Biodynamic Response of Human Fingers in a Power Grip Subjected to a Random Vibration

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Background. Knowledge of the biodynamic response (BR) of the human hand-arm system is an important part of the foundation for the measurement and assessment of hand-transmitted vibration exposure. This study investigated the BR of human fingers in a power grip subjected to a random vibration. Method. Ten male subjects were used in the experiment. Each subject applied three coupling actions to a simulated tool handle at three different finger grip force levels. Results and Conclusions. The BR is practically independent of the hand coupling actions for frequencies at or above 100 Hz. Above 50 Hz, the BR is correlated to finger and hand sizes. Increasing the finger coupling force significantly increases the BR. Therefore, hand forces should be measured and used when assessing hand-transmitted vibration exposure. The results also show that under a constant-velocity vibration, the finger vibration power absorption at frequencies above 200 Hz is approximately twice that at frequencies below 100 Hz. This suggests that the frequency weighting specified in the current ISO 5349-1 (2001) may underestimate the high frequency effect on vibration-induced finger disorders. [DOI: 10.1115/1.1784479]

Introduction

The biodynamic response (BR) such as apparent mass, mechanical impedance and apparent stiffness of human hand-arm system describes its mechanical response to vibration excitation, and determines the vibration power transmission from a vibrating tool to a human hand (ISO 10068, 1998) [1]. The energy transmission and absorption in the system may influence the degree to which the vibration causes injuries and disorders [2,3], which could occur with the prolonged and intensive use of some power hand tools [4–6]. The mechanical response may also affect the perception of vibration and any discomfort it may cause. Furthermore, the mechanical response may also affect the vibration of the source of excitation such as a powered hand tool [7–9], and the effectiveness of vibration isolators and anti-vibration gloves [10,11]. Hence, knowledge of BR is an important part of the foundation for the measurement and assessment of the hand-transmitted vibration exposure [12].

The BR of the entire hand-arm system has been extensively studied. Many of the previously reported studies are listed in the reviews by Burström [13], Gurram et al. [14] and Dong et al. [15]. Based on some of these studies, the International Organization for Standardization (ISO) has set forth a standard (ISO 10068, 1998) [1], in which the mechanical impedance (MI) at the hand driving point is used to represent the biodynamic response. This standard presents recommended MI values and several biodynamic models. These MI values are for the entire hand-arm system, and they are referred to as the "total BR" values in the present study.

It has been reported that the characteristics of vibration power transmission into the palm is quite different from that into the fingers [16]. Different vibration spectra can cause diverse problems at various locations in the hand-arm system [17]. Hence, it is reasonable to assume that the influence of the BR on vibration-induced finger injuries, disorders, and discomfort may also differ from that in the other parts of the hand-arm system, and that an anti-vibration device that is effective at protecting the palm-wrist-arm system may not be effective at protecting the fingers. Therefore, the total BR values for the entire hand-arm system and their related biodynamic models may not be suitable when applied to finger problems. A better understanding of the finger BR and vibration power (or energy) absorption (VPA) may lead to the development of more effective risk assessment methodologies and protection strategies for the fingers.

The mechanical impedance of the fingertips has been investigated by several researchers [e.g. [18–20]]. There is also one study that focused on the MI of the local skin of the fingers and hands [21]. In these studies, the MI was measured by exposing the fingertip or the local skin to vibration, and has been termed the point MI. The operation of many powered hand tools such as chipping hammers, road breakers, grinders, chain saws, and rock drills requires the use of a full power grip when grasping the tool handles, and the entire palmar surface of the hand is exposed to the vibration transmitted from the handles. In such vibration exposures, the fingertip or finger response may depend not only on the dynamic properties of the local tissues of the fingers but also on the overall motion of the entire hand-arm system. Therefore, the point MI may not fully represent the dynamic behaviors of the fingertips or fingers during the operation of many power hand tools. Few studies have investigated MI at the fingers under typical hand-handle coupling conditions [16]. Therefore, the finger BR and its associated vibration power absorption are far from sufficiently understood.

Based on the above-mentioned background, the specific aims of this study are as follows: (i) to quantify and characterize the biodynamic response and power absorption distributed at the fingers in a power grip on a simulated tool handle that is vibrating with a broad-band random spectrum; (ii) to determine the effects of the hand-handle coupling action and the applied finger force on the finger biodynamic response and power absorption; and (iii) to explore the correlation between the anthropometrics and the finger biodynamic response and power absorption.

Experimental Method

Theory. The apparent mass (AM), mechanical impedance (MI), and apparent stiffness (AS) are defined as

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

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 these BR parameters 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 BR parameters, G_{fm} is the cross-spectrum of force and dynamic motion ($\tilde{A}$ for AM, $\tilde{V}$, for MI, or $\tilde{D}$ for AS), and G_{mm} is the auto-spectrum of the motion.

All three BR parameters are generally complex, that is, each of them possess real and imaginary components, and they can be generally expressed as

$$Z(\omega)=Z_R(\omega)+Z_I(\omega)j \tag{3}$$

where $Z_R(\omega)$ and $Z_I(\omega)$ are real and imaginary components of $Z(\omega)$ respectively, and $j=\sqrt{-1}$. These BR represent different physical properties (mass, damping, and stiffness) of the system. Each of the parameters, however, can be derived from another. For example, if the apparent mass (AM) is directly measured, the mechanical impedance (MI) and apparent stiffness (AS) can be simply calculated using the following formula:

$$MI(\omega)=AM(\omega)\cdot j\omega,\quad AS(\omega)=AM(\omega)\cdot(j\omega)^2 \tag{4}$$

Another important parameter that has been frequently used in the study of hand-transmitted vibration is vibration energy/power transmission (P_T). It is defined as

$$P_T=\tilde{F}\cdot\tilde{V} \tag{5}$$

The vibration power transmission can be directly obtained by performing a cross-correlation calculation [13]. If the apparent mass (AM) is directly measured, the vibration power transmission can also be calculated from

$$P_I(\omega)=AM(\omega)\cdot j\omega|\tilde{V}(\omega)|^2 \tag{6}$$

This equation indicates that the vibration power transmission also takes the same general form in the frequency domain as that expressed in Eq. (3) for the three biodynamic response parameters. Hence, the vibration power transmission can also be treated as a biodynamic response parameter. While the imaginary part of the vibration power transmission reflects the combination of the kinetic (mass) and potential (spring) power value of the measured system, its real part represents the vibration power absorption (VPA) measured in the system [13,16].

In the current ISO standard for vibration exposure risk assessment (ISO 5349-1, 2001) [22], it is assumed that vibrations with the same vibration velocity at frequencies above 16 Hz pose the same level of risk. This is the basis for the frequency-weighting specified in this standard. To explore the characteristics of vibration power transmission under the same vibration velocity at different frequencies, a constant-velocity ($|\tilde{V}|=10$ mm/s rms value) is used to predict vibration power transmission in this study. The validation of this approach is based on the assumption that vibration power transmission changes linearly with vibration velocity, as shown in Eq. (6). The results of a previous study [13] demonstrated that this approach was acceptable if the vibration magnitude was limited to a certain range, and that the predicted vibration power absorption values were highly correlated to those actually measured in the operations of several power tools. Hence, this approach, while not always completely accurate, may be acceptable for exploring the fundamental features of vibration power transmission and absorption in the constant-velocity vibration exposure.

