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Tool-specific performance of vibration-reducing gloves for attenuating palm-transmitted vibrations in three orthogonal directions

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Abstract

Vibration-reducing (VR) gloves have been increasingly used to help reduce vibration exposure, but it remains unclear how effective these gloves are. The purpose of this study was to estimate tool-specific performances of VR gloves for reducing the vibrations transmitted to the palm of the hand in three orthogonal directions (3-D) in an attempt to assess glove effectiveness and aid in the appropriate selection of these gloves. Four typical VR gloves were considered in this study, two of which can be classified as anti-vibration (AV) gloves according to the current AV glove test standard. The average transmissibility spectrum of each glove in each direction was synthesized based on spectra measured in this study and other spectra collected from reported studies. More than seventy vibration spectra of various tools or machines were considered in the estimations, which were also measured in this study or collected from reported studies. The glove performance assessments were based on the percent reduction of frequency-weighted acceleration as is required in the current standard for assessing the risk of vibration exposures. The estimated tool-specific vibration reductions of the gloves indicate that the VR gloves could slightly reduce (<5%) or marginally amplify (<10%) the vibrations generated from low-frequency (<25 Hz) tools or those vibrating primarily along the axis of the tool handle. With other tools, the VR gloves could reduce palm-transmitted vibrations in the range of 5%–58%, primarily depending on the specific tool and its vibration spectra in the three directions. The two AV gloves were not more effective than the other gloves with some of the tools considered in this study. The implications of the results are discussed.

Relevance to industry—Hand-transmitted vibration exposure may cause hand-arm vibration syndrome. Vibration-reducing gloves are considered as an alternative approach to reduce the vibration exposure. This study provides useful information on the effectiveness of the gloves when used with many tools for reducing the vibration transmitted to the palm in three directions. The results can aid in the appropriate selection and use of these gloves.

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Keywords

Anti-vibration glove; Vibration-reducing glove; Hand-arm vibration; Hand-transmitted vibration; Hand-arm vibration syndrome

1. Introduction

Prolonged, intensive exposure to hand-transmitted vibration may cause hand-arm vibration syndrome (HAVS) (Griffin, 1990; NIOSH, 1997). To help reduce such exposures, vibration-reducing (VR) gloves have been designed not only to provide typical work glove functions, but also to isolate some vibrations transmitted to the hand-arm system (Rens et al., 1987; Goel and Rim, 1987; Reynolds and Jetzer, 1998; Jetzer et al., 2003). In principle, the vibration isolation effectiveness of a glove depends primarily on the dynamic properties of both the glove and hand-arm system (Dong et al., 2009); any factor affecting their properties may also influence glove effectiveness. It is difficult to judge these gloves without specifying their application conditions. Furthermore, the performances of available commercial VR gloves may vary significantly. To help select appropriate gloves, the International Organization for Standardization (ISO) has set forth a testing method and a set of criteria to classify anti-vibration (AV) gloves (ISO 10819, 1996, 2013). In other words, AV gloves are a subset of VR gloves; they are supposed to reduce more vibration transmitted to the hand than VR gloves that do not fully meet the criteria. Specifically, this test method requires measuring the glove vibration transmissibility of frequency-weighted acceleration at the palm of the hand along the forearm direction with a specified hand and arm posture while forces of 30 N grip and 50 N push are applied to a vibrating 40 mm cylindrical handle. According to the latest version of the standard (ISO 10819, 2013), the glove can be classified as an AV glove if it meets the following three criteria: (i) the transmissibility value in the middle-frequency range (25–200 Hz) is less than or equal to 0.90; (ii) the transmissibility value in the high-frequency range (200–1250 Hz) is less than or equal to 0.60; and (iii) the glove is full fingered; the materials of the glove fingers are the same as those of glove palm; and the thickness of the glove fingers is more than 0.55 times that at the palm of glove.

Whereas the AV glove criteria basically constitute a pass/fail test, the required reductions do not generally represent actual vibration reductions of these gloves when used with specific tools. This is primarily for the following reasons:

a) The vibration attenuation effectiveness of a glove is tool vibration-specific (Griffin,1998; Rakheja et al., 2002; Dong et al., 2002a). No powered hand tool generates the idealized vibration spectrum required in the standardized glove test (ISO 10819,1996, 2013); as a result, the transmissibility values measured with the standard method are not directly applicable to any specific tool.

b) The glove effectiveness is direction-specific (Hewitt, 2010; McDowell et al., 2013a). This is because the dynamic properties of the glove materials and the driving-point biodynamic responses may vary with direction (Dong et al., 2013). As above-mentioned, the standardized glove test prescribes that glove vibration transmissibility be measured only in the forearm direction.

c) The glove effectiveness is also location-specific because the glove properties and the distribution of hand apparent mass generally vary with the locations of the glove and hand (Dong et al., 2009, 2013). This is also clearly reflected by the large differences between the vibration transmissibility spectrum of the glove measured at the palm and that measured at the fingers (McDowell et al., 2013a; Welcome et al., 2014). Tool-specific glove performances at the palm and fingers should also be examined separately.

While the standard glove test is primarily intended to screen gloves (ISO 10819, 1996, 2013), the tool-specific vibration isolation performances of gloves have to be determined using other methods. Intuitively, the vibration transmissibility of a glove can be measured during tool operations at workplaces. Because many factors may affect glove vibration transmissibility, it is usually difficult and expensive to reliably assess glove effectiveness at workplaces, as substantial variations among measurement data have been observed (Pinto et al., 2001). Probably for these reasons, only a few studies have used the direct measurement approach to investigate tool-specific vibration isolation effectiveness of gloves (Goel and Rim, 1987; Cheng et al., 1999; Pinto et al., 2001; Dong et al., 2002a, 2003).

As an alternative method, tool-specific performances of gloves can be estimated using the vibration transmissibility spectra measured in laboratory tests over a sufficiently broad frequency band and with tool vibration spectra measured at workplaces. This approach avoids the difficulties of direct measurement and takes advantage of the available experimental data. It is recommended as an optional method for estimating tool-specific vibration transmissibility in the glove test standard (ISO 10819, 1996, 2013). Several studies evaluated this transfer function method (Rakheja et al., 2002; Dong et al., 2002a; Welcome et al., 2012). Those studies demonstrated that VR glove transmissibility is largely independent of the vibration exposure spectrum. This has led to the replacement of the two excitation spectra used in the original glove test standard (ISO 10819, 1996) with a single excitation spectrum required in the revised test standard (ISO 10819, 2013). This also suggests that it is reasonable to approximate tool-specific glove performances using the transmissibility spectrum of a glove measured in the laboratory. However, the current literature contains only a few reports of tool-specific glove vibration transmissibility values along the forearm direction at the palm of the hand (Rakheja et al., 2002; Dong et al., 2002a). Further studies are required to estimate the tool-specific performances of gloves in multi-axial vibration exposures.

Many tool vibration spectra can be found in the literature. Several studies reported the vibration transmissibility spectra of some typical VR gloves at the palm of the hand along the forearm direction (Dong et al., 2002a, 2002b, 2003, 2004, 2009, Welcome et al., 2011, 2012). A recent study also reported their spectra in three orthogonal directions (3-D) (McDowell et al., 2013a). These experimental data have made it possible to estimate the tool-specific effectiveness of typical VR gloves at the palm of the hand in three orthogonal directions. Therefore, the specific aims of this study are to measure additional glove transmissibility spectra and tool vibration spectra for verifying and enhancing the database for such estimations, to synthesize the representative glove spectra using the available data, and to estimate the tool-specific effectiveness of VR gloves at the palm of the hand. The measured spectra, together with archived data, are also used to further verify the most important assumption of this study: the vibration transmissibility spectrum of a glove is largely independent of the excitation conditions. Based on the estimated vibration reductions provided by the gloves, the appropriate selection and use of VR gloves for various vibrating tools or machines are discussed.

2. Methods

2.1. Vibration transmissibility spectra of gloves at the palm of the hand

2.1.1. Available 3-D transmissibility spectra—McDowell et al. (2013a) reported 3-D transmissibility spectra of six VR gloves and one regular work glove. The 3-D spectra were simultaneously measured on a 3-D vibration test system using a palm adapter method with hand and arm postures similar to those required in the standardized glove test (ISO 10819, 1996, 2013). The basic trends and characteristics of the spectra are consistent with those predicted using a model of the glove-hand-arm system (Dong et al., 2013). These data were considered as part of the basis for synthesizing the transmissibility spectra. Specifically, three air bladder-filled gloves were tested in the reported study (McDowell et al., 2013a). Because these air bladder gloves exhibited similar 3-D transmissibility spectra, only one of them was considered in the current study. The regular work glove did not significantly isolate vibration; thus, that glove was not considered further in the current study. The three remaining VR gloves were manufactured from different materials and had some significant differences among their transmissibility spectra; they were included in the current study. The four VR gloves considered in this study are shown in Fig. 1. Their basic features are listed in Table 1.

Fig. 2 shows the basic test setups used in the measurement by McDowell et al. (2013a). The hand and arm postures used in the study are similar to those required in the standard glove test (ISO 10819, 1996, 2013). Seven adult males participated in the measurement with three hand force treatments (15 N grip + 30 N push, 30 N grip + 50 N push, and 45 N grip + 70 N push). For the purpose of the current study, the spectra measured with the middle force treatment (30 N grip and 50 N push) were selected to represent the average transmissibility spectra of the gloves in the tool operations. Unfortunately, because of the limitation of the 3-D test system, the frequency range of the measured transmissibility spectra is only from 16 to 500 Hz (McDowell et al., 2013a), which does not cover the full range of the frequencies (6.3–1250 Hz) required to assess hand-transmitted vibration exposure (ISO 5349-1, 2001). This study conducted some experiments to measure additional glove transmissibility spectra, which are described in the next subsection.

