

Estimation of Vibration Power Absorption Density in Human Fingers

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The absorption of hand-transmitted vibration energy may be an etiological factor in vibration-induced disorders. The vibration power absorption density (VPAD) may be a better measure of energy than the total power absorption of the hand-arm system. The objectives of the present study are to develop a method to estimate the average absorption density in the fingers and to investigate its basic characteristics. Ten healthy male subjects were used in this study. The biodynamic response of the fingers in a power grip subjected to a broad-band random excitation was measured under three grip forces (15, 30, 50 N) and three push forces (35, 45, 50 N). The response was used to estimate the total finger energy absorption. The response, together with the finger volume, was also used to estimate the amount of tissue effectively involved in the absorption. Then, the average VPAD under constant-acceleration, constant-power density, constant-velocity vibration spectra, and 20 tool vibration spectra were calculated. The correlations between the VPAD and the unweighted and weighted accelerations (ISO 5349-1, 2001) were also examined. The VPAD depends on both the characteristics of the vibration spectrum and the biodynamic response of the finger-hand-arm system. The biodynamic response generally plays a more important role in determining the VPAD in the middle frequency range (31.5–400 Hz) than those at the low and high ends. The applied force significantly affected the VPAD. The finger VPAD was highly correlated to the unweighted acceleration. The average VPAD can be determined using the proposed experimental method. It can serve as an alternative tool to quantify the severity of the vibration exposure for studying vibration-induced finger disorders. [DOI: 10.1115/1.1992526]

Introduction

Prolonged, occupational exposure to hand-transmitted vibration can cause a series of disorders in the vascular, sensorineural, and musculoskeletal structures of the human hand-arm system, which may manifest themselves individually or collectively [1,2]. While the best known vascular disorder is vibration-induced white finger (VWF), all of these disorders have been collectively called hand-arm vibration syndrome (HAVS). The precise conditions causing HAVS are not sufficiently known [3]. Hence, it remains an issue as to how hand-transmitted vibration should be quantified for risk assessment. The International Standard (ISO 5349-1, 2001) [3] recommends the use of frequency-weighted acceleration. The current weighting is based on the subjective perception of the hand-transmitted vibration [4], which may not truly reflect the risk associated with the development of the disorders. Some epidemiological studies have reported results consistent with the predictions in the standard [5,6], but many other studies have reported large discrepancies [7–13]. Therefore, further studies are required to determine a better frequency weighting or vibration measure.

The vibration energy/power absorption in the hand-arm system was proposed as a significant etiological factor of vibration-induced finger disorders [14]. It was also suggested that the energy dissipation in the hand would provide a better indication of vibration damage than would a measure of the vibration acceleration spectrum [14,15]. Since the energy concept was proposed more than 30 years ago, the total power absorption measured at the hand driving point has been studied by many investigators [16–21]. Some investigators have also applied this total energy

method to investigate the effects of several factors on the finger disorders [22,23]. However, some doubts about the total energy method have been raised [1,24].

The total energy method has several fundamental theoretical deficiencies. First, this method ignores the energy concentration effect. A certain amount of power concentrated in a small volume of tissue (e.g., a fingertip) may cause injuries, but that same amount may not generate any tissue damage when it is distributed throughout the entire hand-arm system. Second, the total energy method does not take into account the characteristics of the energy distribution at different frequencies. According to the energy injury concept, a vibration injury at a specific location is associated with the internal friction causing the injury or disorder. This means that disorders should be related to the intensity of the energy absorption at that location. Powered hand tools can generate a wide range of vibration components with frequencies typically from 5 to 1,500 Hz, which is roughly the frequency range of concern for hand-transmitted vibration risk assessment in the current international standard [3]. The vibration transmissibility in the hand-arm system depends on the vibration frequency. For example, vibration below 40 Hz can usually be effectively transmitted throughout the entire hand-arm system, but vibration is largely limited to the hand when its frequency is greater than 100 Hz [25–27]. Hence, the energy absorption distribution and concentration in the hand-arm system also depend on the frequency. The total energy method ignores this effect. Furthermore, tissue resistance and adaptation to vibration-induced disorders could also differ significantly at various locations. Hence, without identifying the distribution and concentration of the vibration power absorption, it is difficult to determine the dose-response relationship between the energy absorption and the disorders.

These deficiencies can be partially overcome by using the local vibration power absorption measured at the fingers [24]. A method has been recently developed to measure biodynamic responses such as mechanical impedance, apparent mass, and apparent stiff-

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ness of the fingers in a hand power grip [28]. The mechanical impedance or apparent mass can be used to estimate the finger total vibration power absorption [24,29]. The apparent mass may also be used to estimate the amount of tissue effectively involved in the vibration. In this study, it is hypothesized that the average power absorption density in the fingers can be evaluated using the total finger power absorption and the finger mass. Theoretically, the density measure should further overcome the above-mentioned deficiencies of the total energy method. Based on these hypotheses, the objectives of the present study are to develop a method to estimate the average power absorption density distributed in the fingers, and to investigate its basic characteristics such as the frequency dependency of the density, the effect of the applied force, and the relationships between the density and other vibration measures.