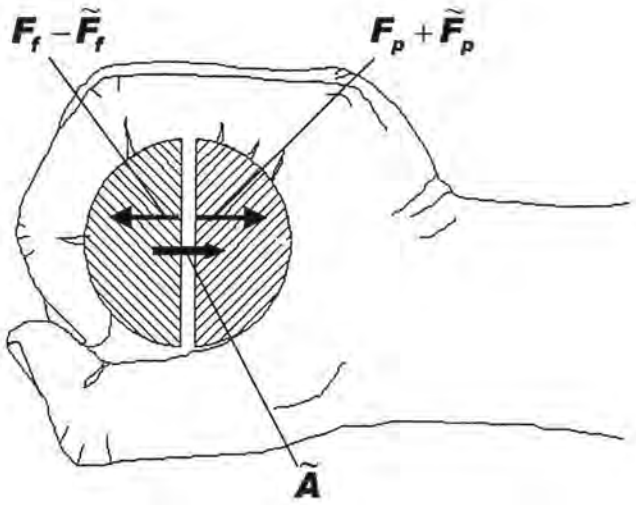

Fig. 1 Dynamic forces and acceleration at the interfaces between the fingers and the handle, and between the palm and the handle (F_f: static grip force on the fingers; F_p: static grip force on the palm; $\tilde{F}_f$: dynanic force acting on the fingers; and $\tilde{F}_p$: dynamic force on the palm; and $\tilde{A}$: handle acceleration)

A cylindrical tool handle can be virtually evenly split into two parts at the centerline, as conceptually sketched in Fig. 1. In the power grip, the total dynamic force acting on the hand, $\tilde{F}$, can be considered as the sum of the two components acting on the surfaces of the two parts of the handle [16]. Therefore, the total biodynamic response of the entire hand-arm system can be divided into the BR distributed at the palm (Z_p) and the BR at the fingers (Z_f) such that:

$$\tilde{Z}=\tilde{Z}_p+\tilde{Z}_f \tag{7}$$

By measuring the handle acceleration and the dynamic force acting at the fingers, the finger biodynamic response was computed in this study.

Apparatus. As illustrated in Fig. 2, an instrumented handle for measuring the finger biodynamic response was designed and constructed in an earlier study [16]. To assure the reliability and accuracy of the measurement, the dynamic behaviors of the instrumented handle were extensively examined. The handle has a fundamental resonant frequency of 1,452 Hz. With the fingers coupled to the handle, the fundamental resonant frequency is only marginally reduced (1,416 Hz). The dynamic evaluation also found that when a vibration feedback system is used, the hand coupling and the handle resonance have little effect on the vibration input to the hand in the frequency range of concern in this study (10–1,000 Hz). Based on the examination using a scanning laser vibrometer [23], it was determined that in this frequency range, the vibration distribution on the measuring cap is highly uniformly distributed (difference <3%). By sequentially attaching several small pieces of metal to the measuring cap, the handle was dynamically calibrated. The pieces of metal weighed 0.24, 0.68, 2.10, 3.10, 5.66, 9.30, 12.31, and 21.60 g, respectively, which were measured using a calibrated balance (Ohaus, SCD010). These evaluation results suggest that this handle can reliably measure the BR represented by the apparent mass greater than 0.5 g in the entire frequency range of concern in this study.

The directly measured data present the combined response of the measuring cap and the true response of the fingers. The effect of the cap effective mass was cancelled using the following formula:

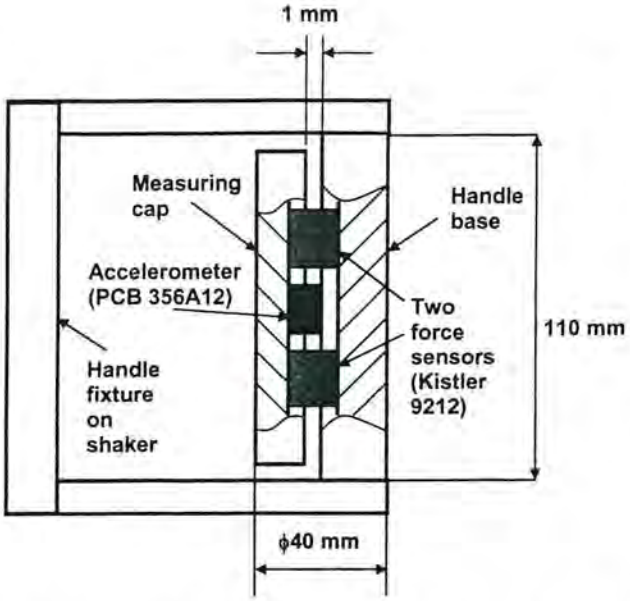

Fig. 2 A sketch of the instrumented handle used for the measurement of the biodynamic responses at the fingers

$$Z_P(\omega) = HI_{pp}(\omega)[Z_{Combined}(\omega) - Z_{Cap}(\omega)] \quad (8)$$

where $Z_{Combined}$ is the combined cap and finger response measured in a subject test, Z_{Cap} is the cap response that is measured without a hand gripping the handle, and HI_{pp} is the measurement system's frequency response function (MSFRF). This formula is derived based on a detailed sensor-structure model described by McConnell [24]. In this study, the MSFRF was estimated from

$$HI_{pp}(\omega) = \frac{m_1}{AM_{Cap}(\omega)} \approx \frac{\text{Real}[AM_{Cap}(\omega)]}{AM_{Cap}(\omega)} \quad (9)$$

where m_1 is the true cap effective mass, and AM_{Cap} is the measured apparent mass of the cap assembly (including the cap mass, attached accelerometer, sensor screws, and a part of the force sensors' mass). With the sensors and electronic devices used in this study, the measurement system's frequency response function is near unity, which is highly desired for assuring the accuracy of the measurement.

The experimental setup used in this study is illustrated in Fig. 3. As generally accepted through the definition documented in ISO-10819 (1996) [25], the grip force shown in Fig. 1 is actually the

