Effects of Hand-Tool Coupling Conditions on the Isolation Effectiveness of Air Bladder Anti-Vibration Gloves

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ABSTRACT
The goals of this study were to determine the vibration isolation effectiveness of a typical (air bladder) anti-vibration glove as a function of vibration frequency, and to investigate the effects of hand-tool coupling action and applied force level on the effectiveness. Six male volunteers were used in the study. A palm adapter method similar to that recommended in the current ISO standard for anti-vibration glove testing (ISO-10819, 1996) was used to measure the transmissibility of the glove. Three different handgrip actions (grip-only, push-only and combined grip and push), three force levels (50, 75 and 100 N), and a broad-band random spectrum were used in the experiment. This study found that the effectiveness of the glove generally increased with an increase in vibration frequency, while the glove did not provide any effective vibration isolation at frequencies less than or equal to 25 Hz. Under the same force level, the push-only action produced the greatest vibration attenuation while the grip-only action resulted in the lowest glove performance among the three actions. Increasing the force tended to increase vibration transmissibility at low frequencies (< 31.5 Hz), while transmissibility decreased at the middle frequencies (63 - 250 Hz). The knowledge generated by this study can be used to augment vibration exposure risk assessments and to promote the appropriate application of anti-vibration gloves at workplaces.

Keywords: *hand-transmitted vibration, anti-vibration glove, human vibration isolation*

1. INTRODUCTION

Prolonged, intensive occupational exposure to vibration generated by powered hand tools may cause a series of disorders in the vascular, sensorineural, and musculoskeletal systems of the hand and arm.[1,2] These disorders have been collectively defined as hand-arm vibration syndrome (HAVS).[3] Several international and national standards or regulations[4-6] have set exposure limits and/or exposure action values to control the exposure intensity. Anti-vibration gloves have been viewed as a simple method to help reduce hand-transmitted vibration exposure, and are increasingly used at workplaces. A comprehensive understanding of the effectiveness of these gloves can improve risk assessments of vibration exposure for workers wearing these gloves and provide some useful information for their appropriate use.

The performance of these gloves is most frequently assessed by measuring the glove vibration transmissibility. Based on this approach, the International Organization for Standardization (ISO) has set forth a standard for the glove screening test (ISO-10819, 1996).[7] Since only a single hand-tool coupling condition (grip at 30 N and push at 50 N) and two specific vibration spectra (M-spectrum and H-spectrum) are required in the experiment, the test results can not tell exactly how effective the gloves will be when used with different tools under different working conditions (e.g. applied forces, tool handle sizes, hand-arm postures, hand-tool coupling actions such as grip, pull, and push).[8]

A few studies indicated that the vibration transmissibility of anti-vibration gloves was tool- or vibration spectrum-specific.[9, 10] These studies further demonstrated that it was acceptable to use the transmissibility measured in the laboratory to estimate the transmissibility of the gloves when used with specific tools or vibration spectra. This approach for determining the tool-specific performance of the gloves in the workplace eliminates the need for field tests, which could be expensive and time-consuming. However, to provide a reasonable prediction, the transmissibility of the gloves under representative hand-tool coupling actions and applied forces should be used. So far, such transmissibility data have not been sufficiently reported.

Because vibration transmissibility in the hand-arm system and its biodynamic response such as apparent mass and mechanical impedance can be influenced by hand-arm postures and hand-tool coupling conditions,[11-14] it is hypothesized that the vibration isolation effectiveness of the gloves can also be associated with these postures and coupling conditions. Very few studies have been performed to test this hypothesis.[15, 16] Paddan reported that varying arm posture generally produced no significant effects on the transmissibility values of several gloves.[15] This may be because arm posture, for the most part, only affects low frequency (≤ 40 Hz) vibration transmissibility in the hand-arm system,[12, 13] and anti-vibration gloves can usually provide significant isolation for higher frequency vibration, as observed in several studies.[9, 11, 15, 17, 9, 18] Therefore, it may be very difficult to detect a statistically reliable difference caused by changes in arm posture. However, the effects of other coupling factors such as hand-tool actions and applied forces on glove transmissibility have not been sufficiently studied and they may not be ignored.

According to the reported data,[19] air bladder anti-vibration gloves are one of the most effective types of the anti-vibration gloves that are commercially available. Besides the data from the ISO-standardized test, little information on the transmissibility of this type of glove under other working conditions is available. Based on the above-mentioned background, the specific aims of the present study were to determine the transmissibility of the gloves as a function of vibration frequency under several hand-tool coupling conditions and to investigate the effects of the hand-handle coupling action and force on the transmissibility.

2. METHODS

2.1 Equipment Setup

The instrumentation setup and the subject's arm posture used in this study are illustrated in Figure 1. This design is similar to what is recommended in the standardized glove test.[7] Briefly, a vibration test system (Unholtz-Dickie TA250-S032) was employed to generate the required vibration source. An instrumented handle (Figure 2) capable of measuring the acceleration components in three orthogonal axes and the grip force was used to measure the vibration input to the tested glove and to provide grip force feedback. This handle was developed in a previous study.[20] Its dimensions and grip force measurement comply with the requirements of the glove test standard.[7] The handle was fixed on the system's shaker using a specially designed handle fixture with its long axis oriented vertically as specified in the test standard. The push force was measured using a force plate (Kistler 9286AA). The grip and push forces were displayed to the subject as strip charts on separate computer monitors. A close-loop feedback control system (UD-VWIN 4.18) was used to generate the desired vibration spectrum. A data acquisition and analysis system (B&K Type 3032A I/O Module) was used to process and record the acceleration data. The results are expressed in the frequency domain, corresponding to the center frequencies of the one third-octave bands from 10 to 1,250 Hz.

The plam adapter used to measure the transmitted vibration at the hand-glove interface was custom-made in accordance with the design specified in the current

