Industrial Health 2005, **43**, 516–526 **Original Article**

Frequency Weightings Based on Biodynamics of Fingers-Hand-Arm System

Ren G. DONG*, Daniel E. WELCOME and John Z. WU

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

Received January 31, 2005 and accepted April 14, 2005

Abstract: The frequency weighting for assessing hand-transmitted vibration exposure is critical to obtaining a true dose-response relationship. Any valid weighting must have a solid theoretical foundation. The objectives of this study are to examine the biodynamic foundation for assessing the vibration exposure and to develop a set of biodynamic methods to formulate the frequency weightings for different anatomical locations of the fingers-hand-arm system. The vibration transmissibility measured on the fingers, hand, wrist, elbow, shoulder, and head was used to define the transmitted acceleration-based (TAB) frequency weighting. The apparent masses measured at the fingers and the palm of the hand were used to construct the biodynamic force-based (BFB) weightings. These weightings were compared with the ISO weighting specified in ISO 5349-1 (2001). The results of this study suggest that the frequency weightings for the vibration-induced problems at different anatomical locations of the hand-arm system can be basically divided into three groups: (a) the weighting for the fingers and hand, (b) the weighting for the wrist, elbow, and shoulder, and (c) the weighting for the head. The ISO weighting is highly correlated with the weighting for the second group but not with the first and third groups. The TAB and BFB finger weightings are quite different at frequencies lower than 100 Hz, but they show similar trends at higher frequencies. Both TAB and BFB finger weightings at frequencies higher than 20 Hz are greater than the ISO weighting.

Key words: Hand-transmitted vibration, Hand-arm vibration, Frequency weighting, Vibration-induced white finger, Hand-arm vibration syndrome

Introduction

It is common knowledge that the same magnitude of vibration at different frequencies may cause different physical sensations and health effects. The normalized parameter or coefficient that can be used to represent an effect as a function of the frequency is conventionally termed 'frequency weighting'. Various effects such as vascular disorders, neurological disorders, joint disorders, and muscle injuries at different anatomical locations of the hand-arm system may have different frequency dependencies. Hence, a single frequency weighting may not be sufficient for representing a multitude of discomfort and health effects[1]. Although many studies have examined frequency dependencies, the exact form of the dependence for each component of hand-arm vibration syndrome (HAVS)[2–4] has not been sufficiently understood. Consequently, the frequency weighting for assessing the severity of the hand-transmitted vibration (HTV) exposure remains one of the most important issues needing further study.

The frequency weighting specified in the current International Standard ISO 5349 (2001)[4] is based on the results of subjective sensation studies[5, 6]. This weighting has no epidemiological, pathological, or physiological base for predicting the best known and unique HAVS component: vibration-induced white finger (VWF)[2]. Although this weighting may provide a good assessment of vibration-induced discomfort[7], it may not be an optimum weighting

*To whom correspondence should be addressed.

for vibration-induced white finger. Although the results of a few epidemiological studies are consistent with this weighting[8, 9], many other studies do not support its predictions[10–16]. Therefore, further study is required to define the optimum frequency weightings for different components of HAVS so that a better overall weighting profile can be established to effectively assess the risks associated with HTV exposure.

The theoretical foundations for the development of the frequency weightings can be broadly classified into four categories[17]: (i) psycho-physical studies of subjective sensation; (ii) epidemiological studies; (iii) studies of the frequency dependencies of pathological and physiological effects of the vibration exposure; and (iv) studies of the biodynamics of the fingers-hand-arm system. Although subjective sensation can provide an indication of overall level of discomfort, it is questionable whether it is appropriate to use such information to determine different weightings for the various HAVS components at assorted locations. A substantial amount of data is required from different cases and conditions to create the reliable frequency weightings based on the results of pathological, physiological, and epidemiological studies. Thus, these approaches represent very significant investments and are expensive, time-consuming, and technically difficult. Data from various worker populations obtained at different workplaces may not be directly comparable. These issues and limitations can be partially avoided if frequency weightings initially are developed by studying the biodynamics using well-controlled laboratory experiments and modeling methods. Then, the preliminary weightings can be tested and improved using pathological, physiological, and epidemiological studies.

Following this strategy, the specific aims of this study are (i) to examine the theoretical foundation of the biodynamic approach, (ii) to develop methodologies for formulating the preliminary frequency weightings based on the biodynamics of the fingers-hand-arm system, and (iii) to conduct a preliminary evaluation of the proposed weighting methods.

Vibration Measures

Vibration is oscillating motion. It can be described using displacement, velocity, and acceleration. In fact, the very first set of HTV exposure limits was defined in terms of vibration displacement[5]. In the current ISO 5349-1 (2001)[4], the effect of HTV exposure is assumed to be approximately proportional to the vibration velocity at frequencies higher than 16 Hz. However, the acceleration measured on a vibrating surface or a powered hand tool is almost exclusively used as a basis to quantify the HTV exposure for risk assessment. There are two very good reasons for this. First, the measurement of acceleration is well developed and, when performed appropriately, is reliable. Second, acceleration is directly related to the dynamic force acting on the fingers-hand-arm system, which likely plays an important role for the development of HAVS. Therefore, it is very reasonable to establish future frequency weightings with respect to the acceleration measured on the tool or vibrating surface.

However, the acceleration measured on the tool represents only the hazard at the vibration source. Without a hand coupled to a tool, no relationship between the acceleration and any vibration-induced disorder can be established. This suggests that the biodynamic response of the hand-arm system may also be important to both the understanding of the mechanisms of HAVS and the establishment of the frequency weightings with respect to the acceleration measured at the input point.