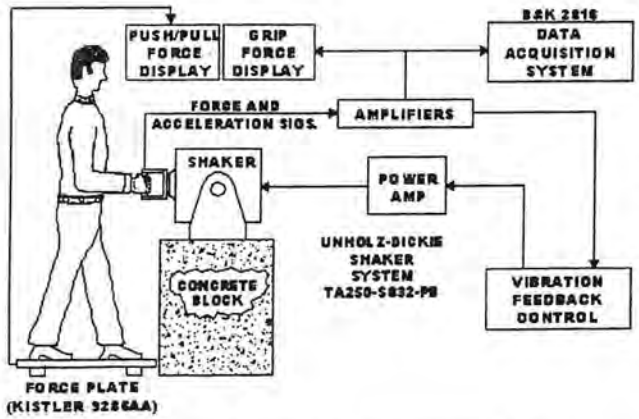

Fig. 3 Subject posture and measurement setup

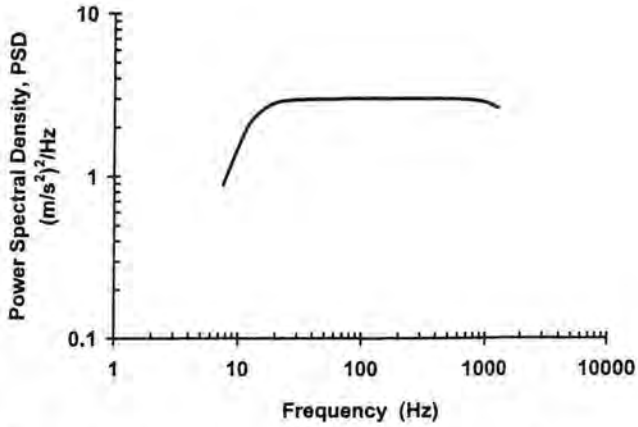

Fig. 4 Vibration power spectral density (PSD) used in the experiment

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 obtain the grip force. A custom program developed using LabVIEW software (National Instruments, Version 5.1) was used to acquire and display the grip force. The grip force was displayed on a computer monitor as a strip chart to serve as feedback for the test subjects. A force plate (Kistler 9286AA) was used to measure the push force acting on the handle, which was also displayed as a strip chart on a separate computer monitor.

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 3.02 $(m/s^2)^2$/Hz in the frequency range of 16–1,000 Hz was used as the stimuli in the experiment, which is shown in Fig. 4. The apparent mass was computed according to Eq. (2) using the PULSE program (HI function) built in the data acquisition system (B&K 2816, Denmark), and the results are expressed at the one-third octave band center frequencies from 10 to 1,000 Hz. The rest of the response parameters were calculated using Eqs. (4) and (6).

As also shown in Fig. 3, the test posture required in the ISO standardized glove test specified in ISO 10819 (1996) [25] was used in the present study. With this posture, the biodynamic response measured in this study is in the Z_h-direction (along the forearm) of the hand biodynamic coordinate system (ISO 5349-1, 2001) [22], which is the dominant vibration exposure direction in the operation of many powered hand tools such as chipping hammers, riveting hammers, rock drills, and jack hammers [6,8,26]. The highest mechanical impedance of the entire hand-arm system is also found in this direction [1].

In general tool operation, there are three typical finger grip actions: grip-only, pull-only, and combined palm push and finger grip. These three coupling actions were considered in the experimental design of this study. To cover a good range of the hand and finger coupling forces, three levels of the effective force acting at the fingers (15, 30, and 50 N) in combination with three levels of palm force (35, 45, 50 N) were used in the experiment. The force levels and coupling actions form a 3×3 test matrix or nine test treatments, which are summarized in Table 1.

Subjects and Experimental Procedures. Ten male volunteers from a local university participated in the experiment. The right hand was used for the test. Table 2 lists the individual anthropometrics for each subject. The test subjects wore normal office clothes without jackets during the experiment. They first went through the test explanation and consent-form-signing procedures. To assure the consistency of the hand grip position around the handle for all the trials and among the subjects, a short section of

Table 1 Experimental treatments

Coupling Action	Total Effective Forces Acting at the Palm (N)		
Grip-only	15 N	30 N	50 N
Pull-only	15 N	30 N	50 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)

a first-aid bandage was placed on the back of the index finger of the hand. A line was marked on the bandage in line with the crease at the base of the subject's third proximal phalange for use as a reference. 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 at a given force level. The sequence of the nine test treatments was randomized among subjects. When the coupling action was stable at the required force level, the investigator recorded the test data for a period of 30 s. After each trial, the subject took a rest for 1 minute. Two trials were sequentially completed for each treatment.

A Summary of the BR Evaluation Procedures. The apparent mass (AM) was directly obtained in the experiment. The measuring cap's apparent mass was measured before and after each subject test. Although no significant differences between the two measurements were observed, the mean value was used to represent the cap's response. After the combined cap and finger response was obtained from the subject test, Eq. (8) was used to cancel the cap's effect such that the pure finger biodynamic response, or finger apparent mass, was obtained. Then, Eqs. (4) and (6) were used to calculate the other BR parameters along with vibration power transmission and absorption.

Data Analysis. A three-factor-repeated-measures analysis-of-variance (ANOVA) was used to conduct the general statistical analysis. The first factor is the effect of the vibration frequency. The second factor is the influence of the applied finger force. The third factor is the hand coupling action. The ANOVA was done using a conventional mixed model with frequency, finger force, and hand action as fixed effects and subject as a random effect. As presented in the next section, there are significant interactions among the fixed factors. Hence, stratified analyses were further performed to determine the specific effects of the coupling and force on the biodynamic response at each frequency. Pursuant to the results of the ANOVA, post hoc comparisons were also carried out using the Tukey method. Linear correlation analyses were also performed to evaluate the associations between the BR and subject anthropometry. All the statistical analyses were performed using MINITAB (Version 13.1). All the differences and effects were considered significant at $p<0.05$ and suggestively significant at $0.05 \leq p<0.10$.

Table 2 Subject anthropometry (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; finger volume=water displaced by hand submerged to crease at proximal end of middle finger)

Subject	Height (cm)	Weight (kg)	Hand Length (mm)	Hand Breadth (mm)	Hand Circumference (mm)	Hand Volume (ml)	Finger Volume (ml)
1	175.3	69.5	185	88	215	360	55
2	177.8	83.0	197	93	215	406	75
3	185.4	90.7	192	97	235	440	70
4	175.3	132.5	207	101	236	550	83
5	175.3	100.2	184	103	250	445	80
6	185.4	66.2	197	93	206	350	52
7	185.4	96.6	200	101	231	445	85
8	175.3	77.1	190	85	205	375	80
9	162.6	61.2	180	80	190	295	48
10	198.1	152.4	205	107	254	550	105
Mean	179.6	92.9	194	95	224	422	73
SD	9.5	29.4	9	9	21	83	18

Table 3 A summary of the ANOVA results

		AM		*MI*		*AS*		*VPA*	
Source	*df*	*F*	*p*	*F*	*p*	*F*	*p*	*F*	*p*
Frequency	20	117.36	<0.001	124.83	<0.001	270.02	<0.001	134.59	<0.001
Force	2	69.07	<0.001	166.31	<0.001	184.99	<0.001	96.92	<0.001
Coupling	2	123.75	<0.001	9.32	0.002	0.60	0.559	41.87	<0.001
Freq.*Coup	40	136.70	<0.001	35.09	<0.001	1.35	0.084	44.00	<0.001
Freq.*Force	40	29.74	<0.001	34.60	<0.001	83.35	<0.001	35.25	<0.001
Force*Coup	4	41.78	<0.001	5.90	0.001	0.80	0.531	10.53	<0.001
Freq.*Force *Coup	80	29.40	<0.001	8.52	<0.001	1.06	0.350	<0.01	1.000

