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Discussion

A discussion on comparing alternative vibration measures with frequency-weighted accelerations defined in ISO standards

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1. Introduction

Whereas human vibration exposures are conventionally quantified using frequency-weighted accelerations defined in several standards (e.g., Refs. [1,2]) established by International Organization for Standardization (ISO), vibration power absorption (VPA) of human body or hand–arm system has also been proposed as an alternative measure to quantify the exposures for more than 40 years [3–5]. However, the relationship between these two measures has not been sufficiently understood.

In a recent study on the vibration power absorption of the hand–arm system [6], the vibration power absorption data were collected under two broadband random vibration spectra with constant acceleration power spectral density in the 8–1000 Hz frequency range. Fig. 1 shows a typical example of the reported power absorption expressed in the one-third octave bands. Fig. 2 shows the frequency weighting specified in ISO 5349-1 [1] for assessing the risk of hand-transmitted vibration exposure. Based on the comparison of these two figures, the reported study made the following conclusions:

> The results suggest that 75–84% of the total power is dissipated in the 8–50 Hz frequency range, irrespective of the excitation magnitude, handle size and hand forces. Considering that a large number of percussion and rotary hand power tools transmit predominant vibration at frequencies below 50 Hz, relatively high injury risk may be associated with exposure to hand-transmitted vibration in this frequency range. Although the frequency-weighting defined in the current standard (ISO 5349-1) emphasize the importance of transmitted vibration up to 16 Hz, it suppresses the vibration at frequencies above 16 Hz at a rate of 6 dB/decade. The results obtained in this study suggest that the weighting function may provide an underestimate of the injury potential. 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.

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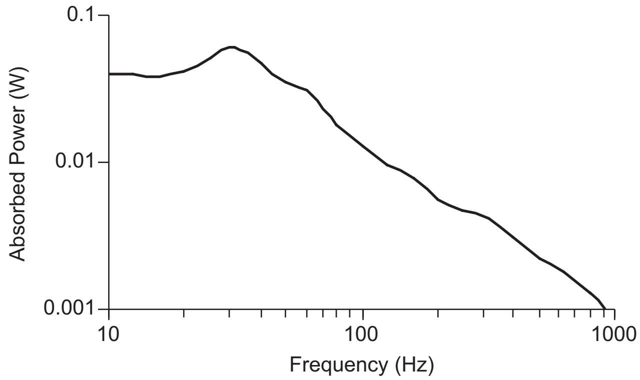

Fig. 1. Absorbed power of the hand–arm system measured under 30 N grip and 50 N push force with a constant acceleration power density spectrum (with ISO-weighted acceleration = $5.0\,m/s^2$), which is similar to that in Ref. [6].

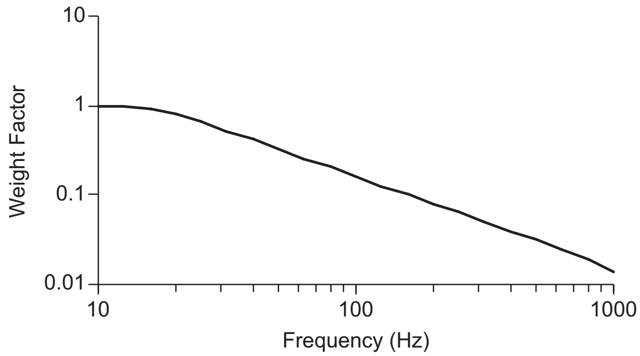

Fig. 2. Frequency-weighting function specified in ISO 5349-1 (2001) [1].

These conclusions are questionable primarily for the following reasons: (1) the vibration power absorption spectrum measured with a specific excitation cannot usually be used to represent vibration power absorption frequency dependency because the vibration power absorption spectrum is excitation spectrum-specific, as shown in Fig. 3; (2) consequently, the reported percentages of absorption in different frequency ranges cannot be generally applied; and (3) it is invalid to directly compare the shape of this excitation-specific vibration power absorption spectrum with that represented by ISO-frequency weighting. Therefore, the fundamental study approach is questionable. A similar problem was observed in an earlier study [7]. Although the related issues were addressed in several other studies [8–10] and debated in an open panel discussion at the 10th International Conference on Hand–Arm Vibration held in 2004, the problems with this recent publication [6] suggest that there is still lack of sufficient understanding of how the vibration power absorption can be appropriately compared with the ISO-defined acceleration measure, or perhaps there are major disagreements among researchers on how these vibration measures should be compared with each other. In either case, it is worthwhile to further discuss it.

