HHS Public Access
Author manuscript
Ergonomics. Author manuscript; available in PMC 2015 October 05.

Published in final edited form as:
Ergonomics. 2013 ; 56(12): 1823–1840. doi:10.1080/00140139.2013.838642.

Vibration-reducing gloves: transmissibility at the palm of the hand in three orthogonal directions

Thomas W. McDowell*, **Ren G. Dong**, **Daniel E. Welcome**, **Xueyan S. Xu**, and **Christopher Warren**

Health Effects Laboratory Division (HELD), National Institute for Occupational Safety and Health (NIOSH), Morgantown, WV, USA

Abstract

Vibration-reducing (VR) gloves are commonly used as a means to help control exposures to hand-transmitted vibrations generated by powered hand tools. The objective of this study was to characterise the vibration transmissibility spectra and frequency-weighted vibration transmissibility of VR gloves at the palm of the hand in three orthogonal directions. Seven adult males participated in the evaluation of seven glove models using a three-dimensional hand–arm vibration test system. Three levels of hand coupling force were applied in the experiment. This study found that, in general, VR gloves are most effective at reducing vibrations transmitted to the palm along the forearm direction. Gloves that are found to be superior at reducing vibrations in the forearm direction may not be more effective in the other directions when compared with other VR gloves. This casts doubts on the validity of the standardised glove screening test.

Practitioner Summary—This study used human subjects to measure three-dimensional vibration transmissibility of vibration-reducing gloves at the palm and identified their vibration attenuation characteristics. This study found the gloves to be most effective at reducing vibrations along the forearm direction. These gloves did not effectively attenuate vibration along the handle axial direction.

Keywords

hand–arm vibration; acceleration exposures; personal protective equipment; musculoskeletal disorders; upper limb disorders

1. Introduction

Work gloves serve many purposes including keeping hands warm, dry and clean, reducing exposures to chemical and biological hazards, preventing cuts and abrasions and reducing hand contact pressures and stresses. As an additional function, vibration-reducing (VR)

*Corresponding author. tmcdowell@cdc.gov.

Disclaimers

The content of this publication does not necessarily reflect the views or policies of the National Institute for Occupational Safety and Health (NIOSH), nor does mention of trade names, commercial products or organisations imply endorsement by the U.S. Government.

Author Manuscript

Author Manuscript

Author Manuscript

gloves are designed to attenuate hand-transmitted vibrations generated by machines or powered hand tools (Goel and Rim 1987; Rens, Dubrulle, and Malchaire 1987; Reynolds and Jetzer 1998). While the effectiveness of VR gloves may vary, anti-vibration (AV) gloves are a subclass of VR gloves that meet the criteria defined in the international standardised AV glove test (ISO 1996). As it stands, none of the available VR gloves can fully meet all the conditions prescribed by the current version of the standard. Because of this, along with several other reasons (see Griffin 1998; Hewitt 1998; Dong, McDowell, et al. 2002), a revised version of the AV glove testing standard has been proposed (ISO 2012). Some currently marketed VR gloves that fail to meet all the criteria of the 1996 version of the standard (ISO 1996) may be classified as AV gloves under the revised standard (Dong et al. 2011; Welcome et al., "Evaluation of the Proposed Revision," 2012).

The use of VR gloves has increased in recent years, but the efficacy of these gloves remains a controversial issue. A few studies have reported that some VR gloves may be beneficial (Brown 1990; Jetzer, Haydon, and Reynolds 2003; Mahbub et al. 2007); other studies suggest that VR gloves do not effectively attenuate hand-transmitted vibration, especially vibration transmitted to the fingers (Dong et al. 2009; Welcome et al., "Effectiveness of Anti-Vibration Gloves," 2012). Although VR gloves may keep hands warmer and reduce more contact pressure than ordinary work gloves, VR gloves generally reduce grip strength and finger dexterity more than typical gloves (Wimer et al. 2010). As a result, many VR glove models are uncomfortable and may result in increased grip efforts and hand fatigue. Increased grip efforts along with repetitive motions have been associated with the occurrence of upper extremity musculoskeletal disorders (NIOSH 1997). It could, therefore, be concluded that in some cases, VR gloves could be implicated in the development of such disorders. Probably for these reasons, VR gloves have not been officially endorsed as personal protective equipment for preventing hand–arm vibration syndrome.

Current evidence does not support the universal application of VR gloves, but these gloves may have some value in the operations of certain tools or machines. Their usefulness depends primarily on the specific tool, the amount of hand force and finger dexterity required in the work task, the hand and arm posture, and the biodynamic properties of the individual worker's hand–arm system. However, the current knowledge base is not sufficient to reliably evaluate the balance between the benefits and disadvantages of VR glove use. An important piece of information required to help resolve this puzzle is a reliable measure of the actual effectiveness of VR gloves for reducing hand-transmitted vibrations. Furthermore, the vibration attenuation needs to be evaluated and quantified at multiple locations on the hand–glove interface and in each vibration direction.

For many practical reasons, the standardised method for evaluating VR gloves focuses on the vibration transmissibility of the glove at the palm of the hand along the forearm direction (ISO 1996). Consequently, the vast majority of the reported glove studies investigated vibration transmissibility at the same location and in the same direction (Hewitt 1998; Dong, McDowell, et al. 2002; Dong, Rakheja, et al. 2002; Rakheja et al. 2002; Dong et al., "Effects of Hand-Tool Coupling Conditions," 2004; Dong et al. 2005, 2009, 2011; Laszlo and Griffin 2011; Welcome et al., "Evaluation of the Proposed Revision," 2012). Based on the fundamental mechanisms of glove vibration attenuation (Dong et al. 2009), it has been hypothesised that this standardised evaluation method generally overestimates the vibration attenuation effectiveness of gloves because the maximum effective mass of the hand–arm system is distributed at the palm of the hand in the forearm direction (Dong et al. 2012); a certified AV glove could actually provide less overall vibration exposure protection than the measured transmissibility data would indicate. This hypothesis has not been sufficiently tested. A recent study reported the three-dimensional (3D) vibration transmissibility of a VR glove, but the investigator raised some concerns on the validity of the experimental data (Hewitt 2010). A few studies also made predictions of vibration transmissibility of gloves when used with different tools (Pinto et al. 2001; Dong et al. 2003; Hewitt 2010). However, direction-specific transmissibility could not be clearly identified, probably because it is very difficult to precisely align the coordinates of the vibration sensors when conducting tool vibration measurements, and because there are usually large variations in tool vibration data. There are little solid data available to reliably determine glove vibration transmissibility distributions in directions other than the forearm direction.

While not directly stated in the AV glove test standard or its draft revision (ISO 1996, 2012), the major glove evaluation criteria of these standards seem to be based on the assumption that if a glove can provide superior vibration reduction in the forearm direction, it will also be more effective at reducing vibration in any other direction. The validity of this assumption has not been seriously scrutinised. The examination of this assumption requires the reliable measurement of glove vibration transmissibility in at least the three orthogonal directions of the hand.

We have hypothesised that not all VR gloves can attenuate palm-transmitted vibrations equally in all three orthogonal directions; certain glove designs are better suited for reducing vibrations in the forearm direction than in the other two orthogonal directions. To test this hypothesis, the specific aims of this study were to measure the vibration transmissibility of several typical VR gloves at the palm of the hand in three orthogonal directions and to identify and understand their vibration attenuation characteristics.

2. Methods

2.1 Human subjects and gloves

The study protocol was reviewed and approved by the NIOSH Human Subjects Review Board. Seven healthy male adults participated in the experiment. Subject anthropometry data are presented in Table 1. Their listed hand sizes are based on the EN 420 protective glove standard (CEN 2003). Four of these human subjects also participated in our earlier reported single-axis (1D) glove testing experiments (Dong et al. 2011; Welcome et al., “Effectiveness of Anti-Vibration Gloves,” 2012).

In our two recent studies, 15 VR glove models were tested on a 1D vibration test system (Dong et al. 2011; Welcome et al., “Effectiveness of Anti-Vibration Gloves,” 2012). These glove models are likely to be sufficiently representative of the VR gloves available on the current market. Based on the identified characteristics of these gloves, six representative models were selected and used in this study. For comparison, an ordinary synthetic leather work glove was also evaluated in this study. The seven gloves are shown in Figure 1. The major vibration attenuation materials for each glove are listed in Tables 2 and 3.

2.2 Instrumentation

The experiment was carried out on a 3D vibration test system (MB Dynamics, 3D Hand–Arm Vibration Test System; Dong, Welcome, and McCormick 2006), as shown in Figure 2. The three orthogonal directions are also defined in the figure: the *z*-axis is along the forearm, the *y*-axis is along the centreline of the instrumented handle in the vertical direction and the *x*-axis is in the horizontal plane perpendicular to the *y*–*z* plane. Figure 3 shows a subject with a gloved hand gripping the test system's instrumented handle. The instrumented handle was equipped with a tri-axial accelerometer (ENDEVCO 65-100) and a pair of force sensors (Kistler 9017B and 9018B; Dong, Welcome, and McCormick 2012); this handle was used to measure the 3D accelerations and the applied grip force. The handle–fixture assembly exhibits a major natural frequency of 650 Hz (Dong et al. 2006). The test subject stood on a force plate (Kistler 9286AA) to measure the push force applied to the handle. The applied grip and push forces were displayed on separate virtual dial gauges on a computer monitor positioned in front of the subject.

A palm adapter equipped with a triaxial accelerometer (ENDEVCO, M35) was used to measure the 3D vibrations transmitted to the palm through each glove. The adapter was fabricated from magnesium based on the design recommended in the standard (ISO 1996), which features light weight (13 g) and sufficient stiffness. This adapter has been extensively used in several previous studies, and no resonance of the adapter was observed in the frequency range (10–1600 Hz) of concern in those studies (Dong et al., "Effects of Hand-Tool Coupling Conditions," 2004; Dong et al. 2009; Welcome et al., "Evaluation of the Proposed Revision," 2012). To evaluate the reliability of the palm adapter in 3D measurements, the vibration transmissibility of the bare adapter was examined by positioning it on the handle using rubber bands at several different orientations from −30° to 30° as shown in Figure 4.

A data acquisition and analysis system (B&K Type 3032A I/O Module, PULSE v11.0) was used to record and process the six acceleration signals from the handle and palm adapter accelerometers. Vibration transmissibility functions were expressed in the frequency domain corresponding to the third-octave bands with centre frequencies from 16 to 500 Hz.