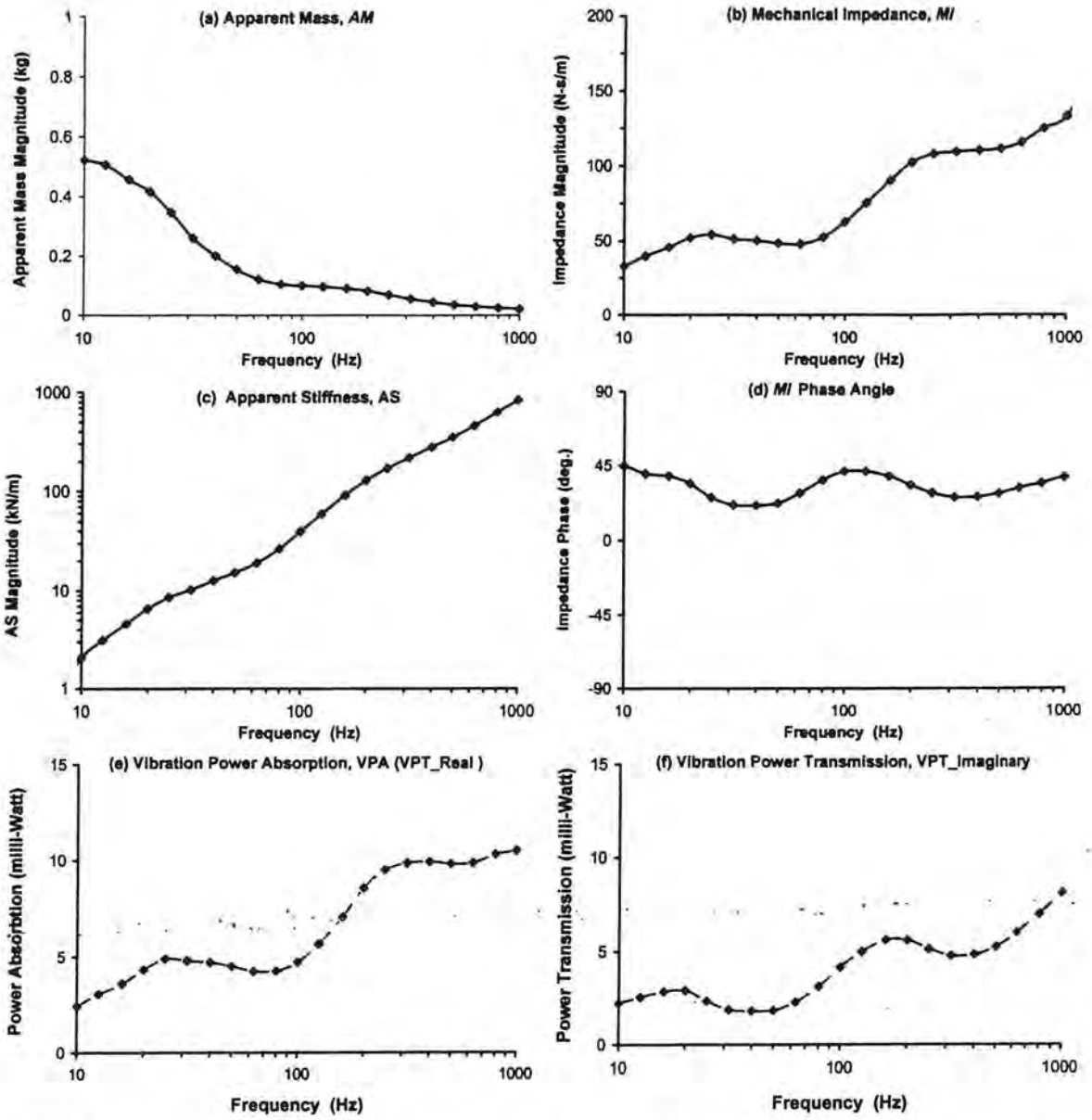

Fig. 5 Biodynamic response parameters as functions of frequency: (*a*) apparent mass, AM; (*b*) mechanical impedance, MI; (*c*) apparent stiffness, AS; (*d*) MI phase angle; (*e*) vibration power absorption, VPA (real part of vibration power transmission); and (*f*) imaginary part of vibration power transmission, VPT_imaginary

Results

The ANOVA results are summarized in Table 3. They show that except for coupling action for the apparent stiffness, all the fixed factors (frequency, force level, and coupling type) significantly affected the biodynamic response parameters. The interactions among the fixed factors are either significant ($p<0.05$) or suggestively significant ($0.05\leq p<0.10$) except for the force-by-coupling and the frequency-by-force-by-coupling for the apparent stiffness (AS) and the three-way interaction for vibration power absorption (VPA). These observations indicate that the influences of the finger force and the coupling action on the biodynamic response (BR) values are generally functions of the frequency, and that the force and coupling action affect the BR values differently.

Effects of the Vibration Frequency. Figure 5 illustrates the overall average BR values of the nine test combinations for all the subjects. As it can be seen in Fig. 5a, the apparent mass (AM) has the maximum value (521 g) at the lowest frequency (10 Hz) of concern in this study. The AM values generally decrease with an increase in frequency. The rate of change for the AM remains at a high level in the frequency range of 12.5 Hz to 50 Hz, but it decreases to a low level at frequencies above 63 Hz. At 100 Hz, the mean AM is 100 g. At 1,000 Hz, the mean AM is only 21 g.

The measured mechanical impedance (MI) magnitude and phase angle as functions of frequency are illustrated in the Figs. 5b and 5d. The phase angles of the apparent mass and stiffness are simply a 90° shift from the MI phase angle, as indicated in Eq. (5). As can be seen, the measured MI magnitude has a resonance-like peak at 25 Hz while the phase angle has the lowest value at 31.5 Hz. The fingers' MI generally increases with an increase in frequency, with the highest rate of increase between 63–200 Hz. There is a second resonance-like peak between 250 and 400 Hz, which can be observed in the responses of most subjects, as

