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Analysis of anti-vibration gloves mechanism and evaluation methods

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Abstract

The primary objectives of the current study are to enhance the understanding of the mechanisms of the anti-vibration gloves and to evaluate the methods for assessing their vibration isolation effectiveness through developing a mechanical-equivalent model of the glove-hand–arm system. The model is developed based on the measured driving-point mechanical impedances distributed at the fingers and the palm of the hand with and without a glove. Six subjects participated in the experiments with two types of anti-vibration gloves (air-bladder glove and gel-filled glove) for measuring the required impedance data. The proposed model is applied to predict the effectiveness of the glove in terms of vibration transmitted to the fingers-glove and palm-glove interfaces, the finger bones, and the wrist. The results show that the gloves could provide some attenuation of the palm-transmitted vibration at frequencies above the fundamental resonant frequency of the gloved hand–arm system, but only little reduction in the finger vibration below the dominant finger resonant frequency. The present standardized methodology based upon the transmissibility measurement at the palm alone would thus be inappropriate for characterizing the overall reduction of the vibration exposure by a glove. Moreover, the palm adapter could introduce some measurement errors because of its mass and misalignment effects and its interference with the glove-palm coupling relationship. Therefore, the standardized method may only be used for general screening tests. On the basis of the model results, several potential improvements in the current standardized methodologies for evaluations of gloves and glove material are proposed and discussed. The proposed model may also serve as a useful tool for further developments of anti-vibration gloves and other anti-vibration devices.
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1. Introduction

Prolonged, intensive exposure to vibration generated by powered hand tools may cause hand–arm vibration syndrome (HAVS) [1,2]. Anti-vibration (AV) gloves have been increasingly used to help reduce the vibration exposure. However, the exact mechanisms of the AV gloves have not been seriously analyzed and sufficiently

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understood. How to appropriately assess the effectiveness of AV gloves for protecting the hand remains an issue for further studies.

An AV glove essentially serves as a cushion or a simple passive suspension system between the tool and the hand. Therefore, the vibration transmissibility of the glove, the ratio of the vibration at the glove-hand interface to the handle vibration, is typically used as a measure of the glove effectiveness. Based on this measure, the International Organization of Standardization has set forth a standard for glove testing [3]. The standard defines a palm adapter equipped with a miniature accelerometer for measuring the vibration transmitted through the glove at the palm of the hand. The standardized methodology has been critically reviewed by several researchers over the past few years, which recommended a number of refinements of the method, see for example Refs. [4–6]. The misalignment of the palm-adapter with respect to the axis of vibration has been identified as the major technical problem of the method; a few studies have proposed methods for compensating for the effects [5,6]. The use of the palm-adapter between the hand and the glove has been another subject of major concern, which is believed to alter the contact conditions and interface properties (contact area, contact pressure and stiffness). Furthermore, such effects are expected to depend on the position of the adapter on the palm in a complex manner. For example, the glove could appear more effective when the vibration transmissibility is measured with the adapter positioned near the foot area of the palm [6]. More critically, the vibration transmissibility measured at the palm is unlikely to be representative of that at the fingers. While the standardized method may be acceptable for a screening test of AV gloves, the vibration transmissibility measured at the palm alone may not be representative of the overall reduction in the hand's vibration exposure, especially that on the fingers [7]. Further studies are thus desirable for developing a more reliable method for quantifying the vibration isolation effectiveness of the gloves.

The use of the palm-adapter could be eliminated when an on-the-hand measurement technique is used to estimate the glove vibration transmissibility. In this method, the glove transmissibility is derived from the vibration values measured on the hand with and without wearing a glove, see for example Refs. [8–13]. The method also poses several measurement challenges and potential sources of errors. The mass of an accelerometer may alter the characteristics of vibration transmitted to a particular measurement location. While a non-contacting laser vibrometer may be applied to eliminate the sensor mass effect, see for example Refs. [14–16], the contributions due to relative motion of the skin to the localized vibration responses may not be negated. Moreover, a portion of the glove must be cut off so that the laser can be directly pointed to the finger or the hand skin.

The glove transmissibility depends not only on the glove material but also on the driving-point biodynamic response of the hand–arm system [17]. The glove material test method defined in Japan national standard [18] includes the simulation of the mechanical impedance response of the hand–arm system measured under a hand vertical push posture. The modeling method proposed by O'Connor [19] includes the modeling of both the glove properties and the biodynamic response of the hand–arm system, in which the stiffness and damping values of a glove were derived from the transmissibility data measured on a 2.5 kg mass loaded on the glove material seated on a vibration exciter. O'Boyle and Griffin [20] improved the material test method by making the applied force adjustable so that the effect of the palm force on the glove can be investigated. The current ISO 13753 [21] for assessing the vibration isolation effectiveness of the glove materials is similar to the method proposed by O'Connor [19]. The standardized method, however, may not provide a reliable prediction of the transmissibility at least for the following two reasons: (i) the recommended hand–arm system model is believed to be unreliable since it was partially based upon erroneous experimental data [22], while the model structure does not reasonably reflect the fundamental features of the hand–arm system [23]; and (ii) the glove material impedance determined using the recommended dead mass method is unlikely to be representative of the conditions associated with the use of a glove. These observations may partially explain why the experimental results measured with this standardized method may be largely different from those measured with the method defined in ISO 10819 [3], as reported by Koton et al. [24].

To avoid any interference of the glove-hand interface, Dong and his colleagues [25] proposed an experimental biodynamic method to derive the transmissibility (T_r) from the apparent mass of the glove alone (M_g), the apparent mass of the coupled glove-hand–arm system (M_{total}), and the apparent mass of the hand–arm system alone (M_{bh}):

$$T_r \approx \frac{M_{\text{total}} - M_g}{M_{\text{bh}}}, \tag{1}$$

whereas M_{total} and M_{bh} can be reliably measured using a driving-point response measurement method, see for example Ref. [22], it is difficult to accurately determine the apparent mass of the glove alone (M_g). From Eq. (1), it can be deduced that the effect of the glove response is not significant when the magnitude of M_{total} is much larger than M_g. This would be valid in the case of the biodynamic response measured at the palm side up to a certain frequency, as verified in the present study. Since the fingers' side biodynamic response could be comparable with that of the glove alone in a large frequency range, Eq. (1) may not be directly used to determine the glove transmissibility at the fingers even at relatively low frequencies. Therefore, further studies are required to improve the biodynamic method.

The primary objectives of the current study are to enhance the understanding of the mechanisms of the AV gloves and to evaluate the methods for assessing their vibration isolation effectiveness through developing a model of the glove-hand–arm system. Upon recognizing that it is technically difficult, time-consuming and expensive to directly simulate the detailed structures of the complex nonlinear gloved hand–arm system, a combined experimental and modeling approach is proposed to predict the glove vibration transmissibility at both the fingers and the palm of the hand. Examples of the model applications are also presented in this paper.

2. Methods

The specific procedures of the proposed approach can be divided into four steps: (a) characterization of the mechanical impedance distributed at the fingers and the palm of the hand for the bare and the gloved hand by performing the driving-point biodynamic response measurements; (b) formulation of a mechanical equivalent model of the hand–arm system using the bare hand experimental data; (c) formulation of a mechanical equivalent model of the gloved hand–arm system by adding a glove model to the bare hand model determined in Step 2, in which parameters of the glove model were determined using the experimental data measured with a gloved hand; and (d) the analysis of vibration transmissibility distributed in the system using the gloved hand–arm system model.

