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Correlations between biodynamic characteristics of human hand–arm system and the isolation effectiveness of anti-vibration gloves

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Abstract

The objective of this study was to identify major individual factors that are directly associated with the effectiveness of anti-vibration gloves. Two series of experiments were performed. The first experiment measured the apparent mass of hand–arm system. The second one measured the transmissibility of a typical anti-vibration glove using a palm adapter method recommended in ISO 10819 (International Organisation for Standardization, Geneva, Switzerland, 1996). Six volunteers participated in the experiments. Nine test combinations consisting of three hand–tool coupling actions (grip-only, push-only, and combined grip and push) and three coupling forces (50, 75, and 100 N) were used. This study found that the vibration transmissibility of the glove was reliably correlated with the apparent mass in the frequency range of 40–200 Hz; and that the glove became more effective when the apparent mass was increased. This study further identified the effective stiffness of the hand–arm system at frequencies from 63 to 100 Hz as the key factor that influenced the biodynamic response and the glove transmissibility measured at the palm of the hand. Although not statistically significant, there was a trend that the anti-vibration glove was less effective in the middle frequency range (50–100 Hz) for people with larger hand sizes.

Relevance to industry

Correlations between glove transmissibility and the biodynamic response of hand–arm system provide a theoretical basis for understanding the effects of various factors that may influence the effectiveness of anti-vibration gloves. This information can also be used to help resolve practical problems with current glove testing standards and to aid in the design, appropriate selection, and effective use of anti-vibration gloves and devices.

Keywords: Arm vibration; Hand-transmitted vibration; Biodynamic response; Glove; Hand

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1. Introduction

Reducing the magnitude of the vibration transmitted from a tool to the hand has been viewed as a potential effective approach to prevent hand–arm vibration syndrome (Griffin, 1990; Pelmear and Wasserman, 1998). In recent years, anti-vibration gloves have been increasingly used to help minimize vibration exposure for tool operators. The effectiveness of these gloves, however, has not been well studied. Such knowledge is required to develop guidance regarding whether to recommend these gloves as well as for the proper selection and use of these gloves.

The effectiveness of anti-vibration gloves has been almost exclusively assessed by measuring their vibration transmissibility. The International Organization for Standardization (ISO) has set forth a test standard (ISO-10819, 1996) for differentiating effective anti-vibration gloves from ineffectual ones. The actual performances of these gloves are tool- or vibration spectrum-specific (Griffin, 1998; Rakheja et al., 2002). The gloves are generally more efficient at isolating high-frequency vibration such as could be generated by riveting hammers than that from low-frequency tools such as soil tampers. However, a tool may generate different vibration spectra under different working conditions. Previous studies (Dong et al., 2002; Rakheja et al., 2002) have demonstrated that it is acceptable to use a cost-efficient transfer function method to predict the spectrum-specific performance of anti-vibration gloves when the characteristics of the vibration spectra are known.

Several studies reported that there were large variations in the glove vibration transmissibility data obtained from different subjects (Paddan and Griffin, 1997; O'Boyle, 2001; Hewitt, 2002). This suggests that the effectiveness of these gloves is also individual-specific. The inter-subject variability of glove transmissibility may cause some difficulties when evaluating the performance of gloves using the ISO standardized test method. A glove may be classified as a true "anti-vibration glove" when tested with some subjects, but not with other subjects (Paddan and Griffin, 2001). The selection of subjects for the standardized test could be manipulated to purposely alter the outcome. Therefore, a thorough understanding of the effects of various individual factors on glove transmissibility is also required to improve the glove testing standard.

Theoretically, the isolation behavior of the gloves should be influenced by the biodynamic properties of hand–arm system. Human anthropometrics may be important individual factors that determine the dynamic properties of the system (Burström, 1997). It would be convenient to use hand and arm sizes as measures to assess the individual effect if these anthropometric parameters are significantly correlated with the transmissibility of the gloves. However, the results of a previous study did not show a reliable association (O'Boyle, 2001). This may be because the dynamic properties depend not only on the sizes of the hand and arm, but also the actual combination of the tissues in the system, the hand–tool coupling condition, and the location and orientation used in the characterization. A convenient method to determine the dynamic properties of the system is to measure the biodynamic response in terms of apparent mass, mechanical impedance, or apparent stiffness measured at the hand driving point (ISO-10068, 1998). The biodynamic response may be directly used as an individual factor to assess the effectiveness of the gloves. This concept has been presented in an ISO standard for glove material testing (ISO-13753, 1999). However, this method has not been experimentally validated. The exact form of the correlation between the biodynamic response and the transmissibility has not been investigated.

Based on this background, the objective of this study was to identify major individual factors that are directly associated with the effectiveness of anti-vibration gloves. Specifically, this study investigated the correlations among the biodynamic characteristics of hand–arm system, the transmissibility of a typical anti-vibration glove, and a few anthropometric parameters.

