11TH INTERNATIONAL CONFERENCE ON HAND-ARM VIBRATION

HOW TO COMPARE ALTERNATIVE VIBRATION MEASURES WITH ACCELERATION MEASURES

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Abstract

A good strategy for evaluating an alternative vibration measure such as vibration power absorption (VPA) is to compare it with weighted and unweighted acceleration values that have been applied to investigate hand-arm vibration exposures for many years. Several studies have made such comparisons, but there have been conflicting conclusions. This is primarily because different comparison methods were used in these studies. To resolve these contradictions, the first objective of this study was to identify an appropriate comparison method. As the second objective, the identified method was used to examine relationships between location-specific VPAs and acceleration measures. This study found that the vibration power absorbed in the palm-wrist-arm system is reasonably correlated with ISO-weighted acceleration, but that absorbed in the fingers is highly correlated with unweighted acceleration. The implications of the findings are discussed.

1. Introduction

Human vibration exposure is conventionally quantified using the frequency weighted acceleration calculated using the method defined in ISO 5349-1 (2001) [1]. Unweighted or unit-weighted acceleration has also been explored by many researchers [e.g. 2, 3]. Several alternative vibration measures such as vibration power absorption (VPA), VPA density, and vibration-induced stress/strain have been proposed to quantify vibration exposure [4]. Because many epidemiological studies have examined dose-response relationships between vibration-induced disorders and weighted and unweighted accelerations, it is a good strategy to evaluate these alternative measures by comparing them with these acceleration measures before directly using the alternative measures in epidemiological studies. Such comparisons are inexpensive and effective means for exploring their potential. It is very important to establish the worthiness of these alternative measures before dedicating additional resources to their further study or incorporating them into field investigation techniques. Therefore, the identification of an appropriate method for comparing the alternative measures with the acceleration-based measures is very important for further studies.

Different comparison methods have been used and have resulted in contradicting conclusions. For example, based on the z_h-direction vibration power absorption (VPA) spectrum in the one-third octave bands measured with a constant-acceleration power density spectrum excitation, a study [5] concluded that "75-84% of the total power is dissipated in the 8-50 Hz frequency range"; therefore, "the cut-off frequency of the recommended weighting function in the order of 50 Hz may better represent the power dissipation properties of the human hand and arm exposed to hand-transmitted vibration"; furthermore, this observation also suggests that "the (ISO) weighting function may provide an underestimate of the injury potential." In another study [6], the VPA spectra measured in the operation of several tools were directly compared with the spectra of the ISO-weighted and unweighted accelerations. Based on the comparisons, this study reported that "Of the methods, the evaluation specified by ISO 5349 pays more regard to low frequencies of vibration (< 50 Hz), absorption of vibration energy middle frequencies (50 – 200 Hz) and NIOSH (unweighted acceleration) high frequencies." "It is therefore not remarkable that no relation between the different evaluation methods was found." Instead of directly comparing the spectra, Dong et al. [7] compared the ISO weighting with the frequency weighting derived from the VPA of the entire hand-arm system. They concluded that the total VPA is a measure similar to ISO-weighted acceleration. To help resolve these contradictions, the first objective of this study was to identify an appropriate approach for comparing the acceleration measures with the alternative measures.

A new model of the hand-arm system has been recently developed by Dong et al. [8]. This model makes it possible to analyze the power absorption distributed in each of the major substructures such as the fingers, palm-wrist, arms, and shoulder. This advancement has also made it possible to test the hypothesis that the vibration power absorption related to the damage to or a disorder in a substructure of hand-arm system is that mainly distributed in that substructure. To test this hypothesis, the second objective of this study was to apply the identified comparison method to determine the frequency weightings of location-specific VPA values.