More importantly, the discussion is useful for further studies of not only hand-transmitted vibration but also whole-body vibration exposures. Besides vibration power absorption, several other alternative measures such as vibration power absorption density [11], vibration stress and strain in local tissues (e.g., Refs. [12–15]), and accelerations measured on the hand and wrist have also been proposed to quantify vibration exposures (e.g., Ref. [16]). Except for the vibration power absorption of the entire system, these alternative measures are location-specific biodynamic responses [9]. Some of them may be more closely related to the location-specific vibration-induced disorders and/or injuries than the ISO-weighted acceleration or the total vibration power absorption, as hypothesized in a few studies (e.g., Refs. [9–14,17]). Therefore, they may become more

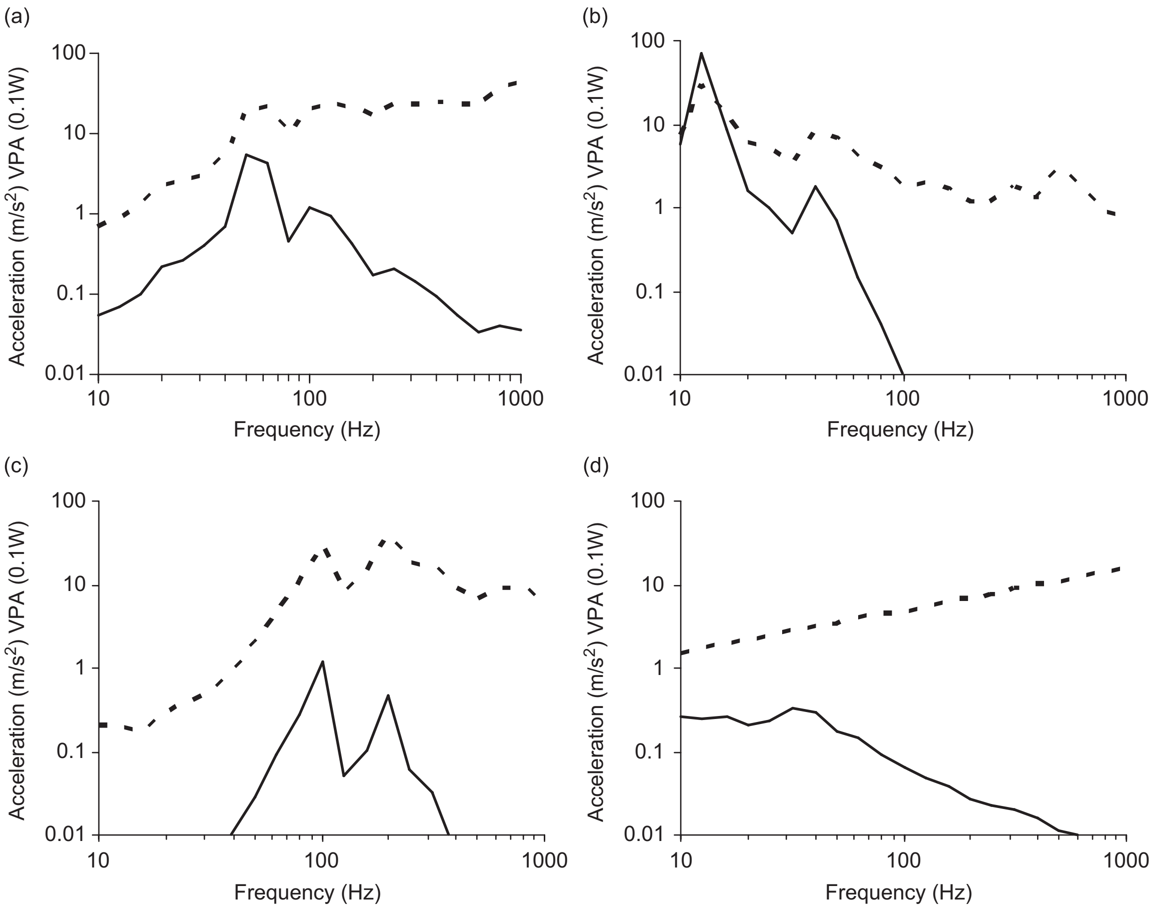

Fig. 3. Comparisons of the vibration power absorption spectra estimated for four different excitation spectra: (a) chipping hammer [26]; (b) petrol wacker [26]; (c) electric angular grinder [26]; and (d) broadband random acceleration spectrum with the ISO-weighted acceleration of 5.0 m/s^2 ((——) vibration power absorption; (- - - - -) excitation).