2.1.2. Measurement of additional transmissibility spectra in the x and y directions—The vibration spectra components at frequencies below 16 Hz cannot be ignored because the highest weighting is applied in this frequency range (ISO 5349-1, 2001). Fortunately, these low-frequency components are not difficult to estimate because the transmissibility in this region is close to unity (Dong et al., 2004, 2005; Welcome et al., 2011, 2012; Hewitt, 2010). This study used the data measured on 1-D test systems to fill in the missing spectra in this low-frequency range. Vibration components at frequencies above 500 Hz are not critical, as only frequency-weighted acceleration is of concern in the current study. This is for the following two reasons: (I) the frequency weighting is less than 0.025 at frequencies above 500 Hz (ISO 5349-1, 2001); and (II) the dominant weighted vibrations of the vast majority of tools or machines are observed at frequencies below 500 Hz (Griffin, 1997). As an approximation, the missed spectra for this frequency range were also estimated using 1-D test data. While the transmissibility spectra of the four selected gloves along the forearm (*z*) directions have been sufficiently measured in our previous studies (Welcome et al., 2011, 2012), the spectra in the other two directions (*x* and *y*) were measured in the current study.

Fig. 3 shows the test setups and subject postures for the measurement in the *x* direction. They are similar to those used in the 3-D test shown in Fig. 2, except that the subject assumed a posture in which the forearm was 90° from the vibration direction, and the hand was subjected to vibration in the *x* direction. The same instrumented handle and palm adapter as used in the 3-D test were used in the current study. Five subjects participated in the experiment. Each subject was advised to position the palm adapter at the prescribed location on the palm and align it with the handle as in the 3-D test. Because the push force in the *x* direction could substantially affect the vibration of the instrumented handle on the 1-D test system, only grip force was applied in the test. To better simulate the palm force under the 30 N grip and 50 N push in the 3-D test, a grip force of 80 N was applied. The handle was rotated about the *y*-axis of the handle fixture by 90° so that the measurement direction of the grip force was the same as that in the 3-D test. The vibration spectrum (from 5 to 1600 Hz) used in the 1-D test is shown in Fig. 4, which is very different from the spectrum used in the 3-D test (also plotted in Fig. 4), but it is identical to that specified in the revised version of ISO 10819 (2013) at frequencies above 25 Hz (also plotted in Fig. 4). The remaining test conditions and test procedures were the same as those used in the 3-D test (McDowell et al., 2013a). To minimize the effect of adapter misalignment on the evaluated transmissibility spectrum (Hewitt, 1998), a total vibration method was used to calculate the transmissibility (Dong et al., 2002b). Each transmissibility spectrum was expressed in the one-third octave bands from 6.3 to 1250 Hz.

To measure the vibration transmissibility spectra of the gloves in the *y* direction, a special instrumented handle was developed and used for the test, as shown in Fig. 5. The hand and arm postures are similar to those in the test for the *x* direction, except the hand was rotated 90° about the forearm axis, as shown in Fig. 6. The palm adapter and the remaining test conditions, procedures, and calculation method are the same as those used in the *x* direction test. The slit in the glove shown in Fig. 6 was made for the alignment of the palm adapter with the handle vibration direction (Welcome et al., 2012; McDowell et al., 2013a).

2.1.3. Synthesis of the representative glove transmissibility spectra—For each glove in each direction, the average transmissibility spectrum of the 3-D and 1-D data was used to represent the spectrum from 16 to 500 Hz. The remaining spectra were from the 1-D data measured in this study or those measured in previous studies (Welcome et al., 2011, 2012).

2.2. Tool vibration spectra

Part of the tool vibration spectra used in this study was collected from our previous studies and literature (Dong et al., 2002a, 2003; McDowell et al., 2009, 2012, 2013b; Goglia et al., 2003; Dewangan and Tewari, 2009). Some of these spectra were measured by the UK Health and Safety Laboratory (Pitts et al., 2012). The remaining part was measured in the current study. The tool vibration spectra were selected and treated using the following criteria and methods:

(i) The vibration spectra were measured with the standard method defined in ISO 5349-1 (2001). Fig. 7 shows some examples of accelerometers installed on tool handles and the hand and arm postures for the vibration measurement in the current study.

(ii) As also shown in Fig. 7, the spectra were simultaneously measured in the three orthogonal translational directions.

(iii) The spectra of impact tools include no significant dc-shift (Griffin, 1990).

(iv) The vibration spectra were expressed in the one-third octave bands. If the original spectra do not include the full frequency range (6.3–1250 Hz), the missing values were taken as zero.

(v) If necessary and possible, the original coordinate axes (*x*, *y*, *z*) of the accelerometer for tool vibration measurement were switched to approximately match with those used in the measurement of the glove transmissibility spectra (Fig. 2). The axes of some data presented in this paper may be labeled differently from those in their original publications.

Some samples of tool vibration spectra are shown in Fig. 8. The basic trends of the spectra in the three directions for each tool are similar. This was also confirmed by the correlation analyses performed in this study. For all tools considered in this study, the vibration spectra in at least two directions are reliably correlated ($r^2 \geq 0.40$, $p < 0.05$). The coherence values at the major peak frequencies generally fall in the range of 0.5–1.0. In many cases, the coherence values are greater than 0.70.

2.3. Calculation of tool-specific glove transmissibility values

According to ISO 10819 (1996, 2013), the transmissibility value of frequency-weighted acceleration in each direction was calculated from

$$T_{w-n}=\frac{\sqrt{\sum_i [T_n(\omega_i)\cdot a_n(\omega_i)\cdot W_h(\omega_i)]^2}}{\sqrt{\sum_i [a_n(\omega_i)\cdot W_h(\omega_i)]^2}}, \quad n=x,y,z \qquad (1)$$

where T_x, T_y, and T_z are the glove vibration transmissibility spectra in three orthogonal directions (*x*, *y*, and *z*), a_x, a_y, and a_z are tool vibration spectra in three orthogonal directions, W_h is the frequency weighting factor for hand-arm vibration exposure defined in ISO 5349-1 (2001), and ω_i is the circular frequency in Rad/s corresponding to the *i*th frequency in the one-third octave bands from 6.3 to 1250 Hz.

Similarly, according to the total vibration (vector sum of the three-axial vibrations) defined in ISO 5349-1 (2001), the transmissibility values for total vibration were calculated as follows (Dong et al., 2002b):

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

After the transmissibility value was obtained, the percent reduction for weighted acceleration (R_w) was calculated from

$$R_w=(1-T_w)\cdot 100\% \quad (3)$$

3. Results

3.1. Comparison of the glove transmissibility spectra measured on 1-D and 3-D test systems

The vibration transmissibility spectra of the four gloves measured in the 1-D and 3-D tests are shown in Fig. 9. Although the tests were performed on different test systems with different subjects under different excitations (McDowell et al., 2013a; Welcome et al., 2011, 2012), the 1-D and 3-D spectra in the common frequency range (16–500 Hz) are similar. The agreement between the spectra of each glove in the *z* direction is especially good, probably because the applied hand forces were the same (30 N grip and 50 N push) in both 3-D and 1-D tests. The 1-D data are also generally consistent with those reported in our other previous studies (Dong et al., 2002a, 2002b, 2003, 2004, 2009). These consistencies suggest that these transmissibility spectra are reliable.

3.2. Synthesized transmissibility spectra of the VR gloves in three directions

The representative transmissibility spectra of the four gloves for the 30 N grip and 50 N push were synthesized using the spectra shown in Fig. 9. The results are plotted in Fig. 10. Probably because air-cushioned elements are the major isolation materials of Gloves B and C, their transmissibility spectra and distributions in the three directions are very similar. On the other hand, although the major isolation material of Glove A is obviously different from that of Glove D, as described in Table 1, their transmissibility spectra and distributions in the three directions are similar. The spectra shown in Fig. 10 indicate that the two air-cushioned gloves are generally more effective at reducing the vibration along the forearm or *z* direction, but they are less effective in the other two directions than the two non-air-cushioned gloves.

3.3. Tool-specific transmissibility values of the VR gloves in three directions

As examples, Table 2 lists the frequency-weighted accelerations of several tools and their corresponding glove transmissibility values in the three directions calculated using Eq. (1) and total vibration transmissibility values calculated using Eq. (2). For low-frequency tools such as the vibrating fork and the pavement tamper, the transmissibility value in each direction for each glove is close to unity because the corresponding transmissibility spectrum of each glove is close to unity in the low-frequency range, as shown in Fig. 10. For other tools, the transmissibility value of the gloves in the *y* direction is generally the highest, except for Glove A. Because Glove C is the most effective in the *z* direction, it can isolate more vibration from the chipping hammer than other gloves because the dominant vibration of the chipping hammer is in this direction. This is, however, not the case when the vibration is more spatially distributed among the three directions, as in the case of the impact wrench. In such a case, the total vibration transmissibility value is close to the average of those in the three directions, and Glove A becomes the most effective glove.

3.4. Tool-specific reduction of the total vibration (vector sum)

In this study, the vibration attenuation effectiveness of a glove is primarily quantified in terms of the percent reduction of the frequency-weighted vector sum acceleration transmitted to the palm of the hand, and it is calculated using Eqs. (2) and (3). To help identify the basic features of tool-specific glove effectiveness, the percent reduction values are classified into three groups. In the first group, the percent reductions are less than 5%, which are listed in Table 3, together with the source information of the tool vibration data and the weighted accelerations. These tools include low-frequency tools (with dominant vibration frequencies below 25 Hz) such as vibrating forks, paving tampers, and rammers. This group also includes tools with their major vibrations distributed in the *y* direction such as straight nutrunners and some rivet bucking bars.