2.1. Measurement of biodynamic response

The biodynamic responses were measured using the method similar to that reported in a previous study [22]. Briefly, the instrumentation set-up and the subject posture used in this study were similar to those recommended in ISO 10819 [3]. A vibration test system (Unholtz-Dickie TA250-S032) was employed to generate a broadband random vibration with a flat power spectral density (PSD) value of 3.0 $(\text{m/s}^2)^2$/Hz in the frequency range of 12.5–1000 Hz. A special instrumented handle was fixed on the vibration exciter to provide the vibration input to the hand and to measure the applied forces and biodynamic responses. Different from any previous study, a new instrumented handle with two measuring caps, developed by Welcome and Dong [26] was used in the experiment (Fig. 1). This handle is equipped with two accelerometers (PCB 356 A12 on the palm side and an Endevco 65–100 on the fingers side) to separately measure the vibrations input to the fingers and the palm. The handle is also equipped with two pairs of force sensors (Kistler 9212). One pair was used to measure the grip force and the biodynamic force distributed at the fingers. The other pair of sensors was used to measure the push force and the biodynamic force distributed at the palm. The applied forces are the low frequency components of the measured total forces and they were visually displayed to each subject for controlling his grip and push actions. The force signals, together with the acceleration signals, were also channeled to a multi-channel signal analyzer (B&K Type 3032A I/O Module) to evaluate the apparent mass by performing the transfer function (H1) analysis built in the Pulse program of the analyzer. The mechanical impedance was subsequently derived from the apparent mass using the relation presented in Ref. [22]. The results were expressed in the frequency domain, corresponding to the center frequencies of the third-octave bands in the 10–1000 Hz frequency range.

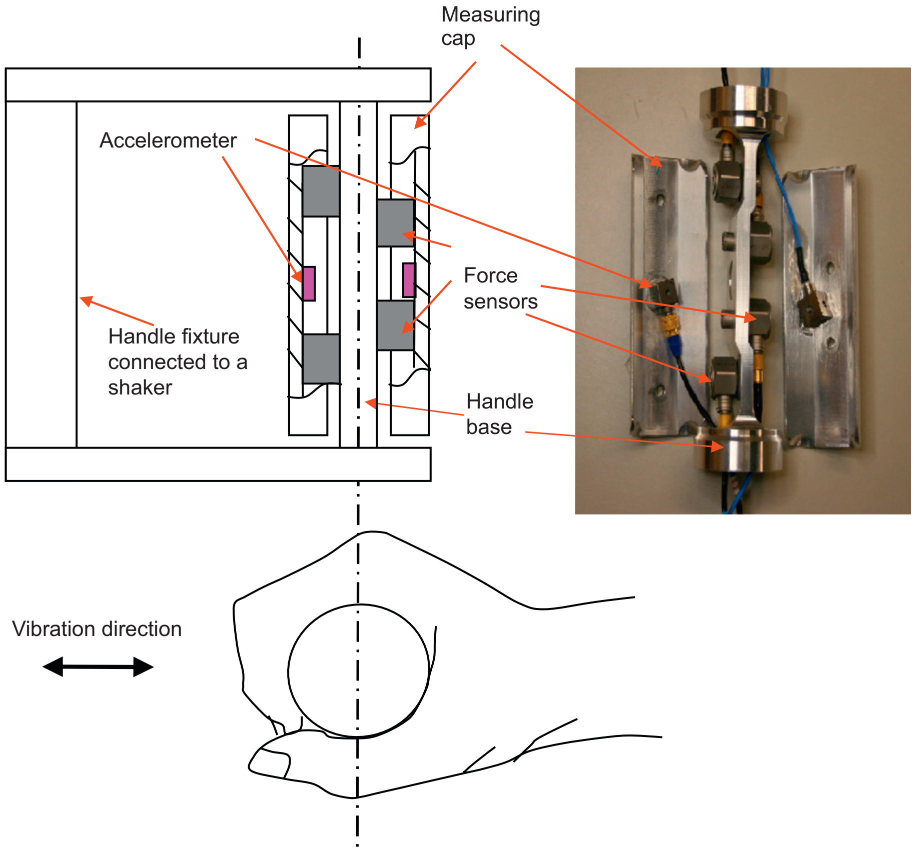

Fig. 1. The instrumented handle (40 mm in diameter and 115 mm effective grip length) used for simultaneously measuring the mechanical impedances distributed at the fingers and the palm of the hand, and the applied grip and push forces [23].

The applied hand forces (30 N grip and 50 N push) used in this study are the same as those recommended in ISO 10819 [3]. For the purposes of this study, two typical types of AV gloves were used: (i) a full finger air-bladder glove with a mass of 78 g, referred to as glove 'A'; and (ii) a gel-filled glove with a mass of 133 g, referred to as glove 'B'. Six healthy male subjects participated in the biodynamic response measurements. The mean hand length of the participants, measured from tip of middle finger to the crease at the wrist, was 194 mm with standard deviation of 9 mm. The mean hand circumference measured at metacarpal of the hand was 227 mm with standard deviation of 12 mm. The mean hand size was 9, which satisfies the requirement of the standardized glove test [3]. The subjects wore normal office clothes without jackets. The only experimental variable considered in this study was the three glove treatments (bare hand, wearing glove A, and wearing glove B). The sequence of the three test treatments was randomized among the subjects, and three trials were performed for each test treatment. The duration of the biodynamic response measurement in each trial was 30 s. Each subject was advised to rest for at least one minute between the successive trials.

2.2. Modeling of the hand–arm system

Two new mechanical-equivalent models of the hand–arm system have been recently proposed in our previous study [27]. These model structures employ two driving-points representing the palm-handle and fingers-handle interactions and the coupling relationships, unlike the earlier models that invariably consider a single-point coupling relationship with the tool handle, see for example Refs. [18–21,28,29]. The reported studies demonstrated that the proposed models can provide a very reasonable fit to the experimental data characterizing the biodynamic responses attributed to palm and finger-side couplings with the handle [27,30].

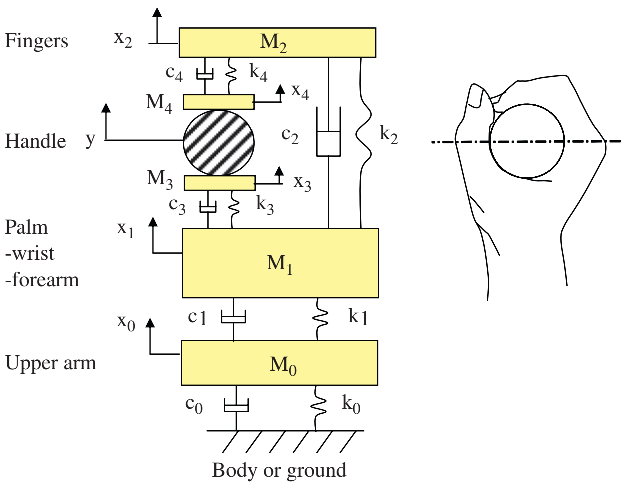

Fig. 2. Hand grip posture and the 5-DOF model of the hand–arm system.

The proposed five degrees-of-freedom (dof) model structure, shown in Fig. 2, is employed in the present study to fully characterize the biodynamic responses of the bare hand–arm system.