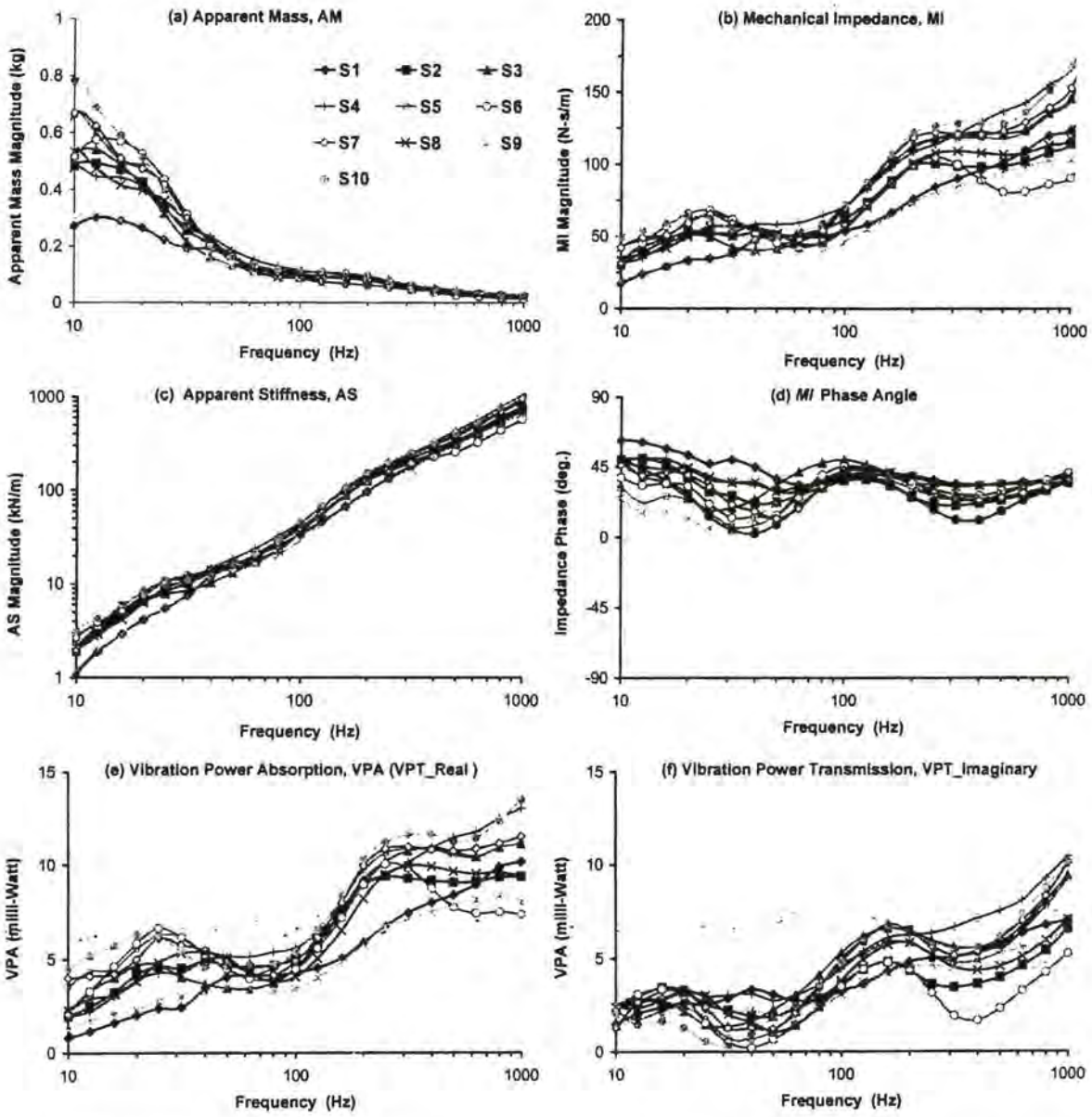

Fig. 6 Effects of coupling action for the three force levels and effects of force level for the three coupling actions on the magnitude of mechanical impedance

shown in Fig. 6. However, the average peak value in Fig. 5b is not obvious, and it is not significantly different from its neighboring values ($p>0.71$).

As shown in Fig. 5c, the apparent stiffness (AS) increases almost proportionally with the vibration frequency, which suggests that the fingers become stiffer as the frequency is increased.

Figures 5e and 5f show the results of vibration power absorption (VPA) and the imaginary part of the vibration power transmission calculated from the apparent mass data using Eq. (6). As shown in Fig. 5e, the basic shape of the VPA is very similar to that of the mechanical impedance magnitude in Fig. 5b. For frequencies at or above 250 Hz, the VPA value only changes slightly. The differences among the VPA values from 250 Hz to 1,000 Hz are less than 10%. The imaginary component of the vibration power transmission remains positive in the entire frequency range. This indicates that the response of the fingers is more mass-like than spring-like [13].

Effects of the Applied Finger Force. The effects of the finger force on the responses at different frequencies are illustrated in Fig. 7. The results show that increasing the force level approximately proportionally increases the magnitude of the response. Increasing the finger force also shifts the entire response curve towards a higher frequency. As a result, the increased force increases the resonant frequency. The large variation in the finger force, however, does not significantly change the vibration power absorption values between 100–160 Hz ($F_{2,18}<3.41$, $p>0.055$). The influence on the other BR magnitudes in the frequency range is also either insignificant or small (<10%). The effect of the finger force on the phase angle is significant ($F_{2,18}>3.50$, $p<0.05$) at most frequencies, but the general trends are complex, as shown in Fig. 7d. Again, the basic trend of the force influence on the VPA (Fig. 7e) is very similar to that on the mechanical impedance magnitude (Fig. 7b).

