HHS Public Access
Author manuscript
Measurement (Lond). Author manuscript; available in PMC 2019 April 02.

Published in final edited form as:
Measurement (Lond). 2019 April ; 137: 362–374. doi:10.1016/j.measurement.2019.01.034.

Development of a finger adapter method for testing and evaluating vibration-reducing gloves and materials

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

Physical Effects Research Branch, Health Effects Laboratory Division, National Institute for Occupational Safety and Health, Morgantown, WV 26505, USA

Abstract

The objective of this study was to develop a convenient and reliable adapter method for testing and evaluating vibration-reducing (VR) gloves and VR materials at the fingers. The general requirements and technical specifications for the design of the new adapter were based on our previous studies of hand-held adapters for vibration measurement and a conceptual model of the fingers-adapter-glove-handle system developed in this study. Two thicknesses (2 mm and 3 mm) of the adapter beam were fabricated using a 3-D printer. Each adapter is a thin beam equipped with a miniature tri-axial accelerometer (1.1 g) mounted at its center, with a total weight ≤ 2.2 g. To measure glove vibration transmissibility, the adapter is held with two gloved fingers; a finger is positioned on each side of the accelerometer. Each end of the adapter beam is slotted between the glove material and the finger. A series of experiments was conducted to evaluate this two-fingers-held adapter method by measuring the transmissibility of typical VR gloves and a sample VR material. The experimental results indicate that the major resonant frequency of the lightweight adapter on the VR material (≥800 Hz) is much higher than the resonant frequencies of the gloved fingers grasping a cylindrical handle (≤300 Hz). The experimental results were repeatable across the test treatments. The basic characteristics of the measured glove vibration transmissibility are consistent with the theoretical predictions based on the biodynamics of the gloved fingers-hand-arm system. The results suggest that VR glove fingers can effectively reduce only high-frequency vibration, and VR effectiveness can be increased by reducing the finger contact force. This study also demonstrated that the finger adapter method can be combined with the palm adapter method prescribed in the standardized glove test, which can double the test efficiency without substantially increasing the expense of the test.

Keywords

Hand-arm vibration; Hand-transmitted vibration; Anti-vibration glove; Vibration-reducing glove; Glove finger test

---

[*]Corresponding author at: PERB/HELD/NIOSH/CDC, 1095 Willowdale Road, MS L-2027, Morgantown, WV 26505, USA. fze2@cdc.gov (X.S. Xu).

1. Introduction

Powered hand tools can generate significant hand-transmitted vibration (HTV). Prolonged, intensive exposure to HTV may cause hand-arm vibration syndrome (HAVS). The hallmark indicator of HAVS is vibration-induced white finger (VWF), which is a compensable occupational disease in many countries. As part of protection measures, vibration-reducing (VR) gloves have been developed and used to reduce HTV exposures and health effects. Although an international standard for VR glove testing and evaluation has been established, and many studies have investigated such gloves [1–22], their effectiveness, particularly for finger protection, remains unclear.

The effectiveness of VR gloves are generally assessed based on their vibration transmissibility, which is defined as the ratio of the vibration transmitted through the glove and that input to the glove [9,10]. As glove vibration reduction is tool- and working condition-specific, it is desired to examine VR glove effectiveness at workplaces. Due to the existence of many uncontrolled variables and other difficulties associated with workplace glove assessments, only a few field studies of VR gloves have been reported [4,5]. Alternatively, preliminary evaluations can be performed to estimate the tool-specific effectiveness of VR gloves using a transfer function method based on workplace tool vibration data in conjunction with laboratory-measured glove vibration transmissibility data [6–8]. Follow-up experiments may be performed at work-places to verify the results of the preliminary evaluations or to further test VR gloves selected from the preliminary studies.

To help conduct the preliminary evaluation and selection of VR gloves, the International Organization for Standardization (ISO) has established a standard to screen anti-vibration (AV) gloves [9]. According to this standard, AV gloves are a subset of VR gloves that can meet the AV glove criteria specified in the standard. Since no convenient and reliable method for measuring the glove transmissibility at the fingers was identified or developed in the past, the original standard only required to measure glove transmissibility at the palm of the hand using a palm adapter method on a 1-D vibration test system [10]. To eliminate measurement errors resulting from the misalignment of the adapter accelerometer with the vibration direction of the instrumented handle on the 1-D vibration test system, the single-axis accelerometer can be replaced with a tri-axial accelerometer [11]; this upgrade has been included in the updated standard as one of the measures for reducing these measurement errors [9]. To assure some effectiveness of a certified AV glove for finger protection, this standard requires that the VR material incorporated into the finger and thumb sections should be the same as that in the palm section [9]. This requirement is questionable because different materials may offer advantages at the fingers due to differences in the structures of the fingers and palm [8,12]. The elimination of this requirement can open up more options for further AV glove development. However, to accomplish this, the standard would have to be revised to include a reliable method for measuring vibration transmissibility at the glove fingers. The existing glove testing standard also has some other limitations [13,14]. Most importantly, the actual effectiveness of VR gloves should be evaluated based on the measurements of glove transmissibility at both the fingers and the palm in three orthogonal directions [7,8,11,12,15–17]. This requires the development of a convenient and reliable 3-D method for measuring the glove transmissibility at the fingers.

Besides the above-mentioned adapter method, the glove vibration transmissibility can also be estimated using the vibration data measured on the fingers or hand with and without wearing a glove [4,12,19–21], which is usually termed as on-the-finger or on-the-hand method. Because the transmissibility on the hand-arm system is location-specific, the glove effectiveness estimated using the on-the-hand method is also location-specific [12]. Since the transmissibility at the glove-hand interface is generally different from that on the top skin of the fingers, the glove vibration transmissibility estimated using the on-the-finger method may also be different from that measured using the adapter method. To make the glove transmissibility measured at the fingers directly comparable with that measured at the palm of the hand, it is very important to develop a reliable finger adapter method, similar to the palm adapter method, for the standardized glove testing and evaluation.

Some researchers have proposed directly inserting an accelerometer (or a finger adapter equipped with an accelerometer) into the interface between a human finger and the glove to measure the glove finger transmissibility [18]. Transmissibility measurements using this method are generally consistent with predictions from a model of the gloved hand-arm system, which provides reasonable simulations of the basic cushioning mechanisms of VR gloves [15]. A major concern with finger acceleration measurement methods is that the accelerometer or adapter structure at the interface may substantially alter the finger contact conditions. The concentrated pressure on the accelerometer may not only make a test subject feel uncomfortable, but may also change the interface conditions and thereby significantly vary the transmissibility measurements. Such effects can be minimized by using a thin accelerometer with a small mass for such measurements. While some thin and lightweight single-axis accelerometers are available, the use of suitable thin tri-axial accelerometers is not well-documented. Furthermore, the fragile wire connections of the available accelerometers are vulnerable to damage when the accelerometer is at the interface during vibration exposure.

While the finger adapter for the above-mentioned glove test was held by a single finger, several two-fingers-held adapters have been proposed and used to measure hand-transmitted vibration exposures [23,24], some of which have been included in ISO 5349–2 [25]. We have examined these adapters and identified their major issues [26]. We hypothesize that their major issues can be resolved by designing a better tri-axial accelerometer-equipped finger adapter for the measurement of VR glove transmissibility at the fingers. Therefore, the specific aims of the current study include: (I) design a new finger adapter to measure the vibration transmissibility of a glove at the fingers; (II) test and evaluate the proposed finger adapter method; and (III) investigate the effectiveness of several typical VR gloves and the effect of finger grip force on glove transmissibility.

2. Methods

2.1. The requirements and design of a new finger adapter

As found in our previous study [26], the major sources of measurement errors with the available two-fingers-held adapters were primarily as follows: (1) a finger adapter may separate from the contact surface if it is not sufficiently constrained by the fingers, which usually occurs in the fundamental resonant frequency range of the fingers or hand; (2) the degree of separation depends on the mass of the adapter or its inertia force; (3) the separation is usually accompanied by some rocking motions of the adapter on the contact surface, especially when the vibration exposure occurs in multiple axes; and (4) the magnitude of the rocking motions generally increases with the height of the adapter. Based on these observations and general knowledge of structural vibration, we propose the requirements of the new finger adapter as follows: (i) the mass of the finger adapter and its tri-axial accelerometer should be as small as possible; (ii) the height of adapter should be as low as possible, and the accelerometer should be installed on the adapter as close to the contact surface as possible; (iii) the adapter configuration should allow for a sufficient finger force to be applied on the adapter to prevent separation from the adapter-glove and adapter-finger contact surfaces under a given excitation; the greater the excitation is, the more finger force is required to prevent loss of contact; (iv) the adapter held by fingers should not substantially change the original glove-finger contact relationship and their dynamic properties; (v) the fundamental natural frequency of the adapter on the glove materials should be much higher than that of the fingers; and (vi) the adapter should have some damping properties to minimize its resonant responses.

Some of these requirements actually contradict each other; an optimized design of the finger adapter is required to balance these requirements so that the designed adapter is acceptable for the measurement. The technical design of the adapter proposed in this study is shown in Fig. 1, which includes two models: one with a beam thickness of 2 mm and the other one with a beam thickness of 3 mm. Fig. 1 also shows a prototype adapter fabricated with a thermoplastic (PLA filament) using a 3D printer (MakerBot Replica-tor 2). A miniature tri-axial accelerometer (Endevco 35B-10) is firmly attached at the center of each adapter using an adhesive.