Methods

Total Power Absorption in the Fingers. The vibration power can be calculated from [16]:

$$P(\omega) = F(\omega) \cdot V(\omega) \quad (1)$$

where F is the dynamic force acting at the interface between hand and tool, and V is the tool vibration velocity at the interface, and ω is vibration frequency expressed in rad/sec. It is convenient and reliable to measure vibration acceleration on tools. Therefore, the velocity is usually derived from the acceleration ($V=A/\omega$).

It is inconvenient and technically difficult to directly measure the power absorption on tools in work environments. For this reason, finger power absorption is frequently calculated using the mechanical impedance or apparent mass of the fingers measured in a laboratory in conjunction with the measured vibration acceleration spectra produced by powered hand tools. If the apparent mass ($M_a=F/A$) of the fingers is available, its imaginary component can be used to calculate the finger total energy absorption with the following formula [28,29]:

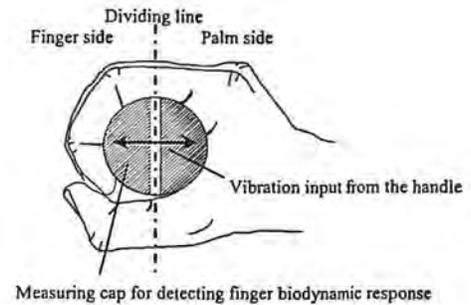
$$P(\omega) = -\text{Im}[M_a(\omega)]|A(\omega)||V(\omega)| \quad (2)$$

This formula was used in this study. The finger apparent mass was measured using the method developed in previous studies [28,29]. An instrumented handle was used to measure both the handle acceleration and the dynamic force generated by the vibration with a hand coupled to the handle in a power grip (see Fig. 1). The directly measured apparent mass includes both the handle measuring cap mass and the apparent mass of the fingers. Hence, the pure finger apparent mass was obtained by subtracting the cap mass from the measured total apparent mass. The cap mass was measured in an empty handle test (without the hand coupled to the handle).

Theoretically, the vibration power absorption determined using the above-described manner may not reflect a completely accurate value of the power actually absorbed by the finger tissues placed on the handle measuring cap, especially at frequencies less than 100 Hz. This is because a part of the vibration power transmitted to the fingers may be further transmitted to and absorbed by the other components of the hand-arm system [24]. However, a portion of the power transmitted to the palm may also be further transmitted to and absorbed by the finger tissues. While it is extremely difficult to use any experimental method to determine the location-specific power absorption accurately, it is reasonable to use the value determined using the above-described method to represent the finger power absorption, as used in the previous studies [24].

Ten male volunteers from a local university participated in the measurement. The right hand was used for the test. The individual anthropometrics for each subject are listed in Table 1. The finger and hand volumes were measured using a water immersion method [30]. The finger total power absorption and apparent mass are assumed to correspond to the finger volume actually placed on

(a)



(b)

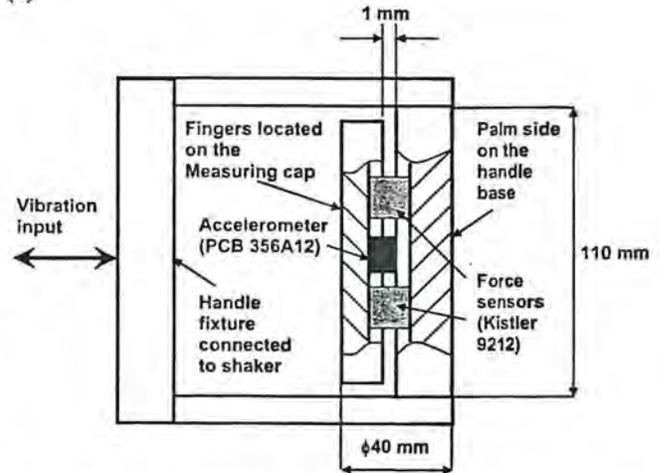


Fig. 1 Measurement of the finger biodynamic response for the estimation of average vibration power absorption density in the fingers: (a) definition of the finger response in a hand power grip on a tool handle, and (b) instrumented handle used for the measurement [28]

half of the instrumented handle [28]. To determine the volume of the fingers with the hand positioned in a power grip, the subject gripped an aluminum pipe with the same diameter (40 mm) as the instrumented handle using the same grip posture as that used in the biodynamic measurement. In the measurement, the fingers were submerged in water up to the handle centerline, as shown in Fig. 2. The finger volume was obtained by subtracting half of the pipe volume.

A broadband random vibration (10–1,250 Hz) with a flat power spectral density (PSD) value of $3.0 \text{ (m/s}^2\text{)}^2/\text{Hz}$ in the frequency range of 16–1,000 Hz was used as vibration input in the experiment [29]. The combined palm push and finger grip with three levels of force combinations (grip 15 N+push 35 N, grip 30 N+push 45 N, and grip 50 N+push 50 N) were used. 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. It was very difficult to maintain the exact force values during the vibration exposure but the error was controlled within $\pm 3 \text{ N}$. The standing height of each subject was adjusted so that his forearm was maintained at a horizontal level while the upper arm was in the vertical direction. The vibration was delivered to the hand along the forearm direction. This test posture is the same as that specified in the international standard (ISO-10819, 1996) for glove tests [31]. The apparent mass was expressed at the one-third octave band center frequencies from 10 to 1,000 Hz.

