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Nonlinear subjective and biodynamic responses to continuous and transient whole-body vibration in the vertical direction

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Abstract

The effect of the magnitude of continuous and transient whole-body vibration in the vertical direction on both subjective and biodynamic responses of human subjects has been investigated experimentally. Additionally, the relation between the subjective responses and the dynamic responses has also been studied. Twelve subjects were exposed to sinusoidal continuous vibrations at five frequencies (3.15–8.0 Hz) and at three magnitudes (0.5–2.0 m s^{-2} rms). They were also exposed to transient vibrations that were modulated one-and-half cycle sinusoidal waveforms at the same frequencies as the continuous vibrations and at three magnitudes corresponding to the magnitudes used for the continuous vibrations. Discomfort was measured by the method of magnitude estimation with reference stimuli having frequency components in the middle of the frequency range used in this study. The driving-point dynamic responses (the ratio between the force and the motion, i.e., acceleration and velocity, at the driving point) were also measured and divided by the responses to the reference stimuli used in the measurement of discomfort so as to allow the comparison of the dynamic responses with the discomfort responses. Both the discomfort estimates and the normalised driving-point dynamic responses were influenced by the stimuli magnitudes, especially with the continuous vibration. At 3.15 and 4.0 Hz, the discomfort estimates and the normalised mechanical impedance and apparent mass increased significantly with increases in vibration magnitude from 0.5–2.0 m s^{-2} rms. Magnitude estimates for discomfort were correlated with the normalised mechanical impedance and apparent mass in the frequency range investigated. For the transient vibrations, the discomfort estimates and the driving-point dynamic responses were interpreted as responses in frequency

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bands around the fundamental frequency of the input motion. The results indicate similar nonlinearities in discomfort and driving-point dynamic responses associated with the principal body response within the range 3.15–8 Hz. The nonlinearity in discomfort at these frequencies may be partially caused by the nonlinear dynamic response of the body and is sufficient to require consideration in methods of predicting discomfort caused by vertical whole-body vibration.

1. Introduction

The prediction of discomfort caused by the whole-body vibration and shock that people experience in their daily lives has been of interest in mechanical, aeronautical and civil engineering. One outcome from previous studies has been standards and guides providing methods of measuring, evaluating and assessing whole-body vibration and shock with respect to comfort, such as BS 6841 [1] and ISO 2631-1 [2].

A factor that must be taken into account in the prediction of the discomfort caused by vibration is the effect of vibration frequency. In BS 6841 [1] and ISO 2631-1 [2], the effect of frequency is represented by frequency weightings defined from various studies of subjective responses of human subjects exposed to vibrations and shocks (e.g., Refs. [3–6]). From those studies, quantitative relations between the discomfort of subjects and the magnitude of motion at the interface between the human body and the supporting surface were represented by 'equivalent comfort contours'. In this approach, the 'system' that determines how subjective responses are induced by oscillatory motion is treated as a 'black box' and is not well understood. Methods of predicting subjective responses to vibration and shock might be improved if the 'motion-to-sensation system' is better understood.

It may be reasonable to assume that when people are exposed to whole-body vibration or shock, the dynamic responses of the body influence the various subjective responses. Knowledge of the relation between dynamic responses and subjective responses should assist understanding of subjective responses caused by vibration and shock. There have been few studies investigating the relation between subjective and biodynamic responses, although Griffin et al. [5] and Griffin and Whitham [7] found some evidence of a relation between subjective response and transmissibility to the head with seated subjects exposed to vertical sinusoidal vibration at frequencies below 6.3 Hz and above 16 Hz.

Mechanical impedance and apparent mass (commonly used to represent driving-point dynamic responses), and measures of the transmission of vibration through the body show resonance phenomena at various frequencies. Around 5 Hz, there is usually a dominant resonance in the vertical driving-point measures (e.g. Refs. [8–13]) and it can be hypothesized that factors affecting this response around 5 Hz will also affect discomfort.

The dynamic responses of the body are nonlinear, depending on the level of vibration (e.g. Mansfield and Griffin [12] and Matsumoto and Griffin [14]). If subjective responses are related to dynamic responses, subjective responses will show a similar nonlinear characteristic. However, many previous studies of discomfort have not investigated the effect of vibration magnitude and those with more than one vibration magnitude have not reported a significant effect of the magnitude of input vibration on subjective responses (e.g., Refs. [6,3,5,15,16]).

The objective of this study was to investigate the effect of the magnitude of the input stimulus on both subjective and biodynamic responses during vertical sinusoidal continuous vibration and transient vibration (or shock). Investigation with sinusoidal continuous vibration was expected to provide fundamental understanding of the problem, while investigation with transient vibration might be related to the practical assessment of various types of stimuli. Subjects were exposed to various magnitudes of sinusoidal continuous and transient vibrations at frequencies around 5 Hz. The ratios between the force and motion (i.e., velocity and acceleration) at the driving-point (i.e., mechanical impedance and apparent mass, respectively, for continuous vibration) were used to represent the dynamic response of the body. The relation between subjective response and dynamic response of the body was also investigated.

2. Method

The experiment was conducted in a laboratory of the Institute of Sound and Vibration Research at the University of Southampton. The Human Experimentation Safety and Ethics Committee of the Institute of Sound and Vibration Research approved the experimental design and procedure described in the following sections.

2.1. Apparatus

A force platform, Kistler Z 13053, was mounted on an electro-dynamic vibrator, Derritron VP180, orientated to produce vertical vibration. Subjects sat on the top surface of the force platform without a backrest, with their feet supported on a stationary footrest. The force at the interface between the seat (i.e., the top surface of the force platform) and subject was measured in the vertical direction with the force platform. The vertical acceleration of the seat was measured with a piezo-resistive accelerometer, Entran EGCSY-240D*-10.

2.2. Subjects

Twelve male volunteers aged from 24 to 46 years from the staff and students of the University of Southampton participated in the experiment. Their heights and weights were in the range 1.70–1.86 m and 63–101 kg, respectively.

2.3. Input stimuli

The input stimuli consisted of sinusoidal continuous and transient vibrations. The frequencies of the continuous vibrations were 3.15, 4.0, 5.0, 6.3, and 8.0 Hz. The duration of the continuous vibration was 4.0 s with the first and the last 0.5 s tapered by a quarter of a sinusoidal function. Three different magnitudes (0.5, 1.0 and 2.0 $m s^{-2}$ rms) were used for the continuous vibrations.