2. Methods

Two series of experiments were carried out: the first experiment measured the apparent mass of human hand–arm system at the palm driving point, which may be referred to as the apparent mass of palm–arm system; and the second experiment measured the transmissibility of a typical anti-vibration glove (air bladder glove) using a palm adapter method recommended in ISO-10819 (1996). Then, possible correlations among the transmissibility, apparent mass, and subject anthropometrics were systematically examined to identify the major human physical characteristics that could influence the effectiveness of anti-vibration gloves.

2.1. Measurement of the apparent mass of the human hand–arm system

The apparent mass (AM) of the human hand–arm system at the hand driving point is defined as

$$AM = \frac{\tilde{F}}{A}, \tag{1}$$

where $\tilde{F}$ and A are the dynamic force and acceleration at the driving point, respectively. The AM is generally complex, that is, it possesses real and imaginary components ($AM_{\mathrm{R}}(\omega)$, $AM_{\mathrm{I}}(\omega)$) in the frequency domain and can be expressed as

$$AM(\omega) = AM_{\mathrm{R}}(\omega) + jAM_{\mathrm{I}}(\omega). \tag{2}$$

Most tool handles have a circular cross-section, which was considered in the present study. The handle can be virtually evenly split into two parts at the centerline, as conceptually sketched in Fig. 1. Since both the fingers and the palm contact the tool handle in a power grip, they can be modeled mechanically as two parallel elements connecting the two parts of the split handle, respectively, to the back of the hand. With such a virtual division, the total vibrating force acting on the hand, $\tilde{F}$, can be considered as the sum of the two components acting on the surfaces of the two parts of the handle (Dong et al., in press), such that

$$\tilde{F} = \tilde{F}_{\mathrm{p}} + \tilde{F}_{\mathrm{f}}, \tag{3}$$

where $\tilde{F}_{\mathrm{p}}$ and $\tilde{F}_{\mathrm{f}}$ are the resultant dynamic forces acting on the palm and the fingers, respectively. If the handle system is sufficiently rigid in the

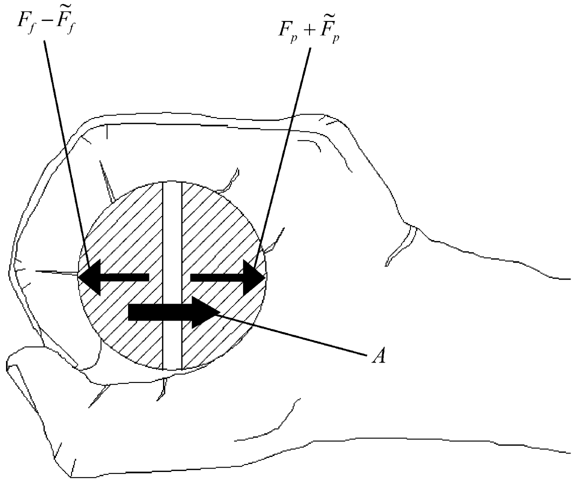

Fig. 1. Dynamic forces and velocity at the interfaces between the fingers and the handle, and between the palm and the handle. (F_{f}: static finger force; $\tilde{F}_{\mathrm{f}}$: dynamic force acting on the fingers; F_{f}: static palm force; and $\tilde{F}_{\mathrm{p}}$: dynamic force on the palm; and A: handle acceleration).

frequency range used for the AM measurement, the acceleration (A) on each part will be considered essentially equal. Replacing the dynamic force expressed in Eq. (1) with that in Eq. (3), the free, total AM of a human hand–arm system at the driving point in the power grip can be divided into the palm apparent mass (AM_{P}) and the finger apparent mass (AM_{F}).

Based on the above-described measurement principle, an instrumented handle for separately measuring AM_{F} and AM_{P} was designed and constructed, as illustrated in Fig. 2. To assure the accuracy and reliability of the measurement, the dynamic characteristics of the adapter-handle measurement system were examined using the methods described in a previous study (Dong et al., 2003). For the purpose of the present study, only the apparent mass measured at the palm side is of interest, because it corresponds to the transmissibility of a glove measured at the palm of the hand. A broadband random vibration (from 8 to 1250 Hz) with a flat power spectral density (PSD) value of 3.0 $(\mathrm{m/s^2})^2$/Hz in the frequency range of 16–1000 Hz was used.

The test equipment setup and subject posture are illustrated in Fig. 3. The test posture used in this study was the same as that required in the ISO standardized glove test specified in ISO-10819 (1996), as shown in Fig. 3. With this hand–arm posture, the vibration was delivered to the handle in the Z_h-direction in the biodynamic coordinate system (ISO-5349-1, 2001).