This study used the methodology reported in Refs. [27,30] for identifying the model parameters. Briefly, the equations of the motions for the five-DOF model and an error function of the model response with respect to the measured responses corresponding to the selected hand forces (30 N grip and 50 N push) were formulated. The model responses were evaluated using a set of pre-selected model parameters and a sinusoidal input at the handle along the forearm direction (Fig. 2) at each center frequency of the one-third octave bands. The mechanical impedance magnitude and phase distributed at the fingers and palm were calculated using the model responses, together with the error function describing the deviation between the measured and model impedance responses. An iterative process was subsequently used to identify each of the model parameters through solution of a constrained error minimization problem [27,30]. The constraints used in the parameter search process are as follows:

$$\begin{aligned}
&M_0, M_1, M_2, M_3, M_4, k_0, k_1, k_2, k_3, k_4, c_0, c_1, c_2, c_3, c_4 > 0,\\
&M_0 < 15\,\text{kg} \quad \text{(shoulder and a part of the upper body)},\\
&M_1 < 5\,\text{kg} \quad \text{(palm, hand back, wrist and forearm)},\\
&M_2 < 200\,\text{g} \quad \text{(fingers bones and part of the finger soft tissues)},\\
&M_3 < 50\,\text{g} \quad \text{(palm contact skin)},\\
&M_4 < 30\,\text{g} \quad \text{(finger contact skin)}.
\end{aligned} \tag{2}$$

2.3. Modeling of the gloved hand–arm system

Physically, a glove can be viewed as an equivalent mechanical system added to the hand–arm system. The model of a gloved hand–arm system can thus be derived by adding equivalent elastic, viscous, and inertia properties of the glove to the hand–arm system model, as shown in Fig. 3. The glove material between the handle and glove-hand interface is represented by its lumped stiffness (k_5 and k_6), damping (c_5 and c_6), and mass properties (M_5, M_6, M_7 and M_8) distributed at the finger- and palm-side interfaces. The distributed lumped sub-models are coupled through the stiffness and damping elements (k_7 and c_7). The other part of the glove is represented by additional masses (M_9 and M_{10}), stiffness (k_8), and damping (c_8), as shown in Fig. 3. This study assumed that the biodynamic properties of the hand–arm system itself remain unchanged in the presence of a glove, which is the same as that assumed in the standardized glove material tests and evaluations [18,21]. Therefore, the parameters of the 5-DOF hand–arm system model were retained and the parameter identification task reduced to those of the glove model alone.

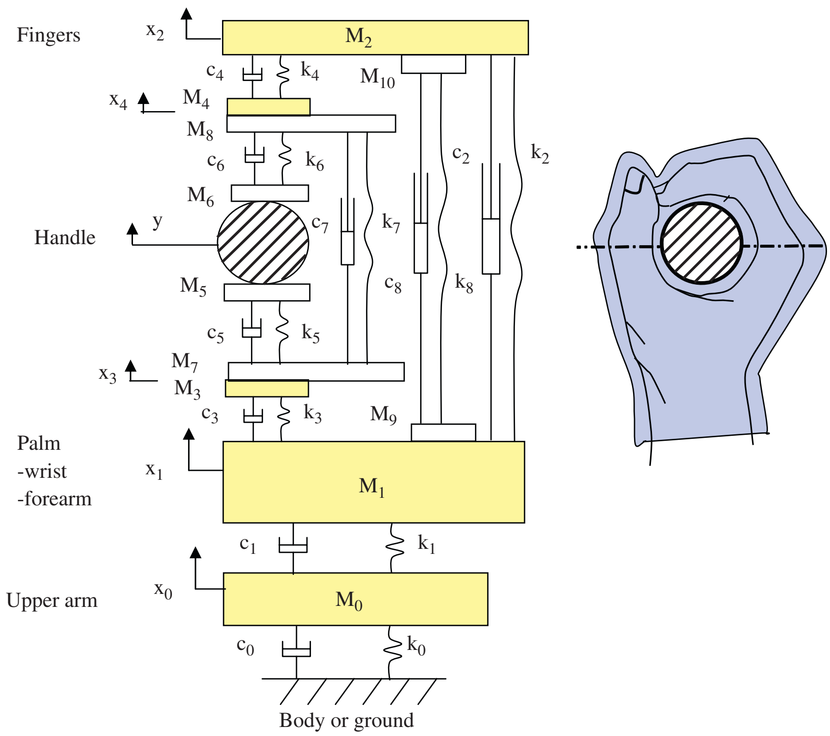

Fig. 3. Gloved hand grip posture and the 7-DOF model of the gloved hand–arm system.

The glove parameters were identified through solution of a constrained error minimization problem using the methodology used in identifying the hand–arm system model parameters. Following inequality constraints were imposed on the glove model parameters:

$$M_5, M_6, M_7, M_8, M_9, M_{10}, k_5, k_6, k_7, k_8, k_9, c_5, c_6, c_7, c_8, c_9 \geqslant 0,$$
$$\sum_{i=5}^{9} M_i \leqslant \text{the mass of glove} \quad (\text{air glove} \leqslant 78\,\text{g and gel-filled glove} \leqslant 133\,\text{g}). \tag{3}$$

2.4. Calculation of the distributed vibration transmissibility responses

The coupled hand-glove model can be employed to determine the properties of vibration transmitted to several important substructures of the model, particularly the substructures coupling the vibrating handle through the glove, such that:

$$\text{finger contact surface } (M_4) \quad T_{\text{Finger\_contact}} = x_4/y, \tag{4}$$

$$\text{finger bones } (M_2) \quad T_{\text{Finger\_bones}} = x_2/y, \tag{5}$$

$$\text{palm contact surface } (M_3) \quad T_{\text{Palm\_contact}} = x_3/y, \tag{6}$$

$$\text{palm-wrist-forearm substructure } (M_1) \quad T_{\text{Wrist}} = x_1/y. \tag{7}$$

The vibration transmissibility characteristics of the glove reflected on the fingers and the wrist (palm) were evaluated using on-the-finger and on-the-wrist methods. The vibration transmission responses of the bare hand–arm and gloved hand–arm system models were used to compute the relative transmissibility functions as follows:

For on-the-finger method:

$$T_{\text{Fingers}} = \frac{[x_2/y]_{\text{Gloved hand}}}{[x_2/y]_{\text{Bare hand}}}, \tag{8}$$

and for on-the-wrist method

$$T_{\text{Wrist}} = \frac{[x_1/y]_{\text{Gloved hand}}}{[x_1/y]_{\text{Bare hand}}}. \tag{9}$$

3. Results

3.1. Biodynamic responses of the bare hand–arm system model

Fig. 4 shows the comparisons of the predicted mechanical impedance responses distributed at the fingers and the palm of the hand without wearing a glove, and the measured responses under 30 N grip and 50 N push forces. The results clearly show that the model responses in terms of mechanical impedance magnitude and phase distributed at the fingers and palm agree well with the corresponding experimental data ($r \geqslant 0.976$). It can thus be ascertained that the mechanical-equivalent model adequately characterizes the biodynamic responses of the hand–arm system corresponding to the selected hand forces.

The parameters of the hand–arm system model are listed in Table 1, together with the model natural frequencies and damping ratios derived from the eigen analysis. The modal vectors suggested that the first resonance frequency of the bare hand–arm system ($f_1 = 7$ Hz) is mainly associated with the motion of the upper arm and shoulder mass (M_0) and its connecting stiffness values (k_0 and k_1). This is also evident from the fact that this frequency can be estimated from $\sqrt{(k_0 + k_1)/M_0}/2\pi = 6.7$ Hz. Similarly, the second resonance frequency ($f_2 = 33$ Hz) is mainly related to the palm contact stiffness (k_3) and the effective mass of the palm–wrist–forearm subsystem (M_1) because it can be estimated from $\sqrt{k_3/M_1}/2\pi = 31$ Hz. The third mode frequency ($f_3 = 230$ Hz) is attributed to the deflections of effective fingers mass (M_2) and the finger contact stiffness (k_4) because it can be estimated from $\sqrt{k_4/M_2}/2\pi = 228$ Hz.