2.3 Experimental conditions and variables

Due to the above-mentioned resonance constraint, the effective frequency range of the 3D shaker system used in this study is limited to a span of 16–500 Hz. The multiaxial vibration controller of the 3D test system was programmed to generate the same broadband random vibration from 16 to 500 Hz in each vibration direction. The overall root-mean-square value of the unweighted acceleration in each direction was 19.6 m/s^2. The frequency range used in these experiments is quite sufficient for the purposes of this study, and can be justified for several reasons. First, the dominant vibrations of the vast majority of powered hand tools fall within this frequency range (Griffin 1997; Pitts et al. 2011). Second, the physical properties of VR gloves greatly limit their ability to attenuate vibrations below 16 Hz (Dong et al. 2009); the standardised AV glove evaluation does not call for glove assessments below 16 Hz (ISO 1996). Third, the frequency weighting at frequencies above 500 Hz is less than 3% of the peak weighting value (0.985; ISO 2001); vibration attenuation provided by gloves in this high-frequency range has no substantial influence on frequency-weighted acceleration which is required for assessing the risk of vibration exposures in the operations of powered hand tools.

Figures 2 and 3 depict the hand and arm postures used in this study. These postures were based on those required in the standardised glove test (ISO 1996). Each subject applied a power grip on the instrumented handle with a neutral wrist posture. The forearm was approximately parallel to the floor and aligned with the *z*-axis. The elbow angle was controlled between 90° and 120°, and shoulder abduction was limited between 0° and 30°. Such postures are likely to be most frequently used in the operations of powered hand tools (ISO 1996). Considering the standard glove test requires 30 N grip + 50 N push, this study used three combinations of grip and push forces (15 N grip + 30 N push, 30 N grip + 50 N push and 45 N grip + 70 N push) to evaluate the effect of hand forces on glove transmissibility.

2.4 Testing procedures

Before and after each human subject test, a bare adapter test was carried out by positioning the palm adapter on the handle at 0° as depicted in Figure 4. Such a test is required to establish the reference baseline for normalising the experimental data in the revised AV glove testing standard (ISO 2012).

Theoretically, during VR glove tests, the adapter should be positioned at the same orientation as that in the bare adapter test to measure the transmissibility functions of each glove in the three directions. In reality, adapter misalignments are common. To minimise adapter misalignment, a slit was cut in the thenar region of each glove to enable the palm adapter to be viewed and adjusted inside the glove as described by Hewitt (1998); one of the modified gloves is shown in Figure 5(a). This alignment control procedure is recommended in the revised standard (ISO 2012). To further ensure proper adapter orientation, alignment marks were scribed on the adapter and the handle to ease positioning.

Prior to testing, the test procedure was explained to each subject, who then read and signed a consent form. Each subject was asked to position the adapter on his right palm at the location shown in Figure 5(b) before donning one of the seven gloves. The position of the adapter could change during donning. Using the slit on each glove, each subject was usually able to quickly adjust the adapter to the required position. Then, the subject was asked to stand on the force plate in front of the shaker. The platform height was adjusted to enable the subject to keep his forearm at the same level as the handle while maintaining the proper elbow angle, as shown in Figures 2 and 3. With this hand–arm posture, the subject was asked to apply the required grip and push forces to the instrumented handle. If the subject felt that the adapter was not at the correct position or the hand felt uncomfortable, he could adjust the adapter position again. When the hand forces were stable at the treatment-specific levels, the investigator recorded the test data for a period of 20 s. The subject was then advised to relax for more than 1 min before performing the next trial. Practice of this process was done until the subject could meet the test requirements. Two trials were carried out for each glove and force treatment; there were 42 trials for each participant (7 gloves × 3 force levels × 2 replications). The glove and force level combinations were randomised among the subjects.

As demonstrated in the results section, the directly measured vibration transmissibility is very sensitive to the actual position and orientation of the adapter in these 3D assessments. Adapter alignment was, therefore, tightly controlled during each trial by monitoring the low-frequency (<25 Hz) vibration transmissibility. Because the vibration transmissibility of any glove is close to unity in the low-frequency range, trials were discarded and repeated whenever the transmissibility data suggested unacceptable adapter misalignment; when the low-frequency data indicated a misalignment of more than 15° from the baseline established in the bare adapter tests, the adapter position inside the glove was re-adjusted, and a replacement trial was carried out.

2.5 Determining vibration transmissibility spectra

The transmissibility, $T_{\text{Raw\_}i}$, at each frequency in each direction was initially computed from

$$T_{\text{Raw\_}i} = \frac{A_{ai\_\text{Glove}}}{A_{hi\_\text{Glove}}}, \quad i = x, y, z, \quad (1)$$

where A_{ai_Glove} and A_{hi_Glove} are the accelerations measured on the palm adapter and on the handle in the ith direction, respectively, during the gloved-hand test.

The total vibration transmissibility, TT_{Raw}, at each frequency was also initially computed from

$$TT_{\text{Raw}} = \frac{\sqrt{A^2_{ax\_\text{Glove}} + A^2_{ay\_\text{Glove}} + A^2_{az\_\text{Glove}}}}{\sqrt{A^2_{hx\_\text{Glove}} + A^2_{hy\_\text{Glove}} + A^2_{hz\_\text{Glove}}}}. \quad (2)$$

Even if each accelerometer is carefully calibrated before being installed on the handle or adapter, the adapter acceleration measurements in each direction may not agree with the handle-mounted accelerometer, even if it was possible to perfectly align the coordinates of the two accelerometers. This is because both the adapter and the handle were observed to exhibit some non-unity transmissibility; these discrepancies also vary with frequency. It is useful to account for such systematic/instrumentation-induced non-unity transmissibility in VR glove assessments by applying a frequency-domain correction, similar to the correction required in the revised standardised glove test (ISO 2012). This correction, $C1$, is the first of two corrections of the directly measured glove transmissibility function, and it is processed using the following formula:

$$(T_i)_{C1} = T_{\text{Raw\_}i} / T_{\text{Adapter\_}i}, \quad i = x, y, z, \text{ and TOTAL}, \quad (3)$$

where T_{Adapter} is the average adapter transmissibility spectrum measured in the bare adapter test when it is positioned at 0° on the handle.

As reflected in the initial results, this correction alone is not sufficient to reliably characterise the actual directional vibration transmissibility of a glove. This is partially because it is impossible, with the experimental set-up used, to perfectly align the adapter accelerometer with the handle accelerometer. More importantly, because the directional transmissibility measurements are very sensitive to adapter position and orientation on the 3D hand–arm vibration test system, it is difficult to precisely monitor and control the adapter orientation inside a glove. Fortunately, the total vibration transmissibility of a glove or the adapter is not as sensitive to adapter orientation variations, as demonstrated in Figure 6. Furthermore, the vibration transmissibility of these gloves below a certain frequency range in each direction is theoretically close to unity, as confirmed by reported experimental data (Dong, Rakheja, et al. 2002; Dong et al. 2005; Hewitt 2010). If the transmissibility in any direction (T_i) is close to unity at low frequencies, it must also be close to the total vibration transmissibility (TT) at such frequencies. As a reasonable approximation, this study assumed that the glove vibration transmissibility in each direction at 20 Hz is the same as the total transmissibility at this frequency ($TT(20\text{ Hz})_{C1}$). Thus, the second correction, $C2$, utilised this total transmissibility value as a reference to correct the directional vibration transmissibility, which is expressed as follows:

$$(T_i)_{C2}=(T_i)_{C1}\frac{[TT(20\,\text{Hz})]_{C1}}{[T_i(20\,\text{Hz})]_{C1}}, \quad i=x, y \text{ and } z. \quad (4)$$

As described above, the vibration excitation in each direction can be considered to be theoretically identical ($A_{hx\_\text{Glove}} = A_{hy\_\text{Glove}} = A_{hz\_\text{Glove}}$). Based on that premise, Equation (2) can be expressed as follows:

$$TT_{\text{Raw}}=\frac{\sqrt{(T_x^2)_{\text{Raw}}+(T_y^2)_{\text{Raw}}+(T_z^2)_{\text{Raw}}}}{\sqrt{3}}. \quad (5)$$

In reality, there are always some differences among the vibrations in the three directions in these experiments. This does not affect the practical application of this equation. As observed in previous studies, small variations in the vibration do not significantly affect glove transmissibility (Rakheja et al. 2002; Welcome et al., "Evaluation of the Proposed Revision," 2012). Because the observed variations among the 3D vibrations in this study were small, the total transmissibility can be alternatively calculated using Equation (5) if the transmissibility function in each direction is directly measured or available. According to this principle, the total transmissibility with the application of the second correction can be calculated from the following formula:

$$(TT)_{C2}=\frac{\sqrt{(T_x^2)_{C2}+(T_y^2)_{C2}+(T_z^2)_{C2}}}{\sqrt{3}}. \quad (6)$$

Theoretically, the second correction should not significantly change the total vibration transmissibility. This was verified by examining the similarity between the total transmissibility values from the first correction, $(TT)_{C1}$, and the further corrected total transmissibility, $(TT)_{C2}$.

2.6 Calculations of frequency-weighted vibration transmissibility values

The standardised AV glove testing method requires that the gloves be assessed in terms of their frequency-weighted acceleration transmissibility values in two frequency ranges: the middle-frequency range (31.5–200 Hz) and the high-frequency range (200–1250 Hz). This evaluation concept was adopted in this study. The middle-frequency range was applied in this study as specified, but the high-frequency assessment was restricted to a range of 200–500 Hz due to limitations of the 3D hand–arm vibration test system.

The frequency-weighted total vibration transmissibility value was calculated using Equations (2) and (3) by replacing the unweighted accelerations at each frequency with frequency-weighted accelerations. The fully corrected transmissibility spectra from Equation (4) were used to calculate the directional frequency-weighted transmissibility values using the following formula:

$$(T_i)_w = \frac{\sqrt{\sum_{k=M}^{N}[w_h(\omega_k)\cdot A_{hi}(\omega_k)\cdot T_i(\omega_k)]^2}}{\sqrt{\sum_{k=M}^{N}[w_h(\omega_k)\cdot A_{hi}(\omega_k)]^2}}, \quad i = x, y \text{ and } z, \quad (7)$$

where w_h is the weighting factor defined in ISO (2001); M and N represent the starting and ending values, respectively, of the frequency range applied in the assessment and $(T_i)_w$ is the fully corrected, frequency-weighted transmissibility spectrum in a specific direction.