The forces associated with the transmission of vibration from the tool to the hand are the interaction forces acting at the hand-tool interface, which are conventionally termed 'biodynamic forces'. The internal dynamic forces associated with the further transmission of vibration from the interface to other anatomical locations of the hand-arm system are termed 'biodynamic stresses'. The stresses cause motion and deformation of the tissues, which can be in the forms of extension, compression, or change of the tissue's shape. The stresses and deformations may be directly associated with injuries to the microstructures and cells of tissues, disturbances of their normal communication and functions, reductions of blood circulation, and/or stimulations or releases of adverse biological agents. The tissues, especially the soft tissues of hand-arm system, have significant damping properties, which result in vibration energy absorption[18–21]. Although the exact processes of the vibration-induced injuries and disorders are not sufficiently known, and further studies are required to understand them, the vibration-induced stresses and deformations are likely among the essential stimuli that directly act on the tissues and cells and cause the development of the disorders. Hence, these internal biodynamic parameters are the most desired vibration measures[21]. To date, however, a reliable experimental means of directly measuring these parameters has not been developed. Although it has been feasible to estimate these mechanical stimuli using the finite element (FE) method[22], it remains a formidable research task to quantify them using the modeling approach.

It is common knowledge that the internal dynamic stress and deformation are directly related to the dynamic force

acting on the interface. Hence, the biodynamic force that can be measured at the interface may be used as an alternative vibration measure. Probably because it is very difficult to measure the biodynamic force at workplaces, few studies have seriously investigated it[23]. The current study used an indirect method to determine the biodynamic force[23], and then used it to derive the frequency weighting.

The total power absorption of the entire hand-arm system has also been used as a measure to quantify the vibration exposure[18–21]. A preliminary study of the frequency weighting derived from this measure has been reported[24]. Because the power absorption is proportional to the square of acceleration[25], the root of the power absorption was considered as a measure to determine the power-based frequency weighting[24]. Surprisingly, the power absorption-based (PAB) weighting at the very low frequencies (< 8 Hz) on the z_h-axis is much greater than the ISO weighting[4] but the PAB weighting is much lower at frequencies higher than 12.5 Hz. Such a weighting would unlikely provide a better prediction than the ISO weighting because many studies suggest that the ISO weighting generally overestimates the low frequency effects but underestimates the high frequency effects[10–16]. While future studies may be required to clarify this issue, the power absorption approach was not used in this study.

The acceleration at an anatomical location on the system can approximately represent the local inertial force at that location. It is speculated that there is a relationship between transmitted acceleration and the internal stress, deformation, and power absorption density. Hence, the transmitted acceleration that can be measured on the surface of the system may also be used as an alternative vibration measure. One study has proposed the use of vibration transmissibility measured at the wrist for wrist risk assessment[26]. Another study has proposed the general use of transmissibility measured at specific anatomical locations of the system as a frequency weighting for assessing the relationship between exposure and HAVS components at those locations[25]. This transmissibility-based method is further elaborated and evaluated in this study.

Frequency Weighting Method Based on Transmitted Acceleration

Vibration transmissibility

The vibration transmission is usually quantified by the transmissibility, which is conventionally defined as follows[27]:

$$T_{Ri} = \frac{A_{Hi}}{A_{Tool}} \tag{1}$$

where T_{Ri} is the transmissibility at the ith point on the fingers-hand-arm system, A_{Hi} is the transmitted acceleration at that point, A_{Tool} is the acceleration at the interface between hand and tool or vibrating surface.

Definitions of transmitted acceleration-based (TAB) frequency weighting

The transmitted acceleration-based (TAB) frequency weighting is defined as follows:

$$W_{TABi}(\omega_k) = T_{Ti}(\omega_k) = \frac{A_{Hi}(\omega_k)}{A_{Tool}(\omega_k)} \tag{2}$$

where W_{TABi} is the TAB weighting for the ith anatomical location of the fingers-hand-arm system, and k is the sequence number of the frequency. The system, in terms of the locations of the HAVS components, may be approximately divided into fingers, hand, wrist, elbow, shoulder, neck, and head. Practically, the TAB weighting for each location can be taken as the transmissibility that is measured at a representative point of each anatomical location or the average transmissibility of the data measured at several representative points at each location.

Because transmissibility values in different exposure directions may be different, the TAB weightings may also be defined in terms of the vibration exposure direction. The current ISO standard recommends the use of total vibration (root-sum-of-squares of the three orthogonal component values)[4]. As an option that is consistent with the standard, a total weighting is defined as

$$W_{ti_t}(\omega_k) = \frac{\sqrt{[\alpha A_{i_x}(\omega_k)]^2 + [\beta A_{i_y}(\omega_k)]^2 + [\gamma A_{i_z}(\omega_k)]^2}}{\sqrt{[A_{tool_x}(\omega_k)]^2 + [A_{tool_y}(\omega_k)]^2 + [A_{tool_z}(\omega_k)]^2}} \tag{3}$$

where W_{ti_t} is the TAB weighting for total vibration, A_{i_x}, A_{i_y}, and A_{i_z} are the acceleration components measured at a location on the fingers-hand-arm system in three orthogonal directions, A_{tool_x}, A_{tool_y}, and A_{tool_z} are the acceleration components measured on a tool where the hand is in contact with the vibrating surface, and α, β, and γ are the orientation weighting factors for the x, y, and z directions, respectively.

Because there is little information available on the impact of variation in orientation upon health effects, it is difficult to determine the orientation weighting factors. As used in the current ISO standard[4], the vibration in each direction is considered equally important. Furthermore, it may be more convenient to use the exposure direction as an additional factor in the risk analysis than to incorporate the orientation effect in the total frequency weighting. Hence, the orientation

weighting factors are taken as unity in this study and the total weighting is simplified as follows:

$$W_{ti_t}(\omega_k) = \frac{\sqrt{[A_{i_x}(\omega_k)]^2 + [A_{i_y}(\omega_k)]^2 + [A_{i_z}(\omega_k)]^2}}{\sqrt{[A_{tool_x}(\omega_k)]^2 + [A_{tool_y}(\omega_k)]^2 + [A_{tool_z}(\omega_k)]^2}} \quad (4)$$

One additional benefit of the total weighting method is that it can take into account the cross-axis effects that may be observed on the system. If the cross-axis effects are secondary or not significant, the total weighting can be estimated using the single axis transmissibility from the following formula:

$$W_{Ti_t}(\omega_k) = \sqrt{[T_{Ri_x}(\omega_k)]^2 + [T_{Ri_y}(\omega_k)]^2 + [T_{Ri_z}(\omega_k)]^2} / \sqrt{3} \quad (5)$$

where T_{Ri_x}, T_{Ri_y}, and T_{Ri_z} are the transmissibility functions in the three orthogonal directions measured in a single axis excitation. The formula makes it possible to use the available transmissibility data to estimate the total TAB weighting.