To measure glove vibration transmissibility, the adapter beam is held with two gloved fingers; a finger is positioned on each side of the accelerometer. The adapter is positioned at the intermediate phalanges of the middle and ring fingers, as shown in Fig. 2(a). The hand-arm postures required in the standard glove test position the adapter centrally on the instrumented handle with the principal axis (z-axis) of the accelerometer/adapter approximately aligned with the vibration direction of the 1-D vibration test system, as shown in Fig. 2(b). To position the adapter at the interface between the glove material and the test subject's finger, slots are cut in the glove fingers to allow insertion of the adapter beam ends as shown in Fig. 2(c). A test subject can simultaneously hold both the finger adapter and the palm adapter required in the standard glove test while keeping the standard hand and arm postures, as shown in Fig. 2(d).

A conceptual dynamic model of the adapter being held by two fingers with the glove materials sandwiched between the adapter and the shaker handle is shown in Fig. 3. This model was proposed and used to guide the design and evaluation of the finger adapter in this study. This model suggests that the bending natural frequency of the adapter can be most effectively increased by minimizing the length of adapter (L_{Total}) and the length of the bridge between two glove fingers (L_{Bridge}). The bridge length can be minimized by selecting a tri-axial accelerometer with the smallest width. Besides the bridge length, the total length of the adapter also depends on the width of the two fingers at the adapter position. We suggest that the section of adapter beam slotted under each finger should not be less than 3/4 of the finger width so that the adapter can be reliably controlled. While such a length varies with hand size, we propose an adapter length in the range of 36 mm to 40 mm to fit most subjects. As shown in Fig. 2(a), a 40 mm adapter can be used by all subjects with hand sizes 7–10 [27] acceptable for the standard glove test [9,27].

Increasing the thickness of the adapter ($L_{Thickness}$) can effectively increase its stiffness and natural frequency in any direction. This can also allow for increased finger pressure applied to the adapter. These advantages, however, may be countered by the increased mass of the adapter and its increased interference with the glove-finger interface. While it is challenging to predict the optimal adapter thickness, we evaluated two levels of beam thickness (2 mm and 3 mm) in this study. The adapter width (L_{Width}) (10 mm in Fig. 1) is another important parameter. A larger adapter width corresponds to a lower potential for rocking motions, larger contact area, and a higher applied finger force, but this will result in decreased adaptability to both the glove and human fingers and altered interface stiffness and contact pressure distribution. As a balanced option, the adapter width should be less than the span between the neighboring distal and proximal finger creases for a comfortable grip on a cylindrical handle, but it should be wider than the length of the selected accelerometer (6 mm in this case) to assure its firm attachment to the adapter. According to our measurements on test subjects from earlier tests with hands with the minimum size acceptable for the standard glove test (size 7) [27], the span between the creases at each end of the intermediate phalange of the ring finger is about 16 mm when grasping a 40 mm handle, and about 10 mm when grasping a 30 mm handle. For these reasons, we chose an adapter width of 10 mm for the finger adapter in this study.

To increase the adaptability of each adapter on the metal handle and to introduce some damping to the adapter, electrical tape was applied to its handle contact surface. This may assure uniform vibration transmissibility in the full frequency range of concern (6.3 to 1250 Hz) in its calibration test. The total mass of the 2 mm adapter assembly was 1.8 g (0.7 g adapter + 1.1 g accelerometer), and the 3 mm version was 2.2 g (1.1 g adapter + 1.1 g accelerometer).

2.2. Experiments

2.2.1. Vibration test system and excitation—The 1-D vibration test system used in this study is the same as that used in many of our previous glove and biodynamic studies [26,29], which meets the requirements of the standard glove test [9]. The vibration excitation defined in the glove test standard was extended at the low-frequency end of the constant velocity spectrum from 25 to 6.3 Hz. This extended frequency spectrum was used as the excitation in all the experiments of this study. The acceleration in the z-axis, or along the forearm direction, was measured by the instrumented handle, and it was used to control the handle vibration using a computer-based closed-loop control system (Unholtz-Dickie).

2.2.2. Adapter tests—Baseline test: Each of the tri-axial accelerometer-equipped adapters requires a near-unity response in the frequency range of interest (6.3 to 1250 Hz) when the adapter is directly attached to the instrumented handle. To verify this and to conduct in-situ calibration of the accelerometer when necessary, each instrumented adapter was attached to the handle with two rubber bands, as shown in Fig. 4(a). The fastening force (equivalent to finger grip force) was controlled to about 30 N. To examine the effect of possible adapter misalignment with the defined vibration direction of the instrumented handle in a glove test, the adapter was attached to the handle at three different angles (−15°, 0°, 15°) from the center line marked on the handle in the test.

Adapter resonance test: The fundamental resonant frequency of each instrumented adapter applied to VR glove material should be much larger than the fundamental resonant frequency of the human fingers so that the glove transmissibility at the fingers can be reliably measured. To verify this, each adapter was attached to sample VR material (air bubble) using rubber bands while the VR material was firmly attached to the handle using two rubber bands, as shown in Fig. 4(b). To take into account the possible bending response of the adapter across the two fingers, the space between two gloved fingers was simulated by attaching two separate sections of the VR material on the handle with a separation similar to that observed between two gloved fingers in the gloved finger test described in Section 2.2.3. Three levels of fastening force (15, 30, and 50 N) were applied in the adapter resonance test.

2.2.3. Human subject tests—The NIOSH Human Subjects Review Board reviewed and approved our study protocol. Six healthy adult males gave informed consent to participate in this study. The subjects ranged in age from 18 to 39 (median age = 26). Anthropometric data are presented in Table 1. The hand sizes listed in Table 1 are based on the protective glove standard EN 420 [27]. According to the identified characteristics of typical VR gloves from our previous studies [8,12,17], three VR gloves (gel, neoprene, and air bubble) were selected for this study. A typical glove VR material (air bubble) was included in the study to verify the usefulness of the finger adapter method for glove material tests. An ordinary work glove was also included in this evaluation to identify the major vibration-attenuation differences between VR gloves and ordinary work gloves that are not designed to reduce vibration. The gloves and VR material presented in Fig. 5 were tested with all six participated subjects.

Upon arriving, basic information about the study and details of the experimental protocol were explained to the test subject. After signing a consent form, a training session was conducted to allow the test subject to practice gripping and pushing the instrumented handle at the target forces during vibration. Instructions on proper positioning of the finger adapter in the glove were also provided. Then, the test treatments were employed to evaluate the 2 mm and 3 mm finger adapters with the selected gloves and VR material.

The hand-arm and body postures required in the standardized glove test [9] were adopted in this study, as shown in Fig. 2(d). We included 4 hand forces (50 N grip, 30 N grip, 15 N grip, and a combination of 50 N push and 30 N grip) in the experiment. Furthermore, one additional treatment condition was included for each glove, when the subject simultaneously used the finger and palm adapters with a combined 50 N push and 30 N grip force. Vibration transmissibility functions for both fingers and palm were measured simultaneously. There were 50 test treatments for each subject comprising 5 hand conditions (4 gloves + 1 VR material) × 5 force conditions (4 forces with finger adapter only + 1 force with both finger and palm adapters) × 2 adapter thicknesses. Two consecutive trials were carried out for each treatment for a total of 100 trials for each test subject. The hand and force conditions were randomized independently among the subjects. For each test trial, whenever the subject reached and maintained the pre-defined target force under the vibration condition, the measurement was started and lasted 20 s per trial.

2.2.4. Calculations of glove transmissibility—To avoid the effect of the adapter misalignment with the vibration direction on the 1-D vibration test system, the glove transmissibility was assessed based on the vector sum of the tri-axial accelerations (*x, y, z*). Specifically, the glove transmissibility (T_{Glove}) at each frequency (f_i) was calculated from

$$T_{Glove}\left(f_i\right) = \frac{\sqrt{\left(a_{x-adapter-i}\right)^2 + \left(a_{y-adapter-i}\right)^2 + \left(a_{z-adapter-i}\right)^2}}{\sqrt{\left(a_{x-handle-i}\right)^2 + \left(a_{y-handle-i}\right)^2 + \left(a_{z-handle-i}\right)^2}} \quad (1)$$

where $a_{adapter}$ is the acceleration measured on the adapter and a_{handle} is the acceleration measured on the instrumented handle. While any transmissibility value less than 1.0 denotes attenuation of the input vibration, any transmissibility value greater than 1.0 indicates amplification of the vibration input.

According to ISO 10,819 [9], the frequency-weighted vibration transmissibility values of each glove in the middle-frequency range (25–200 Hz) ($T_{W\text{-}glove\text{-}middle}$) and high-frequency range (200–1250 Hz) (TW-glove-high) were calculated from

$$T_{W-Glove-k} = \frac{\sqrt{\sum_{i=i_L}^{i_U}\left[a_{x-adapter}^2\left(f_i\right) + a_{y-adapter}^2\left(f_i\right) + a_{z-adapter}^2\left(f_i\right)\right] W_h^2\left(f_i\right)}}{\sqrt{\sum_{i=i_L}^{i_U}\left[a_{x-handle}^2\left(f_i\right) + a_{y-handle}^2\left(f_i\right) + a_{z-handle}^2\left(f_i\right)\right] W_h^2\left(f_i\right)}}, k \quad (2)$$

$= middle;\ or\ high$

where W_h is the ISO standard frequency weighting defined in ISO 5349–1 [28], i_L and i_H are the low-end and high-end frequencies for a given frequency range, respectively.

The unweighted vibration transmissibility value ($T_{UW\text{-}glove}$) of each glove was also calculated from Eq. (2) except that W_h was taken as 1.0.

2.2.5. Statistical analyses—The major influencing factors include feed force, adapter, hand condition, and trial, while subject is treated as a random factor. The significance of the fixed factors on transmissibility, peak frequencies, weighted and unweighted transmissibility values were analyzed using linear mixed-effects model and ANOVA with R statistical software (The R Foundation for Statistical Com puting, version 3.3.3). Significant differences were defined at $p < 0.05$.