2. Methods

2.1 Comparison Approaches

Unweighted acceleration measured at the hand-tool interface is an actual measure of the vibration hazard. All other vibration measures must at least partially depend on the vibration input to the human hand-arm system. Therefore, any vibration measure can be generally expressed as a function of the unweighted vibration acceleration and other factors. For example, the ISO-weighted acceleration (A_{hw}) and the z-axis total vibration power absorption (P) at each frequency can be expressed as follows:

$$A_{hw}(\omega) = W_{hw}(\omega) \cdot A(\omega) \tag{1}$$

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

where W_{hw} is the frequency weighting defined in ISO 5349-1 [1], Z is the z-axis driving-point mechanical impedance of the hand-arm system, A is the rms value of the tool vibration acceleration or unweighted acceleration, and ω is the corresponding frequency in Rad/s.

Although some of these vibration measures may be associated with one another, they are different physical measures. For example, the VPA is obviously different from the acceleration; VPA is expressed in Watts or N·m/s, while acceleration is generally reported in m/s^2. Furthermore, while the ISO-weighted acceleration is a linear function of the unweighted acceleration, as shown in equation 1, the VPA is a power function of the acceleration, as shown in equation 2. These observations suggest that the vibration measures are not generally directly comparable.

There is one exception: if the input acceleration (A) values in equations 1 and 2 are the same and equal to 1 (or unit value) at each frequency of concern, the shapes or the trends of the vibration measures in the frequency domain are directly comparable. The study reported in [5] used several tools to measure the palm VPA. The tool spectra do not meet the conditions of the exception. Therefore, the VPA is not directly comparable with any acceleration spectrum. Consequently, the conclusions made from the direct comparisons are invalid or unfounded.

In another study [6], a broad band random (with a constant-acceleration power density spectrum in a certain frequency range) excitation was used to measure the z-axis VPA spectrum. If the VPA is expressed at constant-bandwidth frequencies, it is theoretically acceptable to use the constant-band VPA spectrum to represent the frequency weighting of the VPA. However, it is still invalid to directly compare such a VPA weighting with the ISO weighting because the VPA is not a linear function of the acceleration. Most critically, the acceleration spectrum of the broad band random excitation does not remain constant at the center frequencies of the one-third octave bands. Therefore, the VPA spectrum measured with the broad-band random vibration spectrum expressed in the one-third octave bands is not directly comparable with the ISO weighted acceleration spectrum. These observations suggest that the conclusions made based on such a direct comparison are also unfounded.

Mansfield and Griffin [9] proposed converting the VPA into a linear function of the unweighted acceleration to evaluate the power absorption for whole-body vibration exposures. Dong et al. [7] applied this concept to study hand-transmitted vibration exposure and proposed a method to derive the frequency weighting of the VPA measured at the hand-driving point. This method is outlined as follows:

First, taking the square root of equation 2, we have

$$\sqrt{P(\omega)} = \sqrt{Re[Z(\omega)]} \cdot A(\omega)/\omega \tag{3}$$

Whereas A in equation 1 is exactly the same as that in equation 3, $\{\sqrt{Re[Z(\omega)]}/\omega\}$ can be considered as a weighting value with respect to A, similar to W_{hw} in equation 1. However, the VPA-based weighting must be normalized to a reference value for its direct comparison with W_{hw} and for its convenient application. Since the maximum value of the ISO weighting in the one-third octave band is 0.958 at 12.5 Hz, the VPA-based weighting (W_{VPA}) is normalized with respect to this value and expressed as follows:

$$W_{VPA}(\omega) = 0.958 \frac{\sqrt{\mathrm{Re}[Z(\omega)]}}{\omega} \Bigg/ \frac{\sqrt{\mathrm{Re}[Z(\omega_{REF})]}}{\omega_{REF}} \tag{4}$$

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

With W_{VPA}, the VPA-weighted acceleration is calculated from

$$A_{VPA}(\omega) = W_{VPA}(\omega) \cdot A(\omega) \tag{5}$$

Obviously, A_{VPA} is directly comparable with A_{hw}; as are W_{VPA} and W_h. Therefore, this method is the most effective and reliable for their comparison. This approach is also generally applicable for comparing many other alternative vibration measures with the acceleration measures. It is further demonstrated in Section 2.3, in which the frequency weightings of the location-specific VPAs described in Section 2.2 are derived and used to compare the distributed VPA measures with the acceleration measures.