Examples of TAB frequency weightings

Several examples of the TAB weightings derived from reported transmissibility values measured on the fingers and hand[28] are shown in Fig. 1, together with the ISO frequency weighting[4]. Because changing the grip force level from 10 to 40 N only marginally changes the transmissibility values[28] and a full set of the data measured under 10 N are available, the TAB weightings presented in Fig. 1 were derived from the data measured under 10 N grip force. The TAB weighting based on the transmissibility at the fingertip remains high up to 630 Hz. The resonance of the fingers is between 63 and 160 Hz[28], which is reflected in the weightings derived from the transmissibility data measured on the phalanxes and the third metacarpal. At frequencies higher than 200 Hz, the weightings decrease significantly with the increase in frequency.

Figure 1 also shows that the TAB weighting more closely approximates the ISO weighting as the vibration measurement point moves closer to the wrist. This is further confirmed from another set of data presented in Fig. 2, in which the TAB weightings were derived from the transmissibility data measured at the wrist, elbow, and shoulder in three orthogonal directions[29]. The wrist TAB weightings follow the ISO weighting fairly well in a large frequency range. The weightings shown in this figure clearly indicate that the weightings are exposure direction-specific.

Examples of the weightings derived from the total vibration transmissibility estimated using Eq.(5), together with the weighting derived from transmissibility measured on the head[30], are presented in Fig. 3. In this case, the wrist weighting closely approximates the ISO weighting up to 160 Hz, which covers the dominant frequencies of many powered hand tools. Although the weighting at the elbow in the horizontal direction is very similar to that at the wrist (see Fig. 2), the weightings at the elbow in the other directions are generally less than those at the wrist. Hence, the total

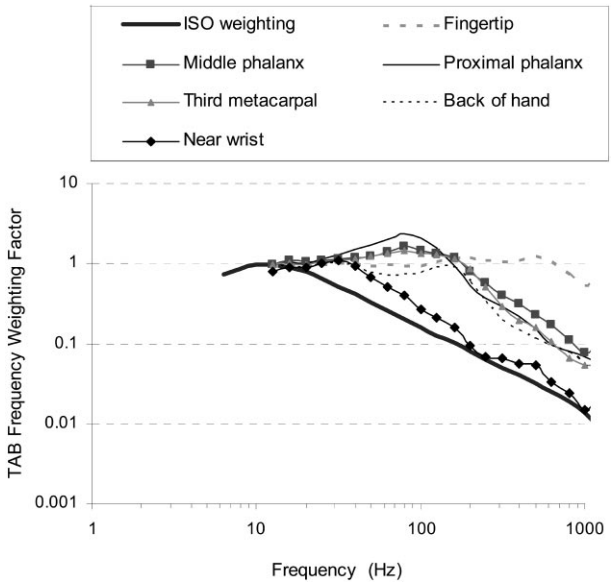

Fig. 1. Comparison of the ISO weighting and the TAB weightings derived from transmissibility values measured at several points on the hand reported by Sörensson and Lundström[28].

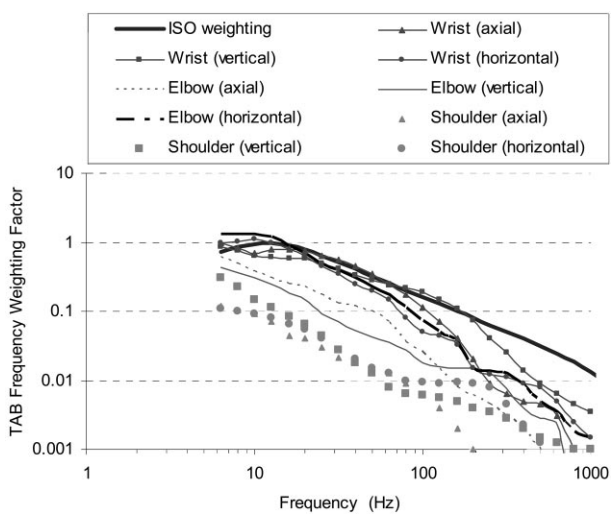

Fig. 2. Comparison of the ISO weighting and the TAB weightings derived from the transmissibility values measured at wrist, elbow, and shoulder reported by Reynolds[29].

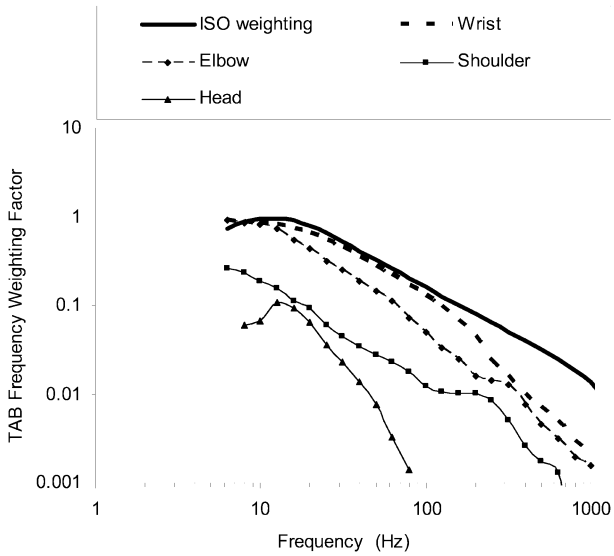

Fig. 3. Comparison of the ISO weighting and the TAB weightings derived from the total transmissibility derived from the data presented in Fig. 2 and the transmissibility measured on the head reported by Sakakibara *et al.*[30].

weighting at the elbow is generally less than that at the wrist, as shown in Fig. 3. Because the shoulder and head are farther away from the vibration source, the weightings at those locations are further reduced at each frequency.