In the second group, the percent reductions are between 5% and 10%, which are listed in Table 4. In the third group, the VR gloves reduce more than 10% of the vibrations transmitted from the tool to the palm of the hand, which are listed in Table 5. These tools are either high-frequency tools such grinders and saws or impact tools with fundamental impact rates above 25 Hz and their major high-frequency components in the *x* and/or *z* direction such as chipping hammers and riveting hammers. It is interesting to note that the vibration reductions of the gloves on the two handles of the same tool may be different. For example, when Gloves B, C, and D are used with the stone chisel, they reduce little vibration (≤2.2%) transmitted to the hand holding the chisel, as indicated in Table 4. This is because the impact vibration on the chisel is primarily along the axis of the chisel or the pure shear (*y*) direction of the hand. On the handle of the same chisel, however, these gloves can reduce more than 15% of the palm-transmitted vibration, as presented in Table 5. This is because both vibration distribution and exposure direction are changed on the handle.

The average vector sum reduction of these four gloves for all three groups of tools is 8.2%. If the first group of tools is eliminated, the average reduction becomes 11.5%. Although Glove A cannot be classified as an AV glove (Welcome et al., 2012), as also noted in Table 1, it is the most effective glove when used with many of the tools, as indicated in Tables 4 and 5. Glove D is also occasionally among the most effective ones (e.g., Rivet hammer S1 and Die grinder). The mean percent reduction of Glove A is not significantly different from that of Glove C in the second and third groups of tools ($p \geq 0.93$). These two gloves are generally significantly ($p < 0.05$) or suggestively ($p < 0.10$) more effective than the other two gloves. Although Glove B can be classified as an AV glove, as also noted in Table 1, it is generally the least effective of the four gloves.

4. Discussion

This study synthesized a group of representative vibration transmissibility spectra of four typical vibration-reducing gloves and applied them to estimate tool-specific vibration attenuation effectiveness of the gloves for reducing frequency-weighted vibrations transmitted to the palm of the hand in three orthogonal directions. The examination of the glove transmissibility spectra and their synthesis enhanced the understanding of the characteristics of VR gloves. The results of the study can be used to help select appropriate gloves for various vibrating tools.

4.1. The testing and evaluation methods for VR gloves

The large differences between the excitation spectra used in the 3-D and 1-D tests shown in Fig. 5 did not lead to substantial differences between the transmissibility spectra measured in the 3-D and 1-D tests in each direction for each glove, as shown in Fig. 9. This suggests that the glove transmissibility spectrum is not sensitive to the excitation spectra, which is consistent with that observed in our previous studies (Rakheja et al., 2002; Dong et al., 2002a; Welcome et al., 2012). This basically suggests that it is acceptable to use the transmissibility spectra measured in the laboratory to crudely estimate tool-specific effectiveness of these VR gloves.

The results of this study also confirm that the effectiveness of a VR glove is direction-specific. A glove that is most effective along the forearm direction measured in the standard test may not be the most effective in the other directions, as evident from the comparisons shown in Fig. 10 and Tables 3 and 4 This suggests that the results of the single-axis test adopted in the standard may not be sufficient to make a fair judgment of the overall performance of a VR glove. The single-axis method is also inconsistent with the standard method for assessing the risk of hand-transmitted vibration exposures (ISO 5349-1, 2001). The 3-D method proposed and applied in the current study is generally applicable for glove evaluations. The comparisons shown in Fig. 9 also suggest that it is acceptable to use the 3-D spectra measured separately on a single-axis vibration test system to approximately represent the transmissibility spectra of the gloves subjected to 3-D vibration exposures. This may make it technically much easier to estimate the performances of VR gloves in multi-axial vibration exposures.

4.2. Selection of gloves

It is generally recommended to wear gloves in the operations of powered hand tools, provided that glove use is consistent with safe work practices and tool control. The performance of VR gloves for reducing vibration is only one of beneficial factors to be considered in the selection of appropriate gloves. The other beneficial factors include keeping hands warm and dry, reducing hand contact stressors, increasing friction force, and protecting hands from cuts, skin abrasions, burns, and chemical exposures. As noted in Table 1, VR gloves also usually substantially increase the grip effort (Wimer et al., 2010;

Welcome et al., 2011, 2012). Some of them may also greatly reduce finger dexterity and make it difficult for the fingers to apply triggering actions. These adverse effects may increase the potential for some hand injuries and safety risks (Silverstein et al., 1987). The optimized selection should consider all the beneficial and adverse factors, as well as features such as durability, cost, waterproofing etc.

As indicated in Table 2, none of the VR gloves could significantly reduce frequency-weighted vibrations from low-frequency tools or tools that produce major vibrations in the axial direction of the tool handle. Regular work gloves are likely to be a better option for these tools because they may not substantially increase the grip effort and should allow for better finger dexterity than VR gloves. Some other approaches for reducing vibration exposures from such tools should be considered; such tactics include regular tool maintenance programs, procedures for identifying and procuring reduced-vibration tools, and sharing tool operations among team members (HSE, 2005).

As presented in Tables 4 and 5, VR gloves are likely to reduce palm-transmitted frequency-weighted vibrations by 5%–58%, depending on the type of tool. Generally speaking, if the vibration is primarily distributed in the *z* direction or along the forearm direction, AV gloves certified according to ISO 10819 (2013) are the best choice, as demonstrated in Table 2. If the tool vibrations are relatively evenly distributed among the three directions, the overall percent reductions of the four gloves considered in this study are not practically substantially different from each other, as also indicated in Table 2. The best option depends primarily on the other glove benefits and functions, as well as their balance with any adverse effects. It should also be noted that two different gloves could be worn in the operation of a tool. For example, an operator could select Glove A for the hand controlling a stone chisel because that glove can reduce more axial vibration. For the other hand holding the chisel handle and controlling the trigger, Glove C or D might be a better choice for maximizing vibration reduction without losing as much finger dexterity.

4.3. Other applications and limitations of the estimated glove effectiveness

The results of an epidemiological study suggest that the current frequency weighing defined in ISO 5349-1 (2001) is acceptable for assessing the risk of the vibration-induced disorders in the wrist (Malchaire et al., 2001). The current frequency weighting is also similar to the biodynamic frequency weighting derived from the vibration power absorption measured at the palm of the hand (Dong et al., 2006, 2008). These observations suggest that the palm-transmitted weighted vibration is likely to be associated with injuries and disorders in the palm-wrist-arm substructures. The results listed in Tables 4 and 5 may be used to estimate the related benefits for these substructures. However, gloves are likely to reduce less vibration transmitted to the fingers (Dong et al., 2009; Welcome et al., 2014). This suggests that it is not appropriate to directly use the listed reduction values to estimate a glove's finger protection.

As mentioned in the introduction, some factors such as the applied hand forces, hand and arm postures, and handle geometries may affect the vibration transmissibility of a glove (Dong et al., 2004; McDowell et al., 2013a). Glove vibration transmissibility and tool vibration may also vary significantly among individuals (Dong et al., 2009; Laszlo and

Griffin, 2011; Welcome et al., 2012). Because averaged spectra were used in this study, the estimated percent reductions listed in Tables 3–5 may represent only the average effectiveness of gloves for reducing palm-transmitted vibration exposures. Furthermore, the glove transmissibility spectra used in this study were not measured under high amplitude of vibrations that may cause some contact separations at the glove-tool-hand interfaces and/or make the glove cushion bottom out; the glove transmissibility spectra in such a vibration exposure may have some differences from those shown in Figs. 9 and 10. The use of the palm adapter for transmissibility measurements may also influence the glove transmissibility (Dong et al., 2005). These observations suggest that the estimated reductions listed in the tables are unlikely to be precise for every possible working condition and each individual. The listed reductions may only be considered as crude approximations of general glove performance.

5. Conclusions

This study proposed and applied an approximation method for estimating tool-specific 3-D performances of four typical vibration-reducing gloves for attenuating frequency-weighted vibrations transmitted to the palm of the hand. Besides the reported evidence supporting this method, it was further justified by the following observations from the current study: the 3-D transmissibility spectra of the gloves simultaneously measured under a 3-D vibration excitation were similar to those separately measured in each direction under different excitations on a 1-D test system. This similarity suggests that glove transmissibility is not sensitive to the input vibration, and it is acceptable to approximately predict the palm-transmitted 3-D vibrations using tool vibration spectra along with measured glove vibration transmissibility spectra.

The results of this study demonstrate that vibration-reducing gloves do not significantly reduce (<5%) vibrations generated by many low-frequency (<25 Hz) tools or those vibrating primarily along the axis of the tool handle. When used with other tools, VR gloves can reduce palm-transmitted vibration in the range of 5%–58%, depending on the specific tool and vibration spectra. While gloves classified as anti-vibration gloves according to the standard glove test are generally more effective along the forearm direction than other VR gloves, AV gloves may be less effective in the other two directions. As a result, in some cases, non-AV gloves can be more effective than AV gloves at reducing palm-transmitted triaxial vector sum vibrations. These observations suggest that the single-axis method defined in the glove test standard may not provide a fair judgment of VR gloves, and AV gloves classified according to the standard may not be the best choice in some cases. An optimized glove selection should consider 3-D vibration transmissibility values. The glove transmissibility spectra synthesized in this study can be used to roughly estimate the transmissibility values for any given tool vibration spectra. The estimated tool-specific vibration reductions at the palm of the hand, along with consideration for each glove's other features and functions, may be applied to perform preliminary glove selection for the operations of some specific powered hand tools. However, as the glove effectiveness may vary significantly with working conditions and individuals, the estimated data may not be used to predict the specific performances of the gloves for each individual at each workplace. Furthermore, the vibration reductions at the palm of the hand do not fully represent the performances of the gloves for hand protection. Because these gloves may not effectively reduce finger-transmitted vibrations, it is on the conservative side to disregard glove vibration reductions in risk assessments of hand-transmitted vibration exposures.

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Fig. 1.

The gloves used in the study and their major vibration isolation materials: Glove A – thick gel pad; Glove B – cellular air bubbles; Glove C – air bladder with pump; and Glove D – dipped neoprene.