attractive and important in further studies as they will be more reliably measured or simulated with further advances in experimental and modeling technologies. On the other hand, both hand-transmitted and whole-body vibration exposures at workplaces have been usually measured and reported using ISO-frequency-weighted acceleration, together with the information on the disorders and injuries. Some studies have also provided valuable information on the effectiveness of the ISO-defined measure (e.g., Refs. [18–23]). The comparison of ISO-weighted acceleration and an alternative measure can be used to identify their differences and to evaluate the potential of the alternative measure (e.g., Refs. [10,14,17]). It is usually inexpensive and efficient to establish the worthiness of the alternative measure before dedicating additional resources to its further study and/or incorporating it into field investigation techniques.

Therefore, the objective of this discussion is to evaluate various comparison methods in order to help identify a reliable and generally applicable method for comparing alternative vibration measures with ISO acceleration measures.

2. Evaluations of comparison methods

The comparison methods that have been used in the reported studies can be broadly classified into four categories: (i) direct spectrum comparison (e.g., Ref. [7]); (ii) comparison of the ISO-frequency weighting and a special spectrum of an alternative measure (e.g., Ref. [6]); (iii) correlation analysis (e.g., Refs. [8,10]); and (iv) frequency-weighting comparison (e.g., Refs. [10,14–17]). For the purpose of this discussion, the vibration power absorption of the entire hand–arm system is used to demonstrate how these different methods could end up with contradictory conclusions; it will also be used to help identify an appropriate comparison method.

Theoretically, the relationship among the driving-point mechanical impedance of the hand–arm system (Z), the root-mean-square acceleration (A) input to the hand, and the vibration power absorption (P) at a frequency (f_i) can be expressed as follows [10,24]:

$$P(f_i) = \mathrm{Re}\,[Z(f_i)]\left(\frac{A(f_i)}{2\pi f_i}\right)^2. \tag{1}$$

If the acceleration used in the calculation is not that used in the quantification of impedance, this relationship may not hold strictly correct because the human body is usually a nonlinear mechanical system; the impedance could vary with changes in vibration excitation. However, a previous study also reported that the impedance measured with a grinder vibration spectrum was very similar to that measured with a chipping hammer vibration spectrum, and that the increase in the vibration magnitude only marginally affected the impedance [25]. As reported in Ref. [6], doubling the excitation level from 2.5 to 5.0 m/s^2 increased the total vibration power absorption by approximately four times, which is consistent with the prediction of Eq. (1). These observations suggest that, as the first degree of approximation, it is acceptable to use Eq. (1) to predict the power absorption using the impedance measured in a laboratory when the tool acceleration spectrum is available. It is readily apparent from Eq. (1) that the vibration power absorption is sensitive to variations in the input acceleration. Several examples of the tool vibration spectra and the predicted vibration power absorption are shown in Fig. 3. The impedance data used in the predictions were from Ref. [28], which were measured on a 40 mm handle under a combined 30 N grip and 50 N push.

2.1. Direct comparison

The direct method was used in the study reported in Ref. [7]. Specifically, the vibration power absorption spectra measured in the operation of several tools were directly compared with the spectra of the ISO-weighted and unweighted accelerations measured on these tools. Based on the comparisons, the 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 (vibration power absorption) middle frequencies (50–200 Hz) and NIOSH (unweighted acceleration) high frequencies." Therefore, the researchers further concluded that "no relation between the different evaluation methods was found". Whereas the aforementioned conclusions from Ref. [6] suggest that vibration power absorption emphasizes the effect of vibration frequencies below 50 Hz, this study [7] suggested that the highest vibration power absorption values are produced by vibration excitations with frequencies from 50 to 200 Hz. These two studies are obviously contradictory.

This direct comparison method has a critical problem: vibration power absorption is measured and reported in units of power (i.e., W or N m/s); however, acceleration is a motion measure reported in units of m/s^2. It is inappropriate to make a direct comparison between a power measure and an acceleration measure. Likewise, the shapes or trends of a vibration power absorption spectrum and an acceleration spectrum are not directly comparable because vibration power absorption is not a linear function of acceleration, as clearly shown in Eq. (1). The shapes of the vibration power absorption spectra measured on different tools could also vary greatly, as shown in Fig. 3. As a result, conclusions based on comparisons of petrol wacker vibration power absorption and acceleration spectra are clearly not applicable to other types of tools. Therefore, the related conclusions made in Ref. [7] are ungrounded.