To determine the independency among the frequency weightings in practical applications, a series of correlation analyses of the weighted acceleration values calculated using different frequency weightings were performed. For the purpose of this study, a group of 20 different tool vibration spectra reported from a previous study[31] were used. Table 1 lists the comparisons of the correlation coefficients (r-values) for each pair of the acceleration root-mean-square (rms) values calculated using the ISO weighting[4], the unit weighting (for unweighted acceleration), and the TAB weightings for six anatomical locations on the fingers-hand-arm system. The TAB finger weighting used in the calculation was the average weighting of those for the fingertip, middle phalanx, proximal phalanx, and the third metacarpal shown in Fig. 1. The TAB weighting for the back of the hand was the same as shown in Fig. 1. The TAB weightings for wrist, elbow, shoulder, and head used in the calculation were those shown in Fig. 3.

Because the ISO-weighted acceleration and the unweighted (or unit weighted) acceleration are poorly correlated[31], they can be considered independent measures[25]. However, as shown in Table 1, the unweighted acceleration is highly correlated with the acceleration values on the fingers and the back of the hand ($r \geq 0.946$) but it is poorly correlated with the acceleration values at other locations. The correlations between the ISO-weighted acceleration and the transmitted accelerations on the fingers and the back of the hand ($r \leq 0.613$) are much lower than those between ISO-weighted acceleration and the transmitted accelerations at the wrist, elbow, and shoulder ($r \geq 0.932$). The ISO-weighted acceleration also shows some correlation with the head TAB-weighted acceleration ($r = 0.801$) but the correlation is not as strong as those for the arm accelerations.

Frequency Weighting Method Based on Biodynamic Force

Biodynamic response

The biodynamic force can be estimated from a biodynamic response parameter and the tool acceleration spectrum[23]. The biodynamic response parameters are conventionally defined as

Table 1. Comparisons of the correlation coefficients for each pair of the acceleration rms values calculated using ISO weighting[4], unit weighting (or unweighted), and the TAB frequency weightings for six different locations on the fingers-hand-arm system

	ISO	Finger	Back of Hand	Wrist	Elbow	Shoulder	Head
Unweighted	0.459	0.948	0.946	0.407	0.185	0.278	–0.033
ISO		0.523	0.613	0.997	0.936	0.932	0.801
Finger			0.986	0.482	0.241	0.320	–0.013
Back of Hand				0.569	0.341	0.422	0.095
Wrist					0.947	0.932	0.817
Elbow						0.984	0.955
Shoulder							0.937

A group of 20 tool vibration spectra reported by Griffin[31] were used in the calculation of the rms values for the correlation analyses.

$$AM = \frac{F_d}{A_{Tool}}, MI = \frac{F_d}{V_{Tool}}, AS = \frac{F_d}{D_{Tool}},$$
$$\text{and } PT = F_d \cdot V_{Tool} \quad (6)$$

where AM, MI, AS, and PT are apparent mass, mechanical impedance, apparent stiffness, and power transmission, respectively, and F_d, A_{Tool}, V_{Tool}, and D_{Tool} are the biodynamic force, acceleration, velocity, and displacement at the hand-tool interface or the vibrating surface, respectively.

The four biodynamic response parameters in Eq.(6) represent different physical properties (mass, damping, stiffness, and power transmission) of the system. Each of the parameters, however, can be derived from another. For example, if the apparent mass is directly measured, the other parameters can be calculated using the following formula:

$$MI(\omega) = AM(\omega) \cdot j\omega, AS(\omega) = AM(\omega) \cdot (j\omega)^2,$$
$$\text{and } PT(\omega) = AM(\omega) \cdot j\omega(|V|)^2 \quad (7)$$

where ω is vibration frequency in Rad/s and $j = \sqrt{-1}$.

Many sets of data on the mechanical impedance of the hand-arm system have been reported[27]. An ISO standard based on some of these MI data has also been established[32]. These data, however, are based on the entire hand-arm system. With these data, the biodynamic effects on the fingers and the rest of the system cannot be differentiated. Our recent study on the response has made the differentiation possible[33] by measuring the biodynamic responses at the fingers and palm of the hand separately.

Definitions of biodynamic force-based (BFB) frequency weightings

As Eq.(7) dictates, the driving-point response parameters are not independent of each other. A single parameter may be sufficient to represent the biodynamic response and derive the frequency weighting. According to Eq.(6), the biodynamic force is linearly related to the apparent mass and source acceleration. Hence, the AM is an ideal frequency weighting factor with respect to the acceleration. Because the weighting must be non-dimensional, the AM values must be normalized to a reference mass value. As a result, the weighting is defined as follows:

$$W_{BFBi}(\omega_k) = \frac{AM_i(\omega_k)}{AM_{ref}} \quad (8)$$

where W_{BFBi} is the biodynamic force-based (BFB) frequency weighting for the ith anatomical location of the fingers-hand-arm, AM_i is the magnitude of the apparent mass distributed on the ith location, and AM_{ref} is the reference mass.

Similar to the simplified total TAB weighting defined in Eq.(5), the simplified total BFB weighting is expressed as follows:

$$W_{BFBi_t}(\omega_k) = \sqrt{[W_{BFBi_x}(\omega_k)]^2 + [W_{BFBi_y}(\omega_k)]^2 + [W_{BFBi_z}(\omega_k)]^2} / \sqrt{3} \quad (9)$$

where W_{BFBi_x}, W_{BFBi_y}, and W_{BFBi_z} are the weightings derived from the apparent mass values in the three orthogonal directions, respectively measured using a single axis vibration test system.

