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On-the-hand measurement methods for assessing effectiveness of anti-vibration gloves

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Abstract

Several technical difficulties have been associated with the current test and evaluation methods for assessing the vibration isolation effectiveness of anti-vibration gloves. The effectiveness of the gloves for specific powered hand tools can be assessed through measurement of acceleration on the head of the third metacarpal or at the wrist. In the present study, the reliability of these on-the-hand measurement methods is evaluated through assessing the vibration transmissibility of gloves while operating chipping hammers. Two different methods, with and without the prior knowledge of tool vibration, for deriving the transmissibility of the gloves are also evaluated. The study used an air bladder glove and a gel-filled glove, two chipping hammers, and feed forces in the 50–200 N range. Six male volunteers were used as test subjects. The transmissibility of the gloves is also estimated using a total vibration transfer function method. The results suggest that the on-the-hand methods offer some unique advantages over the palm adapter method outlined in ISO-10819, but they suffer from poor repeatability when a high degree of tool vibration variability is observed, especially if the tool vibration is not measured and used for the assessment. Glove transmissibility measured at the third metacarpal is more repeatable than that derived from the measurements at the wrist. Reasonably good agreements were observed between the predicted and measured transmissibility values of the air glove. However, the measured transmissibility values for the gel-filled glove suggest that it may perform better than as predicted using the transfer function method.

Relevance to industry

Prolonged exposure to hand-transmitted vibration has been related to an array of health disorders of the vascular, nervous and musculoskeletal systems in the upper extremity. Anti-vibration gloves can be used to help reduce the severity of vibration exposure. The current glove assessment methods exhibit several technical difficulties and do not provide information regarding the effectiveness of the gloves when used with specific power tools. This study examines the effectiveness of on-the-hand measurement methods and the transfer function-based prediction method to determine more reliable glove assessment methods. The study also proposes a test device and method for assessing the vibration

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effectiveness of gloves when used with pneumatic hammers. It is anticipated that the proposed glove assessment method would be applicable to other types of hand-held power tools.

Keywords: Anti-vibration gloves; Vibration transmissibility; Assessment method; Hand–arm vibration; Vibration attenuation; Chipping hammers; Measurement of glove vibration transmissibility; Prediction of tool-specific glove transmissibility

1. Introduction

Prolonged occupational exposure to hand-transmitted vibration has been associated with many forms of upper extremity health disorders, often referred to as the 'hand–arm vibration syndrome' (Gemne and Taylor, 1983). Several types of anti-vibration gloves (e.g. Muralidhar et al., 1999; Reynolds and Jetzer, 1998) have been developed and used as a preventive measure to help minimize the occupational hazards posed by hand-transmitted vibration. It has been established that the vibration isolation performance of gloves is tool- and operation-specific (Griffin, 1998; Rakheja et al., 2002). However, the effectiveness of these gloves when used with specific vibratory tools has not been well studied, primarily due to complexities associated with vibration measurements on the hand-held power tools.

The vibration isolation effectiveness of gloves has been typically assessed through measurement of acceleration transmissibility in the laboratory (Voss, 1996; Hewitt, 1997; Gurram et al., 1994; Griffin et al., 1982). In an effort to develop a uniform method for differentiating effective vibration attenuating gloves from less-effective gloves, the International Organization for Standardization (ISO) has set forth a laboratory-based test method (ISO 10819, 1996). A few studies (Hewitt, 1998; Griffin, 1998; Dong et al., 2002a) have reported fundamental deficiencies and many technical problems with application of the standard and have proposed several improved approaches. In some instances, application of the standard might allow a glove to be classified as an anti-vibration glove when it provides no useful attenuation of vibration from the handle of some types of tools. On the other hand, a glove which provides useful vibration attenuation when used with a specific tool might fail to meet the anti-vibration glove requirements (Griffin, 1998). Since the standardized test method employs an idealized test handle and idealized input vibration spectra that are not representative of those produced by most tools (Griffin, 1998; Rakheja et al., 2002), the effectiveness of anti-vibration gloves when used with power hand tools cannot be assessed. Although this standardized testing method may be considered acceptable for general screening purposes, alternate practical approaches are needed to assess the vibration attenuation performance of gloves when used with specific vibratory tools in the workplace.

A wide range of test methods has been reported for assessing the vibration isolation performance of gloves. The majority of these methods are applicable to simulated test handles in the laboratory. The reported methods may be grouped in two categories on the basis of the measurement method and location used: (i) on-the-hand measurement methods; and (ii) at the hand–glove interface measurement methods. The methods within the first group involve measurement of acceleration transmitted to the fingernail, knuckle, phalange, back of the hand or at the wrist (Gurram et al., 1994; Chang et al., 1999; Griffin et al., 1982; Goel and Rim, 1987; Paddan and Griffin, 2001). The glove isolation effectiveness is evaluated by comparing the acceleration measured when wearing a glove with that measured without the glove (bare hand). The basic concepts for this approach have been adopted in a US national standard (ANSI S3.40, 1989). The test methods within the second group employ a palm adapter equipped with either a single or a three-axis miniature accelerometer that is held in the palm of the hand inside the glove to measure the vibration transmitted to the hand–glove interface (ISO 10819, 1996; Pinto et al., 2001; Dong et al., 2002b). A recommended design of the palm adapter is outlined in the ISO 10819 (1996). It remains unknown whether these two methods provide comparable results, and their relative merits are unclear.

Based on whether the tool vibration information is used, an anti-vibration glove assessment method can be classified as either a direct evaluation method or a relative evaluation method. The direct evaluation method involves determination of vibration transmissibility through direct measurement of both the transmitted acceleration and the tool handle acceleration (Dong et al, 2002a, b; Gurram et al., 1994; Hewitt, 1997, 1998; Voss, 1996). The vibration spectra of the tool is not required for the relative assessment method, which only uses the transmitted accelerations measured with the bare and the gloved-hand tests for the assessment (Goel and Rim, 1987; Chang et al., 1999; Pinto et al., 2001). The differences between the results of these different approaches have not yet been investigated.

