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An examination of the handheld adapter approach for measuring hand-transmitted vibration exposure

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Abstract

The use of a handheld adapter equipped with a tri-axial accelerometer is the most convenient and efficient approach for measuring vibration exposure at the hand-tool interface, especially when the adapter is incorporated into a miniature handheld or wrist-strapped dosimeter. To help optimize the adapter approach, the specific aims of this study are to identify and understand the major sources and mechanisms of measurement errors and uncertainties associated with using these adapters, and to explore their improvements. Five representative adapter models were selected and used in the experiment. Five human subjects served as operators in the experiment on a hand-arm vibration test system. The results of this study confirm that many of the handheld adapters can produce substantial overestimations of vibration exposure, and measurement errors can significantly vary with tool, adapter model, mounting position, mounting orientation, and subject. Major problems with this approach include unavoidable influence of the hand dynamic motion on the adapter, unstable attachment, insufficient attachment contact force, and inappropriate adapter structure. However, the results of this study also suggest that measurement errors can be substantially reduced if the design and use of an adapter can be systematically optimized toward minimizing the combined effects of the identified factors. Some potential methods for improving the design and use of the adapters are also proposed and discussed.

Keywords

Hand-arm vibration; Hand-transmitted vibration; Vibration measurement; Vibration dosimeter; Handheld adapter

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1. Introduction

Various powered hand tools are widely used in many industries. Prolonged, intensive exposure to vibration generated from some of these tools may cause hand-arm vibration syndrome [1,2]. Hand-transmitted vibration exposure has also been identified as a contributing factor towards developing carpal tunnel syndrome [3]. To control hand-transmitted vibration exposure, the International Organization for Standardization has set forth a standard for the measurement, evaluation, and assessment of the exposure [4,5]. The standardized daily exposure dose is termed as A(8), and its value depends basically on two variables: (i) vector sum of the frequency-weighted accelerations in three orthogonal directions measured at or near the area where each hand is in contact with a vibrating tool or machine; and (ii) daily exposure duration. While the international standard does not recommend any specific target for the exposure control, two targets are recommended or required by some countries in their national counterparts to the international standard [6,7]. The targets are termed as Daily Exposure Action Value (DEAV = 2.5 m/s^2) and Daily Exposure Limit Value (DELV = 5.0 m/s^2). While workers should not be exposed to A(8) values beyond the DELV, employers should initiate a program to reduce exposures if a worker's exposure dose exceeds the DEAV [6,7]. The effective and appropriate implementation of the standard or Directive depends partially on whether the daily vibration exposure dose can be conveniently and reliably measured. This remains an important issue for further studies.

Hand-transmitted vibration could vary greatly with many factors such as tool model, tool condition, location and direction on a tool, working material, tool user's biodynamic properties, applied hand force, and working posture [8–10]. The standards recommend that vibration exposures be measured at workplaces under actual working conditions [4,7]. While it is usually unreliable to determine exposure durations based on workers' self-reports [11–13], the exposure duration for the operation of each tool can be accurately measured using several simple methods such as video recording or activity sampling. These approaches can be time-consuming and expensive for long-term measurements. Furthermore, the vibration magnitude could vary with time, and workers can use various tools during each shift; it is desired to determine daily exposure dose by measuring the exposure dose history over an entire shift. To account for day-to-day variations, it is also desired to measure long-term exposure dose history. The history data may also be useful for studying the effects of work-rest patterns on the development of vibration-induced disorders. Such measurements require a convenient, reliable, robust, and inexpensive miniature dosimeter that presents minimal interference with work activities during its operation.

As demonstrated in some studies [14,15], attaching an accelerometer to a location on the hand is probably the most convenient approach for measuring hand-transmitted vibration exposures. The most desired location is at the wrist because it produces minimal interference with hand movements, similar to activity wrist watches. While this approach is acceptable for quantifying exposure duration with sufficient accuracy [16], it may not be generally acceptable for measuring vibration magnitude since much of the hand-transmitted vibration may be attenuated before it reaches the wrist; the near-unity bandwidth of wrist vibration transmissibility is very limited [17–19]. The bandwidth of the on-the-hand approach can be increased by attaching the accelerometer on the dorsum of the hand or a finger, as was done in some studies [14,15]. The data from other studies indicate that the near-unity transmissibility on any part of the hand is usually limited to frequencies below 150 Hz [19–21], except in the fingertip area where it is difficult to fix a conventional tri-axial accelerometer. Furthermore, the vibration transmissibility on the hand in the three orthogonal directions may vary greatly with the specific location, subject, hand force, posture, handle shape and dimension. Therefore, although on-the-hand approaches have some unique advantages, this technique is not recommended in the standardized method for measuring vibration exposure.

The standardized method requires the attachment of an accelerometer on the tool handle to measure the hand-transmitted vibration [4,7]. Four attachment approaches (screwing, gluing, using a hose clamp, or using a handheld adapter) are recommended in the standard [5]. Each of them has unique advantages and disadvantages [22,23]. The handheld adapter approach is most convenient and efficient. With this approach, the accelerometer can also be positioned at the most desired location: the central area of hand-handle interference. Many adapter configurations have been designed [22,24–26]. Some of them have also been adopted in the standard [5]. The adapter approach has also been incorporated into handheld vibration dosimeters [27,28], which can make the measurement very convenient and efficient. On the other hand, the adapter approach is generally considered as the least reliable among the four recommended approaches [22,23]. While the adapter approach is not generally recommended for the measurement of vibration on engineering structures [29], it is considered as the last choice in the standard for measuring the hand-transmitted vibration exposure [5]. Although some studies have been performed to optimize adapter designs [22,26], the exact sources and mechanisms of the measurement errors and uncertainties using the adapter approach have not been clearly identified. In particular, there are few reports on the effects of hand biodynamics on the measurement. Furthermore, while the reported studies primarily investigated fingers-held adapters [22,23,26], it is unclear whether other adapters can provide better measurements. It is also unclear whether and how the adapter approach can be further improved.

Based on this background, the objectives of this study were to identify the major sources of measurement errors and uncertainties using the adapter technique, to enhance the understanding of the mechanisms involved with measurement errors, and to explore improvements in the adapter method. While some preliminary results were briefly reported at a conference [30], the completed study is presented in this paper.

2. Methods

2.1. Experiments

Fig. 1 shows five handheld adapters that have been examined in this study, together with their designed holding positions on the hand. Their sources and major features are listed in Table 1. Adapter 2 has two foot options: (A) with the original foot design of the fingers-held dosimeter and (B) with a modified foot similar to that of the fingers-held adapter (Adapter 3), which adapts better to the instrumented handle. Each of the adapters was equipped with a tri-axial accelerometer.

Five healthy male subjects (ages 19 to 31) participated in the experiment. Their major anthropometries are listed in Table 2. The study protocols were reviewed and approved by the NIOSH Human Subjects Review Board. The experimental setup and operator postures used in this study are shown in Fig. 2. Although a single-axis shaker was used to provide the vibration input to the hand along the forearm or *z*-axis, some vibrations could also be generated in the other two orthogonal axes (*x* and *y*) when a hand grips on the handle [31]. The instrumented handle is equipped with a tri-axial accelerometer (PCB, 356A12), which is firmly affixed to the inner surface of the handle base [31]. The instrumented handle is also equipped with a pair of force sensors (Kistler, 9212) to measure the applied grip force. A commercial force plate (Kistler, 9286AA) was used to measure the applied push force. The fundamental natural frequency of this instrumented handle is above 1700 Hz [32].

If not specified, a broad-band random vibration spectrum from 12.5 to 1000 Hz was used as the excitation in the experiment. Its acceleration spectrum is shown in Fig. 3(a). The dosimeter equipped with the glove-held adapter (Adapter 5) can only measure the frequency-weighted root-mean-square (rms) value; a discrete sinusoidal vibration at each one-third octave band frequency in the tested frequency range was used as the excitation to measure the transmissibility spectrum of this adapter. Its input acceleration amplitude at each frequency is shown in Fig. 3(b).

The accelerometers were calibrated before installing them on the adapters. A series of bare adapter tests was performed to examine the dynamic behaviors of the adapters and to establish their baseline transmissibility spectra. In the tests, each adapter was secured using rubber bands on the handle at the location corresponding to its normal location when the adapter is held in the hand, as shown in Fig. 4. The tightening force was 80 N for palm adapters (including Adapter 5) and 30 N for finger-held adapters (including Adapter 4).