Examples of BFB frequency weightings

The weightings that can be derived from the biodynamic response are currently limited to the driving point response. Four sets of apparent mass functions measured at the fingers and the palm of the hand obtained in a previous study[33] are used in this study and they are plotted in Fig. 4. They were measured under two hand-handle coupling actions (50 N grip-only and combined 50 N grip and 50 N push). Although the apparent mass measured at the fingers at frequencies less than 100 Hz is much less than that at the palm, their values at higher frequencies are fairly comparable. Different coupling actions also resulted in different responses. As also shown in Fig. 4, the system's fundamental resonant frequency was in the range of 16 to 40 Hz. The finger resonant peak is not obvious, but the resonant effect makes the finger apparent mass remain at a fairly constant level from 100 Hz to 250 Hz. Because the fingers-applied force on the handle was the same (50 N) in both types of actions, the mass responses at frequencies equal to and higher than 100 Hz are practically the same for both actions[33].

Figure 5(a) shows the finger apparent mass-based weightings calculated from Eq.(8) using the data shown in Fig. 4. The maximum value of the finger apparent mass under the combined grip and push was used as the reference mass in the calculation. At frequencies lower than 16 Hz, the BFB finger weightings are very similar to the ISO weighting. At higher frequencies, however, the ISO weighting is lower than the BFB weightings. The differences become larger at frequencies equal to and higher than 100 Hz. At frequencies higher than 250 Hz, the reduction rates of the BFB and ISO weightings are very similar to each other.

Figure 5(b) shows the palm BFB weightings. In this case, the maximum value of the palm AM under the combined grip and push was used as the reference mass in the calculation. The peak value of the palm BFB weighting is at a higher frequency (25 Hz) than the ISO weighting (12.5 Hz). Their general shapes, however, are very similar to each

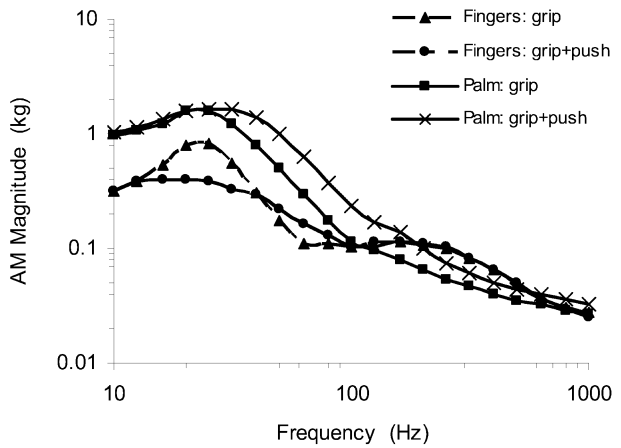

Fig. 4. Apparent mass values measured at the fingers and the palm of the hand[33].

other.

As mentioned above, at frequencies equal to and higher than 100 Hz, the finger response is practically independent of that of the rest of the hand-arm system. The finger inertial force due to the finger acceleration should be closely associated with the finger dynamic force measured at the finger-tool interface. To test this hypothesis, the BFB weighting was derived by normalizing the AM values to that at 100 Hz (or $AM_{ref} = AM_{100\,Hz}$) using Eq. (8). It was compared with the finger TAB weighting, which was the average value of the weightings for fingertip, middle and proximal phalanxes, and the third metacarpal shown in Fig. 1. The comparison is shown in Fig. 6. As expected, the basic shapes of these two weighting curves at frequencies higher than 100 Hz are very similar, although the applied forces were quite different. As expected, the 10 N grip force corresponds to a lower resonance than the 50 N grip.

The same correlation analysis method for evaluating the transmissibility weightings was also used to evaluate the independency of the BFB weightings. The results are presented in Table 2. In this case, the BFB finger weighting derived from the finger AM under the combined grip and push is correlated to both the ISO-weighted and unweighted accelerations at similar levels ($r \geq 0.770$). The correlations between the finger grip and palm grip and between the palm grip and combined grip and push are strong ($r \geq 0.951$). The other BFB-weighted accelerations are reasonably correlated to each other and the ISO-weighted acceleration ($r \geq 0.805$). These observations suggest that the BFB finger weightings are between the ISO weighting and the unit weighting.

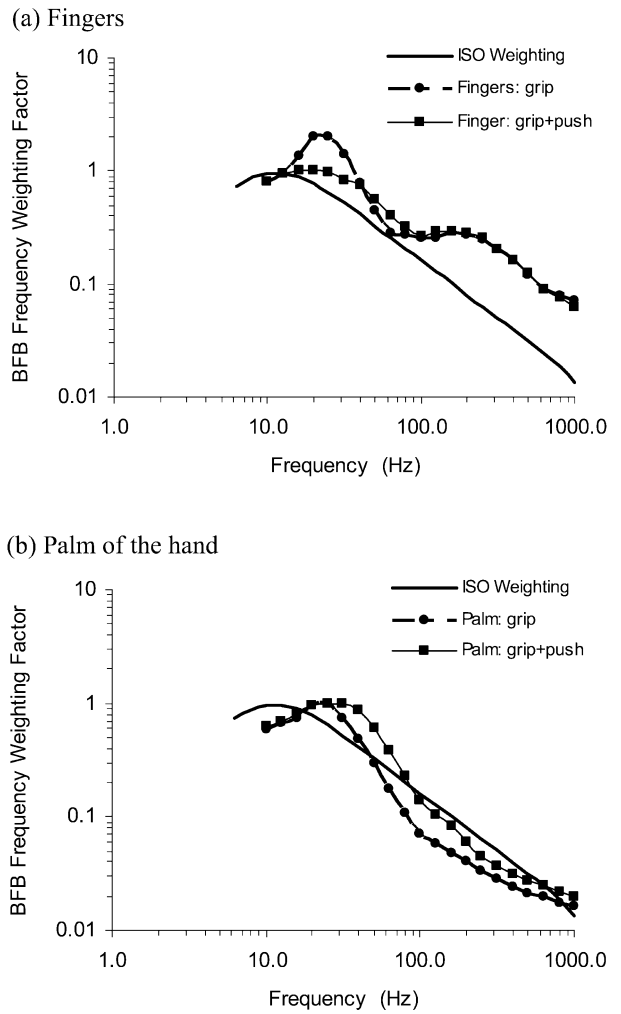

Fig. 5. BFB frequency weightings derived from the apparent mass values shown in Fig. 4: (a) fingers; (b) palm of the hand.