3. Results

3.1. Vibration responses of the finger adapters

Fig. 6 shows the vibration transmissibility spectra measured in the adapter tests with the method displayed in Fig. 4. As shown in Fig. 6(a), the baseline responses of the 2 mm adapter were generally close to the desired unity (1.0) in the range of concern (6.3 to 1250 Hz), with the maximum value of 1.07 at 1250 Hz when the adapter was positioned at −15°. The baseline responses of the 3 mm adapter were generally better, as shown in Fig. 6(c).

As shown in Fig. 6(b) and (d), the resonant frequencies of both adapters were similar; they were in the range from 800 to 1250 Hz. As expected, increasing the contact force on the adapters significantly increased the peak frequency ($p < 0.001$). The resonant peaks for both adapters were similar; the transmissibility values ranged from 2.8 to 3.2. Their transmissibility values were near unity at frequencies below 200 Hz.

3.2. Vibration transmissibility of the gloves and VR material at the human fingers

Fig. 7 shows some examples of the individual vibration transmissibility data measured at the fingers of all the subjects. As shown in Fig. 7(b, d, f), the transmissibility values measured with the 3 mm adapter were uniform and close to unity at frequencies below 20 Hz, especially those under the 30 N and 50 N grip forces. At higher frequencies, the transmissibility spectra varied by subject. However, their general trends and characteristics were consistent. Specifically, there were generally two major peaks for each spectrum. The first peak was observed in the range of 16 to 40 Hz, and the second peak occurred in the range of 100 to 250 Hz. Beyond the second peak frequency, the transmissibility generally decreased as the frequency increased. As shown in Fig. 7(a, c, e), the spectra measured with the 2 mm adapter were generally similar to those measured with the 3 mm adapter, except that the transmissibility values among the subjects were less uniform at frequencies below 20 Hz, and an outlier in the low-frequency range was observed in Fig. 7(c).

Both peaks were smoothed out in the averaging process of the individual glove transmissibility spectra, as shown in Fig. 8. However, the above-mentioned characteristics can still be identified from the averaged spectra. The spectrum measured with the 2 mm adapter (in the left column) was similar to that measured with the 3 mm adapter (in the right column) for each glove under each force treatment. Their first peak frequencies measured with these two adapters were not significantly different ($F_{1,577} = 0.07$, $p = 0.80$). Their second peak frequencies were marginally significantly different ($F_{1,577} = 5.50$, $p = 0.02$). The effect of hand force on these two peak frequencies was statistically significant ($F_{4,577} > 3.87$, $p < 0.01$). The first resonant peak was not as obvious in the lower hand force trials, particularly with the 15 N grip force. As expected, the peak frequencies shifted toward higher frequencies as the grip force increased. The push force had little effect on the peak frequencies of the second peaks.

The differences among vibration transmissibility spectra can also be observed in Fig. 8. As expected, the transmissibility of the ordinary work glove (Glove 1) at the fingers was close to unity at frequencies below 500 Hz, which suggests that such a glove does not increase or attenuate the finger vibration in such a frequency range. Also as expected, Glove 1 was much less effective for reducing finger vibration at higher frequencies, as also shown in Fig. 8. All of the other VR gloves and the VR material started attenuating vibration at frequencies around 160 to 500 Hz, depending on the hand grip force. None of the gloves were effective at attenuating lower-frequency vibration. At the two resonant peaks, all gloves amplified the vibration input to the fingers, especially at the second peak frequency. All gloves had a relatively consistent first resonant peak, while the frequency of second resonant peak for the air bubble glove VR material was obviously higher than the other gloves.

The effects of the hand force on the transmissibility of the gloves at the fingers measured with both adapters were very similar. For clear demonstration of the force effects, the 6-subject-averaged transmissibility spectra of the vibration-reducing gloves and VR material for different hand forces measured with the 3 mm adapter were grouped together and plotted in Fig. 9. The spectra measured with and without the use of the palm adapter were very similar, which suggests that its presence did not affect the measurement at the fingers. Hand force affected the two peak frequencies in different manners. While the push force significantly affected the first peak frequency ($F_{2,339} = 106.83$, $p < 0.001$), it did not affect the second peak frequency ($F_{2,339} = 1.33$, $p = 0.27$). Specifically, the first peak frequency generally shifted to a higher value with increased palm contact force. For example, for Glove 2, the first peak frequency for each force level is as follows: 16 Hz for 15 N, 20 Hz for 30 N, 25 Hz for 50 N, and 31.5 Hz for 80 N (from the combination of 50 N push and 30 N grip) ($F_{2,339} = 106.83$, $p < 0.001$). While the second peak frequency was not correlated with the palm force, it increased with the increase in finger force. For example, for Glove 2, the second peak for 15 N was at 100 Hz, 30 N was at 125 Hz, and 50 N was at 160 Hz.

3.3. Vibration transmissibility values for the gloves and VR material

The mean transmissibility values for unweighted and weighted RMS acceleration for the gloves and VR material at a certain force level are listed in Tables 2 and 3. Statistical analysis showed that the measurements from the two adapters were not significantly different ($F_{1,\ 577} \leq 1.10$, $p \geq 0.30$), except for unweighted acceleration in the middle-frequency range ($F_{1,\ 577} = 5.49$, $p = 0.02$). In the middle-frequency range (Table 2), compared with the ordinary work glove (which should be similar to the bare hand), the VR gloves and VR material tended to amplify unweighted vibration (transmissibility > 1.00). The only exception was at 15 N grip. However, in the high-frequency range (Table 3), all VR gloves greatly reduced both unweighted and weighted vibration (transmissibility < 1.00). The weighted transmissibility values for the air bubble VR material at a couple of force levels were unexpectedly higher than those for the ordinary work glove. For these unweighted and weighted measurements, the effect of glove type and hand force were statistically significant ($F_{4,\ 577} > 52.12$, $p < 0.001$).

3.4. Vibration transmissibility of the gloves and VR material at the palm

The averaged glove vibration transmissibility spectra measured at the palm of the hand are shown in Fig. 10, which were simultaneously measured with the finger adapter measurements. The comparisons of the spectra shown in Fig. 10(a) and (b) suggest that the finger adapter did not have an obvious effect on the transmissibility spectra measured with the palm adapter. The ordinary work glove did not attenuate the vibration at the palm, but even amplified it around 1000 Hz. As expected, all other gloves provided more effective protection at the palm than at the fingers. Specifically, the VR gloves started attenuating vibration at the palm at frequencies above 25 Hz. Even though there was also a resonant peak around 250 Hz, the average peak transmissibility was less than or equal to 0.95. At higher frequencies, profound attenuation was observed. The three VR gloves and the glove VR material showed very similar vibration transmissibility at the palm.

4. Discussion

This study developed a lightweight two-fingers-held adapter method for the testing and evaluation of VR gloves at the fingers. The adapter design was tested by measuring the vibration transmissibility of several gloves and a sample VR material. The study enhanced the understanding of this method and glove vibration transmissibility. The experimental results suggest that this method is acceptable for such measurements.

4.1. General features of the new finger adapter method

This study demonstrated that the proposed finger adapter method is practical and simple. The consistency of the transmissibility measured with and without the palm adapter shown Fig. 8 suggests that the presence of the palm adapter does not significantly affect measurements of transmissibility at the fingers, nor does the use of the finger adapter affect the palm measurements. Therefore, the glove transmissibility at both parts of the hand can be simultaneously measured using the finger and palm adapters in the standard glove test. This approach may also be applicable to investigations at workplaces. This can significantly increase the test efficiency with minimal increases in instrumentation expense.

4.2. General validity of the new finger adapter method

The near unity transmissibility of the adapter on the handle shown in Fig. 6 suggests that this instrumented finger adapter can be used for the measurement of vibration on tool handles or handheld workpieces in the frequency range of interest (6.3 to 1250 Hz). The effective mass of the human fingers (excluding the thumb) is more than 80 g [30]. Then, it is reasonable to estimate that the effective mass of the middle and ring fingers should be more than 40 g, which is more than 18 times the mass of each instrumented adapter (about 2.2 g for 3 mm adapter). Also importantly, the comparison of the resonant frequencies shown in Figs. 6 and 8 indicates that the dominant natural frequencies of the finger adapters used with a typical VR material (air bubble) under typical hand forces are generally close to or more than four times the major resonant frequencies of the gloved fingers. These observations suggest that the finger adapter does not substantially affect the dynamic responses of the gloved fingers.

In principle, a VR glove serves as a passive suspension element in the gloved hand-arm system. This basic mechanism has been simulated using a model of the system [15], which has also been included in the updated ISO 10068 [31]. The basic trends and characteristics of the glove transmissibility measured at the fingers shown in Figs. 7–9 and those at the palm shown in Fig. 10 are very consistent with the model predictions [15,31]. As further discussed in Section 4.3, the hand force effects on the measured glove transmissibility are also consistent with the modeling predictions. These observations not only further validate the model, but also suggest that the transmissibility data measured with the finger and palm adapters are reasonable according to the vibration biodynamics of the gloved fingers-hand-arm system.

4.3. The effects of hand forces

The modeling predictions suggest that the first resonance peak observed in Figs. 7–9 is primarily associated with the resonance of the hand, which depends primarily on the apparent or effective mass and contact stiffness of the hand. Theoretically, these two factors have opposite effects on the resonant frequency and transmissibility [15,32]. Because both the glove material and the hand contact tissues exhibit large non-linear behaviors [32,33], the increased grip force can increase the stiffness of the glove material and that of the hand coupling. Although increasing grip force can also increase the hand effective mass, the percent change of the hand mass is usually much less than that of the contact stiffness in the gripping of a cylindrical handle, as identified from previous modeling studies [30]. These observations explain why the increase in grip force increased the first peak frequency. Under the same grip force, adding push force further increases the hand contact stiffness at the palm, which can also increase the first peak frequency. For these reasons, the first peak frequency is correlated with the hand coupling force (grip force + push force), as also shown in Fig. 9.