In the human subject tests, each operator was advised to assume the same body and hand-arm postures as those required in the standardized glove test [24], as shown in Fig. 2. The applied grip force (30 ± 5 N) and push force (50 ± 8 N) were also the same as those required in this standard. Fig. 5 shows the adapter positions and hand postures used in the human subject tests. To explore the effect of multi-axial vibrations on the measurement, Adapter 3 was tested at two handle contact locations around the handle circumference: (1) aligned with the designed handle vibration direction (*z*), as shown in Fig. 5(d); and (2) oriented about 50° from the handle vibration direction, as shown in Fig. 5(e). The beam adapter (Adapter 4) with a long V-shaped foot can adapt well to the instrumented handle along its axial direction (Fig. 5(f)), but it may not maintain stable contact with many real tool handles. To simulate such a scenario, an additional test was conducted where the beam adapter was purposely misaligned with the handle axis, as shown in Fig. 5(g).

The palm adapter (Adapter 1) was originally designed to measure the vibration transmissibility of anti-vibration (AV) gloves as standardized in ISO 10819 [24]. Unlike AV gloves, typical work gloves do not significantly isolate vibration, and their transmissibility spectra are usually close to unity in the major frequency range of concern; these characteristics have been further confirmed in a recent study [33]. It has been hypothesized that using a palm adapter with such gloves can be useful for measuring vibration exposures

[34]. While the recent study measured the transmissibility spectra of a typical synthetic leather work glove at frequencies up to 500 Hz [33], the same glove, as shown in Fig. 6(a), was considered in the current study to further evaluate the palm adapter when used with a typical work glove. Similar to that shown in Fig. 4(a), a bare adapter-glove test was performed by fixing the adapter inside the glove on the handle with 80 N tightening force using rubber bands. The hand and arm postures used in the human subject test are shown in Fig. 6(b), which are similar to those shown in Fig. 5(a).

As shown in Fig. 2, the vibrations in three orthogonal directions on the adapter ($A_{\text{x\_adapter}}$, $A_{\text{y\_adapter}}$, $A_{\text{z\_adapter}}$) and handle ($A_{\text{x\_handle}}$, $A_{\text{y\_handle}}$, $A_{\text{z\_handle}}$) were simultaneously measured using a commercial data acquisition system (B&K 3032). The results were expressed in the one-third octave bands from 12.5 to 1000 Hz.

2.2. Evaluations

The vibration transmissibility spectra of the adapters were primarily used to examine the adapter approach. The transmissibility spectrum (T_r) of each adapter at each frequency (ω) was calculated from

$$T_r(\omega)=\frac{\sqrt{A^2_{x\_\text{ adapter}}(\omega)+A^2_{y\_\text{ adapter}}(\omega)+A^2_{z\_\text{ adapter}}(\omega)}}{\sqrt{A^2_{x\_\text{ handle}}(\omega)+A^2_{y\_\text{ handle}}(\omega)+A^2_{z\_\text{ handle}}(\omega)}} \quad (1)$$

For the purpose of this study, the transmissibility spectrum of each adapter measured in the bare adapter test was used as a baseline spectrum or in situ calibration factor of the adapter. Similar to that required for correcting the weighted transmissibility value in the standardized glove test [24], the transmissibility spectrum measured in the human subject test ($T_{r\text{\_subject raw}}$) was normalized with respect to the baseline spectrum ($T_{r\text{\_bare adapter}}$) as follows:

$$T_{r\_\text{ subject}}(\omega)=\frac{T_{r\_\text{ subject raw}}(\omega)}{T_{r\_\text{ bare adapter}}(\omega)} \quad (2)$$

Besides the transmissibility spectra, the frequency-weighted vibrations on the handle (A_{Handle}) and adapter (A_{Adapter}) were also used to examine the performances of the adapters. The weighted vibrations were calculated from

$$A_{\text{Handle}}=\sqrt{\sum\left[A^2_{x\_\text{ handle}}(\omega)+A^2_{y\_\text{ handle}}(\omega)+A^2_{z\_\text{ handle}}(\omega)\right]\cdot W_h^2(\omega)}, \quad (3)$$

$$A_{\text{Adapter}}=\sqrt{\sum\left[A^2_{x\_\text{ adapter}}(\omega)+A^2_{y\_\text{ adapter}}(\omega)+A^2_{z\_\text{ adapter}}(\omega)\right]\cdot W_h^2(\omega)}, \quad (4)$$

where W_h is the frequency weighting factor defined in ISO 5349-1 (2001) [4]. The integration was made from 12.5 Hz to 1000 Hz. Similar to the treatment of the transmissibility spectrum, a ratio of the accelerations measured on the adapter and the handle in the bare adapter test was used as a calibration factor to correct the adapter acceleration measured in the human subject test [24]. Then, the percent error of the weighted acceleration for each adapter was calculated from

$$\text{Percent error} = \left[\left(A_{\text{Adapter}} - A_{\text{Handle}}\right) / A_{\text{Handle}}\right] \cdot 100\% \quad (5)$$

Similar to the excitation spectra used in some reported adapter studies [22,23], the spectra used in the current study were not measured on any powered hand tool or machine. The tool vibration spectra should be considered to explore the tool-specific potential error of the adapter approach. As a crude but reasonable approximation, the vibration spectrum of each adapter for each tool (a_{adapter}) was estimated using the adapter transmissibility spectrum measured with each subject (T_r) and the tool vibration spectrum (a_{tool}) measured on a tool handle as follows:

$$a_{\text{adapter}}(\omega) = T_r(\omega) \cdot a_{\text{tool}}(\omega) \quad (6)$$

For the purpose of this study, several representative spectra of tool vibrations reported by Griffin [35] were used in the estimation.

The weighted accelerations of the tool handle and adapter are calculated from

$$A_{\text{Handle}} = \sqrt{\sum \left[a_{\text{tool}}^2(\omega) \cdot W_h^2(\omega)\right]}, \quad (7)$$

$$A_{\text{Adapter}} = \sqrt{\sum \left[a_{\text{adapter}}^2(\omega) \cdot W_h^2(\omega)\right]} \quad (8)$$

The frequency range of the integration was the same as that used in Eqs. (3) and (4). The percent error of the weighted acceleration for each tool was also calculated using Eq. (5).

Where appropriate, a linear model for the analysis of variance (ANOVA) was used to determine the statistical significance of factors that may affect the transmissibility spectra and weighted vibrations.

3. Results

The results of the ANOVA indicate that the vibration transmissibility of the adapters measured in the human subject test is significantly affected by frequency, adapter model, adapter orientation, and adapter position ($p < 0.001$). The transmissibility also generally varied by subject.

Fig. 7(a) shows the palm adapter (Adapter 1) transmissibility spectra measured with the five subjects, together with their mean spectrum and the baseline spectrum. The ideal transmissibility is unity; any value greater than 1.0 means overestimation and less than 1.0 means underestimation. The baseline spectrum measured in the bare adapter test was sufficiently close to unity (error < 5%) in the entire frequency range of concern. This spectrum also suggests that the resonance frequency of the adapter on the handle is above 1000 Hz. These observations suggest that the basic performance of the adapter on the handle is acceptable. However, the vibration of the adapter in the human subject test was substantially amplified at low and middle frequencies (<100 Hz). In contrast, the transmissibility spectra of this adapter with the glove measured in the human subject test were much closer to unity, as shown in Fig. 7(b). Specifically, below the fundamental resonance frequency of the hand-arm system (about 30 Hz for 30 N grip and 50 N push [36]), the glove amplified the transmissibility by less than 5%. At higher frequencies up to 200 Hz, the glove reduced the transmitted vibration by less than 8%. The second resonance occurred above 200 Hz. The resonance peak was 1.90 at 630 Hz in the adapter-glove test, as also shown in Fig. 7(b). The resonance was reduced to 1.15 in the human subject test. The coefficients of variation (CV = standard deviation/mean value) at each frequency were equal to or less than 5%.