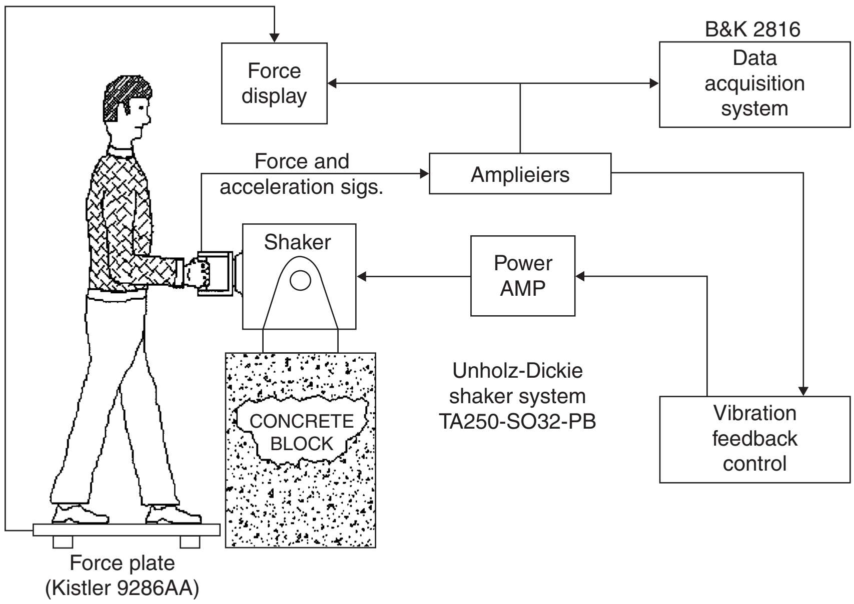

Figure 1 Experimental test setup and subject posture

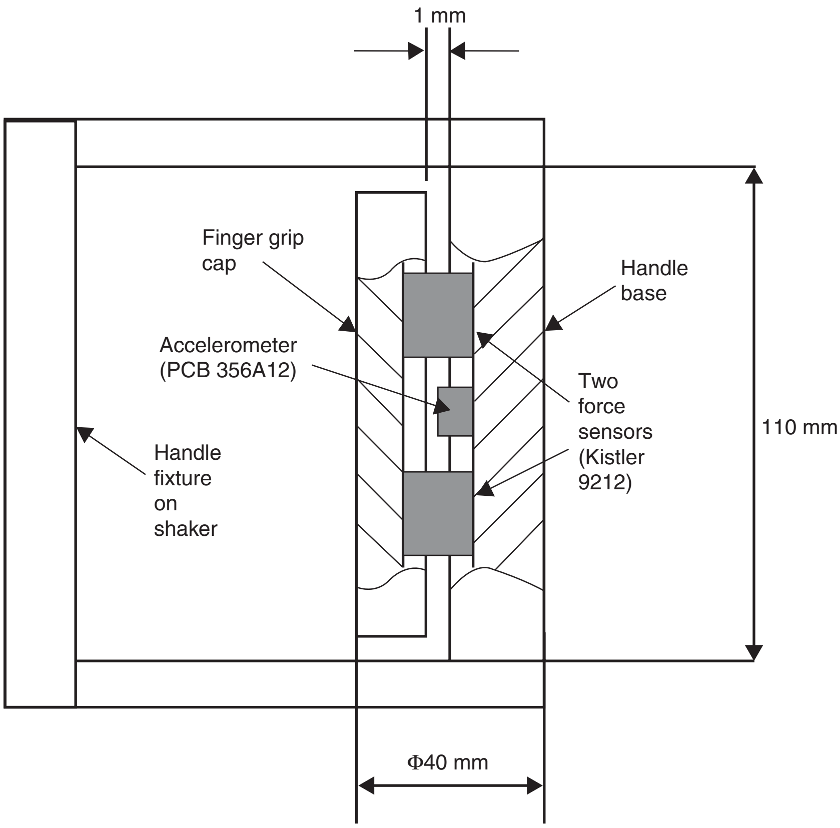

Figure 2 Instrumented handle used for the measurement of glove vibration transmissibility. In the test, palm is in contact with the handle base while the finger grip on the grip measuring cap

ISO 10819 standard.[7] It weighs 12 grams and equipped with a tri-axial accelerometer (Endevco M35) to measure total vibration corresponding to that on the handle. For internal calibration, the adapter was fixed on the handle, and the vibration measurements from the adapter were compared with those obtained simultaneously from the accelerometer installed in the instrumented handle (Figure 2). With no glove present, the ratio of the two measurements was near unity (with a difference < 2%) in the frequency range of concern in this study.

Table I. Anthropometric parameters of six male subjects participated in the study (hand length = tip of middle finger to crease at wrist; 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)

Subject	Height (cm)	Weight (kg)	Hand Length (mm)	Hand Circumference (mm)	Hand Volume (ml)	Forearm Volume (ml)	EN420 Hand Size[21]
1	175	69.5	185	215	360	1370	8
2	178	83.0	197	215	406	1648	9
3	175	100.2	184	240	445	1830	9
4	185	90.7	192	235	440	1723	9
5	175	132.5	207	236	550	2352	10
6	185	83.5	196	218	420	1680	9
Mean	179	93	194	227	437	1767	9
Std	5	22	9	12	63	325	

2.2 Subjects, Test Conditions, and Procedures

This study was carried out using six male subjects with no previous work-exposure to vibration. They were students from a local university. The height, weight, and a few fundamental hand anthropometric parameters of each subject, together with the hand side according to EN420[21] are listed in Table I. In this study, a typical, commercially manufactured, full fingered, large size, anti-vibration glove was used. At the beginning of each subject test, the air pressure was fully inflated by depressing the air pump of the glove for 25 times, as specified in the user's manual of the glove. No air leakage was observed throughout the experiment.

The arm posture used in this study was the same as specified in the ISO standardized glove test and depicted in Figure 1. Briefly, each subject was instructed to stand upright on the force plate located on top of a platform in front of the shaker with his elbow angled at 90°. The platform height was adjusted to enable the subject to keep his forearm at the same level as the handle while maintaining the proper elbow angle. With this hand-arm posture, the vibration was delivered to the hand along the forearm direction or in the Z_h-direction in the biodynamic coordinate system.[22]

For the purpose of this study, a broadband random vibration was used in the experiment, which had vibration components from 10 Hz to 1,250 Hz with a flat power spectral density (PSD) value of 3.0 $(m/s^2)^2/Hz$ in the frequency range of 16 to 1,000 Hz. Previous studies suggest that this spectrum was acceptable to measure the transmissibility for predicting the tool-specific effectiveness of the glove.[9, 10]

The hand-tool coupling conditions used in this study are listed in Table II, together with the identification (ID) for each coupling condition. The combined grip and push action is most frequently used in the tool operation and thus specified in the standardized glove test.[7] In addition to this action, the subjects in the present study also applied grip-only and push-only hand actions in the experiment. These two actions may represent the extreme hand-tool coupling actions. For each action, each subject was asked to keep the same arm posture as specified in the standard. The force levels were prescribed so the applied palm forces were 50 N, 75 N, and 100 N. The middle force level (75 N) is similar to that specified in the glove test standard (80 N: 30 N grip and 50 N push).[7] In a group of ISO standards for tool tests (e.g. chipping hammers, rock drills, pavement breakers, and jackhammers tests), the maximum feed/push force applied from two hands on each tool is 200 N.[23] These observations suggest that the force range used in this study may be frequently

Table II. The nine hand coupling combinations used in the experiment

Coupling Action	ID	Applied Force (N) I	II	III
Grip-Only	G	50	75	100
Push-Only	P	50	75	100
Combined Grip and Push	C	50 (15 grip + 35 push)	75 (30 grip + 45 push)	100 (50 grip + 50 push)

used in the operation of many power tools. For each test combination or treatment (coupling action and force level), two trials were performed in sequence for each subject. The sequence of the treatments was randomized for each subject.