3.2. Gloved hand–arm system response

The error minimization problem was solved to identify the parameters of the two candidate gloves (A and B), which are summarized in Table 2. The table also lists the natural frequencies and damping ratios of the coupled glove-hand–arm model. The results show relatively lower stiffness and damping properties of the air glove (A) compared to those of the gel-filled glove (B). The results further show that effective stiffness

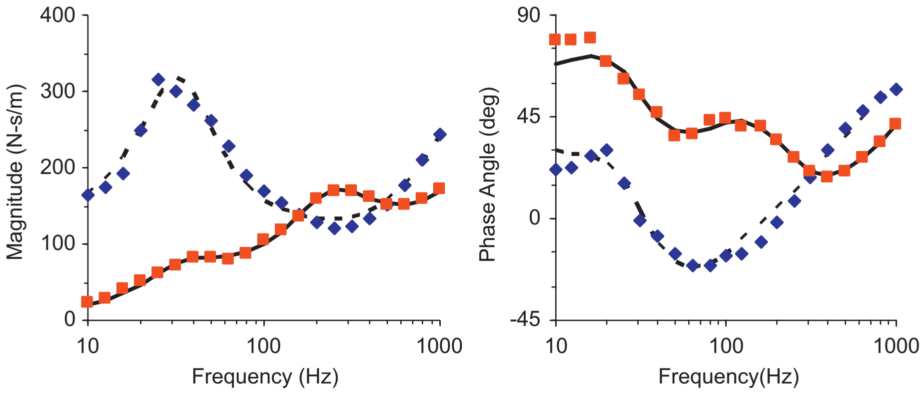

Fig. 4. Comparisons of driving-point mechanical impedance magnitude and phase responses of the bare hand–arm system derived from the model with the experimental data (◆: palm experiment; - - - -: palm modeling; ■: fingers experiment; ——: fingers model).

Table 1
Parameters of the hand-arm system model

Parameter	Unit	Value
M_0	kg	6.015
M_1	kg	1.4618
M_2	kg	0.0958
M_3	kg	0.0338
M_4	kg	0.0186
k_0	N/m	7567
k_1	N/m	2978
k_2	N/m	4221
k_3	N/m	55564
k_4	N/m	196038
c_0	N s/m	106
c_1	N s/m	134
c_2	N s/m	52
c_3	N s/m	126
c_4	N s/m	122
Natural frequency (f) *and damping ratio* (ξ)		
f_1	Hz	7
f_2	Hz	33
f_3	Hz	230
ξ_1		0.493
ξ_2		0.506
ξ_3		0.629

Table 2
Parameters of the gloved hand-arm system model

Parameter	Unit	Glove A	Glove B
M_5	kg	0	0
M_6	kg	0	0.0005
M_7	kg	0.0673	0.0651
M_8	kg	0	0
M_9	kg	0.0107	0.0674
M_{10}	kg	0	0
k_5	N/m	177385	286537
k_6	N/m	327301	454779
k_7	N/m	2116	0
k_8	N/m	923	2417
c_5	N s/m	89	158
c_6	N s/m	75	106
c_7	N s/m	0	0
c_8	N s/m	0	1
Natural frequency (f) *and damping ratio* (ξ)			
f_1	Hz	7	7
f_2	Hz	29	30
f_3	Hz	181	193
f_4	Hz	243	296
f_5	Hz	858	950
ξ_1		0.497	0.495
ξ_2		0.468	0.462
ξ_3		0.485	0.511
ξ_4		0.705	0.778
ξ_5		1.050	1.076

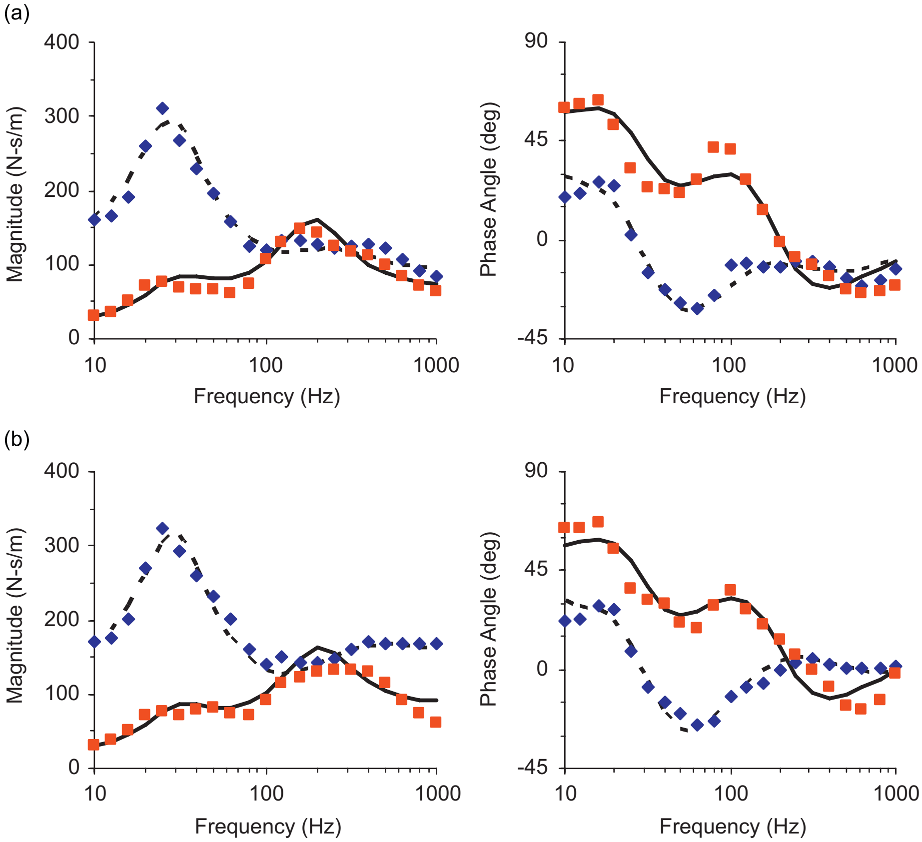

Fig. 5. Comparisons of driving-point mechanical impedance magnitude and phase, derived from the gloved hand–arm model, with the experimental data: (a) glove A and (b) glove B (◆: palm experiment; - - - -: palm model; ■: fingers experiment; ——: fingers model).

values of each glove at the fingers and palm interfaces (k_6 and k_5) are considerably larger than those of the fingers and palm contact stiffness values (k_3 and k_4 in Table 1), respectively. The presence of a glove can thus reduce the overall coupling stiffness between the hand and the handle. Comparisons of the natural frequencies of the coupled glove-hand–arm system model with those of the hand–arm alone reveal that the gloves do not affect the resonant frequency associated with the motion of the mass M_0. The reduction in the coupling stiffness attributed to the glove also yields only slightly lower palm resonant frequency (from 31 to 29 Hz for glove A and to 30 for glove B), while its effect on the finger resonant frequency is quite considerable. The natural frequencies associated with the fingers mass motion (f_3) of the system coupled with the models of gloves A and B are obtained as 181 and 193 Hz, respectively, which are lower than 230 Hz for the bare hand model.

Fig. 5 illustrates comparisons of the model responses in terms of mechanical impedance at the palm and fingers interfaces of the gloved hand–arm system with the corresponding measured data. It should be noted that the bare hand–arm model was employed in the coupled glove-hand–arm model to obtain the biodynamic responses of the coupled model. The results show that the model responses in impedance magnitude and phase at the palm fit the experimental data very well ($r \geqslant 0.961$). Although the deviations between the model and measured finger impedance responses are relatively larger than those observed in the bare hand–arm model responses, the results suggest reasonably good agreement between them ($r \geqslant 0.928$).