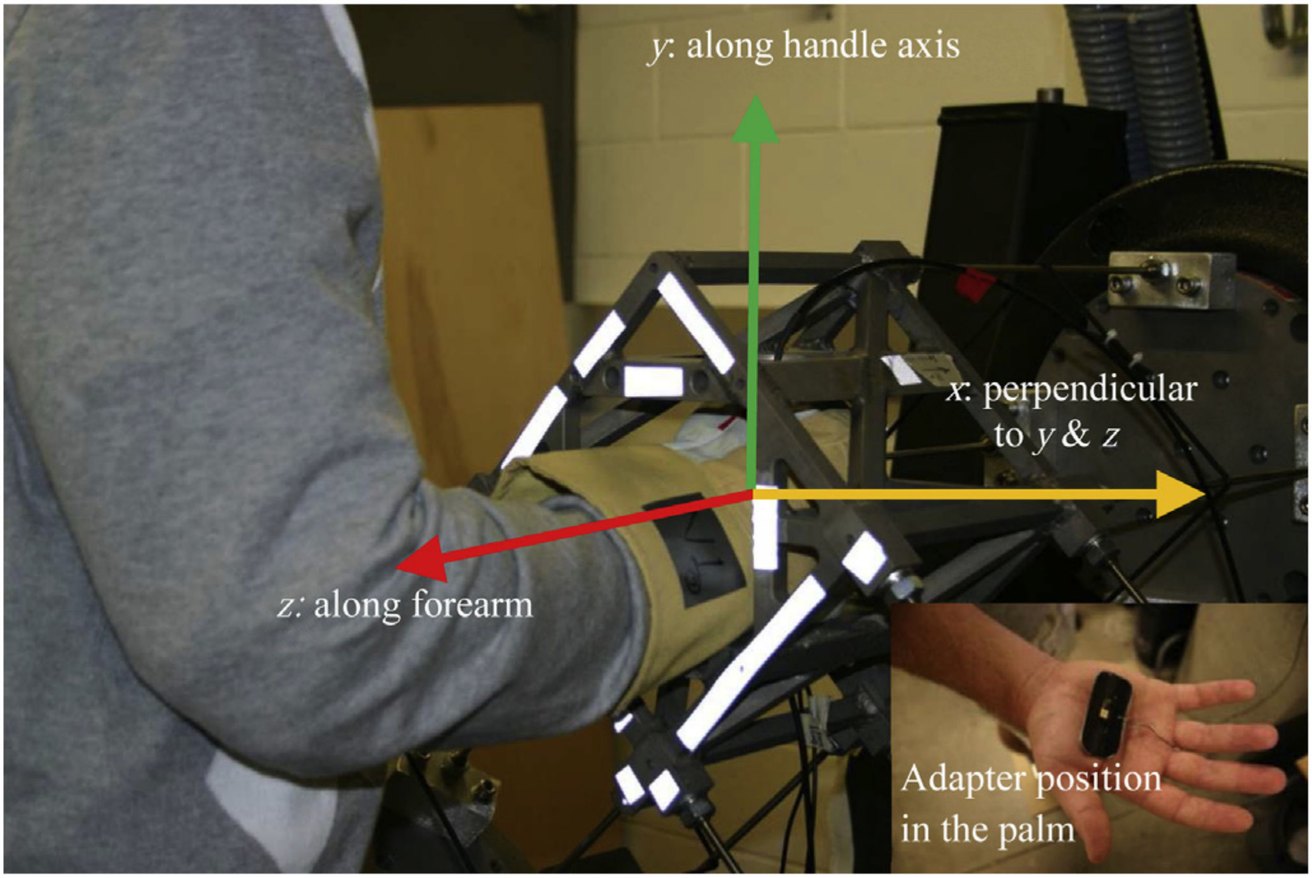


Fig. 2.
The measurements of glove transmissibility spectra at the palm of the hand in the three orthogonal directions (3-D: *x*, *y*, and *z*) using a palm adapter on a 3-D hand-arm vibration test system (McDowell et al., 2013a).

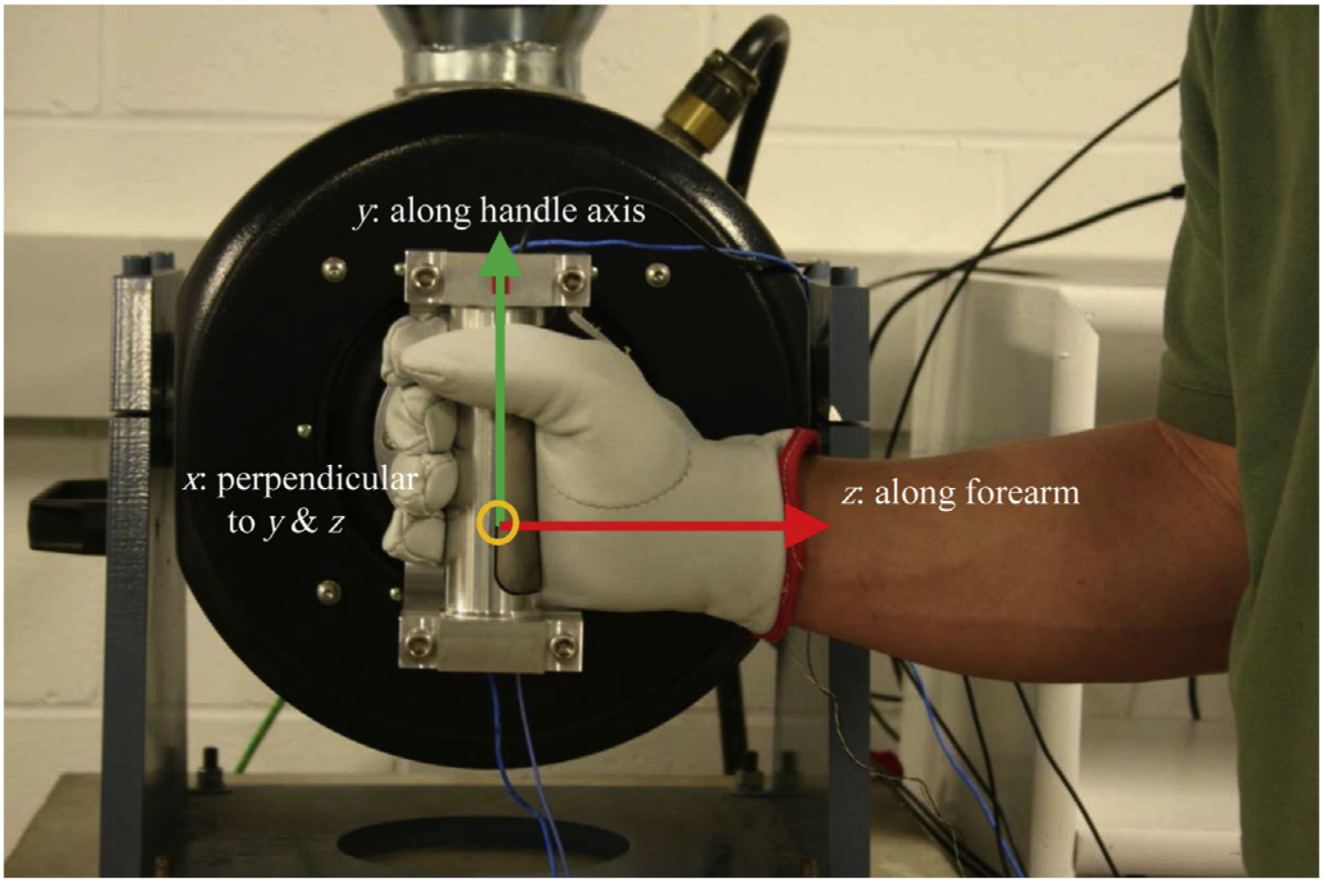


Fig. 3.
The measurement of glove transmissibility at the palm in the *x* direction using a palm adapter on a 1-D vibration test system.