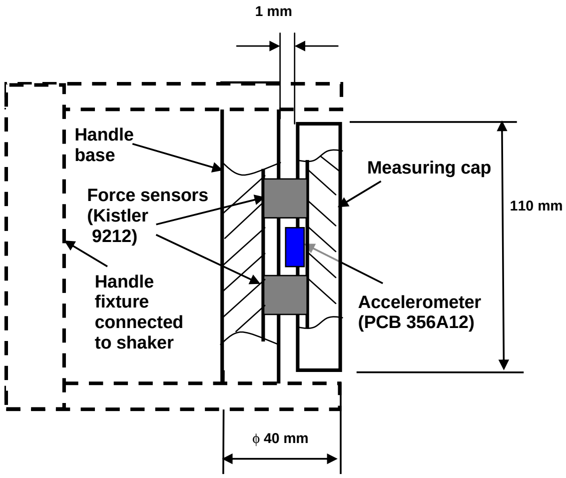

Fig. 2. The instrumented handle used for the measurement of the biodynamic response of the hand–arm system at the palm driving point.

Three hand–tool coupling actions were used in the experiment, which include grip-only, push-only, and combined grip and push actions. For each action, the subjects were asked to maintain the same arm posture as specified in the glove test standard (ISO 10819, 1996). Force levels were prescribed so that the resulting effective palm forces were 50, 75, and 100 N, with nine total test combinations or treatments. In the combined action, the distribution of the grip and push forces was 15 N grip and 35 N push for the 50 N level, 30 N grip and 45 N push for the 75 N level, and 50 N grip and 50 N push for the 100 N level. For each test treatment, two repeated trials were performed in sequence for each subject. The sequence of the test treatments was randomized among the subjects.

This study employed six male subjects. Some individual anthropometrics were measured for each subject and are presented in Table 1. During the experiments, the subjects wore casual clothing. Prior to testing, the test procedure was explained to each subject who then read and signed a consent form. Each subject was asked to stand on the force plate adjusted to an appropriate height, and to apply the required hand action and forces. A palm

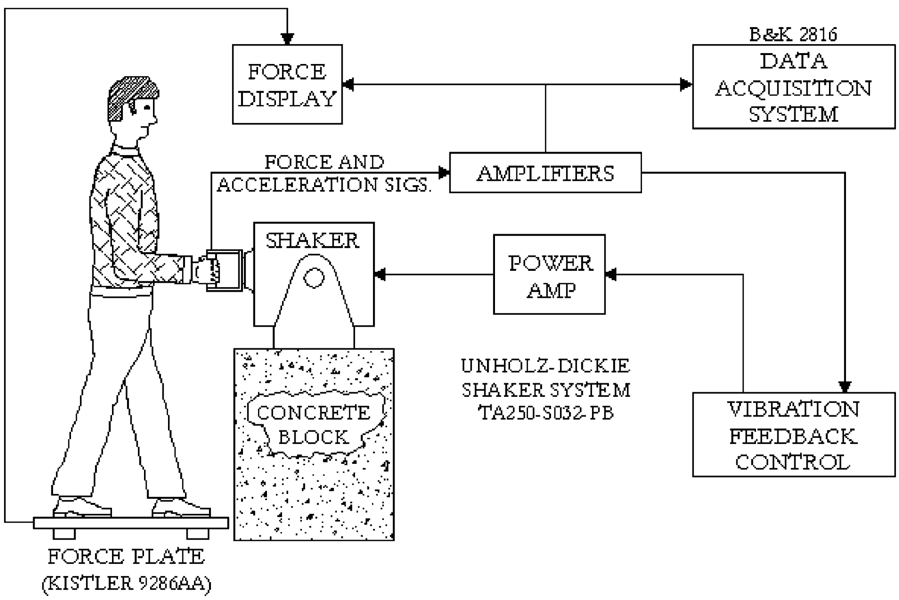

Fig. 3. Subject posture and test set-up.

Table 1
Subject anthropometry

Subject	Height (cm)	Weight (kg)	Hand length (mm)	Hand breadth (mm)	Hand circumference (mm)	Hand volume (ml)	Forearm volume (ml)
1	175	69.5	185	88	215	360	1370
2	178	83.0	197	93	215	406	1648
3	175	100.2	184	103	250	445	1830
4	185	90.7	192	97	235	440	1723
5	175	132.5	207	101	236	550	2352
6	185	83.5	196	95	218	420	1680

Hand length = tip of middle finger to crease at wrist; hand breadth = the width measured at metacarpal of the hand; hand circumference = the circumference measured at metacarpal of the hand; hand volume = water displaced by hand submerged to crease at wrist; forearm volume = water displaced by hand and forearm submerged to elbow crease.

adapter was positioned between the subject's palm and the glove. When the push and/or grip force was stable at the required level, the investigator recorded the test data for a period of 30 s. The subject was then advised to relax for 1 min before performing the next trial. The data were recorded and expressed here as functions of the one-third octave band center frequencies from 10 to 1000 Hz