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 with the adapter located between the 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 seconds. In the push-only action, the hand grip posture remained the same as that in the combined action but the fingers were not allowed to apply any significant force (<3 N) on the handle. The grip force was monitored and displayed to the subject for implementing this requirement. After each trial, the subject was advised to relax for one minute before performing the next trial. The subject test protocol was reviewed and approved by NIOSH Human Subject Review Board.

2.3 Transmissibility Evaluation

Although only an axial vibration was designed in the experiment, the shaker could generate non-axial vibration.[24] Misalignment of the adapter could also generate a significant test error.[24, 25] To overcome these undesired effects, a total vibration method[24] was used to evaluate the transmissibility (T). This method is expressed in the following formula:

$$T(\varpi_i) = \frac{\sqrt{A_{ax}^2(\omega_i) + A_{ay}^2(\omega_i) + A_{az}^2(\omega_i)}}{\sqrt{A_{hx}^2(\omega_i) + A_{hy}^2(\omega_i) + A_{hz}^2(\omega_i)}} \tag{1}$$

where ω_i is the ith one-third octave band center frequency, A_{ax}, A_{ay} and A_{az} are the accelerations measured on the palm adapter, and A_{hx}, A_{hy} and A_{hz} are the accelerations measured on the handle.

2.4 Statistical Analysis

It has been well-known that the glove vibration transmissibility is usually frequency-specific. This was further confirmed in this study, as presented in the next section. To simplify the general statistical analysis, the effect of the frequency was not considered in the analysis-of-variance (ANOVA). The transmissibility data were first analyzed in a two-way analysis-of-variance (ANOVA) to establish the overall significance of the two main factors (coupling action and force level) considered in this study. The ANOVA was done using a mixed model approach with force level and hand action as fixed effects and subject as a random effect. To identify the effects of the two factors within different frequency regions, the data were further analyzed by separate analyses of force and coupling action for each point in frequency. Specifically, at each coupling action, one-way ANOVAs were performed for the data at each frequency using a mixed model with the force as fixed effect and the subject as random effect. Similarly, the one-way ANOVAs were also used to analyze the effect of the coupling action at each force level at each frequency. Post hoc comparisons were also performed for each effect with Tukey's method. A linear

Table III. Results of two-way ANOVA for identifying the overall effects of coupling action and force level

		Effects on Transmissibility	
Source	df	F	p
Force	2	7.65	0.010
Coupling	2	30.98	<0.001
Subject	5	13.79	<0.001
Force×Coupling	4	2.81	0.047
Force×Subject	10	1.34	0.278
Coupling×Subject	10	3.15	0.014

correlation analysis was also performed to evaluate the associations between the transmissibility of the glove and the anthropometrics of the subjects at each frequency. All statistical analyses were performed using MINITAB statistical software (Version 13.1). Differences were considered statistically significant when $p < 0.05$ or suggestively significant when $0.05 \leq p < 0.10$.

3. RESULTS

The results of the two-way ANOVA are presented in Table III. As can be seen, the two main factors (coupling action and applied force level) and the random factor (subject) considered in the analysis are significant. Their interactions are also significant except that between the force level and the subject.

3.1 The Effectiveness of the Glove as a Function of Frequency

Figure 3 shows the overall average transmissibility at different frequencies. At frequencies less than 25 Hz, the transmissibility is over 100% with a peak value at 16 Hz (106.9%), which indicates that the glove marginally amplified the vibration at the low frequencies. The transmissibility curve shows a distinct reduction as the frequency increased from 16 Hz to 63 Hz. In the frequency range of 63 to 125 Hz, the mean transmissibility varies little (from 71.5% to 72.9%). At 250 Hz, transmissibility reaches another peak value (80.3%), which is not reliably different from the values at 200 and 315 Hz but is significantly different from the transmissibility values at any other neighboring frequency. The transmissibility values at frequencies higher than 250 Hz significantly decrease with the increase in frequency. At 500 Hz, on average, the glove could reduce the vibration by 40%, and it could reduce the

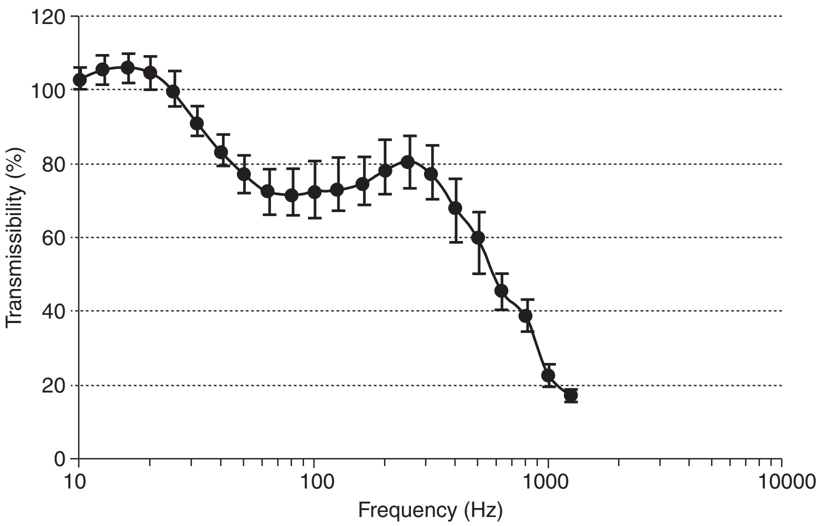

Figure 3 The transmissibility of the air bladder anti-vibration glove as a function of vibration frequency