2.2 Hand-arm system model and calculation of distributed VPAs

Figure 1 shows the structure of a five-degree-of-freedom (DOF) hand-arm system model proposed by Dong et al. [8]. Unlike the other reported models that invariably represent the hand-handle coupling relationship with a resultant force acting at a single driving-point, this model considers this coupling as two driving-points and resultant forces acting on the finger- and palm-sides of the hand. The hand gripping a vibrating handle is represented by a clamp-like structure, as shown. The model comprises two sub-systems located on either side of longitudinal centerline of a cylindrical handle. The upper sub-system represents fingers positioned on one side of the handle, and it is characterized by two masses (M_4 and M_2) coupled through linear stiffness (k_4) and viscous damping (c_4) due to finger tissues. Mass M_4 represents effective mass of the finger skin contacting the handle. Mass M_2 is effective mass due to finger tissues and bones. The energy dissipated by viscous element c_4, which is directly related to relative movement between masses M_2 and M_4, is used to represent the power (P_4) absorbed within fingers tissues.

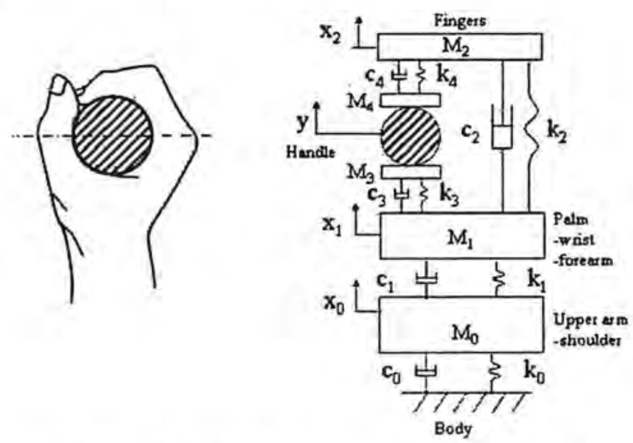


Figure 1 - A 5-DOF model of hand-arm system coupled to a cylindrical handle

The lower sub-system comprises the palm-wrist-forearm substructures, which is represented by two lumped masses (M_3 and M_1) coupled through visco-elastic elements (k_3 and c_3). The mass M_3 could be considered to represent the effective mass of palm skin in contact with the handle and M_1 is the effective mass attributed to the palm-wrist-forearm substructure. Similar to the representation of the finger VPA, the power (P_3) dissipated by c_3 directly relates to the power absorbed in the palm-wrist-forearm substructure.

The two sub-systems of the hand and arm model are also coupled through linear spring-damping elements (k_2 and c_2) coupling the masses M_2 and M_1, as shown in figure 1. The energy storing (k_2) and dissipative elements (c_2) could be considered to represent visco-elastic properties of metacarpo-phalangeal joints. Therefore, the power (P_2) absorbed by c_2 is used to represent the VPA distributed in the metacarpo-phalangeal joints and their surrounding tissues.

The palm-wrist-forearm mass, M_1, is coupled to the effective mass of the upper arm-shoulder substructure through another combination of spring-damping elements (k_1 and c_1). The power dissipated by c_1 relates to the power absorbed by tissues in the forearm and upper arm structures (P_1).

The mass M_0 also includes portions of the upper body terminated as a fixed support through visco-elastic elements k_0 and c_0. The power dissipated by c_0 relates to the power (P_0) absorbed by tissues in the shoulder and the upper body.

The specific method and experimental data used to determine the parameters of the models applied to this study are reported in [10]. Once the model parameters are determined, any tool acceleration spectrum (A_{Tool}) can be used as input to the model to calculate the distributed VPAs using the following formula:

$$P_k(\omega) = c_k \cdot [\Delta V_k(\omega)]^2 \tag{6}$$

where ΔV_k is the rms relative velocity across c_k, evaluated from the modelling.