A general linear model analysis of variance (ANOVA) was conducted for vibration transmissibility measured at the palm for the six VR gloves. (Because the ordinary work glove performed much differently than the VR gloves, to make the statistical analysis more conservative, its data were excluded from these analyses.) The statistical model assessed the influence of two fixed factors: vibration direction (*x*, *y* and *z*) and hand force level (low, middle and high). Tukey HSD post hoc tests were also executed for both factors. The ANOVA and Tukey tests were carried out using the SPSS software (IBM SPSS Statistics, Version 19). Factors were considered to be statistically significant at the $p < 0.05$ level.

3. Results

3.1 Demonstrations of the adapter transmissibility correction methods

Figure 6 shows how the bare adapter vibration transmissibility spectra change as the adapter is oriented at different positions on the handle between −30° and +30° (refer to Figure 4). The first correction (*C*1, instrumentation frequency response correction) expressed in Equation (3) was applied to evaluate these spectra. As expected, the total vibration transmissibility spectra (*TT*) and that in the *y* direction (T_y) remained very close to unity, with a maximum error of less than 3% in the measured frequency range when the adapter alignment was within the range of 0 ± 15° The transmissibility spectra in the *x* and *z* directions (T_x and T_z) also suggest that the first correction effectively levels the transmissibility spectrum throughout the entire frequency range of concern in this study. On the other hand, the magnitudes of the transmissibility in these two directions were very sensitive to adapter orientation. Even if the adapter was visually positioned at 0°, near unity transmissibility (1.00 ± 0.03) could not be achieved in many trials due to imperfect accelerometer axis alignments. Obviously, the off-unity shift does not follow the cosine relationship observed with a single-axis vibration test system (Dong, Rakheja, et al. 2002).

The adapter vibration transmissibility functions depicted in Figure 6 were further corrected by applying the second correction, *C*2, as expressed in Equation (4). The results are shown in Figure 7. These results suggest that the maximum error can be controlled to within ±3% if the orientation of the adapter can be controlled to within ±15°. This adapter orientation control in the glove test was achieved by rejecting and replacing trials when low-frequency (<25 Hz) transmissibility values in the *x* and *z* directions fell outside of the range of 0.70–1.20, which indicates a misalignment of greater than ±15°, as determined from the results shown in Figure 6.

A coherence analysis of the triaxial vibrations was carried out using the vibration data measured in our previous studies on many powered hand tools such as grinders, sanders, chipping hammers, jack hammers, riveting hammers, impact wrenches and vibrating forks (Dong et al., "Evaluation of the Standardized Chipping Hammer Test," 2004; McDowell et al. 2008, 2009, 2012, 2013). The analysis found that the coherence values at the dominant vibration frequencies of these tools generally fall in the range of 0.5–0.9. An experiment was conducted to explore the effect of vibration coherence in this range on the vibration transmissibility measurements. The results confirmed that coherence is one of the factors influencing the transmissibility measurements, but the transmissibility curve was only marginally offset when the coherence was controlled within this range. Moreover, the application of the second correction, *C*2, appeared to be effective at rectifying coherence-induced shifts.

3.2 Basic characteristics of glove transmissibility spectra

Figure 8 shows the *x*, *y*, *z* and total vibration transmissibility spectra of the seven gloves measured under 30 N grip and 50 N push. As dictated by Equation (5), the total vibration transmissibility spectrum (*TT*, solid curve) for each glove represents the average of the *x*, *y* and *z* direction spectra. Both corrections, *C*1 and *C*2, have been applied to these data.

3.2.1 Vibration frequency and direction—As expected, the ordinary work glove (Glove D) exhibited near-unity vibration transmissibility in a large frequency range, and its transmissibility spectra in all three directions were similar. Specifically, this glove exhibited a slight reduction (<8%) in the palm-transmitted vibrations in the middle-frequency range (31.5–200 Hz), but there was marginal vibration amplification (>10%) at frequencies above 400 Hz.

Vibration direction had a significant influence on VR glove vibration transmissibility ($F_{2,747}$ = 441.5, $p < 0.001$). Consistent with the hypothesis of this study, the VR gloves generally attenuated significantly more vibration in the forearm (*z*) direction than in the *x* or *y* direction ($p < 0.001$). The transmissibility of the air gloves (Gloves B, C, E and G) in the *z* direction was generally lower than that in the other two directions at most frequencies. This also generally held true for the transmissibility of Gloves A and F at frequencies below 100 Hz. At higher frequencies, however, these two gloves generally attenuated more vibration in the *x* direction than in the *y* and *z* directions.

The first peaks in the transmissibility spectra in all three directions on all tested gloves occurred within a fairly narrow frequency range (20–31.5 Hz). At or below the peak frequencies, five of the six VR gloves marginally amplified (<10%) the vibration transmitted to the palm; Glove A exhibited considerably more amplification in the *x* direction.

The vibration transmissibility for the VR gloves in the *y* direction was significantly higher than that for the other two directions ($p < 0.001$). The VR gloves only slightly reduced vibrations in the *y* direction at certain frequencies between 31.5 and 200 Hz. At higher frequencies, the air gloves generally amplified the *y*-direction vibration with a peak transmissibility of more than 1.4 at the maximum frequency (500 Hz) examined in this study. The transmissibility spectra of Gloves A and F also show the *y*-direction peaks in the range of 250–400 Hz, but these two gloves show the potential for the *y*-direction vibration reduction at frequencies above 400 Hz, especially Glove A.

3.2.2 Hand force level effects—Hand force level was found to be a significant factor influencing vibration transmissibility ($F_{2,747} = 49.8$, $p < 0.001$). The interaction between hand force level and vibration direction was also found to be significant ($F_{4,747} = 22.0$, $p < 0.001$); the *z*-direction vibration was affected more by force level than the other two directions. The effects of hand force level on glove vibration transmissibility spectra in the *z*-direction are demonstrated in Figure 9. Hand force level did not alter the basic trends of the spectra, but marginally changed the transmissibility magnitudes at some frequencies. Specifically, increasing the hand force level generally increased vibration transmissibility at the low-/middle-frequency range (< 50 Hz) but generally reduced the transmissibility in the high-/middle-frequency range (50–200 Hz). At higher frequencies, reducing the hand force generally reduced vibration transmissibility. As also demonstrated in Figure 9, the force effects were nonlinear. For example, the effects of increasing the hand force from the lowest level (15 N grip, 30 N push) to the middle level (30 N grip, 50 N push) were obvious at many frequencies on the vibration transmissibility spectra for Gloves A, B and F, but increasing the force to the highest level (45 N grip, 70 N push) did not obviously change the transmissibility spectra. While not shown, the basic effects of hand force level on the vibration transmissibility spectra in the *x* and *y* directions were similar, but the force level effects were generally less apparent than those shown in Figure 9 for the *z* direction. As a result, the effects of hand force level on the total vibration transmissibility were also modest.

3.2.3 Comparing gloves—As shown in Figure 10, the palm-transmitted vibration attenuation in the *z* direction varied somewhat from glove to glove. Glove F was generally the least effective among the VR gloves; Gloves E and G were generally the most effective. There were some apparent interactions between glove and hand force level. For example, the effectiveness of Glove A was comparable with that of Gloves E and G at the lowest hand force level but not at the other two force levels. It is also interesting that Glove A reduced more vibrations in the *x* and *y* directions in the high-frequency range, as shown in Figure 8.

Due to greater vibration transmissibility differences among the gloves in the *x* and *y* directions, the features of the total vibration transmissibility spectra of the six VR gloves exhibited some differences from those of the transmissibility spectra in the *z* direction, as can be observed in Figure 8. Glove A generally exhibited the highest transmissibility in the low- and middle-frequency ranges, but on the other hand, this glove was the most effective for reducing the total vibration at frequencies above 315 Hz. Glove F was the least effective glove in the *z* direction, but it was fairly comparable with the other VR gloves at attenuating high-frequency total vibrations; in fact, Glove F was the second most effective glove for reducing palm-transmitted total vibration in this upper frequency range.

3.3 Frequency-weighted vibration transmissibility values

Table 2 lists the frequency-weighted vibration transmissibility values of the seven gloves in the middle-frequency range (31.5–200 Hz) under the three levels of hand force. Consistent with the hypothesis, all the gloves, including the ordinary work glove, produced frequency-weighted transmissibility values in the forearm direction (T_z) which were generally lower than those in the other two directions under each force level. Reducing the hand force generally decreased the frequency-weighted transmissibility value. Overall, Glove E was the most effective at attenuating frequency-weighted vibration in the middle-frequency range.

Table 3 lists the frequency-weighted vibration transmissibility values in the high-frequency range (200–500 Hz). For the air gloves (Gloves B, C, E and G), the frequency-weighted transmissibility values in the forearm direction (T_z) were generally lower than in the other two directions at each force level. However, this did not hold true for the other gloves (Gloves A, D and F). The frequency-weighted transmissibility values for each of the gloves were generally the highest along the handle axis (T_y). All of the frequency-weighted transmissibility averages in the *y* direction were greater than 1.0, which indicates that all of the tested gloves amplified the palm-transmitted weighted vibration in this direction in the high-frequency range. In general, frequency-weighted vibration transmissibility in the *x* and *y* directions was not very sensitive to hand force level. In the *z* direction, five of the six tested VR gloves were most effective at the lowest hand force level. Overall, Glove A was the most effective at reducing frequency-weighted vibration in the high-frequency range.

4. Discussion

The results of this study can be used to help understand the basic characteristics of vibration transmissibility at the palm of the hand in three orthogonal directions. The results can also be used to approximate the relative effectiveness of VR gloves for attenuating palm-transmitted 3D vibration.

4.1 Mechanisms of direction, glove and hand force level effects

The major phenomena observed in this study can be explained using the basic vibration isolation mechanisms of VR gloves as described by Dong et al. (2009): the vibration transmissibility or attenuation effectiveness of a glove depends on both the dynamic properties of the glove and the driving-point biodynamic properties of the hand–arm system.

The effects of the glove dynamic properties between 16 and 500 Hz are clearly reflected by the basic trends of the transmissibility functions shown in Figure 8. In terms of their similarities, the tested gloves can be broadly classified into three categories: (i) Glove D; (ii) Gloves B, C, E and G and (iii) Gloves A and F. These three categories are generally correlated with the major vibration attenuation materials of these gloves listed in Table 2. Specifically, Glove D is made with ordinary synthetic leather, which must have the highest contact stiffness among the gloves. As a result, its transmissibility in each direction is close to unity in a large frequency range, as shown in Figure 8. The results also suggest that the ordinary work glove can slightly reduce the vibration transmitted to the palm of the hand when used with the majority of powered hand tools. In the second category, the major vibration attenuation structures are either air bladders or cellar air bubbles, which should have similar dynamic properties. The major vibration attenuation materials in the third category are either a viscoelastic gel (Glove A) or dipped neoprene (Glove F). The surprising similarities in the patterns of their transmissibility functions in the three directions suggest that their dynamic properties must be similar.