The transient vibrations were formed from one-and-half cycles of a sinusoidal acceleration waveform with upward as the positive direction of the vertical coordinate in accordance with ISO 2631-1 [2]. The frequencies of the sinusoidal waveforms used in this experiment were the same as the frequencies of the continuous vibrations as described above (i.e., 3.15, 4.0, 5.0, 6.3, and

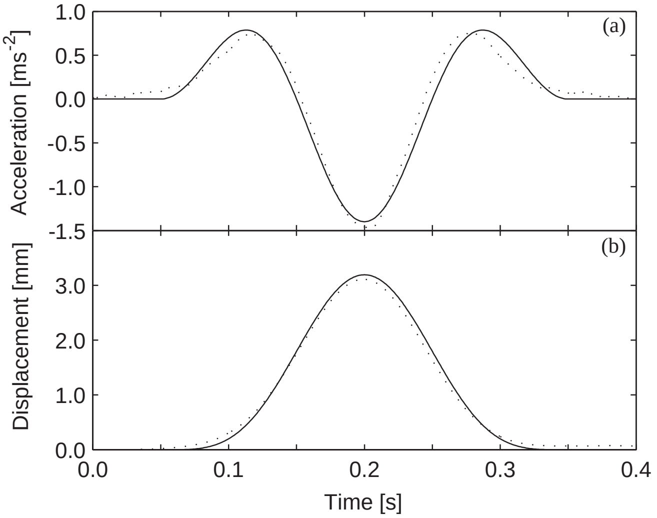

Fig. 1. An example of the acceleration waveform of the transient vibrations used in the experiment. Based on tapered one and half cycles of sinusoidal waveform at 5 Hz ——: desired acceleration; · · · ·: measured acceleration.

8.0 Hz). The sinusoidal acceleration waveform was modulated by a half cycle sinusoid at unit amplitude with a period three times longer than the period of the sinusoidal acceleration (Fig. 1(a)). The acceleration waveform shown in Fig. 1(a) is based on a sinusoidal waveform at 5.0 Hz. The acceleration, with a principal downward peak acceleration accompanied by two smaller upward peaks in acceleration results in a displacement with a single upward peak that returns to the initial position at the end of the motion (Fig. 1(b)). The durations of the input signals for the transient vibrations were dependent on the frequency of the motion: 0.476, 0.375, 0.3, 0.238 and 0.188 s for 3.15, 4.0, 5.0, 6.3 and 8.0 Hz, respectively. The magnitudes of the transient vibrations were defined by the acceleration at the peak: the peak accelerations used in the experiment were −0.7, −1.4 and $-2.8\,\mathrm{m\,s^{-2}}$. The magnitudes of the acceleration stimuli reproduced on the vibrator deviated from the nominal values by less than 10%. The order of presentation of input stimuli was balanced between subjects.

2.4. Measurement

The relative discomfort caused by the input stimuli was measured by the method of magnitude estimation. Subjects were exposed to a series of two vibrations (or two shocks) with an interval of 2.0 s. The stimulus presented first was the 'reference' stimulus and the stimulus presented second was the 'test' stimulus. The combinations of reference and test stimuli used in the experiment are presented in Table 1. As presented in Table 1, the type of reference stimulus (i.e., continuous or transient) was the same as that of the test stimulus. For both the continuous and transient vibrations, stimuli at, or based on, 5.0 Hz were selected as the reference. The magnitude of the reference stimulus was the same as that of the test stimulus (i.e. the same rms acceleration for the continuous vibrations and the same nominal peak acceleration for the transient vibrations). The task for the subjects was to give a value of 100 to the discomfort caused by the reference

Table 1
Combinations of the test and reference stimuli used in the experiment

Set	Test			Reference		
	Type	Frequency (Hz)	Magnitude ($m\,s^{-2}$)	Type	Frequency (Hz)	Magnitude ($m\,s^{-2}$)
1	Continuous	3.15, 4.0, 5.0, 6.3, 8.0	0.5 (rms)	Continuous	5.0	0.5 (rms)
2	Continuous	3.15, 4.0, 5.0, 6.3, 8.0	1.0 (rms)	Continuous	5.0	1.0 (rms)
3	Continuous	3.15, 4.0, 5.0, 6.3, 8.0	2.0 (rms)	Continuous	5.0	2.0 (rms)
4	Transient	3.15, 4.0, 5.0, 6.3, 8.0	−0.7 (peak)	Transient	5.0	−0.7 (peak)
5	Transient	3.15, 4.0, 5.0, 6.3, 8.0	−1.4 (peak)	Transient	5.0	−1.4 (peak)
6	Transient	3.15, 4.0, 5.0, 6.3, 8.0	−2.8 (peak)	Transient	5.0	−2.8 (peak)

stimulus and assign a number to indicate relative discomfort caused by the test stimulus. For example, a subject who considered that a test stimulus was half as uncomfortable as the reference stimulus, should assign it the value of 50. A subject who considered a test stimulus to be twice as uncomfortable as the reference stimulus, should assign it the value of 200.

For the stimuli being judged by the subjects, the acceleration and force at the seat surface (i.e., at the driving-point) were digitised at 1000 samples per second after low-pass filtering at 40 Hz. The high sampling rate was selected so as to obtain a high resolution of the time lag, or phase, in the time history data, particularly for signals at higher frequencies (0.001 s corresponds to a phase difference of 2.88 degrees at 8.0 Hz).

2.5. Analysis

For the data measured with sinusoidal continuous vibration, the apparent masses and mechanical impedances were calculated by dividing the rms value of the measured force by the rms value of the measured motion (i.e., either acceleration or velocity):

$$R_f = F_{\mathrm{rms},f}/X_{\mathrm{rms},f}. \tag{1}$$

Here, R_f is either the apparent mass or mechanical impedance at f Hz, $F_{\mathrm{rms},f}$ and $X_{\mathrm{rms},f}$ are the rms of the force and motion, respectively. The velocity was obtained by numerically integrating the measured acceleration. The rms values were calculated by using the records for a period when the input signal had a constant magnitude, i.e., the middle 3.0 s of the total duration of 4.0 s. The calculated apparent masses and mechanical impedances were normalised by dividing them by the values obtained with stimuli at 5 Hz so as to compare them with the estimates of relative discomfort, which were obtained relative to the discomfort caused by a 5 Hz reference stimulus.