2.2. Comparison of ISO-frequency weighting and a special vibration power absorption spectrum

As above-mentioned, the study in Ref. [6] compared the ISO weighting with a special vibration power absorption spectrum measured using an excitation with a constant acceleration power spectral density in the 8–1000 Hz frequency range. This is also an invalid comparison method.

In ISO 5349-1 [1], the spectrum of ISO-weighted acceleration (A_{hw}) in the one-third octave bands is defined as follows:

$$A_{hw}(f_i) = W_h(f_i)A(f_i), \tag{2}$$

where A is the root-mean square value of the tool acceleration at the ith one-third octave band frequency (f_i), and W_h is the frequency-weighting function specific in ISO 5349-1 [1].

As dictated by Eq. (2), to make a direct comparison with the ISO weighting, the spectrum of an alternative vibration measure should meet the following two conditions: (i) the alternative measure should be a linear function of acceleration; and (ii) the specific spectrum of the alternative measure to be used for the comparison should be measured using an excitation with a constant acceleration value at each one-third octave frequency band. The comparison method used in Ref. [6] violates both conditions: vibration power absorption is not a linear function of acceleration, and an excitation with a constant acceleration power spectral density in the one-third octave bands does not have a constant acceleration at each frequency band, as shown in Fig. 3(d). Consequently, any criticism of the ISO weighting method based on an inappropriate comparison is ungrounded.

This comparison method also has a non-critical problem. Practically, it is very difficult to accurately achieve a constant acceleration power spectral density in the 8–1000 Hz frequency range on the vibration test system used in the reported study [6]. Because the vibration power absorption is approximately proportional to the square of the acceleration, as dictated by Eq. (1), the vibration power absorption spectrum would be very sensitive to any errors in the input spectrum.

2.3. Correlation analysis

Correlation analysis is a statistical method that has been widely used to explore or establish the relationship between two groups of data or two measures. Theoretically, this method does not require that the two measures share the same units or physical attributes. Therefore, it is acceptable to use this method to examine the relationship between vibration power absorption and an acceleration measure. As shown in Fig. 4, the vibration power absorption is highly correlated with the ISO-frequency-weighted acceleration in a nonlinear manner, which suggests that these two measures are strongly associated. This clearly contradicts the "no relation" conclusion made in Ref. [7].

It should be noted that some caution is required in the application of correlation analyses. Theoretically, a significant correlation does not guarantee that the two measures have a relationship, but if they do have a relationship, they must be correlated linearly or nonlinearly. Therefore, the correlation is a necessary but insufficient condition. Moreover, the exact relationship and its reliability also depend on which and how many

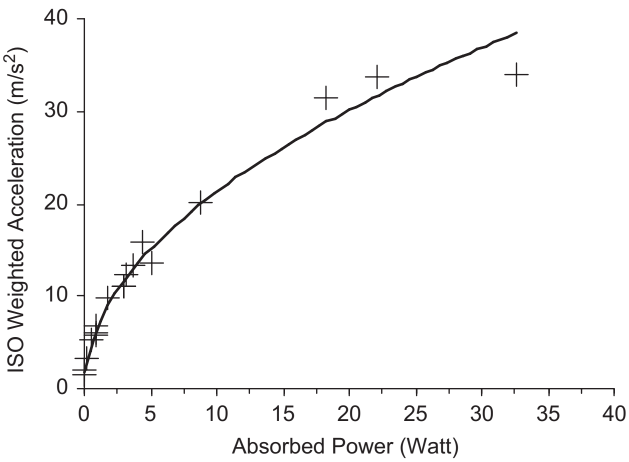

Fig. 4. Correlation relationship between the ISO-weighted accelerations and the total vibration power absorption values predicted with Eq. (1) for the 20 sets of tool vibration data reported in Ref. [26] ((+ + + + +) raw data; (———) trendline).

sets of data are selected and used in the correlation analysis. If the vibration power absorption and acceleration data used in the analysis are collected from a small number of tools with similar vibration spectra, the identified relationship may not be reliable.

