Industrial Health 2005, **43**, 241–255 **Original Article**

Biodynamic Response at the Palm of the Human Hand Subjected to a Random Vibration

Ren G. DONG[1], Thomas W. McDOWELL[1] and Daniel E. WELCOME[1]

[1] Engineering & Control Technology Branch, National Institute for Occupational Safety and Health, 1095 Willowdale Road, Morgantown, West Virginia 26505, USA

Received March 1, 2004 and accepted November 1, 2004

Abstract: This study investigated the biodynamic response (BR) distributed at the palm of the hand subjected to a random vibration. Twelve male subjects were used in the experiment. Each subject applied three coupling actions (grip-only, push-only, and combined grip and push) on a simulated tool handle at three different levels (50, 75, and 100 N) of palm force. This study found that the hand-arm system resonated mostly in the frequency range of 20 to 50 Hz, depending on the specific test treatment and individual characteristics. The maximum vibration power transmission through the palm occurred at the resonant frequency. Increasing the effective palm force generally increased the BR magnitude and resonant frequency. The apparent stiffness measured at the middle frequencies (80–100 Hz) is correlated to the BR in almost the entire frequency range (20–1,000 Hz). Under the same palm force, the push-only action corresponded to the highest BR values while the grip-only action generally produced the lowest values. Since the resonant frequency range matches the dominant vibration frequency range of many percussive tools, it is anticipated that the palm BR and vibration power transmission may have an association with vibration-induced injuries or disorders in the wrist-arm system among the workers using these tools.

Key words: Hand-arm vibration syndrome, Hand-arm vibration, Hand-transmitted vibration, Mechanical impedance, Vibration power absorption

Introduction

Vibrating hand tools and machines such as chipping hammers, road breakers, rock drills, and grinders are widely used in many industrial settings. Users of these tools or machines may experience tingling and numbness, the severity of which usually increases with the magnitude of the vibration generated by the tool. Such acute effects may cause discomfort and lead to loss of control of the tool in severe vibration situations. These acute effects usually disappear in a short period of time following tool use. However, prolonged, intensive exposure to hand-transmitted vibration has been associated with a series of disorders in the vascular, sensorineural, and musculoskeletal structures of the human hand-arm system, which has been collectively called hand-arm vibration syndrome (HAVS)[1–3]. There is a growing demand to protect people from the risks of HAVS, as evidenced from the recent approval and implementation of a European Union (EU) vibration directive[4].

Any vibration-induced injuries or disorders must be associated with vibration actually transmitted to the hand-arm system. Therefore, it is important to understand the transmission of vibration from a tool handle to the hands in interaction with the tool. As an effective and practical approach, the biodynamic response (BR) such as the apparent mass (*AM*), mechanical impedance (*MI*) or apparent stiffness (*AS*) at the hand driving point has been used to investigate the vibration transmission. Knowledge of the BR permits estimation of the vibration power absorbed in the hand-arm system[5], which may be associated with the etiologies of vibration-induced injuries[6–8]. The BR has also been used to develop power tools with less vibration and anti-vibration

*To whom correspondence should be addressed.

devices[9–11]. Furthermore, the BR can also be used to estimate the effectiveness of anti-vibration gloves[12–13].

Probably for these reasons, the biodynamic responses of the human hand-arm system have been extensively studied, and a considerable number of publications can be found in the literature[14–21]. More references can be found in the reviews by Gurram *et al.*[22] and Dong *et al.*[23]. Based on some of the previously reported studies, the International Organisation for Standardization (ISO) has set forth a standard (ISO 10068 1998)[24], in which the standard values of the MI and several biodynamic models are recommended. In these studies and the ISO standard, the BR was determined by measuring the vibration motion and the total response dynamic force at the hand driving point. The BR measured with such an approach represents the response for the entire hand-arm system, which is referred to as the total BR in the present study.

Depending on the frequency characteristics, vibration generated from different tools can be transmitted to different parts of the hand-arm system[25, 26], and may cause various problems at these different locations[2, 3, 27]. It has been reported that the nature of the vibration power transmitted to the palm is much different from that into the fingers[28] and that the mechanical impedance distributed at the fingers is very different from that at the palm of the hand[29]. Because of the exposure variations and the biological structure differences, the pathologic mechanisms of the disorders in the fingers may be quite different from those of the bones, joints, and muscles in the wrist-arm system[30, 31]. Therefore, they should be treated differently in their studies. While the vibration power transmission measured at the fingers may be more closely associated with vibration-induced finger disorders such as vibration white finger, the vibration power transmission measured at the palm may have a better correlation with the disorders in the wrist-arm system. Furthermore, due to the biodynamic response differences, an anti-vibration device that is effective at protecting the wrist and arm may not be effective at protecting the fingers. Therefore, knowledge of the BR distribution at the fingers and the palm of the hand may effectively enhance the understanding of the biodynamic features of the hand-arm system. Such knowledge may also be useful for developing location- or disorder-specific risk assessment methods and vibration type-specific anti-vibration devices.

While the BR of the entire hand-arm system has been extensively investigated[22, 23] and the BRs of the fingers and fingertips have also been reported in a few studies[32–34], only one study reported some information on the mechanical impedance distributed at the palm[29]. Therefore, the palm BR has not been sufficiently studied. Based on this background, the specific aims of the present study are as follows: (i) to quantify and characterize the BR distributed at the palm of the hand subjected to a random vibration; (ii) to determine the effects of the hand-tool coupling action (grip, push, and combined grip and push) and the applied effective palm force on the palm BR; (iii) to examine the vibration power transmission to the hand-arm system through the palm; and (iv) to explore the correlation between anthropometrics and the palm BR.

Materials and Methods

Theory

The three frequently used BR parameters (apparent mass, mechanical impedance, and apparent stiffness) are conventionally defined as

$$AM = \frac{\tilde{F}}{\tilde{A}} \qquad MI = \frac{\tilde{F}}{\tilde{V}} \qquad \mathrm{AS} = \frac{\tilde{F}}{\tilde{D}} \tag{1}$$

where $\tilde{F}$, $\tilde{A}$, $\tilde{V}$, and $\tilde{D}$ are the dynamic force, acceleration, velocity, and displacement at the hand-handle interface, respectively. In the frequency domain, each of the BR parameters defined in equation (1) can be obtained by performing a transfer function or transmissibility-like calculation. Specifically, they can be computed from:

$$Z(\omega) = \frac{G_{fm}(\omega)}{G_{mm}(\omega)} \tag{2}$$

where ω is vibration frequency in rad/s, $Z(\omega)$ represents either of the BRs, G_{fm} is the cross-spectrum of force and dynamic motion (either acceleration for *AM*, velocity for *MI*, or displacement for *AS*), and G_{mm} is the auto-spectrum of the motion.

Another important BR that has been frequently used in the study of hand-transmitted vibration is the vibration energy/power transmission (*VPT*) from a tool handle to a hand. It is defined as

$$VPT = \tilde{F} \cdot \tilde{V} \tag{3}$$

All four of these biodynamic response parameters are generally complex, that is, each of them possess real and imaginary components in the frequency domain, and they can be generally expressed as

$$Z(\omega) = Z_R(\omega) + Z_I(\omega)\, j \tag{4}$$

where $Z_R(\omega)$ and $Z_I(\omega)$ are the real and imaginary components, respectively, and $j = \sqrt{-1}$. These response parameters reflect different physical characteristics (dynamic

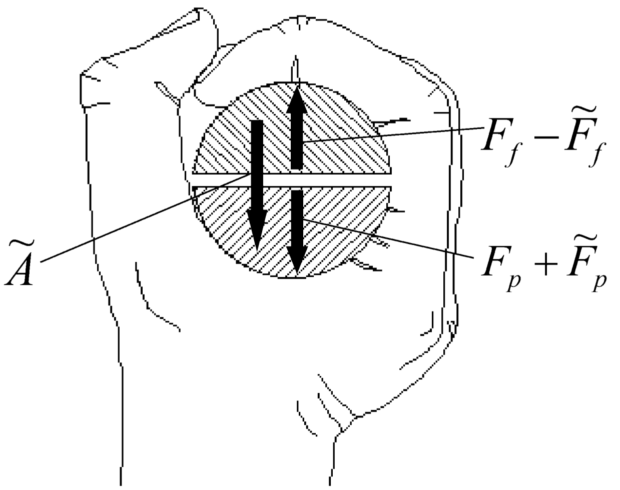


Fig. 1. Dynamic forces and acceleration at the interfaces between the fingers and the handle and between the palm and the handle as viewed from above.