The apparent stiffness (AS) was also examined in this study. It was calculated from the apparent mass using the following formula:

$$AS(\omega) = AM(\omega)(j\omega)^2. \quad (4)$$

2.2. Measurement of vibration transmissibility (TR) of a glove

For the purpose of this study, a typical commercially available anti-vibration glove (IMPACTO, full finger air bladder glove) was used. The palm adapter equipped with a tri-axial accelerometer (Endevco M35) was used to measure the transmitted vibration. It was constructed in accordance with the design specified in the standard (ISO 10819, 1996). Its total weight was 12 g. To be consistent with the measurement of the apparent mass in the same direction, the accelerations in the shaker axial direction (along the forearm direction or the Z_h-direction) measured on both the adapter and handle were used to calculate the transmissibility, which is expressed as

$$TR = \frac{A_{AZ}}{A_{HZ}}, \quad (5)$$

where A_{AZ} and A_{HZ} are the accelerations measured on the adapter and the handle in the Z_h-direction, respectively. To overcome any adapter misalignment problems, the other two adapter acceleration measurements were used to monitor and control the alignment of the adapter with respect to the shaker vibration direction (Smutz et al., 2002). As in the apparent mass measurements, two repeated trials were performed in similar fashion for each of the independently randomized nine test treatments.

2.3. Data analysis

The experimental data were analyzed using a two-way repeated-measures analysis-of-variance (ANOVA) method. The ANOVA was done using a mixed model approach with palm force and hand action as fixed effects and subject as a random effect. Linear correlation analyses were performed to evaluate the associations among transmissibility, apparent mass, and various anthropometric parameters. The results were expressed as functions of the one-third octave band center frequencies from 10 to 1000 Hz. All statistical analyses were performed using MINITAB statistical software (version 13.1). Differences were considered significant when $p < 0.05$ or suggestively significant when $0.05 \leqslant p < 0.10$.

3. Results

3.1. Apparent mass

The ANOVA results for the palm–arm apparent mass are summarized in Table 2. The results indicate that the coupling action and the effective palm force are all significant factors that affect the apparent mass. However, none of the interactions for the mass components were significant. Graphical representations of the effects of these factors on the apparent mass are shown in Fig. 4.

3.2. Vibration transmissibility of the glove

The effects of the hand coupling action and the effective palm force on the glove vibration transmissibility are shown in Fig. 5. The ANOVA results for the effects are summarized in Table 3. Coupling action and palm force were factors that significantly affect the transmissibility. The coupling-by-force interaction was suggestively significant.

3.3. The correlation between the vibration transmissibility and the apparent mass

The overall correlations between glove transmissibility (TR) and the real mass (AM_r), imaginary mass (AM_i), and mass magnitude ($AM_m = \sqrt{AM_r^2 + AM_i^2}$) are shown in Fig. 6. There are 54 pairs of data (6 subjects × 9 test combinations) at each frequency. The correlation becomes statistically significant at the 5% level when Pearson's correlation coefficient (r) is greater than 0.27. As can be seen, transmissibility is generally positively correlated to real mass from 10 to 250 Hz, with a relatively weak but still significant correlation between 40 and 63 Hz. The correlation is strong ($r > 0.80$) in the frequency

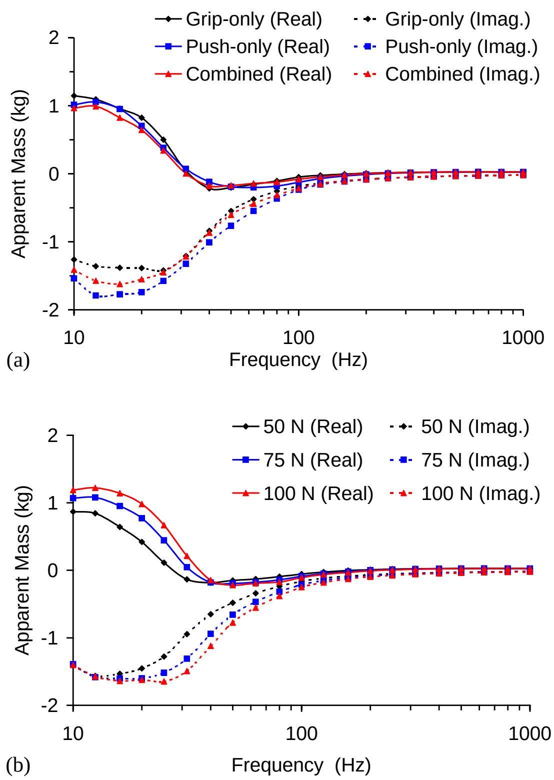

Fig. 4. Average apparent mass measured under: (a) the three different hand coupling actions, and (b) the three different palm effective force levels.

Table 2
The ANOVA results for the apparent mass

Source	DF	Real mass AM_r		Imaginary mass AM_i		Mass magnitude AM_m	
		F-value	p-value	F-value	p-value	F-value	p-value
Coupling action	2	14.50	0.001	13.48	0.001	9.88	0.004
Force level	2	42.73	<0.001	47.17	<0.001	84.22	<0.001
Coupling × force	4	1.49	0.242	2.01	0.132	1.25	0.323

Note: Error degrees of freedom = 1080.