Gloves are usually subjected to shear-only deformation along the *y* direction or handle axial direction shown in Figure 2; they are, however, subjected to combined shear and compression deformations in the *x* and *z* directions. It is common knowledge that these vibration attenuation materials usually exhibit greater stiffness in the compression direction; the gloves should display greater stiffness in the *x* and *z* directions than in the *y* direction. As dictated by vibration transmission principles (Harris 1996), if the effective mass loaded on the gloves in each direction is the same, the transmissibility in the high-frequency range in the *y* direction should be lower than that in the other directions. Obviously, this is not what was observed in this study. As shown in Figure 8, the transmissibility of the VR gloves in the high-frequency range in the *y* direction is generally higher than that in the other directions. This is primarily because the apparent mass or mechanical impedance in the *y* direction is generally smaller than that in the other directions (Dong et al. 2012). Since the highest mechanical impedance at frequencies below 100 Hz is observed along the forearm direction, the lowest transmissibility values of the VR gloves are also generally observed in this direction, as also shown in Figure 8 (T_z).

At frequencies above 100 Hz, the mechanical impedance in the *x* direction is comparable to or higher than that in the *z* direction (Dong et al. 2012); consequently, the vibration transmissibility in the *x* direction should be comparable or lower than that in the *z* direction. This can partially explain why Gloves A and F exhibit lower transmissibility at frequencies above 100 Hz. More importantly, as mentioned above, the glove transmissibility also depends on the glove stiffness, especially in the adapter contact zone. Because the adapter only covers the front portion of the handle, the shear component in the adapter contact zone in the *x* direction must be more than that in the *z* direction; as a result, the effective contact stiffness in the *x* direction is likely to be less than that in the *z* direction during the glove test. This also partially explains the reduced high-frequency transmissibility observed with Gloves A and F.

The above explanations, however, cannot be used to rationalise the high-frequency transmissibility of the air gloves in the *x* direction shown in Figure 8. There are major differences in the effective mass and damping characteristics of the vibration attenuation materials of the gel-filled or dipped neoprene gloves as compared with those of the air gloves. These dynamic property differences are likely to become more important in determining the transmissibility as the vibration frequency increases. It is common knowledge that the distance that vibration is effectively transmitted from the source generally decreases with the increase in vibration frequency; when the frequency reaches a certain value, the glove vibration transmissibility depends more on the dynamic properties of the gloves themselves, as confirmed in a previous study (Xu et al. 2011). Because the mass and damping values of the gel-filled or dipped neoprene glove are larger than those of the air gloves, they are more effective at attenuating high-frequency vibrations (Xu et al. 2011). This explains why the air gloves are less effective at reducing the total vibration (*TT*) at frequencies above 200 Hz, as also indicated in Table 3. This also explains, in conjunction with the fact that the air gloves exhibit the lowest effective mass in the *y* direction, why the air gloves show the largest high-frequency transmissibility in the *y* direction.

Because of the nonlinear dynamic properties of gloves and the hand–arm system, increasing the hand force level generally increases the glove stiffness and the apparent mass of the hand–arm system. An increased stiffness reduces the vibration attenuation effectiveness of a glove, but an increased apparent mass of the hand–arm system would tend to decrease vibration transmissibility. The experimental results of this study suggest that the force level-induced changes in the glove properties play a more dominant role in determining palm-transmitted vibration transmissibility.

4.2 Non-unity vibration transmissibility observed with the bare adapter

The bare-adapter orientation evaluations and the vibration coherence tests suggest that the complex off-unity transmissibility shifts might be inherent with multiaxial vibrations. It is extremely difficult to reliably reduce misalignment errors to within an acceptable range by tightly controlling the adapter position inside a tested glove. This observation led to the creation of this study's second correction method for determining the directional vibration transmissibility functions of a glove.

4.3 Implications of the experimental results

Figure 11 compares the transmissibility spectra for the forearm direction obtained in this study with those measured on a 1D test system in two previous studies (Dong et al. 2011; Welcome et al. 2011). In order to make direct comparisons, the total vibration (root-sum-of-squares) method is also applied to the 1D spectra; this technique sufficiently corrects errors due to adapter misalignments (Dong, Rakheja, et al. 2002). It should be noted that the same adapter was used with both test systems. The handle of the 1D shaker exhibits a higher resonant frequency (1750 Hz) than that (650 Hz) of the 3D system (Welcome et al., "Effectiveness of Anti-Vibration Gloves," 2012; Dong, Welcome, and McCormick 2006). This difference should not substantially affect measurements of glove transmissibility at frequencies at or below 500 Hz. The excitation spectra used in the experiments on the 1D and 3D test systems were somewhat different; the excitation frequency range of the 1D system is wider than that of the 3D system. It should also be noted that while most of the study participants from the 1D studies also participated in this 3D study, there were some substitute participants in the 3D study. As demonstrated in Figure 11, even with the differences in test conditions and the subject pool, the 1D and 3D transmissibility spectra of the seven gloves are quite similar. This suggests that the possible cross-axis responses inherent with 3D excitation are unlikely to substantially influence the basic characteristics of directional palm-transmitted vibration transmissibility measurements. The 1D and 3D comparisons also suggest that measured glove vibration transmissibility is fairly independent of the excitation spectrum, which is consistent with earlier reports (Dong, McDowell, et al. 2002; Rakheja et al. 2002; Laszlo and Griffin 2011). The glove spectra measured in this study can be used as a basis for roughly estimating the vibration attenuation effectiveness of these gloves when used with powered hand tools at workplaces.

The glove spectra shown in Figure 8 suggest that VR gloves could amplify vibration emissions of low-frequency (< 25 Hz) tools such as vibrating forks, sand rammers and earth tampers; generally, the ordinary work glove performed better than the VR gloves in the low-frequency range. According to reported tool vibration spectra (Griffin 1997), the fundamental or dominant vibration frequencies generated by the vast majority of powered hand tools fall in the middle frequency range (31.5–200 Hz). These middle-frequency tools are also commonly associated with the development of hand–arm vibration syndrome (Griffin 1990). The total transmissibility spectrum shown in Figure 8 and the total transmissibility values ($T\ T$) presented in Table 2 suggest that the most effective VR gloves may reduce frequency-weighted vibrations transmitted to the palm from middle-frequency tools by approximately 10–15%. For tools with dominant vibrations at frequencies above 200 Hz, the VR gloves, especially the gel-filled glove, are shown to be more effective, as indicated in the spectra shown in Figure 8 and the transmissibility values listed in Table 3. The effectiveness of VR gloves when paired with specific tools can be more reliably estimated using direction-specific glove vibration transmissibility spectra along with direction-specific tool vibration spectra, when available; such information would be useful for making appropriate glove selections for specific tools.

While every VR glove meets the easily attained middle-frequency transmissibility target ($T_{z\_M} < 1.00$) defined in the original AV glove test standard (ISO 1996), the key criterion for AV glove qualifications is the transmissibility benchmark in the high-frequency range (200–1250 Hz) along the forearm direction ($T_{z\_H} < 0.60$). Many air gloves (e.g. Gloves E and G) may meet this criterion, depending on the test subjects and whether the palm-adapter alignment is tightly controlled during the experiment (Dong et al. 2011; Welcome et al. 2011). The gel-filled glove (Glove A) generally exhibited less transmissibility ($T_{z\_H} \approx 0.70$) in this high-frequency range in the z direction (Dong et al. 2011; Welcome et al. 2011). However, the T_x values listed in Table 3 indicate that the gel-filled glove (Glove A) demonstrates greater high-frequency vibration attenuation in the x direction than any of the air gloves. Likewise, when considering total vibration transmissibility ($T\ T$), the gel-filled glove performed better in the high-frequency range than any other glove in this study. Nevertheless, Glove A cannot be classified as an AV glove despite its generally superior T_x and TT values (Dong et al. 2011; Welcome et al. 2011). These observations suggest that the major assumption behind the most critical screening criterion defined in the current standard may be invalid. These observations also suggest that the so-called AV gloves should not be considered as the sole option when selecting VR gloves.

The standardised AV glove test defined in ISO (1996) is basically a pass/fail test, but it also recommends the evaluation of vibration transmissibility as a function of frequency and the estimation of the effectiveness of the glove for attenuating frequency-weighted acceleration when the tool vibration spectrum is known. The results of this study indicate that the transmissibility spectrum measured along the forearm direction as required by the standard generally overestimates the overall vibration attenuation effectiveness of VR gloves. While the vibration transmissibility spectra determined via measurements along the forearm direction may be used to estimate the maximum attainable vibration reduction at the palm of the hand, the total vibration transmissibility spectra may be used to estimate the average reduction at this hand location. It should also be noted that the use of a palm adapter may exaggerate VR glove effectiveness; the added mass of the palm adapter along with the load concentration effect can result in decreased vibration transmissibility measurements (Dong et al. 2005).

Considering the limited vibration protection and the potential adverse effects resulting from increased gripping forces and reduced finger dexterity, VR gloves should not be considered as the major component of a programme for reducing frequency-weighted hand-transmitted vibration exposures. Furthermore, it is on the conservative side to disregard estimates of glove-afforded vibration reduction during risk assessments of occupational hand-transmitted vibration exposures. Conversely, because VR gloves can attenuate discernible amounts of hand-transmitted vibration, especially high-frequency exposures, VR gloves may have some value when used with certain tools. It is, therefore, appropriate to consider VR glove use as a secondary preventive measure, especially in the operations of tools where the adverse effects of these gloves are not of concern. To maximise the benefits of VR gloves, the results of this study also suggest that the applied hand forces should be as low as possible, provided that is consistent with safe practice and tool control.

5. Conclusions

This study characterised the vibration transmissibility spectra and quantified the frequency-weighted transmissibility values of selected VR gloves at the palm of the hand in three orthogonal directions. The results indicate that VR gloves are generally more effective at reducing vibrations transmitted to the palm along the forearm direction (*z*-axis) than in the other two orthogonal directions. VR gloves do not effectively attenuate frequency-weighted vibrations along the axial direction of a tool handle (*y*-axis). The estimated effectiveness of these gloves in the third direction (*x*-axis) typically falls between that of the forearm direction and the handle axis direction. Because the AV glove evaluation method prescribed by the current international standard is primarily based on palm-adapter measurements of glove vibration transmissibility along the forearm direction, the overall effectiveness of VR gloves is usually overestimated. Furthermore, gloves that are more effective at reducing vibrations along the forearm direction may not be more effective in the other directions. This casts doubts on the reliability of the standardised glove screening test and suggests that certified AV gloves should not be considered as the sole option when selecting VR gloves. The directional vibration transmissibility spectra determined in this study can be used to estimate the tool-specific effectiveness of VR gloves for reducing palm-transmitted vibration exposures and to help appropriately select gloves for specific applications.