3.3. Glove vibration transmissibility

The vibration transmissibility characteristics of the two gloves are derived using the four different methods: (i) the direct method of predicting fingers- and palm-side responses from the model using Eqs. (5) and (7),

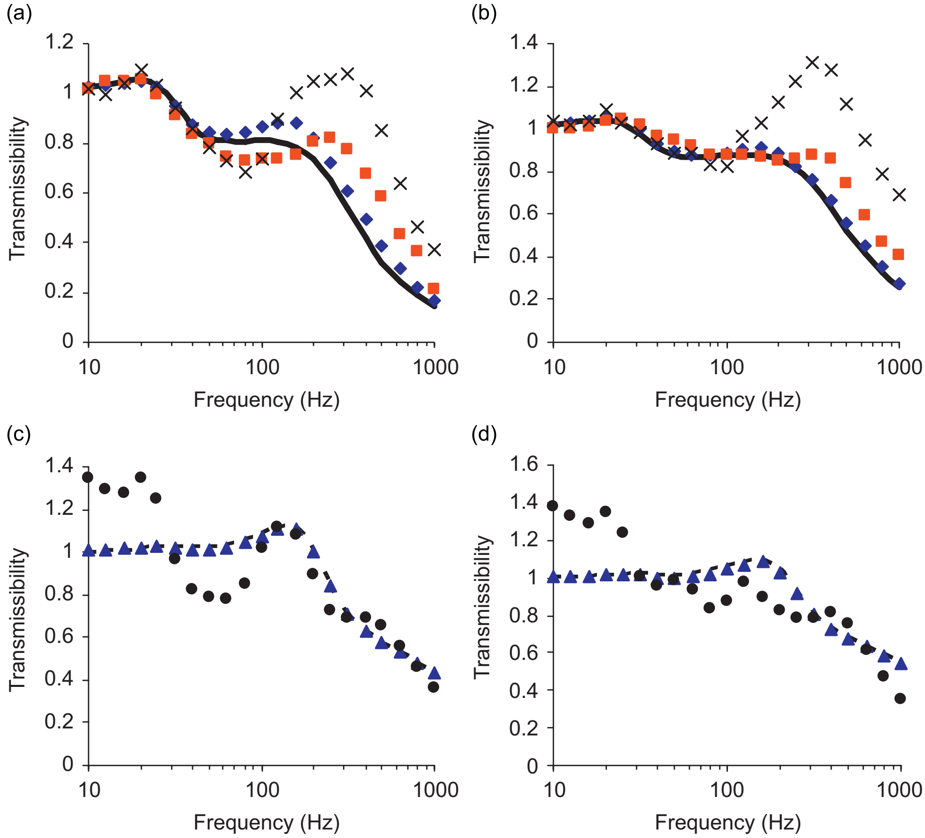

Fig. 6. Comparisons of predicted glove transmissibility magnitude with the experimental data: (a) glove A at the palm; (b) glove B at the palm (——: palm direct method; ◆: palm on-the-wrist method; ■: palm adapter method reported in Ref. [30] for glove A and in Ref. [9] for glove B; ×: palm experimental biodynamic method); (c) glove A at the fingers; and (d) glove B at the fingers (- - - -: finger direct method; ▲: finger on-the-finger method; and ●: finger experimental biodynamic method).

respectively; (ii) the on-the-hand method using Eqs. (8) and (9) for the fingers- and palm-sides, respectively; (iii) the palm adapter method reported in Ref. [31] for glove A and in Ref. [10] for glove B; and (iv) the biodynamic response method using Eq. (1). Fig. 6 shows the comparisons of the glove transmissibility characteristics derived using the four methods. The results suggest that the first three methods yield comparable trends in glove transmissibility at the palm for both the gloves. The magnitudes of palm-side vibration transmissibility are also comparable ($r \geqslant 0.989$) at frequencies less than 80 Hz for glove A and less than 100 Hz for glove B. The results attained from the experimental biodynamic method expressed in Eq. (1) are also comparable ($r \geqslant 0.961$) to those of the other three methods at frequencies less than 100 Hz for the palm for both the gloves. The deviations in the magnitudes derived from the biodynamic response method at higher frequencies are mostly attributable to the lack of compensation for the response or the apparent mass of the glove (M_g), as is evident in Eq. (1).

As seen in Fig. 6, the glove transmissibility at the fingers mass derived from the on-the-hand method is generally very comparable ($r \geqslant 0.999$) with that derived using the model (direct method). The results attained from the experimental biodynamic method are considerably different ($r \leqslant -0.210$) from those of the other methods at frequencies less than 100 Hz. These deviations are also attributable to the lack of glove response cancellation. Surprisingly, however, the results attained from all the three methods at frequencies higher than 100 Hz are fairly consistent ($r \geqslant 0.826$), especially those for glove A, as shown in Fig. 6(c) and (d).

The resonant frequencies and damping ratios of the coupled glove-hand–arm system model, listed in Table 2, can also be used to help interpret the vibration transmissibility responses shown in Fig. 6. Although the responses exhibit peaks in the vicinity of identified resonant frequencies, the magnitudes of the peaks are generally very small due to relatively high damping ratios. It is generally observed that the gloves slightly amplify the vibration transmitted to the palm at frequencies below the gloved palm resonant frequency, near 20 Hz for both the gloves. The gloves tend to attenuate the vibration transmitted to the palm at higher frequencies. The notable attenuation of vibration transmitted to the palm occurs at frequencies above the palm-side glove resonant frequency (f_4), which are 243 Hz for glove A and 296 Hz for glove B. This resonant frequency mainly depends on the palm contact stiffness (k_3), glove stiffness (k_5), palm effective skin mass (M_3) and the glove effective mass (M_7) at the palm interface, such that $f_4 \approx \sqrt{(k_3 + k_5)/(M_3 + M_7)}/2\pi$. As also shown in Fig. 6, the gloves provide only a little attenuation of vibration transmitted to the fingers at frequencies below the gloved finger resonant frequency (f_3) but slightly amplify the fingers vibration in the vicinity of this resonant frequency for both the gloves. The significant reduction in vibration transmitted to the fingers occurs at frequencies above f_3 for both the gloves. The responses do not exhibit notable peaks near fingers-side glove resonance (f_5) due to the high damping ratio corresponding to this resonant frequency ($\xi_5 > 1.0$).

3.4. Effects of glove properties on glove performance

As listed in Table 2, the identified glove parameters values of M_5, M_6, M_8, M_{10}, c_7, and c_8 are either zero or very small, which suggest that they are not essential. A parametric study was further performed to identify the importance of the other glove parameters. The eliminations of M_9, k_7, and k_8 from the glove model only slightly changed the transmissibility of the gloves. The effect of M_7 on the transmissibility could also be ignored at frequencies less than 50 Hz but its variation could largely affect the transmissibility at frequencies higher than 100 Hz. The contact stiffness and damping properties (k_5, c_5, k_6, and c_6) of the gloves are the most critical parameters in view of their vibration transmission characteristics.

Although the materials of each glove at the finger and palm sides are similar, the glove contact stiffness at the finger side (k_6) is substantially greater than that at the palm side (k_5), as also shown in Table 2. This may be because the contact pressure at the fingers is concentrated in a smaller area. The high contact stiffness may be reduced to increase the effectiveness of the gloves. Fig. 7 shows the comparisons of the palm- and finger-side vibration transmissibility responses of glove A derived using the direct method. In this parametric study, the stiffness and damping ratios are proportionally reduced by 80, 60 and 40 percent of the identified values, termed as the nominal values. The results clearly show that lower stiffness and damping values yield greater attenuation of vibration to the palm and fingers at frequencies above the respective resonances, while slightly higher amplifications at frequencies below the resonance are also evident. As also shown in Fig. 7, the glove cannot effectively isolate the vibration transmitted to the fingers at frequencies less than 100 Hz even when its stiffness and damping are reduced substantially to 40 percent of the nominal values.