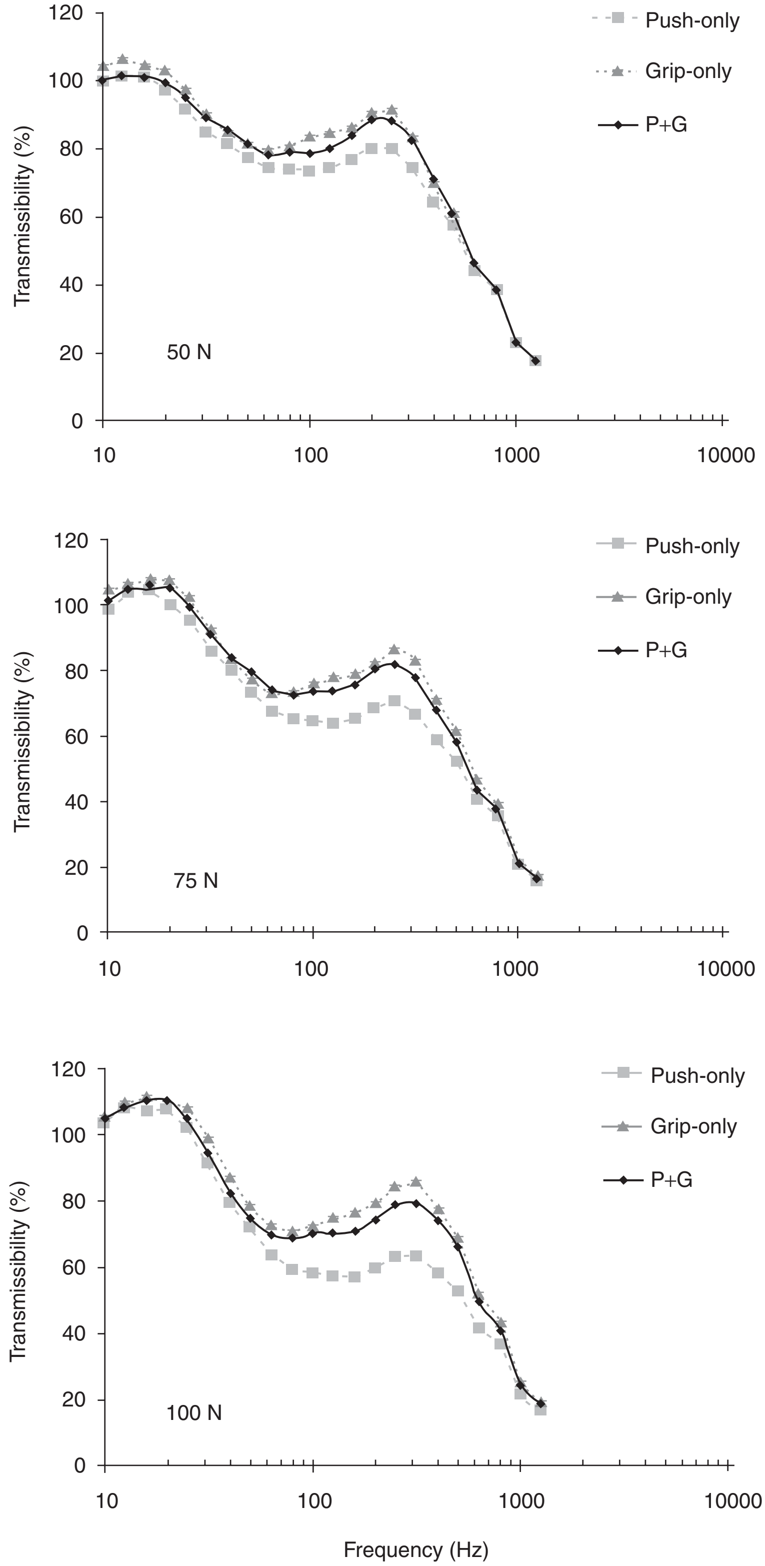

Figure 4 Effect of hand-tool coupling action on the transmissibility of the air bladder anti-vibration glove at the three effective palm forces

vibration by more than 70% at frequencies higher than or equal to 1,000 Hz.

3.2. Effect of Hand Coupling Action at Different Forces

The effect of the hand coupling action on glove transmissibility at the three effective palm forces is plotted in Figure 4. The results of the one-way ANOVA and Tukey

Table IV. Results of the one-way ANOVA and Tukey's test for identifying the influence of the effective palm force on the transmissibility at different coupling actions and frequencies

	Hand-Tool Coupling Action								
	Grip-only (*G*)			Push-only (*P*)			Combined G+P (*C*)		
Freq. (Hz)	F	P	Significant Pair	F	p	Significant Pair	F	P	Significant Pair
10	0.04	0.957		3.46	0.072		1.90	0.200	
12.5	2.50	0.132		4.80	*	*I-III*	4.05	0.052	*I-III*
16	9.42	*	*I-III*	1.94	0.195		9.75	**	*I-III*
20	13.05	**	*I-II, I-III*	25.47	**	*I-III, II-III*	17.26	**	*I-II, I-III*
25	33.41	**	*I-II, I-III, II-III*	7.81	*	*I-III*	10.51	**	*I-III*
31.5	16.03	**	*I-III, II-III*	1.87	0.204		3.41	0.074	
40	0.76	0.494		0.18	0.836		1.39	0.294	
50	1.56	0.258		4.01	0.053	*I-III*	3.27	0.081	
63	12.61	**	*I-II, I-III*	14.38	**	*I-II, I-III*	4.71	*	*I-III*
80	41.09	**	*I-II, I-III, II-III*	28.22	**	*I-II, I-III, II-III*	10.71	**	*I-II, I-III*
100	81.49	**	*I-II, I-III, II-III*	25.31	**	*I-II, I-III, II-III*	8.74	**	*I-III*
125	15.72	**	*I-II, I-III*	33.04	**	*I-II, I-III, II-III*	9.33	**	*I-III*
160	11.08	**	*I-II, I-III*	88.97	**	*I-II, I-III, II-III*	22.33	**	*I-II, I-III*
200	25.90	**	*I-II, I-III*	60.97	**	*I-II, I-III, II-III*	12.59	**	*I-II, I-III*
250	24.02	**	*I-II, I-III*	43.94	**	*I-II, I-III, II-III*	6.53	*	*I-III*
315	1.78	0.219		12.37	**	*I-II, I-III*	2.01	0.185	
400	5.52	*	*I-III*	2.21	0.160		2.83	0.106	
500	4.26	*		1.56	0.258		3.06	0.092	
630	4.56	*	*I-III*	2.39	0.141		3.62	0.066	
800	4.52	*	*I-III*	1.96	0.191		2.66	0.119	
1000	1.60	0.250		1.74	0.224		1.70	0.232	
1250	1.81	0.213		1.24	0.330		1.33	0.307	

Notes: * $p < 0.05$; ** $p < 0.005$; the significant pair column lists the pair IDs where the Tukey tests revealed significantly different means ($p < 0.05$), in which ***I*** = 50 N, ***II*** = 75 N, and ***III*** = 100 N, as also identified in Table 2.

tests are summarized in Table IV. As can be seen in the figure, at each force level, the grip-only action generally corresponds to the highest transmissibility, while the push-only action corresponds to the lowest transmissibility at each frequency, with the combined grip and push action in between. The one-way ANOVA results listed in the table indicate that the effect of the coupling action at all three forces is significant in the frequency range of 63 to 315 Hz. At a 50 N effective palm force, the effect extended to almost all the lower frequencies, but at a 100 N force, the effect extended to all the higher frequencies. This indicates that the frequency range of the significant effect tends to shift from low frequencies towards high frequencies as the force is increased. The results of Tukey's tests confirm the ANOVA significant differences between the grip-only (G) and the push-only (P) coupling actions. Exceptions can be found at 40 Hz at 50 N, and 63 Hz at 75 N. This further confirms the above observation that the grip-only action forms the upper boundary and the push-only action sets the lower limit of the glove vibration transmissibility among the three actions investigated in this study.