The features and influencing factors of the second peak observed in Fig. 9 suggest that it must correspond to the resonance of the gloved fingers alone. This peak frequency depends on the effective mass and contact stiffness of the fingers, as also identified in previous studies [30]. Since changes in the palm force do not affect the finger contact stiffness, the push force is not correlated with the second peak frequency or the finger responses at higher frequencies, as shown in Figs. 8 and 9. The finger force (30 N) in three test treatments (30 N grip, 30 N grip + 50 N push, and 30 N grip + 50 N push with palm adapter) remains unchanged; the corresponding transmissibility data for each glove beyond the first resonant zone are very similar, as also shown in Fig. 9. This also explains why the transmissibility values for each of the VR gloves with these hand forces in the high-frequency range are similar, as indicated in Table 3. However, the grip force is correlated with the finger contact force; increasing the grip force effectively elevates the finger contact stiffness, but it only marginally changes the finger effective mass [30]. Therefore, the grip force at the three levels (15 N, 30 N, and 50 N) were correlated with three different second resonant frequencies.

4.4. Repeatability of the measurements with the new finger adapter method

The vibration transmissibility spectra measured in the two trials for each test treatment by each subject were generally very similar. To further verify the repeatability of the measurements, we repeated the same experiment for one of the subjects on a different day with a different randomized test sequence. The measured glove transmissibility spectra were highly consistent. The good repeatability can also be observed from the results shown in Fig. 8. Even though the two finger adapters have different thicknesses, and the spectra were measured at different times in the experimental sequence, the spectra of the same glove under the same hand force measured with the two adapters were similar to each other. The first and second peak values and frequencies measured with the two adapters were almost identical. These observations further suggest that the measurements with the developed finger adapters are very repeatable. The glove transmissibility spectra measured at the palm of the hand for each glove are also highly consistent, as shown in Fig. 10. This suggests that measurements with the palm adapter method are also highly repeatable.

4.5. The differences between the 2 mm and 3 mm finger adapters

Although these two adapters provided very similar results, the 2 mm adapter seems less reliable than the 3 mm adapter based on the following observations: (i) theoretically, the transmissibility should be close to unity for each glove at low-frequencies (<20 Hz); the transmissibility values for the 2 mm adapter in this frequency range deviated from unity to a greater extent than the 3 mm adapter transmissibility values, as shown in Figs. 7 and 8; (ii) an outlier was observed in the data measured with the 2 mm adapter, as shown in Fig. 7(c); and (iii) in a few trials, we observed that the measured transmissibility spectrum was very different from the normal spectra shown in Fig. 7 or Fig. 8; we actually repeated such trials and advised the test subject to try to apply a more stable grip force on the adapter, which rectified the unusual measurements; however, such outliers were not observed with the 3-mm adapter. These phenomena suggest that the force applied on the adapter by the two fingers may not be sufficient to hold the 2 mm adapter firmly against the glove material in some cases so that the adapter could exhibit larger translational and rotational movements in the vibration responses. The applied force on the 3 mm adapter was more stable than that applied to the 2 mm version. Further increasing the adapter thickness may further increase applied force stability; however, increasing the adapter size might further interfere with the natural configuration of the finger/glove interface and distort the glove transmissibility measurements. The presented results suggest the 3 mm adapter is a good choice for measuring the transmissibility at the middle sections of the fingers. For the measurement at the distal sections, the 2 mm adapter may be a better selection because the fingers usually apply a large contact pressure at this section in a power grip action [34,35].

4.6. Implications of the experimental results

The transmissibility spectra shown in Figs. 7–9 and the transmissibility values listed in Table 2 confirm that the gloves and VR material do not significantly decrease the vibration input to the fingers below 200 Hz. In fact, the gloves amplify many vibration frequencies. Some exceptions are the unweighted vibration attenuation by the gel pad and dipped neoprene gloves under a low grip force (15 N) (Table 2). These results are basically consistent with some previously-reported studies [8,12,18,19]. As the dominant vibrations for many vibrating powered hand tools are in the low- and middle-frequency range [7,36], VR or AV gloves are unlikely to reduce frequency-weighted vibration at the fingers in the operations of these tools.

The results of this study also suggest that, in the frequency range of 200 to 1250 Hz, VR gloves and VR material can effectively reduce finger vibration, especially unweighted vibration, as indicated in Table 3. Many impact tools and handheld workpieces generate significant high-frequency vibrations. The use of VR gloves can reduce such vibrations. If vibration-induced white finger (VWF) is associated with the unweighted vibration, or if high-frequency vibration plays an important role in the development of VWF, the VR gloves should have some value for protecting the fingers. The results also suggest that if applicable, reducing the finger force may also increase the effectiveness of VR gloves.

5. Conclusion

A new method was proposed to measure the vibration transmissibility of VR gloves and glove materials at the human fingers for assessing their effectiveness for attenuating finger vibration exposures. A novel lightweight (2.0 ± 0.2 g) finger adapter was developed to conduct the measurement. It includes a thin beam (2.5 ± 0.5 mm in thickness, 38 ± 2 mm in length, and 10 ± 1 mm in width) that can be easily fabricated with a thermoplastic (PLA filament) using a 3D printer, and a miniature tri-axial accelerometer attached to the center location of the beam. During the measurement, the finger adapter is held by two fingers and positioned at the interface between the glove and fingers.

This method was evaluated through a series of laboratory experiments. The experimental procedures demonstrate that this method is easy to use. The experimental results indicate that this method can provide consistent and reliable measurements of the effectiveness of VR glove fingers and their vibration-reducing materials. The measured glove transmissibility suggest that VR gloves cannot reduce the low- and middle-frequency vibrations transmitted to the fingers, but they may amplify the vibrations at these frequency ranges. However, these gloves can effectively decrease high-frequency vibrations; the level of vibration-attenuation effectiveness depends on the applied finger force.

This study also revealed that the finger adapter method can be combined with the palm adapter method to measure the vibration transmissibility of a glove simultaneously at the fingers and palm of the hand. The inclusion of this finger adapter method in the current standardized glove test can increase the value of the standard without substantially increasing the time or expense of glove assessments.

References

[1]. Brown AP, The effects of anti-vibration gloves on vibration induced disorders: a case study, J. Hand Ther 3 (1990) 94–100.

[2]. Jetzer T, Haydon P, Reynolds DD, Effective intervention with ergonomics, antivibration gloves, and medical surveillance to minimize hand-arm vibration hazards in the workplace, J. Occup. Environ. Med 45 (12) (2003) 1312–1317. [PubMed: 14665818]

[3]. Mahbub H, Yokoyama K, Laskar S, Inoue M, Takahashi Y, Yamamoto S, Assessing the influence of antivibration glove on digital vascular responses to acute hand-arm vibration, J. Occupational Health 49 (3) (2007) 165–171.

[4]. Cheng CH, Wang MJJ, Lin SC, Evaluating the effects of wearing gloves and wrist support on hand-arm response while operating an in-line pneumatic screwdriver, Int. J. Ind. Ergonomics 24 (1999) 473–481.

[5]. Pinto I, Stacchini N, Bovenzi M, Paddan GS, Griffin MJ, Protection effectiveness of anti-vibration gloves: field evaluation and laboratory performance assessment, in: The proceedings of the 9TH International Conference on Hand-Arm Vibration, Nancy, France, 2001, pp. 387–394.

[6]. Rakheja S, Dong RG, Welcome DE, Schopper AW, Estimation of tool-specific isolation performance of anti-vibration gloves, Int. J. Ind. Ergon 30 (2) (2002) 71–87.

[7]. Dong RG, Welcome DE, Peterson DR, Xu XS, McDowell TW, Warren C, Asaki T, Kudernatsch S, Brammer A, Tool-specific performance of vibration-reducing gloves for attenuating palm-transmitted vibrations in three orthogonal directions, Int. J. Ind. Ergon 44 (2014) 827–839. [PubMed: 26726275]

[8]. Welcome DE, Dong RG, Xu XS, Warren C, McDowell TW, Tool-specific performance of vibration-reducing gloves for attenuating fingers-transmitted vibration, Occup. Ergon 13 (2016) 23–44. [PubMed: 27867313]

[9]. ISO 10819 (updated version), Mechanical vibration and shock – Hand-arm vibration – Method for the measurement and evaluation of the vibration transmissibility of gloves at the palm of the hand International Organization for Standardization, Geneva, Switzerland, 2013.

[10]. ISO 10819 (original version), Mechanical Vibration and Shock – Hand-arm Vibration – Method for the Measurement and Evaluation of the VibrationTransmissibility of Gloves at the Palm of the Hand International Organization for Standardization, Geneva, Switzerland, 1996.

[11]. Dong RG, Rakheja S, Smutz WP, Schopper AW, Wu JZ, Evaluating anti-vibration performance of a glove using total effective transmissibility, Int. J. Ind. Ergon 30 (2002) 33–48.

[12]. Welcome DE, Dong RG, Xu XS, Warren C, McDowell TW, The effects of vibration-reducing gloves on finger vibration, Int. J. Ind. Ergon 44 (2014) 45–59. [PubMed: 26543297]

[13]. Griffin MJ, Evaluating the effectiveness of gloves in reducing hazards hand-transmitted vibration, Occup. Environ. Med 55 (1998) 340–348. [PubMed: 9764112]

[14]. Hewitt S, Assessing the performance of anti-vibration gloves – a possible alternative to ISO 10819:1996, Ann. Occup. Hyg 42 (4) (1998) 245–252. [PubMed: 9713247]

[15]. Dong RG, McDowell TW, Welcome DE, Warren C, Wu JZ, Rakheja S, Analysis of anti-vibration gloves mechanism and evaluation methods, J. Sound Vib 321 (2009) 435–453.