As an alternative approach to the experimental methods, an estimation method based on the measured transfer function of a glove has been proposed to predict the performance of anti-vibration gloves for specific tools (Griffin, 1998; Rakheja et al., 2002; Dong et al., 2002b). A total vibration transfer function procedure is also proposed in the present study. The proposed estimation methodology can greatly simplify the assessment of vibration attenuation performance of gloves and considerably reduce the cost associated with field tests involving a representative sample of human subjects and data analyses. Considerable differences between the predicted transmissibility values and the measured data acquired for several real tools in the workplaces, however, have been reported (Pinto et al., 2001). Such discrepancies cast doubts on the reliability of the prediction approach for the field application.

The specific aims of the present study are: (i) to examine the usefulness and reliability of the on-the-hand measurement methods through assessing the vibration isolation performances of two typical anti-vibration gloves when used with chipping hammers; (ii) to evaluate the effectiveness of the proposed total vibration transfer function method for estimating the vibration attenuation performance of gloves, and (iii) to explore the advantages and disadvantages of the direct and relative methods for determining the transmissibility of the gloves.

2. Methods

2.1. Experimental setup

The effectiveness of the on-the-hand measurement methods for assessing anti-vibration gloves is investigated using two chipping hammers. The experiments are performed using a chipping hammer test station that was based on the design specified in ISO 8662-2 (1992) for measuring the vibration emission of chipping hammers. Such a test station may not be used to assess the risk of chipping hammer vibration exposures in the workplace, since the magnitude of the vibration generated on the station may be lower than the average vibration values observed in the field (Brereton, 2001). This deficiency, however, is not critical for the purpose of this study. The use of the standardized test station, however, permits the measurement of stable and reproducible impact vibration due to chipping hammer operation, which is considered to be critical for assessing the reliability of the measurement and prediction methods for the glove assessment.

Fig. 1 illustrates the schematic of the chipping hammer test station. The key feature of the test station is the energy absorber, which is composed of a steel tube filled with hardened steel balls (ISO 8662-2, 1992). The absorber is firmly mounted on a rigid steel base that is secured to a concrete block. The chipping hammer's chisel bit is replaced by a hardened anvil, which is inserted into the energy absorber through a guiding bushing. The flat anvil attached to the bit rests on top of the steel balls, as shown in the figure.

A tri-axis accelerometer (PCB 5611A, USA) was installed on a mounting block and secured to the handle with a hose clamp to measure the tool handle vibration. The measurement of vibration of percussive tools often yields significant DC shift in the piezoelectric accelerometer output (Griffin, 1990). The application of a commercially available

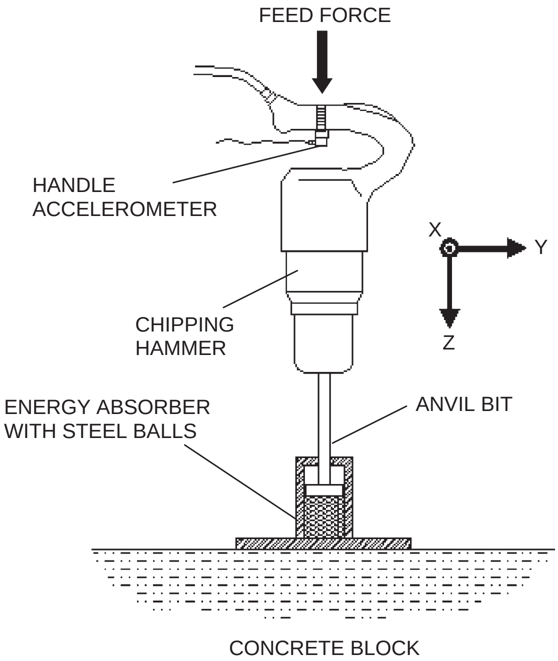

Fig. 1. A schematic of the measurement setup for assessing the vibration transmissibility of a glove used with a chipping hammer.

Fig. 2. A pictorial view of the miniature accelerometer affixed to a small wooden adapter to measure the vibration transmitted at the third metacarpal.

mechanical filter (B&K, UA0059, Denmark) did not help circumvent the difficulty associated with the DC shift of the accelerometer used in this study. Consequently, a mechanical filter comprising a 3 mm thick elastomer was configured in an attempt to eliminate the DC shift. The experiments performed on the candidate tools revealed that this elastomer inserted between the accelerometer clamp and the handle could eliminate the DC shift to a large extent. The effectiveness of this filter was further examined by performing measurements with a non-contacting laser vibrometer (Polytec PI, PSV-300, Germany) and comparing the measured response with that acquired from the handle-mounted accelerometer. From the comparison, it was concluded that the elastomeric mechanical filter satisfactorily minimized the DC shifting of the acceleration signal.

The measurement of vibration transmitted to the head of the third metacarpal was carried out using a lightweight miniature tri-axis accelerometer (Endevco M35, USA). This accelerometer was fixed on a tiny wooden adapter that had a curved surface (approximately 20 mm radius) to adapt to the skin above the metacarpal bone. The adapter increased the contact area and stabilized the position of the accelerometer. The adapter with the accelerometer weighed less than 1.4 g. Hook and loop tape was used to tightly secure the tiny adapter on the head of the third metacarpal of the dominant hand, as shown in Fig. 2.

A three-axis accelerometer (PCB 339B24, USA) was also installed within the frame of a wrist watch for acquiring the vibration transmitted to the wrist of the dominant hand, as shown in Fig. 3, which was similar to that used in a previous study (Gurram et al., 1994). The total weight of the watch with the accelerometer was 29 g. The accelerometer watch-strap was secured to the wrist slightly tighter than a person would normally wear

Fig. 3. A pictorial view of the wrist watch mounted three-axis accelerometer.