Fig. 8(a) shows the test results of the finger-held dosimeter (Adapter 2). Similar to that of the palm adapter, the baseline transmissibility spectrum of this adapter is acceptable. The vibration of the adapter in the human subject test was markedly amplified in the frequency range from 20 to 80 Hz. The average resonant peak was observed around 40 Hz, and its corresponding measurement error was close to 100%. The modified version of Adapter 2 with the V-shaped foot significantly reduced the mean error ($p < 0.001$), but the transmissibility spectra remained far from acceptable, as shown in Fig. 8(b).

To help further understand the resonance of Adapter 2, an additional test was performed using discrete sinusoidal vibrations with one of the operators. With the adapter position and hand posture as shown in Fig. 5(b), the z axis of the adapter was aligned with the handle vibration direction. To identify the contribution of the transmitted vibration of each axis to the total vibration, the ratio of the axial vibration and the total vibration was calculated using the following formula:

$$D_i(\omega)=\frac{A_{i-\text{adapter}}(\omega)}{\sqrt{A^2_{x-\text{adapter}}(\omega)+A^2_{y-\text{adapter}}(\omega)+A^2_{z-\text{adapter}}(\omega)}},\quad i=x,y,z \tag{9}$$

The results are plotted in Fig. 9. Theoretically, the vibration should be primarily distributed in the z-axis ($D_z \approx 100\%$) and those in the other two axes (D_x and D_y) should remain at low percentages at each frequency. However, this was not the case at frequencies below 100 Hz. The z-axis vibration was reduced while those in the other two axes were much higher, especially in x axis from 30 to 60 Hz. This indicates that less vibration was transmitted from the handle to the adapter in the z axis in this frequency range, and the generally amplified total vibration observed in Fig. 8(a) and (b) resulted from the unexpected vibrations in the x and y axes. This indicates that the adapter likely became separated from the handle and oscillated in the other two axes, especially in the x axis.

Fig. 8(c) shows the transmissibility spectra measured with the fingers-held adapter (Adapter 3) with the normal axis of the foot approximately aligned with the vibration direction (Fig.

5(d)). For this configuration, the data for three of the five subjects are fairly close to the baseline data; if the data measured with Subjects 3 and 4 are removed, the mean transmissibility spectrum would be acceptable. As shown in Fig. 8(d), when the adapter was positioned on the handle with a large angle (about 50°) with respect to the handle vibration direction, the measured transmissibility spectra exhibited a pattern similar to that observed with Adapter 2.

Fig. 10(a) shows the transmissibility spectra measured with the beam adapter (Adapter 4) with its longitudinal axis aligned with the handle axis. In this configuration, the adapter was well adapted to the handle surface. The subject data are generally much better correlated with the baseline data than the above-presented spectra for the other adapter configurations. Although the maximum percent error measured with one of the subjects at frequencies below 500 Hz was still about 10%, the mean spectra should be considered acceptable for practical applications. Conversely, as shown in Fig. 10(b), the performance of this adapter was greatly deteriorated when the adapter was positioned on the handle at an angle with respect to the handle axis (Fig. 5(g)).

Fig. 10(c) shows the transmissibility spectra measured with the glove-held adapter (Adapter 5). Unlike the transmissibility spectra measured with other adapters, the mean transmissibility of this adapter was generally less than 1.0, or the acceleration measured at the adapter was less than the excitation acceleration, especially at frequencies above 500 Hz ($p < 0.001$). If the mean transmissibility spectrum is normalized with respect to the average value of the transmissibility data (0.915), the error is less than 5% at frequencies below 500 Hz.

Table 3 lists the percent errors and coefficients of variation of the frequency-weighted accelerations measured in the human subject tests, together with those estimated using the tool vibration spectra and the adapter transmissibility spectra. A positive value of the percent error represents overestimation and any negative value means underestimation. While the maximum overestimation of the weighted accelerations directly measured in this study is 87% (with spectrum-a shown in Fig. 3), the estimated error could be up to 136% if the palm adapter (Adapter 1) were used in the measurement of the vibration on a road breaker. However, the measurement error for each case could be less than 5% if the same palm adapter is used with the glove in the measurement of weighted vibration on every tool listed in the table. The beam adapter (Adapter 4) could also provide measurements with less than 5% error if stable contact with the tool handles could be ensured. Although the overall percent errors were not strongly correlated with the overall coefficients of variation ($r^2 = 0.41$), the low CVs (≤4%) corresponded to the small percent errors (≤7%) for these two cases. On average, measurements with the glove-held adapter could underestimate the tool vibrations by 8%, but it showed a very low inter-operator variation (CV < 5%). The cross-tool CV of this method was also the lowest one (20%) among the tested adapter models. As a result, the error of this method was reduced to less than 5% when the estimated acceleration of each tool was increased by 8% (the mean underestimation).

4. Discussion

The transmissibility spectra shown in Figs. 7, 8 and 10 indicate that the potential errors and variations of the vibration measurements using some of the adapters on many tools can be substantial. This is confirmed by the results listed in Table 3. The percent errors of the finger-held adapters listed in Table 3 are also comparable with those reported by Moschioni et al. [23] and Ainsa et al. [22]. Also consistent with the findings of these studies, the current study confirmed that the measurement error of the adapter approach generally varies with adapter model, adapter orientation, adapter position, and operator. This suggests that it is extremely difficult to correct the measurement errors associated with some of these adapters through any data post-processing, especially with data measured with a vibration dosimeter that only records integrated frequency-weighted acceleration. Consequently, it is necessary to minimize these errors through better adapter design and careful application when the adapter approach is used. This requires clear identification and understanding of the major sources and mechanisms of the measurement errors and uncertainties. The results and phenomena observed in the experiment, together with the features of the adapters listed in Table 1, provide some useful clues to identify and understand the error sources and to explore their solutions.

4.1. Understanding the experimental results

In principle, the vibration at a specific location on the surface of a tool can be accurately measured using an accelerometer if the vibration transmitted to the accelerometer is exactly the same as that at the tool location [29]. This requires the accelerometer to be stably and rigidly fixed on the surface at the measurement location. To achieve this, the connection should meet the following three conditions [29]: (a) sufficient interface adaptation to provide a stable attachment with at least three contact points distributed over a sufficiently large area; (b) ample connection stiffness to assure a sufficiently high resonance of the attachment assembly; and (c) a well-maintained contact force to counterbalance any disturbances from inertial forces of the adapter assembly and the dynamic forces at the tool-adapter and hand-adapter interfaces. The second condition may not be a critical issue because the adapter foot can be made adequately stiff; however, the other two conditions can be of concern when using many adapters.

4.1.1. Palm adapter (Adapter 1)—In this study, the contact surface radius of the palm adapter (23 mm) was larger than that of the handle (20 mm). Under these conditions, the adapter-handle contact theoretically occurs along a single line and is unstable. This instability was not observed in the bare adapter test because there is actually a slightly increased contact area due to the elastic deformation of the contact materials. Since the contact between the magnesium adapter and the aluminum handle is rigid, this contact area must be relatively small. When the palm is in contact with the adapter, the dynamic interaction forces and moments at the palm-adapter interface must affect the rocking motion of the adapter on the handle. The force maintaining the adapter-handle contact comes from the hand-applied grip and push forces, which must vary with time and be influenced by the vibration exposure. More critically, the biodynamic response of the hand-arm system to vibration in the fundamental resonant frequency range (20–50 Hz) of the hand-arm system in the three orthogonal directions can introduce significant motions and dynamic forces at the palm [37]. Similar to whole-body vibration responses, there could also be some significant cross-axis biodynamic response forces at the palm interface at low frequencies. Hence, the total vibration transmissibility of the adapter could be substantially affected by the biodynamic forces acting at the hand-handle interface in the low- and middle-frequency range, as shown in Fig. 7(a). At high frequencies (>100 Hz), the vibration is primarily limited to the local hand tissues, and the biodynamic motions and forces generally decrease with an increase in frequency [37]. This explains why the adapter transmissibility was less affected by the biodynamic responses in the high-frequency range, as also shown in Fig. 7(a).