[16]. Hewitt S, Triaxial measurements of the performance of anti-vibration gloves. HSE research report RR795, (2010). http://www.hse.gov.uk/research/rrhtm/rr795.htm (accessed 6 Feb 2018 and 10 Dec. 2018).

[17]. Welcome DE, Dong RG, Xu XS, Warren C, McDowell TW, An evaluation of the proposed revision of the anti-vibration glove test method defined in ISO-10819 (1996), Int. J. Ind. Ergon 42 (1) (2012) 143–155.

[18]. Peterson DR, Asaki T, Kudernatsch S, Brammer AJ, Cherniack MG, Incorporating a finger adapter into ISO 10819 assessments to measure the vibration transmissibility of gloves at the fingers, in: Proceedings of the 5th American conference on human vibration, guelph, Ontario, Canada, 2014, pp. 33–34.

[19]. Griffin MJ, Macfarlane CR, Norman CD, The transmission of vibration to the hand and the influence of Gloves Vibration Effects on the Hand and Arm in Industry, John Wiley & Sons, New York, 1982, pp. 103–116.

[20]. Paddan GS, Griffin MJ, Measurement of glove and hand dynamics using knuckle vibration Proceedings of the 9th international conference on hand-arm vibration, Section 15 (6) (2001) Nancy, France.

[21]. Hamouda K, Rakheja S, Marcotte P, Dewangan KN, Fingers vibration transmission performance of vibration reducing gloves, Int. J. Ind. Ergon 62 (2017) 55–69.

[22]. Hamouda K, Rakheja S, Dewangan KN, Marcotte P, Fingers' vibration transmission and grip strength preservation performance of vibration reducing gloves, Appl. Ergon 66 (2018) 121–138. [PubMed: 28958422]

[23]. Ainsa I, Gonzales D, Lizaranzu M, Bernad C, Experimental evaluation of uncertainty in hand-arm vibration measurements, Int. J. Ind. Ergon 41 (2) (2011) 167–179.

[24]. Rasmussen G, Measurement of vibration coupled to the hand-arm system Vibration Effects on the Hand and Arm in Industry, Wiley, New York, 1982, pp. 89–95.

[25]. ISO 5349–2, Mechanical vibration – Measurement and evaluation of human exposure to hand-transmitted vibration – Part 2: Practice guidance for measurement in the workplace, 2001.

[26]. Xu XS, Dong RG, Welcome DE, McDowell TW, Wu JZ, Wimer B, Warren C, An examination of the handheld adapter approach for measuring hand-transmitted vibration exposure, Measurement 47 (2014) 64–77. [PubMed: 26744580]

[27]. EN 420: 2003+A1. Protective gloves - General requirements and test methods. The European Standards body, 2009.

[28]. ISO 5349–1, Mechanical vibration - Measurement and evaluation of human exposure to hand-transmitted vibration - Part 1: General requirements International Organization for Standardization, Geneva, Switzerland, 2001.

[29]. Dong RG, Welcome DE, McDowell TW, Wu JZ, Measurement of biodynamic response of human hand-arm system, J. Sound Vib 294 (4–5) (2006) 807–827.

[30]. Dong JH, Dong RG, Rakheja S, Welcome DE, McDowell TW, Wu JZ, A method for analyzing absorbed power distribution in the hand and arm substructures when operating vibration tools, J. Sound Vib 311 (2008) 1286–1304.

[31]. ISO 10068, Mechanical Vibration and Shock – Mechanical Impedance of the Human Hand-Arm System at the Driving Point International Organization of Standard, Geneva, Switzerland, 2012

[32]. Md Rezali KA, Griffin MJ, Transmission of vibration through glove materials: effects of contact force, Ergonomics (2018), 10.1080/00140139.2018.1462407.

[33]. Wu JZ, Krajnak K, Welcome DE, Dong RG, Analysis of the dynamic strains in a fingertip exposed to vibration: correlation to the mechanical stimuli on mechanoreceptors, J. Biomech 39 (2006) 2445–2456. [PubMed: 16168999]

[34]. Amis AA, Variation of finger forces in maximal isometric grasp tests on a range of cylinder diameters, J. Biomed. Eng 9 (1987) 313–320. [PubMed: 3682795]

[35]. Aldien Y, Welcome DE, Rakheja S, Dong RG, Boileau P-E, Contact pressure distribution at hand-handle interface: role of hand forces and handle size, Int. J. Ind. Ergon 35 (2005) 267–286.

[36]. Griffin MJ, Measurement, evaluation, and assessment of occupational exposures to hand-transmitted vibration, Occup. Environ. Med 54 (1997) 73–89. [PubMed: 9072014]

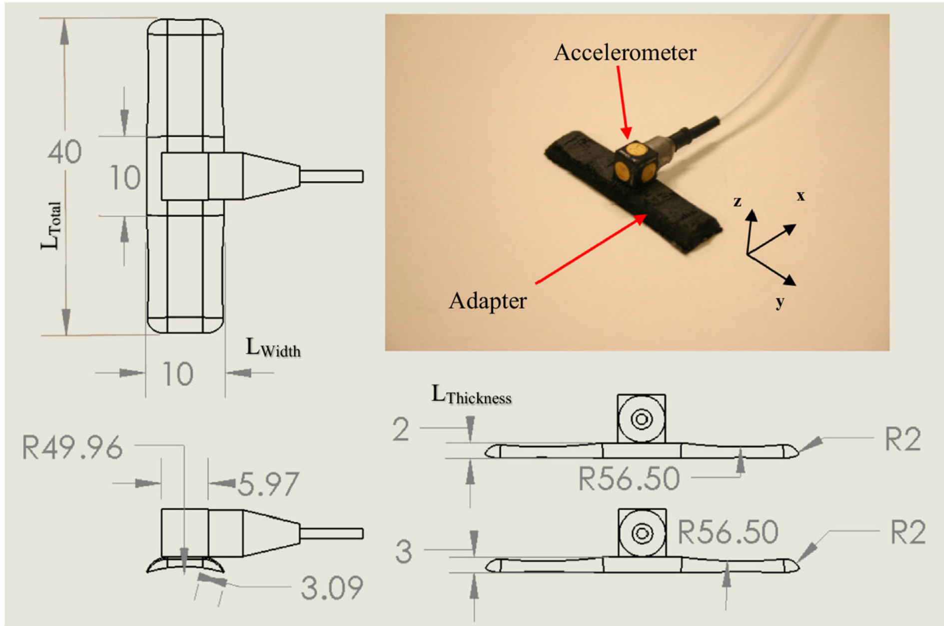


Fig. 1.

Designs of two finger adapters (unit in mm): one with 2-mm thickness and the other one with 3-mm thickness; their other dimensions are the same.

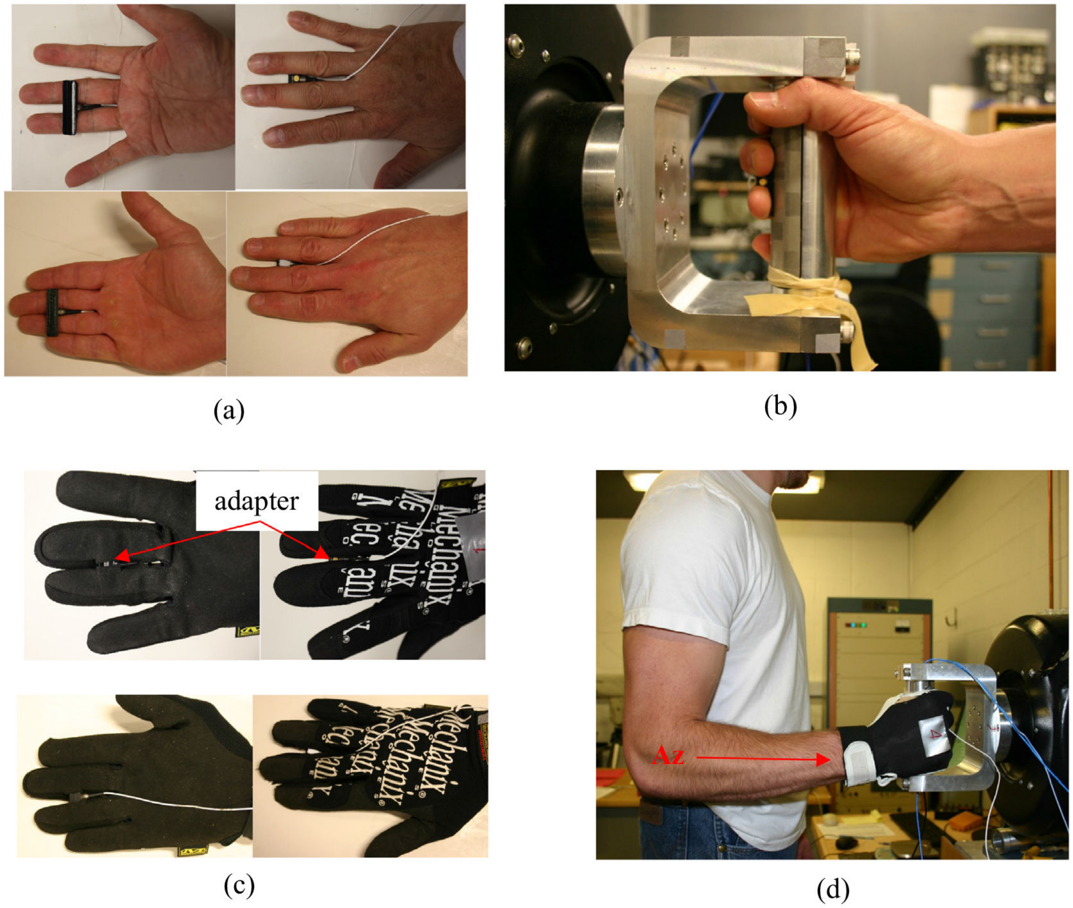


Fig. 2.

