced the hand grip strength, with the exception of only one glove (leather) that showed considerably lower effect. A correlation between the grip strength reduction and the glove thickness could not be established. The glove that showed the largest reduction in the grip strength (air 1) did not possess the largest thickness amongst the gloves.

x. The hybrid glove, constructed with air pockets and gel-foam in the palm- and fingers-regions, respectively, showed relatively lower hand grip reduction and superior vibration isolation performance. The VR glove designs with different isolation materials in the palm and fingers areas may thus yield improved vibration isolation and hand grip force performance.

xi. The frequency response functions (FRFs) could be effectively used to estimate fingers vibration transmissibility characteristics of VR gloves under vibration spectra of different tools considered in this study.

4.3 Recommendations for future work

This dissertation successfully developed Velcro finger adapters to measure the vibration transmitted to the fingers. The adapters demonstrated high degrees of repeatability and reproducibility for fingers vibration measurements. The dissertation also assessed the integrated performance of VR gloves based on the vibration transmissibility performance at the palm and fingers, in addition to the effect of gloves on the deterioration in the hand grip strength. However, the need for additional efforts is recognized to seek enhanced integrated performance of VR gloves, and to develop reliable methods for assessing performance of VR gloves. Some of these are summarized below:

i. Although Velcro adapters showed high degree of repeatability, the validity of the measurements, however, could be further verified using optical methods of measurements.

ii. Efforts are needed to define performance measures of VR gloves on the basis of vibration transmission, and preservation of grip strength and manual dexterity. For this purpose, method for measuring dexterity needs to be established.

iii. Thorough studies on different vibration isolation materials should be undertaken so as to identify palm- and fingers-regions materials for realizing glove designs with optimal integrated performance. This would also require developments in the methods for characterizing visco-elastic properties of materials.

iv. The vibration isolation performance of VR gloves is tool specific, hence it would be beneficial to conduct field measurements of vibration transmissibility of gloves with different hand power tools. This could not only help to categorize the gloves according to their isolation performance with each specific tool, but also contribute to methods for predicting tools-specific performance in a reliable manner.

v. It would be worthy to develop simulation models of the VR gloves, which could help predict their performance when coupled with biodynamic model of hand-arm system.

REFERENCES

[1] S. Hewitt, "Assessing the performance of anti-vibration gloves--a possible alternative to ISO 10819, 1996," The Annals of Occupational Hygiene, vol. 42, pp. 245-252, May, 1998.

[2] M. Griffin, H. Howarth, P. Pitts, S. Fischer, U. Kaulbars, P. Donati and P. Bereton, "Guide to good practice on hand-arm vibration. Non-binding guide to good practice with a view to implementation of Directive 2002/44/EC on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (vibrations)," 2006.

[3] A. DiDomenico and M. A. Nussbaum, "Estimation of forces exerted by the fingers using standardised surface electromyography from the forearm," Ergonomics, vol. 51, pp. 858-871, 2008.

[4] D. Reynolds, R. Basel, D. Wasserman and W. Taylor, "A study of hand vibration on chipping and grinding operators, part III: Power levels into the hands of operators of pneumatic tools used in chipping and grinding operations," Journal of Sound and Vibration, vol. 95, pp. 515-524, 1984.

[5] A. Brammer, "Relations between vibration exposure and the development of the vibration syndrome," Vibration Effects on the Hand and Arm in Industry.New York: Wiley, pp. 283-290, 1982.

[6] P. L. Pelmear and D. E. Wasserman, Hand-Arm Vibration: A Comprehensive Guide for Occupational Health Professionals. OEM press Beverly Farms, MA, 1998.

[7] P. A. Banister and F. V. Smith, "Vibration-induced white fingers and manipulative dexterity," British Journal of Industrial Medicine, vol. 29, pp. 264-267, Jul, 1972.

[8] M. Färkkilä, I. Pyykkö, O. Korhonen and J. Starck, "Vibration-induced decrease in the muscle force in lumberjacks," European Journal of Applied Physiology and Occupational Physiology, vol. 43, pp. 1-9, 1980.

[9] L. E. Necking, G. Lundborg, R. Lundström, L. Thornell and J. Fridén, "Hand muscle pathology after long-term vibration exposure," The Journal of Hand Surgery: British & European Volume, vol. 29, pp. 431-437, 2004.