Figure 4 also shows that the interaction between the coupling action and the force level. To demonstrate this more clearly, the percentage magnitude differences (PD_f) between the transmissibility values from the grip-only action (T_g) and the push-only action (T_p) at the three force levels are illustrated in Figure 5. Percentage magnitude difference is calculated from

$$PD_{fi} = 2\bullet\left(T_{gi} - T_{pi}\right)/\left(T_{gi} + T_{pi}\right)\bullet 100\% \quad \left(i = 50\ N,\ 75\ N \text{ and } 100\ N\right) \tag{2}$$

The post hoc analyses of these percentage differences indicate that the magnitude of the difference at 100 N is generally significantly greater than that at 50 N at frequencies higher than 63 Hz. The effect of the 100 N force is also greater than that at 75 N in the frequency range of 160 to 250 Hz. The magnitude of the differences at 75 N is suggestively greater ($p < 0.10$) than that at 50 N at 250 Hz and 315 Hz. These observations suggest that increasing the effective palm force generally increases the action effect.

3.3 Effect of the Effective Palm Force at Different Hand Coupling Actions

The influence of the effective palm force on glove transmissibility at the three coupling actions is plotted in Figure 6. The results of the one-way ANOVAs and Tukey's tests are summarized in Table V. The results show that increasing the force generally significantly increased the transmissibility in the frequency range of 12.5 to 25 Hz. There was a transition zone between 31.5 and 50 Hz, at which the force effect could not be reliably identified. In the frequency range of 63 to 250 Hz, the transmissibility significantly decreased as the force increased, irrespective of the type of coupling action. Such a trend extended to 315 Hz for the push-only action. At the grip-only and the combined grip and push actions, however, the trend was inversed at 315 Hz, which was significant up to 800 Hz for the grip-only action. The results

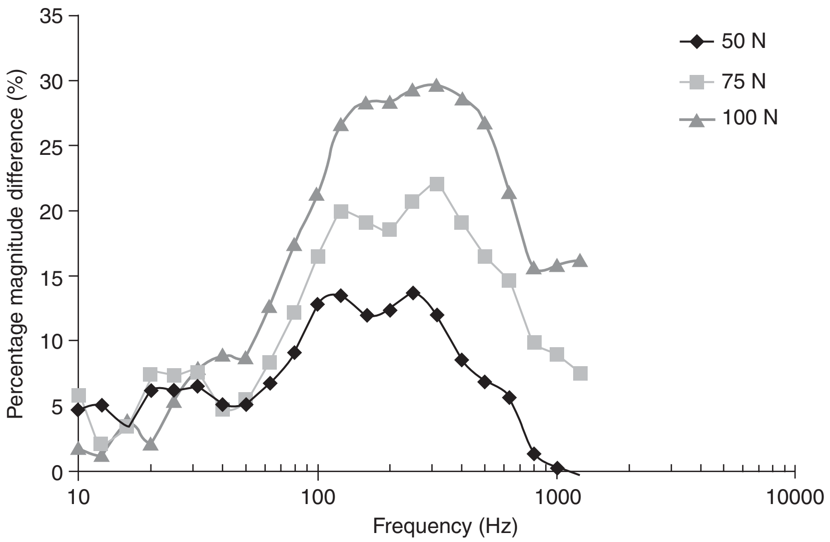

Figure 5 Percentage magnitude difference between the transmissibility values measured with grip-only and push-only actions at the three effective palm forces

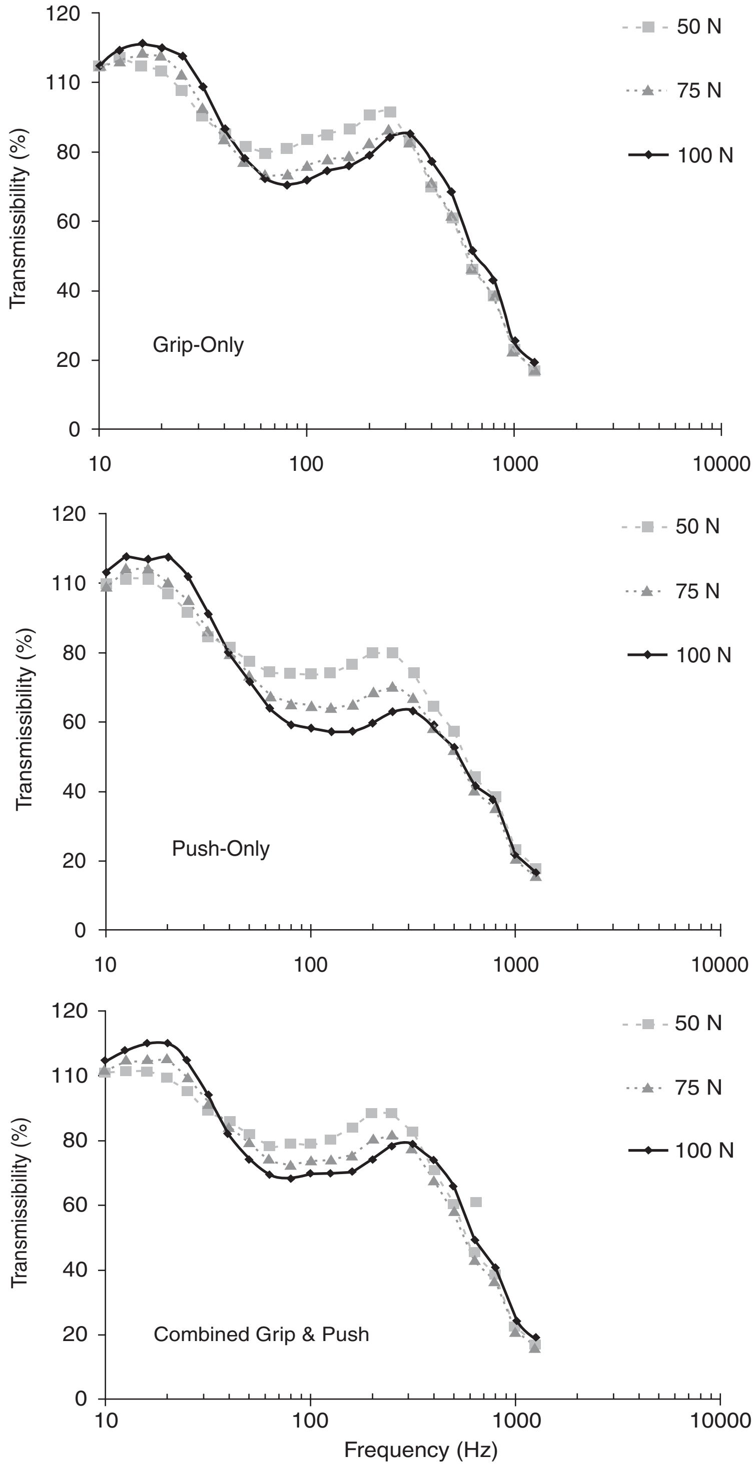

Figure 6 Effect of effective palm force on the transmissibility of the air bladder anti-vibration glove at the three hand-tool coupling actions

depicted in Figure 6 also show that increasing the force tends to increase the resonant frequencies. This is more obvious at the second peak near 250 Hz.