F_f = static grip force on the fingers; F_p = static grip force on the palm; $\tilde{F}_f$ = vibrating force acting on the fingers; and $\tilde{F}_p$ = vibrating force on the palm; and $\tilde{A}$ = handle vibration acceleration.

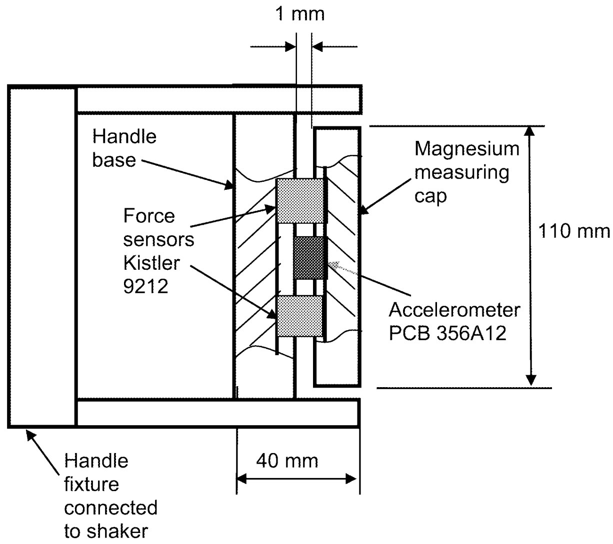


Fig. 2. The instrumented handle used for separate measurements of the biodynamic responses of the fingers and of the palm of the hand.

mass, damping, and stiffness) of the system. The real part of *VPT* is frequently called vibration power absorption (*VPA*). Each of them, however, can be derived from one another. For example, if the AM is directly measured, the MI, AS, and VPT can be simply calculated using the following formulas:

$$MI\ (\omega) = AM\ (\omega) \cdot j\omega,$$
$$AS = AM\ (\omega) \cdot (j\omega)^2,$$
$$VPT\ (\omega) = AM\ (\omega) \cdot j\omega / \tilde{V}(\omega) /^2 \quad (5)$$

Cylindrical handles are frequently used on powered hand tools and such handles are simulated in this study. As conceptually sketched in Fig. 1, a tool cylindrical handle can be virtually evenly split into two parts at the centreline. In a hand power grip that is most frequently used in operating a vibrating tool, the total vibrating force acting on the hand, $\tilde{F}$, can be considered as the sum of the two components acting on the fingers ($\tilde{F}_f$) and the palm ($\tilde{F}_p$)[28, 29], which can be expressed as follows:

$$\tilde{F} = \tilde{F}_f + \tilde{F}_p \quad (6)$$

If the handle is sufficiently rigid, the vibration at the handle-finger and handle-palm interfaces can be considered the same. Replacing the dynamic force ($\tilde{F}$) in Eqs.(1) and (3) with that in Eq. (6), the total BR of the human hand-arm system at the hand driving point can be divided into the BR components distributed at the palm (Z_p) and the BR at the fingers (Z_f)[28, 29] such that:

$$Z = Z_p + Z_f \quad (7)$$

Apparatus

A special instrumented handle for separately measuring the finger and palm BR components was developed in previous studies[28, 29] and it was used in this study to measure the palm BR. Briefly, the handle consists of a measuring cap and a handle base with two force transducers sandwiched between the cap and base, as illustrated in Fig. 2. For the palm BR measurement, the palm is in contact with the measuring cap while the fingers grip on the handle base. An accelerometer is fixed on the measuring cap to measure the vibration for the BR evaluation.

The mass of the measuring cap can also generate inertia force, which is included in the force measured on the force transducers. Therefore, the dynamic response directly measured with this instrumented handle is the combination of the response of the measuring cap and the response of the palm-wrist-arm system. To obtain the true response, the effect of the measuring cap must be eliminated. The cap effective mass is the sum of the masses of the measuring cap, the accelerometer, the connecting screws, and a portion of that of the force sensors. The cap response was measured in an empty handle test (without hand coupling)[29] before and after the tests for each subject. Then, the effect of the cap mass was cancelled using the following formula[29]:

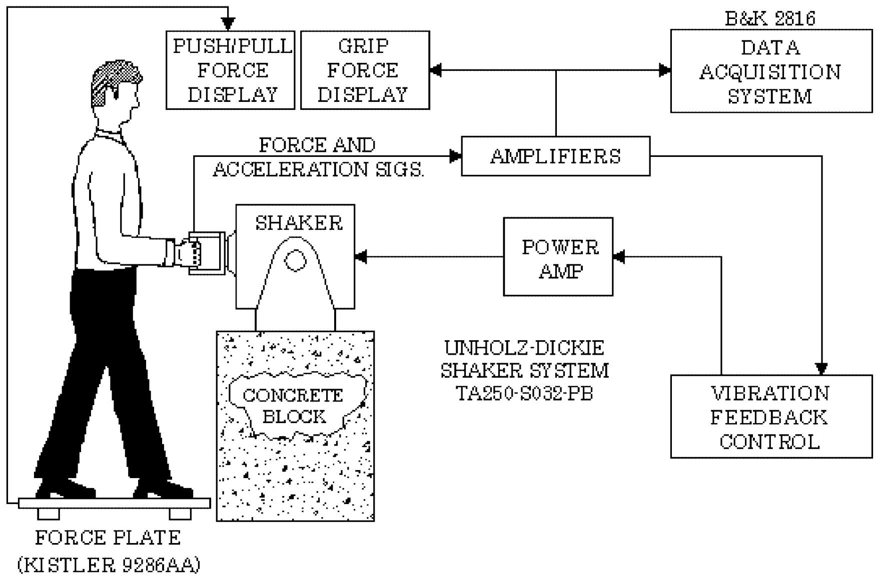


Fig. 3. Subject posture and measurement setup that includes a closed-loop controlled vibration.

$$Z_p(\omega) = Z_{combined}(\omega) - Z_{Cap}(\omega) \quad (8)$$

where $Z_{Combined}$ is the combined system response directly measured in a subject test, Z_{Cap} is the handle measuring cap response.

Figure 3 shows the experimental setup used in this study. The push force acting on the handle was measured using a force plate (Kistler 9286AA) and displayed as a strip chart on a computer monitor. As conventionally defined in ISO 10819 (1996)[35], the grip force in the grip-only action is actually the quasi-static component of the force measured with the two force sensors depicted in Fig. 2. The measured force signal was thus branched to a low-pass filter with a 5 Hz cut-off frequency to derive the grip force. A custom programme was developed using LabVIEW software (National Instruments, version 5.1) to display the grip force. The grip force was displayed on a separate computer monitor as a strip chart, which served as feedback for the test subjects. When the push action was applied, the grip force was determined by subtracting the push force from that measured with the force sensors on the handle. The force plate measurement was verified using the instrumented handle in the push-only action.

Test conditions and study variables

A broadband random vibration in the frequency range of 10 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 16–1,000 Hz was used as excitation in the experiment[34]. The BR was computed according to equation (2) using the programme built in the data acquisition system (B&K 2816, Denmark), and the results are expressed at the one-third octave band centre frequencies from 10 to 1,000 Hz.