Table 1 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 grip volume=water displaced by fingers submerged to the centerline of a 40 mm handle as shown in Fig. 2 and estimated finger soft tissue volume calculated with Eqs. (2) and (3)].

Subject	Height (cm)	Weight (kg)	Hand length (mm)	Hand breadth (mm)	Hand volume (ml)	Finger grip volume (ml)	Estimated finger soft tissue vol (ml)
1	175.3	69.5	185	88	360	115	77
2	177.8	83.0	197	93	406	132	88
3	185.4	90.7	192	97	440	147	98
4	175.3	132.5	207	101	550	183	122
5	175.3	100.2	184	103	445	145	97
6	185.4	66.2	197	93	350	110	73
7	185.4	96.6	200	101	445	119	79
8	175.3	77.1	190	85	375	125	83
9	162.6	61.2	180	80	295	95	63
10	198.1	152.4	205	107	550	195	130
Mean	179.6	92.9	194	95	422	137	91
SD	9.5	29.4	9	9	83	32	21

Estimation of the Amount of Soft Tissue Effectively Involved in the Vibration Response. From a mechanical point of view, the human fingers-hand-arm system is an extremely sophisticated structure. Similar to the finger power absorption, it is extremely difficult to precisely determine the effective mass—that mass effectively involved in the dynamic response. Some approximations have to be made to obtain a reasonable solution. This study assumed that only the soft tissues could effectively absorb the vibration energy in the frequency range of concern (10–1,000 Hz). With this assumption, the problem becomes how to determine the mass or volume of soft tissue effectively in-

involved in the response at different frequencies.

At low frequencies (≤ 10 Hz), the fingers have a strong mass-like response to the vibration, as evidenced from the low apparent mass phase angle ($|\phi| < 20$ deg) [28,29]. Therefore, it is reasonable to assume that almost all finger soft tissues are involved in the vibration response at low frequencies. The volume of the finger soft tissues was determined from the following relationships:

$$\rho_{FS}V_{FS} + \rho_{FB}V_{FB} = \rho_F V_F \quad (3)$$

$$V_{FS} + V_{FB} = V_F \quad (4)$$

where V_{FS} is the finger soft tissue volume, V_{FB} is the finger bone volume, V_F is the finger volume that is directly measured and listed in Table 1, ρ_{FS} is the finger soft tissue mass density, ρ_{FB} is the finger bone mass density, and ρ_F is the overall mass density of the fingers.

According to the reported information [30,32], it is reasonable to take the soft tissue density (ρ_S) as 1.0 g/cm^3 and the bone density (ρ_B) as 1.9 g/cm^3 . The ρ_F value was not found in the literature, so it was estimated based on the following information: the average density of the entire hand can be taken as 1.16 g/cm^3 [29]; based on reported hand anatomy [33], it is assumed that the overall mass density of the fingers is marginally higher than the hand density. Hence, the finger overall density (ρ_F) was taken as 1.3 g/cm^3 in this study. The only unknown variables are V_{FS} and V_{FB} , and they can be resolved from Eqs. (3) and (4). The estimated volume of finger soft tissues for each subject is also listed in Table 1.

The apparent mass usually fluctuates as a function of the applied finger force [29]. To account for this, the effective mass at 10 Hz under the i th of three force levels was estimated using the following formula:

$$M_{FE}(20\pi)_i = \frac{\text{Re}[M_a(20\pi)]_i}{\frac{1}{3} \sum_{i=1}^3 \text{Re}[M_a(20\pi)]_i} M_{FS} \quad (5)$$

where M_{FS} is the mass of the finger soft tissue, and it is calculated from the soft tissue mass density ($\rho_{FS}=1$) and the volume of the finger soft tissue (V_{FS}) listed in Table 1 using the following formula:

$$M_{FS} = V_{FS}\rho_{FS} \quad (6)$$

In this way, the volume and mass of the finger soft tissues at the

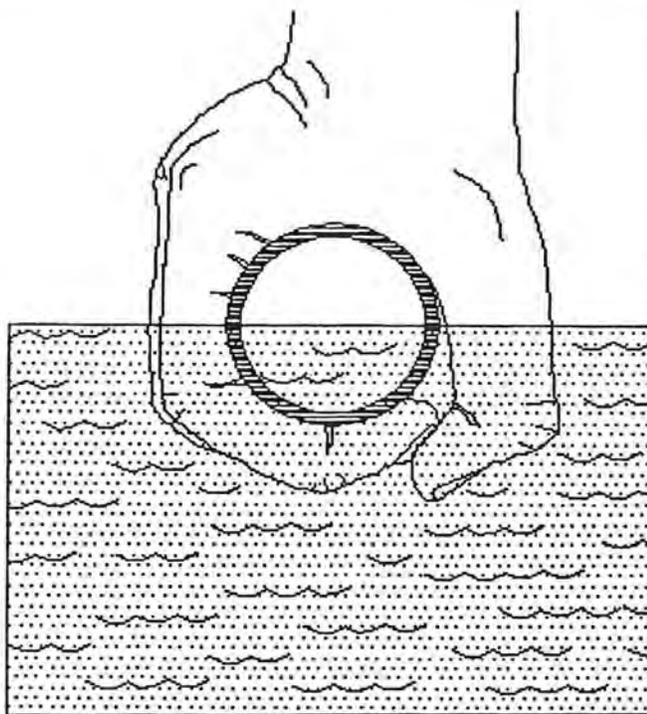


Fig. 2 Hand posture in the measurement of finger grip volume. The subject grasps a short section of pipe with a diameter equal to that of the instrumented handle. The hand is then immersed to a level marked on the index finger that is in-line with the crease at the base of the subject's third proximal phalange.

low frequency (10 Hz) are determined.