Table 1
Physical characteristics of the six male subjects

Subject	1	2	3	4	5	6	Mean	Std. dev.
Height (m)	1.78	1.75	1.80	1.78	1.83	1.88	1.80	0.05
Percentile[a]	64	47	75	64	86	97	—	—
Weight (kg)	78.8	73.8	80.9	75.5	113.3	132.6	92.5	24.5
Percentile[a]	52	37	59	42	99.5	99.99	—	—

[a] Percentile of US male adults based on Gordon et al. (1989).

a watch. A multi-channel data acquisition and analysis system (B&K Type 2816, Denmark) was used to collect all the nine vibration signals simultaneously from the three tri-axial accelerometers, respectively, installed on the tool handle, on the head of the third metacarpal, and at the wrist. The measured data were analyzed and expressed in terms of root-mean-square (rms) acceleration spectra in the one-third octave frequency bands.

In the ISO standardized glove test (ISO 10819, 1996) and also in the chipping hammer test (ISO 8662-2, 1992), three testing subjects are required. To make the test data more reliable, six healthy male subjects are employed in this study. The heights and weights of the subjects are listed in Table 1. As it can be seen, these subjects represented a good range of the general US male population. The experimental protocol was reviewed and approved by the NIOSH Human Subjects Review Board.

After signing a required consent form and donning all necessary personal protective equipment, each subject was provided with brief training on tool operation and was permitted to perform several trial runs for a period of approximately 10 min. The hand, arm and body postures specified in ISO 8662-2 (1992) were adopted in this study. The need to maintain specified hand, arm and body posture was emphasized during these trial runs.

Two different types of full-finger gloves, referred to as ‘glove A’ (an air glove) and ‘glove B’ (gel-filled glove), which are currently being marketed as anti-vibration gloves, were employed in the study. The experiments also involved measurements with the bare or ungloved hand. Two different pneumatic chipping hammers, referred to as 'Tool A' and 'Tool B', weighing 6.6 and 6.9 kg, respectively, were used in the study. The handle of 'Tool B' was covered with an elastomeric material, while that of 'Tool A' was bare steel. The supplied air was regulated to 689 kPa (100 psi), as specified by the tool manufacturers. The length of the chisel bit used in the test was approximately 30 cm.

In an attempt to simplify the tool handle instrumentation, subjects were asked to apply no grip force during the tests. Four different levels of feed/push force (50, 100, 150 and 200 N), however, were applied to the tool handle during the measurement. A force measurement plate (Kistler Type 9286AA, USA) was used to measure the feed force, which was displayed on a computer monitor as a horizontal line on a strip chart. The display monitor, placed directly in front of the test subject at the eye level at a distance of approximately 0.7 m, served as a feedback for the subject to control the force to the desired magnitude. The limits on the strip chart were adjusted for each target force so that the size and position of the target range remained constant throughout the testing.

2.2. Experimental procedure

Each test subject was instructed to stand on the force platform and apply a downward feed force on the tool handle while assuming the same arm posture as specified in the standardized vibration emission test procedure for chipping hammers (ISO 8662-2, 1992). The platform height was adjusted for each subject to ensure proper posture and to maximize comfort. The glove was worn on the dominant hand in the gloved-hand test trials. The subjects were also instructed to apply the majority of the feed force with the dominant hand on which the acceleration was measured, while the non-dominant hand partially overlapped the dominant hand to help stabilize the tool. In order to maintain consistent coupling forces, each subject's hand and arm postures were closely monitored during the testing. Each tool's switch was fixed at the "on" position with adhesive tape, while a test assistant used a ball valve at the regulated air supply to control the tool's on/off operation during the test. This permitted the subject to focus his attention on his posture and monitoring and control of the feed force. The acquisition of the handle and response vibration data was initiated when the subject achieved a stable tool position and feed force magnitude. The signals from all the three tri-axial accelerometers were simultaneously acquired for a duration of 8 s, which is the minimum duration required by the standardized chipping hammer test method (ISO 8662-2, 1992). The subject rested for approximately 1 min between the trials.

The sequence of the tests involving different combinations of the tools and the gloves (including bare hand) was randomized for all the six subjects. The sequence of the four different magnitudes of the feed force was also randomized for each tool–glove combination. Two trials were completed sequentially for each test combination.

2.3. Glove vibration transmissibility

In the present study, the vibration transmissibility characteristics of the candidate gloves are evaluated using the direct and relative evaluation methods. In the direct method, the vibration measured at the tool handle is used. Specifically, the vibration transmissibility of the bare hand (T_b) and the gloved hand (T_g) are derived from the ratios of measured response (measured on the hand: third metacarpal or the wrist) and handle accelerations, such that

$$T_b = \frac{A_{bw}}{H_{bw}} \quad \text{and} \quad T_g = \frac{A_{gw}}{H_{gw}}, \tag{1}$$

where A_{bw} and H_{bw} are the weighted total rms accelerations due to vibration measured on the bare hand and the tool handle, respectively, and A_{gw} and H_{gw} are those measured with the gloved hand. The weighted total rms accelerations are computed from the rms accelerations due to vibration along the three translational axes (x, y

and z) in the following manner:

$$A_{bw} = \sqrt{\sum_{i=1}^{22} (A_{bxi}^2 + A_{byi}^2 + A_{bzi}^2) w^2(f_i)},$$

$$H_{bw} = \sqrt{\sum_{i=1}^{22} (H_{bxi}^2 + H_{byi}^2 + H_{bzi}^2) w^2(f_i)},$$

$$A_{gw} = \sqrt{\sum_{i=1}^{22} (A_{gxi}^2 + A_{gyi}^2 + A_{gzi}^2) w^2(f_i)},$$

$$H_{gw} = \sqrt{\sum_{i=1}^{22} (H_{gxi}^2 + H_{gyi}^2 + H_{gzi}^2) w^2(f_i)}, \quad (2)$$

where A_{bxi}, A_{byi}, and A_{bzi} are the unweighted rms accelerations due to vibration measured on the bare hand (third metacarpal or the wrist) along the three orthogonal directions corresponding to center frequency of the ith one-third octave band. H_{bxi}, H_{byi}, and H_{bzi} are those measured on the tool handle during the bare-hand test. A_{gxi}, A_{gyi}, and A_{gzi} are the unweighted rms accelerations due to vibration measured on the hand in the gloved-hand tests, and H_{gxi}, H_{gyi}, and H_{gzi} are the corresponding components due to vibration measured on the tool handle. f_i is the center frequency of the ith one-third octave band in the range of 10–1250 Hz, and $w(f_i)$ is the corresponding weighting function value defined in ISO 5349-1 (2001).