References

Brown AP. The Effects of Anti-Vibration Gloves on Vibration-Induced Disorders: A Case Study. Journal of Hand Therapy. 1990; 3(2):94–100.

CEN. EN 420: General Requirements for Protective Gloves. Comité Européen de Normalisation (CEN); 2003.

Dong RG, McDowell TW, Welcome DE, Barkley J, Warren C, Washington B. Effects of Hand-Tool Coupling Conditions on the Isolation Effectiveness of Air Bladder Anti-Vibration Gloves. Journal of Low Frequency Noise, Vibration and Active Control. 2004; 23(4):231–248.

Dong RG, McDowell TW, Welcome DE, Rakheja S, Caporali SA, Schopper AW. Effectiveness of a Transfer Function Method for Evaluating Vibration Isolation Performance of Gloves When Used with Chipping Hammers. Journal of Low Frequency Noise, Vibration and Active Control. 2002; 21(3):141–155.

Dong RG, McDowell TW, Welcome DE, Smutz WP, Schopper AW, Warren C, Wu JZ, Rakheja S. On-the-Hand Measurement Methods for Assessing Effectiveness of Anti-Vibration Gloves. International Journal of Industrial Ergonomics. 2003; 32(4):287–298.

Dong RG, McDowell TW, Welcome DE, Warren C, Schopper AW. An Evaluation of the Standardized Chipping Hammer Test Specified in ISO 8662-2, 1992. Annals of Occupational Hygiene. 2004; 48(1):39–49. [PubMed: 14718344]

Dong RG, McDowell TW, Welcome DE, Wu JZ, Rakheja S. Analysis of Anti-Vibration Gloves Mechanism and Evaluation Methods. Journal of Sound and Vibration. 2009; 321(1–2):435–453.

Dong RG, Rakheja S, McDowell TW, Welcome DE, Wu JZ, Warren C, Barkley J, Washington B, Schopper AW. A Method for Assessing the Effectiveness of Anti-Vibration Gloves Using Biodynamic Responses of the Hand–Arm System. Journal of Sound and Vibration. 2005; 282(3–5): 1101–1118.

Dong RG, Rakheja S, Smutz WP, Schopper AW, Welcome DE, Wu JZ. Evaluating Anti-Vibration Performance of a Glove Using Total Effective Transmissibility. International Journal of Industrial Ergonomics. 2002; 30(1):33–48.

Dong, RG.; Welcome, DE.; McCormick, R. A Novel 3-D Hand–Arm Vibration Test System and Its Preliminary Evaluation. Proceedings of the 1st American Conference on Human Vibration; Morgantown, WV, USA. 2006.

Dong, RG.; Welcome, DE.; Xu, XS.; Warren, C.; McDowell, TW.; Wu, JZ.; Rakheja, S. The U.S. Naval Supply Systems Command/Navy Clothing and Textile Research Facility (NAVSUP/ NCTRF) and National Institute for Occupational Safety and Health (NIOSH) Partnership for Improving Protection from Work-Related Hand–Arm Vibration Syndrome (HAVS). NORA symposium; Cincinnati, OH, USA. 2011.

Dong RG, Welcome DE, Xu XS, Warren C, McDowell TW, Wu JZ, Rakheja S. Mechanical Impedances Distributed at the Fingers and Palm of the Human Hand in Three Orthogonal Directions. Journal of Sound and Vibration. 2012; 331(5):1191–1206.

Goel V, Rim K. Role of Gloves in Reducing Vibration: An Analysis for Pneumatic Chipping Hammer. American Industrial Hygiene Association Journal. 1987; 48(1):9–14.

Griffin, MJ. Handbook of Human Vibration. London: Academic Press; 1990.

Griffin MJ. Measurement, Evaluation, and Assessment of Occupational Exposures to Hand-Transmitted Vibration. Occupational & Environmental Medicine. 1997; 54(2):73–89. [PubMed: 9072014]

Griffin MJ. Evaluating the Effectiveness of Gloves in Reducing Hazards of Hand-Transmitted Vibration. Occupational and Environmental Medicine. 1998; 55(5):340–348. [PubMed: 9764112]

Harris, CM. Shock and Vibration Handbook. New York: McGraw-Hill; 1996.

Hewitt S. Assessing the Performance of Anti-Vibration Gloves – A Possible Alternative to ISO 10819, 1996. Annals of Occupational Hygiene. 1998; 42(4):245–252. [PubMed: 9713247]

Hewitt, S. Triaxial Measurements of the Performance of Anti-Vibration Gloves (Research Report RR795). Health and Safety Executive; UK: 2010.

ISO. ISO 10819, 1996: Mechanical Vibration and Shock – Hand–Arm Vibration – Method for the Measurement and Evaluation of the Vibration Transmissibility of Gloves at the Palm of the Hand. Geneva, Switzerland: 1996.

ISO. ISO 5349-1: Mechanical Vibration – Measurement and Evaluation of Human Exposure to Hand-Transmitted Vibration –Part 1: General Requirements. Geneva, Switzerland: 2001.

ISO. ISO 10819/DIS, 2012: Mechanical Vibration and Shock – Hand–Arm Vibration – Method for the Measurement and Evaluation of the Vibratiion Transmissibility of Gloves at the Palm of the Hand. Geneva, Switzerland: 2012.

Jetzer T, Haydon P, Reynolds D. Effective Intervention with Ergonomics, Antivibration Gloves, and Medical Surveillance to Minimize Hand–Arm Vibration Hazards in the Workplace. Journal of Occupational & Environmental Medicine. 2003; 45(12):1312–1317. [PubMed: 14665818]

Laszlo HE, Griffin MJ. The Transmission of Vibration Through Gloves: Effects of Push Force, Vibration Magnitude and Inter-Subject Variability. Ergonomics. 2011; 54(5):488–496. [PubMed: 21547793]

Mahbub MH, Yokoyama K, Laskar MS, Inoue M, Takahashi Y, Yamamoto S, Harada N. Assessing the Influence of Antivibration Glove on Digital Vascular Responses to Acute Hand–Arm Vibration. Journal of Occupational Health. 2007; 49(3):165–171. [PubMed: 17575396]

McDowell TW, Dong RG, Xu X, Welcome DE, Warren C. An Evaluation of Impact Wrench Vibration Emissions and Test Methods. Annals of Occupational Hygiene. 2008; 52(2):125–138. [PubMed: 18212244]

McDowell TW, Marcotte P, Warren C, Welcome DE, Dong RG. Comparing Three Methods for Evaluating Impact Wrench Vibration Emissions. Annals of Occupational Hygiene. 2009; 53(6): 617–626. [PubMed: 19465462]

McDowell TW, Warren C, Welcome DE, Dong RG. Laboratory and Field Measurements of Vibration at the Handles of Selected Riveting Hammers. Annals of Occupational Hygiene. 2012; 56(8):911–924. [PubMed: 22539561]

McDowell TW, Welcome DE, Warren C, Xu XS, Dong RG. Assessment of Hand-Transmitted Vibrations from Vibrating Forks Used for Beach Cleaning Operations. Annals of Occupational Hygiene. 2013; 57(1):43–53. [PubMed: 22952387]

NIOSH. Musculoskeletal Disorders and Workplace Factors: A Critical Review of Epidemiologic Evidence for Work-Related Musculoskeletal Disorders of the Neck, Upper Extremity, and Low Back, NIOSH Publication 97-141. Cincinnati, OH: U.S. Department of Health and Human Services, National Institute for Occupational Safety and Health; 1997.

Pinto, I.; Stacchint, N.; Bovenzi, M.; Paddan, GS.; Griffin, MJ. Protection Effectiveness of Anti-Vibration Gloves: Field Evaluation and Laboratory Performance Assessment. Proceedings of the 9th International Conference on Hand–Arm Vibration, Section 15(2); Nancy, France. 2001.

Pitts PM, Mason HJ, Poole KA, Young CE. Relative Performance of Frequency Weighting Wh and Candidates for Alternative Frequency Weightings When Used to Predict the Occurrence of Hand–Arm Vibration Induced Injuries. Canadian Acoustics. 2011; 39(2):96–97.

Rakheja S, Dong RG, Welcome DE, Schopper AW. Estimation of Tool-Specific Isolation Performance of Anti-Vibration Gloves. International Journal of Industrial Ergonomics. 2002; 30(2):71–87.

Rens G, Dubrulle P, Malchaire J. Efficiency of Conventional Gloves Against Vibration. Annals of Occupational Hygiene. 1987; 31(2):249–254. [PubMed: 3688714]

Reynolds, D.; Jetzer, T. Use of Air Bladder Technology to Solve Hand Tool Vibration Problems. Proceedings of the 8th International Conference on Hand–Arm Vibration; Umea, Sweden. 1998.

Welcome DE, Dong RG, Xu XS, Warren C, McDowell TW. An Evaluation of the Proposed Revision of the Anti-Vibration Glove Test Method Defined in ISO-10819 (1996). International Journal of Industrial Ergonomics. 2012; 42(1):143–155.

Welcome, DE.; Dong, RG.; Xu, XS.; Warren, C.; McDowell, TW.; Wu, JZ. Effectiveness of Anti-Vibration Gloves for Reducing Finger Vibration. 4th American Conference on Human Vibration; Hartford, CT: University of Connecticut; 2012.

Welcome, DE.; McDowell, TW.; Xu, XS.; Warren, C.; Dong, RG. An Evaluation of Anti-Vibration Gloves Based on ISO 10819 (1996), Revised Method, and Grip Strength Reduction (Phase ii). Morgantown, WV: National Institute for Occupational Safety & Health (NIOSH); 2011.

Wimer BM, McDowell TW, Xu XS, Welcome DE, Warren C, Dong RG. Effects of Gloves on the Total Grip Strength Applied to Cylindrical Handles. International Journal of Industrial Ergonomics. 2010; 40(5):574–583.

Xu XS, Riley DA, Persson M, Welcome DE, Krajnak K, Wu JZ, Govindaraju SR, Dong RG. Evaluation of Anti-Vibration Effectiveness of Glove Materials Using an Animal Model. Biomedical Materials and Engineering. 2011; 21(4):193–211. [PubMed: 22182788]

Figure 1.