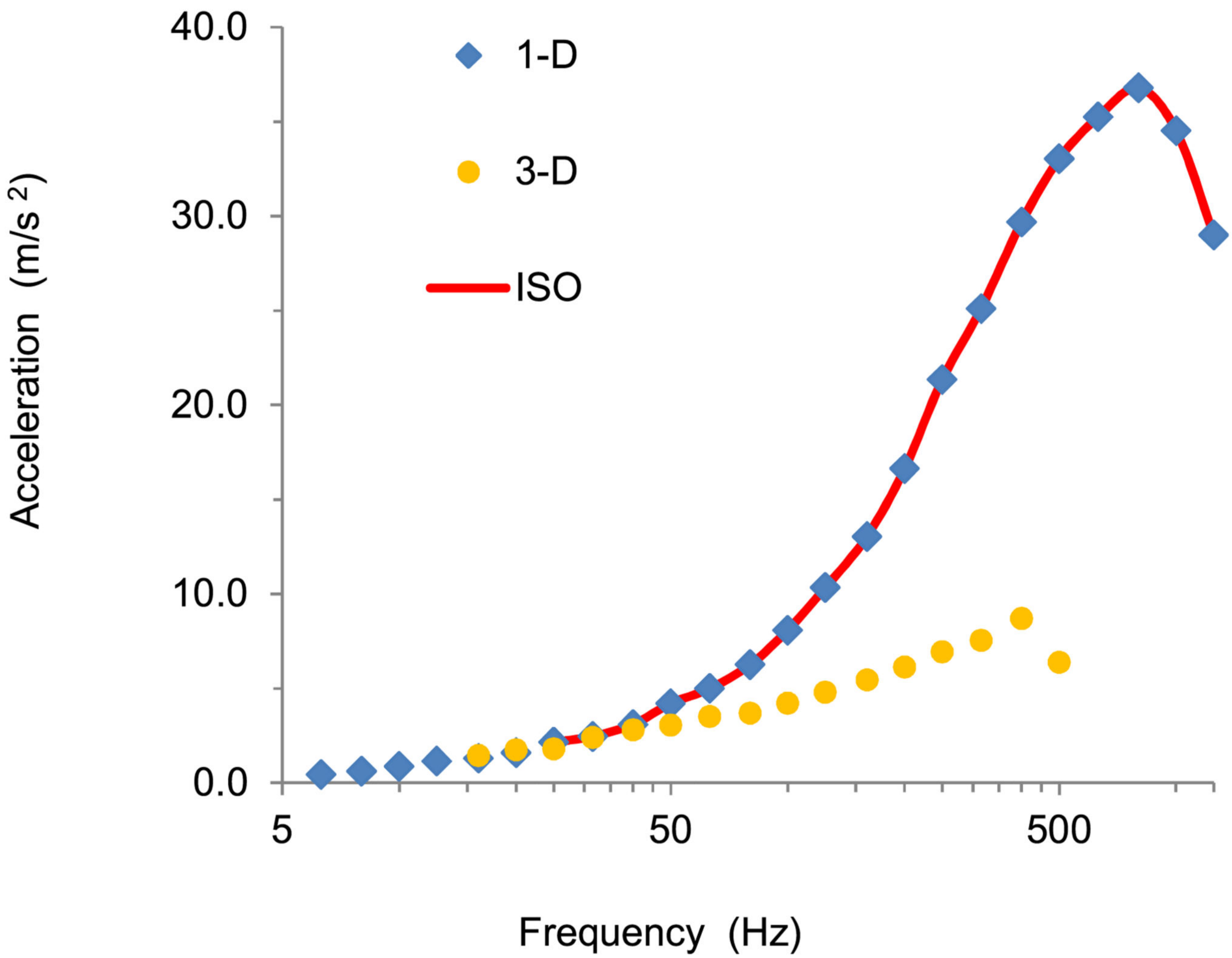


Fig. 4.

Comparisons of the excitation spectra used in the measurements of glove transmissibility spectra in the 1-D and 3-D test systems and that in the revision of the ISO 10819 (2013).

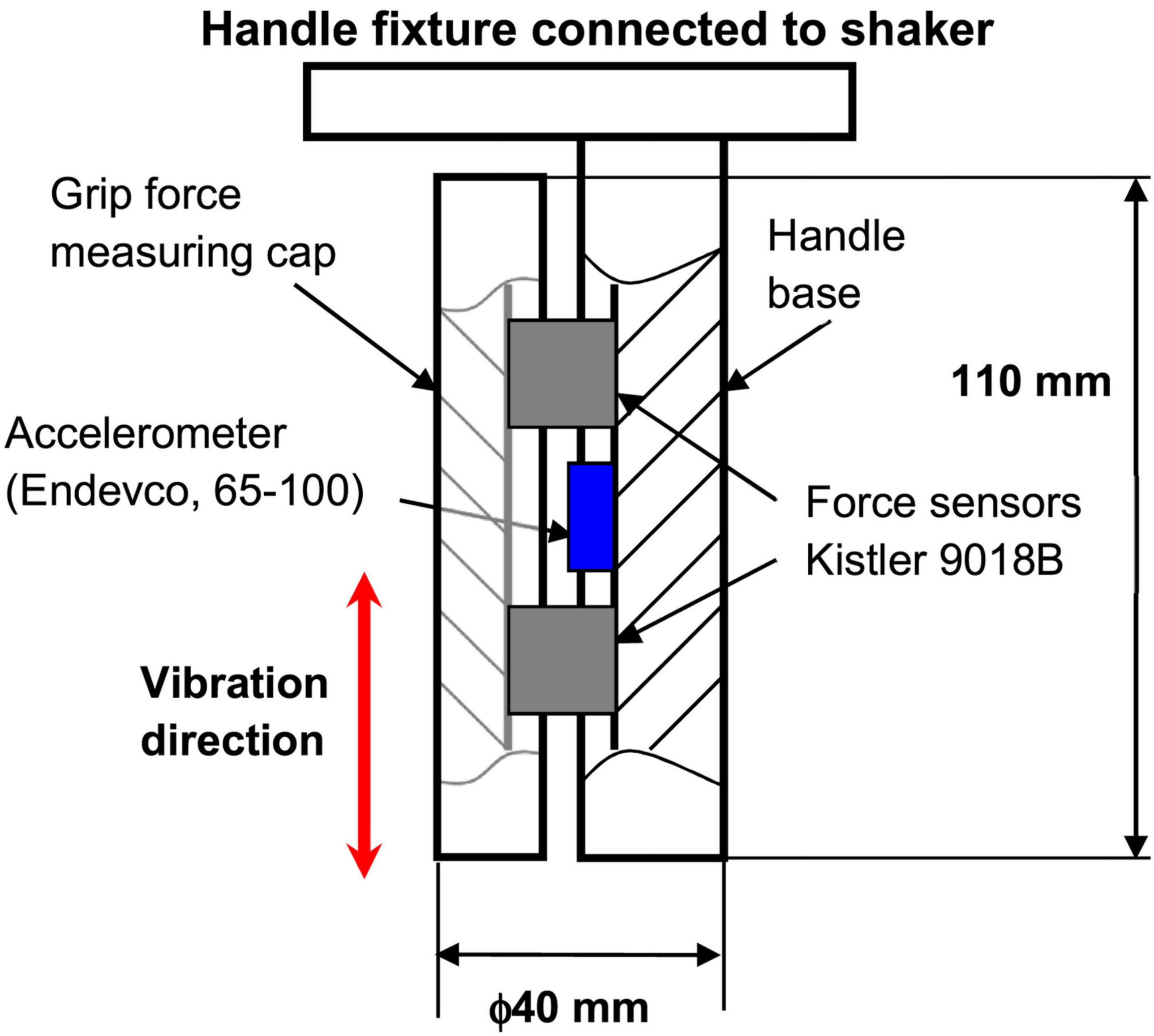


Fig. 5.
A sketch of the instrumented handle for the measurement of glove transmissibility in the *y* direction.

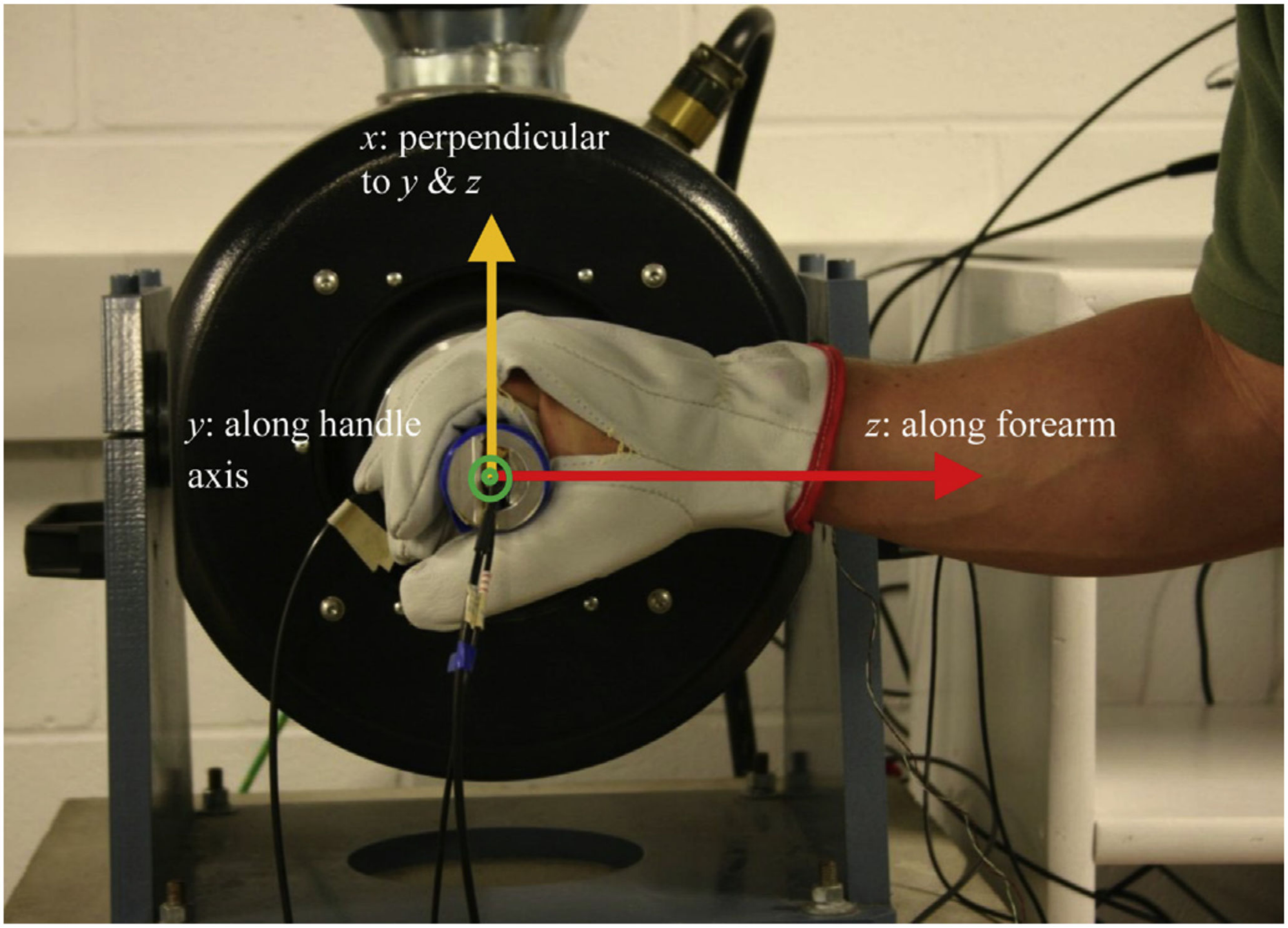
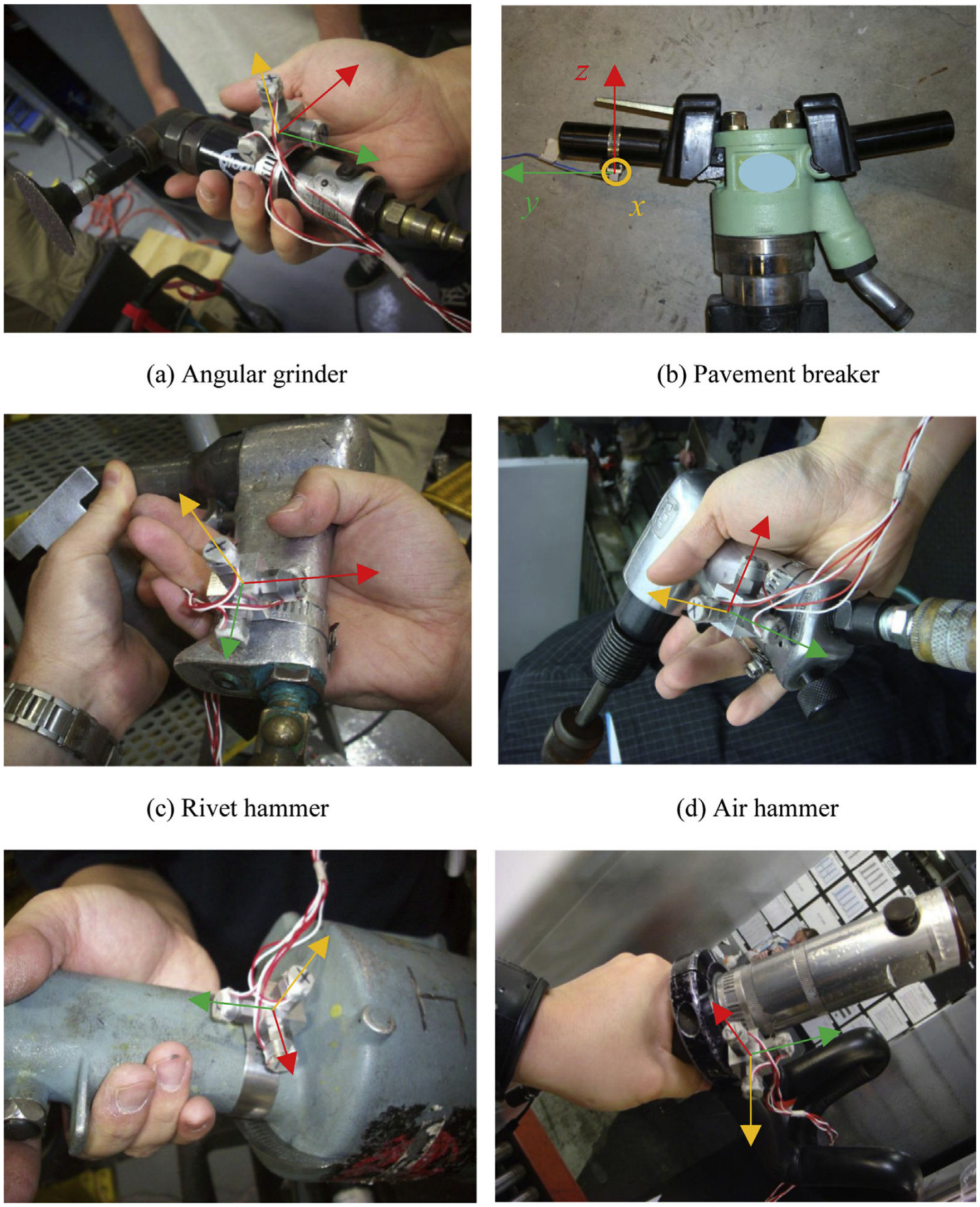