[10] G. Gemne and H. Saraste, "Bone and Joint Pathology in Workers Using hand-held Vibrating Tools an Overview," Scandinavian Journal of Work, Environment & Health, vol. 13, pp. 290-300, 1987.

[11] M. Bovenzi, "Medical aspects of the hand-arm vibration syndrome," International Journal of Industrial Ergonomics, vol. 6, pp. 61-73, 1990.

[12] G. Moschioni, B. Saggin, M. Tarabini and M. Marrone, "Reduction of vibrations generated by an impact wrench," Canadian Acoustics, vol. 39, pp. 82-83, 2011.

[13] H. Lindell, "Redesign of hand-held impact machines to reduce hand-arm vibration," Canadian Acoustics, vol. 39, pp. 80-81, 2011.

[14] E. V. Golysheva, V. I. Babitsky and A. M. Veprik, "Vibration protection for an operator of a hand-held percussion machine," Journal of Sound and Vibration, vol. 274, pp. 351-367, 7/6, 2004.

[15] H. Lindell, V. Berbyuk, S. L. Gretarsson and M. Josefsson, "Hand-held impact machines with nonlinearly-tuned vibration absorber," Proceedings of the 13th International Conference on Hand-Arm Vibration, Beijing, China, 2015.

[16] D. Scaccabarozzi, B. Saggin and M. Tarabini, "Reduction of the vibration transmitted to the hand by the chisel of pneumatic chipping hammers," Proceedings of the 13th International Conference on Hand-Arm Vibration, Beijing, China, 2015.

[17] R. G. Dong, T. W. McDowell, D. E. Welcome, C. Warren, J. Z. Wu and S. Rakheja, "Analysis of anti-vibration gloves mechanism and evaluation methods," Journal of Sound and Vibration, vol. 321, pp. 435-453, 2009.

[18] D. E. Welcome, R. G. Dong, X. S. Xu, C. Warren and T. W. McDowell, "An evaluation of the proposed revision of the anti-vibration glove test method defined in," International Journal of Industrial Ergonomics, vol. 42, pp. 143-155, 1, 2012.

[19] S. Hewitt, R. G. Dong, D. E. Welcome and T. W. McDowell, "Anti-vibration gloves?" The Annals of Occupational Hygiene, vol. 59, pp. 127-141, Mar, 2015.

[20] D. E. Welcome, R. G. Dong, X. S. Xu, C. Warren and T. W. McDowell, "The effects of vibration-reducing gloves on finger vibration," International Journal of Industrial Ergonomics, vol. 44, pp. 45-59, 1, 2014.

[21] T. W. McDowell, D. E. Welcome, C. Warren, X. S. Xu and R. G. Dong, "The Effect of a Mechanical Arm System on Portable Grinder Vibration Emissions," The Annals of Occupational Hygiene, Nov 30, 2015.

[22] Y. Pan, C. Chen, C. Chang, J. Liu, H. Chen and S. Lu, "Mitigation of hand-arm vibration in workers on a pneumatic nail gun assembly line," Canadian Acoustics, vol. 39, pp. 84-85, 2011.

[23] D. Rempel and A. Barr, "A universal rig for supporting large hammer drills: Reduced injury risk and improved productivity," Safety Science, vol. 78, pp. 20-24, 10, 2015.

[24] ISO 10819, "Mechanical vibration and shock - method for the measurement and evaluation of the vibration transmissibility of gloves at the palm of the hand," Geneva, Switzerland, 2013.

[25] D. R. Peterson, T. Asaki, S. Kudernatsch, A. Brammer and M. G. Cherniack, "Incorporating a finger adapter into ISO 10819 assessments to measure the vibration transmissibility of gloves at the fingers," Proceedings of the 5th American Conference on Human Vibration, Guelph, Ontario, Canada, 2014.

[26] K. A. Md Rezali and M. J. Griffin, "Transmission of vibration through gloves: effects of material thickness," Ergonomics, pp. 1-12, 2015.

[27] B. Wimer, T. W. McDowell, X. S. Xu, D. E. Welcome, C. Warren and R. G. Dong, "Effects of gloves on the total grip strength applied to cylindrical handles," International Journal of Industrial Ergonomics, vol. 40, pp. 574-583, 2010.