Seven glove models were evaluated in the study. Models A–C and E–G were VR gloves while Model D was an ordinary synthetic leather work glove.

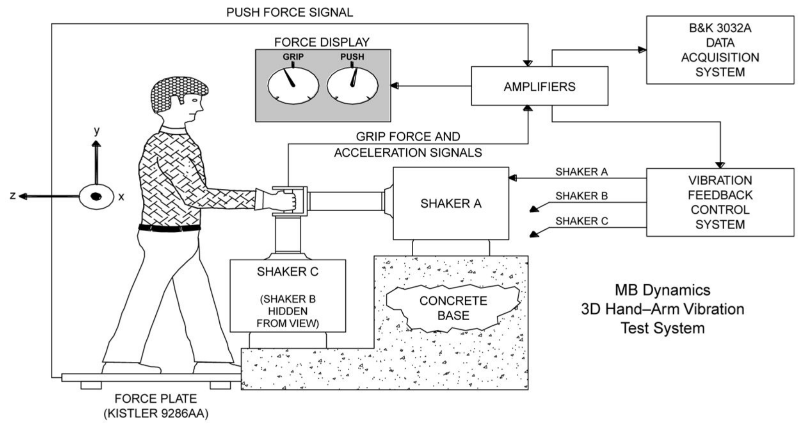

Figure 2.
The test set-up that includes a closed-loop controlled 3D hand–arm vibration test system, a vibration and response measurement system, and grip–push force measurement and display systems.

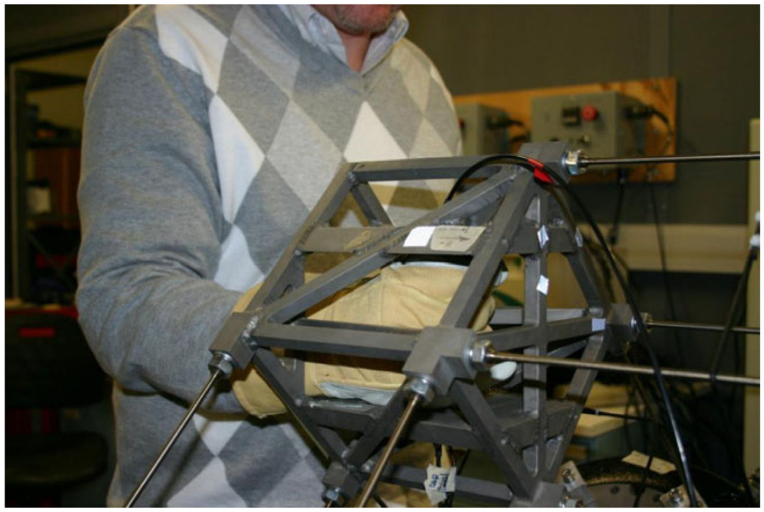

Figure 3.

A view of a subject employing the prescribed posture with a gloved hand gripping the instrumented handle of the 3D hand–arm vibration test system.

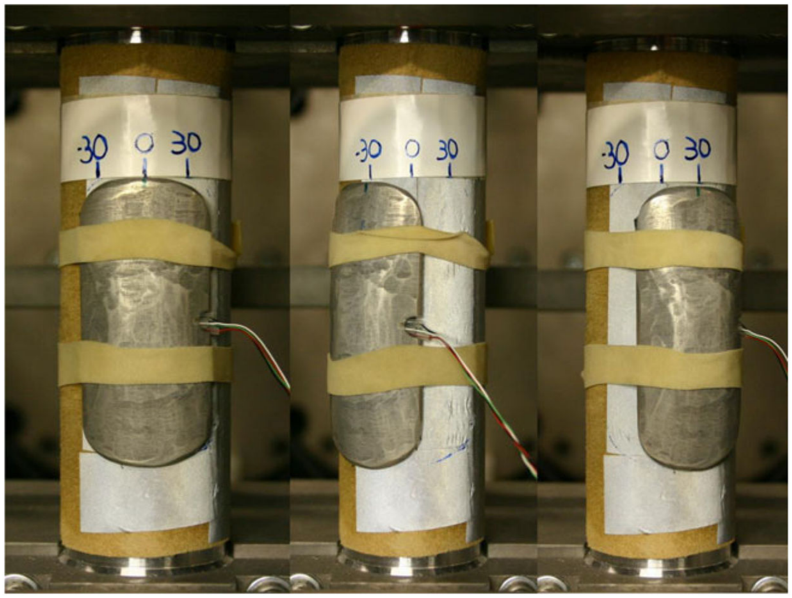

Figure 4.
To evaluate the reliability of the palm adapter, the vibration transmissibility of the bare adapter was examined by positioning it on the instrumented shaker handle using rubber bands at several different orientations from −30° to 30°.

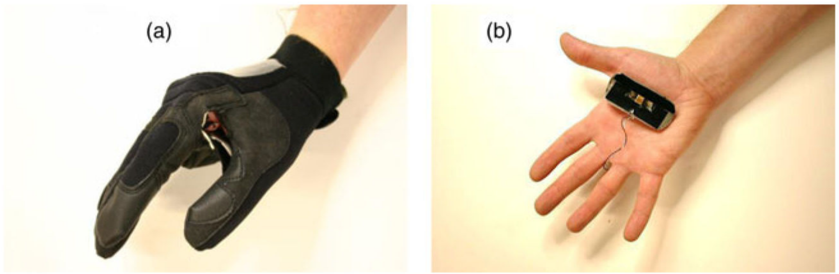

Figure 5.

(a) To minimise adapter misalignment, a slit was cut in the thenar region of each glove to enable the palm adapter to be viewed and adjusted inside the glove. (b) The final position of the adapter was near the heel of the palm.

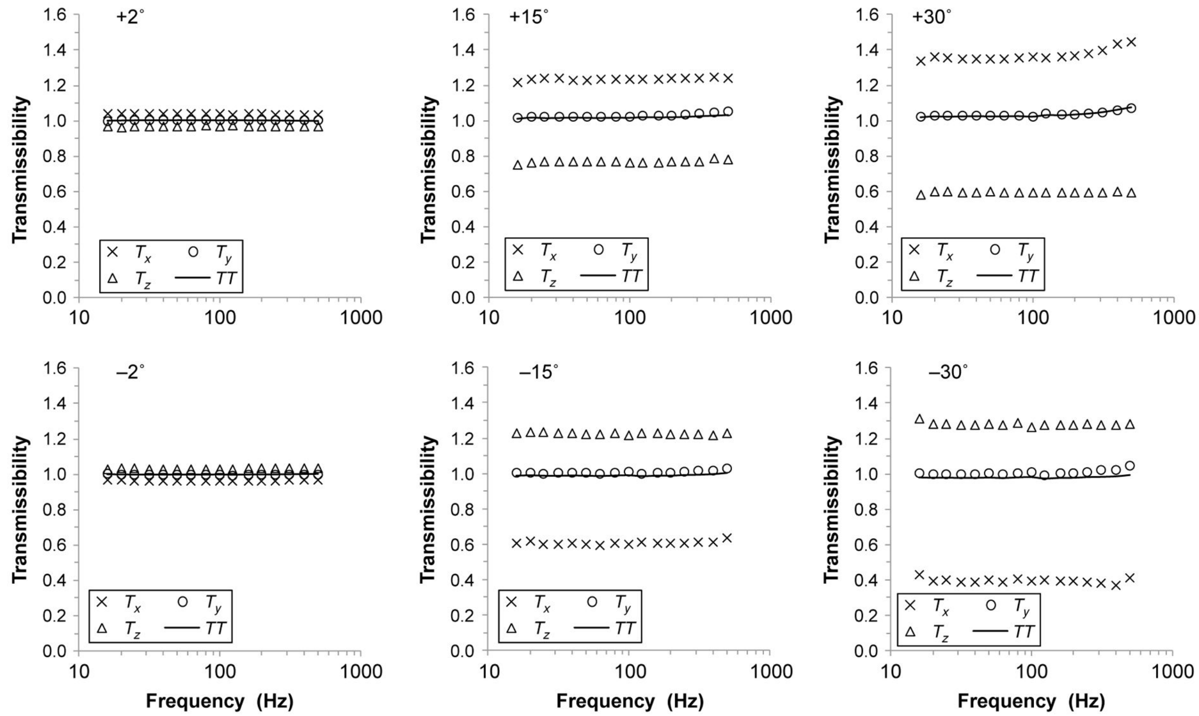

Figure 6.

Directional (T_x, T_y, T_z) and total (TT) vibration transmissibility spectra of the bare adapter as the adapter is oriented at different positions on the handle between −30° and +30° (refer to Figure 4). The frequency correction, $C1$ defined in Equation (3), was applied to these data.

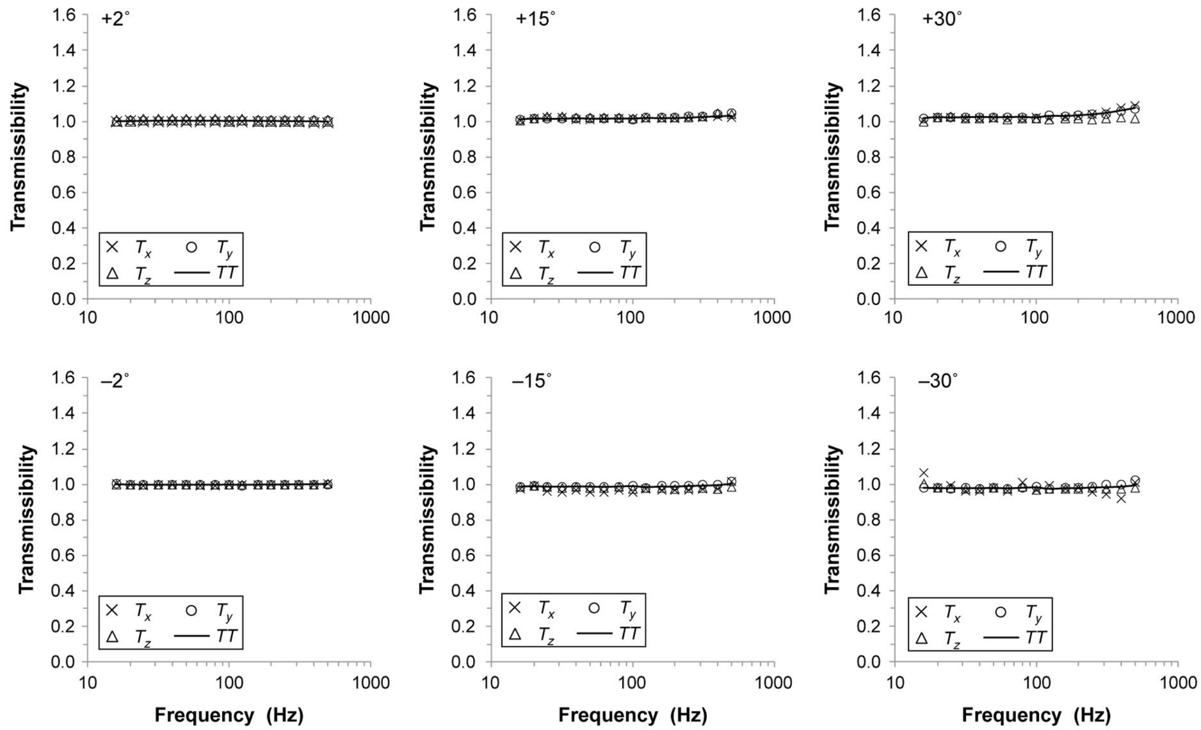

Figure 7.

