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Frequency weighting derived from power absorption of fingers–hand–arm system under z_h-axis vibration

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Abstract

The objectives of this study are to derive the frequency weighting from three vibration power absorption (VPA) methods (finger VPA, palm VPA, and total or hand VPA), and to explore whether these energy methods are better than the currently accepted acceleration method. To calculate the VPA weightings, the mechanical impedance of eight subjects exposed to a broadband random vibration spectrum in the z_h-axis using 18 combinations of hand couplings and applied forces was measured. The VPA weightings were compared with the frequency weighting specified in ISO 5349-1 [2001. Mechanical Vibration—Measurement and Evaluation of Human Exposure to Hand-Transmitted Vibration—Part 1: General Requirements. International Organization for Standardization, Geneva, Switzerland]. This study found that the hand and palm VPA weightings are very similar to the ISO weighting but the finger VPA weighting for the combined grip and push action is much higher than the ISO weighting at frequencies higher than 25 Hz. Therefore, this study predicted that the total power absorption of the entire hand–arm system is likely to be correlated with psychophysical response or subjective sensation. However, if the ISO weighting method cannot yield good predictions of the vibration-induced disorders in the fingers and hand, the hand and palm energy methods are unlikely to yield significantly better predictions. The finger VPA is a vibration measure between unweighted and ISO weighted accelerations. The palm VPA method may have some value for studying the disorders in the wrist–arm system.
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Keywords: Hand-transmitted vibration; Hand–arm vibration; Energy absorption; Frequency weighting; Vibration-induced white finger

1. Introduction

Hand–arm vibration syndrome (HAVS) is collective terminology for a series of vibration-induced disorders in the vascular, sensorineural, and musculoskeletal structures of the human hand–arm system (Griffin, 1990; Pelmear and Wasserman, 1998). The precise conditions causing each component of the HAVS are not sufficiently known (ISO 5349-1, 2001). Hence, it remains unclear which measure is best for quantifying the severity of vibration exposure for risk assessment. The international standard ISO 5349-1 (2001) recommends the use of frequency-weighted acceleration. This weighting function was derived from sensation data of the hand–arm system (Miwa, 1968), which may not truly reflect the risk of developing injuries or disorders. While a few epidemiological studies have reported results consistent with the predictions in the standard (Brammer, 1986; Anttonen and Virokannas, 1992), many other studies have reported large differences (Dandanell and Engstrom, 1986; Bovenzi et al., 1988; Nilsson et al., 1989; Starck et al., 1990; Pelmear et al., 1989; Lundström and Lindmark, 1982). Therefore, an improved vibration exposure measure or frequency weighting is required.

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More than 40 years ago, several investigators (Pradko et al., 1965; Lidström, 1973; Cundiff, 1976) proposed that the vibration energy/power absorption (VPA) might be a significant etiological factor in regards to vibration-induced disorders. Furthermore, the measurement of VPA can also reflect many influencing factors such as hand-tool coupling conditions, hand–arm posture, and vibration direction in tool operation. Based on these observations, Lidström (1973) further hypothesized that the power dissipation in the hand–arm system could provide a better indication of vibration damage than would the measure of the tool vibration acceleration. Since the energy concept was proposed, a total energy method expressed as the VPA of the entire hand–arm system has been almost exclusively used to study the power absorption by many investigators—as reviewed by Dong et al. (2001). It has also been reported that a correlation exists between subjective annoyance and the total VPA (Reynolds, 1977). There was only one reported epidemiological study that directly investigated the relationship between the VPA and vibration-induced white finger (Lidström, 1977), which is the most recognized and important component of the HAVS (ISO 5349-1, 2001). The results showed that the prevalence of the finger disorders increased with the total VPA but the relationship was substantially nonlinear. Although these investigations were far from sufficient to validate the energy method, some investigators concluded that the ‘‘measurement of the energy absorbed in the hand and arm may be a better and more objective method for risk assessment of hand-transmitted vibration’’ (e.g. Burström, 1990). Hence, they used this method to investigate several factors that could affect the development of HAVS (e.g. Burström and Bylund, 2000; Bylund and Burström, 2003). This total energy method was not seriously questioned until Dong et al. (2001) started to examine it. They recently pointed out that although the energy concept may have some value for studying the hand-transmitted vibration exposure, the implementation of the total vibration power absorption has several fundamental deficiencies and this method is not likely to provide good predictions of vibration-induced disorders in the fingers and hand (Dong et al., 2004a, b). However, more studies are required to clarify this issue.

From the point-of-view of biomechanics, the human hand is a very sophisticated and flexible structure. The biodynamic response distributed on the fingers is very different from that distributed on the palm of the hand (Dong et al., 2005). Therefore, the energy transmission and absorption at these two parts of the hand could also generally be very different (Dong et al., 2004a). Whereas most of the VPA measured at the palm is likely in the palm–wrist–arm system, the energy absorption measured at the fingers is likely in the finger soft tissues at frequencies higher than 100 Hz (Dong et al., 2004a). Hence, if the energy absorption is really associated with the vibration-induced disorders, the finger VPA and palm VPA may play different roles in the development of the disorders. They may thus be used to predict different types of disorders in the hand–arm system. A method has been recently developed to measure them separately (Dong et al., 2004a). Because the local energy method can partially overcome the deficiencies of the total energy method, the finger VPA method may provide better predictions of the finger disorders than the total VPA method. This hypothesis has not been investigated.

The direct testing of the energy hypotheses requires a comprehensive epidemiological study. Such a study may not only be expensive and time-consuming but also technically difficult in terms of both the energy measurement and the diagnoses of the disorders. The measurement of the VPA requires measuring both the dynamic force and acceleration simultaneously. The development of a convenient and reliable device to measure the distributed power absorption values remains a formidable research task. Hence, without sufficiently proving the potential of these energy methods, it may not be worth performing such a development and conducting the epidemiological study. Alternatively, the energy hypotheses can be indirectly investigated by identifying the frequency dependencies of these energy measures in laboratory studies and comparing them with the ISO weighting that has been tested in many epidemiological studies. Such an approach has been used in the study of whole-body vibration exposure by Mansfield and Griffin (1998). Donati (2001) has also performed a preliminary study of the frequency weighting derived from the total energy method. However, this method has not been applied to evaluate the finger and palm energy methods. Furthermore, the establishment of the VPA-based frequency weighting can make it convenient to further evaluate the energy methods when more reliable tool acceleration spectra and medical data are available from field studies.

Based on this background, the specific aims of this study are (a) to clarify and further develop the method for deriving the VPA-based frequency weighting; (b) to derive the frequency weightings of the finger VPA, palm VPA, and total or hand VPA methods by measuring the biodynamic responses under the z_h-axis vibration (ISO 5349-1, 2001) or along the forearm direction; (c) to investigate the effects of hand coupling actions and applied forces on the frequency weightings; (d) to compare the VPA-based weightings with the ISO weighting; and (e) to use the comparisons as bases to explore whether these energy methods are better than the currently accepted acceleration method for studying various components of the hand–arm vibration syndrome.