2.3 Frequency weightings derived from location-specific VPAs

Taking the square root of equation 6, we have

$$\sqrt{P_k(\omega)} = \sqrt{c_k} \cdot \Delta V_k(\omega) \tag{7}$$

Because the model shown in figure 1 is a linear model, the response must be proportional to the input acceleration at each frequency. Therefore, equation 7 can be expressed as follows:

$$\sqrt{P_k(\omega)} = \left[\sqrt{c_k} \cdot \eta_k(\omega)\right] \cdot A_{Tool}(\omega) \tag{8}$$

where η_k is a function of the model parameters. The expression $\left[\sqrt{c_k} \cdot \eta_k(\omega)\right]$ can be considered as a weighting function (W_{VPA_k}) with respect to A_{Tool}. However, it is difficult to express such a function in its explicit form. Practically, W_{VPA_k} is determined by letting the handle have a constant rms acceleration at each frequency, calculating ΔV_k using the model, taking the square root of each VPA using equation 7, and normalizing the obtained spectrum.

3. Results and Discussion

By applying equation 4 to the mechanical impedance data reported by Kihlberg [11], Marcotte et al. [12], and Dong et al. [13], the basic pattern of total VPA weighting was identified. As shown in figure 2, the weighting derived from the VPA of the entire hand-arm system is consistent with the ISO weighting. This observation further supports the conclusions made by Dong et al. [7], but it contradicts those reported in two other studies [5,6].

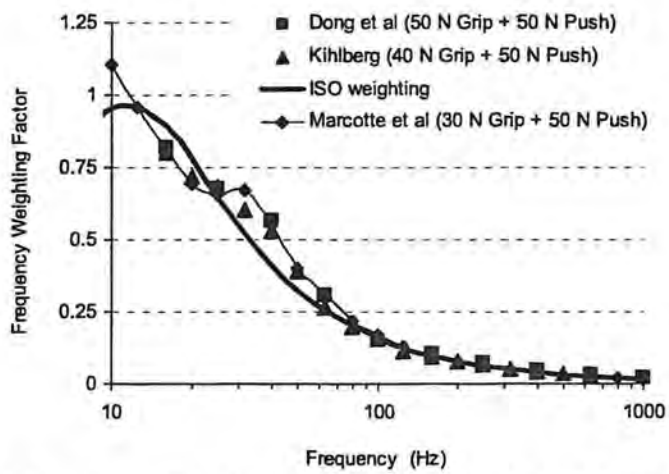
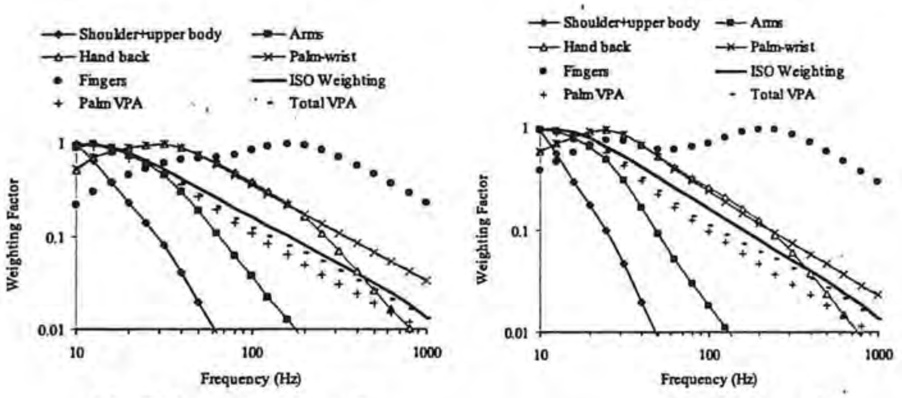


Figure 2 - Comparisons of ISO and VPA weightings derived from three sets of experimental data