[28] R. Gurram, "A study of vibration response characteristics of the human hand-arm system," Ph.D. Thesis, Concordia University, Montreal, Canada, 1993.

[29] ISO 5349-1, "Mechanical vibration - measurement and evaluation of human exposure to hand-transmitted vibration - part 1: General requirements. international organization for standardization," Geneva, Switzerland, 2001.

[30] W. Taylor, D. Wasserman, V. Behrens, D. Reynolds and S. Samueloff, "Effect of the air hammer on the hands of stonecutters. The limestone quarries of Bedford, Indiana, revisited," British Journal of Industrial Medicine, vol. 41, pp. 289-295, Aug, 1984.

[31] W. Taylor, T. Wilcox and D. Wasserman, "Health Hazard Evaluation Report No. HHE-80-189-870, Neenah Foundry Company, Neenah, Wisconsin," 1981.

[32] T. Matsumoto, N. Harada, S. Yamada and F. Kobayashi, "On vibration hazards of chipping-hammer operators in an iron foundry. Part 1. Results of the first investigation (author's transl)," Sangyo Igaku.Japanese Journal of Industrial Health, vol. 23, pp. 51-60, Jan, 1981.

[33] V. Behrens, W. Taylor, T. Wilcox, R. Miday, S. Spaeth and J. Burg, "Vibration syndrome in chipping and grinding workers." J.Occup.Med., vol. 26, pp. 765-788, 1984.

[34] T. Oliver, R. Pethybridge and K. Lumley, "Vibration white finger in dockyard workers," Arg Hig Rada Toksikol, vol. 30, pp. 683-693, 1979.

[35] J. N. AGATE, "An outbreak of cases of Raynaud's phenomenon of occupational origin," British Journal of Industrial Medicine, vol. 6, pp. 144-163, Jul, 1949.

[36] J. Starck, M. Farkkila, S. Aatola, I. Pyykko and O. Korhonen, "Vibration syndrome and vibration in pedestal grinding," British Journal of Industrial Medicine, vol. 40, pp. 426-433, Nov, 1983.

[37] W. Taylor and P. L. PELMEAR, Vibration White Finger in Industry. A Report, Comprising Edited Versions of Papers Submitted to the Department of Health and Social Security in December 1973. Academic Press Inc.(London) Ltd, 24/28 Oval Road, London NWI, 1975.

[38] D. S. Chatterjee, A. Petrie and W. Taylor, "Prevalence of vibration-induced white finger in fluorspar mines in Weardale," British Journal of Industrial Medicine, vol. 35, pp. 208-218, Aug, 1978.

[39] T. Matsumoto, S. Yamada and N. Harada, "Comparative Study of Vibration Hazards Among Operators of Vibrating Tools in Certain Industries," Arhiv Za Higijenu Rada I Toksikologiju/Archives of Industrial Hygiene and Toxicology, vol. 30, pp. 701-707, 1979.

[40] H. Iwata, "Effects of Rock Drills on Operators," Industrial Health, vol. 6, pp. 37-46, 1968.

[41] M. Bovenzi, L. Petronio and F. Di Marino, "Epidemiological survey of shipyard workers exposed to hand-arm vibration," International Archives of Occupational and Environmental Health, vol. 46, pp. 251-266, 1980.

[42] P. Pelmear, W. Taylor and J. Pearson, "Raynaud's phenomenon in pedestal grinders," The Vibration Syndrome, W.Taylor (Ed.).London: Academic Press Inc, 1974.

[43] D. D. Walker, B. Jones, S. Ogston, E. G. Tasker and A. J. Robinson, "A study of white finger in the gas industry," British Journal of Industrial Medicine, vol. 42, pp. 672-677, Oct, 1985.

[44] R. GERRY, Neuromuscular Effects of Vibrating Hand Tools on Grip Exertions, Tactility, Discomfort, and Fatigue, 1986.

[45] T. Cherian, S. Rakheja and R. B. Bhat, "An analytical investigation of an energy flow divider to attenuate hand-transmitted vibration," International Journal of Industrial Ergonomics, vol. 17, pp. 455-467, 6, 1996.