The position and orientation of the adapter held by two fingers in the subject test: (a) the location of the adapter at the fingers of two subjects (with hand size 7 (top) and hand size 10 (bottom) according to EN 420 [27]); (b) the position and orientation of the adapter held by the bare fingers on an instrumented handle with the hand and arm postures required in the standard glove test [9]; (c) the adapter held by gloved fingers of the two subjects with hand size 7 and hand size 10; and (d) the hand, arm, and body postures of a subject with a gloved hand holding a finger adapter and a standard palm adapter in a glove test.

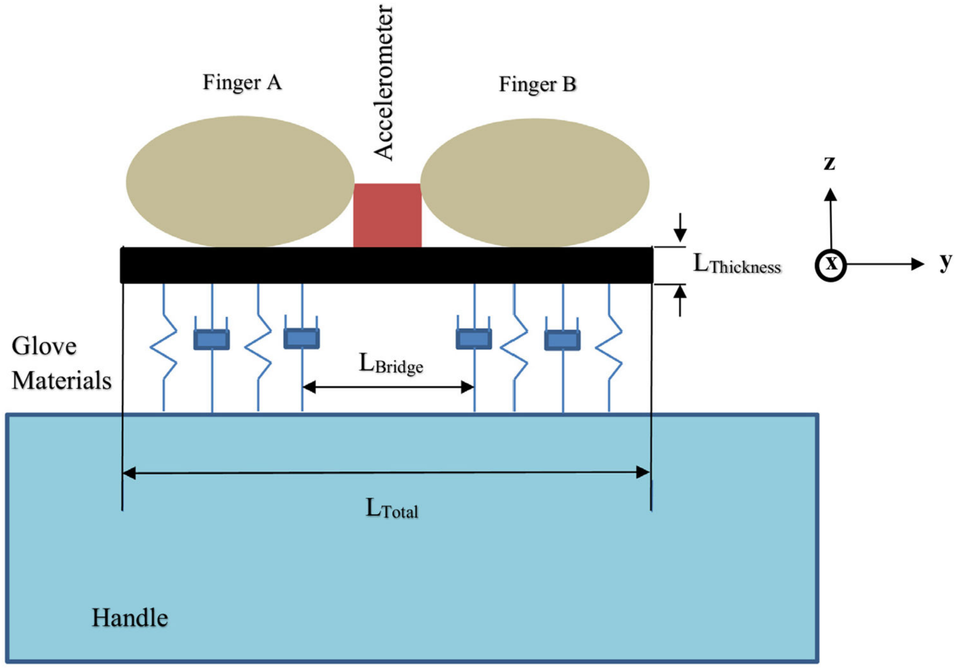
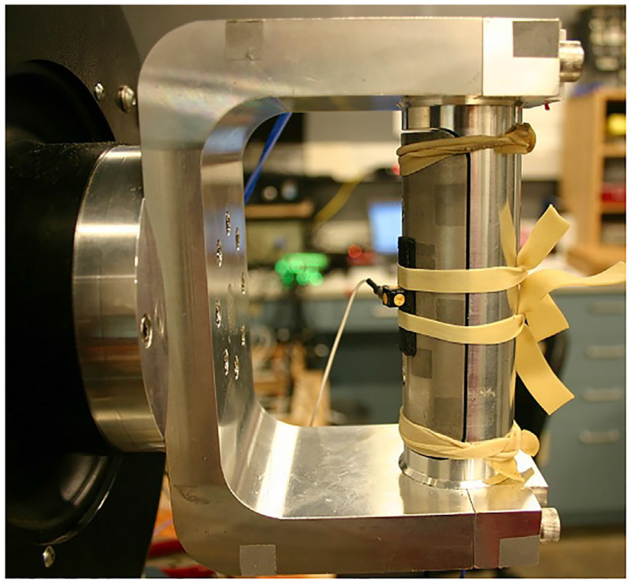


Fig. 3.
A conceptual dynamic model of the finger adapter on glove materials and held by two fingers.

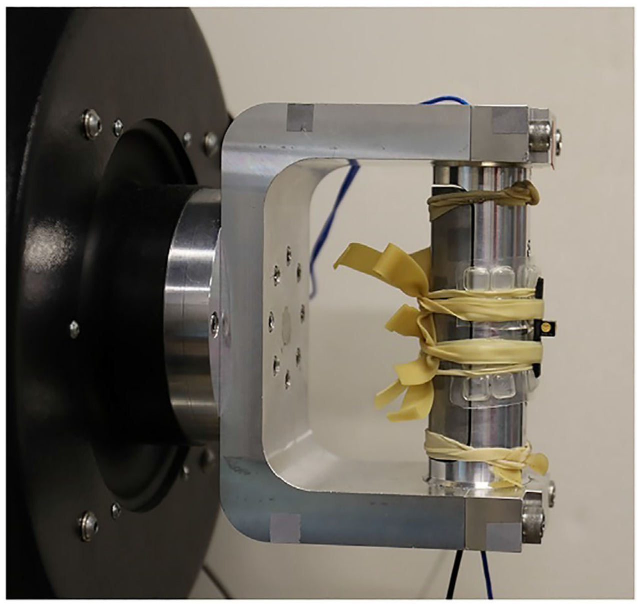
Author Manuscript

Author Manuscript

Author Manuscript



(a)



(b)

Fig. 4.

Adapter tests: (a) the measurement of the baseline frequency response of each adapter attached on the instrumented handle with rubber bands; (b) the measurement of the resonant response of each adapter on a VR material.

Fig. 5.

Four types of gloves and one glove VR material tested in the study: ordinary work glove (Glove 1); gel glove (Glove 2); neoprene glove (Glove 3); air bubble glove (Glove 4); and a VR material (air bubble – Glove 5).

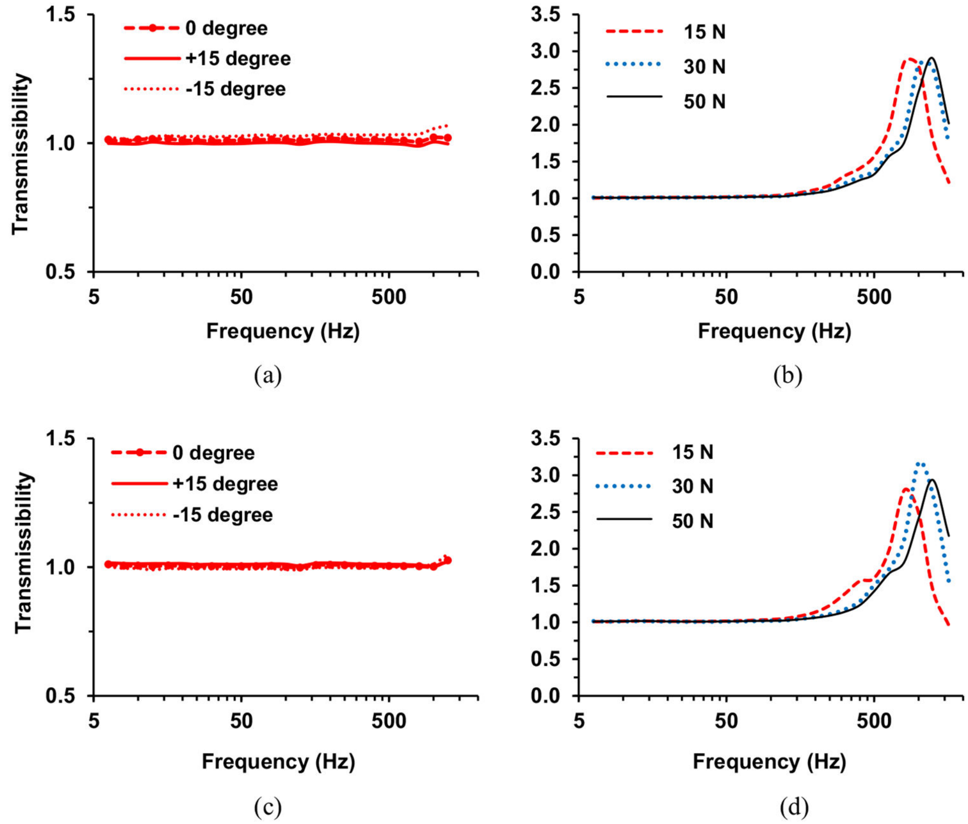


Fig. 6.

Vibration transmissibility spectra measured in the adapter tests: (a) 2-mm adapter baseline responses at three different angular positions; (b) 2-mm adapter resonant responses under three fastening forces; (c) 3-mm adapter baseline responses at three different angular positions; (d) 3-mm adapter resonant responses under three fastening forces.