The vibration attenuation provided by the glove (R) is computed from the measured transmissibility in the following manner:

$$R = \frac{T_b - T_g}{T_b}. \quad (3)$$

In the direct method, the vibration transmissibility of a glove (MT_d) is computed from

$$MT_d = 1 - R = \frac{T_g}{T_b} \quad \text{or} \quad MT_d = \frac{A_{gw}}{A_{bw}} \frac{H_{bw}}{H_{gw}}. \quad (4)$$

The relative evaluation approach does not require the acceleration on the tool handle and may thus be considered suitable for applications where such measurements are complex or impractical. The relative vibration transmissibility of the glove (MT_r) is calculated from the following relationship:

$$MT_r = 1 - \frac{A_{bw} - A_{gw}}{A_{bw}} = \frac{A_{gw}}{A_{bw}}. \quad (5)$$

To find how the variation of the tool vibration affects the evaluation of the transmissibility, the relative difference between the vibration data measured in the bare-hand test (H_{bw}) and gloved-hand test (H_{gw}) is examined. The relative difference is defined as

$$\text{Relative difference } (D) = \frac{H_{gw} - H_{bw}}{H_{bw}}. \quad (6)$$

2.4. Estimation of glove vibration transmissibility

The vibration transmissibility of a glove may be estimated from its transfer function, which can be determined in the laboratory (Griffin, 1998; Rakheja et al., 2002). In the present study, a total vibration transfer function procedure was formulated for estimation of the glove vibration transmissibility. A series of additional tests were conducted to measure the total vibration transfer functions of the two gloves, using the methodology similar to that reported in a previous study (Rakheja et al., 2002). Briefly, the measurements were conducted under a broad-band random excitation in the 8–1600 Hz frequency range produced on an electrodynamic vibration test system (Unholtz Dickie S032). The adapter method similar to that outlined in ISO 10819 (1996) for the standardized glove test was used to measure the transmitted vibration through the glove. An instrumented simulated handle fixed on the exciter of the vibration test system was used to provide the vibration to the glove–hand–arm system. In order to simulate the coupling condition used in the test involving the chipping hammers, the subjects were instructed not to apply a grip force during the measurement, while two different levels of feed force (50 and 100 N) were applied. Like the chipping hammer tests, the feed forces measured by the force plate were displayed on a computer monitor to provide feedback. The instrumented handle was also used to monitor the grip force to assure that no significant force was applied during the gripping. The experiments in the present study differed from those reported in an earlier study (Rakheja et al., 2002) that only considered the accelerations along the dominant vibration direction for deriving the transfer function. The proposed method allows for analyses on the basis of the vibration total values defined in the current ISO 5349-1 (2001), i.e. the root-sum-of-squares of the three frequency-weighted rms component values measured along the three orthogonal axes on the instrumented handle and the palm adapter, thereby reducing the potential errors caused by the adapter misalignment and non-axial vibration produced by the exciter (Dong et al., 2002a). The magnitude of the resulting total transfer function of a glove corresponding to center frequencies of the third octave bands is calculated from the rms spectra of the handle and palm adapter accelerations:

$$T(f_i) = \frac{\sqrt{A_{xi}^2 + A_{yi}^2 + A_{zi}^2}}{\sqrt{H_{xi}^2 + H_{yi}^2 + H_{zi}^2}}, \quad i = 1, 2, 3, \ldots, 22, \quad (7)$$

where A_x, A_y, and A_z are the unweighted rms acceleration components measured on the adapter along the three orthogonal directions; and H_{bx}, H_{by}, and H_{bz} are those measured on the instrumented handle under a broad-band random excitation.

The acceleration transmissibility of a glove when used with a chipping hammer can be conveniently predicted from the total vibration transfer function method:

$$PT = \frac{\sqrt{\sum_{i=1}^{22} (H_{gxi}^2 + H_{gyi}^2 + H_{gzi}^2) T^2(f_i) w^2(f_i)}}{\sqrt{\sum_{i=1}^{22} (H_{gxi}^2 + H_{gyi}^2 + H_{gzi}^2) w^2(f_i)}}. \quad (8)$$

The numerator in the above equation defines the overall frequency-weighted rms acceleration due to vibration transmitted to the hand (for on-the-hand measurement) or the palm (for glove-hand interface measurement). The denominator defines the overall frequency-weighted rms acceleration due to vibration transmitted to the handle of the chipping hammer.

2.5. Data analysis method

The repeatability of the measurements is one of the essential components for judging the reliability of the test data for the tool and glove tests. The repeatability is usually evaluated using standard derivation (SD) or coefficient of variance (CV = SD/Mean) of the data (ISO 8662-2, 1992; ISO 10819, 1996; Hewitt, 2002). This evaluation approach was adopted in this study. A t-test was used to detect the significance of the differences between the mean values of two groups of comparable data whenever applicable.

3. Results

Fig. 4 illustrates the magnitudes of the mean transfer functions derived from the measured data from Eq. (7). The graphs display the mean values of the transfer functions of the two gloves corresponding to two different magnitudes of feed force. The transfer functions of both the gloves suggest their potential for attenuating vibration above 30 Hz. Eqs. (4) and (5) are used to derive the glove transmissibility on the basis of direct and relative assessment methods. The mean transfer function for each glove corresponding to a specified feed force is applied to predict the glove transmissibility in conjunction with the chipping hammer, using Eq. (8).