Fig. 6.
The measurement of glove transmissibility at the palm in the *y* direction using a palm adapter on a 1-D vibration test system.



(a) Angular grinder

(b) Pavement breaker

(c) Rivet hammer

(d) Air hammer

(e) Cherry gun

(f) Nutrunner

Fig. 7.

Examples of accelerometers mounted on several tools and the hand grip postures in the measurements of tool vibrations.

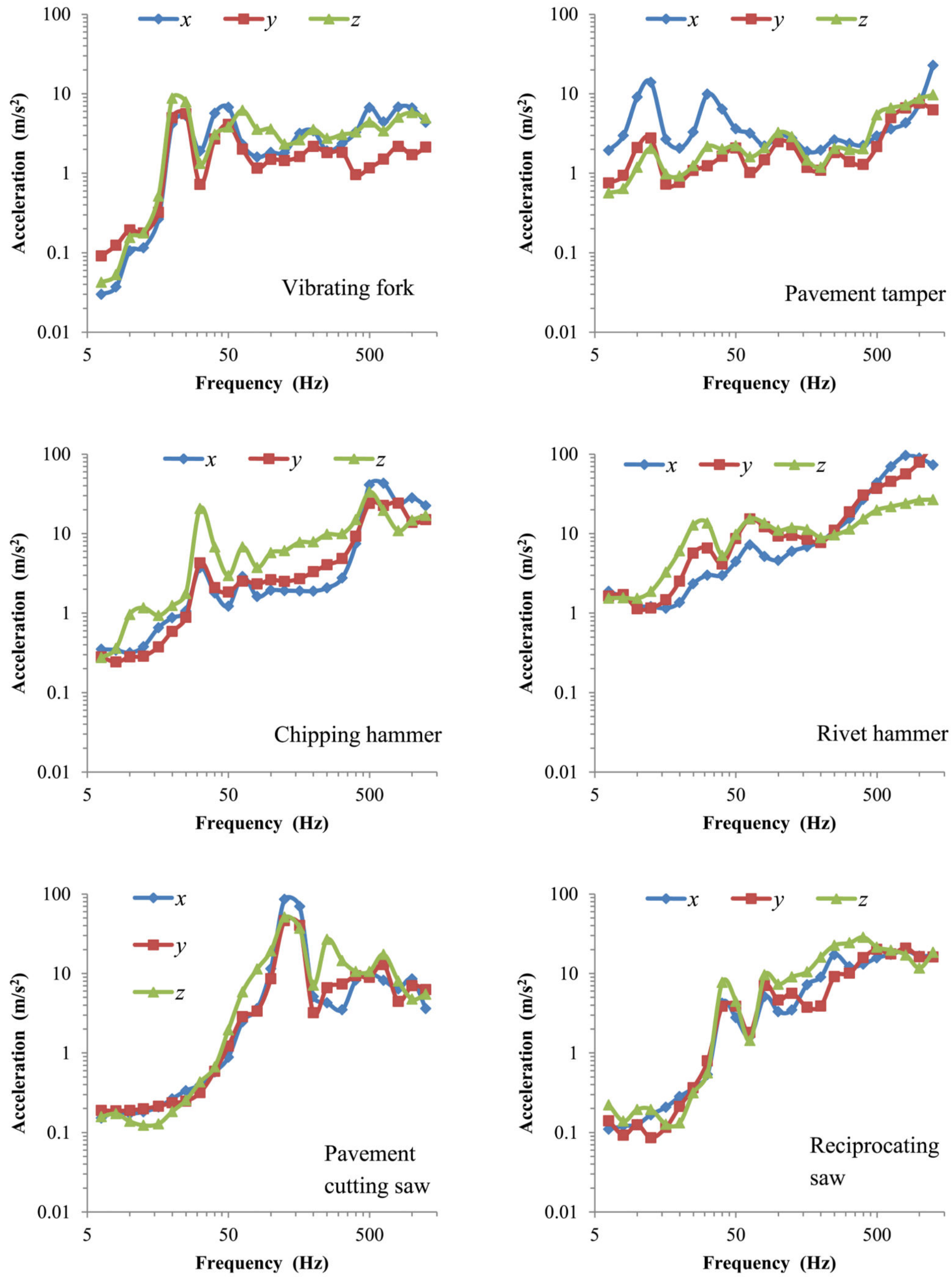


Fig. 8.
Examples of tool vibration spectra used in the study.