Using the model parameters reported in [10], the distributed VPAs were calculated and the corresponding frequency weightings were derived. As examples, figure 3 shows the frequency weightings derived from the distributed VPAs at two combinations of hand forces (30 N grip + 45 N push; and 50 N grip-only), together with the ISO frequency weighting. The VPA-based weightings are normalized with respect to the maximum value of the VPA spectrum for each substructure at each hand force combination. Consistent with those shown in figure 2, the weighting derived from the total VPA is very similar to the ISO weighting. Although the ISO-weighting emphasizes the low frequency components, the shoulder (c_0) VPA-based weighting emphasizes even lower frequency components. The wrist VPA-based weighting is also close to the ISO weighting, but unlike the ISO weighting, it reveals relatively higher weighting up to 50 Hz. The finger weighting emphasizes the middle frequency range from 16 to 500 Hz.

Using the tool spectra reported by Griffin [14] and the frequency weightings shown in figure 3, their corresponding weighted accelerations were calculated and their correlations were analyzed. Table 1 lists correlation coefficients among the alternative and acceleration measures. The results show trends that are consistent with those observed from the weighting curves shown in figure 3. The total VPA and VPA measured at the palm are highly correlated with the ISO-weighted acceleration. The VPAs distributed in the palm-wrist and arms also generally well-correlated with the ISO-weighted acceleration. The finger VPA, however, is poorly correlated with the ISO-weighted acceleration, but it is highly correlated with the unweighted acceleration. This may provide an explanation of the phenomenon reported in [2]: unweighted acceleration had a better correlation with vibration-induced white finger than ISO weighted acceleration.



(a) 30 N grip + 45 N push (b) 50 grip-only

Figure 3 - Comparisons of ISO weighting and the weightings derived from the distributed VPAs

Table 1 - Correlations among the vibration measures calculated using twenty tool spectra reported by Griffin [14]

Hand Actions	30 N grip+45 N push		50 N grip	
Vibration Measure	Weighted acceleration	Unweighted acceleration	Weighted acceleration	Unweighted acceleration
c_0: shoulder, neck and head	0.7183	0.3384	0.6879	0.3145
c_1: forearm and upper arm	0.9275	0.1308	0.8693	0.0307
c_2: hand back and meta-carpophalangeal joints	0.8698	0.7222	0.9319	0.6149
C_3: palm-wrist	0.8760	0.7242	0.9367	0.5942
C_4: fingers	0.3925	0.9688	0.4210	0.9747
VPA into the palm	0.9898	0.3384	0.9847	0.3145
Total VPA	0.9966	0.3960	0.9930	0.3719

4. Conclusions

This study concluded that some of the reported studies [e.g., 5,6] used inappropriate methods to compare VPA with acceleration measures. Consequently, the conclusions made in these studies are unfounded. The comparison approach used by Mansfield and Griffin [9], and Dong et al. [7] is appropriate.

The results presented in this paper further confirmed the conclusions made by Dong et al. [7]: the frequency weighting derived from the total power absorption measured in the z_h-axis is consistent with the ISO frequency weighting; the total energy method is similar to the ISO-weighted acceleration method.

The frequency weightings derived from the distributed VPAs indicate that the vibration power absorption is mostly distributed in the arm and shoulder when operating low frequency tools such as rammers. The power absorption is mostly concentrated in the fingers and hand when operating high frequency tools such as grinders. The major resonances of the hand-arm system are closely reflected in VPA distributed in the fingers. The VPA results further suggest that vibration exposure in the middle frequency range (16 to 500 Hz) generally poses a higher risk of finger disorder development than does exposure to vibration at other frequencies. Whereas the finger VPA was found to be correlated with the unweighted acceleration measured on many tools, the VPA distributed in the palm-wrist-arm system was correlated with the ISO-weighted acceleration. These results could provide better understanding of the findings of the reported physiological and epidemiological studies. Although further studies are required to take into account the contributions of major influencing factors and to improve hand-arm system models, the proposed local energy method shows promising potential for the assessment of exposure dosage and associated health effects.

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