2. Methods

2.1. Theory

Vibration power absorption (P) is conventionally defined as

$$P = \boldsymbol{F} \cdot \boldsymbol{V}, \tag{1}$$

where $\boldsymbol{F}$ is the vibration force acting at the driving-point, and $\boldsymbol{V}$ is the vibration velocity at the same acting point. There is generally a phase difference between the velocity and force at each frequency. Hence, it is convenient to express them in complex form. As Eq. (1) dictates, the power absorption at each frequency depends on the magnitudes of the force and velocity and their relative phase angle. Hence, we can always use the velocity signal as a reference and assume its phase angle to be zero at each frequency. The velocity and force signals in the complex domain are thus written as

$$\begin{aligned} \boldsymbol{V} &= |\boldsymbol{V}|\cos(0) + \mathrm{j}|\boldsymbol{V}|\sin(0), \\ \boldsymbol{F} &= |\boldsymbol{F}|\cos(\varphi) + \mathrm{j}|\boldsymbol{F}|\sin(\varphi), \end{aligned} \tag{2}$$

where φ is the phase difference between velocity and force, and $\mathrm{j} = \sqrt{-1}$. Hence, the power absorption at each frequency can be calculated from

$$P = |\boldsymbol{F}||\boldsymbol{V}|\cos(\varphi). \tag{3}$$

It is inconvenient to measure the power absorption directly on real tools because special instrumentation is required. Alternatively, the absorption can be estimated using the driving-point mechanical impedance of the hand–arm system ($\boldsymbol{Z}$), which is defined as

$$\boldsymbol{Z} = \frac{\boldsymbol{F}}{\boldsymbol{V}}. \tag{4}$$

Unlike the power absorption, the impedance is generally complex. It can be determined using the auto-correlation ($\boldsymbol{G}_{VV}$) and cross-correlation ($\boldsymbol{G}_{FV}$) (Bendat and Piersol, 1986):

$$\boldsymbol{Z} = \frac{\boldsymbol{G}_{FV}}{\boldsymbol{G}_{VV}} = \mathrm{Re}(\boldsymbol{Z}) + \mathrm{j}\mathrm{Im}(\boldsymbol{Z}). \tag{5}$$

From the above equations, the impedance can be expressed as

$$\begin{aligned} \boldsymbol{Z} &= \frac{|\boldsymbol{F}|\cos(\varphi) + \mathrm{j}|\boldsymbol{F}|\sin(\varphi)}{|\boldsymbol{V}|\cos(0) + \mathrm{j}|\boldsymbol{V}|\sin(0)} \\ &= \frac{|\boldsymbol{F}|\cos(\varphi) + \mathrm{j}|\boldsymbol{F}|\sin(\varphi)}{|\boldsymbol{V}|} \cdot \frac{|\boldsymbol{V}|}{|\boldsymbol{V}|} \\ &= \frac{|\boldsymbol{F}||\boldsymbol{V}|\cos(\varphi) + \mathrm{j}|\boldsymbol{F}||\boldsymbol{V}|\sin(\varphi)}{|\boldsymbol{V}|^2} \\ &= \frac{\boldsymbol{F} \cdot \boldsymbol{V} + \mathrm{j}|\boldsymbol{F}||\boldsymbol{V}|\sin(\varphi)}{|\boldsymbol{V}|^2} = \frac{P + \mathrm{j}|\boldsymbol{F}||\boldsymbol{V}|\sin(\varphi)}{|\boldsymbol{V}|^2} \\ &= \mathrm{Re}(\boldsymbol{Z}) + \mathrm{j}\,\mathrm{Im}(\boldsymbol{Z}). \end{aligned} \tag{6}$$

Hence,

$$P(\omega) = \mathrm{Re}[\boldsymbol{Z}(\omega)] \cdot |\boldsymbol{V}(\omega)|^2 = \mathrm{Re}[\boldsymbol{Z}(\omega)] \cdot \left|\frac{\boldsymbol{A}(\omega)}{\omega}\right|^2, \tag{7}$$

where $\boldsymbol{A}$ is tool acceleration, and ω is frequency in rad/s. This equation makes it possible and convenient to estimate the power absorption when the tool acceleration spectrum is available.

The currently accepted weighting in ISO 5349-1 (2001) is established with respect to acceleration. To make the VPA-based weighting directly comparable with ISO weighting, the square root of the VPA can be considered as a vibration measure that has a linear relationship to acceleration (Mansfield and Griffin, 1998). Furthermore, the weighting should be normalized to a reference value for direct comparison and its convenient application. Since the maximum value of the ISO weighting in the $\frac{1}{3}$ octave band is 0.958 at 12.5 Hz, the VPA weightings are normalized with respect to this value in this study. Therefore, from expressed in Eq. (7), the VPA-based frequency weighting (W_{VPA}) at each frequency is expressed as follows:

$$\mathrm{W}_{\mathrm{VPA}}(\omega_i) = 0.958\,\frac{\sqrt{Re[\boldsymbol{Z}(\omega_i)]}}{\omega_i}\bigg/\frac{\sqrt{Re[\boldsymbol{Z}(\omega_{\mathrm{REF}})]}}{\omega_{\mathrm{REF}}}, \tag{8}$$

where ω_{REF} is the frequency of the reference impedance, which can be selected based on the convenience for the weighting comparisons or the purpose of a study.

2.2. Impedance measurement

As shown in Eq. (8), the only biodynamic response parameter required for the determination of the VPA-based weighting is the driving-point mechanical impedance (MI). The impedance on z_{h}-axis is the maximum one among the three orthogonal axes (ISO 10068, 1998). This axis is also the dominant vibration direction in the operation of many tools such as rock drills, chipping hammers, rivet guns, road breakers et al. Therefore, the trends of the VPA-based weighting on this axis are probably the most important. Hence, in this study, the MI values on z_{h}-axis distributed at the fingers (finger MI) and at the palm of the hand (palm MI) were measured separately using the method developed in an earlier study (Dong et al., 2005). Their summation was used to represent the total or hand MI (Dong et al., 2005).

Specifically, the measurement experiment was performed using a special handle (40 mm diameter) instrumented for direct acquisition of the driving-point excitation and force response, and monitoring of the mean grip force, as described by Dong et al. (2005). The handle consisted of an aluminum semicircular section (handle base) and a magnesium semicircular section (measuring cap), joined together through two force sensors (Kistler 9212) to measure the grip and dynamic response forces. The driving-point excitation was measured using an accelerometer fixed at the center point of the measuring cap. The handle was mounted to a handle fixture that was fixed on the shaker of a vibration test system (UNHOLTZ-DICKIE, TA250-S032-PB). A closed-loop vibration control system was used to assure the consistency of the vibration input to the hand. A force plate (Kistler 9286AA) was used to monitor and control the applied pull or push force.

A broadband random vibration from 8 to 1250 Hz with a power spectral density (PSD) of 3.0 $(m/s^2)^2/Hz$ was used as the vibration input in the experiment (Dong et al., 2004c). The subject posture required in the ISO standardized glove test specified in ISO 10819 (1996), was used in the present study. With this posture, the MI values measured in this study are in the z_h-direction of the hand biodynamic coordinate system (see ISO 5349-1, 2001). When the fingers were placed on the measuring cap in a hand power grip, the finger MI was measured (Dong et al., 2005, 2004c). By rotating the handle 180°, the palm was positioned on the measuring cap, and the palm MI was measured using the same handgrip condition and arm posture. By aligning a marker on the index finger with the centerline of the handle, the grip posture and hand position on the handle were controlled during the finger and palm impedance measurements (Dong et al., 2005).