The glove basically serves as a cushion between the adapter and the handle [36]. This must reduce the contact stiffness and resonance frequency, as reflected in the bare adapter-glove response shown in Fig. 7(b). Fortunately, the major resonances can be substantially suppressed by the hand, as also shown in Fig. 7(b), which is consistent with the results of a recent study [33]. The remaining cushion functions of the glove are beneficial: the glove material converts a solid line-contact into a deformable area contact; the glove further increases the contact area and stability by increasing the effective diameter of the handle; the glove may also increase the friction at the adapter-handle interface to reduce the sliding/vibration of the adapter in the tangential directions. The large palm force (80 N) was primarily applied to the handle through the adapter, which must also play an important role to maintain the beneficial functions of the glove. For these reasons, the vibration spectra of the palm adapter were much better than those measured without using the glove, as shown in Fig. 7(b). These observations also suggest that maintaining high contact stiffness is less important than providing a stable area of contact if the resonances of the adapter can be effectively suppressed.

4.1.2. Fingers-held dosimeter (Adapter 2) and fingers-held adapter (Adapter 3) —The original foot of the fingers-held dosimeter (Adapter 2-A) has only two points in contact with the cylindrical handle; it cannot be stable. For this reason, its bare adapter test had to be conducted by attaching both the foot and the body of the dosimeter on the handle (Fig. 4(b)). Because of this, this dosimeter could not provide a reasonable measurement. Naturally, this led to the replacement of its foot design with one (Adapter 2-B) similar to that of Adapter 3. Such an adapter foot has a curved interface; it has stable contact with the cylindrical handle. However, this does not overcome the following problems with this adapter: large mass, large mounting height of the accelerometer, and the fingers-held stem structure. The large mass at the adapter head must correspond to larger inertial vibration forces and moments. This configuration requires relatively large finger forces to hold the dosimeter. It was observed that the fingers could not always provide the required force, especially in the resonant frequency range of the hand. As a result, the adapter foot could partially or totally lose contact with the handle. This condition may also be magnified if the fingers tightly holding the stem lift the adapter when the fingers are forced to move away from the handle during their resonant responses. Once the loss of contact occurs, less vibration can be transmitted in the designed (*z*) vibration direction. Under such circumstances, driven by the inertial moments on the dosimeter head, the dosimeter could vibrate substantially in its rotational directions. Because the *x* axis has the minimum constraints, the translational vibration from the rotational or rocking motion was the highest. These mechanisms explain the phenomena observed in Fig. 9 and those shown in Fig. 8(a and b).

In principle, the translational vibrations tangential to the contact surface due to the rotational or rocking motions relative to the contact points of the adapter are proportional to the distance from the contact points to the mounted accelerometer. The large mounting height of the accelerometer on Adapter 2 basically served as an effective amplifier of the errors and uncertainties which resulted from its unstable contact, large inertial forces, and the limited and varying force applied by the fingers to maintain contact. The geometric amplification effect of the mounting height may also be compounded when the adapter is used on some tools that generate significant rotational vibrations. A large mounting height also generally reduces the bending stiffness of the adapter and decreases its fundamental natural frequency. Thus, minimizing the mounting height is an effective method for reducing errors and uncertainties. This is also consistent with the findings of a reported experimental study [22].

The major problems observed with Adapter 3 are similar to those of Adapter 2, except that Adapter 3 has less head mass and requires less finger-applied force for maintaining contact with the handle. Due to the large mounting height of its accelerometer, the inertial vibration moments on the adapter head could be greatly increased when the adapter is exposed to multi-axial vibrations. The counterbalance moments applied by the fingers on the adapter foot may not be sufficient to keep the adapter stable; as a result, the transmissibility spectrum deteriorated when the vertical axis of the adapter was not aligned with the vibration direction, as shown in Fig. 8(d). Similar phenomena were observed in the studies by Moschioni et al. [23] and Ainsa et al. [22].

4.1.3. Beam adapter (Adapter 4)—Similar to Adapter 3, the beam adapter has a V-shaped foot; its foot contact can be stable if the V-shaped axis is aligned with the handle axis. Although some signs of influence from the resonant biodynamic responses can be identified, as shown in Fig. 10(a), the transmissibility spectra suggest that the force applied by the fingers on the adapter to maintain contact is generally sufficient to counterbalance the two stimulating forces (inertial vibration force of the adapter and the hand vibration force acting on the adapter). However, as shown in 10(b), the advantages of the V-shaped beam may be lost if the contact becomes unstable, which may happen when the adapter is used with a handle with irregular geometry.

4.1.4. Glove-held adapter (Adapter 5)—The mechanisms of the glove-held adapter are similar to those of the palm adapter used with a glove shown in Fig. 6. Unlike the palm adapter, the glove-held adapter has a flat contact surface, which makes it less adaptive to the handle. Furthermore, due to the constraints of the adapter pocket, the glove-held adapter can't be easily aligned with the direction of the handle vibration. These poor adaptations may be similar to those encountered when using the glove-held adapter to make actual tool vibration measurements. The glove material served as a useful medium for the adapter to adapt to the handle. Similar to the palm adapter, the accelerometer on the glove-held adapter has a smaller mounting height (<6 mm including the glove material) than the finger-held adapters, which minimizes the inertial moments and the geometric amplification effects. Although the palm force is not fully applied on the glove-held adapter, the adapter requires less force to maintain its stability in the test since it has a much smaller mass (5 g) than the palm adapter. Tightly constrained in its pocket by the glove and the palm of the hand, the glove-held adapter is unlikely to vibrate independently in the frequency range of concern. As a result, its vibration largely depends on the vibration response of the glove-hand subsystem. As shown in Fig. 10(c), the glove material generally reduces the vibration transmitted to the adapter or accelerometer, especially in the high-frequency range. This explains why the glove-held adapter generally provides underestimated measurements of the vibration, as also indicated in Table 3.

4.2. Summary of the error sources and mechanisms of the adapter approach

The above discussions suggest that the major sources and mechanisms of the measurement errors and uncertainties using the adapter approach at workplaces are as follows:

- *Unstable adapter contact:* Even though the handle used in this study is uniform and smooth, some of the adapters (e.g., Adapters 1 and 2) exhibited unstable contact with the handle. Many real tool handles do not feature uniform and smooth geometries; it is anticipated that a handheld adapter with a solid foot (e.g., Adapters 1–4) may not be well adapted to the handles of many tools. If a tool handle is contaminated with oil or debris, the reduced friction force may further increase contact instability.

- *Limited and unstable adapter contact force:* Unlike other accelerometer mounting approaches, the adapter attachment force is primarily provided by the fingers or palm of the hand. The applied hand force could vary with time and operator. The force for maintaining adapter contact is limited, especially with a small contact foot held by the fingers (e.g., Adapter 2). The force applied on the adapter could also be partially or totally cancelled by the vibration-induced dynamic forces of the adapter, especially when the mass of the adapter-accelerometer assembly is large (e.g., Adapter 2). The hand could also partially or fully lose contact with the handle in the resonant biodynamic response, which in turn could reduce or eliminate the adapter contact force.

- Unavoidable hand biodynamic forces acting on the adapter: Besides providing the adapter maintaining force, the hand or fingers also introduce disruptive forces to the adapter, especially in the fundamental resonance frequency range of the hand-arm system.

- *Inappropriate designs of adapter structures:* Besides poor foot design (e.g., Adapters 2), other inappropriate structure designs such as large adapter mass (e.g., Adapter 2), large mounting height of the accelerometer (e.g., Adapter 2 and 3), and a finger-held stem structure (e.g., Adapters 2 and 3) can also reduce the reliability of the measurement.

This study also found that the effects of the hand biodynamics on the adapter responses are not always detrimental. A unique benefit of the handheld adapter approach is that the substantial damping provided by the operator's hand can sometimes effectively suppress the resonances of the measurement system, as demonstrated in this study's tests of the palm adapter with the glove and the glove-held adapter.

