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Time–frequency characterization of hand-transmitted, impulsive vibrations using analytic wavelet transform

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Abstract

Current guidelines to assess health risk of hand–arm vibration are based on the frequency-weighted rms acceleration level, therefore do not fully consider the effect of temporal variations of the spectral energy. Time averaging effect involved with the frequency analysis may severely underestimate the risk of impact tools. A time–frequency (*T–F*) analysis is necessary to characterize a highly transient signal whose spectral characteristics change rapidly in time. The analytic wavelet transform (AWT) is an ideal *T–F* analysis tool as it possesses the advantages of both the Fourier and wavelet transforms. The AWT is applied to acceleration signals measured from six tools, five impact type tools and one relatively steady-type tool, to explore possible improvements of the current risk assessment method of hand–arm vibration exposure. Based on the unique capability of the AWT, several new concepts including frequency-weighted time history, cumulative injury function, and cumulative injury index are defined in this study. Possible applications of these new concepts to hand–arm vibration research are described. Based on the results from this study, needs for future research are discussed.
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1. Introduction

Prolonged, extensive exposure to hand-transmitted vibration could cause a series of vibration-induced disorders in the vascular, sensorineural, and musculoskeletal structures of the human hand–arm system [1,2], which has been collectively called hand–arm vibration syndrome (HAVS). The precise conditions causing the disorders are not sufficiently known [3,4]; hence, it remains unclear how the vibration should be quantified to assess the risk of the exposure. The international standard ISO 5349-1 [3] recommends using the measure of root-mean-square (rms) acceleration for the evaluation. Since the vibration transmissibility and health effects

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Nomenclature

Variables

$a(t)$	acceleration time history
$\bar{a}_f(t)$	frequency-weighted time history
a	acceleration (scalar value) obtained by summing the frequency components
$\bar{\mathbf{a}}$	acceleration (scalar value) obtained by summing the *T–F* components
$A(f)$	1/3 octave rms amplitude of acceleration
$\bar{A}(f,t)$	instantaneous 1/3 octave rms amplitude of acceleration
f	frequency
f_i	center frequency of the *i*th 1/3 octave band
$g(t)$	Gaussian function
s	scale used in the wavelet transform
$w(f)$	frequency weighting function
$W_s a_x(t)$	AWT of $a_x(t)$
η,σ	AWT parameters
$\psi(t)$	wavelet function

Subscripts

f	indicates the quantity is frequency weighted: for example, $\bar{A}_f(f,t)$ is frequency-weighted instantaneous 1/3 octave rms amplitude of acceleration
x, y, z	indicates directions

are generally frequency-dependent, ISO 5349-1 also recommends a frequency weighting function to calculate the weighted rms acceleration for the risk assessment.

While a few epidemiological studies have reported results consistent with the predictions in the ISO standard [5,6], many other studies have reported large discrepancies [7–10]. To establish a more reliable dose–response relationship and develop a better methodology for quantifying the vibration exposure, further studies on this subject are essential. The major issues in the current international standard ISO 5349-1 (2001) are considered as follows:

(i) The recommended frequency weighting may not be suitable for predicting the disorders in the fingers and hand [11,12].
(ii) The required frequency range for the vibration measurement may be too narrow [10].
(iii) The daily and life-time exposure durations may not be properly considered [1].
(iv) Many factors that may be important contributors to HAVS such as applied hand forces, hand–arm postures, environment temperature, individual differences, vibration exposure direction are not taken into account [3].
(v) The frequency-weighted rms acceleration may not be a proper metric to represent the detrimental effect of impulsive vibration as it ignores the effect of temporal variation of vibration [9].

For these reasons, it has been regarded that ISO 5349-1 (2001) may only be provisionally applicable for shock/impact vibration, as it is noted in the standard itself. Addressing this issue, developing a better characterization method for impact vibrations was the motivation of this paper.

Some investigators have proposed the use of impulsiveness of vibration as an additional factor in the risk assessment [9]. However there seem to be many other factors that influence the exposure risk of impact vibrations [13]. Measurement and characterization of an impulsive vibration signal is a complicated task that involves various issues such as choice of physical parameters, selection of the frequency range and weighting functions, setting up the applied forces and postures, and the signal analysis method.

For a highly transient signal, the time and frequency characteristics have to be considered simultaneously because they are interwoven concepts in transient signals [14]. The wavelet transform is well suited for transient signal analysis because it breaks down the signal using variable *T–F* atoms, thus optimizes the *T–F* resolution [15]. Despite this obvious advantage, the wavelet transform has not been widely accepted for transient vibration signal analysis possibly because most existing data and standards in this field are in Fourier terms, i.e., frequency and amplitude. The analytic wavelet transform (AWT) is a very attractive option for this reason because it is a wavelet transform that characterizes signals in Fourier terms, frequency and amplitude. AWT has never been applied to hand-transmitted vibration problems as far as the authors know. Consequently, little information is known on the *T–F* characteristics of the tool vibrations.

The specific aims of this study are:

(a) Demonstrate how the AWT can be used for *T–F* analysis of impulsive tool vibrations.
(b) Study *T–F* characteristics of impact vibrations in comparison with steady-state vibrations.
(c) Develop a strategy to utilize *T–F* information from the AWT for HAVS study.
(d) Identify future research needs for the application of AWT technique in HAVS study.

2. Traditional frequency domain analysis

2.1. Tool vibration measurement

Vibration signals were measured from total 6 tools, which consist of a concrete saw that generates relatively smooth vibration and 5 impact tools, i.e. 2 chippers and 3 riveters, which generate impact vibrations. The measurements were conducted according to the method recommended in ISO 5349-2 (2001) for vibration measurement. For impact tools, accelerations were measured according to the test setup specified in ISO 8662-2 (1992) for the laboratory test of chipping hammers. For the concrete saw, accelerations were measured during a field test when the saw was used to cut part of a damaged concrete pavement. A sampling rate of 16,386 Hz was used in digitizing time histories of the signals in all measurements. Accelerations in 3 orthogonal directions, namely $a_x(t)$, $a_y(t)$ and $a_z(t)$, were measured using a palm adapter equipped with a tri-axial accelerometer on the handle of the tools. Accelerations of impact tools are clearly different compared to the relatively smooth acceleration of the concrete saw. Fig. 1 shows the *x*-direction accelerations $a_x(t)$ measured for the concrete saw, a steady rotary type tool, and chipper 2, one of percussion tools. Accelerations in *y* and *z* directions showed similar characteristics. Five percussion tools showed similar time–frequency characteristics. Therefore, only one percussion tool is used in figures for qualitative comparison of characteristics of percussion and rotary tools, while quantitative comparisons in Tables 1 and 2 include all 6 tools.