Table 1
Subject anthropometry (hand length = tip of middle finger to crease at wrist; hand breadth = the width measured at metacarpal of the hand)

Subject	Height (cm)	Weight (kg)	Hand length (mm)	Hand breadth (mm)
1	175.3	69.5	185	88
2	177.8	83.0	197	93
3	185.4	90.7	192	97
4	175.3	132.5	207	101
5	175.3	100.2	184	103
6	185.4	66.2	197	93
7	185.4	96.6	200	101
8	175.3	77.1	190	85
Mean	179.4	89.5	194	95
SD	5.1	21.2	8	7

Eight male volunteers from a local university participated in the experiment. The right hand was used for the test. Individual anthropometrics for each subject are listed in Table 1. Nine hand-handle coupling conditions for each side of the hand were used in the experiment, which are listed in Table 2. The forces were chosen so that the forces effectively acting at the fingers or palm at each force level under the three coupling actions (grip-only, push- or pull-only, and combined grip and push) were the same. The sequence of force and coupling combinations was randomized among the subjects. Two sequential trials were performed for each test treatment. The results were expressed at the one-third octave band center frequencies from 10 to 1000 Hz

To determine the significance of the influence of the applied force and action on the impedance, a two-factor-repeated-measures analysis-of-variance (ANOVA) was used to conduct the general statistical analyses of the finger and palm impedance data at each $\frac{1}{3}$ octave-band frequency. The first factor is the effect of the coupling action (grip, push/pull, and combined grip and push), and the second is the influence of the applied force. The ANOVA was executed using a conventional mixed model with action and force as fixed effects and subject as a random effect. The statistical analyses were performed using MINITAB statistical software (Version 13.1). Each effect is considered significant when p-value is less than 0.05.

2.3. Correlations among five vibration measures

To explore the sensitivity of the differences among the frequency weightings of five vibration measures or methods (three VPA measures, ISO weighted acceleration, and unweighted or unit-weighted acceleration) in practical applications, a series of linear correlation analyses of their corresponding weighted accelerations

Table 2
Experimental treatments

Coupling Action	Palm impedance measurement total effective force acting at the palm (N)		
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)
Coupling Action	**Finger impedance measurement total effective force acting at the fingers (N)**		
Grip-only	15 N	30 N	50 N
Pull-only	15 N	30 N	50 N
Combined grip and push	15 N (15 N grip + 35 N push)	30 N (30 N grip + 45 N push)	50 N (50 N grip + 50 N push)

were performed. For the purpose of this study, a group of 20 different tool vibration spectra reported by Griffin (1997) were used to calculate the acceleration root-mean-square (rms) values for the five vibration measures. These spectra represent a large range of different vibration characteristics of powered hand tools. The weighted rms values for each tool were calculated from

$$A_{\text{Wtool}}(m) = \sqrt{\sum_{i=1}^{21}[W_m(\omega_i)A_{\text{tool}}(\omega_i)]^2}, \qquad (9)$$

where W_m is the weighting for Method m. The integration was done from 10 to 1000 Hz.

3. Results

3.1. Mechanical impedance

As examples, Fig. 1 shows the MI modulus and phase angle values for the entire hand–arm system measured under combined grip and push actions, together with the ISO-recommended mean, high, and low values (ISO 10068, 1998). The general trends of both the modulus and phase angle obtained in this study are consistent with the ISO-recommended data. The magnitudes measured at combined 15 N grip and 35 N push follow the ISO mean values fairly well in the entire frequency range. The data at the other force levels are also generally within the range of the ISO low and high limits, except the values in the resonant frequency range. Since the ISO data were synthesized based on seven sets of data that were measured at 25–50 N grip force (Gurram et al., 1995), the recommended limits may not be applicable to some other cases.

Only the real part of the MI is of most interest for the purpose of this study. Hence, the full set of the data was statistically analyzed and presented in this paper. The real parts of the mechanical impedance values measured at the fingers (finger MI), at the palm (palm MI), and their summation (hand MI) are presented in Fig. 2 for combined grip and push action, Fig. 3 for grip-only action, and Fig. 4 for finger pull-only and palm push-only actions. As shown in Fig. 2, under the same hand forces, the mechanical impedance of the entire hand–arm system is mainly distributed at the palm at frequencies lower than 200 Hz. The results in Figs. 3 and 4 also demonstrate that under each force level, the palm MI is greater than the finger MI at frequencies lower than 160 Hz ($F \geqslant 65.4$, $p \leqslant 0.001$). At higher frequencies, however, the finger and palm MI values are fairly comparable.

For the palm MI, the interaction between the coupling action and palm-applied effective force is significant ($F \geqslant 2.87$, $p \leqslant 0.041$) from 12.5 to 20 Hz and from 63 to 200 Hz. The palm MI has a resonance in the frequency range of 20–63 Hz. Except at frequencies equal to or less than 16 Hz, the palm-applied force significantly influences the palm MI ($F \geqslant 11.85$, $p \leqslant 0.001$). Increasing the force increases the impedance resonant frequency and magnitude. Except at 25 and 31.5 Hz, the effect of the coupling action on the palm MI is also significant ($F \geqslant 4.73$, $p \leqslant 0.027$). Under the same palm effective force, the push-only action corresponds to the highest resonant frequency and MI value.

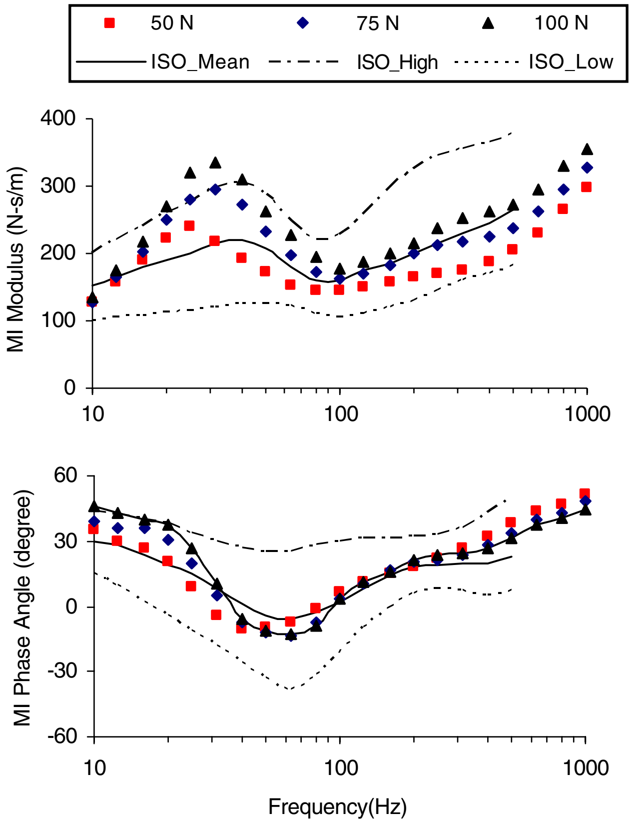

Fig. 1. Magnitudes and phase angles of the driving point mechanical impedance (MI) measured under combined grip and push actions, together with the ISO recommended mean, high, and low limits for 50 N or less grip force (ISO 10068, 1998). (G: grip; P: Push).

At frequencies greater than 40 Hz, the force and coupling action interaction on the finger MI is not significant ($F \leqslant 1.95$, $p \geqslant 0.129$), except at 80 Hz ($F = 3.37$, $p = 0.023$). At frequencies higher than 40 Hz, the coupling action has no significant effect ($F \leqslant 2.25$, $p \geqslant 0.142$) on the finger MI. However, except at 100–160 Hz, the effect of force on the finger MI is significant ($F \geqslant 10.84$, $p \leqslant 0.001$). Increasing the finger force generally increases the finger MI value.