$$\overline{R}_f = R_f/R_{5\,\mathrm{Hz}}. \tag{2}$$

The transient vibrations used in this study had modulated sinusoidal acceleration waveforms, as shown in Fig. 1: the figure shows the nominal acceleration time history together with the acceleration measured in the experiment. The modulation used in this study truncated and modulated sinusoidal waveforms so that the resulting modulated sinusoidal accelerations had input energy in a frequency band around the frequency of the base sinusoid (called the fundamental frequency in this paper); for example, Fig. 2 shows the frequency content of the transient vibration based on a 5 Hz sinusoid, although the estimation of the spectrum is not reliable because of the short data length. The transient vibrations are designated by their fundamental frequency hereafter. For the data measured with the transient vibrations, the 'nominal' apparent mass, 'nominal' mechanical impedance and the corresponding phases for each input stimulus were obtained using the same method described for the sinusoidal vibrations (i.e., Eqs. (1) and (2)). However, the period for the calculation of the rms values of the transient vibrations was between the beginning of the input signal sent to the vibrator and 0.5 s after the end of the input signal, to include free vibration responses observed in the force data. An example of the time histories of the acceleration and force used to calculate the rms values is shown in Fig. 3.

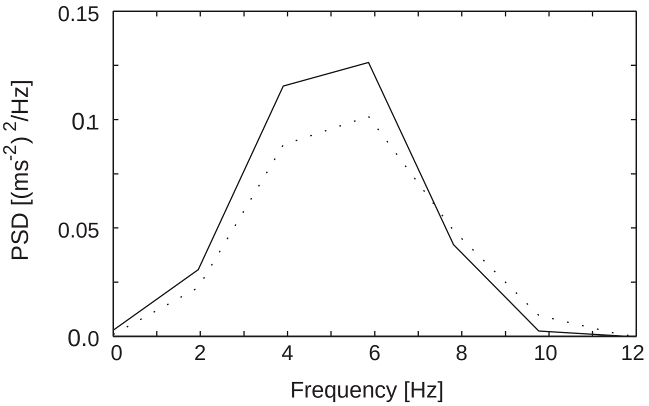

Fig. 2. Power spectral density of the transient vibration based on 5 Hz sinusoid.

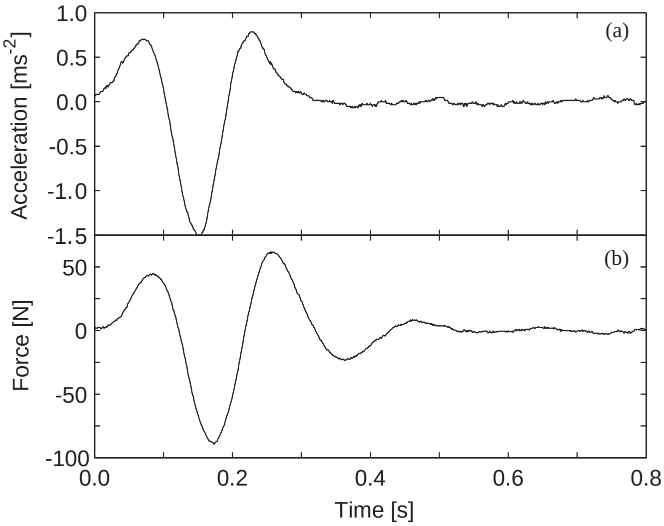

Fig. 3. An example of the acceleration and force records used in the calculation of rms values.

The 'nominal' apparent mass and 'nominal' mechanical impedance obtained did not necessarily represent the response at a particular frequency. The rms values of the force could be considered as a 'frequency weighted acceleration' with the biodynamic response characteristics being a type of frequency weighting. The rms value of the force was divided by the rms value of the corresponding acceleration so as to make it possible to compare the results between different magnitudes of input stimuli. The rms values are not, in general, a sufficient method of predicting discomfort from transient vibration and shocks. However, for the objective of this study being the investigation of the effect of stimulus magnitude, several different descriptors of the shock severity, including the rms values, would have been equally useful.

Statistical analyses were performed to understand the significance of differences or associations observed in the measured data. Nonparametric statistics were used because the assumption of normality may not be reasonable.

3. Results

3.1. Relative discomfort

Fig. 4 compares the medians of the magnitude estimates of the relative discomfort indicated by the 12 subjects when exposed to sinusoidal continuous vibration at the five frequencies and three vibration magnitudes. As expected, for all three vibration magnitudes, the magnitude estimates for 5 Hz are close to 100, because the test vibration was the same as the reference vibration at this frequency. At 0.5 and 1.0 $m\,s^{-2}$ rms, the median magnitude estimate was greatest at 5.0 and 6.3 Hz. At 2.0 $m\,s^{-2}$ rms, the median magnitude estimate was greatest at 4.0 Hz. The median magnitude estimate measured at 3.15 Hz was lower than at the other frequencies. The effect of frequency on the magnitude estimates was statistically significant for all magnitudes ($p<0.01$ for 0.5 and 1.0 $m\,s^{-2}$ rms and $p<0.05$ for 2.0 $m\,s^{-2}$ rms; Friedman two-way analysis of variance).

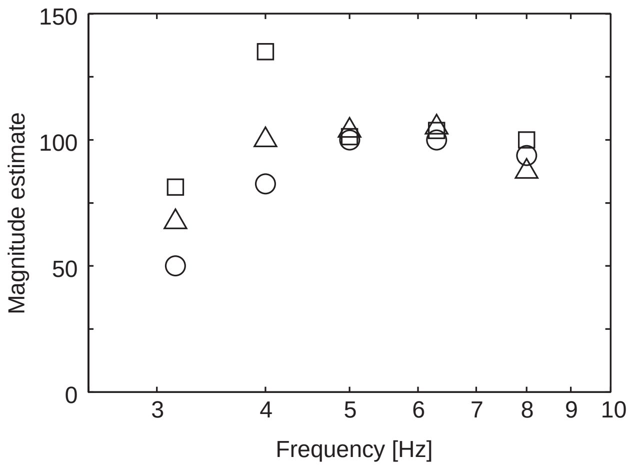

Fig. 4. Medians of magnitude estimates measured with twelve subjects exposed to continuous vibrations. ○: 0.5 $m\,s^{-2}$ rms; △: 1.0 $m\,s^{-2}$ rms; □: 2.0 $m\,s^{-2}$ rms.