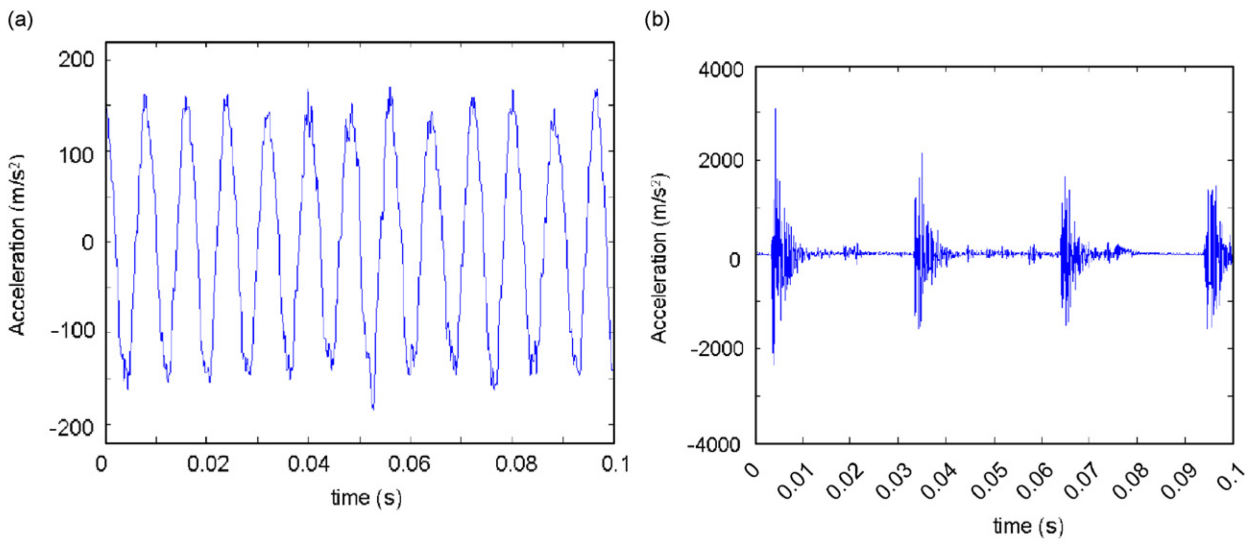

Fig. 1. Time histories of 6 measured acceleration responses: (a) concrete saw and (b) chipper 2.

Table 1
Unweighted, frequency weighted and T–F weighted rms amplitude of total accelerations of 6 tools (m/s^2)

Tool	rms amplitude without frequency weighting	rms amplitude with wrist–arm frequency weighting	rms amplitude with finger frequency weighting
Concrete saw	108.82	13.97	81.84
Chipper 1	127.62	13.98	46.37
Chipper 2	127.18	12.42	35.49
Riveter 1	95.3	5.72	26.10
Riveter 2	117.63	6.82	34.99
Riveter 3	150.59	10.29	49.83

Table 2
Exposure risk index calculated from the hand–arm and finger frequency-weighted rms acceleration time histories

Tool	Index based on hand–arm weighting	Index based on finger weighting
Concrete saw	0.0326	1.0406
Chipper 1	0.0208	0.0939
Chipper 2	0.0126	0.0309
Riveter 1	0.0000	0.0001
Riveter 2	0.0000	0.0055
Riveter 3	0.0040	0.1857

2.2. *Fourier transform-based frequency domain analysis*

Current method for HAVS risk assessment is based on the frequency domain analysis, thus steady-state concepts. The frequency spectra of the rms acceleration $A_x(t)$, $A_y(t)$ and $A_z(t)$ can be obtained from the Fourier transform data of the measured accelerations $a_x(t)$, $a_y(t)$ and $a_z(t)$. These spectra can be summed to calculate the frequency spectrum of the total rms acceleration $A(f)$:

$$A(f) = \sqrt{A_x(f)^2 + A_y(f)^2 + A_z(f)^2}. \quad (1)$$

A frequency weighting function $w(f)$ can be multiplied to $A(f)$ to reflect the perception sensitivity or health effects of human hand–arm or fingers exposed to vibration. Fig. 2 shows the frequency-weighting curves recommended in ISO 5349-1 (2001), along with a frequency-weighting derived from the vibration transmissibility on the fingers [16]. Because the ISO weighting is likely to be best suitable for assessing disorders in the wrist–arm system [13] and it is consistent with the weighting derived from the biodynamic response of the palm–wrist–arm system [12], it is called *wrist–arm weighting* in this study. The need for a different weighting for fingers has been constantly raised, which seems obvious because the resonance frequency of fingers is much higher than that of hand–arms [13,16]. Whereas, a validated weighting for assessing the vibration-induced disorders in the fingers and hand has not been established, the unit weighting (or unweighted acceleration) and the finger transmissibility-based weighting (or finger weighting) are also used to demonstrate the new concepts proposed in this study. Fig. 3 shows the hand–arm weighted 1/3 octave spectrum $A(f)w(f)$ compared to the unweighted spectrum $A(f)$ for the two tools whose acceleration time histories are shown in Fig. 1. Fig. 4 presents the finger weighted spectrum compared with the unweighted spectrum. These weighted spectra are currently used to estimate the exposure limit to the vibration.