The test posture required in the ISO standardized glove test specified in ISO 10819 (1996)[35] was used in the present study, which is also shown in Fig. 3. With this posture, the BR measured in this study is in the Z_h-direction of the hand biodynamic coordinate system[36], which is usually the most severe vibration exposure direction for the palm-wrist-arm system in the operation of most power hand tools.

In general tool operation, a combined push and grip action on the tool handle is most frequently used. The grip-only and push-only may represent two extreme coupling actions. Therefore, these three coupling actions were considered in this study. To cover an ample range of hand coupling forces, three levels (50 N, 75 N, and 100 N) of the effective force acting at the palm were used in this study. These two study variables form a 3 × 3 test matrix or nine test treatments, as summarized in Table 1.

Subjects and Experimental Procedures

Twelve male volunteers from a local university participated in the experiment. The right hand was used for the test. Some individual anthropometrics were measured for each subject and are presented in Table 2. The test subjects wore casual clothing during the experiment. The subjects first underwent an explanation of the test procedure and signed a consent form. To assure the consistency of the hand grip

Table 1. Experimental treatments

Coupling Action	Total Effective Forces Acting at the Palm		
Grip-only	50 N	75 N	100 N
Push-only	50 N	75 N	100 N
Combined grip and push	50 N (15 N grip + 35 N push)	75 N (30 N grip + 45 N push)	100 N (50 N grip + 50 N push)

Table 2. Subject anthropometry

Subject	Height (cm)	Weight (kg)	Hand Length (mm)	Hand Breadth (mm)	Circumference (mm)	Hand Volume (ml)	Hand & Forearm Volume (ml)
1	175.3	69.5	185	88	215	360	1370
2	177.8	83.0	197	93	215	406	1648
3	185.4	90.7	192	97	235	440	1723
4	175.3	132.5	207	101	236	550	2352
5	185.4	83.5	196	95	218	420	1680
6	175.3	100.2	184	103	250	445	1830
7	177.8	86.2	203	97	240	440	1785
8	185.4	66.2	197	93	206	350	1290
9	185.4	96.6	200	101	231	445	2210
10	175.3	77.1	190	85	205	375	1510
11	162.6	61.2	180	80	190	295	1075
12	198.1	152.4	205	107	254	550	2550
Mean	179.9	91.6	195	95	225	423	1752
SD	8.8	26.8	9	8	20	75	438

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.

position around the handle for all the trials and among the subjects, a short section of a first-aid bandage was placed on the back of the index finger of the subject. A line was marked on the bandage in line with the crease at the base of the subject's third proximal phalange, which served as a reference for aligning the hand with the handle in the subsequent trials. Each subject was advised to stand on the force plate adjusted to an appropriate height, and to grip the vibrating handle with the alignment mark in line with the handle-splitting line. Once the grip posture and position were set, an investigator advised the subject to perform a specific hand-handle coupling. The sequence of the nine test combinations was randomized among the subjects. When the coupling action was stable at the required force level, the investigator recorded the test data for a period of 30 s. The subject was then advised to relax for one minute. Two trials were sequentially completed for each combination.

Data analysis

The BR data were evaluated by a three-factor-repeated-measures analysis-of-variance (ANOVA). The effect of the vibration exposure frequency was defined as the first factor, the second factor was the influence of the applied effective palm force, and the third factor was the hand coupling action. The ANOVA was performed using a conventional mixed model with frequency, palm force, and hand action as fixed effects and subject as a random effect. Upon recognizing that the interactions among all the fixed factors were generally significant, as presented in the next section, a stratified ANOVA for the data at each one-third octave band center frequency was performed to further identify the influences of these factors on the BR. Post hoc comparisons were also made using the Tukey method to identify the effects of each coupling action and force level.

Linear correlation analyses were also performed to evaluate the associations between the resonant frequencies of the MI and the AS at a critical frequency found in this study, and those between the BR and the anthropometrics of the subjects. Paired t-tests were also used in several special cases to determine the significance of the difference between a target

Table 3. A summary of the ANOVA results

Source	Df	*AM*		*MI*		*AS*		*MI Phase Angle*	
		F	p	F	p	F	p	F	p
Frequency	20	175.28	<0.001	44.48	<0.001	484.24	<0.001	124.20	<0.001
Force	2	146.60	<0.001	338.69	<0.001	188.00	<0.001	0.76	0.478
Coupling	2	21.97	<0.001	55.59	<0.001	14.55	<0.001	13.58	<0.001
Freq*Coup	40	6.31	<0.001	12.34	<0.001	5.08	<0.001	13.90	<0.001
Freq*Force	40	28.14	<0.001	27.47	<0.001	19.62	<0.001	34.62	<0.001
Force*Coup	4	2.21	0.084	4.52	0.004	1.61	0.190	3.94	0.008
Freq*Force*Coup	80	1.58	0.001	3.88	<0.001	1.27	0.061	2.41	<0.001

value and the mean of the measured data. The differences were considered significant at $p<0.05$. All statistical analyses were performed using MINITAB statistical software (Version 13.1).

Results

The *MI* values calculated from the *AM* data using equation (5) were compared with those directly measured in the experiment. The comparison showed that they were almost identical. This provided a confirmation on the validity of the theory, the instrumentation, and the programme used in this study. Therefore, the *AS* and *VPA* values presented in this paper were calculated from equation (5) using the measured *AM* values. Because the phase angles of AM and AS are simply a subtraction or addition of 90° from that of the *MI*, they are not presented.

The ANOVA results are summarized in Table 3. Except for the force-by-coupling interaction of the AS, all the interactions are either significant ($p<0.05$) or suggestively so ($p<0.10$). Therefore, the influences of the force and coupling condition on the BR are generally functions of the frequency.

Effects of the vibration frequency

Figure 4 illustrates the overall average BR values of the nine test combinations for all the subjects. As can be seen in Fig. 4 (a), the *AM* reaches its peak value at 12.5 Hz. The *AM* values generally decrease with an increase in the frequency. The rate-of-change for the *AM* remains steep in the frequency range of 12.5 Hz to 31.5 Hz, but it gradually decreases to a low level at about 100 Hz. At 250 Hz, the mean *AM* is 64 g and the mean *AM* is only 31.8g At 1,000 Hz.

The measured *MI* magnitude and phase angle as functions of frequency are illustrated in Figs. 4 (b) and 4 (d), together with the low limits, mean values, and high limits of the MI values recommended in the current ISO 10068 (1998)[24] (Note: only the values from 10 Hz to 500 Hz are provided in the standard). As can be seen, the measured MI magnitude has a resonant peak at 31.5 Hz.

Below this fundamental resonant frequency, the *MI* values suggest a mass-like characteristic, but at higher frequencies up to approximately 160 Hz, a spring-like characteristic is indicated. The magnitude bottoms out at about 250 Hz. From this point, it increases with an increase in frequency. As can also be seen, the palm *MI* is fairly comparable to the ISO mean value of the total *MI* for the entire hand-arm system from 12.5 Hz to 100 Hz, although there is about 8 Hz difference between their fundamental resonant frequencies. At frequencies above 125 Hz, however, the palm MI is significantly lower than the ISO low limit (*t*-test, $p<0.001$).

As shown in Fig. 4(d), the basic shape of the phase angle obtained in this study is similar to that presented in the ISO standard for the entire hand-arm system. The phase value is also very similar to that in the ISO standard at frequencies up to 31.5 Hz and is within the ISO limits up to 100 Hz. Beyond 100 Hz, it dips lower than the ISO low limit in the frequency range of 125 to 250 Hz, and returns to within the ISO limits at higher frequencies.