Friedman two-way analysis of variance showed that there was not a statistically significant difference in the magnitude estimates measured with the three magnitudes of vibration at 5.0 Hz ($p > 0.1$). Statistical analyses of the effect of vibration magnitude on the magnitude estimate curves therefore assumed that a magnitude estimate of 100 was obtained for 5 Hz vibration. The effect of vibration magnitude on the magnitude estimates were statistically significant at 3.15 and 4.0 Hz ($p < 0.0001$, Friedman). The magnitude estimates at 3.15 and 4.0 Hz increased significantly with each increase in vibration magnitude ($p < 0.01$ at 3.15 Hz and $p < 0.05$ at 4.0 Hz, Wilcoxon matched-pairs signed ranks tests).

The effect of frequency on magnitude estimates for the transient vibrations is less clear than in the magnitude estimates for the continuous vibration (Fig. 5). However, for the transient vibrations, the effect of frequency on the magnitude estimates was statistically significant at all magnitudes ($p < 0.05$ for $-0.7\,m\,s^{-2}$ peak and $p < 0.01$ for -1.4 and $-2.8\,m\,s^{-2}$ peak, Friedman two-way analysis of variance). At all three magnitudes, the median magnitude estimates at 8.0 Hz were lower than those at the other frequencies.

The effect of stimulus magnitude on the magnitude estimate curve was less clear for transient vibrations than for continuous vibration. Friedman two-way analysis of variance showed that there was no statistically significant difference in the magnitude estimates for the transient vibrations at 5.0 Hz between the three different magnitudes ($p > 0.05$). There were statistically significant differences in the magnitude estimates obtained with the shocks at 3.15 and 4.0 Hz ($p < 0.05$, Friedman). The median magnitude estimates obtained with the transient vibrations having $-2.8\,m\,s^{-2}$ peak were significantly greater than those for transient vibrations having -0.7 and $-1.4\,m\,s^{-2}$ peaks at 3.15 Hz and that for the transient vibrations having $-0.7\,m\,s^{-2}$ peak at 4.0 Hz ($p < 0.05$, Wilcoxon matched-pairs signed ranks tests).

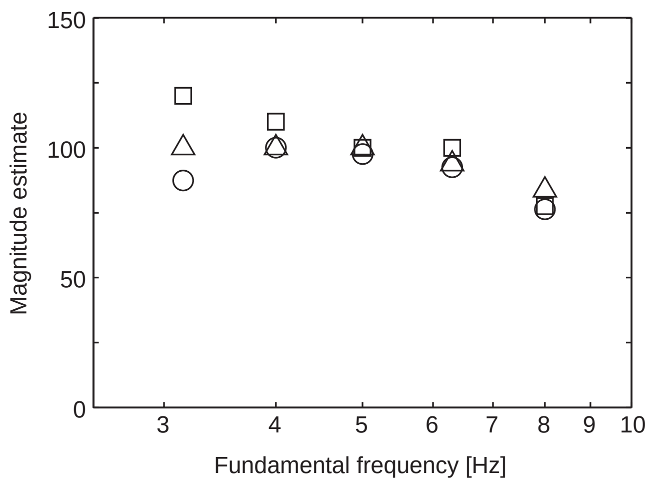

Fig. 5. Medians of magnitude estimates measured with twelve subjects exposed to transient vibrations. ○: $-0.7\,m\,s^{-2}$ at peak; △: $-1.4\,m\,s^{-2}$ at peak; □: $-2.8\,m\,s^{-2}$ at peak.

3.2. Apparent mass and mechanical impedance

The median apparent masses and mechanical impedances of twelve subjects exposed to the continuous vibrations are presented in Fig. 6 for the five frequencies and the three vibration magnitudes. The apparent mass and mechanical impedance varied depending on the frequency, as observed in previous studies (e.g. Refs. [8–13]). The effect of vibration magnitude on both apparent mass and mechanical impedance was statistically significant for all frequencies ($p<0.05$, Friedman). At 3.15 Hz, the apparent mass and mechanical impedance increased significantly with each increase in vibration magnitude ($p<0.01$, Wilcoxon). At 4.0 Hz, the apparent mass and mechanical impedance measured with $0.5\,\mathrm{m\,s^{-2}}$ rms were significantly less than that with $1.0\,\mathrm{m\,s^{-2}}$ rms ($p<0.05$, Wilcoxon). At 5.0, 6.3 and 8.0 Hz, the apparent mass and mechanical impedance decreased significantly with each increase in vibration magnitude ($p<0.05$, Wilcoxon).

Fig. 7 shows the median nominal apparent masses and nominal mechanical impedances of the 12 subjects exposed to transient vibrations at five fundamental frequencies and three magnitudes. For transient vibrations, the effect of frequency on the nominal apparent mass and mechanical impedance is not so clear as with the continuous vibration. This may imply a contribution to the measured values from frequency components other than at the fundamental frequency. However, there were statistically significant effects of the frequency of transient vibration on both nominal

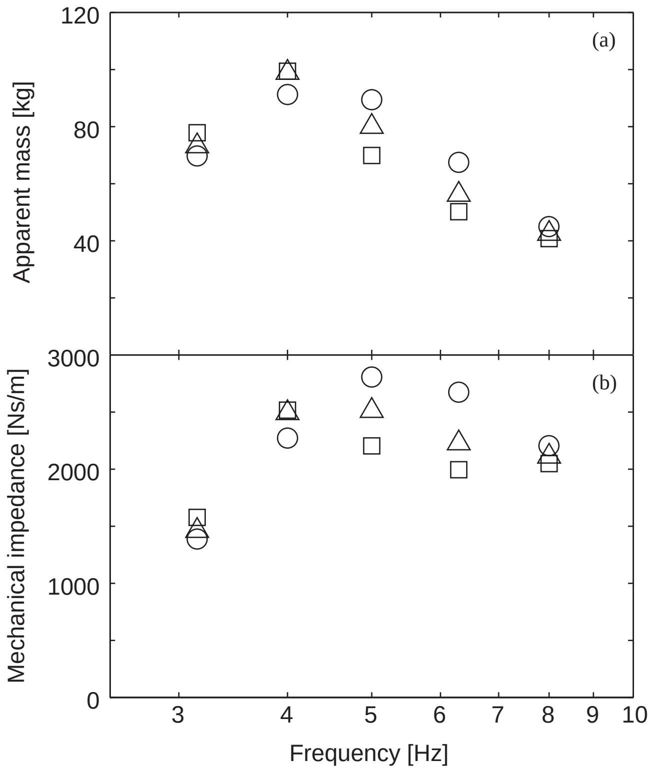

Fig. 6. Median apparent masses (a) and mechanical impedances (b) measured with twelve subjects exposed to continuous vibrations. ○: $0.5\,\mathrm{m\,s^{-2}}$ rms; △: $1.0\,\mathrm{m\,s^{-2}}$ rms; □: $2.0\,\mathrm{m\,s^{-2}}$ rms.