The frequency components of a spectrum can be summed to calculate the rms amplitude as follows:

$$\mathbf{a} = \sqrt{\sum_{i=1}^{n_f} A(f_i)^2}, \quad (2)$$

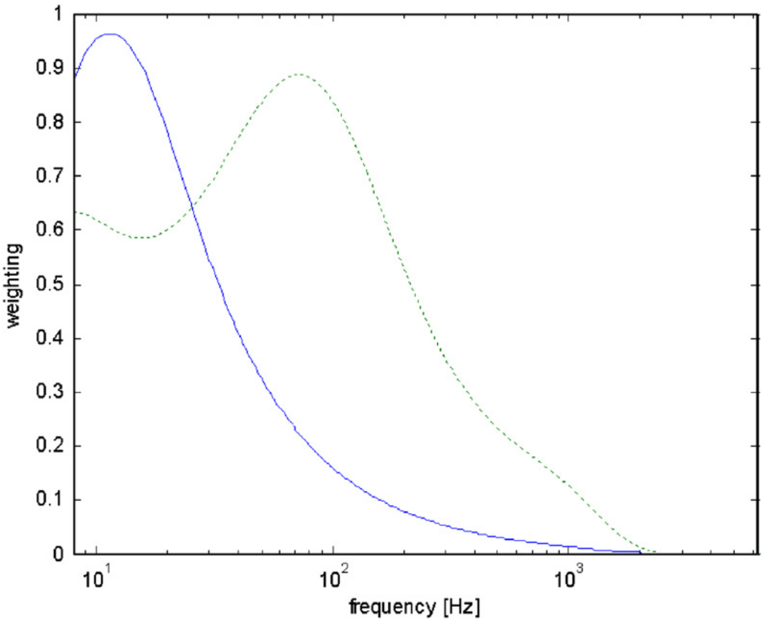

Fig. 2. Frequency-weighting curves; (——) recommended by ISO for hand–arm injuries (ISO 5349-1, 2001), (-----) derived from finger vibration transmissibility (Dong et al. [13] (-----): (a) concrete saw and (b) chipper 2).

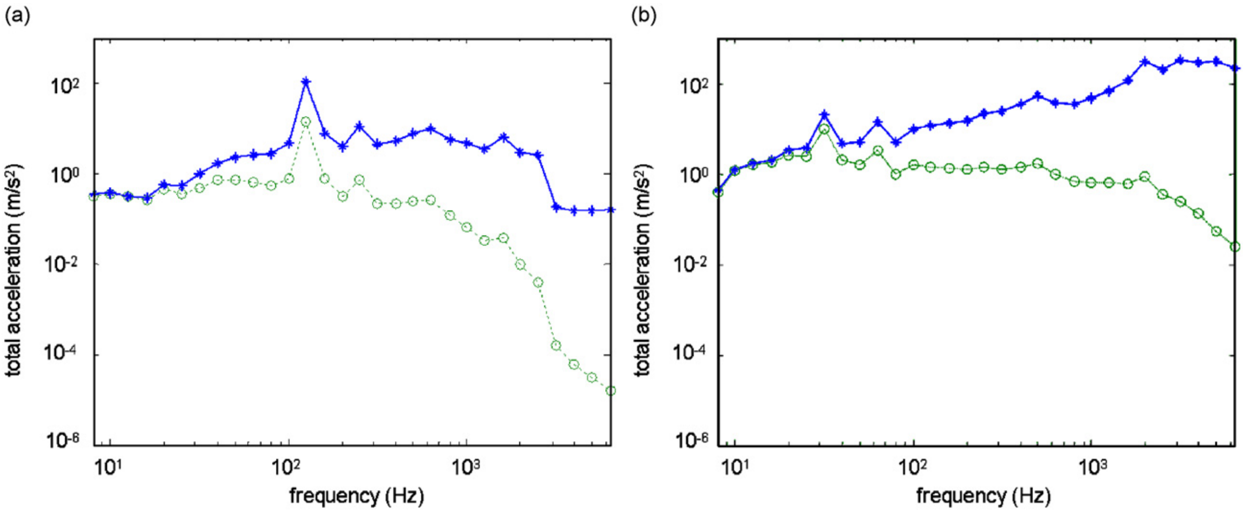

Fig. 3. Unweighted and hand–arm frequency-weighted frequency spectra of the total rms accelerations of concrete saw and chipper 2; (+) unweighted, (O) weighted: (a) concrete saw and (b) chipper 2.

$$\mathbf{a}_f = \sqrt{\sum_{i=1}^{n_f} A_f(f_i)^2} = \sqrt{\sum_{i=1}^{n_f} A(f_i)^2 w(f_i)^2}, \tag{3}$$

where $\mathbf{a}$ and $\mathbf{a}_f$ denote un-weighted and weighted rms accelerations, f_i is the center frequency of the ith 1/3 octave band, $w(f_i)$ is the frequency-weighting at f_i, and n_f is the number of frequency components to be

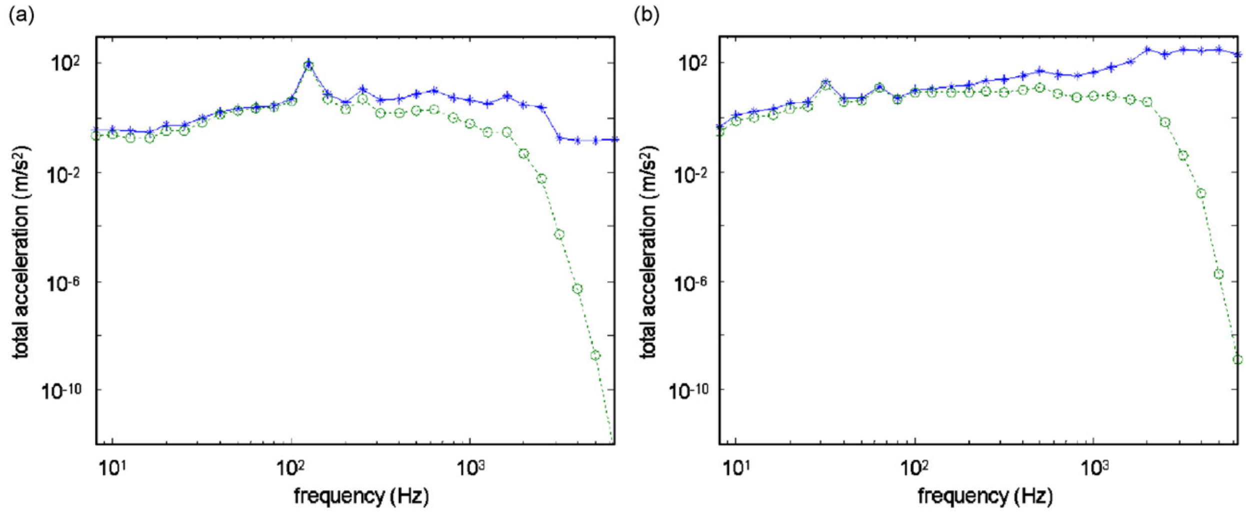

Fig. 4. Unweighted and finger frequency-weighted frequency spectra of the total rms accelerations of concrete saw and chipper 2; (+) unweighted, (O) weighted: (a) concrete saw and (b) chipper 2.

summed. Table 1 compares the unweighted, wrist–arm weighted and finger weighted rms accelerations of the six tools. The values of these measures are not reliably correlated to each other ($p > 0.10$).