[46] D. Reynolds, D. Wasserman, R. Basel, W. Taylor, T. Doyle and W. Asburry, "Vibration acceleration measured on pneumatic tools used in chipping and grinding operations," Vibration Effects on the Hand and Arm in Industry, Wiley, New York, 1982.

[47] M. Futatsuka and T. Ueno, "Vibration exposure and vibration-induced white finger due to chain saw operation," Journal of Occupational and Environmental Medicine, vol. 27, pp. 257-264, 1985.

[48] P. Pelnar, G. Gibbs and B. Pathak, "A pilot investigation of the vibration syndrome in forestry workers of Eastern Canada," Vibration Effects on the Hand and Arm in Industry.New York: John Wiley & Sons, pp. 173-187, 1982.

[49] T. Hempstock and D. O'Connor, "The measurement of hand-arm vibration," Vibration White Finger in Industry.Academic Press, London, pp. 111-122, 1975.

[50] M. Farkkila, "Grip force in vibration disease," Scand J Work Environ Health, vol. 4, pp. 159-166, 1978.

[51] R. G. Dong, T. W. McDowell, D. E. Welcome, C. Warren and A. W. Schopper, "An evaluation of the standardized chipping hammer test specified in ISO 8662-2," The Annals of Occupational Hygiene, vol. 48, pp. 39-49, Jan, 2004.

[52] BRITISH STANDARDS INSTITUTION, BSI 6842, "GUIDE TO THE MEASURMENT AND EVALUATION OF HUMAN EXPOSURE TO VIBRATION TRANSMITTED TO THE HAND," London. England, 1987.

[53] AMERICAN NATIONAL STANDARDS INSTITUTE, ANSI S.3.34, "Guide for the measurement and evaluation of human exposure to vibration transmitted to the hand," 1986.

[54] AMERICAN CONFERENCE OF GOVERNMENT INDUSTRIAL HYGIENISTS, ACGIH-TLV, "Threshold limit values for hand-arm vibration," 2001.

[55] L. Burström, "Absorption of vibration energy in the human hand and arm," Ph.D. Thesis, Lulea University of Technology, Sweden, 1990.

[56] A. Brammer, "Exposure of the hand to vibration in industry." 1984.

[57] S. A. Adewusi, "Distributed biodynamic characteristics of the human hand-arm system coupled with vibrating handles and power tools," Ph.D. Thesis, Concordia University, Montreal, Canada, 2009.

[58] Y. H. Ko, O. L. Ean and Z. M. Ripin, "The design and development of suspended handles for reducing hand-arm vibration in petrol driven grass trimmer," International Journal of Industrial Ergonomics, vol. 41, pp. 459-470, 2011.

[59] S. S. Rao, Mechanical Vibrations. Upper Saddle River, N.J.: Prentice Hall, 2004.

[60] I. Dianat, C. M. Haslegrave and A. W. Stedmon, "Methodology for evaluating gloves in relation to the effects on hand performance capabilities: a literature review," Ergonomics, vol. 55, pp. 1429-1451, 2012.

[61] T. W. McDowell, R. G. Dong, D. E. Welcome, X. S. Xu and C. Warren, "Vibration-reducing gloves: transmissibility at the palm of the hand in three orthogonal directions," Ergonomics, vol. 56, pp. 1823-1840, 2013.

[62] G. Rens, P. Dubrulle and J. Malchaire, "Efficiency of conventional gloves against vibration," The Annals of Occupational Hygiene, vol. 31, pp. 249-254, 1987.

[63] V. K. Goel and K. Rim, "Role of gloves in reducing vibration: An analysis for pneumatic chipping hammer," American Industrial Hygiene Association Journal, vol. 48, pp. 9-14, 1987.

[64] S. Rakheja, R. Dong, D. Welcome and A. Schopper, "Estimation of tool-specific isolation performance of antivibration gloves," International Journal of Industrial Ergonomics, vol. 30, pp. 71-87, 2002.

[65] R. Dong, S. Rakheja, W. Smutz, A. Schopper, D. Welcome and J. Wu, "Effectiveness of a new method (TEAT) to assess vibration transmissibility of gloves," International Journal of Industrial Ergonomics, vol. 30, pp. 33-48, 2002.