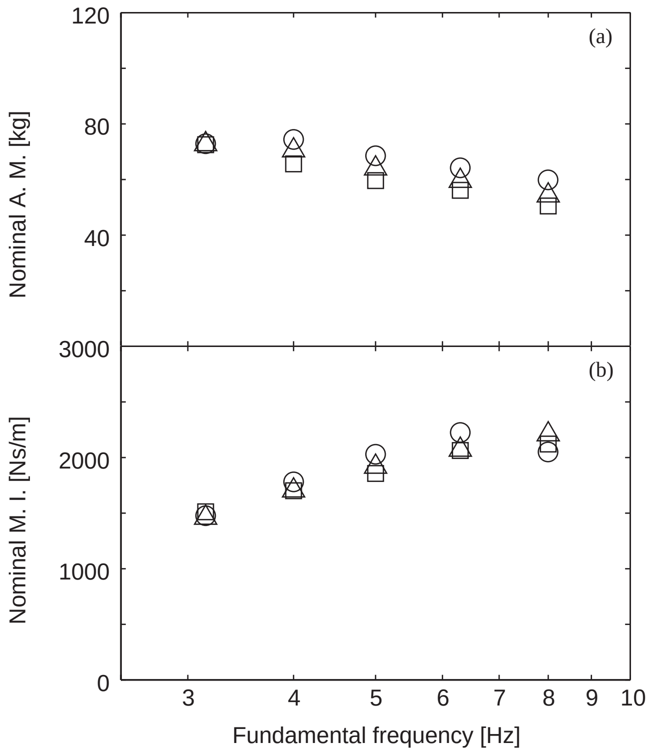

Fig. 7. Median nominal apparent masses (a) and mechanical impedances (b) measured with twelve subjects exposed to transient vibrations (A. M.: apparent mass; M. I.: mechanical impedance). ○: $-0.7\,m\,s^{-2}$ at peak; △: $-1.4\,m\,s^{-2}$ at peak; □: $-2.8\,m\,s^{-2}$ at peak.

apparent mass and mechanical impedance for all magnitudes ($p<0.01$, Friedman). The effect of magnitude of transient vibration on the nominal apparent mass was statistically significant at all frequencies except 3.15 Hz ($p<0.01$, Friedman): at 4.0, 5.0, 6.3 and 8 Hz the nominal apparent mass decreased with each increase in the magnitude of transient vibration ($p<0.05$, Wilcoxon). The effect of magnitude of transient vibration on the nominal mechanical impedance was statistically significant at 3.15, 6.3 and 8.0 Hz (for 3.15 and 6.3 Hz: $p<0.05$, Friedman). At 3.15 Hz, the nominal mechanical impedance measured with the transient vibration at $-0.7\,m\,s^{-2}$ peak was less than at the other magnitudes; at 6.3 and 8.0 Hz, the nominal mechanical impedance measured with the transient vibration at $-1.4\,m\,s^{-2}$ peak was greater than that with the transient vibration at $-2.8\,m\,s^{-2}$ peak ($p<0.05$, Wilcoxon).

3.3. Comparison between relative discomfort and dynamic responses

The apparent masses and mechanical impedances (and nominal values for the transient vibrations) were normalised (i.e. division by the values obtained at 5 Hz) so as to compare them with the magnitude estimates of discomfort obtained relative to that caused by the 5 Hz stimuli of the same magnitude. The median normalised apparent masses and mechanical impedances are

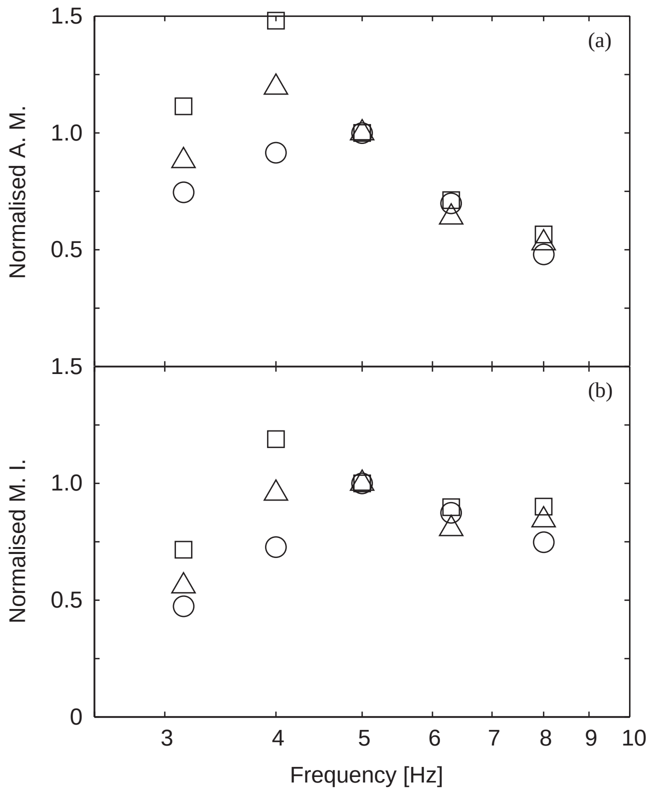

Fig. 8. Median apparent masses (a) and mechanical impedances (b) normalised by the value obtained at 5.0 Hz for continuous vibrations (A. M.: apparent mass; M. I.: mechanical impedance). ○: 0.5 m s^{-2} rms; △: 1.0 m s^{-2} rms; □: 2.0 m s^{-2} rms.

presented in Fig. 8 for the continuous vibrations and the median normalised nominal apparent masses and mechanical impedances are shown in Fig. 9 for the transient vibrations. For continuous vibrations, it seems that the normalised apparent mass and normalised mechanical impedance in Fig. 8 show similar trends to the relative discomfort in Fig. 4, particularly the trend caused by the changes in stimulus magnitude. For the transient vibrations, the relative discomfort in Fig. 5 might be more similar to the normalised nominal apparent mass in Fig. 9(a) than the normalised nominal mechanical impedance presented in Fig. 9(b).