The MI values measured under the finger pull-only and palm push-only actions shown in Fig. 4 actually represent the response of the entire hand–arm system in two extreme conditions. They are generally different from the hand MI values for the combined grip and push action shown in Fig. 2. However, when the finger

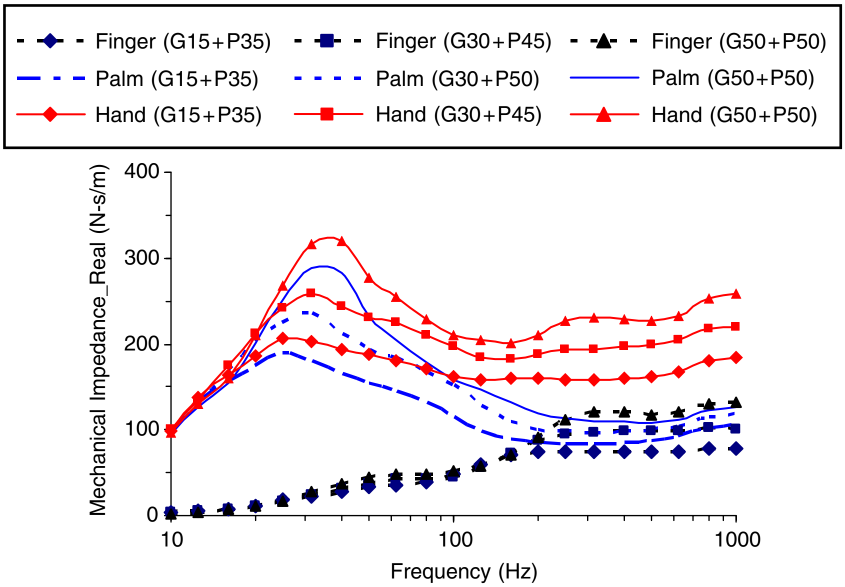

Fig. 2. Driving point mechanical impedance (MI) values (real parts) measured at the fingers, the palm of the hand, and their summation for the entire hand–arm system under combined grip (G) and push (P) action (force unit: N).

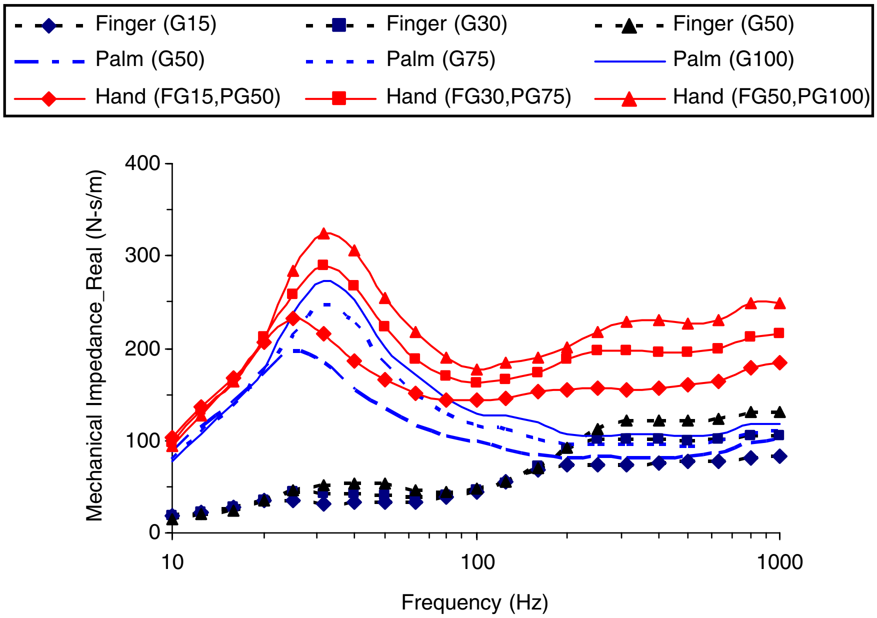

Fig. 3. Driving point mechanical impedance (MI) values (real parts) measured at the fingers, the palm of the hand, and their summation for the entire hand–arm system under grip-only (G) action (FG: finger grip force; PG: palm grip force; force unit: N).

and palm values at each force level in Fig. 4 are summed together to form a 'virtual' hand MI, it is not significantly different from that in Fig. 2 at frequencies greater than 160 Hz ($F \leqslant 2.03$, $p \geqslant 0.168$). Similarly, the hand MI values shown in Fig. 3 were obtained by summing the finger MI and palm MI measured under different grip forces, which does not represent a 'true grip' either. However, the effect of hand coupling action on the hand MI values for such a 'virtual' grip condition is not significant either ($F \leqslant 2.03$, $p \geqslant 0.168$) in the same high frequency range. These data demonstrate that the type of action is not important in the high frequency exposure. However, except at 10 Hz, the effect of the applied force on the hand MI is significant ($F \geqslant 5.35$, $p \leqslant 0.019$). These observations confirm that only the local hand tissues respond to the excitation at the high frequencies but the applied force affects the amount of tissues involved in the response.

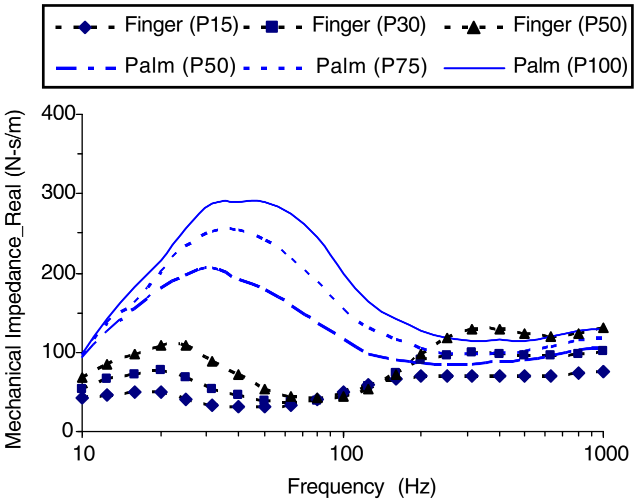

Fig. 4. Driving point mechanical impedance (MI) values (real parts) measured at the fingers, the palm of the hand under finger pull-only (P) or palm push-only (P) action (force unit: N).

3.2. VPA-based frequency weightings

The frequency weightings derived from Eq. (8) using the data for the combined grip and push action are illustrated in Fig. 5. The impedance value at 12.5 Hz for the combined 30 N grip and 45 N push for each of the finger, palm, and hand MI values was taken as the reference value in the corresponding weighting evaluation. Despite the significant effect of the force on the response, there are only marginal differences among the derived weighting functions under the three force levels. These finger VPA weightings are greater than those derived from the palm and hand VPA methods. The weightings for the palm and hand VPA methods are similar to each other. At frequencies greater than 25 Hz, the finger weighting is greater than the ISO weighting but the palm weighting is less than the ISO weighting. As a result, the hand weighting follows the ISO weighting very well in the entire frequency range of concern in this study.

The weightings for the grip-only action are shown in Fig. 6 and those for the finger pull-only and palm push-only actions are shown in Fig. 7. The MI values at 12.5 Hz for the middle force level (30 N for finger or 75 N for palm or hand) were used as the reference values in the evaluations. The palm and hand weightings are very similar to those shown in Fig. 5. The finger weightings become much closer to ISO weighting than those in Fig. 5. In the case of finger pull-only action, the weightings are generally lower than the ISO weighting. The palm weightings for the palm push-only action are also similar to those in Figs. 5 and 6.

3.3. Correlation relationships

The correlation coefficients (r^2-value) of the weighted acceleration rms values calculated from Eq. (9) using all the VPA weightings shown in Figs. 4–6, ISO weighting, and unit weighting (for unweighted) are listed in Table 3. The combined grip and push is likely to be the most frequently used action in the operation of most vibrating tools. The weightings for such an action were thus used in the calculation. A few examples of the correlation relationships are shown in Fig. 8. The results indicate that the ISO-weighted acceleration is poorly correlated to unweighted acceleration. The hand and palm VPA-weighted accelerations are highly correlated to ISO-weighted acceleration but they are poorly correlated to unweighted acceleration. The finger VPA-weighted acceleration is somehow correlated to both unweighted and ISO-weighted accelerations.