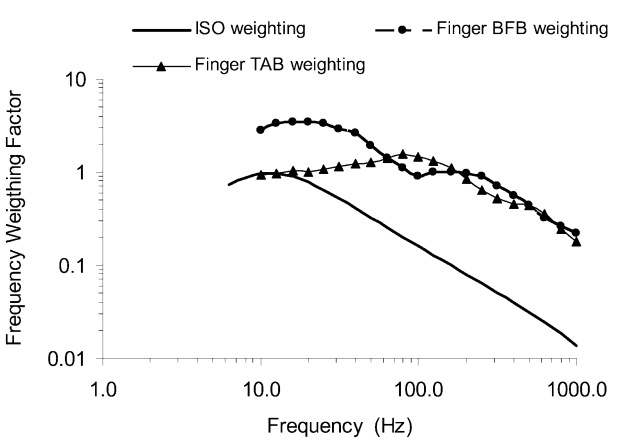

Fig. 6. A comparison of the BFB and TAB frequency weightings as the BFB weighting is normalized the AM value at 100 Hz and TAB weighting is taken as the average value of those for fingertip, middle and proximal phalanxes, and the third metacarpal shown in Fig. 1.

Table 2. Comparisons of the correlation coefficients for each pair of the acceleration rms values calculated using ISO weighting[4], unit weighting (or unweighted), and the BFB frequency weightings shown in Fig. 5

	ISO	Finger (grip – only)	Finger (grip + push)	Palm (grip – only)	Palm (grip + push)
Unweighted	0.459	0.507	0.770	0.297	0.456
ISO		0.893	0.893	0.919	0.921
Finger (grip – only)			0.898	0.951	0.916
Finger (grip + push)				0.805	0.879
Palm (grip – only)					0.955

The same group of spectra[31] as those used in Table 1 were also used in the calculation.

Discussion

Although the biodynamics of the fingers-hand-arm system represent important theoretical foundations for the measurement, evaluation, and risk assessment of hand-transmitted vibration exposure, the frequency weightings based on biodynamics have not been seriously studied. In this study, the theoretical basis of the biodynamics-based frequency weighting was examined and a set of preliminary frequency weightings based on this foundation were proposed.

Evidence supporting the TAB and BFB weighting methods

A recent study[34] indicated that the unweighted acceleration was better than the ISO-weighted acceleration for the assessment of the vibration-induced white finger. Because the major vibration components of most powered hand tools are equal to or less than 250 Hz[31], the finger TAB-weighted acceleration is highly correlated to the unweighted acceleration, as presented in Table 1. Hence, it is anticipated that the TAB finger weighting is better than the ISO weighting for finger risk assessment.

Many studies have indicated that the ISO weighting method underestimates the effects of high frequency components on the disorders in the fingers and hand[10–16, 35, 36]. As shown in Fig. 1, the TAB finger weighting has a much higher value than the ISO weighting at frequencies higher than 20 Hz. As shown in Fig. 5(a), the BFB finger weighting also has a higher value than the ISO weighting in this frequency range. Hence, it is also anticipated that the TAB and BFB finger weightings can provide better predictions of vibration-induced white finger than the ISO weighting at high frequencies.

The TAB weighting for the fingers (Fig. 6) indicates that the biodynamic effect in the frequency range of 63 to 200 is higher than those in the lower and higher frequency ranges. This trend seems consistent with the results of several epidemiological, physiological, and pathological studies. For example, a frequency weighting derived from a set of epidemiological data revealed that the high weighting factors are at frequencies greater than 50 Hz[35]. This suggests that the ISO weighting not only underestimates the high frequency effect but also overestimates the low frequency effect. The frequency dependency of the temporary threshold shift of the vibration sense at the fingertip suggests that the relative high value of the acute neurological effect is in the range of 63 to 500 Hz, with a peak effect at 100–250 Hz[37, 38]. Vascular studies also found that the relatively stronger vibration effect on the digital blood flow was in the middle frequency range (30 to 500 Hz), with the strongest effect at 125 Hz[24, 39].

The weighted accelerations calculated using the wrist, elbow, and shoulder TAB weightings and the palm BFB weighting are highly correlated to the ISO weighted acceleration. This suggests that the ISO weighting may be acceptable for assessing the vibration-induced problems in these anatomical locations. A study reported that there was a relationship between the ISO-weighted acceleration and the incidence of the wrist disorders[40]. This supports the wrist TAB and the palm BFB weightings proposed in this study.

Although there are still some large differences between the biodynamics-based weightings and the frequency dependencies of the physiological, pathological, and epidemiological effects, the agreements in the above-mentioned aspects suggests that the biodynamics of the system may have a strong linkage to the health effects.

Influencing factors

Many factors such as coupling force, coupling type (grip, push, pull, and their combinations), vibration magnitude, handle geometry, and individual differences could affect transmissibility and apparent mass[27], and thus the TAB and

BFB weightings. Examples of the TAB and BFB weightings presented in this paper may represent only a portion of the possible cases. Further studies are required to obtain more data for determining the possible range of the weighting variation. However, the presented examples may represent the fundamental distribution characteristics of the weightings at the different anatomical locations of the system.

The relationships between TAB and BFB weightings

Without a vibrating force input to the fingers and hand, it is impossible to have a distributed acceleration on the system. The TAB weighting method is actually based on the distributed inertial force due to acceleration, but the BFB is based on the biodynamic force response. Therefore, they emphasize two different-but-related aspects of the same response. This explains why the weightings derived from these two methods are very similar in some cases. For example, the wrist TAB weighting is very similar to the palm BFB weighting; hence, the accelerations calculated from both weightings are highly correlated with the ISO-weighted acceleration ($r \geq 0.919$), as shown in Tables 1 and 2.