3.5. Effects of biodynamic factors on the glove performance

The biodynamic responses of the hand–arm system are generally affected by an array of factors, such as hand forces or actions, hand–arm posture, and handle size and geometry. The variation in these factors may thus also affect the glove performance. The glove parameters identified in this study may be used to predict the basic trends in their influences, when the biodynamic response data are available. As an example, Fig. 8 shows the effects of variations in the hand actions and forces on the vibration transmitted to the palm derived using the direct method, together with those measured with a palm adapter reported in Ref. [31]. For this purpose, the nominal parameters of glove A, listed in Table 2, are considered together with the parameters of the hand–arm system model for the four combinations of the hand actions and forces reported in Ref. [30]. Although the glove parameters were held constant for all the cases, the predicted transmissibility responses show trends that are surprisingly consistent with those observed in the experimental data. This observation suggests that the proposed model can be used to predict the effects of the biodynamic factors on the glove performance (Table 3).

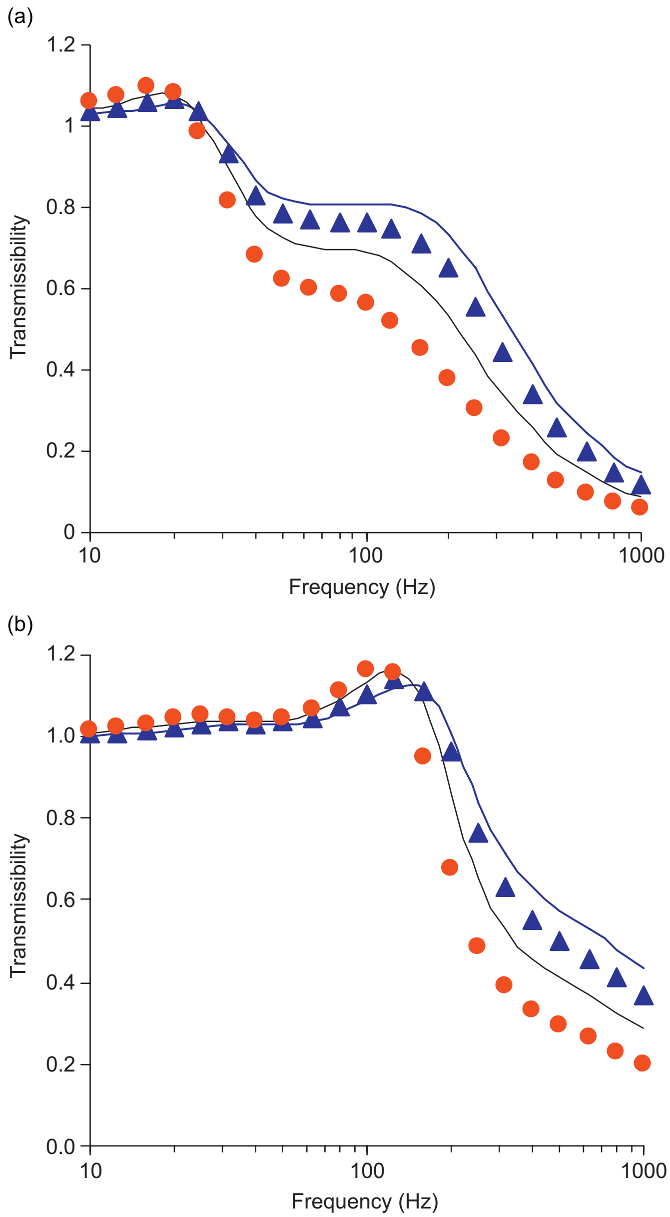

Fig. 7. Effects of stiffness and damping properties on the transmissibility of glove A: (a) at the palm; (b) at the fingers (——: nominal k_5, c_5, k_6, c_6 values in Table 2; ▲: 0.8 times of nominal k_5, c_5, k_6, c_6 values; ——: 0.6 times of the nominal k_5, c_5, k_6, c_6 values; and ●: 0.4 times of the nominal k_5, c_5, k_6, c_6 values).

4. Discussion

This study proposed a new biodynamic approach for evaluating the overall effectiveness of the AV gloves for hand protection. This approach, unlike the adapter and on-the-hand methods, see for example Refs. [3,8–13], does not require an interface or the on-the-hand measurement device, which are known to not only interfere with the handle gripping task but also alter the dynamic properties of the glove-hand system. Different from the experimental biodynamic method [25], the proposed approach does not require any modifications to the glove structures during the experiments. Different from other methods [18–21], the glove properties are identified from the experimental data measured with a gloved hand. Since the fundamental principle of an

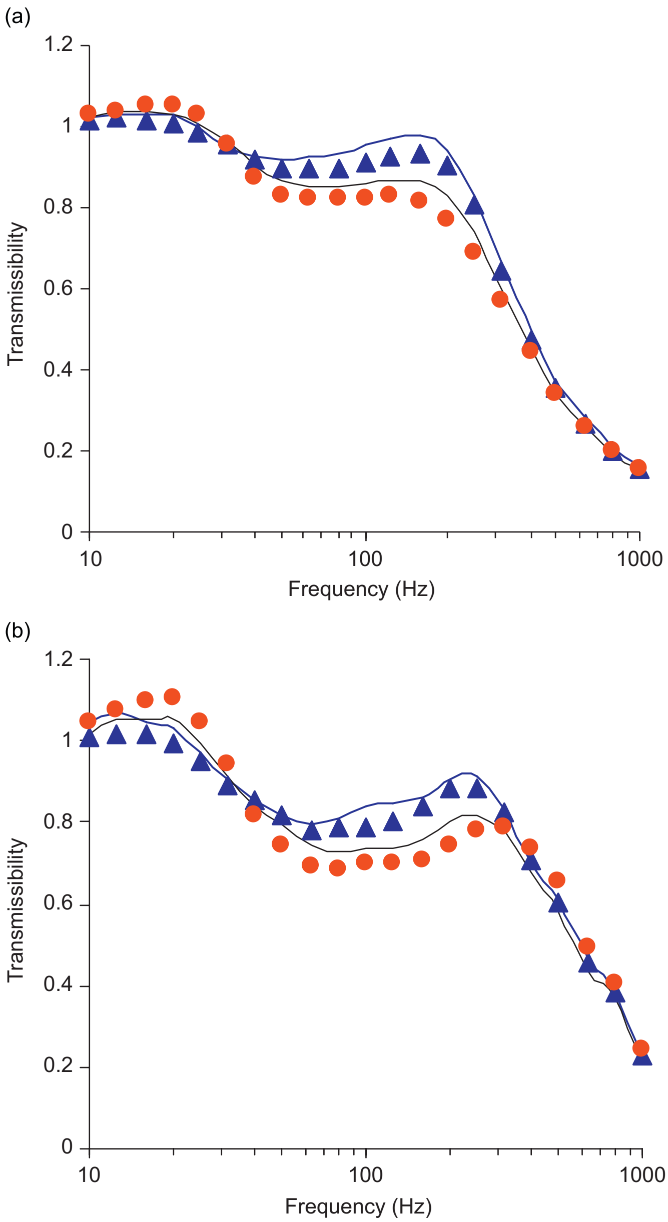

Fig. 8. Comparisons of the predicted and measured palm transmissibility data: (a) predicted; and (b) the experimental data measured with a palm adapter [30] (——: 50 N grip-only; ▲: 15 N grip and 35 N push; ——: 30 N grip and 45 N push; and ●: 50 N grip and 50 N push).