4. Discussion

The vibration power absorption (VPA) of the hand–arm system has been a major research topic in the study of hand-transmitted vibration exposure for more than 40 years. The VPA is also the only biodynamic parameter that has been seriously considered as an alternative vibration measure. Many researchers have had high expectations for the energy method for a long time. However, although many papers on this topic have been published, it remains a critical issue whether the measurement of vibration power absorption provides an appropriate means for assessing the risk of hand–arm vibration syndrome. This study provided an answer to this question.

In this study, the driving point mechanical impedance data were measured using a broad-band random vibration spectrum. In several previous studies, a constant-velocity sinusoidal vibration (Dong et al., 2005), a grinder spectrum, and a chipping hammer spectrum (Kihlberg, 1995) were used to measure the impedance. Their impedance values, general trends, and resonant frequencies are very similar to those presented in this study. The comparisons shown in Fig. 1 also suggest that the data obtained in this study are generally within range of the previously reported data. The influences of the hand coupling actions and applied forces on the impedance of the entire hand–arm system are also consistent with those reported from previous studies (e.g. Kihlberg, 1995; Dong et al., 2005). The characteristics of the impedance distribution on the fingers and palm of the hand observed in the present study are also the same as those reported in the previous study (Dong et al., 2005). These observations suggest that the MI data obtained in this study for deriving the VPA-based frequency weightings are generally representative of many cases.

The total VPA-based frequency weighting reported from the preliminary study by Donati (2001) emphasizes much more low frequency effect than those obtained in

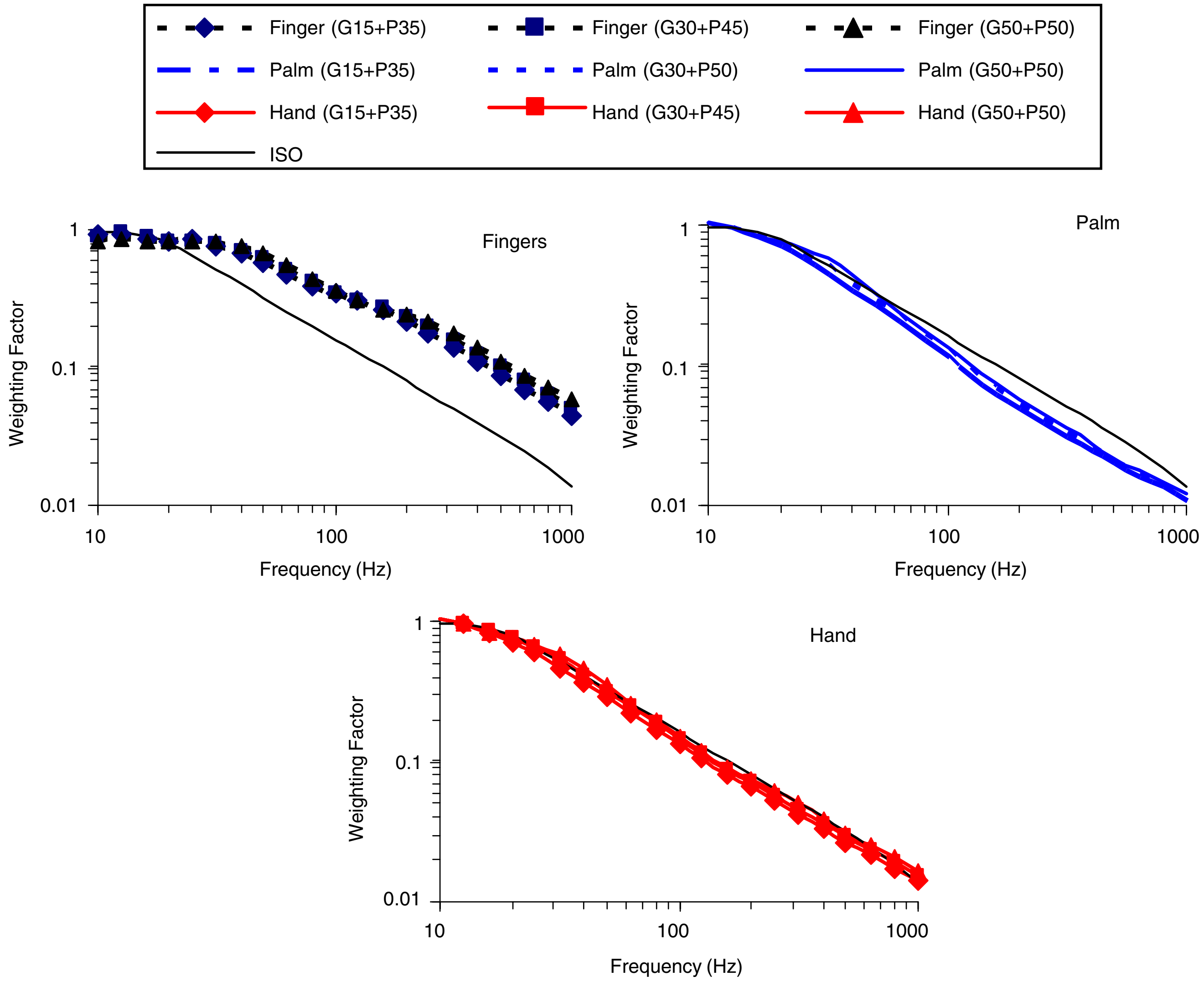

Fig. 5. VPA-based frequency weightings for fingers, palm, and hand under combined grip (G) and push (P) action with different levels of the applied forces (N).

this study. This is also true when the impedance data measured by Gurram et al. (1995) are used to derive the VPA weighting. However, as shown in Fig. 9, the VPA weighting curves derived from the majority of the reported impedance data are similar to the ISO weighting. This supports the major finding of this study.

In fact, although the majority of the reported MI data are consistent in trend, their specific values at each frequency were quite different (Gurram et al., 1995). Such differences, however, do not change the fundamental characteristic of the hand VPA-based frequency weighting, as shown in Fig. 9. As presented in the last section, the significant effects of the coupling action and applied force on the impedance are not proportionally transferred into the changes of the VPA weighting. Mathematically, this is because the process of taking the square root of the impedance data evens out their differences and the vibration frequency (ω) plays a dominant role in determining the VPA weighting, as dictated in Eq. (8). Hence, the VPA-based weighting is not sensitive to the variations of the mechanical impedance. The correlation results also suggest that the marginal variations of the VPA weightings are not likely to change the fundamental relationship between the ISO weighting method and the total energy method. These observations suggest that the association between these two methods is strong.

Based on the correlation results, the five vibration measures examined in this study can be broadly classified into three groups, as illustrated in Fig. 10. The unweighted acceleration is practically independent to ISO-weighted acceleration and it can be classified into one group. The ISO-weighted acceleration, palm VPA, and hand VPA are highly correlated and they can be put into the second group. The finger VPA in the third group is a measure between the first and second groups.