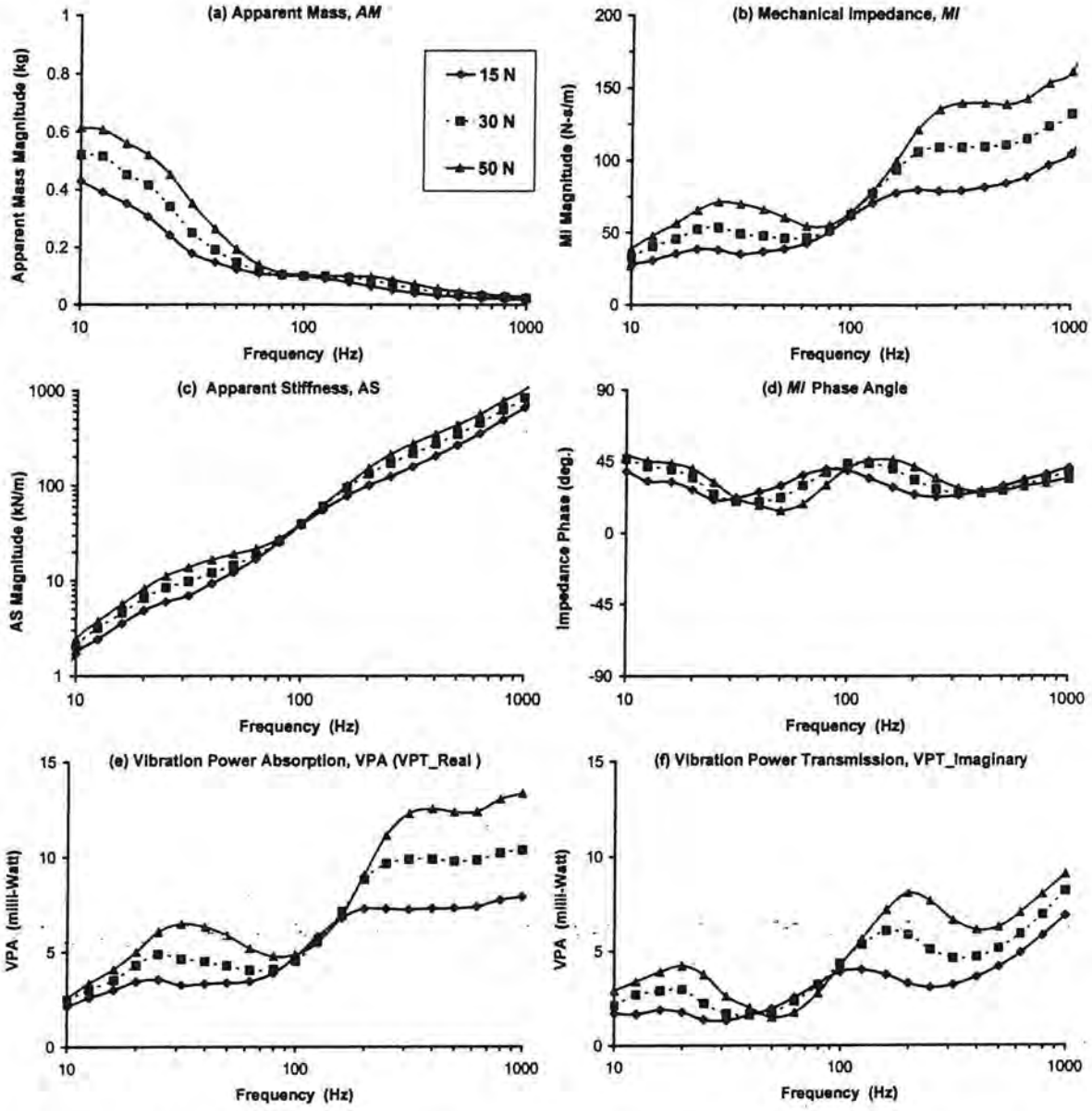

Fig. 7 Effects of the hand coupling action on the biodynamic response parameters: (*a*) apparent mass, AM; (*b*) mechanical impedance, MI; (*c*) apparent stiffness, AS; and (*d*) MI phase angle; (*e*) vibration power absorption, VPA; and (*f*) vibration power transmission, VPT_imaginary

Effects of the Coupling Action. The effects of the hand-handle coupling action on the biodynamic responses are plotted in Fig. 8. The results show that below 40 Hz, the coupling action obviously affects the response ($F_{2,18}>3.74$, $p<0.044$). The pull-only action corresponds to the highest level and the combined grip and push to the lowest level for all the magnitudes of the apparent mass, mechanical impedance, apparent stiffness, and vibration power absorption. In the 40–100 Hz range, the stratified ANOVA results also reveal that the effect of the coupling action is still generally significant ($F_{2,18}>3.50$, $p<0.05$). The post hoc analyses indicate that the significant differences are mostly between the pull-only action and the combined coupling action. The differences, however, are generally less than 20%. At frequencies above 100 Hz, the differences among the three actions are less than 10%. The effect of the coupling action is generally not significant in this frequency region ($F_{2,18}<3.50$, $p>0.05$).

The statistical results further suggest that starting at 50 Hz, the effect of the coupling action on vibration power absorption is generally not significant. However, the significant differences in the phase angle of the mechanical impedance and the imaginary component of the vibration power transmission extend to a higher frequency (100 Hz).

As also shown in Fig. 8, the phase angles remain positive in the entire frequency range in the combined and grip-only actions. The resonance in these two actions is not very obvious. These observations indicate that the responses in these actions correspond to a large damping ratio. In the case of the pull-only action, however, the resonance is fairly profound, because the entire hand-arm system is loaded on the fingers.

As shown in Figs. 9(a, c, and e), although the effects of the finger force for each coupling action are statistically significant at the majority of the frequencies, the degree of the influence on the mechanical impedance magnitude under different coupling actions is obviously different at frequencies below 100 Hz. The influence is lowest for the combined action and highest for the pull-only

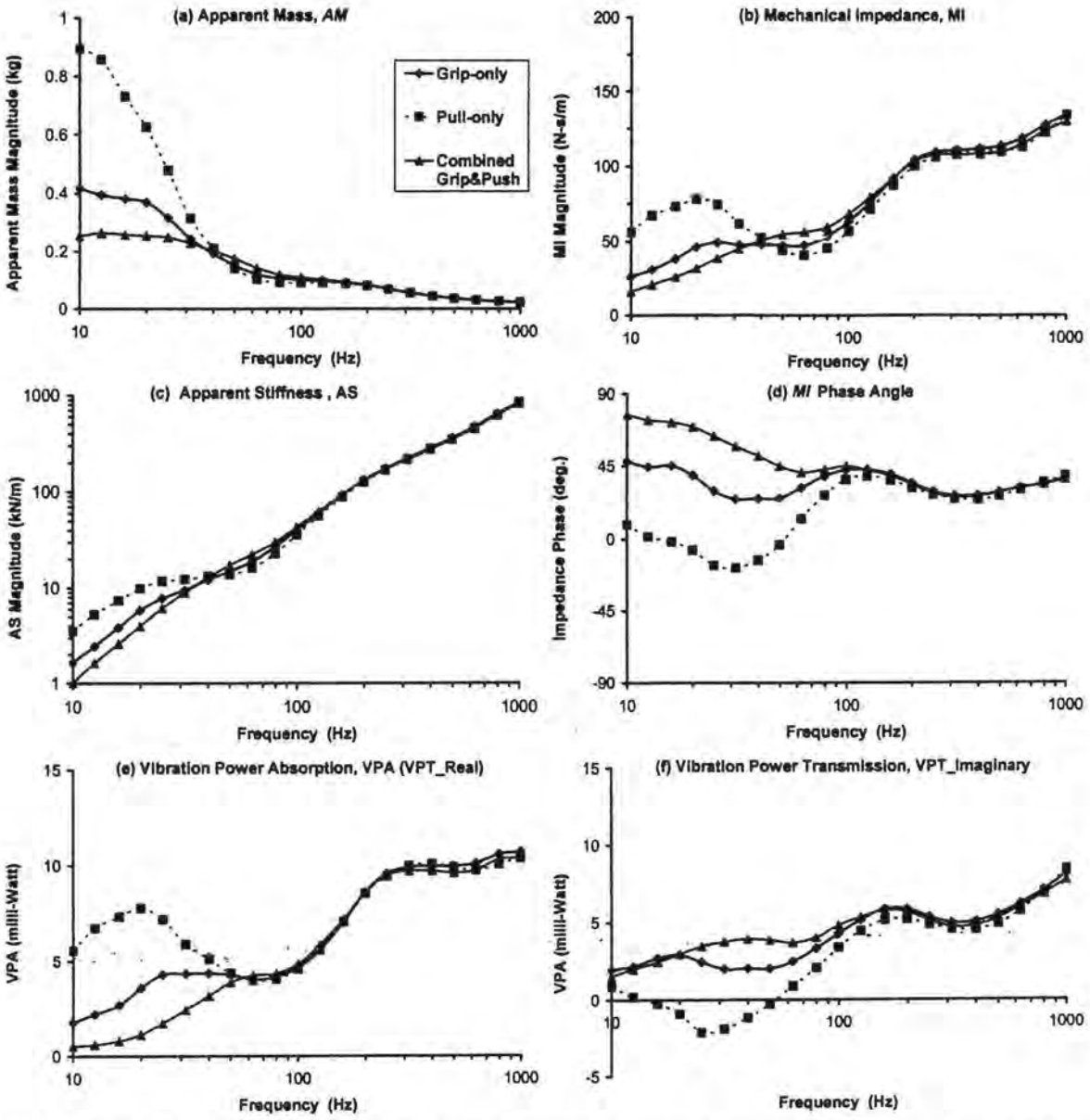

Fig. 8 Effects of the finger grip force on the finger biodynamic response parameters: (*a*) apparent mass, AM; (*b*) mechanical impedance, MI; (*c*) apparent stiffness, AS; and (*d*) MI phase angle; (*e*) vibration power absorption, VPA; and (*f*) vibration power transmission, VPT_imaginary

action. Again, between 80–125 Hz, the force effect is either statistically insignificant ($F_{2,18}<3.50$, $p>0.05$) or the influence is very small.