[66] R. Dong, S. Rakheja, T. McDowell, D. Welcome, J. Wu, C. Warren, J. Barkley, B. Washington and A. Schopper, "A method for assessing the effectiveness of anti-vibration gloves using biodynamic responses of the hand–arm system," Journal of Sound and Vibration, vol. 282, pp. 1101-1118, 2005.

[67] G. S. Paddan and M. J. Griffin, "Individual variability in the transmission of vibration through gloves," Contemporary Ergonomics, pp. 320-325, 1997.

[68] M. J. Griffin, "Evaluating the effectiveness of gloves in reducing the hazards of hand-transmitted vibration," Occupational and Environmental Medicine, vol. 55, pp. 340-348, May, 1998.

[69] H. E. Laszlo and M. J. Griffin, "The transmission of vibration through gloves: effects of push force, vibration magnitude and inter-subject variability," Ergonomics, vol. 54, pp. 488-496, 2011.

[70] P. Boileau, J. Boutin, S. Rakheja and R. Dong, "Critical evaluation of a laboratory test procedure for measuring the vibration transmissibility of gloves," in Proceeding of the 37th UK Conference on Human Responses to Vibration, 2002, pp. 106-117.

[71] M. O'Boyle and M. Griffin, "Inter-subject variability in the measurement of the vibration transmissibility of gloves according to current standards," in 9th International Conference on Hand-Arm Vibration, 2001, pp. 8Nancy.

[72] ISO 10819, "Mechanical vibration and shock - method for the measurement and evaluation of the vibration transmissibility of gloves at the palm of the hand," Geneva, Switzerland, 1996.

[73] I. Pinto, N. Stacchint, M. Bovenzi, G. Paddan and M. Griffin, "Protection effectiveness of anti-vibration gloves: Field evaluation and laboratory performance assessment," in Proceedings of the 9th International Conference on Hand-Arm Vibration, 2001, pp. 387-396.

[74] T. W. McDowell, D. E. Welcome, C. Warren, X. S. Xu and R. G. Dong, "Assessment of hand-transmitted vibration exposure from motorized forks used for beach-cleaning operations," The Annals of Occupational Hygiene, vol. 57, pp. 43-53, Jan, 2013.

[75] R. G. Dong, T. W. McDowell, D. E. Welcome, W. P. Smutz, A. W. Schopper, C. Warren, J. Z. Wu and S. Rakheja, "On-the-hand measurement methods for assessing effectiveness of anti-vibration gloves," International Journal of Industrial Ergonomics, vol. 32, pp. 283-298, 10, 2003.

[76] Dong, McDowell, Welcome and Barkley, "Effects of Hand-Tool Coupling Conditions on the Isolation Effectiveness of Air Bladder Anti-Vibrations Gloves," Low Frequency Noise, Vibration and Active Control, vol. 23, pp. 231-248, 2004.

[77] B. A. Silverstein, L. J. Fine and T. J. Armstrong, "Occupational factors and carpal tunnel syndrome," American Journal of Industrial Medicine, vol. 11, pp. 343-358, 1987.

[78] R. G. Radwin, T. J. Armstrong and D. B. Chaffin, "Power hand tool vibration effects on grip exertions," Ergonomics, vol. 30, pp. 833-855, 1987.

[79] S. Riedel, "Consideration of grip and push forces for the assessment of vibration exposure," Central European Journal of Public Health, vol. 3 Suppl, pp. 139-141, 1995.

[80] M. Färkkiäla, S. Aatola, J. Starck, O. Korhonen and I. Pyykkö, "Hand-grip force in lumberjacks: two-year follow-up," International Archives of Occupational and Environmental Health, vol. 58, pp. 203-208, 1986.

[81] C. Chang and Y. Shih, "The effects of glove thickness and work load on female hand performance and fatigue during a infrequent high-intensity gripping task," Applied Ergonomics, vol. 38, pp. 317-324, 2007.

[82] P. Marcotte, S. Adewusi and S. Rakheja, "Development of a low-cost system to evaluate coupling forces on real power tool handles," Canadian Acoustics, vol. 39, pp. 36-37, 2011.

[83] D. C. Buhman, J. A. Cherry, L. Bronkema-Orr and R. Bishu, "Effects of glove, orientation, pressure, load, and handle on submaximal grasp force," International Journal of Industrial Ergonomics, vol. 25, pp. 247-256, 2000.