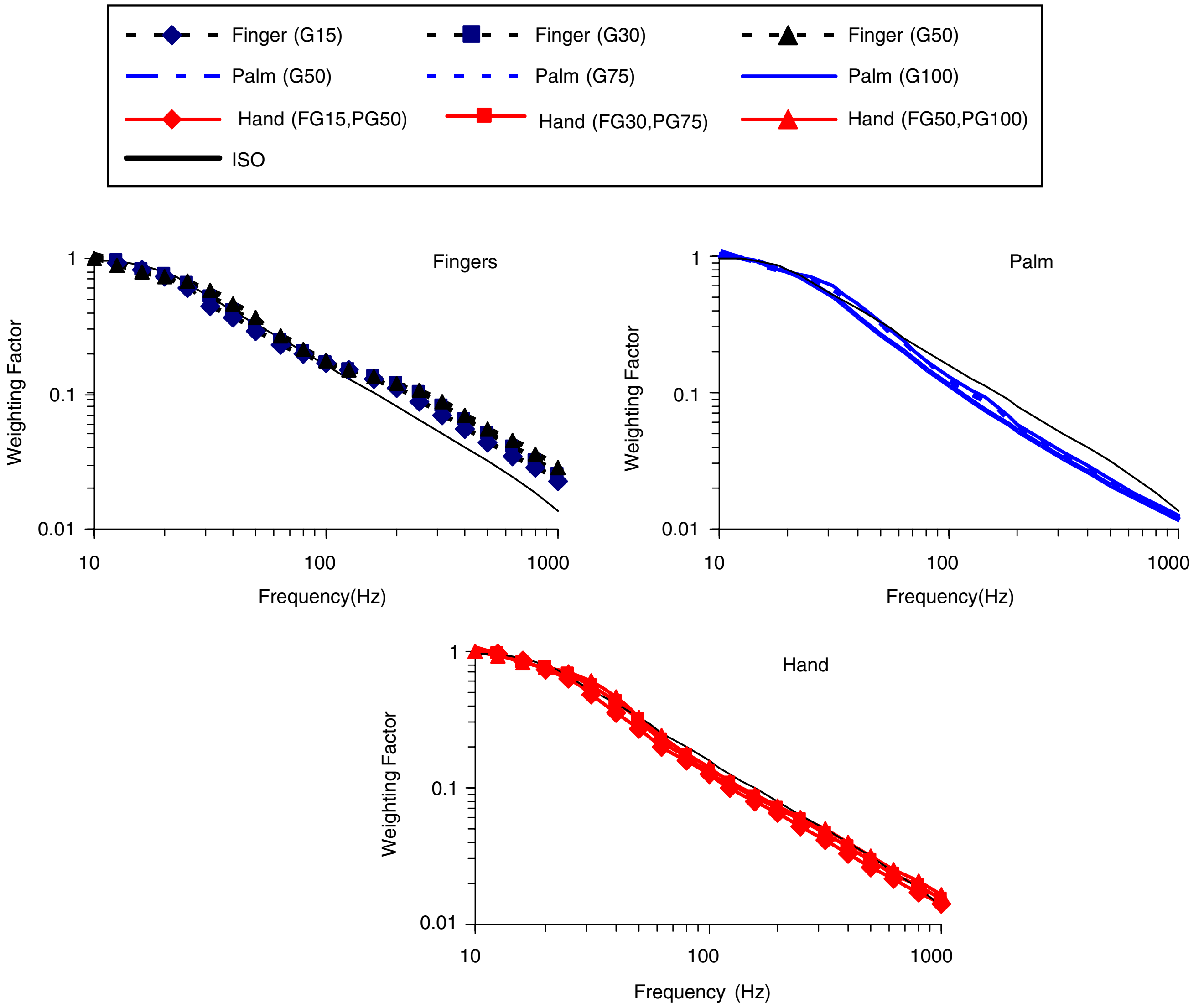

Fig. 6. VPA-based frequency weightings for fingers, palm, and hand under grip-only (G) action (FG: finger grip force; PG: palm grip force; force unit: N).

4.1. Total energy method (hand VPA)

The ISO weighting is based on psychophysical experimentation (Miwa, 1968). The agreement between the total VPA-based weighting and the ISO weighting suggests that the total power absorption of the entire hand–arm system is likely to be highly correlated with the subjective sensation or discomfort. The results reported by Reynolds (1977) support this prediction, which showed that the total power absorption is correlated with the subjects' annoyance. Hence, the total energy method may be used as an alternative tool to further investigate the discomfort or psychophysical response.

If the psychophysical response were directly associated with the mechanisms of the vibration-induced disorders or injuries in the fingers and hand, the ISO-recommended risk assessment method would provide a reasonable prediction of the major component of hand–arm vibration syndrome: vibration-induced white finger (VWF). This does not seem to be the case. Vibration at low frequencies (<25 Hz) can be effectively transmitted to the entire hand–arm system, while high frequency (>100 Hz) vibration components are mostly limited to the hand (Pyykkö et al., 1976; Reynolds and Angevine, 1977). Test subjects stated that low frequency vibration was not felt on the fingers and hand but on the arm (Reynolds, 1977). The workers using low frequency tools had no VWF but they complained of pain and discomfort in the arms and shoulders (Tominaga, 1993). Hence, the weighting based on the low frequency sensation data in these parts of the body likely has no direct linkage to the disorders in the fingers and hand. Many epidemiological studies on VWF have been

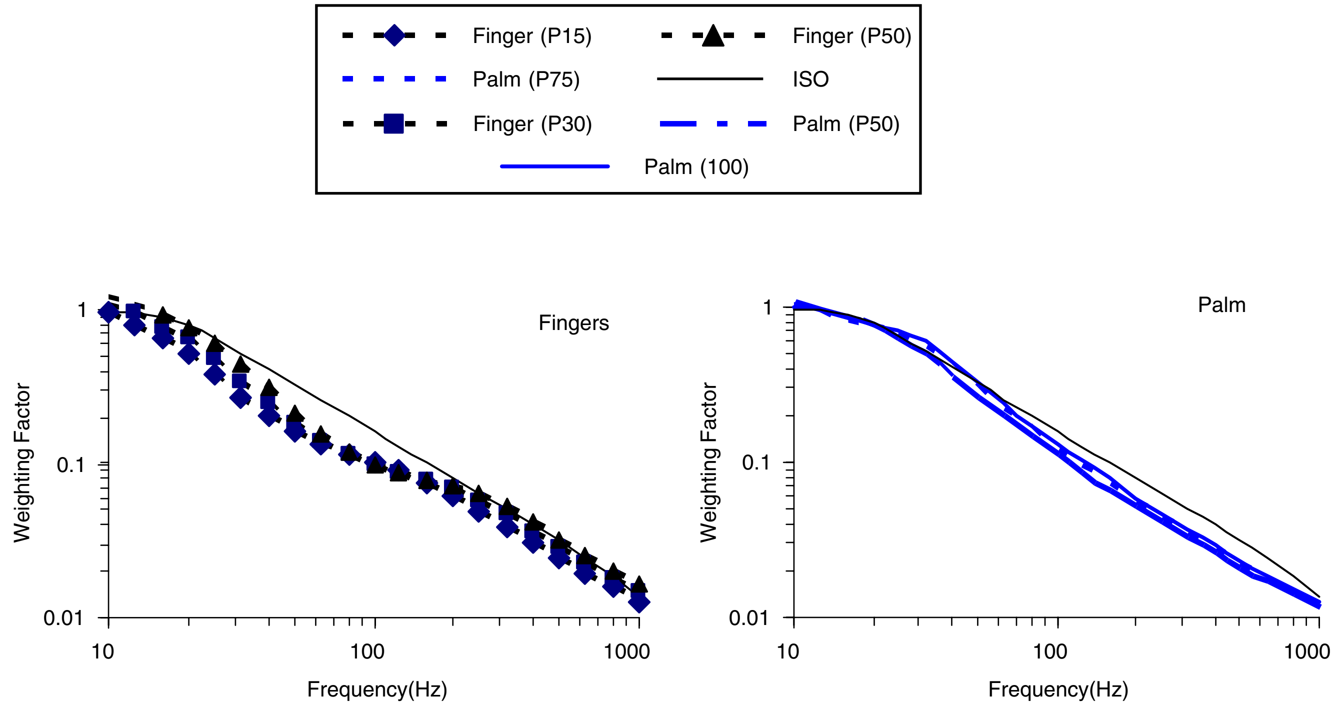

Fig. 7. VPA-based frequency weightings for fingers and palm under finger pull-only (P) or palm push-only (P) action (force unit: N).