The acceleration data acquired from the tools' handles and the third metacarpal are analyzed to evaluate the transmissibility using the direct evaluation approach, expressed in Eq. (4). Table 2 summarizes the mean results attained from the measured data together with the predicted values of the glove transmissibility derived from the transfer function method expressed in Eq. (8). The transfer function attained corresponding to 50 N feed force was applied to predict the vibration transmission of the glove under the same feed force employed in the tool tests, while the

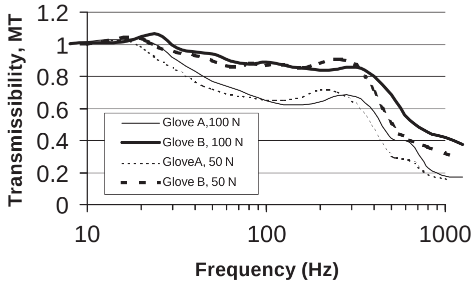

Fig. 4. The magnitudes of the measured transfer functions of the two gloves (broad-band excitation).

Table 2
Mean values and coefficients of variation for tool vibration, measured transmissibility, and predicted transmissibility—third metacarpal method

Third metacarpal	50 N feed force		100 N feed force		150 N feed force		200 N feed force	
	Mean	CV	Mean	CV	Mean	CV	Mean	CV
Glove A with Tool A								
Tool handle vibration (m/s^2)	12.49	0.09	11.38	0.11	12.76	0.12	12.39	0.28
Measured transmissibility (MT)	0.84	0.08	0.85	0.04	0.85	0.07	0.82	0.38
Predicted transmissibility (PT)	0.82	0.04	0.83	0.02	0.84	0.03	0.73	0.11
Glove A with Tool B								
Tool handle vibration (m/s^2)	14.37	0.04	13.94	0.09	15.02	0.12	10.36	0.27
Measured transmissibility (MT)	0.84	0.13	0.86	0.08	0.88	0.09	0.77	0.27
Predicted transmissibility (PT)	0.83	0.01	0.87	0.01	0.86	0.02	0.85	0.06
Glove B with Tool A								
Tool handle vibration (m/s^2)	12.21	0.07	10.40	0.09	11.99	0.11	13.23	0.27
Measured transmissibility (MT)	0.87	0.09	0.90	0.07	0.86	0.07	0.74	0.20
Predicted transmissibility (PT)	0.94	0.01	0.94	0.01	0.93	0.02	0.77	0.11
Glove B with Tool B								
Tool handle vibration (m/s^2)	14.33	0.05	13.66	0.08	14.92	0.05	13.67	0.19
Measured transmissibility (MT)	0.86	0.13	0.88	0.10	0.89	0.07	0.86	0.14
Predicted transmissibility (PT)	0.94	0.01	0.96	0.01	0.95	0.01	0.90	0.04

mean 100 N transfer function was used for predicting the vibration transmissibility of the gloves corresponding to 100, 150 and 200 N feed forces employed in the tool tests. To evaluate the reliability of the test data, the CVs of the tool vibration data and the glove transmissibility values are also listed in the table.

As can be seen, the mean values of frequency-weighted rms accelerations range from 10.40 to 13.23 m/s^2 for 'Tool A', and from 10.36 to 15.02 m/s^2 for 'Tool B'. The coefficients of variation (CVs) of the handle accelerations are equal to or less than 12% for both tools, and the CVs of the measured glove transmissibility values are generally less than 10% when the feed force is equal to or less than 150 N. The CVs for the predicted acceleration transmissibility values are considerably lower than those for the measured data ($p<0.001$). The high feed force of 200 N, however, yields considerably higher CV values for the handle accelerations, and the measured and predicted glove transmissibility values ($p<0.05$).

Table 3
Probability values (p-values) from t-tests between predicted and measured transmissibility values at the third metacarpal

Test combination	Feed force (N)			
	50	100	150	200
Tool A, Glove A	0.44	0.25	0.75	0.53
Tool B, Glove A	0.96	0.68	0.65	0.65
Tool A, Glove B	0.11	0.24	0.04	0.36
Tool B, Glove B	0.14	0.08	0.05	0.38

As can also be seen in Table 2, the predicted transmissibility values for the air bladder glove (Glove A) are very close to the measured values except those corresponding to 200 N feed force. In the case of the gel-filled glove (Glove B), however, the measured transmissibility values are observed to be lower than the predicted values ($p<0.05$). The results of the t-test for the predicted and the measured transmissibility values are listed in Table 3. The results suggest that difference for Glove A cannot be reliably identified while the difference for Glove B is reliable at 10% level for

Table 4
Mean values and coefficients of variation for tool vibration, measured transmissibility, and predicted transmissibility—wrist method

Wrist	50 N feed force		100 N feed force		150 N feed force		200 N feed force	
	Mean	CV	Mean	CV	Mean	CV	Mean	CV
Glove A with Tool A								
Tool handle vibration (m/s^2)	12.49	0.09	11.38	0.11	12.76	0.12	12.39	0.28
Measured transmissibility (MT)	0.82	0.29	0.80	0.20	0.86	0.17	0.88	0.47
Predicted transmissibility (PT)	0.82	0.04	0.83	0.02	0.84	0.03	0.73	0.11
Glove A with Tool B								
Tool handle vibration (m/s^2)	14.37	0.04	13.94	0.09	15.02	0.12	10.36	0.27
Measured transmissibility (MT)	0.67	0.28	0.81	0.22	0.85	0.17	0.81	0.39
Predicted transmissibility (PT)	0.83	0.01	0.87	0.01	0.86	0.02	0.85	0.06
Glove B with Tool A								
Tool handle vibration (m/s^2)	12.21	0.07	10.40	0.09	11.99	0.11	13.23	0.27
Measured transmissibility (MT)	0.97	0.20	0.90	0.23	0.94	0.11	0.79	0.30
Predicted transmissibility (PT)	0.94	0.01	0.94	0.01	0.93	0.02	0.77	0.11
Glove B with Tool B								
Tool handle vibration (m/s^2)	14.33	0.05	13.66	0.08	14.92	0.05	13.67	0.19
Measured transmissibility (MT)	0.87	0.26	1.04	0.32	0.94	0.19	0.93	0.27
Predicted transmissibility (PT)	0.94	0.01	0.96	0.01	0.95	0.01	0.90	0.04

half of the combinations except the 200 N feed force data that have large CVs.