4.3. Potential improvements of adapter designs and applications

Adapter-induced errors and uncertainties can be curtailed by minimizing their sources and maximizing the benefit of the hand biodynamics in the design/selection and application of the adapter. Several general methods for improving the designs and applications of the adapters are proposed and discussed as follows:

- *Select or design appropriate adapter structures.* According to the results of this study and those reported before [22,23], the finger-held adapters, similar to Adapters 2 and 3, should be avoided. The results of this study suggest that the palm adapters are better choices than finger-held adapters. To minimize the adapter size, the selected accelerometer should be as small as possible, but it should also meet the measurement requirements [5]. The mass and height of the adapter should be minimized. The mounting height of the accelerometer should also be as close to the tool surface as possible. The V-shaped foot seems more adaptive to tool handles than other foot geometries. It is unclear whether adapter foot size should be minimized. While increasing the foot size can increase the adapter contact area and the applied palm force on the adapter, this may reduce the adaptability of the adapter on irregular handle geometries. This issue may be resolved using the next method.
- Consider tool-handle specific adaptive shoes and/or gloves made from high friction material with suitable deformability for each adapter. While it is impossible for each adapter foot to adapt to all tool handles, we hypothesize that adaptive shoes can be designed to achieve better contact stability. The results shown in Fig. 7 and Fig. 10(c) suggest that it is neither necessary nor beneficial to require the contact stiffness of the adapter to be maximized if the mounting height of the acceleration can be minimized. There may be optimized contact stiffness. The specific value may depend on the specific design of the adapter and adaptive shoe, which require further studies. When a well-designed adaptive shoe is not available, some simple methods can be used to improve the adaptation and stability of the available palm adapters. For example, thin rubber strips or electrical tape could be bonded to the two sides of the palm adapter contact surface, which can at least improve the fit of the adapter to a wider range of cylindrical handle diameters and increase the contact friction. As demonstrated in this study, the use of a typical work glove may also be an effective and practical solution. Another important function of this adaptation-enhancing method is that it can resolve the DC-shift problem in the measurement of impulsive vibrations [34,38]. Some tool handles are covered with a layer of vibration-attenuation material. The above discussions also suggest that it is neither appropriate nor necessary to remove such material when measuring the handle vibration using the palm adapter method.
- Place the adapter on the palm at an appropriate location for each tool. The measurement location on each tool should also be as close as possible to that

recommended in the standards [5,39]. In the case of impact tools, the recommended measurement position is usually on the tool surface normal to the impact direction [5,39]. This practice is consistent with the principle identified in this study because it can reduce the required adapter contact force for counterbalancing the inertial moments of the adapter-accelerometer assembly. This may be difficult to achieve with the current design of the glove-held adapter (Adapter 5). Alternative pockets may be considered on the glove to make it possible to measure the vibration at the desired locations on different tools.

- *Apply additional force on the adapter.* Whenever applicable, a palm adapter can be fastened tightly on the tool handles using some elastic materials such as rubber bands. While this will not introduce significant interference, it also prevents the adapter from falling from the handle and makes it easier and safer for the worker to focus on his/her tool operation during the vibration measurement. In the cases of large tools such as chipping hammers, road breakers, and rock drills, additional grip force may also be applied to increase the stability of the adapter. While increasing the push/feed force could change the tool vibrations [40], the increased grip force is unlikely to significantly change the vibrations of these tools.
- Apply vibration transmissibility spectra measured in laboratory human subject tests as correction factors for reducing measurement errors. The glove-induced errors in the palm adapter method and the glove-held adapter method are systematic and measurable in laboratory human subject tests. These laboratory tests can be considered as in situ calibrations of these adapter methods, and the transmissibility results can be used to correct measurement errors. This correction method is further justified based on the following observations:

  (a) Fig. 11(a) shows the comparison of the transmissibility spectra measured in this study and that measured on a 3-D test system reported from a previous study [33]. Although the excitation spectra used in these tests were significantly different, the transmissibility spectra are very similar in the major frequency range of concern. This is consistent with the findings of some other studies [41]. This feature supports the method expressed in Eq. (6) for estimating the adapter vibration from a given tool vibration spectrum. It also justifies the use of the glove transmissibility spectrum measured in the laboratory as a reference to normalize the tool test data measured with the adapter-glove method.

  (b) As shown in Fig. 11(b and c), the transmissibility spectrum of this glove does not vary substantially with the vibration directions and applied forces at frequencies ≤350 Hz [33], which also makes this adapter-glove method suitable for tool vibration measurement.

  (c) As shown in Fig. 11(d), the basic trend of the transmissibility distribution across the entire frequency range is very similar to the trends shown in Fig. 11(a–c). The variation of all the experimental data at each frequency was ≤5% at frequencies up to 315 Hz. Because the dominant weighted-vibrations of the vast majority of powered hand tools are within this frequency range [35], the use of the mean spectrum to correct the tool spectra measured using the adapter-glove method can reduce the error of the measured mean vibration value induced from the non-unity response function of the glove. The overall reliability of the measurement may be estimated by repeatability tests as explained in a recent study [42].

The near-unity transmissibility and low variability are reflections of the glove material properties; ordinary work gloves usually exhibit larger contact stiffness values than AV gloves. The stiffness effect was also verified using a model of the glove-hand-arm system developed in another previous study [36]. This mechanism suggests that many other ordinary work gloves can also be used for the measurement. To assure the accuracy, a series of human subject tests is desired to establish the reference spectrum for each glove selected for the measurement. If the proposed adaptive shoes are designed to exhibit similar stiffness but larger damping than the glove, this correction method may make such adapters more acceptable, which may be an interesting topic for further studies.

5. Conclusions

While the handheld adapter approach for the measurement of hand-transmitted vibration exposure is the most convenient, efficient, and widely-applied technique, the results of this laboratory study confirm that this approach may cause substantial measurement errors if used inappropriately. This study also finds that the measurement errors are influenced by the adapter design, mounting position, mounting orientation, powered hand tool, and by the operator. The major problems with this approach include unavoidable involvement of the biodynamic responses of the hand, unstable attachment contact, insufficient and unstable attachment forces in both normal and tangential directions at the contact surface, and inappropriate design of the adapter structure. However, the results of this study also suggest that adapter measurement errors can be substantially reduced if the design and use of an adapter can be systematically optimized toward minimizing the combined effects of the identified problems and taking advantage of the hand damping for suppressing the resonances of the adapter. Some specific methods for improving the design and appropriate use of the adapters are proposed. While this study concluded that the use of fingers-held adapters should be avoided, it also identified glove-held palm adapters as promising candidates for further testing and evaluation.

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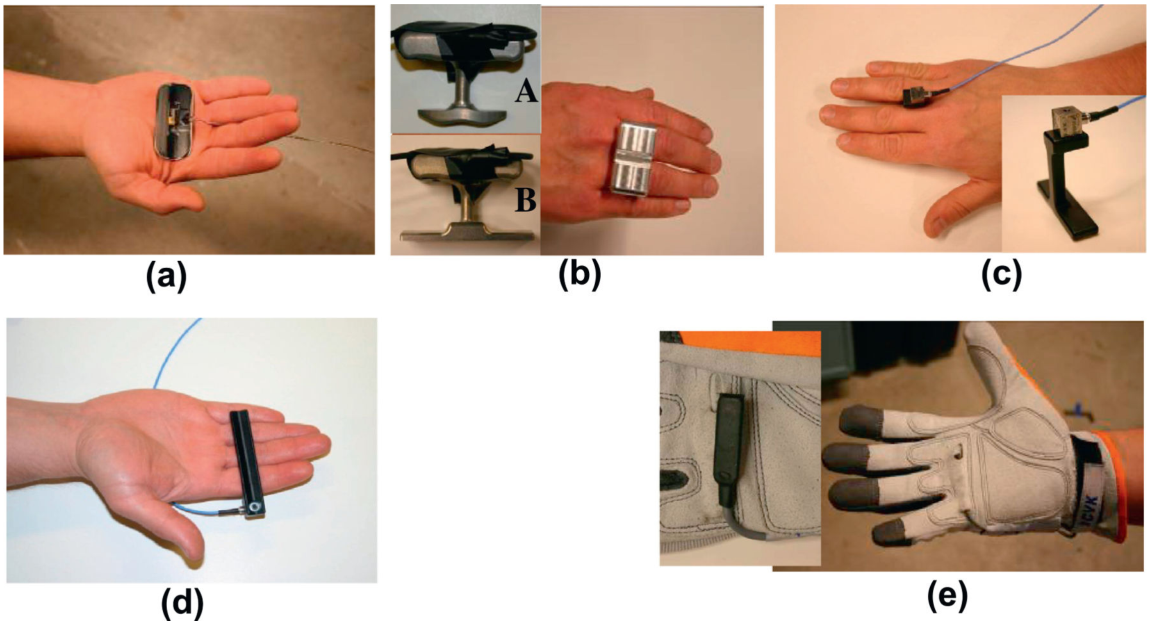


Fig. 1.