As shown in Fig. 4 (c), the *AS* increases with vibration frequency. Unlike the *AM* and *MI*, the *AS* has a relatively low rate-of-change in the middle-frequency range (40 to 250 Hz), with the lowest rate between 80–100 Hz.

Figures 4 (e) and 4 (f) show the vibration power transmission calculated from the *MI* data using equation (5). A constant-velocity (10 mm/s) vibration is assumed in this case, which is a simulation of the frequency-weighting specified in the current ISO 5349-1 (2001)[36] for vibration exposure risk assessment. While the real part of VPT (or VPA) represents the power absorbed by the hand-arm system, the imaginary part reflects the combination of the kinetic (mass) and potential (spring) power to the system. As shown in Fig. 4(e), the maximum *VPA* at the palm of the hand occurs at approximately at 31.5 Hz, which corresponds to the *MI* resonant frequency. At this resonant frequency, the imaginary

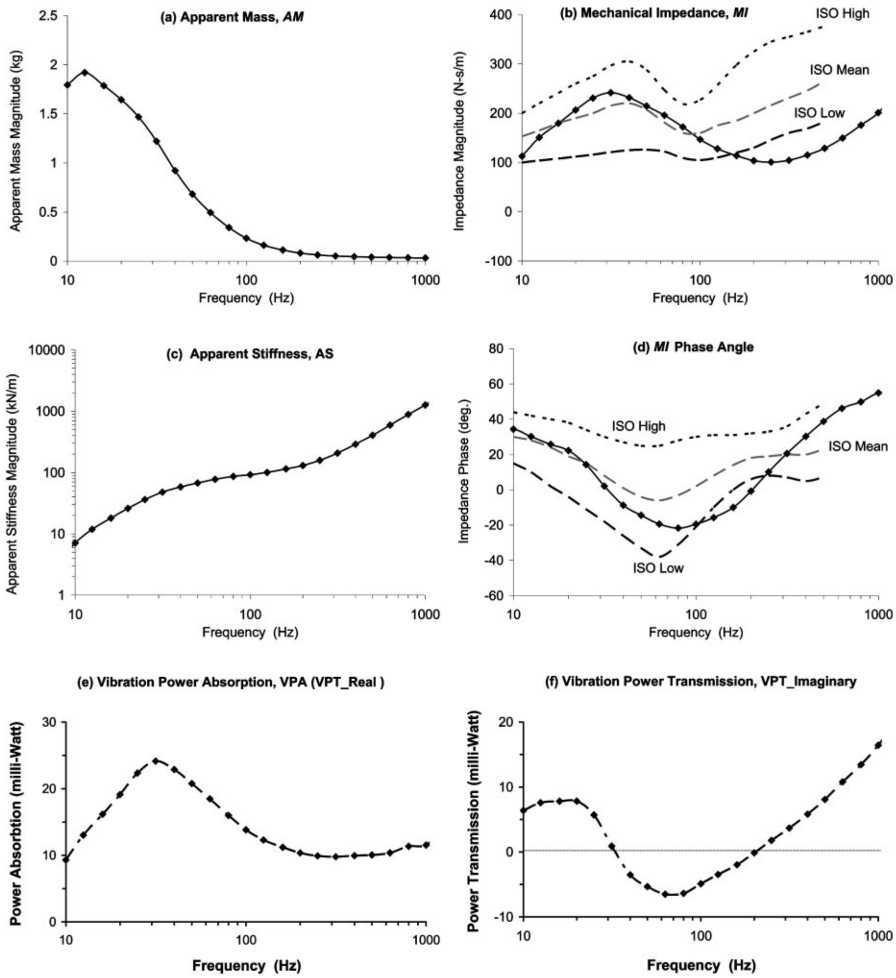


Fig. 4. Effects of vibration frequency on the biodynamic responses.
(a) apparent mass, AM; (b) mechanical impedance, MI; (c) apparent stiffness, AS; (d) MI phase angle; (e) vibration power absorption, VPA (real part of vibration power transmission); and (f) imaginary part of vibration power transmission, VPT_imaginary.

VPT is close to zero. At frequencies above 160 Hz, while the system shows more mass response characteristics, the *VPA* remains relatively unchanged.

Effects of the applied palm force

The effects of the palm force on the biodynamic responses at different frequencies are illustrated in Fig. 5. The results show that increasing the force level increases the magnitudes of the responses at all frequencies. The post hoc results also indicate that the palm force level effects are significantly different ($p<0.05$) throughout the entire frequency range, except for 75 N versus 100 N at two frequencies (10 and 1,000 Hz).

The data analysis also revealed a significant force-by-frequency interaction in the magnitudes of all the BR parameters, as shown in Table 3. To further investigate this interaction, the percentage difference (=difference/mean value) of the responses measured at different forces were calculated, and the results are plotted in Fig. 6. Because the three BR parameters differ from each other by a constant at each frequency (refer to equation 5), the constant is cancelled when the percentage difference is evaluated. Therefore, the data in Fig. 6 applies to all the BR measures. This figure shows that the percentage differences in the middle-frequency range (25 Hz to 250 Hz) are larger than those at the low and high frequencies (*t*-test, $p < 0.05$). It is also interesting to note that a nearly constant high level of percentage difference occurs between 40 Hz and 160 Hz, as can also be seen in the figure.

According to the ANOVA results presented in Table 3, there are significant interaction effects on MI phase angle between frequency and coupling ($F_{40,440}=13.90$, $p<0.001$) and

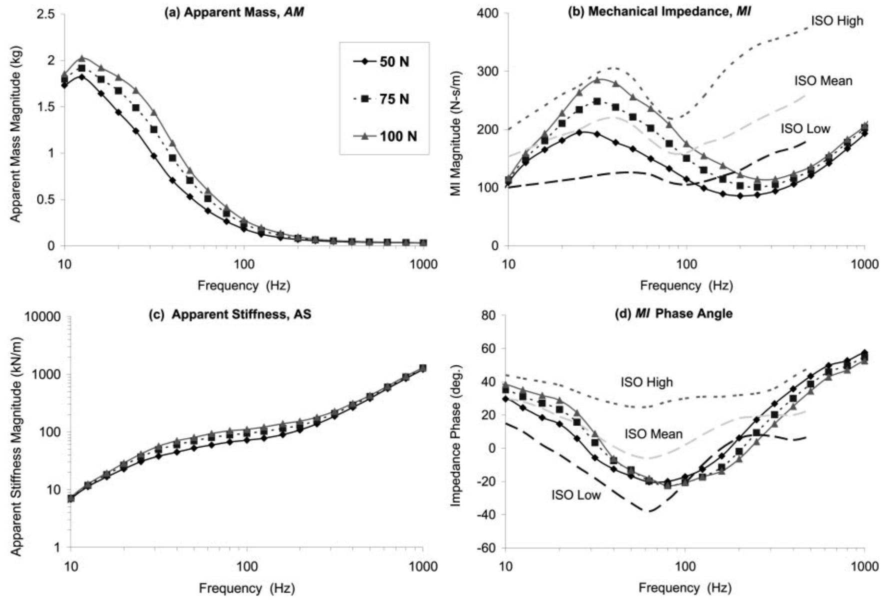


Fig. 5. Influence of the effective palm force on the biodynamic responses.
(a) apparent mass, AM; (b) mechanical impedance, MI; (c) apparent stiffness, AS; and (d) phase angle.

between frequency and force ($F_{40,440}$=34.62, p<0.001). The post-hoc analyses reveal that the phase angles of the responses at the three force levels are significantly different (p≤0.021) at frequencies below 40 Hz and above 160 Hz. A higher force seems to cause a right-hand shift of the phase angle. As can be seen in Fig. 5 (b), increasing the palm force also generally increases the *MI* resonant frequency. It is also interesting to note that the mean values of both magnitude and phase responses at the three force levels are all within the ISO limits at frequencies below 125 Hz.