At very high frequencies ($\geq 1,000$ Hz), only the soft tissue in contact with the handle is likely to be effectively involved in the vibration response. The finger response at such frequencies also reflects a fairly strong masslike characteristic [28,29]. Therefore, it is assumed that the real part of the finger apparent mass is representative of the mass effectively involved in the response at high frequencies. The effect of the finger force on the mass at the high end of the frequency range (1,000 Hz) can be taken into account by using the measured real part of the apparent mass. In such a way, the amount of soft tissue involved in the response at this high frequency (1,000 Hz) is also determined.

Because vibration transmission distance generally reduces with an increase in frequency [25,26], the effective mass should generally decrease with an increase in frequency. Therefore, it may be a good approximation to use a power decay function to represent the relationship between the amount of effective soft tissue and the vibration frequency. The power function ($=\lambda\omega^{-\beta}$, where β and λ are constants determined by curve fitting) fits the real part of the finger apparent mass very well (Pearson correlation coefficient > 0.95 , $p < 0.001$). Hence, it is assumed that the mass of the finger effective soft tissue (M_{FE}) has the same trend as the real part of the apparent mass, which is expressed as follows:

$$M_{FE}(\omega) = \lambda\omega^{-\beta} \quad (7)$$

The two parameters in this equation are determined from the effective mass values at 10 Hz and 1,000 Hz. In this way, the effective mass of finger soft tissue from 10 and 1,000 Hz is fully determined.

Finger Power Absorption Density. In this study, the average power absorption density (σ) is defined as the ratio of the power absorption to the effective mass of the finger soft tissues. From Eqs. (2) and (7), it is expressed as follows:

$$\sigma(\omega) = \frac{P}{M_{FE}} = \left\{ \frac{-\text{Im}[M_a(\omega)]}{M_{FE}(\omega)} \right\} \cdot \{|A(\omega)||V(\omega)|\} \quad (8)$$

The form of this equation clearly indicates that the product of acceleration (A) and velocity (V) has a power density unit, which can also be confirmed through dimensional analysis. Therefore, the product represents the vibration power density flowing from the tool handle or vibration source. In this study, it is called source power density (SPD). The remaining part of Eq. (8) (in the first big bracket) is a nondimensional parameter. It reflects the capacity of the fingers to absorb the vibration energy. Hence, it is termed as power absorption coefficient (PAC) in this study. With this terminology, Eq. (8) is reduced to

$$\sigma(\omega) = \xi(\omega) \cdot p_s(\omega) \quad (9)$$

where ξ is the power absorption coefficient function, and p_s is the source vibration power density function. They are evaluated from:

$$\xi(\omega) = \frac{-\text{Im}[M_a(\omega)]}{M_{FE}(\omega)}, \quad (10)$$

$$p_s(\omega) = |A(\omega)||V(\omega)| \quad (11)$$

Equation (9) indicates that the average finger power absorption density (σ) depends on both the tool vibration and the finger response. Hence, the characteristics of the finger power absorption density can be understood by examining the features of the finger response coefficient in Eq. (10) and the source power density in Eq. (11). Three types of idealized excitations (constant-acceleration, constant-SPD acceleration, and constant-velocity acceleration) were used to examine the fundamental characteristics of these parameters.

In addition, 20 tool vibration spectra reported by Griffin [34] were also used to examine the correlations among ISO standardized frequency-weighted acceleration (A_w) [18], unweighted ac-

celeration (A_u), and tool power absorption density (σ). These three vibration measures are calculated from the following formulas:

$$A_w = \sqrt{\sum_{i=1}^{21} (w_i a_{ui})^2} \quad (12)$$

$$A_u = \sqrt{\sum_{i=1}^{21} (a_{ui})^2} \quad (13)$$

$$\sigma_i = \sum_{i=1}^{21} \sigma(2\pi f_i) = \sum_{i=1}^{21} \xi(2\pi f_i) p_s(2\pi f_i) = \sum_{i=1}^{21} \xi(2\pi f_i) \cdot (a_{ui})^2 / (2\pi f_i) \quad (14)$$

where f is the 1/3 octave band frequency from 10 Hz to 1,000 Hz, i is the frequency index, and a_{ui} is the tool acceleration value at the i th 1/3 octave band frequency.

Data Statistical Analysis. In this study, a two-factor-repeated-measures analysis-of-variance (ANOVA) was used to conduct the general statistical analysis. The first factor is the effect of the vibration exposure (frequency), and the second one is the influence of the applied force. The ANOVA was done using a conventional mixed model with frequency and force as fixed effects and subject as a random effect. A stratified ANOVA was further performed to identify the effect of the force at each one-third octave band center frequency. Post hoc comparisons were also calculated using Tukey's method to determine the effect at different force levels. The statistical analyses were performed using MINITAB statistical software (version 13.1).