3. Time–frequency analysis by AWT

3.1. T–F representation by AWT

T–F analysis has to be used to properly characterize highly transient events such as accelerations of impact tools because their spectral characteristics change rapidly in time. In fact, *time* and *frequency* are not separate, but interwoven concepts [14].

The AWT, a continuous wavelet transform, can be viewed as a hybrid of the wavelet transform and Fourier transform [14]. The AWT characterizes a signal by its frequency and amplitude as in the Fourier transform. However, the AWT is a function of time, unlike in the Fourier transform [15]. The AWT is an ideal tool for analysis of transient events in vibration and acoustics problems.

The AWT of a signal $a_x(t)$, $W_s a_x(t)$, is defined as

$$W_s a_x(t) = \int_{-\infty}^{\infty} a_x(u)\psi_s^*(u-t)\,\mathrm{d}t = \int_{-\infty}^{\infty} \frac{1}{s} a_x(u) g\left(\frac{u-t}{s}\right) \mathrm{e}^{-\mathrm{j}\eta(u-t/s)}\,\mathrm{d}t, \tag{4}$$

where s is the scale, $\psi_s(u) = g(u/s)\,\mathrm{e}^{\mathrm{j}\eta(u/s)}$ is the wavelet function of scale s, $\mathrm{j} = \sqrt{-1}$, and η is a parameter that relates the scale with the frequency. A Gaussian function is used for $g(t)$ in the AWT in this work, which is

$$g(t) = \frac{1}{(\sigma^2\pi)^{1/4}}\,\mathrm{e}^{-(t^2/2\sigma^2)}, \tag{5}$$

$W_s a_x(t)$ obtained from Eq. (4) is a complex valued time series that represents the amplitude of the signal components contained in the frequency band centered at ω. The frequency is related to the scale as follows:

$$\omega = \frac{\eta}{s}. \tag{6}$$

The width of the frequency band depends on the parameters adopted for $g(t)$ [15]. Choosing σ and η so that $\sigma^2\eta^2 = 58$ produces the 3 dB drop at the upper and lower limit frequencies of the typical 1/3 octave band [15]. Further, choosing $\sigma = 1.05$, $\eta = 7.252$ makes 0 dB drop at the points 1/24 octave apart from the center frequency. With this set-up, AWT emulates a real-time 1/3 octave filter, thus each $W_s a_x(t)$ represents the time history of the 1/3 octave component of the signal at the center frequency f_c.

As the scale s becomes smaller, the frequency resolution becomes wider while the time resolution becomes smaller, and the opposite happens as s becomes larger. This way the wavelet transform optimizes T–F resolutions while the size of the T–F atom is fixed, which is stated by the Heisenberg's principle [17]. A fast changing, high-frequency component is picked up by the AWT with a large s (short wavelet), and a slow changing, low-frequency component is picked up by the AWT with a small s (long wavelet).

The complex amplitude $W_s a_x(t)$ can be converted to a real-valued amplitude $\bar{A}_x(f,t)$ as follows:

$$\bar{A}_x(f,t) = \sqrt{\frac{1}{2} W_s a(t) W_s a^*(t)}. \tag{7}$$

The factor of 1/2 is used to make the definition compatible with the rms amplitude. Thus, $\bar{A}_x(f,t)$ represents the instantaneous rms amplitude of a transient signal and the rms amplitude of a steady-state signal.

Fig. 5 shows two sets of $\bar{A}_x(f,t)$ calculated from the accelerations of the concrete saw and the riveter obtained for the center frequencies of 12.5, 50, 125 Hz, 1, 2 and 4 kHz. It is seen in Fig. 5a that vibration of