Effects of the coupling action

The effects of the hand-handle coupling action on the biodynamic responses are plotted in Fig. 7. The results show that the push-only action generally corresponds to the highest level of response and the grip-only action to the lowest level for all responses. The post hoc analyses reveal that the differences between the push-only and grip-only actions are significant (p<0.05) except at a few frequencies (10, 25, 250, 800, and 1,000 Hz). The difference between the grip-only and the combined grip and push action and that between the push-only and the combined grip and push are generally significant (p<0.05) in the middle frequencies (50 Hz to 200 Hz). The mean values of the responses at the three coupling actions are also within the ISO limits at frequencies below 125 Hz.

Figure 8 shows the percentage differences of the biodynamic responses at the three coupling actions. Similar

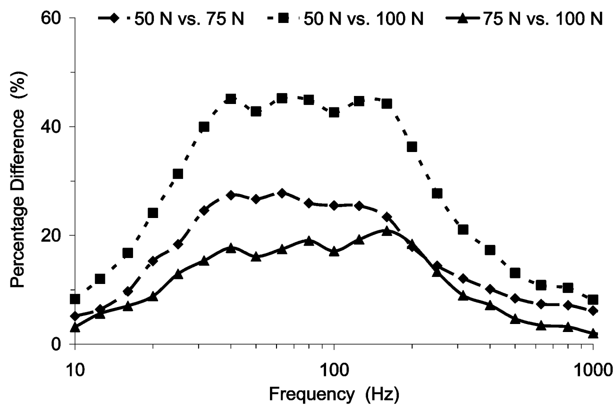


Fig. 6. Percentage differences between the biodynamic responses at the three effective palm forces: 50 N, 75 N and 100 N.

to the force effects, relatively large differences are also found in the middle frequencies (50 to 125 Hz). However, the frequency range is somewhat smaller, and the magnitudes of the response differences are not as pronounced as those produced by the force effects.

At the majority of the frequencies, the phase angles associated with each of the coupling actions are significantly different. At frequencies above 250 Hz, however, the post hoc analyses reveal that the differences between the grip-only and the push-only, and those between the grip-only and the combined grip and push are generally not significant (p>0.05).

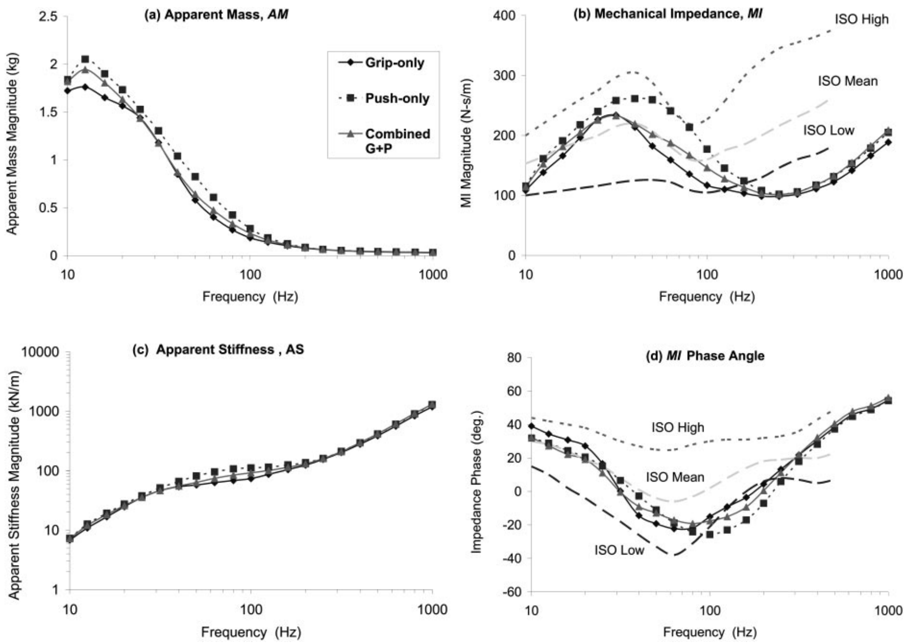


Fig. 7. Effects of the hand-handle coupling action on the biodynamic responses.
(a) apparent mass, AM; (b) mechanical impedance, MI; (c) apparent stiffness, AS; and (d) phase angle.

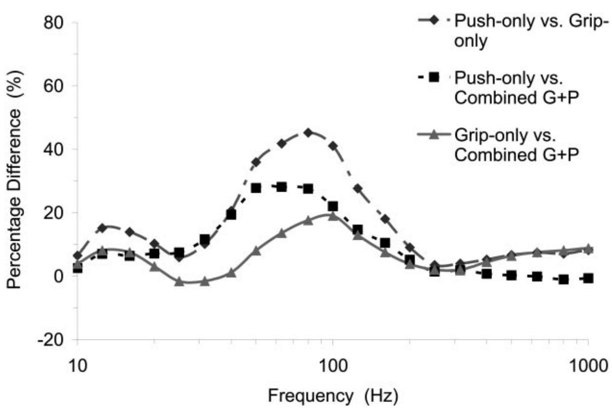


Fig. 8. Percentage differences between the biodynamic responses at the three hand-handle coupling actions: grip-only, push-only and combined grip and push.

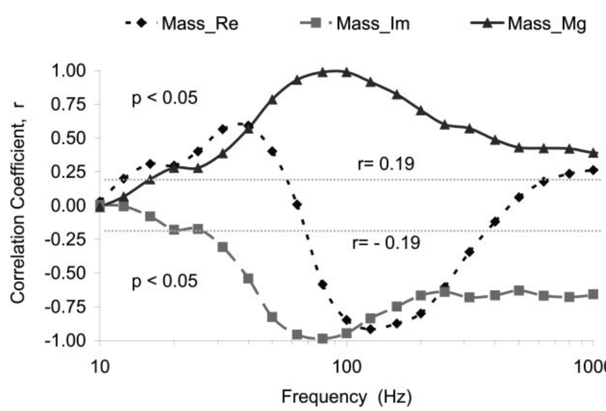


Fig. 9. Correlations between the apparent mass (real, imaginary and magnitude) and the apparent stiffness magnitude in the middle frequencies (the mean of the AS values between 80 and 100 Hz).

The roles of the apparent stiffness in the middle frequencies (80–100 Hz)

The above observations suggest that the dynamic responses in the middle frequencies are more sensitive to the two main influencing factors (applied force and coupling action). The apparent stiffness exhibits its smallest rate-of-change with respect to frequency in the range between 80 and 100 Hz. This stiffness is correlated to the apparent mass in a broad frequency range (20 to 1,000 Hz), as shown in Fig. 9. There are 108 (9 × 12) pairs of data at each frequency for these correlation calculations. With this size dataset, any *r*-value greater than 0.19 is significant ($p<0.05$). Further analyses reveal that the middle-frequency *AS* values are highly correlated to the *MI* resonant frequency values, as shown in Fig. 10.

Inter-subject difference

The responses from each subject are plotted in Fig. 11. For clarification, the subject ID legends are shown in Fig. 11(a). As can be seen, different subjects generally have

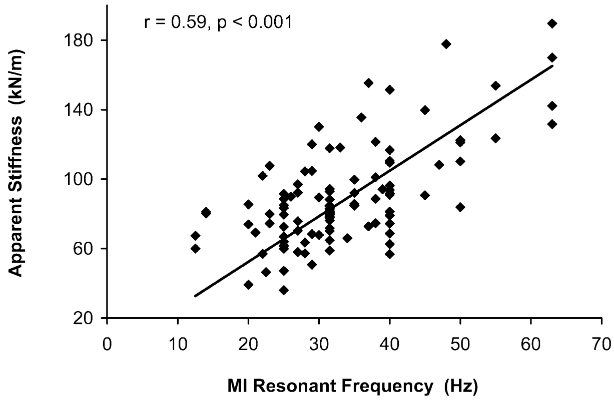


Fig. 10. The correlation between the fundamental resonant frequency of the MI and the middle-frequency stiffness (the average value of the AS values between 80 and 100 Hz).

different BR values and MI resonant frequencies. The AM differences among the subjects generally decrease with an increase in frequency. For example, at 10 Hz, the maximum inter-subject difference is 1,757 g; at 100 Hz, it becomes 107 g; at 1,000 Hz, the maximum inter-subject difference is only 5 g. The maximum percentage difference (= max. difference/mean) also decreases with an increase in frequency, which is 98.4% at 10 Hz, 45.9% at 100 Hz, and 15.7% at 1,000 Hz. Such percentage differences also apply to the MI and the AS for the above mentioned reason (refer to equation 5).