Directional (T_x, T_y, T_z) and total (TT) vibration transmissibility spectra of the bare adapter as the adapter is oriented at different positions on the handle between −30° and +30° The second correction, *C*2 defined in Equation (4), was applied to these data.

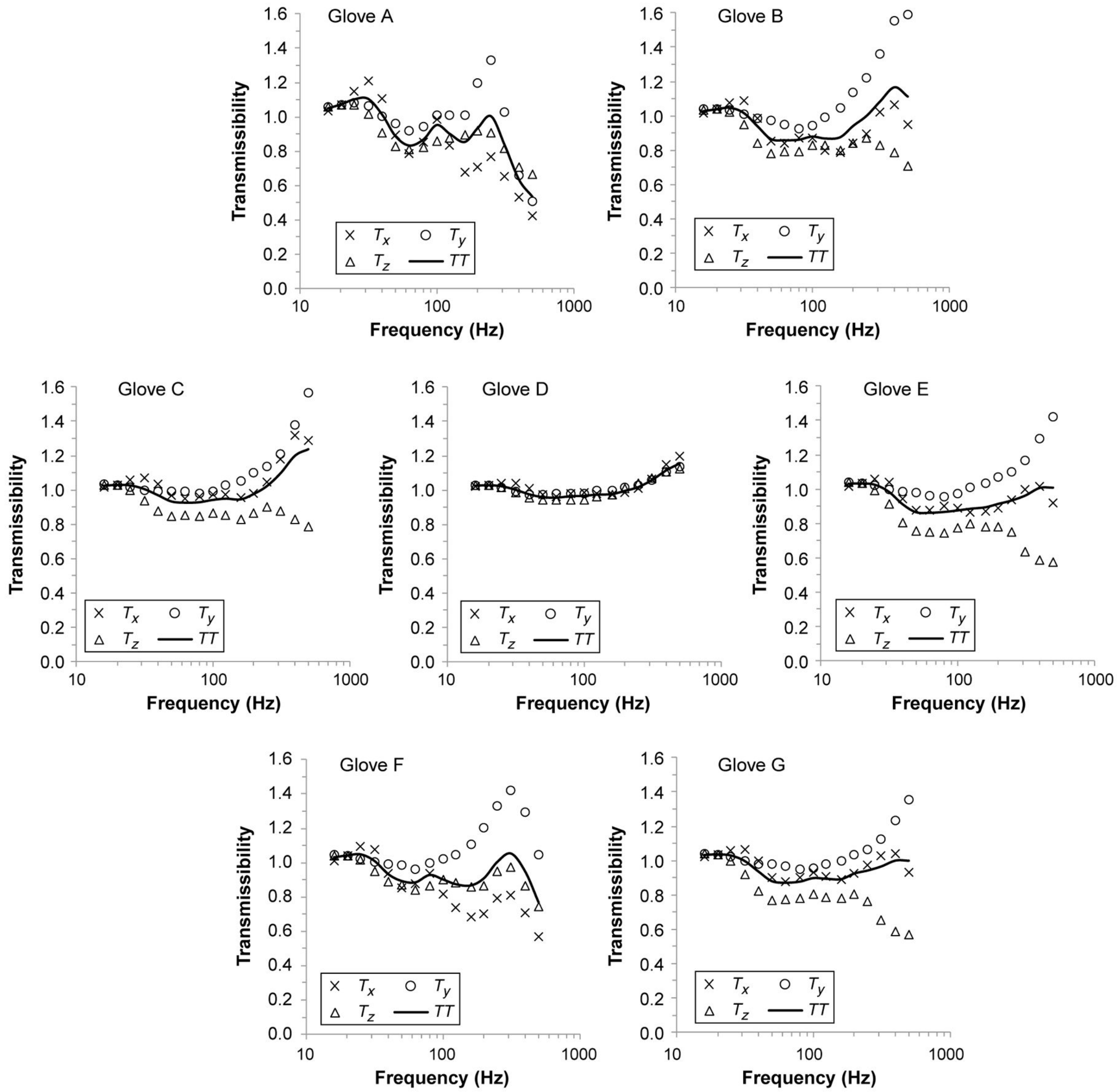

Figure 8.

Directional (T_x, T_y, T_z) and total (TT) vibration transmissibility spectra of the seven gloves measured under the middle force level (30 N grip + 50 N push). The total vibration transmissibility spectrum for each glove represents the average of the *x*, *y* and *z* direction spectra. Both corrections, *C*1 and *C*2, have been applied to these data.

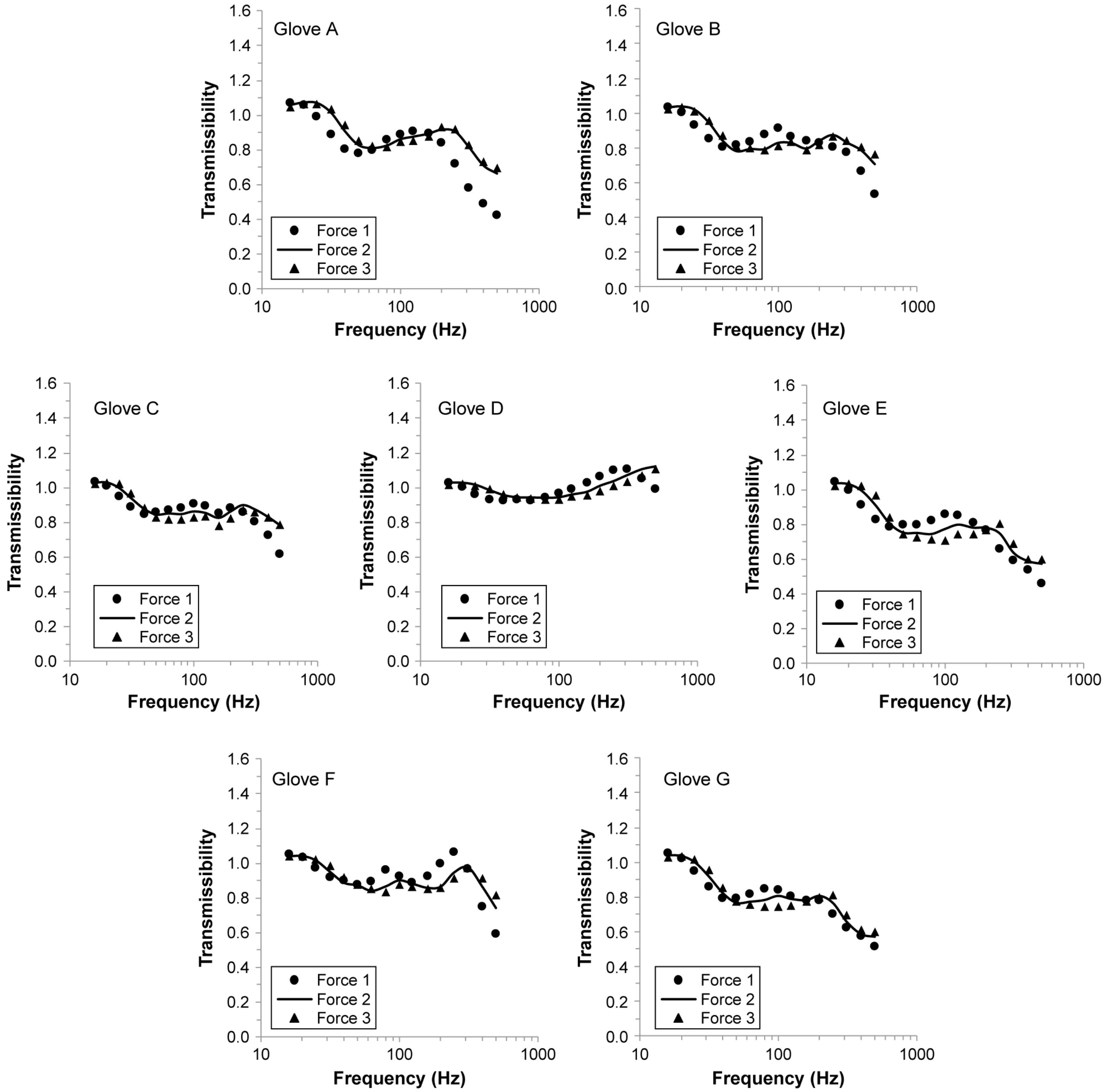

Figure 9.

The *z*-direction vibration transmissibility spectra for each glove at the three hand force levels (*F*1, 15 N grip + 30 N push; *F*2, 30 N grip + 50 N push; *F*3, 45 N grip + 70 N push).