Results

Apparent Mass and Finger Power Absorption Coefficient. As indicated in Eq. (2), the imaginary part of the apparent mass is related to the power absorption, and the results are presented in Fig. 3(a). As found in an earlier study, the response of the entire hand-arm system measured at the palm has a resonant frequency in the range of 25–63 Hz [28]. Affected by this resonance, the imaginary component in this frequency range also displays a resonantlike value [Fig. 3(a)]. The results of the stratified ANOVA at each frequency indicate that the effect of the force from 40 to 80 Hz and from 200 to 1,000 Hz is significant ($F_{2,18} \geq 4.64$, $p < 0.024$). The results of the post hoc comparisons suggest that the imaginary mass measured at different force levels is generally significantly different ($p < 0.05$) in these frequency ranges. As shown in Fig. 3(a), increasing the applied finger force generally increases the imaginary part of the apparent mass and thus the energy absorption.

The results of the real part of the apparent mass are plotted in Fig. 3(b). The ANOVA results also indicate that the frequency-by-force interaction is significant ($F_{40,360} = 3.56$, $p < 0.001$). Except at 80 and 100 Hz, the effect of the force on the real part is either significant ($F_{2,18} \geq 6.83$, $p \leq 0.003$) or suggestively significant ($F_{2,18} \geq 2.58$, $0.05 \leq p \leq 0.10$). The results of the post hoc comparisons also confirm that increasing the applied force generally increases the real part of the apparent mass ($p < 0.05$).

The effective mass (M_{FE}) values at the three force levels are also shown in Fig. 3(b). A higher force combination corresponds to a higher effective mass. The effective mass is very close to the real component of the apparent mass at frequencies higher than 400 Hz, which suggests that the approximation of the effective mass with the power decay function is reasonable, at least in this frequency range.

The power absorption coefficient (PAC) function is plotted in Fig. 4. The significant frequency-by-force interaction ($F_{40,360} = 3.29$, $p < 0.001$) indicates that the effect of the force at different

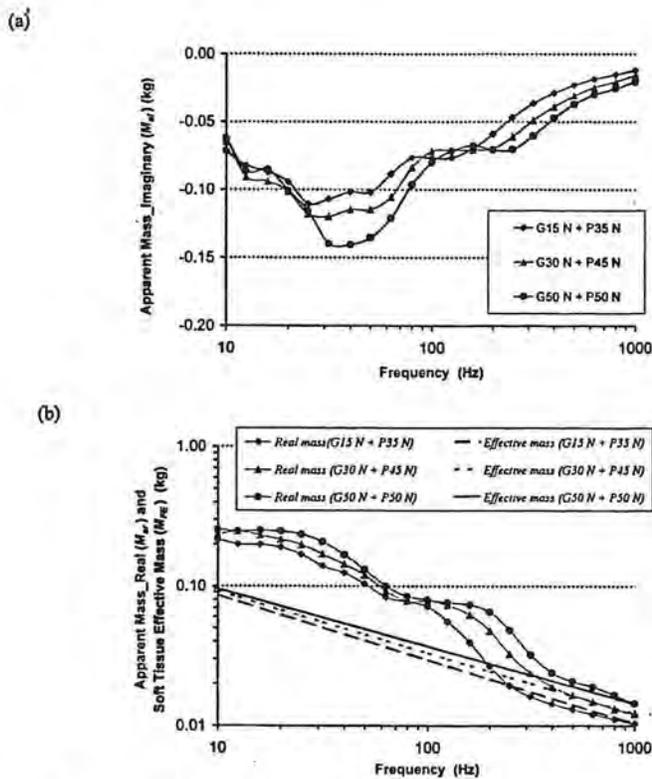


Fig. 3 Apparent mass at the fingers measured with ten male subjects: (a) the imaginary component (M_{im}) of apparent mass (imaginary mass); (b) the real component (M_{re}) of apparent mass (real mass), and the estimated mass (M_{fe}) effectively involved in the response. Three combined grip (G) and push (P) actions were used in the experiment.

frequencies is generally different. The effects of the force on the real and imaginary components seem approximately proportional at some frequencies. Therefore, the effects are at least partially cancelled when their ratio (the PAC function) is evaluated. This leads to the insignificant force effect from 10 to 80 Hz ($F_{2,18} \leq 2.34, p \geq 0.116$). Higher than 80 Hz, however, the effect is significant ($F_{2,18} \geq 4.29, p \leq 0.018$) except at 200 Hz ($F_{2,18} = 1.48, p = 0.235$). The power absorption coefficient in the middle frequency range (31.5–400 Hz) is generally higher than that at the lower (<31.5 Hz) and higher (>400 Hz) frequencies. There are also two peak values in the middle frequency range. Depending