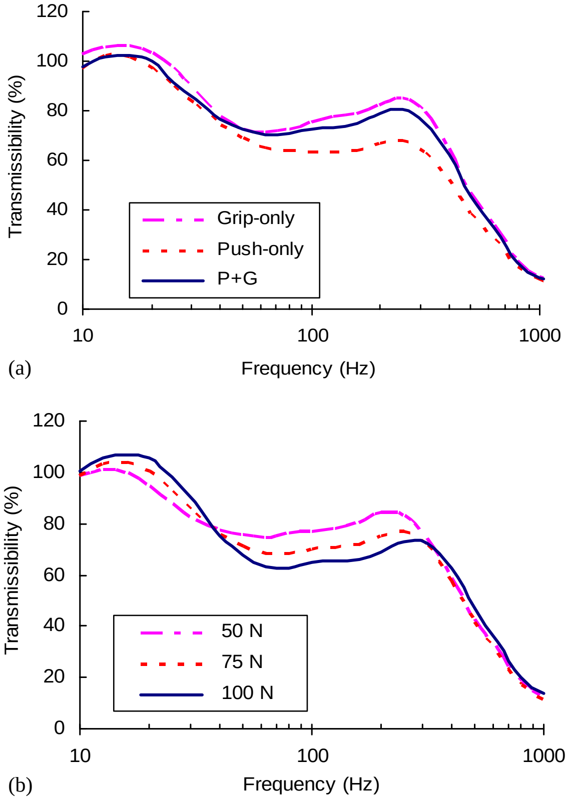

Fig. 5. Average vibration transmissibility of the glove measured: (a) under the three different coupling actions, and (b) under the three different palm effective force levels.

Table 3
The ANOVA results for the glove transmissibility

Source	DF	Transmissibility	
		F-value	*p*-value
Coupling action	2	25.34	<0.001
Force level	2	9.58	0.005
Coupling × force	4	2.54	0.071

Note: Error degrees of freedom = 1080.

range of 100–200 Hz. At frequencies higher than 500 Hz, the real mass becomes negatively correlated to the transmissibility at relatively low levels. The imaginary mass in the middle frequency range from 40 to 250 Hz is also positively correlated to the transmissibility generally at a fairly high level ($r > 0.60$). Approximately symmetrical to the imaginary mass correlation curve with respect to the horizontal axis, the mass magnitude is negatively correlated to the transmissibility in the same frequency range as that for the imaginary mass. At frequencies higher than 630 Hz, the mass magnitude becomes negatively correlated to the transmissibility again but at fairly low but statistically significant levels.

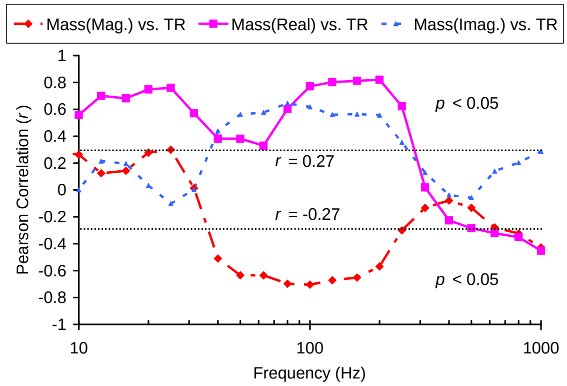

Fig. 6. The Pearson correlations (r) at the third octave-band center frequencies for the correlations of the glove vibration transmissibility to the apparent mass magnitude, real mass, and imaginary mass measured under the nine test combinations and with the six subjects.

To examine possible correlations among the changes in transmissibility, apparent mass, and coupling conditions, the average values of the apparent mass quantities and the glove transmissibility for each test combination for the six subjects were calculated. Fig. 7 shows the transmissibility correlations with these mass quantities. At each frequency, there are nine pairs of data that correspond to the nine test combinations. Hence, the correlation is significant at the 5% level when $r > 0.65$. As can be seen, transmissibility is generally positively correlated to real mass from 12.5 to 250 Hz, except that the correlation is negative at 31.5 Hz. The correlation is strong ($r > 0.90$) in the frequency range of 63–160 Hz. The imaginary mass in the middle frequency range (50–200 Hz) is also positively correlated to the transmissibility at a high level ($r > 0.82$). Approximately symmetrical to the imaginary mass correlation curve with respect to the horizontal axis, the mass magnitude is negatively correlated to the

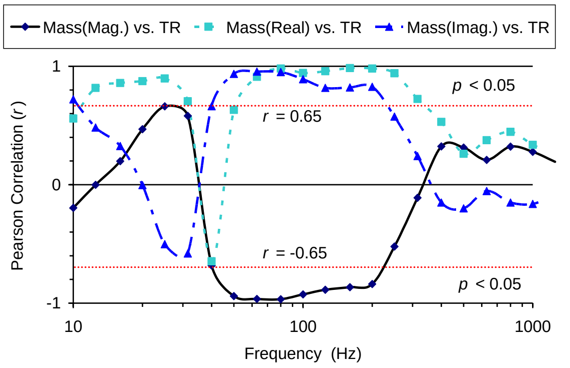

Fig. 7. The Pearson correlations (r) at the third octave-band center frequencies for the correlations of the glove vibration transmissibility to the apparent mass magnitude, real mass, and imaginary mass measured under the nine test combinations.