The median magnitude estimates are compared with the median normalised apparent masses and the median normalised nominal apparent masses in Fig. 10, and compared with the median normalised mechanical impedances and the median normalised nominal mechanical impedances in Fig. 11. Table 2 shows Kendall's τ_b correlation coefficients between the median magnitude estimates and the median normalised dynamic responses obtained for the three magnitudes. For the continuous vibration, the magnitude estimates show greater correlation with the normalised mechanical impedance than with the normalised apparent mass (Figs. 10(a) and 11(a)). The difference between the correlations is due to the frequency dependence in response, which is reflected in a different rank order of the stimuli in their normalised mechanical impedance and

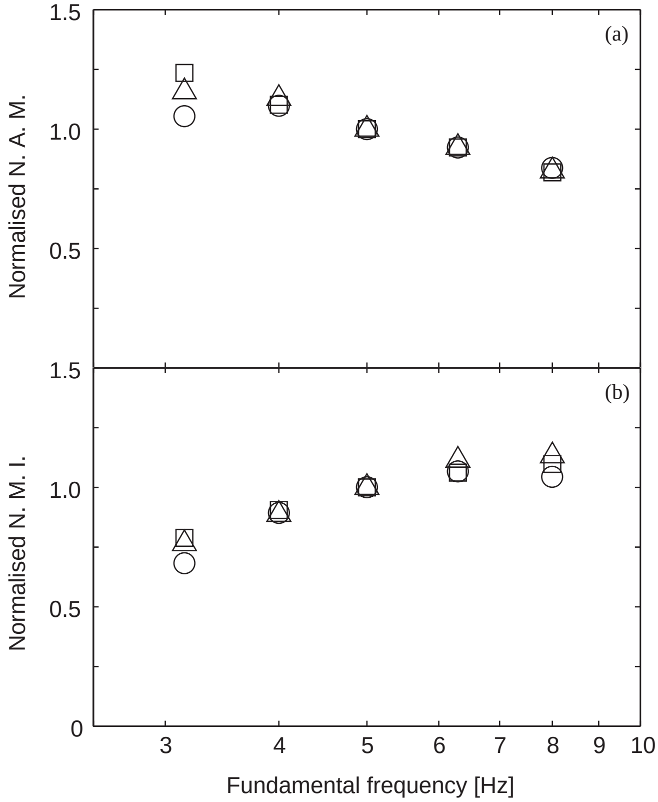

Fig. 9. Median nominal apparent masses (a) and mechanical impedances (b) normalised by the value obtained at 5.0 Hz for transient vibrations (N. A. M.: nominal apparent mass; N. M. I.: nominal mechanical impedance). ○: $-0.7\,m\,s^{-2}$ at peak; △: $-1.4\,m\,s^{-2}$ at peak; □: $-2.8\,m\,s^{-2}$ at peak.

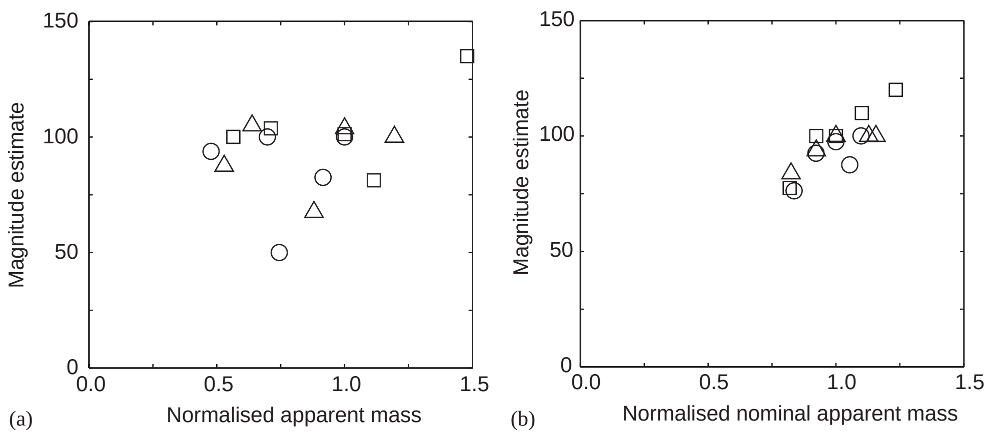

Fig. 10. Comparison between median magnitude estimates and (a) median normalised apparent masses for continuous vibrations (○: $0.5\,m\,s^{-2}$ rms; △: $1.0\,m\,s^{-2}$ rms; □: $2.0\,m\,s^{-2}$ rms) and (b) median normalised nominal apparent masses for transient vibrations (○: $-0.7\,m\,s^{-2}$ at peak; △: $-1.4\,m\,s^{-2}$ at peak; □: $-2.8\,m\,s^{-2}$ at peak).

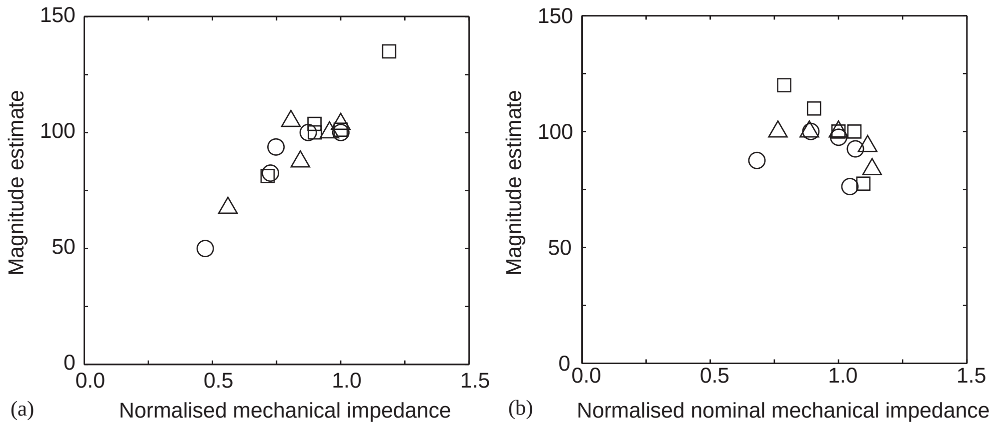

Fig. 11. Comparison between median magnitude estimates and (a) median normalised mechanical impedances for continuous vibrations (○: $0.5\,\mathrm{m\,s^{-2}}$ rms; △: $1.0\,\mathrm{m\,s^{-2}}$ rms; □: $2.0\,\mathrm{m\,s^{-2}}$ rms) and (b) median normalised nominal mechanical impedances for transient vibrations (○: $-0.7\,\mathrm{m\,s^{-2}}$ at peak; △: $-1.4\,\mathrm{m\,s^{-2}}$ at peak; □: $-2.8\,\mathrm{m\,s^{-2}}$ at peak).