Five handheld adapters and their normal positions relative to the hand: (a) Adapter 1: palm adapter; (b) Adapter 2: fingers-held dosimeter with foot A and B; (c) Adapter 3: fingers-held adapter; (d) Adapter 4: beam adapter; (e) Adapter 5: glove-held adapter.

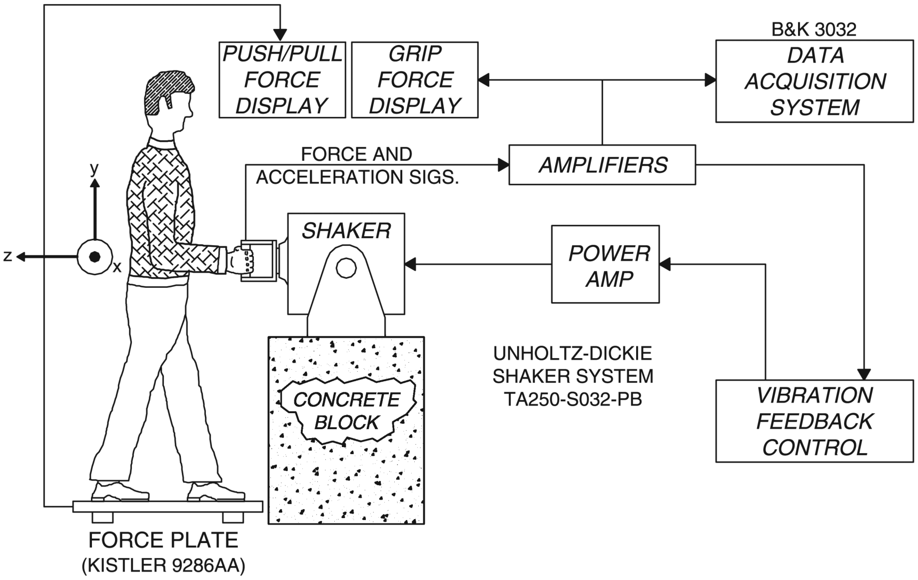
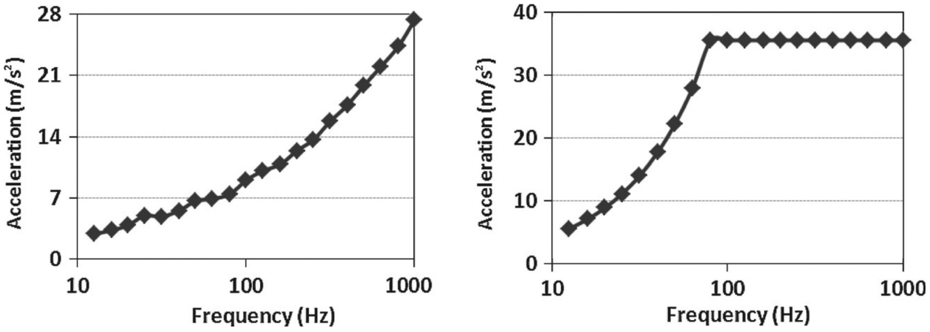


Fig. 2.

Experimental test setup on a 1-D vibration test system.



(a) broad-band random vibration (b) discrete sinusoidal vibration

Fig. 3.

Input acceleration excitation.

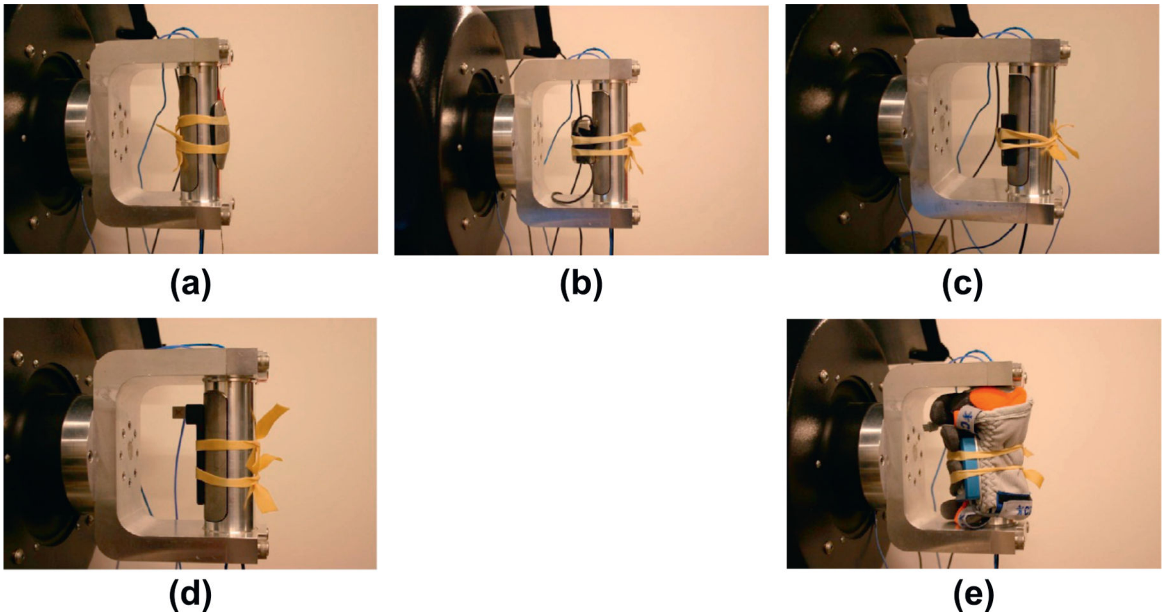


Fig. 4.

Baseline test of the adapters: (a) Adapter 1: palm adapter; (b) Adapter 2: fingers-held dosimeter with foot A or B; (c) Adapter 3: fingers-held adapter; (d) Adapter 4: beam adapter; (e) Adapter 5: glove-held adapter.

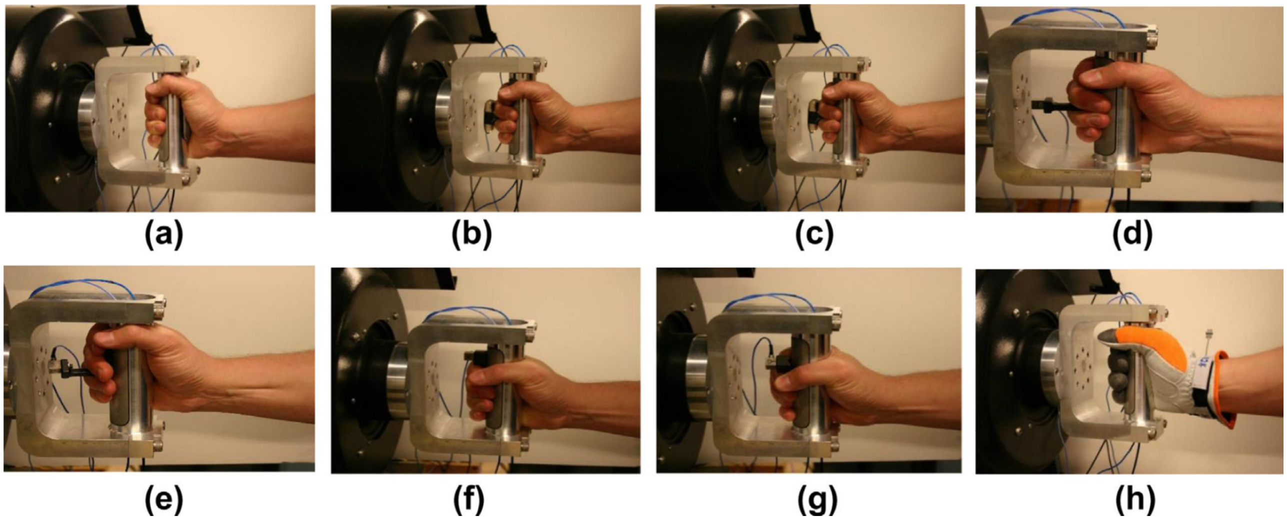


Fig. 5.

Human subject test of the adapters: (a) Adapter 1; (b) Adapter 2 with foot A; (c) Adapter 2 with foot B; (d) Adapter 3 aligned; (e) Adapter 3 unaligned; (f) Adapter 4 aligned; (g) Adapter 4 unaligned; (h) Adapter 5.