[84] G. Waddington, J. Diong and R. Adams, "Development of a hand dynamometer for the control of manually applied forces," Journal of Manipulative and Physiological Therapeutics, vol. 29, pp. 297-304, 2006.

[85] A. Amis, "Variation of finger forces in maximal isometric grasp tests on a range of cylinder diameters," Journal of Biomedical Engineering, vol. 9, pp. 313-320, 1987.

[86] W. W. Banks and G. S. Goehring, "The effects of degraded visual and tactile information on diver work performance," Human Factors, vol. 21, pp. 409-415, Aug, 1979.

[87] J. V. Bradley, "Effect of gloves on control operation time," Human Factors: The Journal of the Human Factors and Ergonomics Society, vol. 11, pp. 13-20, 1969.

[88] J. M. McGinnis, C. K. Bensel and J. M. Lockhart, Dexterity Afforded by CB Protective Gloves, 1973.

[89] R. Plummer, T. Stobbe, R. Ronk, W. Myers, H. Kim and M. Jaraiedi, "Manual dexterity evaluation of gloves used in handling hazardous materials," in Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 1985, pp. 819-823.

[90] C. K. Bensel, "The effects of various thicknesses of chemical protective gloves on manual dexterity," Ergonomics, vol. 36, pp. 687-696, 1993.

[91] A. Muralidhar, R. R. Bishu and M. S. Hallbeck, "The development and evaluation of an ergonomic glove," Applied Ergonomics, vol. 30, pp. 555-563, 12/1, 1999.

[92] I. Dianat, C. M. Haslegrave and A. W. Stedmon, "Short and longer duration effects of protective gloves on hand performance capabilities and subjective assessments in a screw-driving task," Ergonomics, vol. 53, pp. 1468-1483, 2010.

[93] C. Gauvin, C. Tellier, R. Daigle and T. Petitjean-Roget, "Évaluation de tests de dextérité appliqués aux gants de protection," Bibliothèque Et Archives Nationales, Études Et Recherches, IRRST, 2007.

[94] J. H. Dong, R. G. Dong, S. Rakheja, D. E. Welcome, T. W. McDowell and J. Z. Wu, "A method for analyzing absorbed power distribution in the hand and arm substructures when operating vibrating tools," Journal of Sound and Vibration, vol. 311, pp. 1286-1304, 2008.

[95] G. Gemne and W. Taylor, Hand-Arm Vibration and the Central Autonomic Nervous System. Multi-Science, 1983.

[96] E. Christ, "Anti-vibration gloves; Performance tests," Die Berufsgenossenschaft, 1982.

[97] M. Griffin, C. Macfarlane and C. Norman, "The transmission of vibration to the hand and the influence of gloves," Vibration Effects on the Hand and Arm in Industry, pp. 103-116, 1982.

[98] D. D. Reynolds and E. Wolf, "Evaluation of antivibration glove test protocols associated with the revision of ISO 10819," Industrial Health, vol. 43, pp. 556-565, 2005.

[99] R. G. Dong, D. E. Welcome, X. S. Xu, C. Warren, T. W. McDowell, J. Z. Wu and S. Rakheja, "Mechanical impedances distributed at the fingers and palm of the human hand

in three orthogonal directions," Journal of Sound and Vibration, vol. 331, pp. 1191-1206, 2/27, 2012.

[100] Y. Aldien, D. Welcome, S. Rakheja, R. Dong and P. Boileau, "Contact pressure distribution at hand–handle interface: role of hand forces and handle size," International Journal of Industrial Ergonomics, vol. 35, pp. 267-286, 2005.

[101] R. G. Dong, J. H. Dong, J. Z. Wu and S. Rakheja, "Modeling of biodynamic responses distributed at the fingers and the palm of the human hand–arm system," Journal of Biomechanics, vol. 40, pp. 2335-2340, 2007.

[102] M. Griffin, "Handbook of human vibration," Academic, London, 1990.

[103] G. Paddan and M. Griffin, "Measurement of glove and hand dynamics using knuckle vibration," in Proceedings of the 9th International Conference on Hand-Arm Vibration, Section, 2001, .