Similar to the coupling action effect, the percentage magnitude difference (PD_c) between the transmissibility values at 50 N (T_{50}) and 100 N (T_{100}) is defined as

$$PD_{cj} = 2 \bullet \left(T_{50j} - T_{100j}\right) / \left(T_{50j} + T_{100j}\right) \bullet 100\% \tag{3}$$

(j = grip-only, push-only, combined grip and push)

Table V. Results of the one-way ANOVA and Tukey's test for identifying the effect of the hand coupling action on the transmissibility at different effective palm forces and frequencies.

	Total Effective Force Acting at the Palm								
	50 N (*I*)			75 N (*II*)			100 N (*III*)		
Freq. (Hz)	F	p	Significant Pair	F	p	Significant Pair	F	p	Significant Pair
10	3.65	0.065		3.23	0.083		1.11	0.368	
12.5	7.64	*	*G-C, G-P*	0.55	0.594		0.76	0.491	
16	3.59	0.067		3.35	0.077		3.32	0.079	
20	11.49	**	*G-C, P-G*	16.82	**	*C-P, P-G*	2.72	0.114	
25	5.55	*	*P-G*	5.64	*	*P-G*	8.32	*	*P-G*
31.5	4.46	*	*P-G*	3.44	0.73		9.07	*	*P-G*
40	4.95	*	*C-P*	1.33	0.308		9.24	*	*C-G, P-G*
50	5.10	*	*C-P, P-G*	3.32	0.078		7.91	*	*G-C, P-G*
63	4.30	*	*P-G*	4.86	*	*C-P*	23.35	**	*C-P, P-G*
80	4.82	*	*P-G*	4.80	*	*P-G*	24.22	**	*C-P, P-G*
100	9.52	*	*P-G*	8.69	*	*C-P, P-G*	25.11	**	*C-P, P-G*
125	16.21	**	*P-G, G-P*	17.92	**	*C-P, P-G*	36.45	**	*C-P, P-G*
160	19.72	**	*C-P, P-G*	19.91	**	*C-P, P-G*	37.45	**	*C-P, P-G*
200	10.30	**	*C-P, P-G*	11.09	**	*C-P, P-G*	41.47	**	*C-P, P-G*
250	13.38	**	*C-P, P-G*	12.99	**	*C-P, P-G*	34.76	**	*C-P, P-G*
315	9.17	*	*C-P, P-G*	19.88	**	*C-P, P-G*	24.05	**	*C-P, P-G*
400	3.19	0.085		13.13	**	*C-P, P-G*	15.64	*	*C-P, P-G*
500	1.09	0.373		11.15	**	*C-P, P-G*	9.63	*	*C-P, P-G*
630	0.61	0.562		7.36	*	*P-G*	6.78	*	*C-P, P-G*
800	0.05	0.954		3.36	0.076		6.32	*	*P-G*
1000	0.07	0.933		1.54	0.261		5.87	*	*P-G*
1250	0.01	0.994		1.03	0.394		5.41	*	*P-G*

Notes: * $p < 0.05$; ** $p < 0.005$; the significant pair column lists the pair IDs where the Tukey tests revealed significantly different means ($p < 0.05$), in which G = grip-only, P = push-only, and C = combined grip and push, as also identified in Table 2.

The results are illustrated in Figure 7. The post hoc analyses of these percentage differences indicate that the magnitude of the difference at the push-only action is generally significantly greater than that at the grip-only action and the combined grip and push action at frequencies higher than 63 Hz. However, the difference between the grip-only and combined grip and push actions is not significant at any frequency. These observations suggest that the effective palm force generally has a more pronounced effect with the push-only action, but similar effects with the grip-only and combined grip and push actions.

3.4 The Correlations between Transmissibility and the Subject Anthropometrics

The results of the ANOVA presented in Table III indicate that the subject is a significant factor that influences the transmissibility. The effect of this factor is shown in Figure 8. It is difficult to establish any correlation between the transmissibility and the hand size listed in Table I. The significant interaction between the subject and the coupling action also suggests that the influence of subject also depends on

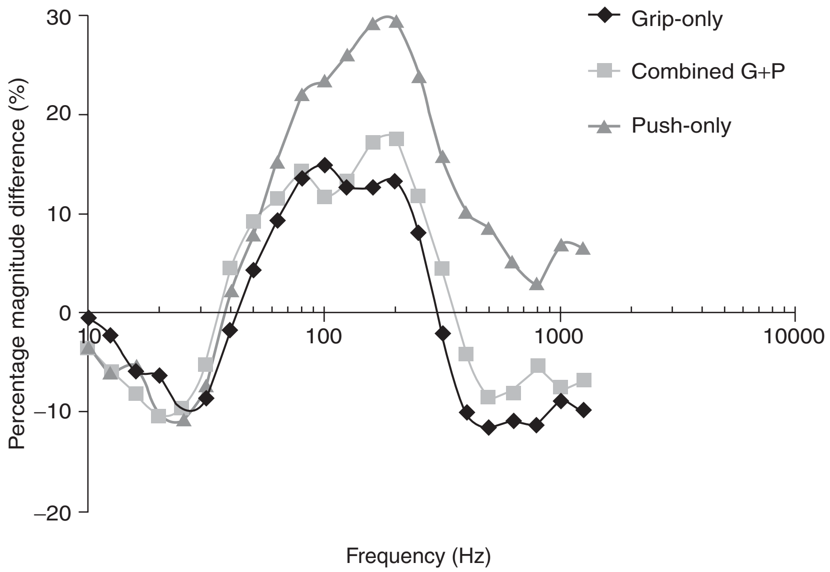

Figure 7 Percentage magnitude difference between the transmissibility values measured at 50 N and 100 N with the three hand-tool coupling actions

the type of coupling action. To explore the individual effect, the correlations between the subjects' anthropometric characteristics and the transmissibility data from the nine different test treatments at each one-third octave-band center frequency were analyzed. The linear correlation coefficients expressed as functions of the frequency are illustrated in Figure 9. For six pairs of data, the linear correlation is considered significant ($p < 0.05$) when Pearson's product-moment coefficient of correlation (r) is greater than 0.81, or suggestively significant ($0.05 \leq p < 0.10$) when the correlation coefficient is between 0.73 and 0.81. Since the body weight and the forearm volume measured in this study are highly correlated to the hand volume ($r = 0.99$, $p < 0.001$), and they have correlation coefficients similar to hand volume, their correlation coefficients are not plotted in the figure for clarification.