Table 4 illustrates the mean values of frequency-weighted tool handle rms accelerations and the measured and predicted values of glove transmissibility derived from the data acquired at the subjects' wrists. The results show that the measured transmissibility values agree reasonably well with the predicted values in some of the combinations. The CV values of the measured transmissibility values, however, are generally considerably larger than those measured at the head of the third metacarpal ($p<0.001$). The results suggest poor repeatability of the wrist measurement method, when compared with the data obtained from the measurements performed on the head of the third metacarpal ($p<0.05$).

Tables 5 and 6 illustrate comparisons of the standard derivations of mean glove transmissibility and CV values derived from both the direct method, expressed in Eq. (4), and the relative evaluation approach, expressed in Eq. (5), respectively, from the measurements on the third metacarpal and at the wrist. The results show that both methods yield fairly comparable values for both gloves, except for the extreme feed force of 200 N, irrespective of the chipping hammer used. To confirm this, a t-test is performed to detect the significance of the difference between each pair of the mean transmissibility values calculated from the two methods for the same test treatment (the same combination of glove, tool, and force level). The p-values are in the range of 0.15–0.77, except in two treatments (Tool A/GloveB/100 N; Tool B/Glove A/100 N) in which their p-values are 0.08 and 0.09, respectively. These statistics confirm that the differences are small. The CV values derived from both methods at 50–100 feed forces are generally very comparable, at which the tool vibration is highly repeatable. The transmissibility values derived from the relative approach at 150 and 200 N feed forces, however, generally yield obviously higher CV values when compared with those attained from the direct approach ($p<0.05$). At these force levels, especially at 200 N, the tool vibration usually had a large CV, as can be seen in Table 2 or 4.

The relationship between the relative difference calculated from Eq. (6) and the transmissibility values from the measurement performed at the

Table 5
Measured transmissibility values and their CVs derived from direct and relative evaluation approaches—third Metacarpal method

Evaluation approach (tool—feed force)	Direct approach (used tool vibration data)		Relative approach (not used tool vibration data)	
	Mean	CV	Mean	CV
Glove A				
Tool A—50 N	0.84	0.08	0.85	0.09
Tool B—50 N	0.84	0.13	0.83	0.12
Tool A—100 N	0.85	0.04	0.86	0.08
Tool B—100 N	0.86	0.08	0.90	0.09
Tool A—150 N	0.85	0.07	0.86	0.14
Tool B—150 N	0.88	0.09	0.90	0.10
Tool A—200 N	0.82	0.38	0.95	0.74
Tool B—200 N	0.74	0.20	0.80	0.41
Glove B				
Tool A—50 N	0.87	0.09	0.84	0.11
Tool B—50 N	0.86	0.13	0.85	0.12
Tool A—100 N	0.90	0.07	0.85	0.08
Tool B—100 N	0.88	0.10	0.90	0.09
Tool A—150 N	0.86	0.07	0.83	0.14
Tool B—150 N	0.89	0.07	0.91	0.12
Tool A—200 N	0.77	0.26	0.69	0.48
Tool B—200 N	0.86	0.14	0.94	0.31

Table 6
Measured transmissibility values and their CVs derived from direct and relative evaluation approaches—wrist method

Evaluation approach (tool—feed force)	Direct approach (used tool vibration data)		Relative approach direct (not used tool vibration data)	
	Mean	CV	Mean	CV
Glove A				
Tool A—50 N	0.82	0.29	0.81	0.31
Tool B—50 N	0.70	0.26	0.69	0.25
Tool A—100 N	0.80	0.20	0.82	0.18
Tool B—100 N	0.82	0.20	0.85	0.21
Tool A—150 N	0.86	0.17	0.89	0.24
Tool B—150 N	0.85	0.15	0.88	0.18
Tool A—200 N	0.88	0.47	1.02	0.75
Tool B—200 N	0.79	0.30	0.85	0.43
Glove B				
Tool A—50 N	0.97	0.20	0.92	0.19
Tool B—50 N	0.88	0.23	0.87	0.24
Tool A—100 N	0.90	0.23	0.84	0.22
Tool B—100 N	1.02	0.29	1.04	0.30
Tool A—150 N	0.94	0.11	0.90	0.15
Tool B—150 N	0.94	0.17	0.97	0.22
Tool A—200 N	0.81	0.39	0.73	0.54
Tool B—200 N	0.93	0.27	1.03	0.45

head of the third metacarpal at 200 N feed force is shown in Fig. 5. Obviously, there is a fairly strong correlation between them. The results shown in this figure indicate that when the acceleration due to handle vibration with the bare hand is considerably larger than that with the gloved hand, the transmissibility is unrealistically low. Conversely, the apparent effectiveness of the glove unrealistically diminishes when the acceleration due to handle vibration with the gloved hand is considerably larger than that with the bare hand. Therefore, the quality of the assessment would be improved if the difference between the tool vibrations from the bare- and the gloved-hand tests could be controlled within a certain acceptable range. For example, the exclusion of the data

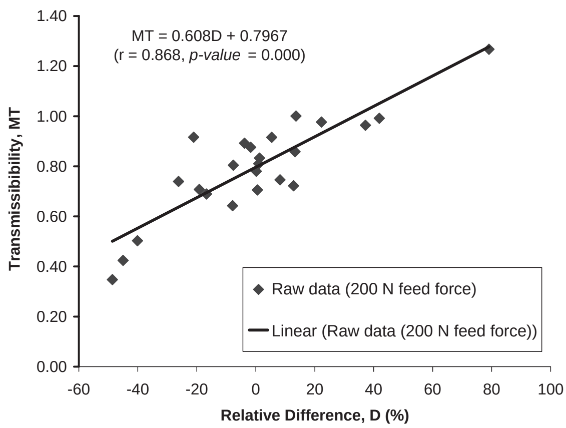

Fig. 5. The correlation between the relative difference and the transmissibility measured on the head of the third metacarpal at 200 N feed force.