As can be seen in Fig. 11 (b) and 11 (d), the majority of the individual *MI* data are within the range of the ISO limits at frequencies up to 100 Hz. However, at a few one-third octave band center frequencies, the responses from several subjects were beyond the ISO limits at frequencies below 100 Hz. All the subjects have a near constant effective stiffness in the frequency range of 80 to 100 Hz (see Fig. 11 (c)).

Correlations between BRs and anthropometrics

The correlations between the BR responses at each frequency and the anthropometric measurements of the twelve subjects were calculated. The correlation coefficients (r-values) as functions of frequency are plotted in Fig. 12. The body weight, the volume of the hand and arm, the hand volume are highly correlated to each other ($r>0.94$, $p<0.001$). Hence, their correlations to the responses are very similar. To simplify the presentation, only the correlations between the responses and the body height, hand breadth measured at the metacarpal, the hand length, the hand circumference measured at the metacarpal, and the hand volume are plotted. Since each dataset has twelve pairs of values, the correlation is significant at the 95% confidence level when the r-value is greater than 0.58.

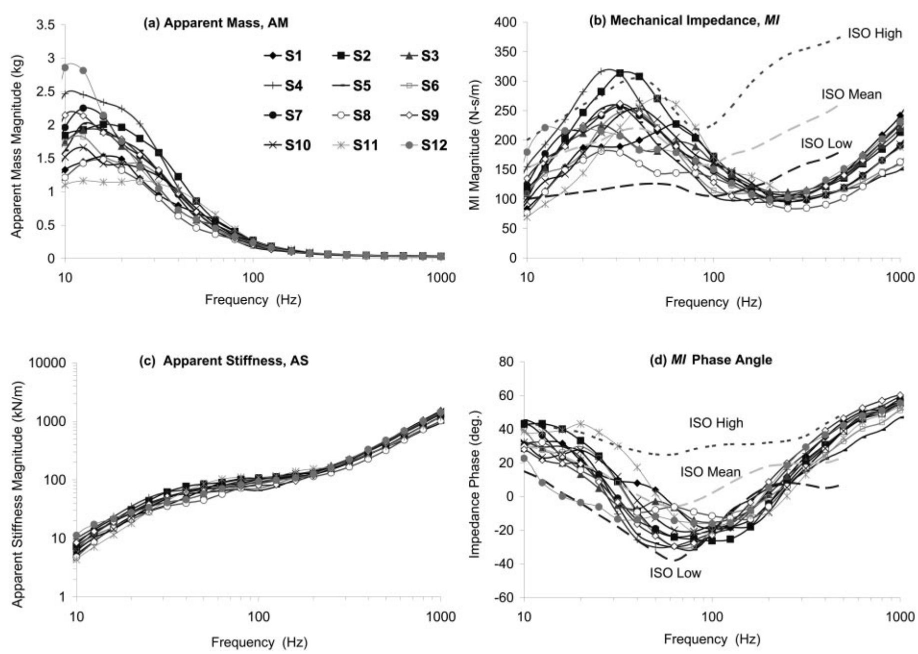
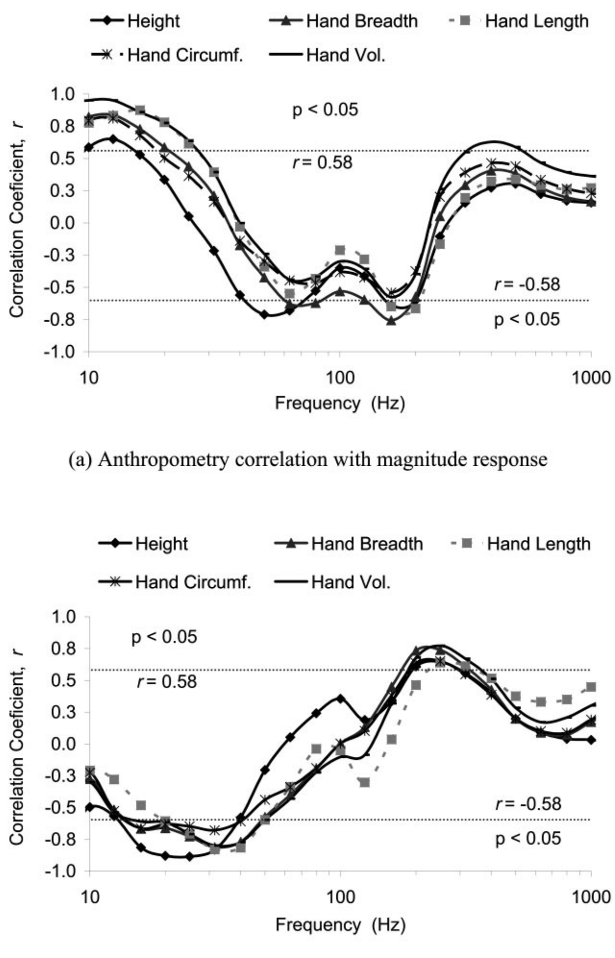


Fig. 11. Effects of the individual difference (subject) on the biodynamic responses.
(a) apparent mass, AM; (b) mechanical impedance, MI; (c) apparent stiffness, AS; and (d) phase angle.



(a) Anthropometry correlation with magnitude response

(b) Anthropometry correlation with phase response

Fig. 12. Correlations between the biodynamic responses and a few anthropometrical parameters.
(subject height, hand breadth at the metacarpal, hand length, hand circumference, finger volume, and hand volume) at different frequencies.

As can be seen, the basic trends of the correlation coefficients for all the anthropometric parameters over frequency are similar. At frequencies below 31.5 Hz, the hand size is generally positively correlated with the magnitude response ($r>0.58$, $p<0.05$). The hand breadth is generally negatively correlated with the magnitude response in the frequency range of 63 to 200 Hz ($r<–0.58$, $p<0.05$). The hand volume shows the highest positive correlation at both the low (<40 Hz) and high (>250 Hz) frequency regions. However, its correlation at frequencies above 500 Hz cannot be reliably determined.

Significant correlations ($|r| >0.058$, $p<0.05$) between the anthropometric measurements and the phase response exist in two frequency ranges (see Fig. 12 (b)). The first range is between 12.5 Hz and 40 Hz and the second one is between 200 Hz and 315 Hz.

Discussion

This study investigated the four biodynamic response parameters of the palm-wrist-arm system in the forearm direction (or the z-direction of the hand-arm biodynamic coordinate)[36] and their basic characteristics. The data can be used to estimate the transmissibility of an anti-vibration glove at the palm, the dynamic coupling force between the palm and vibrating surface, and the vibration power absorption in the palm-wrist-arm system. Therefore, the data are useful in the study of palm-transmitted vibration, vibration-induced injuries or disorders in the palm-wrist-arm system, vibration isolation, and tool design.