As can be seen, in general, none of the anthropometric parameters are reliably correlated to transmissibility in any broad frequency range. Specifically, hand size (represented by the hand length), hand volume, and circumference tend to be negatively correlated to glove transmissibility at a few frequencies in the frequency range of 25 to 50 Hz, which varied with the coupling condition. Hand circumference tends to be positively correlated to the transmissibility in the frequency range of 50 to

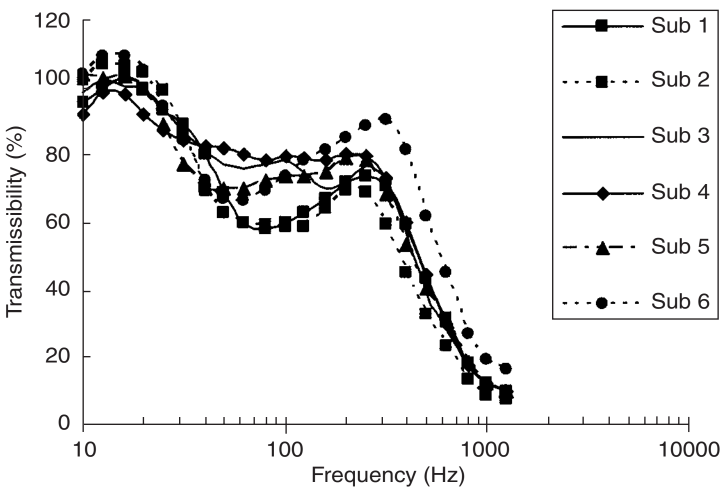

Figure 8 Transmissibility values of the six subjects (each curve represents the average value of nine treatments for each subject)

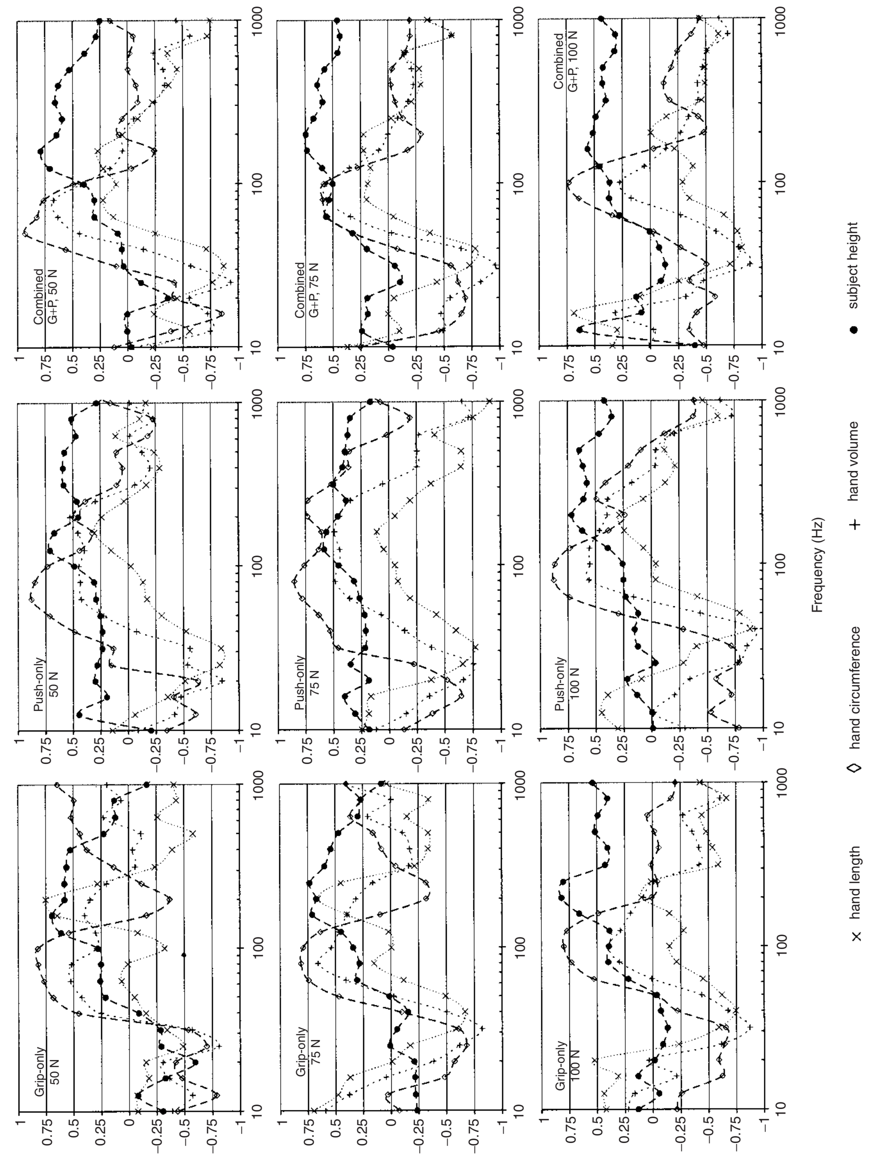

Figure 9 Correlations between transmissibility values and relevant hand anthropometry parameters of the six subjects

Table VI. Examples of tools and their fundamental vibration frequencies

Tool	Fundamental Frequency (Hz)
*Petrol wacker	12.5
Pole scabbler	25
****Rammer	12.5
*Road breaker 1	16
***Road Breaker 2	20
**Chipping hammer 1	25
*Metal drill	25
*Impact wrench	31.5
*Nutrunner	31.5
*Rock drill	40
*Chipping hammer 2	50
*Needle gun	50
*Riveting gun	63
*Dolly w/rivet gun	63
**Grinder	80
*Pn. 7″ vertical grinder	80
*Rand orbital sander	100
*Wire swagin	100
*Elec.9″ angle grinder	100
*Pn. 5″ straight grinder	100
*Non-AV chainsaw	125
*AV chainsaw	200
*Etching pen	200
*Pn. rotary file	200

*Griffin[26]; **Xu et al. [27]; *** Tasker[28]; ****Tominaga[29]

125 Hz, and the correlation at a few frequencies in this range in many treatments is significant or suggestively significant ($r > 0.73$, $p < 0.1$). Subject height, surprisingly, shows a better correlation than any other anthropometric parameter in the high-end middle frequency range (125 to 500 Hz) in the majority of the experimental treatments, although the correlation is not statistically significant at the majority of frequencies.