Table 2
Kendall's τ_b correlation coefficient between dynamic responses (nominal values for the transient vibrations) and subjective magnitude estimates

	Normalised apparent mass	Normalised mechanical impedance
Continuous		
0.5	0.105	0.949**
1.0	0.000	0.400
2.0	0.200	0.600
Transient		
−0.7	0.600	−0.200
−1.4	0.837*	−0.837*
−2.8	0.949**	−0.949**

**Statistically significant at $p<0.05$.
*Marginally statistically significant at $p<0.1$.

normalised apparent mass. There was a significant correlation between the median magnitude estimates and the median normalised mechanical impedances at $0.5\,\mathrm{m\,s^{-2}}$ rms ($p<0.05$; Table 2). For the transient vibrations, the magnitude estimates show greater correlation with the normalised nominal apparent mass than with the normalised nominal mechanical impedance (Figs. 10(b) and 11(b)); there was a significant positive correlation between the median magnitude estimates and the median normalised nominal apparent masses at $-2.8\,\mathrm{m\,s^{-2}}$ peak ($p<0.05$; Table 2). There was a negative correlation between the median magnitude estimates and the median normalised nominal mechanical impedances at $-2.8\,\mathrm{m\,s^{-2}}$ peak ($p<0.05$), although a positive correlation could be expected between the relative discomfort and the dynamic response (i.e., generally, more discomfort could be expected with greater dynamic response).

4. Discussion

With sinusoidal continuous vibration, the relative discomfort obtained by the magnitude estimation method was dependent on the vibration magnitude (Fig. 4). With increases in vibration magnitude, there were significant increases in the relative discomfort obtained at 3.15 and 4.0 Hz compared to the reference vibration at 5.0 Hz: more than 60% increase in the relative discomfort from 0.5 m s^{-2} rms to 2.0 m s^{-2} rms. There was no significant change in the relative discomfort between 5 Hz and either 6.3 or 8 Hz.

Miwa and Yonekawa [6], Griffin et al. [5] and Corbridge and Griffin [3], which seem to have influenced current standard methods for vibration assessment, e.g., BS 6841 [1] and ISO 2631-1 [2], investigated the effect of vibration magnitude on equivalent comfort contours. Those previous studies, including some other studies reviewed by Dupuis and Zerlett [15] and Griffin [16], concluded that the shape of equivalent comfort contour was not significantly influenced by changes in the vibration magnitude in practical situations where equivalent comfort contours may often be used. However, a similar trend in the equivalent comfort contour caused by changes in the vibration magnitude to the trend found in this study can be observed in the previous studies: in Miwa and Yonekawa [6] for their data at 3 Hz and in Griffin et al. [5] for their data at 4 Hz. These comparisons were made by calculating the relative discomfort with respect to discomfort at 5 Hz from the equivalent comfort contours obtained in those studies. In the present study, the frequency of the reference vibration was 5.0 Hz so it might have been relatively easy for subjects to judge the difference in the relative discomfort between test vibrations at 3.15 and 4.0 Hz and the reference vibration at 5.0 Hz. Miwa and Yonekawa [6] and Griffin et al. [5] used a higher frequency for the reference vibration, 20 Hz in Miwa and Yonekawa [6] and 10 Hz in Griffin et al. [5], so that it may have been more difficult to represent the relative discomfort between 3 or 4 Hz and 5 Hz. Corbridge and Griffin [3] found no statistically significant differences in the equivalent comfort contour at different vibration levels. The range of vibration used in their study, 0.25 and 0.75 m s^{-2} rms, was different from that used in this study (0.5, 1.0 and 2.0 m s^{-2} rms), which may be one of the reasons for the absence of a significant difference in their study.

Possible causes of the changes in the relative discomfort at 3.15 and 4.0 Hz observed in the present study include, but may not be restricted to, the nonlinear dynamic response that induces movements in the body that do not increase in linear proportion to the vibration magnitude. As observed in Fig. 8, the apparent masses and mechanical impedances normalised by the values at 5.0 Hz increased significantly with increasing vibration magnitude at 3.15 and 4.0 Hz. An increase in apparent mass indicates either greater motion of the body parts relative to the seat surface or more body mass (i.e., more body parts) moving relative to the seat surface, or both. The relative movements within the body involved in the motions mentioned above could cause increased discomfort.

At all magnitudes, the discomfort caused by the different frequencies of sinusoidal continuous vibration was more highly correlated with mechanical impedance than with apparent mass, although the correlation was only statistically significant for impedance at a magnitude of 0.5 m s^{-2} rms (Fig. 10 and Table 2). The correlation between the mechanical impedance and relative discomfort was less at 1.0 and 2.0 m s^{-2} rms because, at 1.0 m s^{-2} rms, the mechanical impedance at 6.3 Hz was almost equal to that at 8.0 Hz and, at 2.0 m s^{-2} rms, the mechanical impedance was lower at 6.3 Hz than at 8.0 Hz (Fig. 8(b) and Table 2). Fig. 12(a) compares the