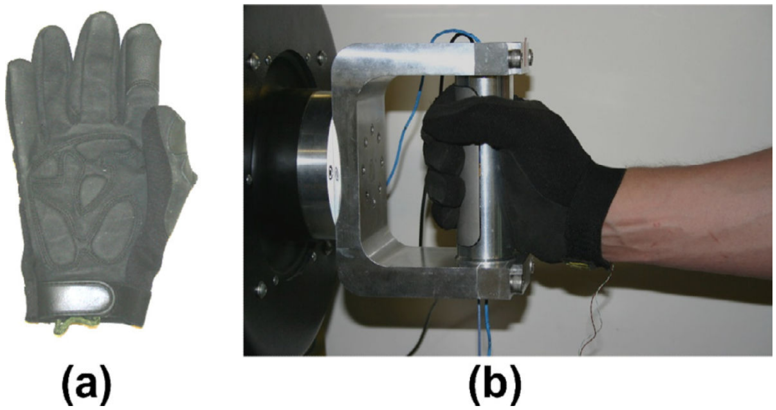


Fig. 6.

Additional test of the palm adapter (Adapter 1) with a synthetic work glove.

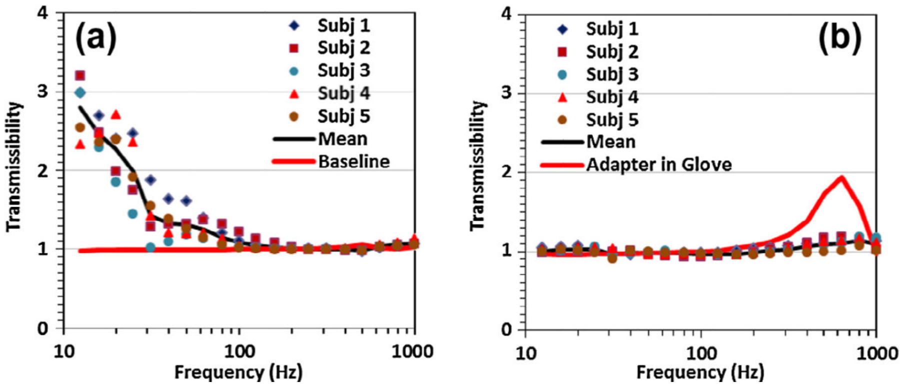


Fig. 7.

Vibration spectra measured with the palm-held adapter (Adapter 1): (a) in the bare-hand test; (b) in the gloved-hand test.

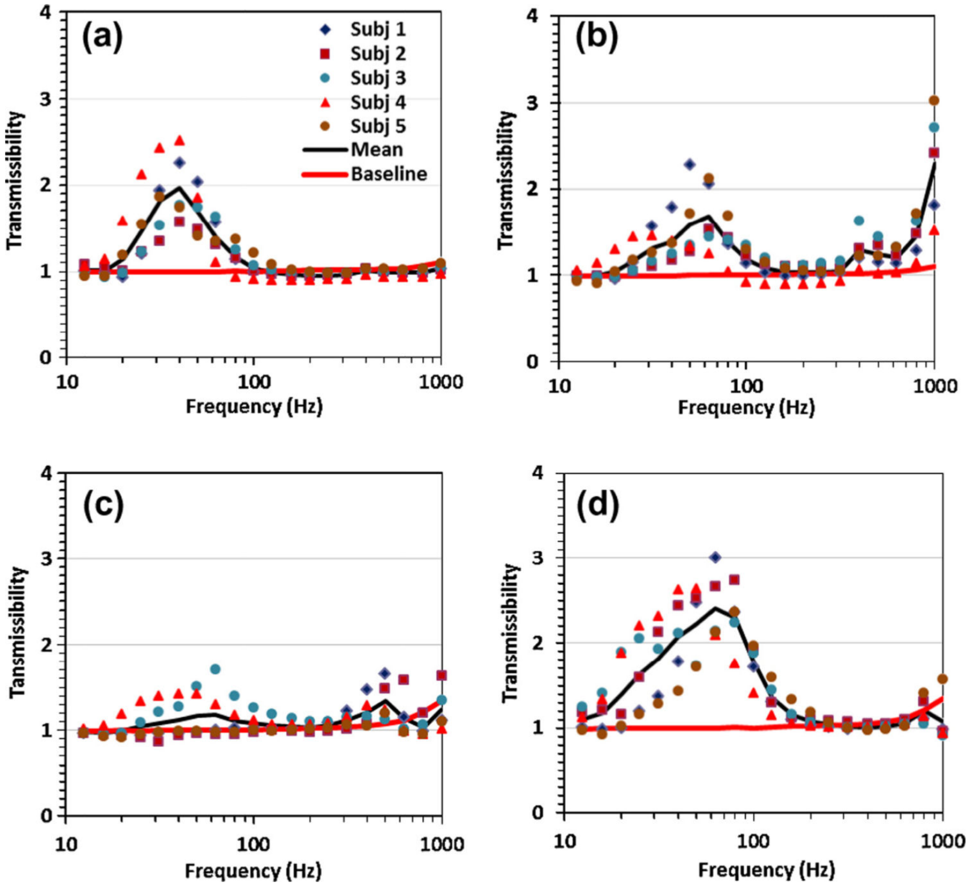


Fig. 8.

Vibration spectra measured with fingers-held adapters: (a) Adapter 2 with foot A; (b) Adapter 2 with foot B; (c) Adapter 3 aligned; (d) Adapter 3 misaligned.

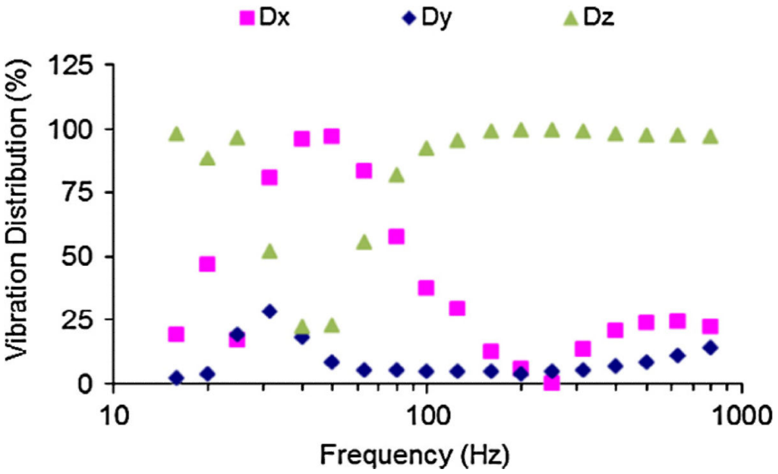


Fig. 9.
Vibration distribution in three orthogonal directions of Adapter 2.