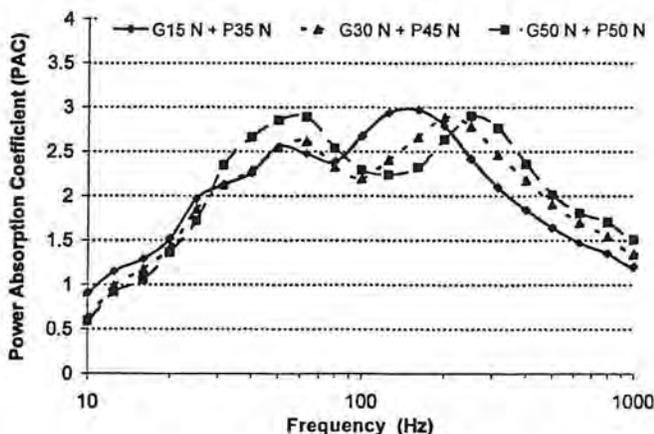


Fig. 4 Power absorption coefficient functions under three combined grip (G) and push (P) actions

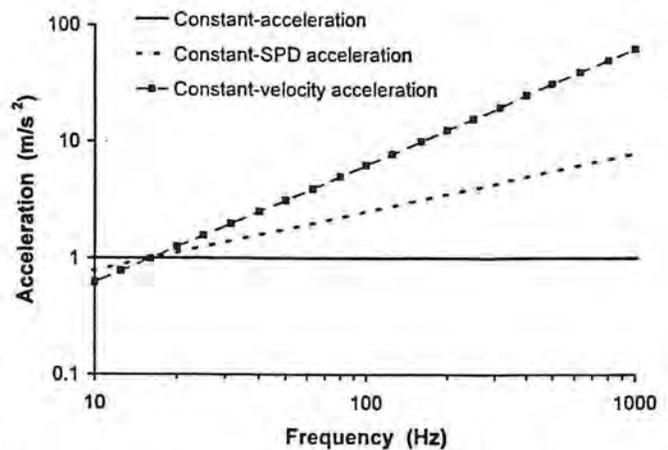


Fig. 5 Accelerations with constant-acceleration, constant-velocity, and constant-source power density, which are normalized to the value at 16 Hz

on the force level, one is in the range of 40–63 Hz, and the other one is between 125 Hz and 315 Hz. For the second peak value, the lower force obviously corresponds to a lower resonant frequency.

Source Power Density (SPD). As shown in Eq. (11), the source power density is proportional to the vibration velocity and acceleration. If a constant SPD value is assumed, the acceleration is proportional to the square root of the frequency. The accelerations for the three types of idealized excitations (constant-acceleration, A_{ACC} , constant-SPD acceleration, A_{SPD} , and constant-velocity acceleration, A_{VEL} , can be expressed as follows:

$$A_{ACC} = \kappa \omega^{0.0} \quad A_{SPD} = \gamma \omega^{0.5} \quad A_{VEL} = \eta \omega^{1.0} \quad (15)$$

where κ , η , and γ are constants that can be determined from a given value at a specific frequency. Equation (15) indicates that the differences among these accelerations are in their power indexes of frequency. The relationships among these three accelerations are illustrated in Fig. 5. The change rate of the constant-SPD acceleration is much lower than that of constant-velocity acceleration. For example, at 1,000 Hz, the constant-velocity acceleration becomes 62.5 times the acceleration at 16 Hz, but the constant-SPD acceleration is only 7.9 times that at 16 Hz.

Finger Vibration Power Absorption Density (VPAD) for Three Special Spectra. For the purpose of this study, the mean value of the power absorption coefficients (PACs) measured with the three force levels was used to examine the fundamental characteristics of the average vibration power absorption density in the fingers. The three types of idealized acceleration excitations were used to calculate the power absorption density. The results were normalized to the value at 16 Hz and plotted in Fig. 6. For comparison, the finger total vibration power absorption (VPA) is also plotted in this figure.

At frequencies higher than 16 Hz, except in the cases of the constant-acceleration vibration at frequencies higher than 80 Hz [see Fig. 6(a)], the relative weighting of the finger total power absorption (VPA) is higher than that of the ISO-weighted acceleration [see Figs. 6(b) and 6(c)]. The weighting of the finger VPAD relative to that at 16 Hz is always higher than that of the finger VPA in all three cases. Their relationships to the unweighted acceleration depend on the characteristics of the source vibration. The relative weighting becomes significantly higher than that of the unweighted acceleration in the case of constant-velocity vibration, while in the other two cases, the relative weighting of the unweighted acceleration is higher than that of the finger VPAD at 40 Hz in the constant-acceleration vibration and at 100 Hz in the constant-SPD vibration.