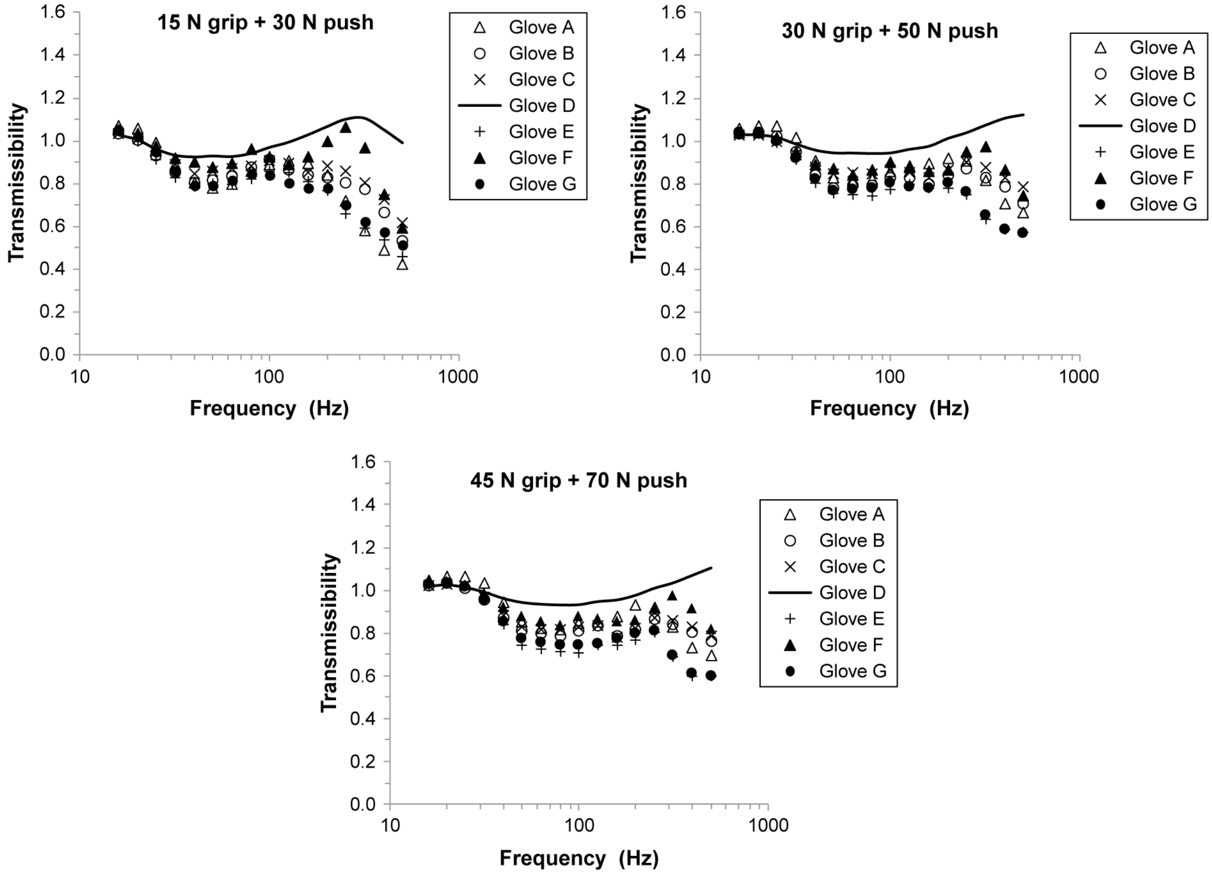

Figure 10.

The *z*-direction vibration transmissibility spectra for the seven gloves at the three hand force levels.

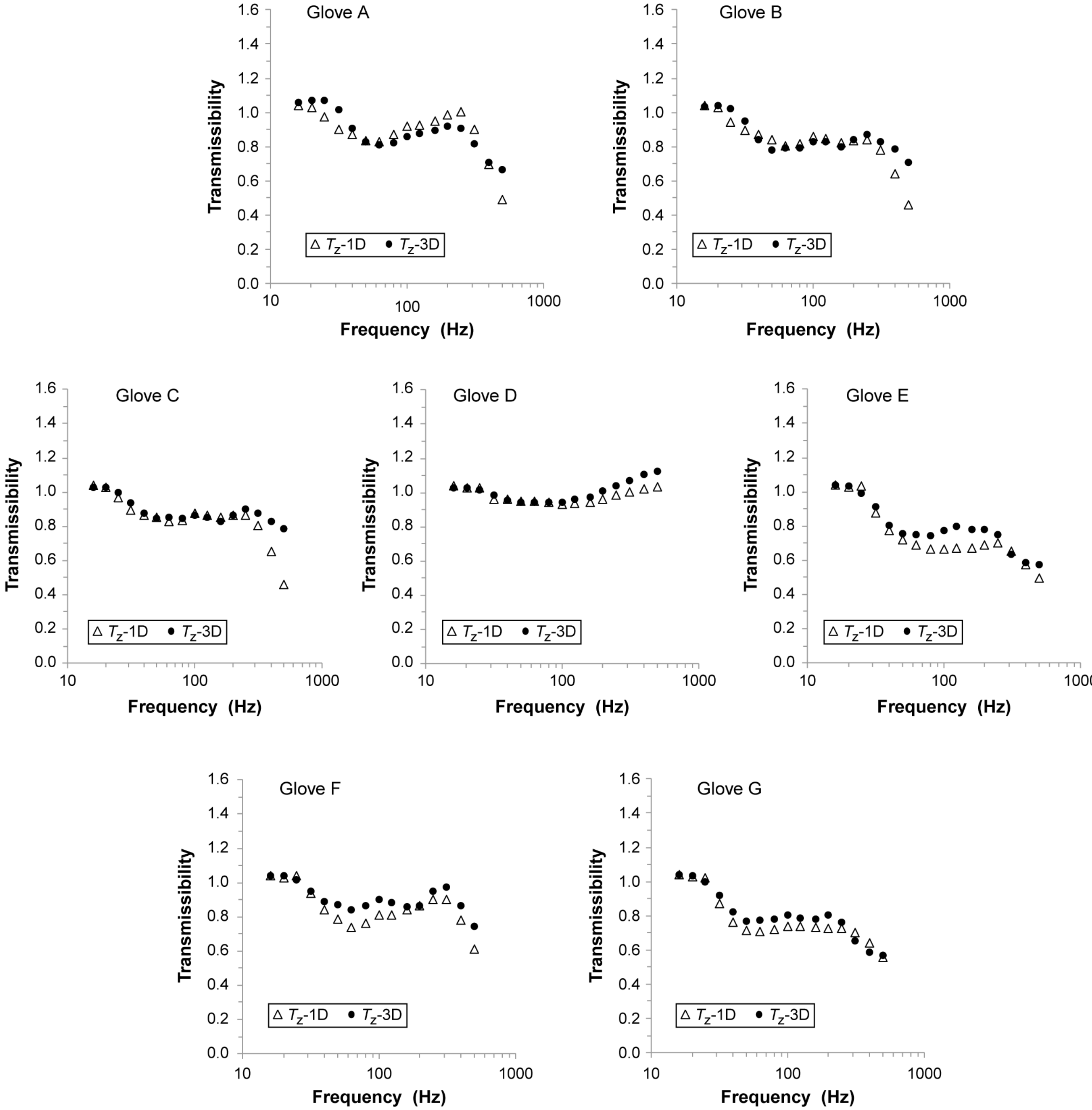

Figure 11.

The *z*-direction vibration transmissibility spectra for the seven gloves from this study with those measured on a 1D test system in two previous studies (Dong et al. 2011; Welcome et al. 2011).

Table 1

Subject anthropometry.

Subject	Stature (cm)	Weight (kg)	Hand length (mm)	Hand breadth (mm)	Hand size
1	181.6	99.8	200	94	9
2	185.4	69.1	192	86	9
3	182.9	69.0	192	84	9
4	176.5	79.8	193	83	9
5	180.3	88.5	192	89	9
6	180.8	80.7	200	90	9
7	179.1	87.0	190	89	8
Mean	180.9	82.0	194	88	
SD	2.8	11.0	4	4	

Notes: Hand length, tip of middle finger to crease at wrist; hand breadth, the width measured at the metacarpals; hand size based on EN 420 (CEN 2003).

Table 2

Frequency-weighted directional (T_x, T_y, T_z) and total (*TT*) vibration transmissibility values of the seven gloves in the middle-frequency range (31.5–200 Hz) under three levels of hand force (*F*1, 15 N grip + 30 N push; *F*2, 30 N grip + 50 N push; *F*3, 45 N grip + 70 N push).

		T_x			T_y			T_z			*TT*		
Glove ID	**Major AV materials**	***F*1**	***F*2**	***F*3**	***F*1**	***F*2**	***F*3**	***F*1**	***F*2**	***F*3**	***F*1**	***F*2**	***F*3**
A	Thick gel pad	0.88	0.99	1.04	1.02	1.01	1.02	0.84	0.89	0.91	0.91	0.96	0.99
B	Cellular air bubbles	0.85	0.93	0.97	0.97	0.99	0.98	0.84	0.84	0.85	0.88	0.92	0.93
C	Air bladder with pump	0.93	1.00	1.01	1.01	1.00	0.99	0.87	0.88	0.87	0.93	0.96	0.96
D	Ordinary work glove	0.95	1.00	1.00	0.99	0.98	0.99	0.95	0.96	0.96	0.96	0.98	0.98
E	Air bladder with pump	0.86	0.93	0.97	0.98	0.99	0.98	0.81	0.81	0.81	0.88	0.91	0.92
F	Dipped neoprene	0.84	0.92	0.96	1.04	1.01	1.00	0.91	0.89	0.90	0.91	0.93	0.95
G	Air bladder with pump	0.90	0.96	0.99	0.99	0.98	0.98	0.82	0.82	0.83	0.90	0.92	0.94

Table 3

Frequency-weighted directional (T_x, T_y, T_z) total (*TT*) vibration transmissibility values of the seven gloves in the high-frequency range (200–500 Hz) under three levels of hand force (*F*1, 15 N grip + 30 N push; *F*2, 30 N grip + 50 N push; *F*3, 45 N grip + 70 N push).

		T_x			T_y			T_z			*TT*		
Glove ID	**Major AV materials**	***F*1**	***F*2**	***F*3**	***F*1**	***F*2**	***F*3**	***F*1**	***F*2**	***F*3**	***F*1**	***F*2**	***F*3**
A	Thick gel pad	0.69	0.68	0.69	1.09	1.11	1.18	0.69	0.85	0.87	0.81	0.87	0.91
B	Cellular air bubbles	0.96	0.94	0.96	1.34	1.31	1.24	0.77	0.83	0.83	1.03	1.04	1.02
C	Air bladder with pump	1.11	1.12	1.05	1.31	1.21	1.16	0.82	0.87	0.84	1.09	1.07	1.02
D	Ordinary work glove	1.12	1.05	1.02	1.11	1.05	1.04	1.08	1.05	1.02	1.10	1.05	1.03
E	Air bladder with pump	0.93	0.95	0.96	1.24	1.16	1.09	0.66	0.71	0.73	0.96	0.95	0.94
F	Dipped neoprene	0.71	0.74	0.74	1.31	1.29	1.27	0.96	0.90	0.90	0.96	0.96	0.96
G	Air bladder with pump	0.98	0.98	0.96	1.21	1.11	1.11	0.69	0.72	0.74	0.98	0.95	0.95