Theoretically, the palm soft tissues function like an anti-vibration glove or a natural cushion for the hand-arm system. It can be approximately modeled as a spring-damping system and the remaining structures of the palm-wrist-arm system as a mass-spring-damping system that is connected to the palm spring-damping system. This theoretical model can be used to explain many phenomena observed in this study. Like an anti-vibration glove, the isolation effectiveness of the palm spring-damping system depends on vibration frequency. At low frequencies (<40 Hz), the palm cannot effectively isolate vibration, so the vibration can be effectively transmitted to the entire hand-arm system[25–26], and a large percentage of the hand-arm system mass is involved in the low-frequency motion. Therefore, a larger hand-arm size can provide more mass to the response and result in a positive correlation between the anthropometrics and the magnitude of the biodynamic response. This explains the correlation observed in the low-frequency range, as shown in Fig. 12 (a).

As also shown in Fig. 12(a), the hand size tends to be negatively correlated with the responses in the middle-frequency range (50 to 200 Hz). This may be because the palm soft tissue spring-damping system can provide more effective isolation in this frequency range, as evidenced from the system's strong spring response characteristic (negative phase angle and negative imaginary VPT) as shown in Fig. 4. The effectiveness of this isolation system may depend on the mechanical properties of each individual. A large hand likely has relatively thick soft palm tissue, and thus lower palm contact stiffness. Although a large hand-arm system usually exhibits large mass qualities, the lower stiffness can isolate more handle vibration resulting in a lessened biodynamic response. This suggests that the palm can serve as a vibration isolator in this frequency range and that a person with a large hand-arm size may be less vulnerable to vibration-induced injuries at the wrist, elbow, and shoulders than a person with a thin hand in the operation of power hand tools with dominant vibrations in this middle-frequency range.

The frequency range from 20 to 50 Hz is a transition region from positive correlations to negative correlations. As shown in Fig. 4 (e), the hand-arm resonance and the maximum power absorption occur in this frequency range. Unfortunately, most percussive tools such as rock drills, chipping hammers, and jackhammers have their dominant vibration frequencies (equal to impact rate) within this frequency range[2]. This may be one of the possible reasons that exposure to vibration from such tools could cause wrist, bone, joint, and muscle disorders[30, 31]. Some air bladder anti-vibration gloves may provide limited protection, but they do not seem to be very effective in this frequency range[13]. Because reducing the applied force can effectively reduce the vibration power transmission, an effective measure for the worker's self protection is to reduce the push force and let the tool do the work, provided that this is consistent with safe work practice and tool control. However, this may not be practical on some tools that require a large force to control the tool and to achieve desired productivity during certain operations. Therefore, the isolation of the vibration produced by these tools remains a very challenging research task. A good preventative solution is to improve the designs of these tools so that the vibration can be reduced at the source.

At high frequencies (>250 Hz), the correlation relationship between the palm BR and hand size returns to the positive side (see Fig. 12). Although not always statistically significant, the response tends to be positively correlated with hand size. This may be because the high-frequency vibration can only be effectively transmitted to the local soft tissues of the palm, and the palm spring-damping system cannot effectively isolate such vibration. A larger hand may have more tissue in contact with the handle thus resulting in a higher response. At such frequencies, the vibration cannot be transmitted beyond the hand[25, 26], and the energy absorption is likely limited to the local hand tissues. The VPA values at the high frequencies are also relatively low. Therefore, high-frequency VPA is unlikely an essential cause of injuries or disorders in the arm and shoulder. However, the VPA density or VPA per unit volume of tissue at the palm may not be reduced at the high frequencies, and it may be associated with hand disorders.

The results of this study indicate that the effective/apparent stiffness measured in the middle-frequency range, especially between 80 and 100 Hz plays an essential role in determining the biodynamic responses of the system measured at the palm. A higher stiffness likely corresponds to a higher resonant frequency, as shown in Fig. 10. The stiffness is also strongly correlated with the biodynamic responses in almost the entire frequency region of concern in this study. This critical stiffness value is likely associated with the palm soft tissue contact stiffness. Changing the palm effective stiffness can influence the effectiveness of anti-vibration gloves. This may be useful information for the effective use and/or further development of anti-vibration devices.

The results also indicate that a higher palm force generally resulted in a higher biodynamic response. This is likely because the stiffness of the palm soft tissues exhibits non-linear behavior, and it generally increases with an increase in the palm coupling force. The grip-only action generated the lowest response while the push-only action corresponded to the highest response. A main explanation for this is that the push-only action requires more effort from the arm system than the grip action, and the connection stiffness of the wrist and elbow joints is increased. Therefore, the responses measured with these two actions (push-only and grip-only) can be used to determine the upper and lower limits of the palm BR value along the forearm direction.

The results of this study also indicate that as individuals have different heights and weights, they may also exhibit unique BR values. It is thus very reasonable for the ISO 10068[24] to recommend a range of the MI data instead of a single value at each frequency. However, the range of the data recommended in the current standard may need some improvements. As shown in Fig. 11, some palm MI values measured at frequencies below 100 Hz exceed the upper ISO limit. With the addition of the finger MI, the total MI of the entire hand-arm system will likely further exceed the ISO limit. This observation is consistent with the data reported from several other studies[19, 21, 29]. This may be due in part to the fact that the ISO-recommended values are based on data measured with the grip action in a fairly low force range (25–50 N)[22]. The operation of many power tools, especially percussive tools, frequently requires a hand force higher than 50 N, as evidenced from the specifications for many tool tests[37]. Therefore, the limits in the standard may not be realistic or practically applicable to some conditions commonly found at workplaces. These observations suggest that this standard needs some revisions.

The human hand is a very flexible structure and cannot be considered as a lumped mass. The effectiveness of an anti-vibration glove is location-specific. The glove may significantly reduce the vibration transmitted to the palm but it may provide little reduction of the vibration transmitted to the fingers in a large frequency range. This is because the apparent mass at the palm is much larger than that at the fingers[29]. This requires that the effectiveness of the glove for finger and palm protections be examined separately. In ISO 13753 (1999)[12], it is recommended to use the *MI* data presented in ISO 10068 (1998)[24] for estimating the transmissibility of anti-vibration glove material. The *MI* data in ISO 10068 are for the entire hand-arm system, which is the summation of the finger and palm mechanical impedance. With this method, the effectiveness of the glove material for the finger protection will be substantially overestimated. It may result in only a marginal overestimation for the protection on the palm side, but the estimated value cannot be used as a good indication of the overall effectiveness of the glove for the hand protection. Furthermore, in ISO 10819 (1996)[35], the transmissibility of the glove is measured at the palm, in which only the palm BR is effectively involved in the response that determines the glove performance[13]. Therefore, there is an inconsistency in the use of mechanical impedance between ISO 13753 and ISO 10819. Using the finger and palm MI data separately for the estimation can not only resolve such an inconsistency but also provide more realistic results.

Conclusions

Based on the results and observations of this study, several conclusions are made as follows:

- The palm BR value is frequency-specific. There is an obvious resonant frequency in the biodynamic response of the hand-arm system. Under the test conditions used in this study, this resonant frequency usually falls in the frequency range of 20 to 50 Hz. Because of the resonance, this frequency range corresponds to the maximum vibration power transmission and absorption to the hand-arm system through the palm. Such a resonant frequency range coincides with the dominant vibration frequencies of many percussive tools. This resonance may thus have some association with vibration-induced injuries or disorders in the wrist-arm system among workers using percussive tools.
- Increasing the effective palm force generally raises the resonant frequency and increases the magnitude of the biodynamic response and vibration power transmission. The influence of the applied force on the biodynamic response is more pronounced in the middle-frequency range (40–200 Hz) than at other frequencies.
- At the same palm force level, the push-only action corresponds to the highest BR value while the grip-only action generally produces the lowest BR value. The combined grip and push coupling action BR values fall in between these two extremes. Therefore, the BR values from the push-only and grip-only actions define the boundary of the biodynamic response along the forearm direction (z_h-direciton in the biodynamic coordinate[36]).
- The biodynamic response is also generally individual-specific. A person with a large hand-arm size likely exhibits a large palm BR value at the low frequencies (<40 Hz). Although not always statistically significant, this person may also produce large BR values at frequencies above 300 Hz. However, he/she may present low BR values in the middle-frequency range (50–200 Hz).
- The palm tissue contact stiffness likely plays an important role in determining the BR value at frequencies above 20 Hz. The apparent stiffness in the middle-frequency range is correlated with the fundamental resonant frequency of the system and the BR values in a broad frequency range.