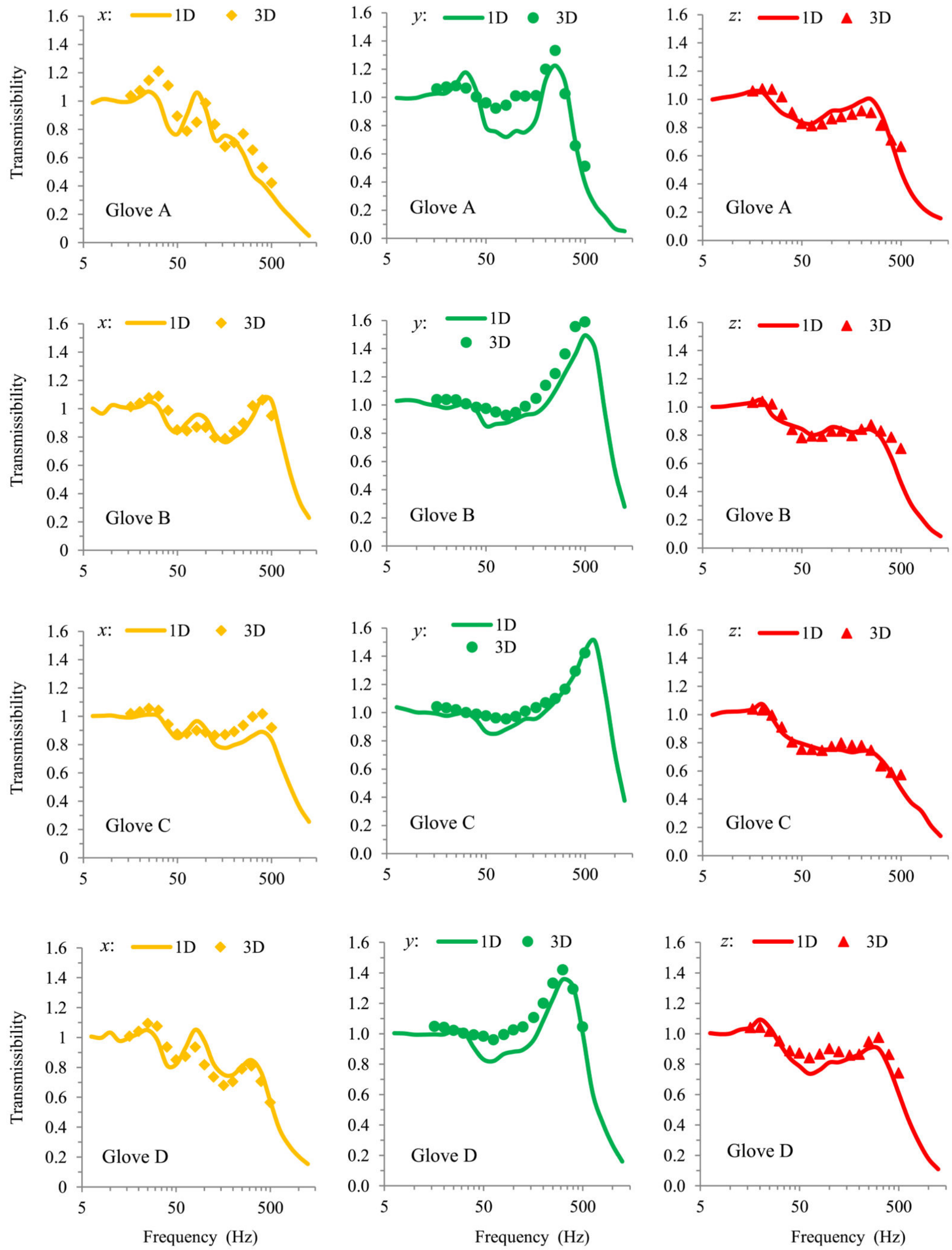


Fig. 9.
Comparisons of the transmissibility spectra of the gloves measured on a 1-D test system with those measured on a 3-D vibration test system (McDowell et al., 2013a).

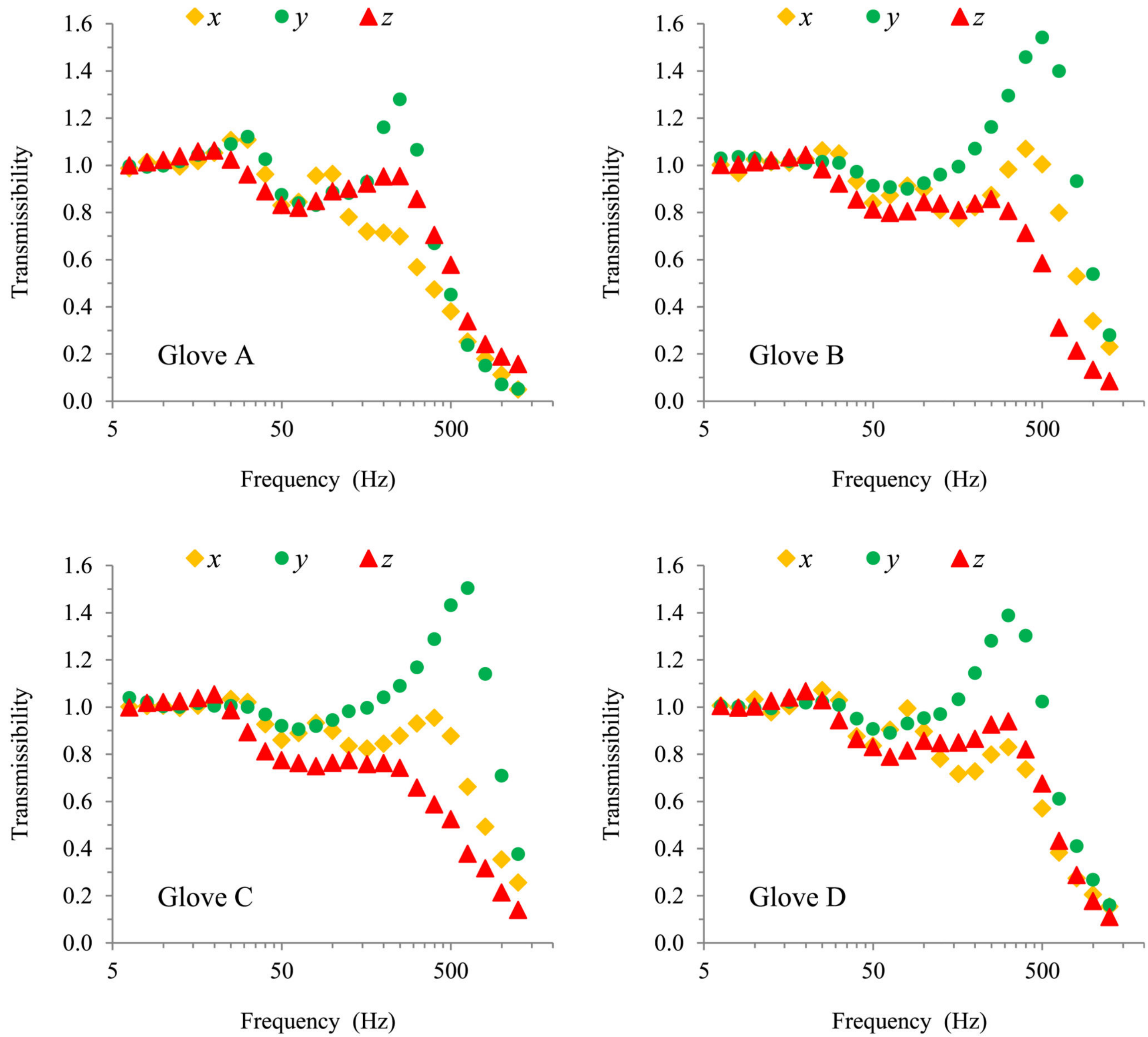


Fig. 10.
Vibration transmissibility spectra of the four gloves synthesized using the data measured at the palm of the hand in the three orthogonal directions.

Table 1

Major features of the selected vibration-reducing gloves.

Glove ID	Major AV materials	AV glove classification according to ISO 10819 (2013) (Welcome et al., 2011)	Grip strength reduction (%) (Welcome et al., 2011)	Other features and potential problems
A	Thick gel pad	No	42	Bulky and low finger dexterity; good thermal feature; low contact stress
B	Cellular air bubbles	Yes, barely.	34	Uneven contact stress due to distributed air bubbles; could lose local AV function from the air leak from an air cell.
C	Air bladder with pump	Yes, with a good margin	31	Requires pumping every use; could lose the major AV function from air leak at any location.
D	Dipped neoprene	No	26	Inexpensive; comfortable.

Table 2

Examples of the tool frequency-weighted accelerations (A_w) and their corresponding transmissibility values (T_w) in the three directions (x_h, y_h, z_h) calculated using Eq. (1) and total vibration transmissibility values calculated using Eq. (2).

Tool		**Vibrating fork**				**Paving tamper**			
Direction		*x*	*y*	*z*	Sum	*x*	*y*	*z*	Sum
A_w (m/s^2)		5.3	5.1	10.1	12.7	11.4	10.2	4.3	18.2
T_w	Glove A	1.02	1.05	1.03	1.04	0.98	1.01	0.99	1.01
	Glove B	0.99	1.01	1.00	1.01	0.99	1.01	0.97	1.01
	Glove C	0.99	1.00	1.01	1.01	0.98	1.00	0.96	1.00
	Glove D	0.98	1.01	1.03	1.02	0.97	0.99	0.97	0.99
Tool		**Chipping hammer**				**Riveting hammer**			
Direction		*x*	*y*	*z*	Sum	*x*	*y*	*z*	Sum
A_w (m/s^2)		2.8	2.8	11.6	12.3	6.8	8.3	17.9	20.8
T_w	Glove A	0.78	0.96	0.94	0.93	0.79	0.90	0.96	0.93
	Glove B	0.95	1.07	0.90	0.92	0.93	1.09	0.92	0.95
	Glove C	0.90	1.07	0.87	0.88	0.90	1.09	0.89	0.93
	Glove D	0.80	0.97	0.92	0.92	0.83	0.99	0.94	0.94
Tool		**Pavement cutting saw**				**Reciprocating saw**			
Direction		*x*	*y*	*z*	Sum	*x*	*y*	*z*	Sum
A_w (m/s^2)		8.4	5.3	6.8	12.1	2.5	2.5	4.9	6.0
T_w	Glove A	0.77	0.91	0.90	0.85	0.78	0.87	0.87	0.86
	Glove B	0.82	0.98	0.83	0.86	0.89	1.11	0.82	0.88
	Glove C	0.85	0.99	0.77	0.85	0.88	1.08	0.76	0.84
	Glove D	0.78	0.99	0.85	0.85	0.81	1.02	0.85	0.87
Tool		**Impact wrench**				**Impact drill**			
Direction		*x*	*y*	*z*	Sum	*x*	*y*	*z*	Sum
A_w (m/s^2)		4.7	3.7	4.2	7.3	8.7	8.4	6.4	14.4
T_w	Glove A	0.66	0.86	0.89	0.79	0.76	0.80	0.87	0.84
	Glove B	0.86	1.04	0.84	0.91	0.93	1.11	0.83	0.95
	Glove C	0.82	1.06	0.78	0.88	0.90	1.09	0.79	0.93
	Glove D	0.72	0.93	0.87	0.83	0.84	0.96	0.86	0.90

Table 3

The first group of tools and working conditions in which the estimated reductions of the frequency-weighted total vibrations are less than 5% for any of the four VR gloves (negative value means amplification) (note: the tool vibration spectra without specifying the source were measured in the current study).