2.4. Frequency-weighting comparison

The above discussions make it clear that if an alternative measure is a linear function of acceleration, the shape of the measured spectrum can be compared with that of the acceleration measures. If the alternative measure shares the same units as the ISO-frequency-weighted acceleration, their weighting functions with respect to the acceleration input to the hand are also directly comparable. Several alternative vibration measures such as unweighted (or unit weighted) acceleration and the accelerations measured on the hand and body can be directly compared with the ISO-weighted accelerations. Vibration transmissibility can also be directly compared with the ISO-frequency weightings.

Various approaches such as the analytical approach expressed in Eq. (1), the magnitude test approach used in Ref. [6], and the correlation analysis used in Ref. [8] can be applied to identify the basic relationship between the alternative measure and the input acceleration. If the relationship is nonlinear, the alternative measure can be transformed into a derived measure that meets the conditions required for a valid comparison. For example, the total vibration power absorption has been transformed into a linear function of acceleration by taking its square root [10,27]. Similarly, the vibration power absorption density, the vibration power absorptions distributed in substructures, and the stress-based measure have also been transformed into linear functions of acceleration to derive their frequency weightings [9,14,17].

This transformation approach was initially used in a whole-body vibration power absorption study by Mansfield and Griffin [27] and in a hand-transmitted vibration power absorption study by Donati [28], in which the measured vibration power absorption and the input acceleration or velocity were used in their evaluations. To avoid using the measured vibration power absorption that is sensitive to the excitation and to simplify the evaluation procedures proposed in Ref. [27], Dong et al. [10] derived a formula from Eq. (1) to calculate vibration power absorption-weighted acceleration (A_{VPA}), which is expressed as follows:

$$A_{\mathrm{VPA}}(f_i) = W_{\mathrm{VPA}}(f_i)A(f_i), \tag{3}$$

where W_{VPA} is the vibration power absorption-based frequency weighting [10] and is derived using impedance data as follows:

$$W_{\mathrm{VPA}}(f_i) = \alpha(f_{\mathrm{REF}})\frac{\sqrt{\mathrm{Re}\,[Z(f_i)]}}{2\pi f_i}\Bigg/\frac{\sqrt{\mathrm{Re}\,[Z(f_{\mathrm{REF}})]}}{2\pi f_{\mathrm{REF}}}, \tag{4}$$

where f_{REF} is the frequency of the reference impedance, which is selected based on the particular characteristics of a given study, and α is the ISO-defined weighting value at the reference frequency. For example, in the case of the hand-transmitted vibration exposure, the reference frequency could be 12.5 Hz, at which the ISO weighting for the one-third octave bands reaches its maximum value (0.958) [1].

Fig. 5 shows the comparisons of the derived vibration power absorption weightings and ISO weighting defined in ISO 5349-1 [1]. One set of the impedance data used in the vibration power absorption weighting calculation were from the study reported in Ref. [29], in which the experimental conditions and instrumentation were basically the same as those used for the measurement of the vibration power absorption in Ref. [6]. The basic trends of these derived vibration power absorption weightings are very similar to the ISO weighting, which are consistent with those reported in Ref. [10]. Contradicting to the conclusions made with the first two comparison methods but consistent with the results from the correlation analysis shown in Fig. 4, the similarity suggests that the vibration power absorption of the hand–arm system along the forearm direction is strongly associated with ISO-weighted acceleration. This similarity also suggests that the vibration power absorption of the hand–arm system could be associated with the overall subjective sensation of the hand–arm system because the ISO weighting was established based on sensation data [30]. Also importantly, the strong similarity suggests that if the ISO-weighted acceleration overestimates the low-frequency effect and underestimates the high-frequency effect on the development of vibration-induced white finger, as suggested in