[104] R. G. Dong, D. E. Welcome, D. R. Peterson, X. S. Xu, T. W. McDowell, C. Warren, T. Asaki, S. Kudernatsch and A. Brammer, "Tool-specific performance of vibration-reducing gloves for attenuating palm-transmitted vibrations in three orthogonal directions," International Journal of Industrial Ergonomics, vol. 44, pp. 827-839, 11, 2014.

[105] EN 420 European Committee for Standardization, "General requirements for gloves," European Committee for Standardization, 1994.

[106] R. Gurram, S. Rakheja and G. Gouw, "A study of hand grip pressure distribution and EMG of finger flexor muscles under dynamic loads," Ergonomics, vol. 38, pp. 684-699, 1995.

[107] Y. Aldien, "A study of han-handle interactions and hand-arm biodynamic response to vibration," Ph.D. Thesis, Concordia University, Montreal, Canada, 2005.

[108] J. Rossi, E. Berton, L. Grélot, C. Barla and L. Vigouroux, "Characterisation of forces exerted by the entire hand during the power grip: effect of the handle diameter," Ergonomics, vol. 55, pp. 682-692, 2012.

[109] X. S. Xu, D. A. Riley, M. Persson, D. E. Welcome, K. Krajnak, J. Z. Wu, S. R. Govinda Raju and R. G. Dong, "Evaluation of anti-vibration effectiveness of glove materials using an animal model," Bio-Medical Materials and Engineering, vol. 21, pp. 193-211, 2011.

[110] P. L. Pelmear and D. E. Wasserman, "Hand-arm vibration," 1998.

[111] D. Reynolds, D. Weaver and T. Jetzer, "Application of a new technology to the design of effective anti-vibration gloves," Central European Journal of Public Health, vol. 4, pp. 140-144, May, 1996.

[112] K. Hamouda, P. Marcotte and S. Rakheja, "Performance evaluation of vibration reducing gloves at the fingers using finger adapter," Proceedings of the 13th International Conference on Hand-Arm Vibration, Beijing, China, 2015.

[113] R. G. Dong, D. E. Welcome, J. Z. Wu and T. W. McDowell, "Development of hand-arm system models for vibrating tool analysis and test rig construction," Noise Control Engineering Journal, vol. 56, pp. 35-44, 2008.

[114] R. G. Dong, D. E. Welcome, T. W. McDowell and J. Z. Wu, "Modeling of the biodynamic responses distributed at the fingers and palm of the hand in three orthogonal directions," Journal of Sound and Vibration, vol. 332, pp. 1125-1140, 2013.

[115] S. L. Fleming, C. W. Jansen and S. M. Hasson, "Effect of work glove and type of muscle action on grip fatigue," Ergonomics, vol. 40, pp. 601-612, 1997.

[116] J. M. Cabeças and R. J. Milho, "The efforts in the forearm during the use of anti-vibration gloves in simulated work tasks," International Journal of Industrial Ergonomics, vol. 41, pp. 289-297, 5, 2011.

[117] B. P. Bernard and V. Putz-Anderson, Musculoskeletal Disorders and Workplace Factors: A Critical Review of Epidemiologic Evidence for Work-Related Musculoskeletal Disorders of the Neck, Upper Extremity, and Low Back. US Department of Health and

Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health Cincinnati, OH, USA, 1997.

[118] M. Jung and M. S. Hallbeck, "Quantification of the effects of instruction type, verbal encouragement, and visual feedback on static and peak handgrip strength," International Journal of Industrial Ergonomics, vol. 34, pp. 367-374, 11, 2004.

[119] R. G. Dong, J. Z. Wu, D. E. Welcome and T. W. McDowell, "A new approach to characterize grip force applied to a cylindrical handle," Medical Engineering & Physics, vol. 30, pp. 20-33, 2008.

[120] R. G. Dong, J. Z. Wu, T. W. McDowell, D. E. Welcome and A. W. Schopper, "Distribution of mechanical impedance at the fingers and the palm of the human hand," Journal of Biomechanics, vol. 38, pp. 1165-1175, 5, 2005.

[121] E. Concettoni and M. Griffin, "The apparent mass and mechanical impedance of the hand and the transmission of vibration to the fingers, hand, and arm," Journal of Sound and Vibration, vol. 325, pp. 664-678, 8/21, 2009.