Because the TAB emphasizes the distributed effect but the BFB emphasizes the overall effect, these two weightings also have some significant differences. The average transmissibility values measured on the fingertip, the phalanxes, and the third metacarpal may represent the general exposure level of the fingers. It may be reasonable, therefore, to use their average value as a general TAB weighting for the fingers. Because the BFB finger weighting is derived from the overall mass response of the fingers, TAB and BFB weightings should have a strong relationship. However, their trends are significantly different at frequencies lower than 100 Hz, as shown in Fig. 6. This is because at frequencies lower than 100 Hz, the dynamic force acting on the fingers is partially transmitted to the other parts of the system through the bones and joints inside the fingers, hand, and arm. The BFB weighting thus represents both local and global responses in this frequency range, whereas the TAB is principally based on the local tissue acceleration. At higher frequencies, the finger response is practically independent of the rest of the system, and the global response can be ignored. This is why the BFB and TAB weightings were similar at high frequencies, as also shown in Fig. 6.

Major topics for future studies

A major assumption made in this study was that biodynamic force components of the same magnitude are equally important at different frequencies. This may not hold true. Unfortunately, the frequency dependency of any medical effect on the biodynamic force has not been established. Without any knowledge of their relationships, as an initial trial, it may be reasonable to use this 'equal effect' assumption. When information on the dynamic force-effect relationship becomes available, the biodynamics-based weightings can be improved.

The BFB weightings are currently limited to one direction (along the forearm direction). The reported data may not be sufficient to represent the general population of workers using powered hand tools. The reported data should also be further confirmed or verified. Many factors could affect the BFB and TAB weightings, and they have not been sufficiently investigated. Both the BFB and TAB weightings may be non-linear functions of the source vibration magnitude that could affect the biodynamic responses[41], but few sets of data are available to determine their relationships.

Further experimental and modeling studies on the biodynamics of the system are also required to determine the relationships among the biodynamic force, transmitted acceleration, and biodynamic stress and deformation. As mentioned above, the use of vibration-induced stress, deformation, or power absorption density as a basis for deriving the biodynamics-based frequency weightings represents the best theoretical approach. Hence, the development of a practical and reliable method for quantifying these internal biodynamic response parameters is an interesting and useful research topic for future studies.

Finally, it should be emphasized that the proposed weighting factors presented in this paper are based solely on the overall biodynamic responses of the fingers-hand-arm system in the frequency domain. Biodynamics alone may not address every important factor that could influence the initiation and development of vibration-induced disorders and injuries. This may be a reason that the biodynamics-based frequency weightings have some large differences from those derived from the other foundations. The determinations of the frequency weightings may need the combinations of the knowledge and results from all the four theoretical foundations. Nevertheless, the biodynamic responses represent a unique and important aspect of the vibration exposure. Although further study is required, this study demonstrated that the biodynamics can be used as an alternative tool for developing preliminary frequency weightings, and the results are encouraging.

Summary and Conclusions

This study examined the biodynamic foundation for assessing the risk associated with vibration exposure to the

fingers-hand-arm system. A set of biodynamic methods were proposed to formulate the preliminary frequency weightings for assessing the risks associated with vibration exposures at different anatomical locations of the system. Specifically, the vibration transmissibility measured on the fingers, hand, wrist, elbow, shoulder, and head was used to define their respective transmitted acceleration-based (TAB) frequency weightings. The apparent mass measured at the fingers and the palm of the hand was used to construct the biodynamic force-based (BFB) weighting. Further studies are required to improve the proposed frequency weighting methods.

The results of this study suggest that the frequency weightings for the vibration-induced problems at different anatomical locations of the hand-arm system can be basically divided into three groups: (a) the weighting for the fingers and hand, (b) the weighting for the wrist, elbow, and shoulder, and (c) the weighting for the head. The ISO weighting is highly correlated with the weighting for the second group but not with the first and third groups. The TAB and BFB finger weightings are quite different at frequencies lower than 100 Hz, but they show similar trends at higher frequencies. Both TAB and BFB finger weightings at frequencies higher than 20 Hz are greater than the ISO weighting.

Acknowledgement

The authors thank Chris Warren for his assistance in the study.

References

1) Kihlberg S, Attebrant M, Gemne G, Kjellberg A (1995) Acute effects of vibration from a chipping hammer and a grinder on the hand arm system. Occup Environ Med **52**, 731–7.
2) Griffin MJ (1990) Handbook of human vibration. Academic Press, London.
3) Pelmear PL, Wasserman DE (1998) Hand-arm vibration: A comprehensive guide for occupational health professionals. 2nd ed. OEM Press, Beverly Farms, MA.
4) 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.
5) Louda L (1990) Assessment and standard on hand-transmitted vibration. In: Proceeding of the 5th International Standard on Hand-arm Vibration. 341–3, Tokyo, Japan.
6) Miwa T (1968) Evaluation methods for vibration effects. Part 4: Measurement of vibration greatness for whole-body and hand in vertical and horizontal vibration. Ind Health **6**, 1–10.
7) Haasnoot RA, Mansfield NJ (2004) Effect of push/pull force on perception of vibration at steering wheel. In: Proceeding of the 10th International Conference on Hand-arm Vibration. 127–8, Las Vegas, USA.
8) Anttonen H, Virokannas H (1992) Hand vibration among snowmobile drivers and prediction of VWF by vibration standard. In: Proceedings of the 6th International Conference on Hand-arm Vibration. 875–83, Bonn, Germany.
9) Brammer A (1986) Dose-response relationships for hand-transmitted vibration. Scand J Work Environ Health **12**, 284–8.
10) Dandanell R, Engstrom K (1986) Vibration from riveting tools in the frequency range 6 Hz-10 MHz and Raynaud's phenomenon. Scand J Work Environ Health **12**, 338–42.
11) Bovenzi M, Franzinelli A, Strambi F (1988) Prevalence of vibration-induced white finger and assessment of vibration exposure among travertine workers in Italy. Int Arch Occup Environ Health **61**, 25–34.
12) Nilsson T, Burström L, Hagberg M (1989) Risk assessment of vibration exposure and white fingers among platers. Int Arch Occup Environ Health **61**, 473–81.
13) Starck J, Jussi P, Ilmari P (1990) Physical characteristics of vibration in relation to vibration-induced white finger. AIHAJ **51**, 179–84.
14) Pelmear PL, Leong D, Taylor W (1989) Measurement of vibration of hand-held tools: Weighted or unweighted? J Occup Med **31**, 902–8.
15) Lundström R, Lindmark A (1982) Effects of local vibration on tactile perception in the hands of dentists. J Low Freq Noise Vib **1**, 1–11.
16) Lundström R (1985) Effects of local vibration transmitted from ultrasonic devices on vibrotactile perception in the hands of therapists. Ergonomics **28**, 793–803.
17) Griffin MJ (1994) Foundation of hand-transmitted vibration standards. Nagoya J Med Sci **57** (Suppl), 147–64.
18) Pradko F, Lee RA, Greene JD (1965) Human vibration-response theory. American Society of Mechanical Engineers. Paper No. 65-WA/HUF-19.
19) Cundiff JS (1976) Energy dissipation in human hand-