Tool	Available tool information and working conditions	A_w (m/s^2)	Percent reduction (%)			
			Glove A	Glove B	Glove C	Glove D
Vibrating fork	Cleaning simulated beach contaminated by leaked oil (McDowell et al., 2013b)	12.7	−3.7	−0.9	−0.9	−2.2
Paving tamper	Tamping asphalt pavement	18.2	−1.0	−0.9	0.5	0.8
Floor rammer	Ramming sand/cement mix in to mould (Pitts et al., 2012)	23.7	−1.2	−1.1	0.1	0.7
Bench rammer	Ramming sand/cement mix in to mould (Pitts et al., 2012)	30.5	−3.1	−0.1	0.2	−0.6
Hand-held tractor	6.7 kW; transportation at 1.31 m/s; rota-tilling at 0.45 m/s; rota-puddling at 0.45 m/s (Dewangan and Tewari, 2009).	6.7	−2.4	0.5	1.9	1.2
A low vib. wrench	Tightening 10 large nuts on a simulated work station (McDowell et al., 2009)	2.7	0.6	1.7	2.7	2.1
Straight nutrunner 1	Tightening machine screws to secure refrigerator door hinges	2.5	0.1	1.2	1.3	1.2
Straight nutrunner 2	Tightening machine screws to secure refrigerator door hinges	2.3	3.4	4.3	4.8	4.3
Pistol nutrunner	Installing machine screws to secure adapters in refrigerator	2.6	2.5	2.3	3.3	3.1
Hilock gun	Installing Hi-Lok style fasteners in helicopter frames	1.8	−0.9	−0.3	−0.1	0.1
Shear gun	Cutting sheet metal	5.4	−2.7	0.2	0.9	−0.5
Terry motor	Installing Hi-Lok style fasteners in helicopter frames	1.9	0.8	1.8	2.4	1.9
CH bucking bar	Installing Hi-Lok style fasteners in helicopter frames	15.8	4.1	4.1	4.8	3.4
DF bucking bar	Installation of rivets in helicopter frames	28.0	2.2	3.4	4.1	3.2
Foot bucking bar	Installation of rivets in helicopter frames	12.6	3.9	1.7	2.3	2.6
ARO gun	Installation of panels on the backside of refrigerator	5.3	0.2	3.1	3.8	0.9
Screw gun 1	Attaching a palette-like skid plate to the bottom of refrigerator	4.2	−1.0	−0.2	0.4	0.5
Screw gun 2	Installation of a pan at the bottom of refrigerator	5.6	−2.9	−1.0	−0.2	−1.0
Rivet hammer 2	Riveting airplane frames (McDowell et al., 2012)	15.9	3.9	4.2	4.7	3.9
Cherry max gun	Riveting Cherry-Max style rivets	3.7	2.9	−8.4	−4.2	−6.3
Heavy rotary hammer	Electricity 110 V, 11 kg, drilling concrete with 32 × 250 mm masonry bit (Pitts et al., 2012)	18.9	−5.4	1.6	3.1	1.7
Mean		**10.5**	**0.0**	**0.8**	**1.7**	**1.0**

Table 4

The second group of tools and working conditions in which the estimated reductions of the frequency-weighted total vibrations are in the range of ≥5% and ≤10% for at leas one of the four VR gloves (note: the tool vibration spectra without specifying the source were measured in the current study).

Tool	Working conditions and data sources	A_w (m/s^2)	Percent reduction (%)			
			Glove A	Glove B	Glove C	Glove D
Paving breaker	Breaking damaged pavement (Dong et al., 2003)	31.6	2.7	5.1	6.5	4.5
Impact wrench 3	Tightening 10 large nuts on a simulated work station (McDowell et al., 2009)	9.4	7.7	5.9	7.0	6.8
Impact wrench 4	Tightening 10 large nuts on a simulated work station (McDowell et al., 2009)	8.3	7.3	4.7	5.7	5.9
Rivet hammer 1	Riveting airplane frames (McDowell et al., 2012)	20.8	7.1	5.2	7.2	6.0
Rivet hammer 4	Riveting airplane frames (McDowell et al., 2012)	29.7	7.2	6.7	8.5	6.5
Rivet hammer 5	Riveting airplane frames (McDowell et al., 2012)	13.6	8.1	6.6	8.3	7.5
Rivet hammer 6	Riveting airplane frames (McDowell et al., 2012)	18.0	5.0	5.1	6.2	5.0
L bucking bar	Installation of rivets in helicopter frames	7.8	9.8	1.3	2.3	2.8
TR bucking bar 1	Installation of rivets in helicopter frames	14.6	8.9	1.7	2.3	2.6
TR bucking bar 2	Installation of rivets in helicopter frames	21.4	4.1	7.2	9.6	6.6
Screw gun 3	Installing machine screws to secure damper cover in refrigerator	3.1	3.3	5.0	5.8	4.6
Straight nutrunner 3	Tightening machine screws to secure refrigerator door hinges	3.0	6.2	7.4	8.5	7.1
Angular nutrunner	Installing machine screws to secure refrigerator door hinge pins	2.9	3.5	5.8	7.5	5.1
Stone chisel	Chiseling granite with 1 inch masonry chisel (Pitts et al., 2012)	19.8	8.1	−1.7	2.2	−2.5
Mean		**14.6**	**6.4**	**4.7**	**6.3**	**4.9**

Table 5

The third group of tools and working conditions in which the estimated reductions of the frequency-weighted total vibrations are greater than 10% for at least one of the four VR gloves (note: the tool vibration spectra without specifying the source were measured in the current study).

Tool	Working conditions and data sources	A_w (m/s^2)	Percent reduction (%)			
			Glove A	Glove B	Glove C	Glove D
Chipping hammer A	6.6 kg chipping hammer; standard chipping hammer test (Dong et al., 2003)	11.0	8.9	11.8	15.6	10.9
Chipping hammer B	6.9 kg chipping hammer; standard chipping hammer test (Dong et al., 2003)	12.3	6.6	8.3	11.6	7.9
Impact drill A	3 kg impact drill; drilling a concrete plate	14.4	15.9	5.1	6.5	9.6
Impact drill B	6 kg impact drill; drilling a concrete plate	10.7	6.1	8.4	10.9	9.4
Impact drill C	Electric 110 V, 8 mm masonry bit, drilling concrete block (Pitts et al., 2012)	20.2	57.8	35.1	33.6	44.9
Pneumatic Rock drill	15.6 kg, drilling concrete (Pitts et al., 2012)	11.7	9.3	12.5	16.1	11.4
Reciprocating saw	Cutting a concrete plate	6.0	14.4	11.8	15.9	13.0
Chain saw	4.9 kg, idling (Pitts et al., 2012)	9.9	15.2	14.6	14.2	14.9
Clay spade	Digging a hole	27.3	9.3	10.2	11.7	9.6
Pavement cutting saw	Cutting asphalt pavement	12.1	15.3	14.5	15.4	15.0
Tractor driving wheel	A small diesel tractor (22 kW) with 4-wheel drive; idling and fully loaded.	16.8	8.5	12.4	17.3	11.0
Impact wrench 1	Tightening 10 large nuts on a simulated work station (McDowell et al., 2009)	7.3	21.0	9.5	12.3	17.4
Impact wrench 5	Tightening 10 large nuts on a simulated work station (McDowell et al., 2009)	5.5	12.5	8.8	11.4	11.3
Rivet hammer 3	Riveting airplane frames (McDowell et al., 2012)	28.5	15.3	12.6	16.9	14.1
Rivet hammer 7	Riveting airplane frames (McDowell et al., 2012)	21.2	12.8	14.2	18.0	13.6
Rivet hammer 8	Riveting airplane frames (McDowell et al., 2012)	21.2	12.0	12.8	16.5	12.6
Rivet hammer S1	Riveting helicopter frames	3.5	22.8	21.5	22.1	22.8
Rivet hammer S2	Riveting helicopter frames	2.6	13.2	13.4	15.6	13.2
Rivet hammer S3	Riveting helicopter frames	2.7	11.3	7.7	9.1	10.3
Rivet hammer S4	Riveting helicopter frames	5.7	12.3	12.7	14.0	12.4
Angular grinder	Electricity 240 V, cutting paving slab with 230 diamond wheel (Pitts et al., 2012)	10.1	11.4	12.2	14.8	12.6
Angular grinder	Surface grinding of helicopter frames	5.7	10.6	13.8	16.7	11.7
Die grinder	Fine surface grinding of helicopter frames	2.0	15.7	13.7	13.3	15.2
Drill	Drilling holes to prepare for riveting	2.9	13.2	15.1	17.5	15.0
Palm hammer	Pounding the plastic light covers into place in refrigerator	17.0	11.1	16.0	21.8	12.7
Air hammer	Pounding the rubber drain plug into place in refrigerator	9.9	18.6	11.8	16.0	13.6
Handle of atone chisel	Chiseling granite with 1 inch masonry chisel (Pitts et al., 2012)	21.4	16.5	15.0	17.0	16.1
Hedge trimmer	45 cm blade, trimming hedge (Pitts et al., 2012)	13.7	15.8	13.0	13.4	13.4
Strimmer	Strimming grass (Pitts et al., 2012)	7.4	16.2	7.9	8.9	10.1

Tool	Working conditions and data sources	A_w (m/s^2)	Percent reduction (%)			
			Glove A	Glove B	Glove C	Glove D
Multi-use tool	Electricity 110 V, cutting 20 mm chipboard with a 35 mm oscillating blade (Pitts et al., 2012)	13.9	37.6	10.4	17.4	19.0
Needle scaler	Scaling rusty metal with 19 × 3 mm chisel needle (Pitts et al., 2012)	11.9	15.1	8.2	7.3	6.2
Rand orbit sander	Preparing train carriage for repainting with 320grit aluminum oxide (Pitts et al., 2012)	4.8	9.0	11.4	16.8	9.6
Triple headed scabbler	Scabbling concrete (Pitts et al., 2012)	12.8	5.1	7.2	7.4	10.3
Mean		**11.6**	**15.0**	**12.5**	**14.9**	**13.7**