The force level effects interact with the effects of the coupling action on the magnitude of mechanical impedance, as shown in Figs. 9(b, d, and f). The influence of the coupling action increases as the force is increased. The increased force also increases the intersecting frequency at which the responses of the combined action become higher than those of the pull-only action. Specifically, the intersection is between 25 and 31.5 Hz for 15 N, between 31.5 and 40 Hz for 30 N, and between 40 and 50 Hz for 50 N. Therefore, the critical frequency that divides the influence of the coupling action is between 25 and 50 Hz.

Inter-Subject Difference. Figure 6 illustrates the 10 subject average responses. The subject ID legends are shown in Fig. 6a for clarification. As it can be seen, subjects generally display unique biodynamic response values, just as different people have their own individual heights and weights. The apparent mass differences among the subjects generally decrease with an increase in frequency. For example, at 10 Hz, the maximum inter-subject difference is 510 g; at 100 Hz, it becomes 41 g; and at 1,000 Hz, the maximum inter-subject difference is only 10 g.

The correlations between the ten magnitudes of subject average responses at each frequency and the corresponding subject anthropometry were analyzed. The Pearson correlation coefficients (r-values) as functions of frequency are plotted in Fig. 10. For ten pairs of data, the correlation is significant at the 95% confidence level when the r-value is greater than 0.63. The body weight, hand volume, finger volume, hand breadth, and hand circumference at the metacarpal are correlated to each other ($r>0.76$, $p<0.010$). Hence, their correlations to the BR values are very similar. As can be seen in the figure, the magnitude of the biodynamic response is generally positively correlated to all the anthropometrical hand parameters between 63–315 Hz. At higher frequencies, the body weight and the hand parameters except the hand length are also significantly correlated to BR magnitude. Because of the similar-

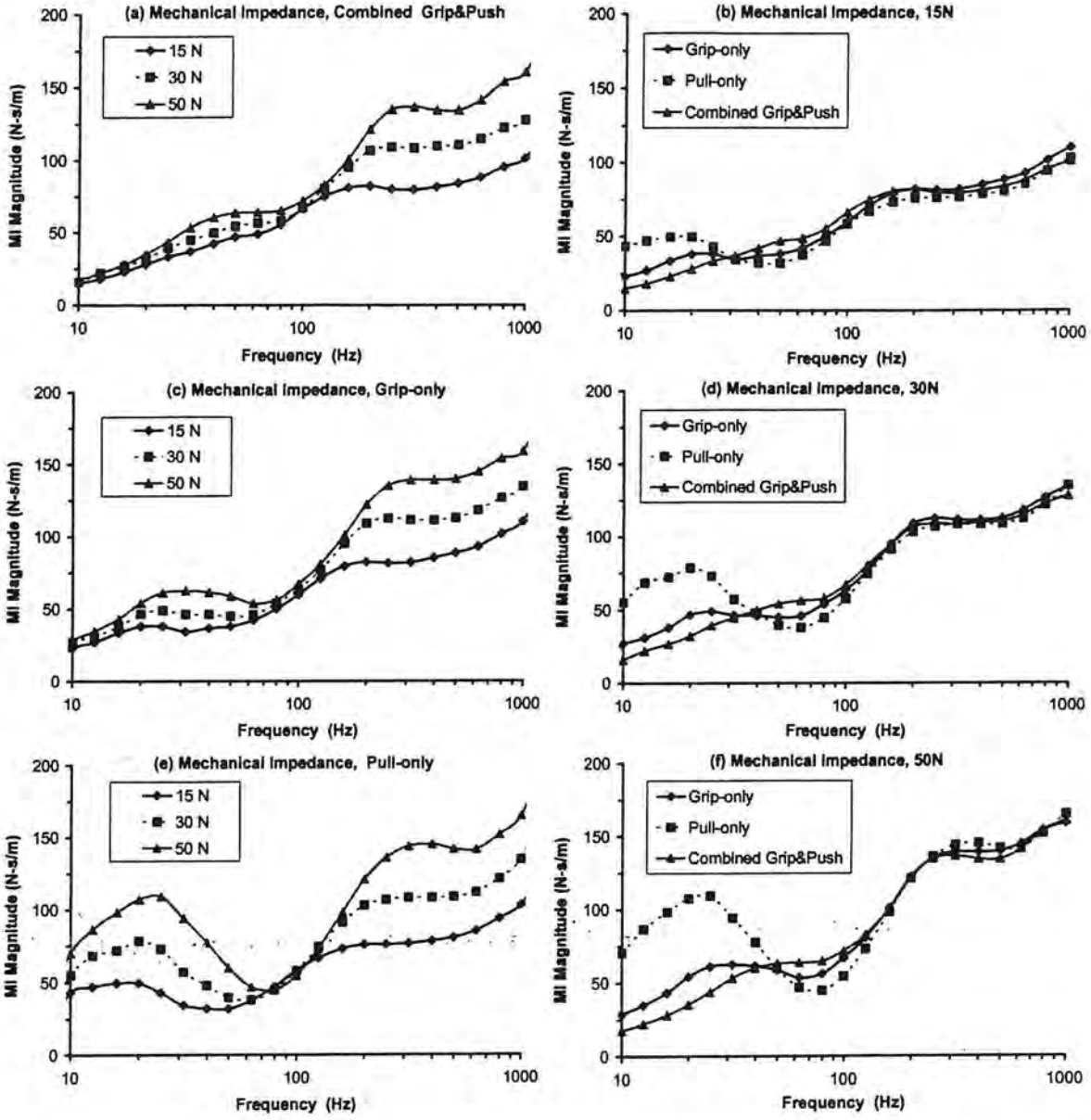

Fig. 9 Effects of the individual difference (subject) on the biodynamic response parameters: (*a*) apparent mass, AM; (*b*) mechanical impedance, MI; (*c*) apparent stiffness, AS; and (*d*) MI phase angle; (*e*) vibration power absorption, VPA; and (*f*) vibration power transmission, VPT_imaginary

ity between the vibration power absorption value and the mechanical impedance magnitude, as shown in Figs. 9b and 9e, the correlations between the vibration power absorption and the anthropometrical parameters are also very similar to those shown in Fig. 10.

Discussion

To obtain good control of vibrating tools, the power grip is the most frequently used hand-tool coupling in the operation of many vibrating tools [27,28]. In the present study, the biodynamic response (BR) of human hand-arm system subjected to a random vibration distributed at the fingers was investigated. The related vibration power transmission (VPT) to the fingers was also examined. The finger BR and VPT can provide useful information for a more comprehensive understanding of the dynamic characteristics of the human hand-arm system and help study the mechanisms of vibration-induced injuries or disorders in the fingers. They can also be applied to develop more effective prevention strategies and anti-vibration devices for finger protection.