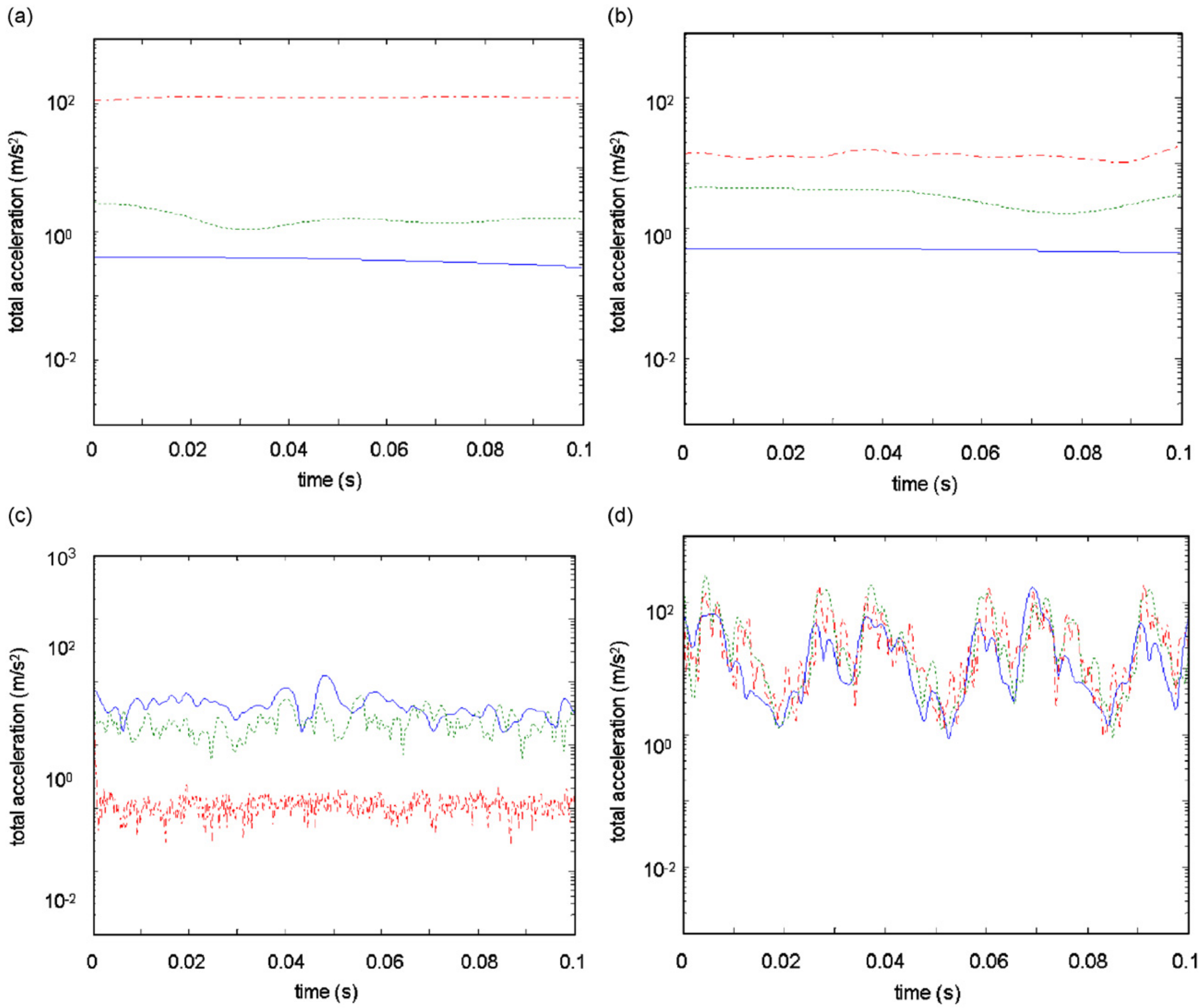

Fig. 5. Time histories of selected 1/3 octave components of total rms accelerations obtained by AWT for the concrete saw and riveter 1; (——) 12.5 Hz, (-----) 50 Hz, (_·_·_) 125 Hz: (a) concrete saw and (b) riveter 1; (——) 1 kHz, (-----) 2 kHz, (_·_·_) 4 kHz: (c) concrete saw and (d) riveter 1.

both tools is dominated by the 125 Hz component that is nearly constant in time, which is the primary operating frequency of the tool. Fig. 5a shows that low frequency components of both tools remain relatively constant over the time. Fig. 5b shows that temporal changes of the two tools are drastically different; high frequency components of the riveter change significantly in time while those of the concrete saw remain relatively constant.

The 1/3 octave time histories obtained for x, y, and z accelerations can be added to obtain the time history of the total acceleration $\bar{A}(f,t)$ as follows:

$$\bar{A}(f,t) = \sqrt{\bar{A}_x(f,t)^2 + \bar{A}_y(f,t)^2 + \bar{A}_z(f,t)^2}. \tag{8}$$

$\bar{A}(f,t)$ obtained by the above equation represents the instantaneous 1/3 octave component of the rms amplitude of the total acceleration. A set of $\bar{A}(f,t)$ over a given range of frequency will be called *T–F spectrum*.

Fig. 6 show 3-D plots of the *T–F* spectra of the concrete saw and chipper 2. The figures were obtained by placing $\bar{A}(f,t)$ at every 1/12th octave frequency point, i.e., placing 4 times in each 1/3 octave band for smoother representation. The height of the surface represents the instantaneous rms amplitude of the 1/3 octave component at the given time and frequency. Cutting the surface along the line A–A shown in Fig. 6(b), an instantaneous frequency spectrum will be obtained. Cutting the surface along the line B–B, a time-history of the 1/3 octave component at the frequency will be obtained.

3.2. Frequency-weighted *T–F* spectrum of vibration signal

Frequency weighting can be applied to each 1/3 octave time history to obtain a frequency-weighted *T–F* spectrum $\bar{A}_f(f,t)$ as follows:

$$\bar{A}_f(f,t) = \bar{A}(f,t)w(f). \tag{9}$$

Fig. 7 shows the *T–F* spectra of the two tools in Fig. 6 obtained by applying the hand–arm weighting. A large frequency component that is almost constant in time is observed in the lower frequency range in all six spectra, which corresponds to the cycles of the basic operation of the tools. No other significant components are observed in the *T–F* spectrum of the concrete saw. Quite a few high peaks are observed in the high frequency side in the spectra of the chipper, which change significantly in time.

Fig. 8 shows the *T–F* spectra of the same tools but with the finger weighting. The spectrum of the chipper is dominated by high frequency peaks which change rapidly in time. This indicates that the effect of temporal variation of the spectrum will be more important for finger injuries.

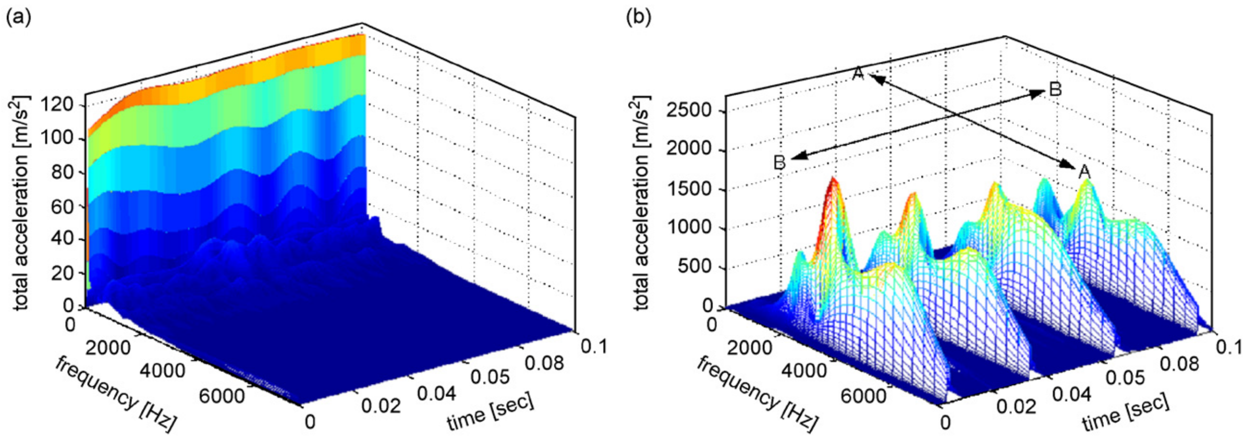

Fig. 6. *T–F* spectra of the total rms accelerations of concrete saw and chipper 2 obtained by AWT without frequency weighting: (a) concrete saw and (b) chipper 2.