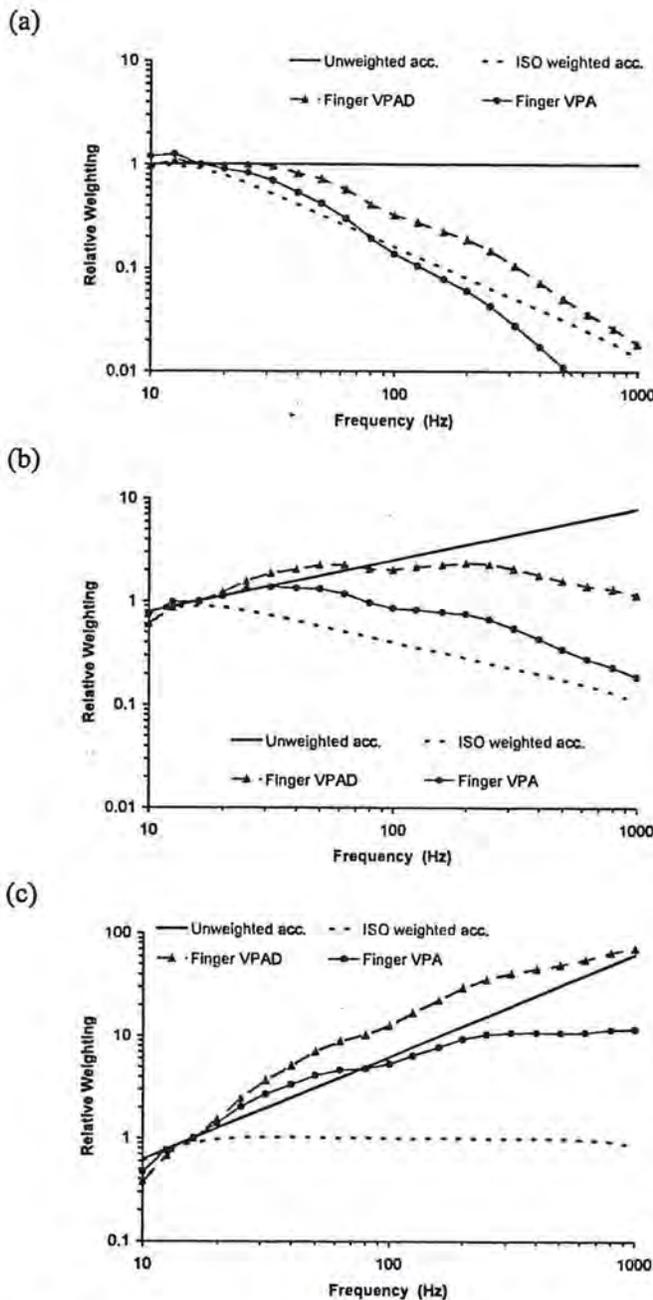


Fig. 6 The relative frequency weightings of the four vibration measures [unweighted acceleration, ISO-weighted acceleration, average finger vibration power absorption density (VPAD), and finger vibration power absorption (VPA)] for the three different types of idealized vibration inputs: (a) constant-acceleration; (b) constant-source power density (SPD) acceleration; and (c) constant-velocity acceleration. The weightings are normalized to the value at 16 Hz.

Finger Vibration Power Absorption Density (VPAD) on 20 Tool Spectra. The correlations among the ISO frequency-weighted acceleration, the unweighted acceleration, and the tool power absorption density of the 20 tools [34] are shown in Fig. 7, which are calculated from Eqs. (12)–(14). For direct comparison, the data for each type of the three vibration measures are normalized to the value for one (rock drill) of the tools. While the ISO frequency-weighted acceleration is poorly correlated to the unweighted acceleration [Fig. 7(a)], the finger VPAD has a stronger correlation to the unweighted acceleration [Fig. 7(c)], than to the ISO weighted acceleration [Fig. 7(b)].

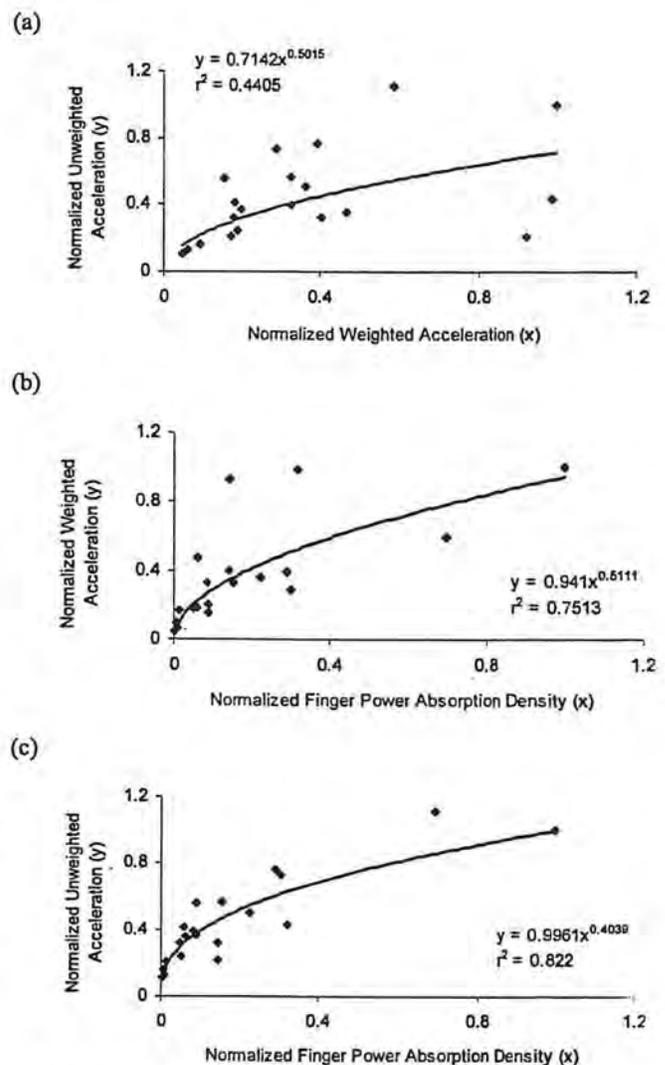


Fig. 7 Correlations among the finger vibration power absorption density and two acceleration measures: (a) frequency-weighted acceleration vs unweighted acceleration, (b) finger VPAD vs weighted acceleration, and (c) finger VPAD vs unweighted acceleration. The results are calculated using 20 tool vibration spectra reported by Griffin [32] and the data are normalized to the values for one of the tools (rock drill).