When calibrated as described, a mass up to 0.5 g can be reliably detected with the instrumented handle employed in this study. The lowest apparent mass at 1,000 Hz observed in this study was 11 g, which was measured at the lowest force level (15 N). Therefore, the measurement error caused by the instrumentation should be less than 5% of the true values. This accuracy level is acceptable for any practical engineering application of the BR data.

The results of this study indicate that the finger BR magnitude and vibration power absorption are independent of the hand coupling action at frequencies above 100 Hz. This suggests that the majority of the vibration power transmitted to the fingers at the higher frequencies is unlikely transmitted to other parts of the hand-arm system, and the power absorption occurs mainly in the finger tissues. This is consistent with previously reported results

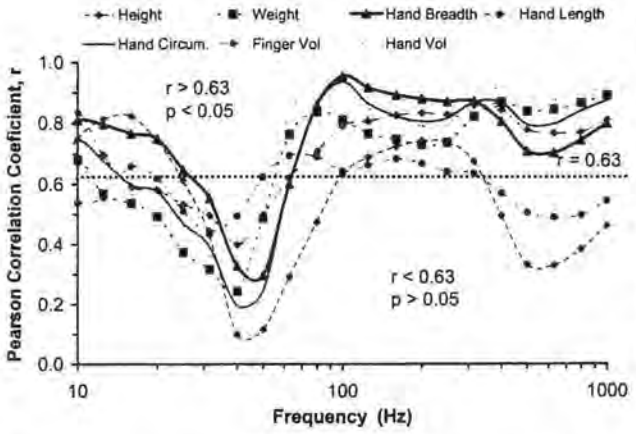

Fig. 10 Correlations between the biodynamic response magnitude and a few anthropometrical parameters (height, weight, hand breadth at the metacarpal, hand length, hand circumference at metacarpal, finger volume, and hand volume) at different frequencies

on the vibration transmission [29,30] and vibration power absorption [16]. In the transition zone (25–50 Hz), depending on the applied force, the effect of the coupling action is also fairly small (<20%). Considering there are large differences among people, such an effect may not be practically important. Coincidently, the anthropometrics are also correlated to the BR and VPA at frequencies above 50 Hz (Fig. 10). The positive correlation suggests that larger fingers generally correspond to higher BR and VPA values. This further indicates that the finger responses in the intermediate and higher frequency ranges depend mostly on the properties of the local finger tissues. This may be an important characteristic for the risk assessment and the development of effective methods for the finger protection.

Experimental results have demonstrated that additional push force in the combined coupling action results in an increased BR and VPA of the entire hand-arm system [e.g. [31]]. However, this study finds that the combined grip and push action corresponds to the lowest finger BR and VPA in the low frequency range (<40 Hz), which is consistent with the phenomenon observed in the data measured under a constant-velocity sinusoidal vibration [16]. This is likely because the soft tissues of the palm display nonlinear stiffness and the fingers move in phase with the rest of the hand-arm system at the low frequencies. The additional push force increases the palm contact stiffness and increases the vibration power transmission to the palm [16]. However, the increased palm contact stiffness reduces the relative motion between the hand and the handle at low frequencies. At the same grip force, it is unlikely that the finger contact stiffness changes significantly. Hence, the reduced relative displacement reduces the dynamic force acting on the fingers, which further reduces the vibration power transmission to the fingers.

Risk assessments using the current ISO 5349-1 (2001) standard [22] do not take into account the effect of hand force on the vibration exposure. The results of this study demonstrate that the effects of the finger force on the biodynamic response and vibration power absorption are very significant. Therefore, the hand force should be measured and considered in these exposure assessments.

Unlike the trend of the mechanical impedance (MI) in the z-direction, the MI of the entire hand-arm system in the x-direction increases with an increase in frequency [1]. In the y-direction, the BR values at different frequencies are comparable [1]. These trends indicate that vibration power absorption under a constant-velocity vibration in these directions either increases with the frequency or is comparable at different frequencies. This is because the vibration in these directions is perpendicular to the forearm orientation. In these directions, the arm tissues are less involved in the response than that in the z-direction. The wrist joint may also isolate more vibration in these directions than in the z-direction. A previous study has also demonstrated that more than 75% of the VPA in the z-direction in a regular coupling condition at frequencies less than 40 Hz is distributed at the palm and strongly influenced by the push action [16]. Hence, the high MI value of the entire hand-arm system at the low frequencies in the z-direction is largely attributed to the arm response. The results of the present study further confirmed that if the arm response is separated, the mechanical impedance of the hand structures (e.g. fingers) at the high frequencies could be higher than that at the low frequencies.

It is common knowledge that the vibration transmission distance generally reduces with the increase in frequency. For example, at frequencies above 100 Hz, less than 10% of vibration is transmitted beyond the hand [29,30]. Therefore, the vibration power absorption at the high frequencies is mostly distributed in the hand. At very high frequencies (>500 Hz), the VPA is likely distributed in the finger and hand tissues that are closely in contact with the handle. Hence, even if the total VPA value at the high frequencies is the same as that at the low frequencies, the high frequency vibration power actually absorbed in the fingers and hand must be significantly higher than the low frequency vibration power absorbed in these structures. In other words, the high frequency vibration power absorption density (VPAD=VPA per unit of tissue) in these structures must be higher than the low frequency VPAD, if the vibration velocity remains the same at all frequencies. If vibration power absorption is really a significant etiologic factor in vibration-induced finger disorders such as vibration-induced white finger, as proposed in several previous studies [3,13], the adverse vibration effects should generally increase with the VPA density. Therefore, these observations suggest that the current ISO 5349-1, 2001 [22] that assumes equal effect at the same vibration velocity for frequencies above 16 Hz underestimates the high frequency vibration effect on vibration-induced fingers and hand disorders. This finding is consistent with the results of several field studies [32–35], and NIOSH guidance on hand-transmitted vibration [36].

Conclusions

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

- The finger mechanical impedance (MI) in a power grip generally increases with vibration frequency up to approximately 250 Hz. In the frequency range of 250–1,000 Hz, the MI only changes slightly (<10%). These trends indicate that the vibration power absorption in the fingers under a constant-velocity excitation at the higher frequencies is greater than that at low frequencies (<40 Hz). Therefore, the constant-velocity weighting used in the current ISO 5349-1, 2001 standard [22] may underestimate the high frequency vibration effect on vibration-induced finger disorders.
- The biodynamic response and vibration power absorption can be practically considered independent of the type of hand coupling action when the vibration frequency is above 100 Hz. Below a certain frequency (25–50 Hz), depending the applied force, the finger BR and VPA are significantly influenced by the overall response of the hand-arm system. The hand push action decreases the finger BR and VPA at the low frequencies.
- The hand dimensions such as finger volume, hand volume, hand breadth, and hand circumference are generally positively correlated to the finger BR and VPA values at frequencies above 50 Hz. Because body weight is correlated to these hand parameters for the subjects used in this study, it is also correlated to the BR and VPA values.
- Increasing finger grip force significantly increases finger biodynamic response and vibration power absorption. Below 100 Hz, the influence is more significant under the pull-only and grip-only

actions than that under the combined grip and push action. Therefore, the coupling action, particularly the finger force, should be considered as a factor when assessing hand-transmitted vibration exposure.

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Disclaimer

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