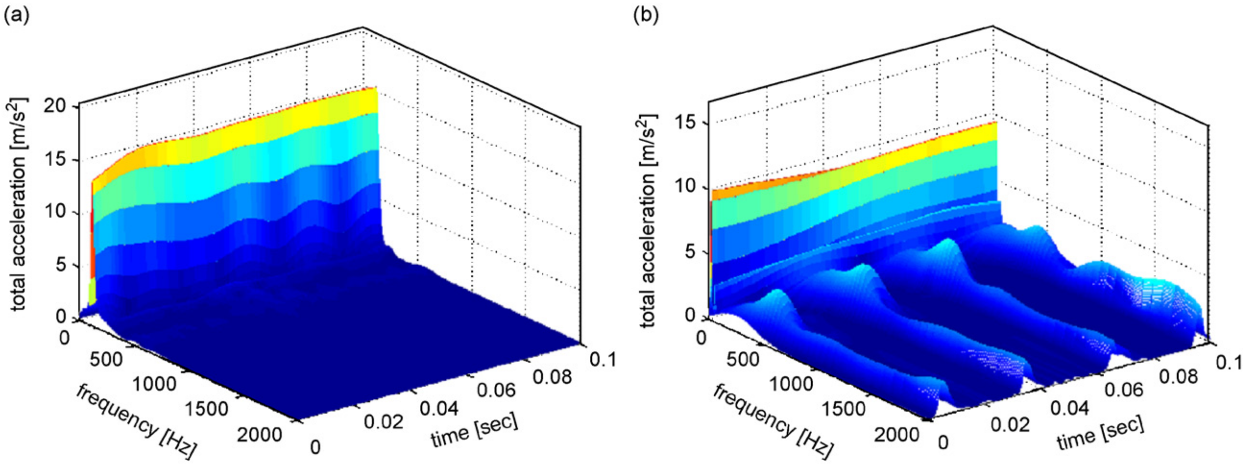

Fig. 7. *T–F* spectra of the total rms accelerations of concrete saw and chipper 2 obtained by the AWT with hand–arm frequency weighting: (a) concrete saw and (b) chipper 2.

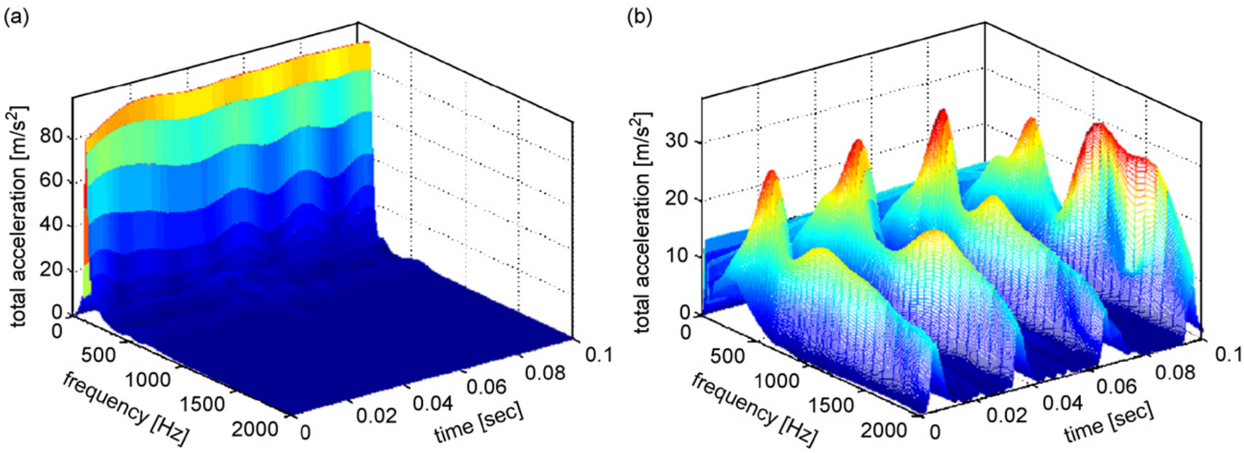

Fig. 8. *T–F* spectra of the total rms accelerations of concrete saw and chipper 2 with finger frequency weighting obtained by the AWT: (a) concrete saw and (b) chipper 2.

4. New concepts proposed for HAVS study based on *T–F* spectrum

A *T–F* spectrum is effective to represent characteristics of impulsive vibrations; however too complicated to be used directly for experimental and demographic studies of HAVS. Two new concepts are defined, which we named *frequency-weighted time history* and *cumulative injury* function. Based on these definitions, a single valued metric which we named *exposure risk index* is defined as a potential assessment tool for HAVS due to impact vibrations.

4.1. Frequency-weighted time history

From the frequency-weighted *T–F* spectrum, a *frequency-weighted time history* can be obtained by summing the frequency components at each time point as follows:

$$\bar{a}_f(t) = \sqrt{\sum_{i=1}^{n_f} \bar{A}_f(f_i, t)^2} = \sqrt{\sum_{i=1}^{n_f} \left(\bar{A}(f_i, t)w(f_i)\right)^2}, \tag{10}$$

where f_i is the center frequency of the ith 1/3 octave component and n_f is the number of 1/3 octave components in the frequency range. The summation in Eq. (10) is conducted along the line A–A at each time point. $\bar{a}_f(t)$ obtained as such becomes the time series of the frequency-weighted rms amplitude of acceleration.

The frequency-weighted time histories obtained with the hand–arm weighting and finger weighting are shown for the concrete saw and chipper 2 in Figs. 9 and 10, respectively. These time histories can be considered as the vibration stimuli that hand–arms and fingers feel within the accuracy of the frequency weighting and the AWT processing. This potentially very useful concept is defined for the first time in this work as far as the authors know.