Discussion

This study developed a practical method to estimate the average vibration power absorption density of the fingers while using a powered hand tool. This method overcomes some critical deficiencies of the traditional total energy method that has been almost exclusively used for more than 30 years. Hence, this method provides a new means to study hand-transmitted vibration exposure and the mechanisms of vibration-induced finger disorders.

This study finds that there are two major peak values in the power absorption coefficient function. The first peak frequency range (between 40 Hz and 63 Hz) corresponds to that of the overall resonance of the hand-arm system [24]. The second peak (between 125 Hz and 315 Hz) is in the frequency range of the finger resonance on the handle [28,29]. A lower finger force results in a lower contact stiffness, which explains why the lower force corresponds to a lower resonant frequency. Because of these two resonant effects, the absorption coefficient in the middle frequency range is generally higher than those in the other frequency regions (<31.5 Hz or >400 Hz) (see Fig. 3). This means that the fingers are forced to absorb more energy because of the resonance effects.

nances. This seems consistent with the nature of vibration-induced structure risks. Hence, the proposed density measure reflects this natural phenomenon.

The energy concentration effect is also well reflected in the finger vibration power absorption density measure. As shown in Fig. 6, the relative weighting of the density measure (finger VPAD) in the high frequency range is always greater than that of the finger total energy measure (finger VPA). The results shown in Fig. 6(c) indicate that a severe high frequency vibration can result in a high power density but the total power is not very significant at the high frequency. Based on this observed energy concentration effect, it is reasonable to anticipate that high frequency vibration exposure may cause finger local injuries or disorders. Many percussive tools such as chipping hammers, riveting hammers, and rock drills exhibit fundamental vibration frequencies in the low-middle frequency range (20–63 Hz). However, these tools can also generate significant high frequency components that may also result in a fairly high energy density. Dental tools and ultrasonic devices can also generate very high frequency vibration that may cause some disorders [12,13]. According to the frequency weighting recommended in the current international standard (ISO-5349-1, 2001) [3], such high frequency vibration (>500 Hz) components are almost totally ignored. This may at least partially explain the inconsistencies between the epidemiological study results [7–13] and the predictions of the ISO-recommended assessment method. The power absorption density measure can take into account the high frequency effects.

A recent study reported that the unweighted acceleration has a better correlation with the vibration-induced white finger [35]. This is also consistent with the position on this issue published by U.S. National Institute for Occupational Safety and Health [36]. As shown in Fig. 7, the proposed density measure has a strong association with the unweighted acceleration. Compared with the tool acceleration method, the energy method has some unique advantages. For example, the hand-tool coupling condition, the vibration direction, and individual differences can be taken into account in the vibration exposure study [15,22,23]. Therefore, the proposed power density method may be a good alternative tool for studying hand-transmitted vibration exposure.

Finally, it should be noted that the method proposed in this study is an approximation method, and it is far from perfect. In addition to the approximations mentioned in the method section, the proposed density measure also has several other deficiencies. First, the vibration power absorption may mainly concentrate in the finger soft tissues that exhibit large deformations. The averaging technique cannot identify the detailed local concentration. Second, this study assumes that the power absorption increases linearly with an increase in the vibration magnitude. This assumption is acceptable when the vibration magnitude is limited to within a certain range [19]. The power absorption may become significantly nonlinear when the source vibration reaches a certain high level [21]. The nonlinear behavior, however, should not change the fundamental characteristics of the average power density observed in this study. Third, there may be some errors in the estimation of the soft tissue volume involved in the vibration. Such errors can be reduced when a better finger density value or a more reliable soft tissue measurement method is available. Fourth, the precise volume of the soft tissues effectively involved in the vibration response could be a very complicated function of the frequency. The function used in this study may only be a rough approximation. Without using a comprehensive computer model of the entire finger-hand-arm system, it is difficult to determine the exact distribution and magnitude of the vibration power absorption density. Nevertheless, the proposed method represents the very first effort in quantifying the vibration power absorption density in human fingers. Despite its various limitations, this method can certainly be used as an alternative tool to investigate hand-transmitted vibration exposure.

Conclusions

A novel energy method for studying hand-transmitted vibration exposure was developed. The technique is based on the measurement of the average vibration power absorption density in human fingers. Based on the results and observations of this study, several conclusions are made as follows:

- (1) The finger vibration power absorption density depends on both the characteristics of the source vibration and the biodynamic response of the finger-hand-arm system.
- (2) The power density method largely overcomes the deficiencies of the traditional total energy method that has been almost exclusively used.
- (3) The proposed density method can also take into account many influencing exposure factors such as the resonance of the finger-hand-arm system, the hand-tool coupling condition (applied force and coupling action), and individual differences. It can serve as an alternative tool to quantify the severity of the vibration exposure for studying vibration-induced finger disorders.

Disclaimer

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