4. DISCUSSION

The benefit of using anti-vibration gloves depends on the actual effectiveness of the glove and the balance between the merits and the disadvantages such as the increased cost and potential adverse effects (e.g. reduced grip strength, dexterity, and tactility). The transmissibility values presented in this paper can be used to estimate the effectiveness of the air bladder anti-vibration glove when used with specific tools.[9, 10] The results of this study indicate that the glove generally isolates more vibration at high vibration frequencies than at low vibration frequencies. The glove-hand-arm system has a resonance in the frequency range of 10 to 20 Hz, as shown in Figures 3, 4, 6, and 8. Therefore, the glove can not help reduce the vibration generated on low frequency tools such as rammers and road breaker that have the dominant frequencies less than or close to 25 Hz. As also shown in these figures, the glove-hand-arm system has another resonant peak at the neighborhood of 250 Hz. Although this resonance also tends to increase the transmitted vibration, the transmissibility at this frequency is at a significantly reduced level (approximately 80%). This suggests that the glove can help reduce the vibration at this resonant frequency. At high frequencies (>500 Hz), the glove can effectively attenuate the vibration. In a large part of the middle frequency range (25 to 500 Hz), the applied force and coupling action have the most pronounced influences on the effectiveness of the glove. As listed in Table VI, the fundamental/dominant frequencies of many tools[26-29] are in this frequency range. Therefore, it is useful to understand the effects of the force and coupling action on the performance of the glove.

A previous study reported that there was a trend (not statistically reliable) that increase in hand size resulted in increases in glove vibration transmissibility, in which 20 subjects were used.[16] This trend is basically consistent with that observed in the frequency range of 50 to 125 Hz in the current study, in which the hand circumference is reliably or suggestively correlated to the transmissibility in many test treatments (Figure 9). However, both studies suggested that there were generally no statistically significant correlations between the transmissibility and the hand anthropometry in a broad frequency range. This suggests that the hand anthropometry alone may not be sufficient to determine the glove transmissibility.

Theoretically, the glove can be approximately modeled as a spring-damping system and the hand-arm system as a mass-spring-damping system loaded on the glove. The isolation effectiveness of the glove should depend on the dynamic properties of the hand-arm system. The dynamic properties may be affected not only by the hand and arm anthropometry but also by many other individual factors such as the actual combination of the hand and arm tissues (e.g. bone percentage, muscle percentage, et al), the biomechanical properties (mass, stiffness, and damping) of the tissues, and the hand-handle contact condition. The biodynamic response such as apparent/effective mass and mechanical impedance of hand-arm system may be used to represent the overall effect of these factors. It is anticipated that the biodynamic response may have some association with the glove transmissibility.

Increasing the applied force increases the hand-arm system stiffness, especially the palm contact stiffness. The increased force also increases the glove stiffness. The changes of these stiffness values can result in mixed effects. Theoretically, higher system stiffness should correspond to a higher resonant frequency and a higher transmissibility. This holds true in the relatively low frequency range, as shown in Figure 6. However, the transmissibility in the middle frequency range is reduced, as also shown in Figure 6. This may be because the increased hand-arm system stiffness may also increase the effective mass of the system that may play a more dominant role in determining the transmissibility.

The effects of the coupling action can also be explained using the effective mass concept. The push-only action requires more arm force than the grip-only action does. The increased arm force may increase the stiffness of the wrist and arm joints such that a higher effective mass is seen at the palm driving point. As a result, the higher effective mass in the push-only action reduces the transmissibility or increases the effectiveness of the glove.

The results of this study revealed that varying the hand coupling action did not alter the basic trends of the glove transmissibility as a function of frequency, as shown in Figure 3, but only affected the transmissibility magnitude, as shown in Figure 4. This suggests that it may not be necessary to use a combined grip and push action during glove evaluations if the sole purpose of the test is glove screening. For convenience and cost savings, either the grip-only action or the push-only action can be used as the standard grip action for glove screening tests. The major difference between the two is that at the same force level, the grip-only action would likely produce conservative transmissibility values, while the push-only action would result in overestimations of glove effectiveness. These observations support the use of the push-only action in the standardized glove test, which was proposed in a previous study.[15] It is, however, difficult to maintain a consistent hand grip posture and the force applied at the palm in the test without applying the grip action, as experienced in the present study. Hence, it is desired to continue the combined grip and push action in the standard glove test.

This study observed that there was great inter-subject variation in the transmissibility data, especially in the frequency range of 31.5 to 630 Hz, as shown in Figure 8. This phenomenon was also observed in a few other studies.(15, 16) This means that anti-vibration gloves may provide more protection for some people than for others or the effectiveness of an anti-vibration glove is individual-specific. This may be one of the reasons that large differences have been observed among the data obtained from different subjects in different laboratories during round robin testing.(19) In the current ISO standard,(7) only three subjects with hand sizes in the range of 7 to 9 (EN 420)(21) are required to perform the test. Such a number of subjects may not be sufficient to account for the effects of the individual differences on the measurement of glove transmissibility.

5. CONCLUSIONS

Based on the results and observations of this study, a few conclusions are drawn as follows:

- The vibration isolation effectiveness of the air bladder anti-vibration glove measured at the palm of the hand generally increases with the vibration frequency. This type of glove, however, cannot reduce vibration at frequencies equal to or lower than 25 Hz. This suggests that the glove cannot provide effective vibration isolation for the dominant vibrations of low frequency tools. An approach to reduce the low frequency vibration exposure is to grip the tool as lightly as possible, provided that this is consistent with safety work practice and tool control.
- The glove is more effective with a push-only action, less effective with a grip-only action, and in the middle with the combined action. The most pronounced divergence is in the middle frequencies from 63 Hz to 350 Hz. In the force range used in this study (50-100 N), increasing the force generally increases the difference.
- At the same hand-tool coupling action, increasing the force within the range used in this study generally increased the transmissibility in the low frequency range (< 31.5 Hz), but it decreased the transmissibility in a large middle frequency range (63 to 250 Hz). The major force effect can also be found in the middle frequency range, and this effect is most sensitive with the push-only action.
- The effectiveness of the glove is also individual-specific. However, there were generally no statistically significant correlations between the transmissibility and the anthropometry in a broad frequency range. Additional studies may be required to further clarify this conclusion and to understand the individual effects.

DISCLAIMER

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 U.S. Government.

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