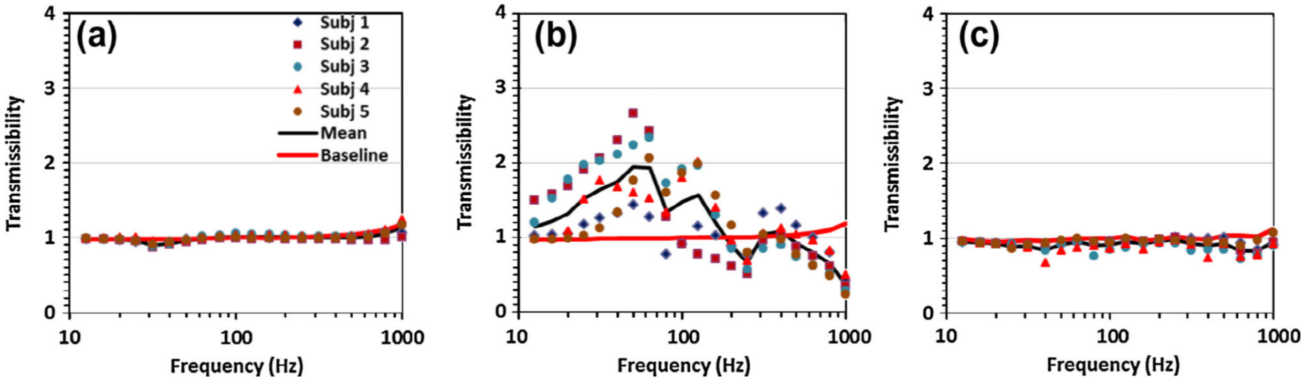
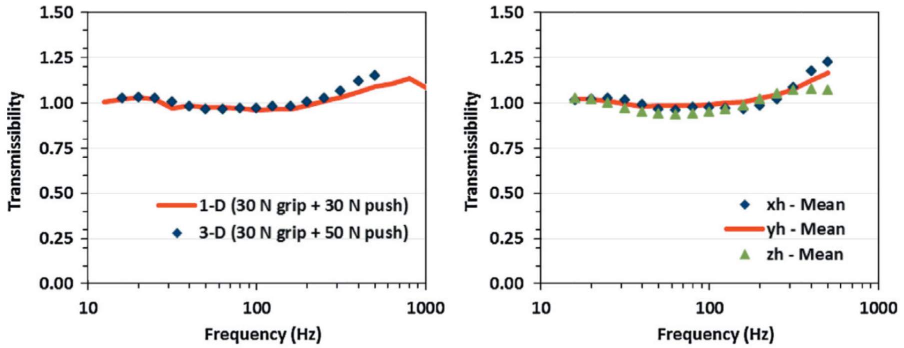
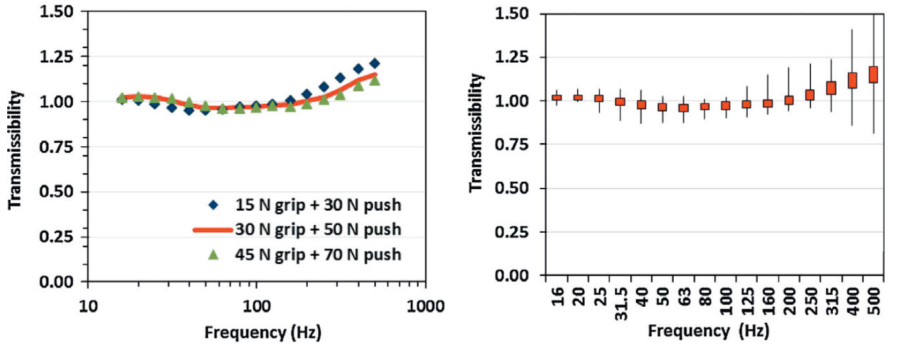


Fig. 10.

Vibration spectra measured with the beam adapter and glove-held adapter: (a) Adapter 4 aligned; (b) Adapter 4 misaligned; (c) Adapter 5.



(a) Comparision of 1-D and 3-D data (b) Effect of vibration direction



(c) Effect of applied hand force (d) Transmissibility distributions

Fig. 11.

The effects of several factors (excitation spectrum, applied hand force, vibration direction, and operator) on the vibration transmissibility of the palm adapter within a synthetic work glove measured by McDowell et al. [33].

Table 1

Handheld adapters examined in this study.

ID	Name	Major features	
1	Palm-held adapter	Fabricated in house using Magnesium based on the design recommended in ISO 10819 (1996) [24]. Partial moon-like cross-section with a cylindrical contact surface: radius = 23 mm, length = 67 mm, and width = 31 mm. Accelerometer (Endevco, M35A) is installed near the contact surface with an effective height of about 10 mm. Total weight/mass: 13 g	
2	Fingers-held dosimeter adapter	Fabricated in house using Aluminum as a close simulation of a commercial fingers-held vibration dosimeter [27]. A stem rigidly connects the foot and body of the dosimeter. The stem is held between two fingers during measurement. Total height of the dosimeter = 39 mm. Accelerometer (Endevco, M35A) installed in the body of the dosimeter. Total mass = 33 g, with the major mass in the body of the dosimeter	Foot A: the same as that on the original dosimeter; usually two-point contact with a handle Foot B: V-shaped foot similar to that of Adapter 3. Foot length = 58 mm. Width = 16 mm
3	Fingers-held adapter	A commercial product from Larson-Davis. A typical adapter model recommended in the standard [5]. Similar structure to the dosimeter, except much less mass at the accelerometer mounting base. V-shaped contact foot that can adapt to cylindrical handles with many different radiuses. Foot length = 50 mm, width = 12.8 mm. Total height of the adapter with the installed accelerometer (PCB, 356B11) = 52 mm. Total mass = 21 g	
4	Beam adapter	A commercial product from Larson-Davis. Another typical adapter model recommended in the standard [5]. V-shaped contact foot that can adapt to cylindrical handles with many different radiuses. Foot length = 87 mm, width = 14 mm. Total height of the adapter with the installed accelerometer (PCB, 356B11) = 25 mm. Total mass = 24 g	
5	Glove-held adapter	A commercial dosimeter equipped with an instrumented glove from CVK [28]. The adapter is held in a pocket in front part of the glove palm. The thickness of the glove pocket leather in contact with a handle is about 1 mm. The adapter has a rectangular shape: length = 36 mm, width = 11 mm, and height = 5 mm. Its accelerometer (OEM installed) is sealed inside the adapter. The mass of the adapter is about 5 g	

Table 2

Operator anthropometry.

Subject	Height (cm)	Weight (kg)	Hand length (mm)	Hand breadth (mm)
1	184.8	88.4	189	90
2	183.0	69.2	190	88
3	185.4	94.8	192	91
4	165.1	76.6	184	90
5	184.5	73	202	90
Mean	180.6	80.4	191.4	89.8
SD	8.7	10.8	6.6	1.1

Table 3

Percent errors of the frequency-weighted vibrations measured with the adapters and their coefficients of variation (CV = standard deviation/mean value).

Tool	A_{Tool}	Adapter 1		Adapter 1 with glove		Adapter 2 with foot A		Adapter 2 with foot B		Adapter 3 aligned		Adapter 3 unaligned		Adapter 4 aligned		Adapter 4 unaligned		Adapter 5	
		Error (%)	CV (%)	Error (%)	CV (%)	Error (%)	CV (%)	Error (%)	CV (%)	Error (%)	CV (%)	Error (%)	CV (%)	Error (%)	CV (%)	Error (%)	CV (%)	Error (%)	CV (%)
Spectrum-a in Fig. 3	7.4	87	8	1	2	43	14	25	9	7	13	71	14	−3	1	51	21	−9	2
Spectrum-b in Fig. 3	32.1	69	9	−1	1	43	11	31	10	8	15	85	10	−3	1	58	20	−9	3
Rock drill	42.3	46	10	−1	1	69	15	45	16	13	19	109	14	−4	1	74	23	−11	7
Road breaker	15.7	136	6	2	2	12	10	7	6	−1	7	32	16	−2	1	30	24	−7	1
Non-AV chainsaw	22.6	14	5	−1	2	13	4	24	10	11	8	54	5	0	2	39	16	−8	5
AV chainsaw	2.0	22	5	−2	2	13	4	17	8	7	9	47	4	0	2	31	13	−6	3
Chipping hammer	14.5	31	9	−2	2	32	11	22	6	8	11	60	7	−2	2	47	15	−8	4
Needle gun	13.6	38	12	−2	1	64	13	54	23	15	22	117	17	−3	2	87	24	−8	5
Rand orbital sander	12.2	8	7	−4	2	5	10	18	14	8	11	74	12	1	2	50	33	−8	6
Impact wrench	10.9	70	10	−1	1	50	13	33	11	9	15	87	12	−3	2	60	21	−9	3
Riveting gun	1.6	16	6	−2	1	19	6	33	14	12	14	81	9	0	2	56	18	−7	5
Nutrunner	5.8	64	18	−1	4	70	22	28	13	7	18	75	24	−7	3	60	26	−10	1
Metal drill	3.2	66	17	0	2	57	17	34	12	10	17	86	17	−4	2	64	23	−10	2
Elec.9″ angle grinder	6.7	8	6	−3	2	6	8	19	12	8	10	68	11	1	2	36	26	−7	5
Pneum. Rotary file	9.8	2	2	−1	3	−3	4	4	8	4	5	11	6	1	2	−6	21	−4	2
Straight grinder	6.4	18	8	−3	1	29	6	36	14	11	15	101	8	0	2	60	20	−9	6
Vertical grinder	6	14	8	−3	2	15	11	33	15	10	14	108	13	1	2	44	26	−9	7
Mean	12.5	42	9	−1	2	32	11	27	12	9	13	74	12	−2	2	49	22	−8	4
CV(%)	87	86		95		76		46		42		38		146		42		20	