AV glove is similar to that of AV handle wrap, the proposed approach can also be applicable for assessing the vibration isolation effectiveness of the handle wraps. Although the specific method may need further improvements, the approach offers considerable potential for enhancing an understanding of the vibration isolation effectiveness of the gloves and for establishing improved glove design, testing, and evaluation methods.

4.1. Assessment of the effectiveness of the AV gloves

Although the standardized palm adapter method can be considered to be effective for glove screening tests, the measured glove transmissibility, however, may not be adequate for accounting for the reduction in the

Table 3
Parameters of the modified gloved hand-arm system model

Parameter	Unit	Glove A	Glove B
M_3	kg	0.0338	0.0338
M_4	kg	0.0167	0.0142
k_3	N/m	51932	55294
k_4	N/m	152099	136277
c_3	N s/m	114	138
c_4	N s/m	117	148
M_5	Kg	0	0
M_6	Kg	0	0.0005
M_7	Kg	0.0673	0.0650
M_8	Kg	0	0
M_9	Kg	0.0107	0.0674
M_{10}	Kg	0	0
k_5	N/m	195001	277482
k_6	N/m	365737	462648
k_7	N/m	0	0
k_8	N/m	1717	1526
c_5	N s/m	86	163
c_6	N s/m	57	75
c_7	N s/m	0	0
c_8	N s/m	0	0
Natural frequency (f) *and damping ratio* (ξ)			
f_1	Hz	7	7
f_2	Hz	29	30
f_3	Hz	172	171
f_4	Hz	249	292
f_5	Hz	893	1038
ξ_1		0.497	0.496
ξ_2		0.463	0.478
ξ_3		0.544	0.693
ξ_4		0.638	0.833
ξ_5		0.981	1.255

Note: The remaining parameters for the hand-arm system are the same as those listed in Table 1.

hand vibration exposure for the following two reasons:

(i) The standardized method addresses the measurement of vibration transmissibility in the forearm direction, where the effective mass or the impedance of the hand–arm system tends to be the highest [29]. According to the vibration isolation principle of the gloves, the reduction in the vibration exposure in the other two orthogonal directions could be overestimated if the transmissibility in the forearm direction is used in the calculation.

(ii) The results of the current study confirm that the vibration transmissibility at the palm is considerably different from that at the fingers, as shown in the Fig. 6. Although a reduction in the vibration transmitted to the palm may also help reduce the vibration at the fingers, the vibration transmitted to the fingers is likely to play a major role in the development of the fingers disorders. It would thus be inappropriate to directly use the vibration transmissibility measured at the palm to deduce reduction in the finger vibration exposure.

While the transmissibility measured at the palm may be used for exposure assessment in the wrist–arm system, the hand exposure reduction should be assessed using the transmissibility values at both the fingers and the palm in each vibration direction. However, the relative contributions of the palm and finger vibration remain an issue for further studies.

If the frequency weighting recommended in the current ISO-5349-1 standard [32] is applied to assess the effectiveness of the gloves, the results of this study suggest that the two types of gloves could not provide much protection for the hand, especially the fingers, in the operations of many powered hand tools. The use of the unweighted acceleration, however, would imply that both the gloves would provide some attenuation of vibration, especially for the operation of a high frequency tool or a tool that generates high frequency vibration components. Whereas the frequency weighting remains one of the major issues for further studies [1,30], the approach proposed in this study, together with that for predicting the tool-specific transmissibility [4,33], may help perform the exposure assessment at workplaces in a more reliable manner. Such a study may further help understand the actual roles of the gloves and provide evidence for improving the frequency weighting for assessing the risk of the finger vibration exposure.

4.2. Approaches for increasing the effectiveness of AV gloves

The results of this study demonstrate that the vibration isolation effectiveness of a glove is controlled by the resonant frequencies of the glove-hand–arm system and that reducing the resonant frequencies can increase the effectiveness of the glove. This can be achieved using two different approaches: (I) to reduce the glove contact stiffness (k_5 and k_6) and (II) to increase the effective mass of the hand (M_2 and M_3). As shown in Fig. 8, the use of the first approach can be effective for the reduction of the vibration transmitted to the palm but it is not very effective for the reduction of the vibration transmitted to the fingers. This is mainly because the finger effective mass (M_2) is generally very small, as shown in Table 1. Moreover, the stiffness properties of a glove, however, cannot be reduced greatly to ensure adequate control and guidance of the tools. A relatively soft glove would most likely yield a thick design, which may bring about other ergonomic problems in the tool operation.

The effective mass due to the fingers may also be increased by increasing the mass of the glove coupling the fingers or M_8 in the model shown in Fig. 3. Similarly, the effective mass at the palm side may also be increased by increasing the coupled glove mass (M_7). The higher glove mass coupled with the contact surface properties, however, would pose design and implementation challenges, since it could raise some ergonomic problems related to dexterity loss, glove weight, and handling and control of the tool. A feasible approach is perhaps to apply a rigid metal cover on the top of an AV handle wrap, which could yield more rigid coupling (k_7) between the distributed glove masses (M_7 and M_8) and take advantage of the larger palm impedance for finger protection. This is actually the vibration isolation principle of a suspended handle. More effective handle wraps may thus be designed using this principle.

4.3. Potential improvements in glove material test

If the glove apparent mass could be reliably canceled and wearing the glove would not change the biodynamic response of the hand–arm system itself, the experimental biodynamic method described in Ref. [25] or Eq. (1) is theoretically more reliable than the modeling method proposed in this study because the modeling could bring additional errors in the estimation. The experimental biodynamic method may be more suitable for glove material and handle wrap screening tests. As shown in Fig. 6, the effect of the glove response on the glove transmissibility is not significant at less than 100 Hz for the transmissibility at the palm side. At higher frequencies, the critical issue of this method is to sufficiently cancel the glove response. To minimize the potential error, the tested material can be firmly attached to the instrumented handle using double side adhesive tape and some electric tape. In this way, the glove or handle wrap material response (M_g) can be measured and canceled together with the tare mass of the measuring cap using the method described in Ref. [25]. If an air bladder matrix is used to isolate vibration, the air inside the bladder matrix fixed on the handle can be released to measure the tare mass of the handle with the glove material and to measure the biodynamic response of the bare hand; then, the bladder can be inflated to measure the 'gloved' hand–arm response. This is exactly the method used in the study reported in Ref. [25].

According to the glove isolation principle confirmed in this study, the gloves tested in this study cannot provide any vibration reduction at frequencies lower than 20 Hz. However, the transmissibility at such low frequencies estimated from Eq. (1) could be marginally less than 1.0, as also observed in some of the data reported in Ref. [25]. This suggests that the experimental biodynamic method could overestimate the effectiveness of a glove or glove material, partially for the reasons explained in Section 4.5. Such an error may be partially corrected by normalizing the original transmissibility function such that the resulting transmissibility value at the frequency equal to or less than 10 Hz is equal to 1.0. This may be achieved by adding a constant value ($=1-$transmissibility at 10 Hz or less) to the original transmissibility function or by dividing the function by the original transmissibility value at the low frequency. The modeling method proposed in the current study can be used to verify the resulted transmissibility values at the low frequencies.