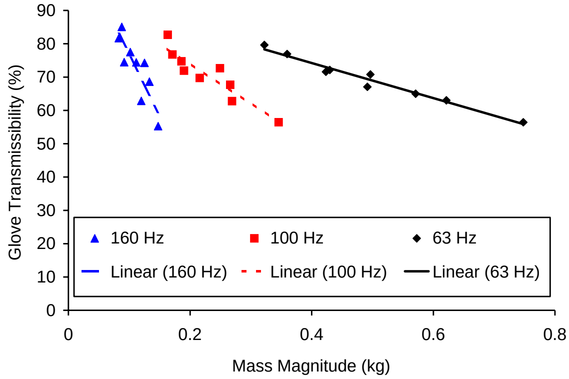

Fig. 8. The correlations of the glove vibration transmissibility to the apparent mass magnitudes at 63 Hz ($r = 0.96$, $p < 0.001$), 100 Hz ($r = 0.93$, $p < 0.001$), and 160 Hz ($r = 0.87$, $p < 0.003$). (Linear: linear regression curve).

transmissibility in the same frequency range as that for the imaginary mass. These correlations are extremely strong ($r > 0.90$) in the frequency range of 50–100 Hz. As examples, the relationships between the mass magnitude and the transmissibility at several frequencies are shown in Fig. 8.

The correlation between the average transmissibility of each subject and its corresponding mass magnitude is shown in Fig. 9. Because only six pairs of data at each frequency were available for the calculation, the correlation was reliably significant at the 5% level when $r > 0.81$. At this level, the correlation at most frequencies was not found to be reliably significant. However, the basic shapes of the correlation curves were similar to those shown in Figs. 6 and 7.

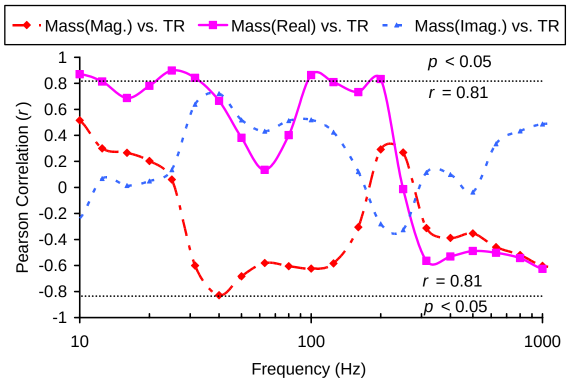

Fig. 9. The Pearson correlations (r) at the third octave-band center frequencies for the correlations of the glove vibration transmissibility to the apparent mass magnitude, real mass, and imaginary mass measured with the six subjects.

3.4. The correlations between the apparent mass and the anthropometrics

The correlation between the six pairs of each subject's average apparent mass and anthropometric characteristics listed in Table 1 was examined. For simplicity, the r values at different frequencies are expressed as functions of the one-third octave band center frequency and illustrated in Fig. 10. Because body weight, hand volume, and forearm volume are highly correlated ($r > 0.98$, $p < 0.001$), their correlations to apparent mass are very similar. Therefore, to simplify the figure, only the correlation curve for hand volume is plotted. As can be seen, the r values for the hand circumference and hand breadth are also very similar because these two anthropometrical parameters are also highly correlated ($r = 0.91$, $p = 0.012$). As can also be seen, except at a few isolated frequencies (12.5 and 50 Hz), there are generally no significant correlations between the apparent mass and the anthropometrical parameters in the frequency range of concern in this study.

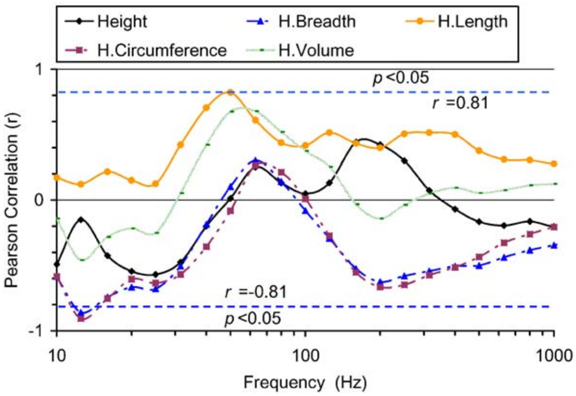

Fig. 10. The Pearson correlations (r) at the third octave-band center frequencies for the correlations of anthropometric parameters to the apparent mass magnitudes for the six subjects.