Author Manuscript

Author Manuscript

Author Manuscript

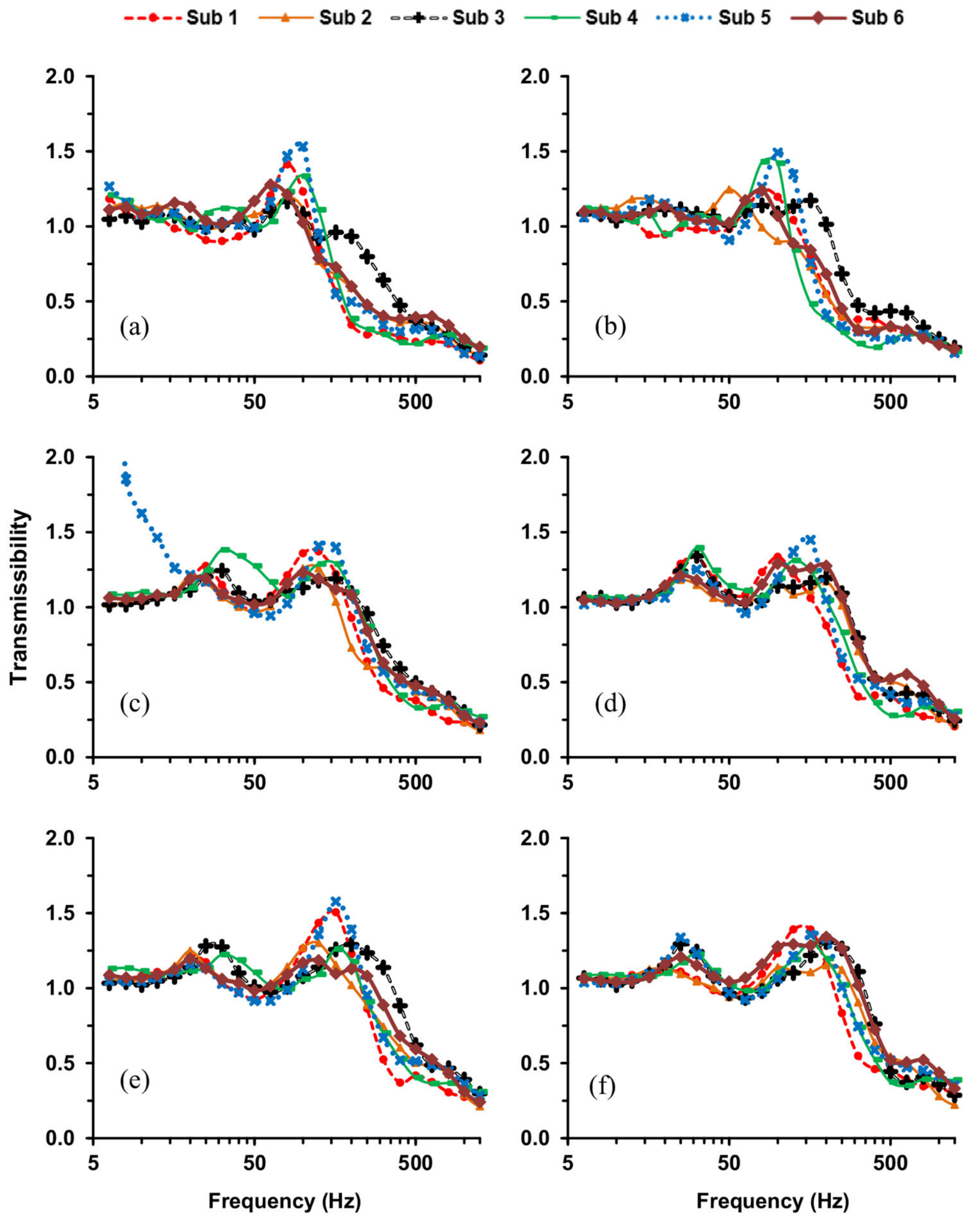


Fig. 7.

Examples of the vibration transmissibility spectra of neoprene glove (Glove 3) at the fingers of the six subjects: (a) with 2-mm adapter under 15 N grip; (b) with 3-mm adapter under 15 N grip; (c) with 2-mm adapter under combined 30 N grip and 50 N push; (d) with 3-mm adapter under combined 30 N grip and 50 N push; (e) 2-mm adapter under 50 N grip; (f) 3-mm adapter under 50 N grip.

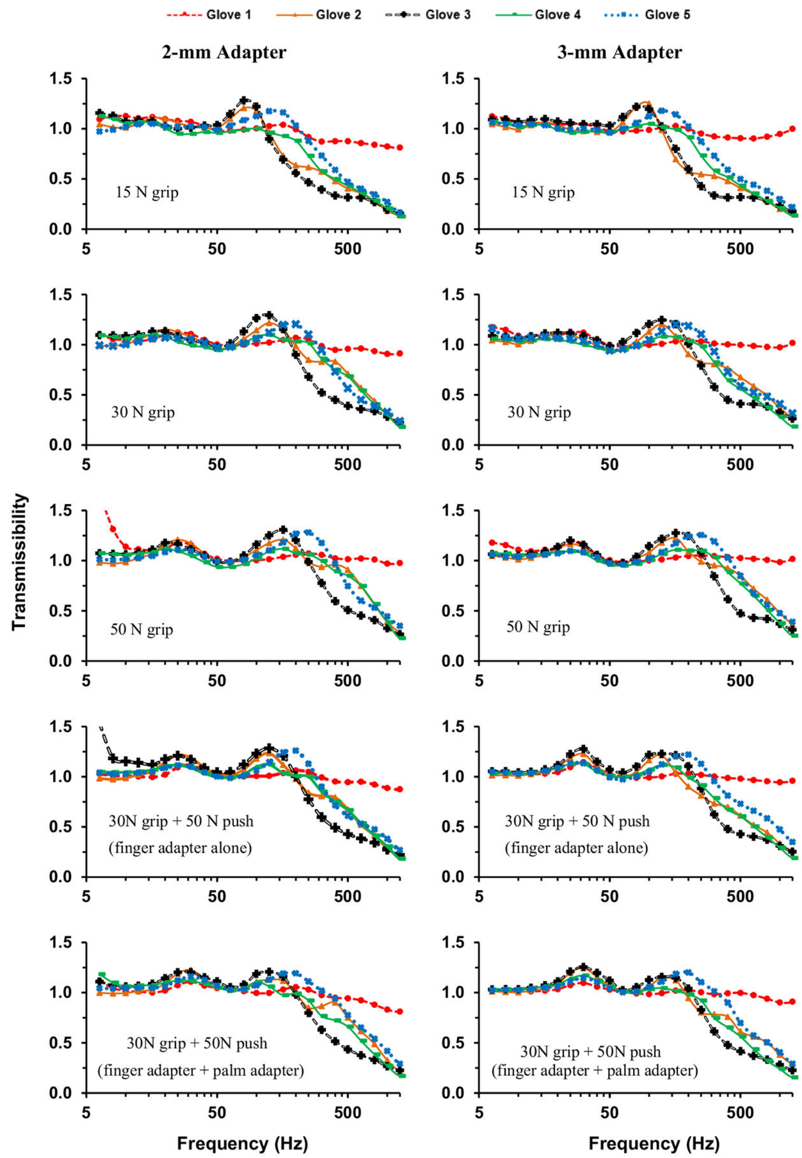


Fig. 8.

Six-subject-averaged vibration transmissibility spectra of the five gloves at the fingers measured with 2-mm adapter (left column) and 3-mm adapter (right column) under five different hand forces (15 N grip, 30 N grip, 50 N grip, 30 N grip + 50 N push for finger adapter alone, and 30 N grip + 50 N push for finger adapter + palm adapter).

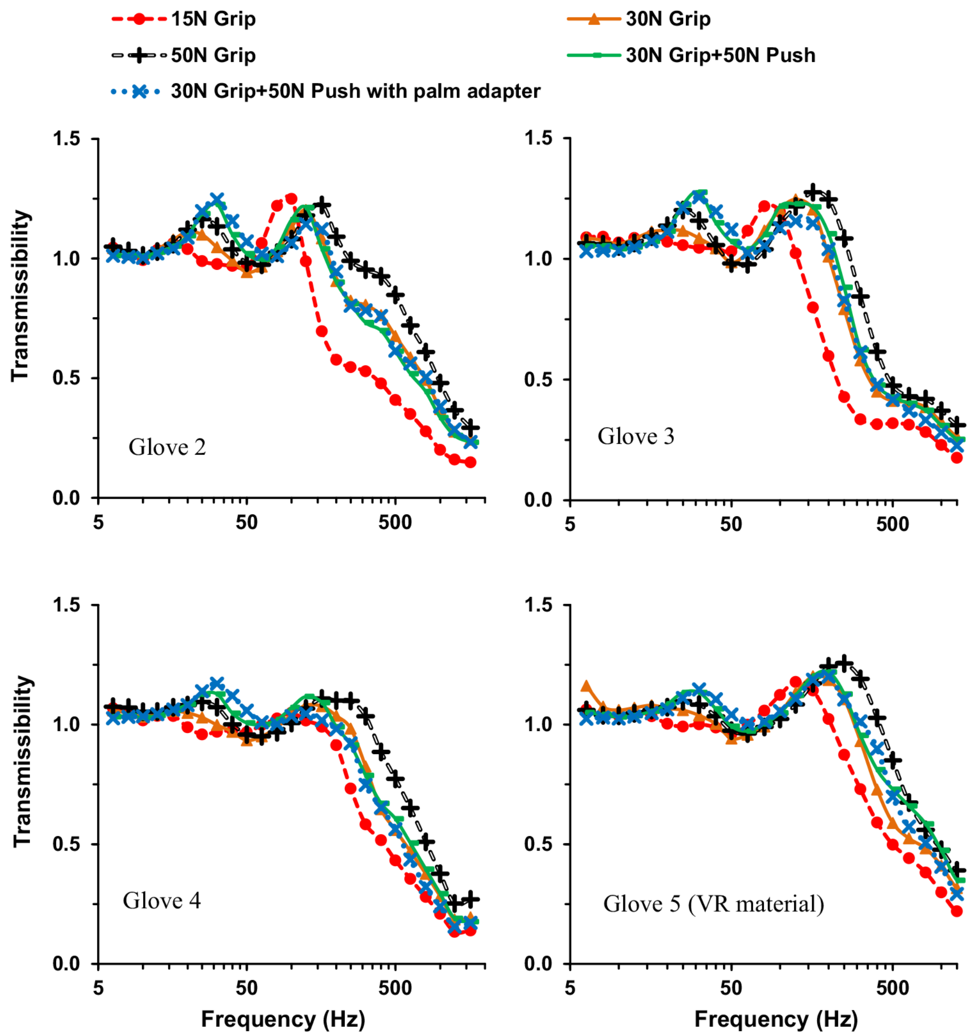


Fig. 9.
The effects of the hand forces on 6-subject-averaged finger vibration transmissibility of the three VR gloves (Gloves 2–4) and one VR material (Glove 5).