Table 3
Comparisons of the correlation coefficients (r^2-value) for each pair of the acceleration rms values calculated using ISO weighting (ISO 5349-1, 2001), unit weighting (or unweighted), and finger, palm, and hand VPA-based weightings

Vibration Measure	r^2-value			
	ISO	Finger	Hand	Palm
Unweighted	0.2103	0.6233	0.1796	0.1328
ISO		0.7807	0.9981	0.9879
Finger			0.7487	0.6883
Hand				0.9953

The calculation used a group of 20 tool vibration spectra reported by Griffin (1997) and one set of the impedance data (30 N Grip + 50 N Push) shown in Fig. 1.

conducted (Griffin, 1990; Pelmear and Wasserman, 1998; NIOSH, 1997). The reported data are very scattered and some of them are even controversial. However, the majority of them suggest that the ISO weighting greatly overestimates the low frequency effect but significantly underestimates the high frequency effect on the disorders of the fingers and hand such as vibration-induced white finger (e.g. Dandanell and Engstrom, 1986; Bovenzi et al., 1988; Nilsson et al., 1989; Starck et al., 1990; Pelmear et al., 1989; Lundström and Lindmark, 1982; Tominaga, 1993; Bovenzi, 1998; Griffin et al., 2003). The results of many physiological and pathological studies also suggest the same tendency (e.g. Bovenzi et al., 2000, 2001; Harada and Griffin, 1991; Sakakibara, 1998). Hence, any frequency weighting that is less than the ISO weighting at high frequencies or greater than it at the low frequencies is likely to be worse at predicting finger and hand disorders than the ISO weighting.

If the total energy method were validated for assessing VWF, the agreement between the ISO weighting and the total VPA weighting would support the ISO weighting method. This 'if', however, does not exist. The energy method is based on the hypothesis that the vibration power absorption may be a significant etiological factor in regards to vibration-induced disorders. No physiological and pathological studies have directly tested this hypothesis. From biomechanical point-of-view, this hypothesis should have a reasonable basis. Vibration is a mechanical motion that can induce dynamic stresses and strains in the tissues of the system. The stresses and strains could directly or indirectly cause biological changes, tissue injuries, or dysfunctions in the system. The power absorption likely results from the damping effect of the tissues in the dynamic stress or strain processes. Hence, it may be used to measure the severity of the dynamic stress or strain processes that may be directly associated with the vibration-induced disorders. If the power absorption in the fingers was a fairly constant percentage of the total VPA in the entire frequency range of concern, it would be reasonable to use the total VPA as a measure for risk assessment. This condition does not exist. The results of this study

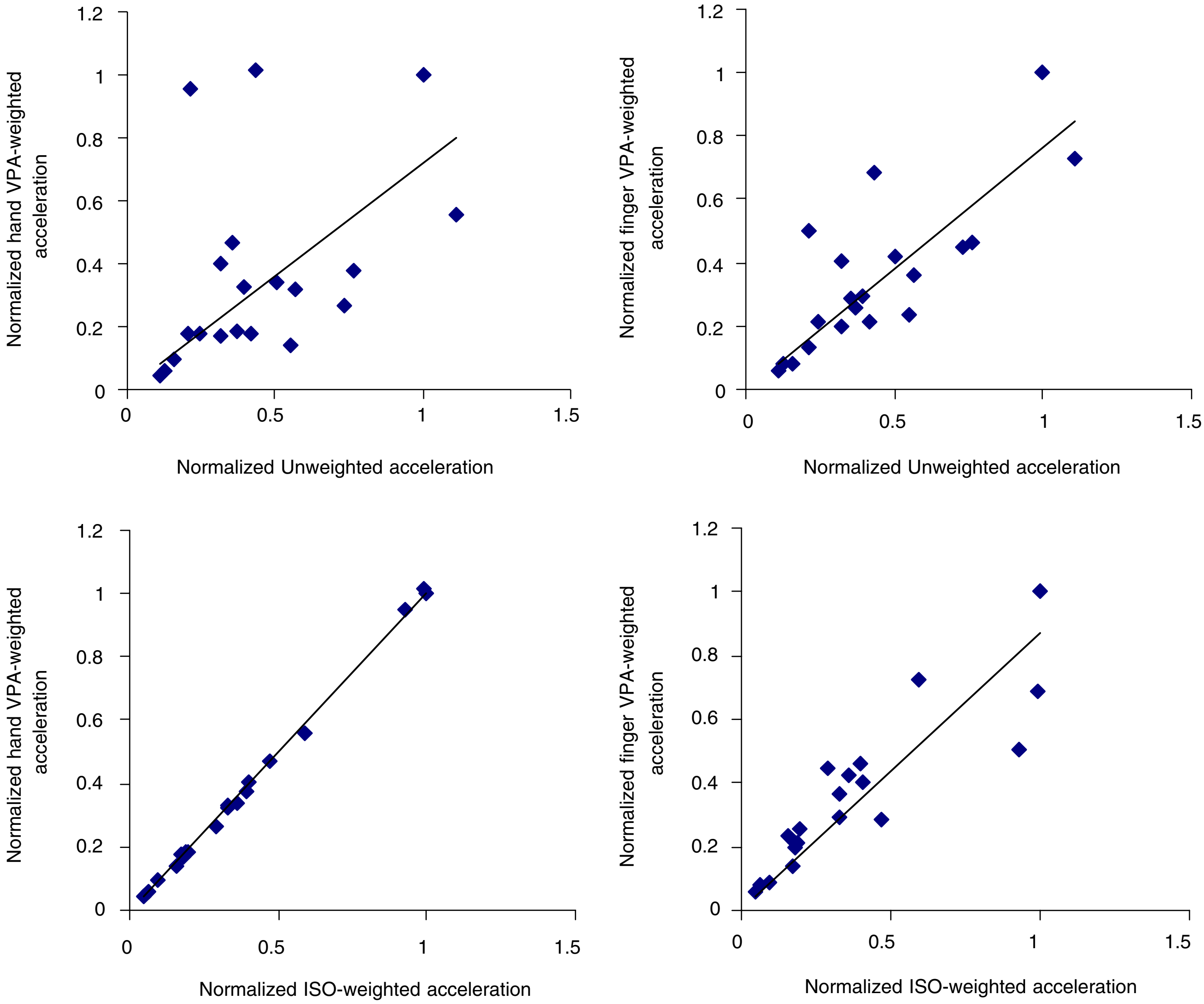

Fig. 8. Correlation relationships between hand and finger VPA-weighted accelerations and ISO-weighted and unweighted (or unit-weighted) accelerations. Twenty tool spectra reported by Griffin (1997) and the VPA weightings for combined 30 N grip and 45 N push shown in Fig. 4 are used in the calculation. The weighted accelerations for each vibration measure are normalized to its corresponding value of rock drill.

demonstrate that the percentage of the finger VPA in the total VPA is generally a function of frequency. At low frequencies, the total VPA is distributed in the entire system but it is concentrated in the fingers and hand at high frequencies. As it can be estimated from data shown in Fig. 2, the finger VPA at less than 63 Hz is generally less than 25% of the total VPA. At some frequencies in this range, it is less than 10%. Furthermore, at the low frequencies, the VPA measured on the fingers could be further transmitted to the other part of the hand–arm system, as indirectly evidenced from the fact that the palm coupling condition could affect the finger MI at the low frequencies. Therefore, only a small portion of the total power is actually absorbed by the fingers at the low frequencies. On the other hand, the finger VPA at frequencies higher than 250 Hz could count for more than 50% of the total VPA. It is also likely to be totally absorbed by the fingers. Therefore, there is no biodynamic basis that supports the use of the total VPA as a vibration measure for predicting VWF.