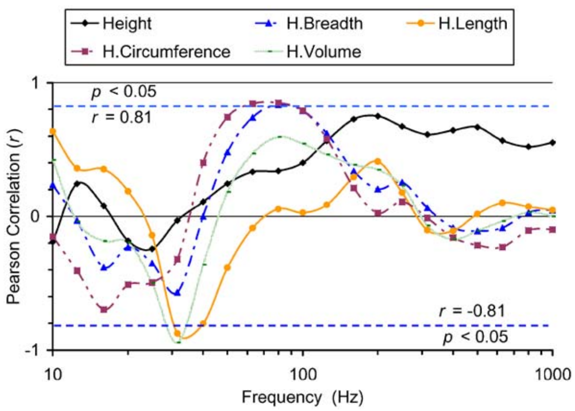

Fig. 11. The Pearson correlations (r) at the third octave-band center frequencies for the correlations of anthropometric parameters to the glove vibration transmissibility values for the six subjects.

3.5. *The correlation between glove transmissibility and hand anthropometrics*

The correlations between the average transmissibility values and the six subjects' anthropometrical parameters were examined, and the r values are illustrated in Fig. 11. There are significant or suggestively significant correlations ($r > 0.76$, $p < 0.10$) between hand circumference and average transmissibility in a narrow frequency range (50–100 Hz). Because hand breadth is well correlated with hand circumference, such a correlation trend naturally applies to hand breadth. Hand volume, like arm volume or body weight, is suggestively correlated with hand breadth ($r = 0.78$, $p = 0.08$) and with hand circumference ($r = 0.70$, $p = 0.16$). Thus, the r curve for hand volume is similar to those for hand breadth and circumference. At 31.5 Hz, hand volume and hand length have reliable correlations with transmissibility. Surprisingly, there is a trend where transmissibility increases with subject stature in a broad high-frequency range (160–1000 Hz), while none of the other anthropometrical parameters exhibit correlations with transmissibility.

The correlations between the anthropometrics and the individual transmissibility data obtained from each subject and test combination were also explored. No consistently significant correlations in any broad frequency range were identified.

3.6. *Other correlations*

After systematically exploring possible correlations between the transmissibility and different physical quantities (apparent mass, mechanical impedance, and apparent stiffness), it was found that the apparent or effective stiffness of the hand–arm system measured in the middle frequency range (63–100 Hz) has strong correlations with glove vibration transmissibility and with the

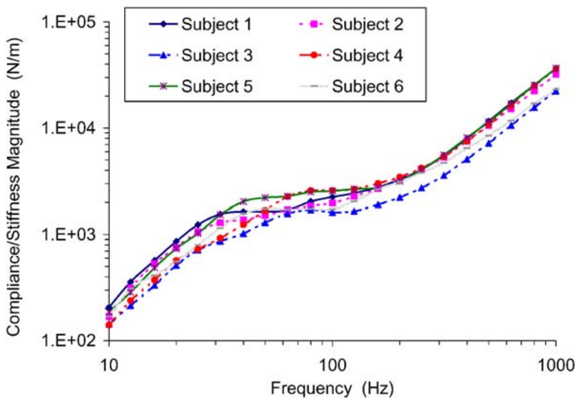

Fig. 12. Apparent stiffness values measured with six subjects.

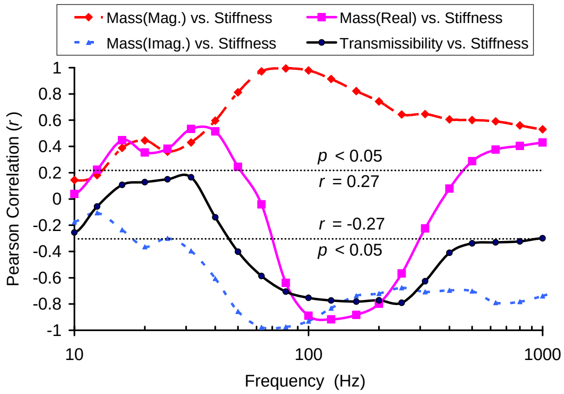

Fig. 13. The Pearson correlations (r) at the third octave-band center frequencies for the correlations of the apparent stiffness between 63 and 100 Hz to the apparent mass magnitude, real mass, imaginary mass, and glove vibration transmissibility.

apparent mass. As an example, Fig. 12 shows a group of stiffness curves. The stiffness generally increases with the increase in frequency. It remains more or less constant when the frequency is in the range of approximately 50–160 Hz. The actual frequency range of this relatively constant stiffness varied with different test combinations and subjects. However, a common frequency range approximately between 63 and 100 Hz was observed. Therefore, the average stiffness value in this frequency range was used to evaluate the correlations between the stiffness and glove transmissibility and the biodynamic responses.

Fig. 13 shows the stiffness correlations with transmissibility and with apparent mass. The stiffness values were reliably correlated to the mass magnitude and to the imaginary mass component in nearly the entire frequency range of interest in this study. However, the strongest correlations are generally in the middle frequency range (63–250 Hz). The results indicate that an increase in stiffness increases the apparent mass magnitude but reduces the glove vibration transmissibility at frequencies higher than 50 Hz.