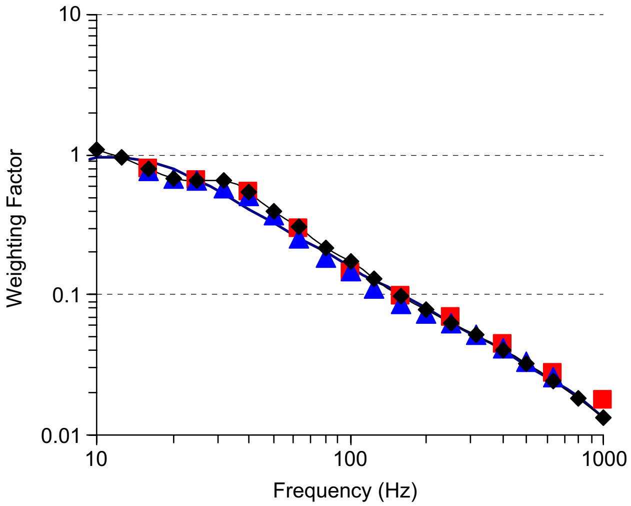

Fig. 5. Comparisons of the ISO-frequency weighting [1] and the vibration power absorption-based frequency weightings ((——) ISO weighting [1]; (—◆—) vibration power absorption weighting derived from the impedance data in Ref. [29]; (—▲—) vibration power absorption weighting derived from the impedance data in Ref. [25]; and (■) vibration power absorption weighting reported in Ref. [10]).

many reported studies [18–23], the total energy method could exhibit the same deficiencies. Therefore, the total energy method may not have great potential for studying vibration-induced white finger; other alternative measures should be explored for this purpose. However, the total energy method could be used to study vibration-induced disorders in the wrist–arm system, because ISO-weighted acceleration is correlated with some disorders in this sub-system [31]. These observations demonstrate that an appropriate comparison of an alternative measure and the ISO-standardized measure can be very useful for understanding the alternative measure and for assessing its potential for further studies and applications.

Many factors could affect an alternative measure. For example, the nonlinear behaviors of human responses to vibration exposure, hand forces, and postures can all potentially influence impedance and vibration power absorption of the hand–arm system and its substructures. The derived vibration power absorption frequency-weighting method provides a convenient and reliable approach to investigate these potential influential factors; those influences can be taken into account in the frequency weighting.

It should also be noted that in some instances, two studies using the same comparison method could end up with different results. For example, the vibration power absorption frequency-weighting functions shown in Fig. 5 are largely different from that reported in Ref. [28]. The effects of the influencing factors would be unlikely to fully account for such a large difference. In such a case, the validity of the impedance data or vibration power absorption data used in the weighting calculations should be more carefully examined. In some cases, a simple analysis can help identify the major reason of the difference [32]. For example, the vibration power absorption weighting on z_h-axis in Ref. [28] was derived from the data reported in Ref. [33], in which the vibration velocity was 14 mm/s for each frequency and the vibration power absorption values ranged approximately from 0.018 to 0.52 N m/s with the maximum value at 5 Hz (according to Fig. 6 in Ref. [33]). With these data, the real part of the impedance estimated using Eq. (1) ranges from 92 to 2653 N s/m. Estimated using these impedance data and their corresponding frequencies in the range of 5–1000 Hz, the imaginary part of the apparent mass ranges from 0.06 to 84 kg. Therefore, the maximum value of the imaginary apparent mass is greater than the average mass (64 kg) of the subjects who participated in the vibration power absorption measurement using a single hand [33]. This is obviously unrealistic, and it suggests that the reported vibration power absorption data and/or velocity value could contain serious errors; the vibration power absorption-based weighting derived from these data could be unreliable. This example also suggests that it is better to avoid using the vibration power absorption and excitation to derive the weighting, especially when the excitation acceleration or velocity is not simultaneously measured together with the vibration power absorption.

3. Conclusions

It is invalid to perform a direct comparison of an alternative vibration measure and ISO-frequency-weighted acceleration if the alternative measure cannot be considered as a linear function of the acceleration. This is the major problem in the first two comparison methods evaluated in this discussion. It is acceptable to use a third method, correlation analysis, to examine the relationship between the alternative measure and the ISO-weighted acceleration. A fourth method, frequency-weighting derivation and comparison, is the most appropriate method to determine the frequency dependency of the alternative measure and to identify its relationship to ISO weighting. The combination of correlation analysis and derived frequency weighting may provide a comprehensive analysis and understanding of an alternative method.

Each of the vibration exposure measures can generally be divided into two components: (i) the quantification of raw vibration inputs to the hand or body; and (ii) vibration frequency weighting. Although there may be some interaction between these two components [9,25], each represents a different aspect of the vibration exposure assessment. While methods for measuring raw vibration inputs continue to evolve, the determination of appropriate frequency weighting remains a major issue and further studies are certainly required. The generalized frequency-weighting method outlined in this discussion provides a tool for deriving frequency weightings for various biodynamic measures and for identifying similarities and differences among them. This frequency-weighting method is also useful for investigating the influences of various factors on each measure. Frequency weightings can also be modified to take into account any such factors.

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