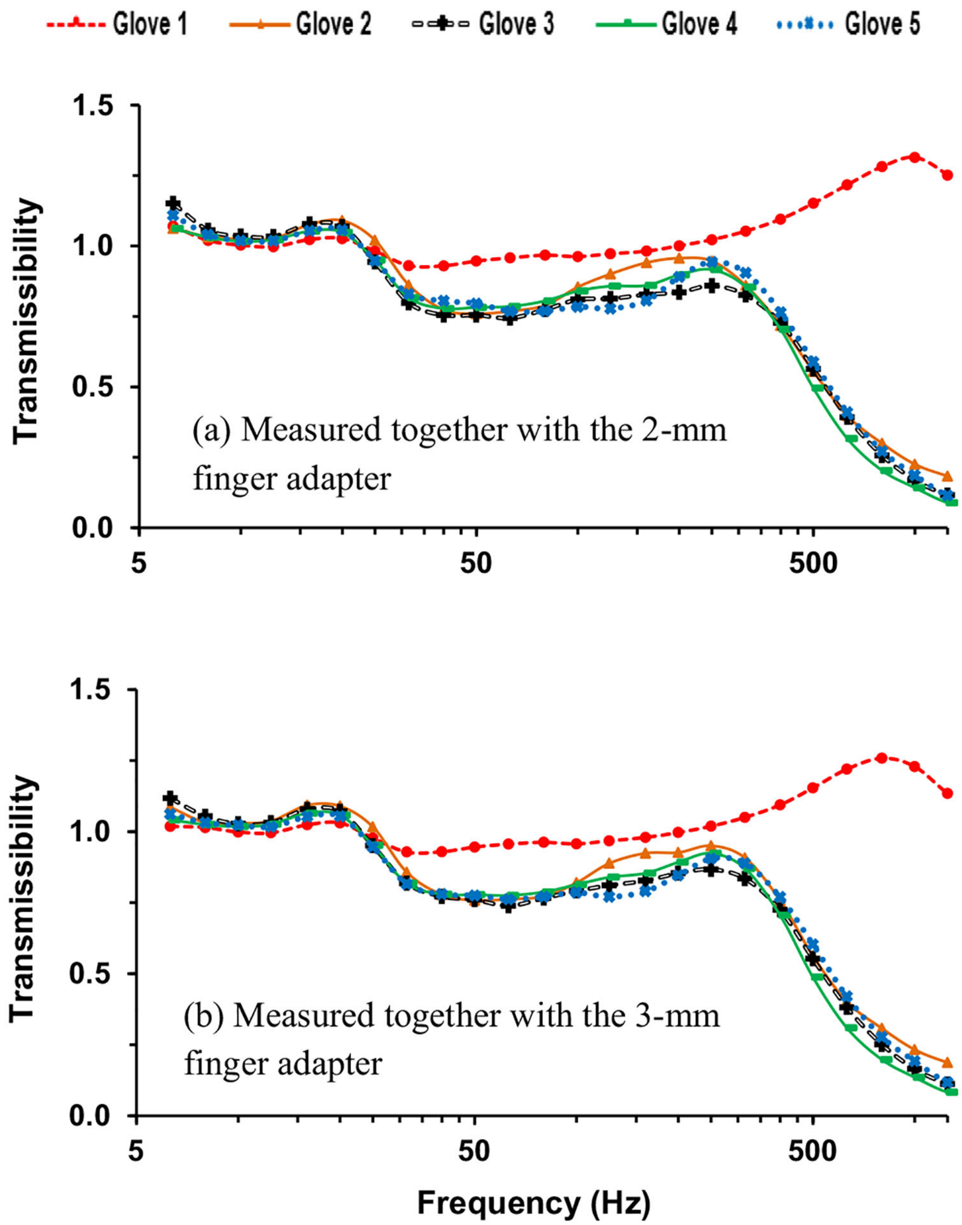


Fig. 10.
Six-subject-averaged vibration transmissibility spectra of the four gloves and one VR material at the palm of the hand measured with the palm adapter: (a) together with the 2-mm finger adapter; (b) together with the 3-mm finger adapter.

Table 1

Anthropometry data of the subjects in the glove adapter evaluation experiments (hand length = tip of middle finger to crease at wrist; hand breadth = the width measured at metacarpal; hand size based on EN 420 [27]).

Subject	Height (cm)	Weight (kg)	Hand Length (mm)	Hand Circumference (mm)	Hand Size
1	193	91	87	206	10
2	195	92	93	206	10
3	170	101	83	184	8
4	179	82	81	197	9
5	185	103	94	201	10
6	175	89	83	176	8
Mean	183	93	87	195	
SD	10.0	7.8	5.5	12.4	

Table 2

Six-subject-averaged unweighted and weighted Root Mean Square (RMS) total acceleration transmissibility of the gloves and glove VR material in the middle-frequency range (25–200 Hz) under five levels of hand force.

Unweighted RMS		**2 mm Adapter Measurements**					**3 mm Adapter Measurements**				
GloveID	**Glove description**	**Grip Only**			**Grip + Push**		**Grip Only**			**Grip + Push**	
		15 N	**30 N**	**50 N**	**(30N + 50 N)**		**15 N**	**30 N**	**50 N**	**(30N + 50N)**	
					A*	**B****				**A***	**B****
1	Ordinary work glove	1.01	1.04	1.03	1.03	1.03	1.01	1.03	1.03	1.02	1.02
2	Thick gel pad	0.86	1.08	1.14	1.09	1.07	0.86	1.04	1.13	1.04	1.05
3	Dipped neoprene	0.84	1.09	1.21	1.13	1.10	0.89	1.13	1.21	1.16	1.10
4	Cellular air bubbles	0.94	1.04	1.06	1.05	1.02	0.99	1.05	1.07	1.06	1.02
5	Cellular air bubble material	1.10	1.14	1.16	1.18	1.15	1.09	1.14	1.15	1.16	1.15
Weighted RMS		**2 mm Adapter Measurements**					**3 mm Adapter Measurements**				
GloveID	**Glove description**	**Grip Only**			**Grip + Push**		**Grip Only**			**Grip + Push**	
		15 N	**30 N**	**50 N**	**(30N + 50N)**		**15 N**	**30 N**	**50 N**	**(30N + 50N)**	
					A*	**B****				**A***	**B****
1	Ordinary work glove	1.02	1.03	1.04	1.02	1.04	1.01	1.03	1.05	1.04	1.03
2	Thick gel pad	1.01	1.07	1.09	1.10	1.10	1.00	1.04	1.09	1.10	1.11
3	Dipped neoprene	1.02	1.09	1.12	1.12	1.13	1.04	1.11	1.13	1.17	1.14
4	Cellular air bubbles	0.97	1.02	1.01	1.04	1.06	1.00	1.01	1.03	1.06	1.06
5	Cellular air bubble material	1.07	1.06	1.07	1.08	1.11	1.05	1.06	1.07	1.09	1.10

*A represents measurements with finger adapter alone.

**B represents measurement with both finger and palm adapters.

Table 3

Six-subject-averaged unweighted and weighted Root Mean Square (RMS) total acceleration transmissibility of the gloves and glove VR material in the high-frequency range (200–1250 Hz) under five levels of hand force.

Unweighted RMS		**2 mm Adapter Measurements**					**3 mm Adapter Measurements**				
GloveID	**Glove description**	**Grip Only**			**Grip + Push**		**Grip Only**			**Grip + Push**	
		15 N	**30 N**	**50 N**	**(30N + 50N)**		**15 N**	**30 N**	**50 N**	**(30N + 50N)**	
					A*	**B****				**A***	**B****
1	Ordinary work glove	0.87	0.96	1.02	0.94	0.92	0.93	1.00	1.02	0.97	0.96
2	Thick gel pad	0.40	0.63	0.76	0.60	0.66	0.38	0.62	0.76	0.57	0.61
3	Dipped neoprene	0.32	0.43	0.57	0.46	0.47	0.32	0.48	0.59	0.50	0.47
4	Cellular air bubbles	0.43	0.62	0.75	0.62	0.59	0.44	0.57	0.72	0.57	0.54
5	Cellular air bubble material	0.52	0.62	0.78	0.66	0.75	0.53	0.66	0.83	0.73	0.71
Weighted RMS		**2 mm Adapter Measurements**					**3 mm Adapter Measurements**				
GloveID	**Glove description**	**Grip Only**			**Grip + Push**		**Grip Only**			**Grip + Push**	
		15 N	**30 N**	**50 N**	**(30N + 50 N)**		**15 N**	**30 N**	**50 N**	**(30N + 50 N)**	
					A*	**B****				**A***	**B****
1	Ordinary work glove	0.91	1.00	1.04	1.00	0.98	0.94	1.01	1.04	1.00	1.00
2	Thick gel pad	0.53	0.81	0.95	0.80	0.84	0.50	0.78	0.94	0.74	0.77
3	Dipped neoprene	0.42	0.60	0.84	0.68	0.68	0.41	0.68	0.88	0.74	0.70
4	Cellular air bubbles	0.63	0.84	0.95	0.83	0.79	0.64	0.81	0.95	0.78	0.76
5	Cellular air bubble material	0.75	0.91	1.07	0.93	0.99	0.75	0.92	1.09	0.97	0.97

* A represents measurements with finger adapter alone.

** B represents measurement with both finger and palm adapters.