Table 7
Effect of eliminating extreme data sets with a relative difference of more than 25% on the transmissibility values and CVs—third metacarpal method at 200 N feed force

Test combination	Original data		Adjusted data[a]	
	Mean	CV	Mean	CV
Tool A, Glove A	0.82	0.38	0.82	0.15
Tool B, Glove A	0.74	0.20	0.75	0.06
Tool A, Glove B	0.77	0.26	0.85	0.14
Tool B, Glove B	0.86	0.14	0.83	0.13

[a] Data sets with a relative difference of more than 25% are eliminated for the calculation.

with an absolute relative difference of more than 25% yields considerably lower CV values of the transmissibility, as shown in Table 7.

4. Discussion

Theoretically, the best location for measuring the transmitted vibration for assessing the glove's overall isolation performance is at the hand–glove interface, because the hand itself could attenuate or amplify the vibration, mainly depending on the vibration frequency. However, many studies have identified various technical difficulties associated with measurements at the interface without using an adapter, specifically when measurements involve actual tools. The palm adapter introduces additional mass to the coupled hand–glove–handle system, and it may alter the pressure distribution on the glove and the palm and the viscoelastic properties of the coupled hand and glove system. These changes may considerably influence the dynamic behavior of the gloves, which have not yet been sufficiently studied and are not well understood. The use of on-the-hand measurement methods obviously eliminates the need for the palm adapter. The on-the-hand method may also be used to assess the effectiveness of the gloves for the attenuation of the vibration transmitted to a specific location of the hand–arm system. The method, however, also imposes many limitations. One of the objectives of the present study was to identify these limitations and to determine the reliability of the method for more general practical applications.

The transmissibility of vibration measured on the head of the third metacarpal is near unity for frequencies up to 150 Hz (Sörensson and Lundström, 1992). The magnitude of frequency-weighting applied for hand-transmitted vibration at frequencies higher than 150 Hz, however, is very small (ISO 5349-1, 2001). Considering that the chipping hammers emit dominant vibration in the 30–60 Hz frequency range, the on-the-hand measurement method involving measurements at the third metacarpal should be acceptable for assessing the glove transmissibility, especially when frequency-weighted acceleration values are considered.

When the tool vibration was fairly repeatable, as in the cases of 50–150 N feed forces, the CV values of the measured transmissibility for both gloves obtained in the present study (see Table 2) are comparable to those reported in earlier studies (Dong et al., 2002b). These values are also comparable to those reported on the basis of measurements performed under well-controlled laboratory vibration test conditions with the adapter method (Griffin, 1998; Hewitt, 1997, 1998; Rakheja et al., 2002). These suggest that the on-the-hand method offers reliability similar to the adapter method.

Several previous studies (Reynolds and Angevine, 1977; Pyykkö et al., 1976) have suggested that only vibrations below 40 Hz can be transmitted to the wrist without any noticeable attenuation, and vibrations greater than 100 Hz cannot be effectively transmitted to the forearms. The vibration measured at the wrist using an instrumented watch could be significantly higher than the source vibration in the frequency range of 50–125 Hz, as reported in another previous study (Gurram et al., 1994). The results of the present study revealed that the measurements at the wrist generally yield considerably larger CV values than those at the third metacarpal. These observations suggest that the wrist measurement method has a lower-frequency application range and is less reliable than the third metacarpal measurement method for the glove transmissibility assessment.

The difference between the predicted and the measured transmissibility values for the air glove

(Glove A) at feed forces up to 150 N was within the range of the inter-subject difference observed in the previously reported studies (Hewitt, 1997; 1998; Dong et al., 2002a) with the standard test method (ISO 10819). The difference was much smaller than that between the results obtained from different laboratories using the standard test method (Hewitt, 1997, 2002). These observations suggest that the transfer function method can provide reasonable prediction of chipping-hammer-specific vibration transmissibility for this glove.

The transfer functions presented in Fig. 4 suggest that the air glove could obviously attenuate more vibration than the gel glove at frequencies higher than 30 Hz. The data measured at the third metacarpal shown in Table 1, however, reveal that the differences between those gloves are not as great as predicted from the transfer functions. The measured transmissibility values of the gel-filled glove (Glove B) are lower than the predicted values, even though the differences are not always statistically reliable for all the cases. Such deviations were not observed when a palm adapter was used to measure the transmitted vibration in the previous studies (Rakheja et al., 2002; Dong et al., 2002b). Considering that the glove transfer functions in the reported and present studies were established through measurements performed with a palm adapter, the use of the adapter with actual tools may represent a better simulation of the transfer function measurement conditions and thus may yield better agreement between the predicted and measured data. However, the transmissibility values obtained from the adapter method may not truly reflect the vibration isolation effectiveness of some types of gloves when used with real tools. It is speculated that the presence of the palm adapter between the glove and the hand may influence the hand–glove–handle coupling properties and the pressure distribution and thus the transfer function or the transmissibility of the glove. The adapter properties, however, may interact with the materials, the geometry, and the structures of the tested glove in a highly complex manner, which may also be glove-specific. The differences in the transmissibility values of 'Glove B' attained from the adapter and on-the-hand measurement methods may be attributed to the contributions of these palm adapter and glove interactions, which need further studies.

A high variability of the tool vibration at the high feed force (200 N) was observed in the present study. This may be because the vibration emission of the tools corresponding to this high feed force are very sensitive to possible changes in the orientation of the tool-bit, caused by clearance between the bit and the guide bushing and the subjects inability to maintain stable tool position under a high feed force. At such a high variability of the tool vibration, the on-the-hand methods suffer from poor repeatability. The comparison of the CVs obtained from the direct and the relative methods shown in Tables 5 and 6 suggest that the direct method can provide significantly better repeatability for glove assessments in such a situation. This means that less numbers of subjects and trials are required to achieve statistically reliable test data if the direct method is used. This may be especially useful in field studies, where the tool vibration could vary in a large range.