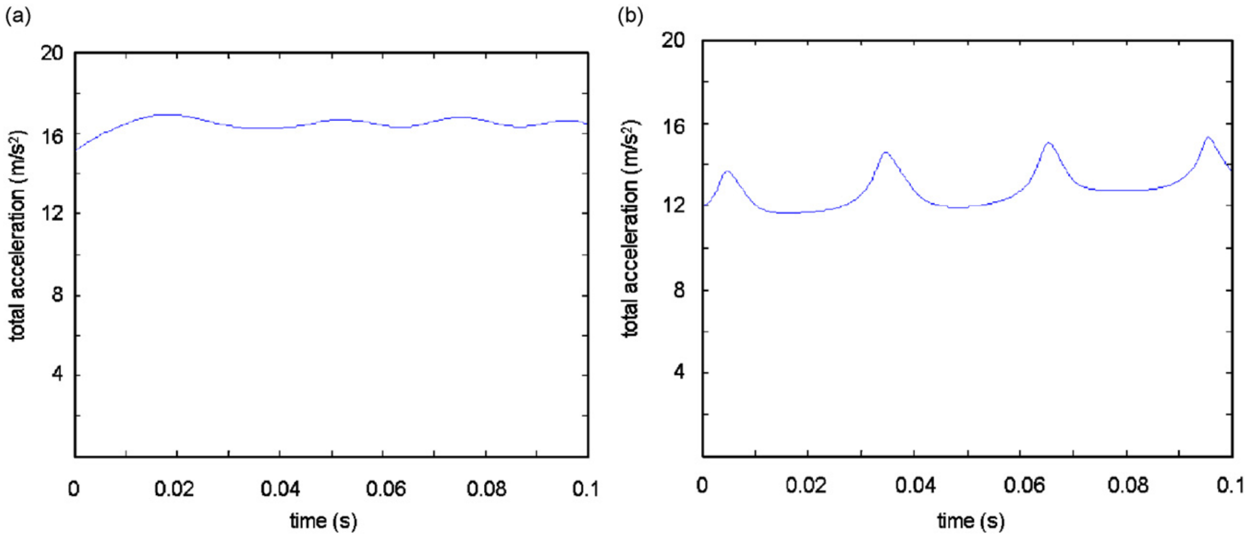

Fig. 9. Frequency-weighted time histories of total rms accelerations of concrete saw and chipper 2 with the wrist–arm frequency weighting: (a) concrete saw and (b) chipper 2.

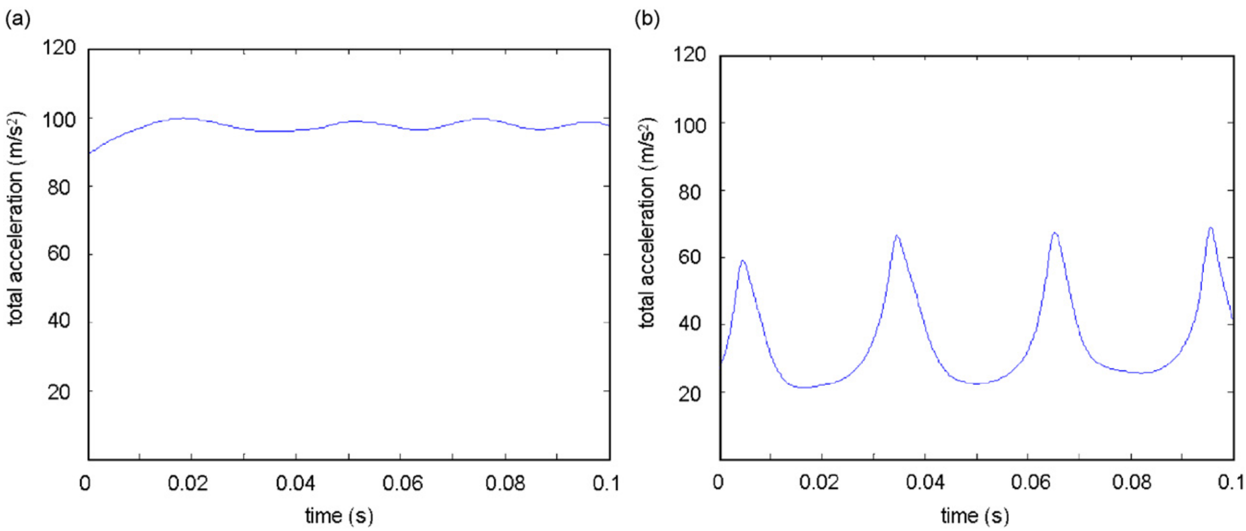

Fig. 10. Frequency-weighted time histories of total rms accelerations of concrete saw and chipper 2 with the finger frequency weighting: (a) concrete saw and (b) chipper 2.

4.2. Exposure risk index

Various single-valued metrics may be defined from the frequency-weighted time history for assessment of HAVS. One possible definition, which we call exposure index (EI), is defined as

$$\mathrm{EI} = \frac{1}{T}\int_0^T I(t)\,\mathrm{d}t = \frac{1}{T}\int_0^T \langle f(\bar{a}_f(t))\rangle\,\mathrm{d}t. \tag{11}$$

$I(t)$ in Eq. (11) is what we call the *cumulative risk probability* function. $\langle f\rangle$ is a nonlinear function defined as

$$\langle f\rangle = |f| \text{ if } f>0, \; = 0 \text{ if } f<0. \tag{12}$$

In this work, we used a quadratic functional form for $I(t)$ such as

$$I(t) = \left\langle \frac{\bar{a}_f(t) - a_{\mathrm{th}}}{a_{\mathrm{th}}}\right\rangle^2, \tag{13}$$

where a_{th} is a threshold value that has to be selected. Because the vibration data is in a discrete time series, Eq. (11) is actually evaluated as

$$\mathrm{EI} \approx \frac{1}{N}\sum_{i=1}^{N}\left\langle \frac{\bar{a}_f(t_i) - a_{\mathrm{th}}}{a_{\mathrm{th}}}\right\rangle^2. \tag{14}$$

The rationale of choosing $I(t)$ as the form in Eq. (13) can be explained with Fig. 11. It is assumed that exposure to vibration is harmful only when the frequency-weighted rms amplitude exceeds the threshold level, and thereafter the hazard risk increases nonlinearly, by a quadratic function in this case. Choosing a quadratic form for the function in Eq. (14) is based on the fact that the power absorbed by human hand and arm is nearly proportional to the square of the acceleration amplitude. A different functional form may be considered for $I(t)$. For example, an exponential form will emphasize the risk of high amplitude vibrations more significantly. The major issue will be selecting the threshold value a_{th}, which will be a very formidable task. Selecting a proper value of the threshold value and proper interpretation of the resulting risk index will be essential for the proposed concept to be useful; therefore will have to be the subjects of future studies.

For a demonstration purpose in this work, $I(t)$ was calculated using the form defined in Eq. (13) and a_{th} value of $12\,\mathrm{m/s^2}$ for the hand–arm and $40\,\mathrm{m/s^2}$ for the finger, which are shown in Figs. 12 and 13, respectively. It is noted that these threshold levels are *frequency-weighted* rms accelerations; therefore cannot be compared directly with each other. The EI values calculated according to Eq. (14) are listed in Table 2 for the 6 tools examined in this study and two frequency weightings. Because of the way it is defined in Eq. (13), EI represents the accumulated risk per unit time.