Acknowledgements

The authors thank Mr. Chris Warren and Mr. Bryan Washington for their assistance in the study.

Disclaimer

The content of this publication does not necessarily reflect the views or policies of NIOSH, nor does mention of trade names, commercial products, or organisations imply endorsement by the U.S. Government.

References

1) Gemne G, Taylor W (1983) Foreword: Hand-arm vibration and the central autonomic nervous system. J Low Freq Noise and Vib **Special Volume**, 1–12.
2) Griffin MJ (1990) Handbook of human vibration. Academic Press, London.
3) Pelmear PL, Wasserman DE (1998) Hand-arm Vibration: A Comprehensive Guide for Occupational Health Professionals, 2nd ed. OEM Press, Beverly Farms, MA, USA.
4) EU Directive. 2002/44/EC of 25 June 2002 on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (vibration) (Sixteenth individual directive within the meaning of article 16(1) of directive 89/391/EEC). The European Parliament and the Council of the European Union (EU), Luxembourg.
5) Reynolds DD, Basel R, Wasserman DE, Taylor W

(1984) A study of hand vibration on chipping and grinding operators, part III: Power levels into the hands of operators of pneumatic tools used in chipping and grinding operations. J Sound Vib **95**, 515–24.

6) Pradko F, Lee RA, Greene JD (1965) Human vibration-response theory. 65-WA/HUF-19, American Society of Mechanical Engineers.
7) Cundiff JS (1976) Energy dissipation in human hand-arm exposed to random vibration. J Acous Soc Am **59**, 212–4.
8) Lidström IM (1977) Vibration injury in rock drillers, chiselers, and grinders. Some views on the relationship between the quantity of energy absorbed and the risk of occurrence of vibration injury. In: Proceedings of the international conference on hand-arm vibration, 77–83, Cincinnati.
9) Miwa T, Yonekawa Y, Nara A, Kanada K, Baba K (1979) Vibration isolators for portable vibrating tools, part 1: a grinder. Ind Health **17**, 85–122.
10) Jahn R, Hesse M (1986) Applications of hand-arm models in the investigation of the interaction between man and machine. Scand J Work Environ Health **12**, 343–6.
11) Dobry MW, Barczewski R, Stammers CW (1992) A pneumatic tool vibration isolator. J Sound Vib **153**, 171–5.
12) ISO 13753: Mechanical vibration and shock—hand-arm vibration—method for measuring the vibration transmissibility of resilient materials when loaded by the hand-arm system. International Organisation for Standardization, Geneva.
13) Dong RG, Rakheja S, McDowell TW, Welcome DE, Wu JZ, Warren C, Barkley J, Washington B, Schopper AW (2004) A method for determining the transmissibility of antivibration gloves using biodynamic responses of hand-arm system. J Sound Vib (corrected proof available on-line).
14) Griffin MJ, Macfarlane CR, Norman CD (1982) The transmission of vibration to the hand and the influence of gloves. In: Vibration Effects on the Hand and Arm in Industry. eds. by Brammer AJ, Taylor W, 103–16, John Wiley & Sons, New York.
15) Hempstock TI, O'Connor DE (1989) Measurement of impedance of the hand-arm system. Proc Inst Acous **11**, 483–90.
16) Lundström R, Burström L (1989) Mechanical impedance of the human hand-arm system. Int J Ind Ergo **3**, 235–42.
17) Burström L (1990) Measurements of the impedance of the hand and arm. Int Arch Occup Environ Health **62**, 431–9.
18) Cronjager L, Hesse M (1990) Hand-arm system's response to stochastic excitation. In: 5th international conference on hand-arm vibration, 39–42, Kanazawa.
19) Kihlberg S (1995) Biodynamic response of the hand-arm system to vibration from an impact hammer and a grinder. Int J Ind Ergo **16**, 1–8.
20) Rakheja S, Wu JZ, Dong RG, Schopper AW (2002) A comparison of biodynamic models of the human hand-arm system for applications to hand-held power tools. J Sound Vib **249**, 55–82.
21) Marcotte P, Aldien Y, Boileau PE, Rakheja S, Boutin J (2003) Influence of hand size and coupling forces on the biodynamic response of the hand-arm system. In: Proceedings of the 38th United Kingdom conference on human responses to vibration, Alverstoke, Gosport, UK.
22) Gurram R, Rakheja S, Brammer AJ (1995) Driving-point mechanical impedance of the human hand-arm system: synthesis and model development. J Sound Vib **180**, 437–58.
23) Dong RG, Rakheja S, Schopper AW, Han B, Smutz WP (2001) Hand-transmitted vibration and biodynamic response of the human hand-arm: a critical review. Crit Revs in Biomed Eng **29**, 393-439.
24) ISO 10068: Mechanical vibration and shock—free, mechanical impedance of the human hand-arm system at the driving point. International Organisation for Standardization, Geneva.
25) Pyykkö I, Färkkilä M, Toivanen J, Korhonen O, Hyvärinen J (1976) Transmission of vibration in the hand-arm system with special reference to changes in compression force and acceleration. Scand J Work Environ Health **2**, 87–95.
26) Reynolds D, Angevine EN (1977) Hand-arm vibration, part II: Vibration transmission characteristics of the hand and arm. J Sound Vib **51**, 255–65.
27) Tominaga Y (1993) The relationship between vibration exposure and symptoms of vibration syndrome. J Sci Labour **69**, 1–14.
28) Dong RG, Schopper AW, McDowell TW, Welcome DE, Wu JZ, Smutz WP, Warren C, Rakheja S (2004) Vibration energy absorption (VEA) in human fingers-hand-arm system. Med Eng Physics **26**, 483–92.
29) Dong RG, Wu JZ, McDowell TW, Welcome DE, Schopper AW (2004). Distribution of mechanical impedance at the fingers and the palm of human hand. J Biomech (corrected proof available on-line).

30) Bovenzi M, Fiorito A, Volpe C (1987) Bone and joint disorders in the upper extremities of chipping and grinding operators. Int Arch Occup Environ Health **59**, 189–98.

31) Gemne G, Saraste H (1987) Bone and joint pathology in workers using hand-held vibration tools. Scand J Work Environ Health **13**, 290–300.

32) Mann NAJ, Griffin MJ (1996) Effect of contact conditions on the mechanical impedance of the finger. Cent Euro J Pub Health **4**, 46–49.

33) Nakazawa N, Ikeura R, Inooka H (2000) Characteristics of human fingertips in the shearing direction. Bio Cybern **82**, 207–214.

34) Dong RG, McDowell TW, Welcome DE, Wu JZ (2004) Biodynamic response of human fingers in a power grip subjected to a random vibration. J Biomech Eng **126**, 446–56.

35) ISO 10819 (1996): Mechanical vibration and shock—hand-arm vibration—method for the measurement and evaluation of the vibration transmissibility of gloves at the palm of the hand. International Organisation for Standardization, Geneva.

36) ISO 5349-1 (2001): Mechanical vibration—measurement and evaluation of human exposure to hand-transmitted vibration—part 1: General requirements. International Organisation for Standardization, Geneva.

37) ISO 8662 (1992-1999): Hand-held portable power tools—measurement of vibrations at the handle—parts 2–14. International Organisation for Standardization, Geneva.