Three types of tools were used in the only experimental study on the relationship between the total VPA and VWF (Lidström, 1977). The reported power absorption was 21 W (1 W = 1 N m/s) for rock drilling, 2.7 W for chiseling, and 0.07 W for grinding. The corresponding prevalence of VWF was 72% for rock drilling, 53% for chiseling, and 21% for grinding. This group of data suggests that VWF could generally increase with the power absorption. Such a relationship, however, is not generally applicable. As estimated from Eq. (7) using the impedance data presented in this study or those recommended in ISO 10068 (1998), the hand

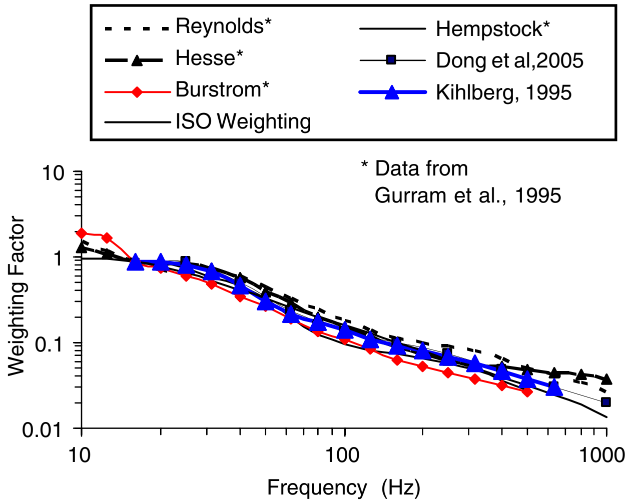

Fig. 9. Comparison of ISO weighting and those derived from the mechanic impedance data reported in the literature. As applicable, the real part of the MI used in the calculation is calculated from: $\mathrm{Re}(\boldsymbol{Z}) = |\boldsymbol{Z}| \cdot \cos(\varphi)$. Because many of these data start at 16 Hz, the weighting curves in this figure were normalized to the ISO weighting at this frequency.

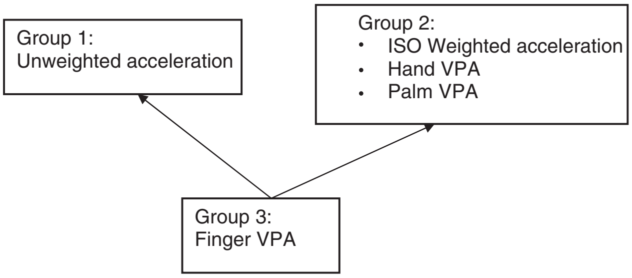

Fig. 10. Relationships among the five vibration measures.

can absorb more than 0.07 W when it is exposed to less than 2.5 m/s^2 rms at any frequency between 10 and 16 Hz. If the above relationship were true, this vibration magnitude would cause a prevalence of more than 21%. However, such a magnitude is less than the daily exposure action value (2.5 m/s^2) specified in the current EU Directive (2002). This casts a strong doubt on the validity of the reported relationship. As reported by Tominaga (1993), the dominant vibration of a rammer is usually in the range of 8–12.5 Hz with a value of 30 m/s^2 rms. Regardless of whether the impedance data on z_h- or y_h-axis (e.g. in ISO 10068, 1998) are used to estimate the hand VPA, it is more than 8 W, which is more than 100 times of that absorbed in the grinding and about three times of that in the chiseling reported by Lidström (1977). However, the prevalence of VWF was zero among the rammer users (Tominaga, 1993). Hence, there is unlikely to be a reliable relationship between the total power absorption and the vibration-induced white finger. These observations also suggest that the total energy method could greatly overestimate the effect of the low frequency vibration such as that on the rammer but it could substantially underestimate the effect of the high frequency vibration such as that on the grinder (Note: the dominant frequencies of grinders are usually about 100 Hz). This is consistent with the above-mentioned biomechanical prediction.

Overall, the ISO weighting method and the total energy method are fundamentally equivalent to each other. The results of both theoretical analyses and experimental studies have cast doubts on both methods for assessing vibration-induced problems in the fingers and hand. Both of them have the same fundamental deficiencies. If one of them cannot provide a reasonable prediction, the other one will unlikely generate a magic result.

4.2. *Palm energy method (palm VPA)*

Vibration-induced injuries and/or disorders are not limited to the fingers and the hand. The measurement of palm VPA may be used to study the injuries or disorders in the other parts of the hand–arm system. The resonant frequency for vibration power absorption of the palm has been found to be in the range of 20–63 Hz, as shown in Figs. 1–3. This frequency range encompasses the fundamental vibration frequencies of many types of percussive tools (Griffin, 1997). These tools could cause obvious discomfort and some injuries in the arm system, as reported in a few studies (Gemne and Saraste, 1987; Bovenzi et al., 1987). Another study reported that ISO-weighted acceleration was better than unweighted acceleration for assessing the risk of vibration-induced wrist injuries (Malchaire et al., 2001). Since the palm VPA is highly correlated with the weighted acceleration, the palm VPA may also be associated with these wrist injuries. Similar to the hand VPA method, the palm VPA method can also automatically include some influencing factors in risk assessment.

For the problems in the wrist–arm system, the frequency range of concern is likely below 200 Hz. At frequencies below 200 Hz, the hand impedance is dominated by palm impedance which depends on the force effectively acting at the palm, as shown in Figs. 1–3. Thus, measuring the hand VPA may serve the same purpose as measuring palm VPA. However, for field applications, the palm energy method is more convenient and technically more feasible than the total energy method. This is because an instrumented palm adaptor can be easily designed and conveniently used to conduct such measurement. The applied palm force may also be important in such risk assessment and it can also be measured using the same palm adaptor.

4.3. *Finger energy method (finger VPA)*

As a step towards developing a new energy method, the finger energy method was proposed in our earlier study (Dong et al., 2004a). The finger VPA method quantifies the vibration power transmitted to the fingers. At frequencies higher than 100 Hz, the vibration can only be transmitted to the local tissues. Hence, the estimated finger VPA can be considered as the true finger VPA. Below 100 Hz, however, a portion of the transmitted vibration components may not be absorbed in the fingers but further transmitted to other parts of the hand–arm system. Conversely, vibration power transmitted to the palm at such frequencies may also partially be transmitted to and absorbed by finger tissues. Hence, the finger VPA measure may be used to approximately represent the VPA in the fingers. Since the finger energy method can partially overcome the deficiencies of the total energy method, it may be better than the methods in the second group for assessing the risk of vibration-induced finger disorders. The finger VPA-based frequency weighting suggests that the ISO weighting underestimate high frequency effect.

However, the finger VPA method is far from perfect. Besides the uncertainty at the low frequencies, the detailed distribution of the power absorption in the fingers at frequencies higher than 100 Hz may also be important. The current finger energy method cannot take these factors into account. The finger VPA method increases the frequency weighting at the high frequencies but it is unknown whether such an increase is sufficient. Hence, more studies are required to improve, understand, and test the local energy method. The VPA density may also be a good candidate for future study.

5. Conclusion

This study clarified and further developed a method for deriving the VPA-based frequency weighting. The weightings derived from three energy methods were compared with the frequency weighting defined in ISO 5349-1 (2001). Based on the comparisons, this study predicted that the total power absorption of the entire hand–arm system is likely to be correlated with subjective sensation or discomfort. However, if the ISO weighting method cannot yield good predictions of the vibration-induced disorders in the fingers and hand, the hand and palm energy methods are unlikely to yield significantly better predictions. The finger VPA is a vibration measure between unweighted and ISO weighted accelerations. The palm VPA method may have some value for studying the disorders in the wrist–arm system.

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