With the use of the hand–arm system model used in this study, it is anticipated that ISO 13753 [21] may provide a more reliable prediction of the transmissibility of the glove materials. A mechanical-equivalent model that includes the four essential glove parameters (k_5, c_5, k_6, and c_6) can be established using the experimental data measured with a dead mass method, see for example Refs. [19–21]. The closely related mass parameters (M_5, M_6, M_7, and M_8) may also be included in such a model. The modeling and parameter identification task may be simplified by assuming that the stiffness and damping properties of the glove material on the finger side are identical to those of the palm side material. Although the transmissibility values predicted using such a model may not be exactly the same as those obtained from the glove test, the resulting values can be conveniently applied to screen the glove materials. In order to enhance the prediction abilities of the model, it would be essential that the size of the glove material to be tested and the dead masses and applied forces for each side be appropriately selected to closely simulate the finger and palm contact areas and pressures.

4.4. Potential improvements in ISO 10819 methodology

In the standardized method, only portions of the forces and vibration are transmitted through the palm adapter, which characterize the transmission of vibration from the glove to the palm of the hand. The proposed model of the gloved hand–arm system is most likely insufficient for simulating the effects of the adapter on the coupled system's response. The model, however, may be used to understand the effects of the palm adapter in a qualitative manner. The effect of the adapter mass can be approximately simulated by adding its mass ($\leqslant 15$ g as specified in the glove test standard [3]) to glove mass M_7 in contact with the palm skin mass M_3. As expected [4], the addition of the adapter mass reduces the vibration transmissibility, and the percent difference between the responses attained with and without the adapter mass generally increases with increase in the frequency, as shown in Fig. 9. The adapter may also alter the palm and glove properties (k_3, c_3, k_5, c_5). A lower glove stiffness coupled with higher palm contact stiffness would generally yield lower vibration transmissibility measured at the palm-adapter. The modeling also suggests that the adapter-induced changes do not alter the basic trends in the transmissibility response, which is also consistent with the observations reported in Ref. [25]. The standardized adapter method can thus be considered acceptable for the glove screening tests.

Besides the use of the tri-axial acceleration method proposed in an earlier study [6], a few other measures can also be applied to further advance the consistency in the data reported by different laboratories. For example, the adapter shape and its dimensions need to be more specific so that more consistent contact pressure distributions at the glove-adapter and the adapter-palm interfaces could be realized in different test laboratories. The adapter can be reliably calibrated by fastening it to the handle with several elastic bands with a contact force in the order of 80 N. The exact position of the adapter at the palm should be more specific (e.g., at the center of the palm if the tri-axial method is used). The required M- and H-spectrum can be replaced with a single broad-band random vibration with a constant-acceleration PSD or a constant-velocity PSD [10,33,34], which can reduce the number of trials by half.

4.5. Potential improvements of the proposed modeling approach

The biodynamic properties of the hand–arm system may be affected by the glove in a highly complex manner. The presence of a glove could alter the effective hand contact area and the relative position of the fingers on the handle. Furthermore, the glove would also influence the hand contact pressure distribution, since the contact texture and geometry of the glove are generally different from those of a real handle. These

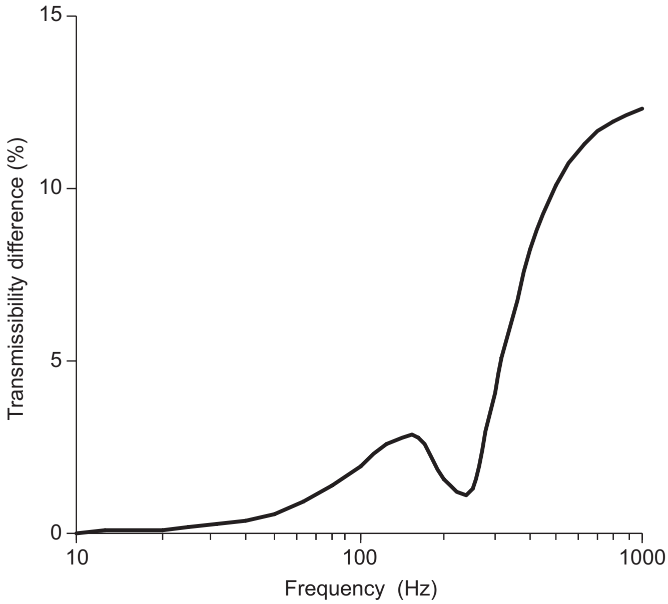

Fig. 9. Effect of the adapter mass on the glove transmissibility at the palm.

variations would also alter the biodynamic properties of the hand–arm system. Moreover, if the fingers and hand are tightly held by the glove, the glove-applied constraints may also influence the hand biodynamic properties. The consideration of the biodynamic response of the bare hand–arm system in the proposed coupled hand-glove system analysis would thus be expected to yield some errors. The derivation of Eq. (1) is also based on the assumption that there are no changes to the hand properties when wearing a glove [25], which may also cause some errors in the transmissibility estimation using the experimental biodynamic method. As above mentioned, such an assumption is also actually used in the standardized glove material test [21]. Further efforts would thus be desired for the characterization of the hand–arm biodynamics with appropriate considerations of some of the influencing factors, such as effective contact area, contact pressure distribution, and relative positions of the palm and the fingers.

The model results shown in Fig. 6 suggest that the glove transmissibility measured with the at-the-interface method should be similar to that measured with the on-the-hand method, provided that the vibration measured using on-the-hand method can be considered to represent the vibration of the bones of these substructures. This may be achieved by measuring the transmitted vibrations on or very close to the bony areas of the fingers or hand. The on-the-hand transmissibility data may also be used to help improve the proposed modeling approach.

It should also be noted that the proposed models are established based on the biodynamic responses measured in one direction (forearm direction) with a specific posture of the hand–arm system and a specific combination of the hand forces (30 N grip and 50 N push). More experimental data are required to establish the models for the predictions of the glove transmissibility in other directions and under many other conditions. Furthermore, the proposed model is mono-dimensional and it is thus limited when complex kinematics is studied. The biodynamic response in one direction could affect the response in other direction and thus the glove transmissibility. Therefore, a more comprehensive model is required to take into account these factors.

5. Conclusions

A new approach for assessing the transmissibility of anti-vibration gloves was proposed and evaluated in this study. A distinct advantage of this approach is that the glove transmissibility can be predicted without imposing any interference to the glove and the hand–arm system, which makes it possible to assess the true vibration isolation effectiveness of the glove. Another advantage is that this approach can be used to determine the overall transmissibility values at both the palm and the fingers for a comprehensive examination of the glove. Although the specific method may need further improvements, the approach offers considerable potential for enhancing an understanding of the vibration isolation effectiveness of the gloves and for establishing improved glove design, testing, and evaluation methods.

The identified mechanisms of the anti-vibration gloves suggest that it is very difficult to significantly reduce the finger vibration exposure at less than 100 Hz using the anti-vibration glove approach. The other approaches such as anti-vibration handles or suspended handles may be more effective for the finger protection.

Whereas some improvements in the methodology stipulated in ISO 10819 [3] are recommended, the results of this study suggest that the palm adapter approach specified in this standard is acceptable for glove screening tests. However, it is not appropriate to directly use the transmissibility measured with this standardized method to account for the reduction of the hand vibration exposure, mainly because the glove transmissibility at the palm is largely different from that at the fingers. The vibration isolation principle described in this study also suggests that there may be large differences among the glove transmissibility values in different vibration directions.

The combined experimental and modeling method proposed in this study may be a useful tool for further testing and assessing anti-vibration gloves and handle wrappers. The proposed model of the glove-hand–arm system may be used for improving the designs of these anti-vibration devices. This model can also be used to improve ISO 13735 [21] methodology for testing of glove materials.

Disclaimers

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

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