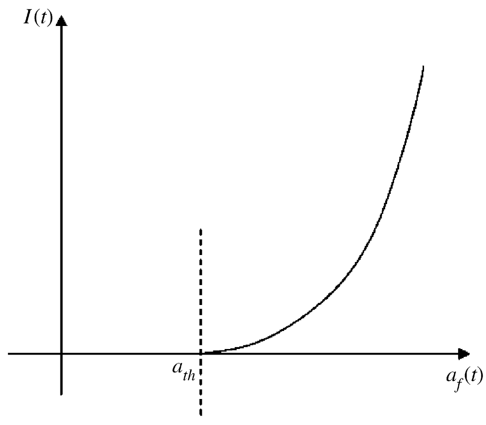

Fig. 11. The concept of the proposed cumulative risk probability function $I(t)$.

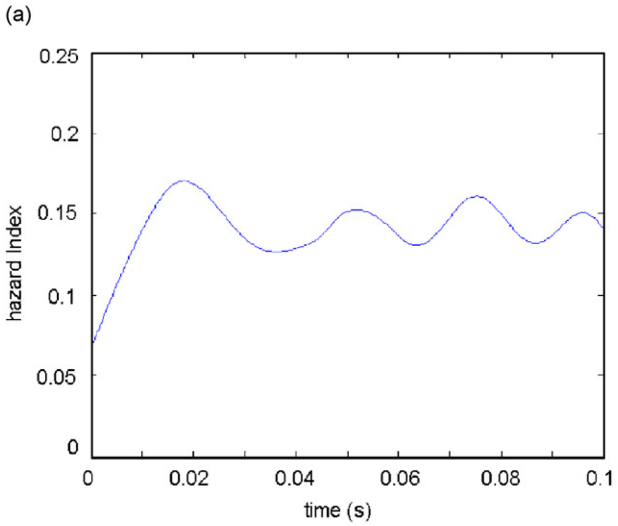

Fig. 12. Proposed cumulative risk probability function calculated for concrete saw and chipper 2 using the wrist–arm frequency weighting and $a_{th} = 12\,m/s^2$: (a) concrete saw and (b) chipper 2.

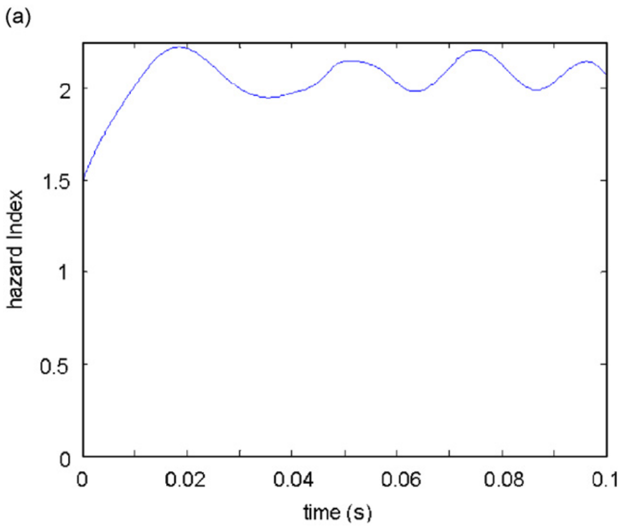

Fig. 13. Proposed cumulative risk probability function calculated for concrete saw and chipper 2 using the finger frequency weighting and $a_{th} = 40\,m/s^2$: (a) concrete saw and (b) chipper 2.

5. Discussions

The data presented in Table 1 demonstrate that the order of the 6 tools could vary significantly when the risk is assessed using different rms accelerations. Hence, these rms accelerations can be considered as independent vibration measures. As dictated by Eq. (11), whether the exposure risk index values of the 6 tools listed in Table 2 could be correlated to the rms accelerations in Table 1 depends on both the *frequency-weighted time history* and the *cumulative risk probability* function. Whereas the determination of the risk function will rely on future research on the vibration medical effects, the AWT technique can be used to calculate the frequency-weighted time history for any given frequency weighting. This study developed a general strategy on the application of AWT to study the hand-transmitted vibration exposure and health effects.

The risk assessment method for HAVS due to impact vibrations which may eventually be developed in the future will have to have the following elements:

1. Measure the acceleration time series.
2. Apply AWT analysis to obtain *T–F* spectrum.
3. Apply a proper frequency weighting.
4. Calculate a risk assessment metric, for example EI proposed in this study, that represents the severity of vibration reflecting effects of temporal variations of spectral components.
5. Recommend the maximum exposure time based on the metric.

Considering the current state-of-the-art in comparison with the above list, further research needs are identified as:

1. More accurate frequency-weighting functions for wrist–arm and especially for hand or fingers.
2. Develop an injury risk assessment metric that correlate well with HAVS prevalence and latency. In the case of developing EI into such a metric, it will be necessary to find the nonlinear function form of the vibration-induced health effects, from which proper threshold value a_{th} for the wrist–arm system and the hand and fingers may be identified.
3. Design and conduct correlation studies to relate the metric and HAVS risk by combining epidemiological, physiological, pathological, subjective sensation, and biodynamic approaches.

Another interesting idea will be to investigate the possibilities of using methods developed in other research areas, for example research on impulsive noise-induced hearing loss (NIHL) [18]. The NIHL has many parallels with the impact vibration-induced HAVS; therefore the techniques developed for NIHL research may be borrowed and modified for HAVS study. For example, a similar concept to the temporary threshold shift (TTS) [19] and related test method may be defined in hand–arm vibrations, which may be used for low intensity human tests.

6. Conclusion

Although hand-transmitted vibration has been studied for more than 80 years, the dose–response relationship for the most important component (vibration-induced white finger) of the hand–arm vibration syndrome (HAVS) remains elusive [20]. One of the major reasons is likely that the exposure dose is not quantified properly by the current guidelines. Specifically, the current guidelines do not provide any means to reflect the rapid temporal variation of the frequency components in the dose quantification. This study investigated the possibility of applying the analytic wavelet transformation (AWT) to HAVS risk assessment to address these problems.

In this study, the AWT was applied to 6 transient acceleration signals measured from 1 steady-state-type tool and 5 impact tools to study their time–frequency (*T–F*) characteristics. Applying the frequency-weightings recommended for hand–arm and finger injuries to these *T–F* spectra, new concepts such as the frequency-weighted time history, cumulative injury function, and exposure risk index were defined and their implications for future HAVS studies were explained. Future research needs to realize the development of a quantitative risk assessment method of HAVS was also discussed.

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