arm exposed to random vibration. J Acoust Soc Am **59**, 212–4.

20) Lidström IM (1977) Vibration injury in rock drillers, chiselers, and grinders. Some views on the relationship between the quantity of energy absorbed and the risk of occurrence of vibration injury. In: Proceedings of the 2nd International Conference on Hand-arm Vibration. 77–83, Cincinnati, OH, USA.
21) Dong RG, Schopper AW, McDowell TW, Welcome DE, Wu JZ, Smutz WP, Warren C, Rakheja S (2004) Vibration energy absorption (VEA) in human fingers-hand-arm system. Med Eng Physics **26**, 483–92.
22) Wu JZ, Dong RG, Schopper AW, Smutz WP (2003) Analysis of skin deformation profiles during sinusoidal vibration fingerpad. Ann Biomed Eng **31**, 867–78.
23) Dong RG, Welcome DW, Wu JZ (2005) Estimation of the biodynamic forces distributed on the fingers and the palm exposed to vibration. Ind Health **43**, 485–94.
24) Donati P (2001) Evaluation of occupational exposure to hand-transmitted vibration: frequency weighting and exposure time (a preliminary survey) Vibration Injury Network, Appendix H4A (http://www.humanvibration.com/EU/VINET/).
25) Dong RG, McDowell TW, Welcome DE, Wu JZ (2004) An investigation of the relationship between vibration-induced white finger and power absorption. In: Proceeding of the 10th International Conference on Hand-arm Vibration. Las Vegas, USA.
26) Thomas M, Beauchamp Y (1998) Development of a new frequency weighting filter for the assessment of grinder exposure to wrist transmitted vibration. Computers Ind Eng **35**, 651–4.
27) Dong RG, Rakheja S, Schopper AW, Han B, Smutz WP (2001) Hand-transmitted vibration and biodynamic response of the human hand-arm: A critical review. Crit Rev Biomed Eng **29**, 393–439.
28) Sörensson A, Lundström R (1992) Transmission of vibration to the hand. J Low Freq Noise Vib **11**, 14–22.
29) Reynolds DD (1977) Hand-arm vibration: A review of 3 years research. In: Proceedings of the 2nd International Conference on Hand-arm Vibration. 99–128, Cincinnati, OH, USA.
30) Sakakibara H, Kondo T, Miyao M, Yamada S, Nakagawa T, Kobayahsi F, Ono Y (1986) Transmission of hand-arm vibration to the head. Scand J Work Environ Health, 359–61.
31) Griffin MJ (1997) Measurement, evaluation, and assessment of occupational exposures to hand-transmitted vibration. Occup Environ Med **54**,73–89.
32) ISO 10068 (1998) Mechanical vibration and shock—Free, mechanical impedance of the human hand-arm system at the driving point. International Organisation for Standardization), Geneva, Switzerland.
33) Dong RG, Wu JZ, McDowell TW, Welcome DE, Schopper AW (2005) Distribution of mechanical impedance at the fingers and the palm of human hand. J Biomech **38**, 1165–75.
34) Griffin M, Bovenzi M, Nelson CM (2003) Dose-response patterns for vibration-induced white finger. Occup Environ Med **60**, 16–26.
35) Tominaga Y (2004) Frequency weighting of hand-arm vibration. In: Proceedings of the 10th International Conference on Hand-arm Vibration. Las Vegas, USA.
36) NIOSH publication 89-106 (1989): Criteria for a recommended standard: Occupational exposure to hand-arm vibration. ed. by U.S. Department of Health and Human Services, National Institute for Occupational Safety and Health, Cincinnati, OH.
37) Harada N, Griffin MJ (1991) Factors influencing vibration sense thresholds used to assess occupational exposures to hand-transmitted vibration. Br J Ind Med **48**, 185–92.
38) Maeda S, Griffin MJ (1993) Temporary thresholds shifts in fingertip vibratory sensation from hand-transmitted vibration and repetitive shocks. Br J Ind Med **50**, 360–7.
39) Bovenzi M, Lindsell CJ, Griffin MJ (2000) Acute vascular responses to the frequency of vibration transmitted the hand. Occup Environ Med **57**, 422–30.
40) Malchaire J, Piette A, Cock N (2001) Associations between hand-wrist musculoskeletal and sensorineural complaints and biomechanical and vibration work constraints. Ann Occup Hyg **45**, 479–91.
41) Kihlberg S (1995) Biodynamic response of the hand-arm system to vibration from an impact hammer and a grinder. Int J Ind Ergon **16**, 1–8.