The strongest correlation between stiffness and any anthropometric parameter is its relationship with hand breadth measured at the metacarpal. This correlation, however, is not significant ($r = 0.65$, $p = 0.16$).

4. Discussion

The results of this study indicate that the magnitude of the apparent mass is reliably negatively correlated to glove transmissibility in the middle frequency range (40–200 Hz). Stated otherwise, the glove is more effective for a person exhibiting a higher magnitude of biodynamic response in this frequency range, as shown in Figs. 6–8. In principle, the glove can be virtually considered as a spring and damper system, and the hand–arm system can be approximately modeled as a frequency-dependent mass system in contact with the glove. Theoretically, increasing the mass of the system generally reduces the vibration transmissibility because a higher mass corresponds to a lower acceleration for the same dynamic force transmitted from the glove spring–damping system. Therefore, the correlations observed in this study are basically consistent with the general vibration isolation principle.

However, it is interesting to note that, depending on the vibration frequency, a higher magnitude of apparent mass does not necessarily correlate to a larger hand. Common sense would dictate that since a larger hand has more mass and contact area, it should result in a larger apparent mass. This is true at low-frequency vibrations (say, <25 Hz) when the majority of the hand–arm mass is involved and moving in-phase with the vibration. On the other hand, a larger hand may also be associated with a thicker layer of soft tissue at the palm, which can also be virtually considered as another spring–damping system that can provide vibration isolation to the other parts of the hand–arm system. This isolation system becomes more effective at certain frequencies. Therefore, the actual apparent mass depends on which of these frequency-dependent opposing effects is dominant. As shown in Fig. 11, an increasing hand size (measured by hand length and volume) results in an increase in apparent mass at frequencies from 40 to 80 Hz, although this trend is not statistically significant. There is also a trend in the middle frequency range (50–100 Hz) where increases in hand size result in increases in vibration transmissibility (or reductions in the isolation effectiveness of the glove), as shown in

Fig. 12. These relationships between hand size and transmissibility are basically consistent with those reported in a previous study (O'Boyle, 2001).

This study also found that the effective stiffness measured in the middle frequency range (63–100 Hz) is a key factor that strongly influences the magnitude of the apparent mass and transmissibility, as shown in Fig. 14. Coincidently, hand size is also suggestively correlated to transmissibility in a similar frequency range. This suggests that this effective stiffness may be associated with the palm contact stiffness. A person with a large hand size will likely have a thicker layer of soft palm tissue than would a person with a small hand. The palm contact stiffness of a large hand under the same effective palm force may be lower than that exhibited by a smaller hand. Conversely, a larger hand may also have a larger contact area, which could also increase the stiffness. Again, these opposing effects increase the complexity of the anthropometrics/transmissibility relationship. This is further complicated by the fact that different individuals manifest diverse mechanical properties in their soft tissues and joints. These observations suggest that while there may be some correlations between anthropometric parameters and glove transmissibility, such correlations may not be strong or easily identified. On the other hand, the biodynamic response is relatively sensitive to these variations and can be used to reflect the overall effect of the individual differences.

Another source of variability with glove test data obtained via the ISO standardized adapter method may be the inconsistency of adapter placement. If the adapter were to be placed near the heel of the palm, the apparent mass and effective stiffness of the palm–arm system would likely be higher than if the adapter were positioned at the center of the palm. As a result, the transmissibility of the glove in the middle frequency range could be reduced, according to the correlation principle found in this study. The adapter alignment with the handle was well controlled in this study, but its actual position relative to the palm was not as tightly monitored and controlled. This may be one of the reasons that the correlation data depicted in Fig. 11 is not generally statistically significant. Such a problem may be overcome by using a larger number of subjects in the test. However, it may be more effective to maintain strict control over the adapter position with respect to both the handle and the subject's palm.

The correlation relationship found in this study also provides a direction for using anti-vibration gloves more effectively. That is, any method or device that can effectively increase the magnitude of the apparent mass or the effective stiffness of the system in the middle frequency range should, in turn, increase the isolation effectiveness of the glove in this frequency range. This is important because many power tools have dominant vibration frequencies in such a frequency range. This principle may also play a role in the design and application of new anti-vibration devices.

5. Conclusion

In conclusion, the present study reveals that there is a strong linear correlation between the isolation effectiveness of a typical anti-vibration glove and the biodynamic characteristics of the human hand–arm system in a broad frequency range (40–200 Hz). Such a correlation provides a theoretical basis for understanding the mechanisms involved in the use of gloves for attenuating hand-transmitted vibration and the effects of various factors that influence the effectiveness of anti-vibration gloves. The results of this study suggest that an effective approach to increase the effectiveness of anti-vibration gloves is to increase the effective mass of hand–arm system. However, the effectiveness is vibration frequency-dependent.

Disclaimer

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