However, the direct measurement of the vibration produced by certain power hand tools may pose many complexities. For example, a conventional accelerometer or a mechanical filter could be damaged or ruptured within seconds if it is directly installed on the chisel of a chipping hammer (Goel and Rim, 1987; Clarke et al., 1986). Furthermore, a special measure is usually required to minimize the DC shift when measuring the impact vibration on percussive tools (Griffin, 1990), which is also experienced in the present study. In many cases, it is very difficult to fully attenuate the DC shift with a mechanical filter without sacrificing the accuracy of the measurement in the high-frequency range. The installation of an accelerometer and the mounting structure on some tools may change the tool vibration characteristics. Moreover, the installation of the accelerometer and its mounting fixture on a tool handle may also make it difficult for a subject to hold the handle appropriately. In such cases, the effectiveness of gloves can be alternatively assessed using the relative evaluation approach without using the tool vibration information as used by a few investigators (Goel and

Rim, 1987; Pinto et al., 2001). A comparison of Eqs. (4) and (5) clearly indicates that the relative and direct approaches would converge to similar values if the vibration spectra measured on the tool handle during the gloved-hand test is equivalent to that in the bare-hand test (or $H_{bw} = H_{gw}$). The results of this study illustrated in Tables 5 and 6 demonstrate that if H_{bw} and H_{gw} are fairly consistent, the relative and direct method can provide very similar reliability. However, the relative approach is more vulnerable to variation in the tool vibration than the direct evaluation approach when the tool vibration has a high degree of variability.

The higher vulnerability of the relative approach can be theoretically explained by further examination of the difference between the equations for these two evaluation approaches. When the vibration emitted by the tool is obviously higher than the average value, the resulting magnitude of the transmitted vibration should also be higher even if the transmissibility may not change linearly with the magnitude of the vibration on the tool handle. Therefore, the relative change in the ratio (A_{gw}/H_{gw}) would not usually be as high as that in the transmitted vibration (A_{gw}). For a given set of bare-hand test data (A_{bw}, H_{bw}), the change in the transmissibility magnitude calculated from Eq. (4) arises from the change in the ratio (A_{gw}/H_{gw}) measured in the gloved-hand test, and that from Eq. (5) is caused by the change in the transmitted vibration magnitude (A_{gw}). Consequently, the relative change from Eq. (4) is usually less than that from Eq. (5), or the relative method results have greater variability than the direct method results.

In order to increase the reliability of the results attained from the relative method, the investigator may increase the number of test trials and the number of subjects. While the relative method may appear to be more costly due to the increased number of trials and the number of subjects, the instrumentation and data collection costs are reduced since the measurements of tool vibration are not required. Alternating the sequence of the bare- and gloved-hand tests may also help minimize the differences between the measured tool vibration spectra. However, frequently donning and doffing the glove during a test sequence may change the position of the accelerometer on the hand and may reduce the reliability of the test data. Cautions should be taken to secure the accelerometer on the hand near the same location.

The results of this study indicate that the transmissibility of the gloves is correlated to the actual tool vibration spectrum, as shown in Fig. 5. This is basically consistent with the observation that the transmissibility of anti-vibration gloves is vibration-spectrum-specific (Rakheja et al., 2002). Various working conditions and chipping hammers may generate different vibration spectra, and the actual isolation performance of the gloves may be different from that presented here. Therefore, while the basic measurement and evaluation methodologies proposed in this study may be generally applicable for different gloves, tools, and working conditions, the transmissibility values of the anti-vibration gloves presented in this paper should only be used as a reference for any practical applications.

The above discussions are based on the data obtained from the on-the-hand measurement methods. It is anticipated that many of the general principles and the formulas derived from this study may also be applicable to the adapter method, provided that the transmitted accelerations measured on the hand are replaced with those measured on the adapter.

5. Summary

This study investigated the effectiveness of the on-the-hand measurement methods for assessing the vibration isolation performance of gloves when used with chipping hammers. The major findings of the study are summarized below:

- The on-the-hand methods can measure the effectiveness of the gloves under the true hand–glove–handle coupling relationship. The reliability and repeatability of the vibration transmissibility of the glove coupled with the chipping hammers, derived from the transmitted frequency-weighted acceleration acquired on the head of the third metacarpal of the hand, is comparable to that attained from the adapter method.

- The reliability of the on-the-hand methods, however, is limited to a certain frequency range because of the vibration-amplification and -attenuation effects of the hand. The methods also suffer from poor repeatability when a high degree of tool vibration variability is observed. The reliability of the assessment, however, can be considerably enhanced when the variations in the vibration emitted by the tool with bare and gloved hands are comparable.
- Glove assessment based on transmitted vibration measurements taken at the head of the third metacarpal are more reliable than those based on the wrist vibration measurements using the instrumented watch.
- There are two approaches to determine the transmissibility of gloves involving either known or unknown tool handle vibration spectra. The evaluation of glove transmissibility without the tool handle vibration spectra would minimize the data collection costs and eliminate the difficulties and errors associated with tool handle vibration measurement, specifically in the case of percussive tools. However, this approach is more sensitive to tool vibration variability. When practical, tool handle vibration measurements should be performed and used in conjunction with the transmitted vibration for the glove assessment.
- The accuracy of the transfer function method for predicting the glove transmissibility varied for the two different types of gloves considered in the study. While the predicted transmissibility values for the air glove agreed reasonably well with the measured data, the transfer function method underestimated the effectiveness of the gel glove. Thus, the reliability of the transfer function method needs further studies.
- Since the predicted transmissibility values for the air glove were very close to those reported from the adapter method, it is anticipated that the on-the-hand method and the adapter method could provide comparable results for the air glove when used with the chipping hammers.

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