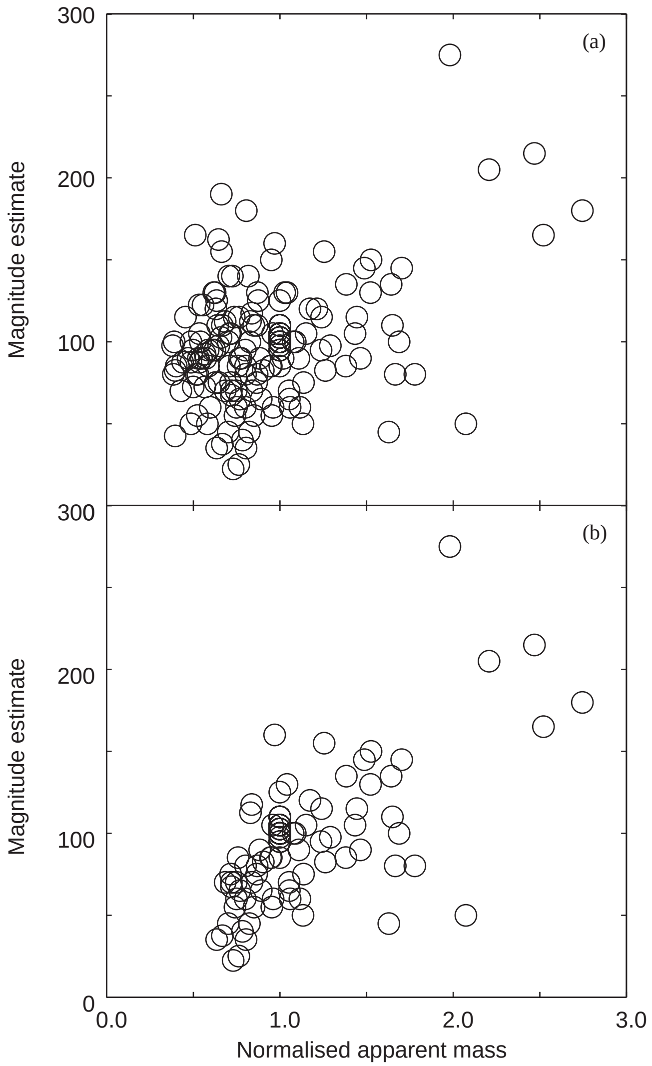

Fig. 12. Comparison between the normalised apparent masses and the magnitude estimates for all individual subjects for continuous vibrations: (a) the data in all experimental conditions, (b) the data at 3.15, 4.0 and 5.0 Hz.

normalised apparent mass and the magnitude estimates for all individual subjects in all experimental conditions used in this study, while Fig. 12(b) excludes 6.3 and 8.0 Hz data from the comparison. Fig. 12 implies that the correlation between the apparent mass and the relative discomfort may improve if only data at 3.15, 4.0 and 5.0 Hz are considered. The prediction of discomfort from the apparent mass appears to underestimate discomfort at 6.3 and 8.0 Hz. These results suggest that although dynamic response measured at the input can be correlated with variations in subjective responses caused by variations in stimulus magnitude, neither apparent mass nor mechanical impedance reflect the frequency-dependence of discomfort, except over a narrow frequency range.

It has been observed in previous studies that motions of various parts of the body have vibration modes in the frequency range between 3.15 and 5.0 Hz [11,17]. In the vertical direction, those motions appeared to occur almost in phase with each other in that frequency range. The occurrence of those body motions can be represented by the mechanical impedance and apparent mass because the inertial force induced with those motions is relatively great. Therefore, if a combination of those motions of the body is a main source of discomfort in the frequency range between 3.15 and 5.0 Hz, it is reasonable that the correlation between vibration discomfort and the mechanical impedance and apparent mass is relatively high in this frequency range, as observed in this study. At higher frequencies, independent local vibration modes of different body parts may become dominant, as commonly found in engineering structures, and the contribution of those local body motions to discomfort may increase: for example, Whitham and Griffin [18] reported that the head was clearly the position where most discomfort was felt by subjects exposed to 16 Hz vertical vibration. Those local body motions occurring independently do not significantly affect the mechanical impedance or apparent mass because of the relatively small mass of body parts, compared to the mass of the whole body, involved. Therefore, a correlation between discomfort and the mechanical impedance or apparent mass is not expected at high frequencies.

The effect of frequency on relative discomfort is less clear for the transient vibrations than for the sinusoidal vibrations (Figs. 4 and 5). One of the reasons for this may be that the transient vibrations used in this study consisted of the fundamental frequency and various frequency components around the fundamental frequency due to the modulation of the fundamental frequency component (Fig. 2). Motions at frequencies other than the fundamental frequency may have influenced discomfort and this 'smearing' may effect have reduced the clarity of the effect of frequency on the relative discomfort.

The relative discomfort was influenced by changes in the magnitude of transient vibration, principally at lower frequencies, although the influence of magnitude was less clear for the transient vibrations than for the continuous vibrations (Figs. 4 and 5). Possible causes of the change in the relative discomfort at lower frequencies (i.e., 3.15 and 4.0 Hz) include those described for continuous vibration.

The discomfort caused by 3.15 Hz transient vibrations tended to be greater than that caused by 4.0 Hz transient vibrations, unlike with continuous vibrations. At all magnitudes, the discomfort caused by the transient vibrations at 8.0 Hz tended to be less than that at 4.0, 5.0 and 6.3 Hz, unlike for continuous vibration. These differences may indicate that the discomfort caused by the transient vibrations showed a tendency to decrease with increasing frequency, compared to the discomfort measured for the continuous vibrations. This may be related to the varying stimulus durations with the different frequencies of transient vibrations. The difference may also be influenced by the frequency-spreading in the transient vibrations.

For the transient vibrations, the relative discomfort was more highly correlated with the nominal apparent mass than the nominal mechanical impedance (Fig. 11 and Table 2). As described above, both the relative discomfort and dynamic responses measured with the transient vibrations may have been influenced by frequency components at frequencies other than the fundamental frequency. In general, the mechanical impedance included a greater contribution from higher frequencies than the apparent mass: the mechanical impedance of a rigid mass increases in proportion to the frequency, while the apparent mass of a rigid mass is constant irrespective of frequency. In the relative discomfort, contributions from higher frequencies may not have been so significant as those in the mechanical impedance. Additionally, in the present study, transient vibrations with higher fundamental frequencies had shorter durations, which may have decreased discomfort at the higher frequencies, as described in the preceding paragraph. It is therefore reasonable that a high correlation between the relative discomfort and the nominal mechanical impedance was not found with transient vibrations even though it was found with the continuous vibration. The nominal apparent mass measured for all the transient vibrations used in this study may have included contributions from the resonance response in the frequency range from 4 to 5 Hz, such as observed with the continuous vibration as shown in Fig. 4(a). The effect of duration on the relative discomfort may have increased the correlation between the relative discomfort and the normalised nominal apparent mass at higher frequencies. However, at frequencies below 5.0 Hz, an effect of duration on the relative discomfort was not clear, as observed in Fig. 5. So, a high correlation between nominal apparent mass and relative discomfort for the transient vibrations (Table 2) may imply that the relative discomfort was affected by the resonance response of the body for all the transient vibrations.

Frequency weightings are defined in ISO 2631-1 [2], BS 6841 [1] and other standards and guides so as to take account of the frequency-dependence of human responses to vibration and shock. It is assumed in the standards that the effect of frequency on human response is linear: the effect at each frequency increases in proportion to stimulus magnitude, so that a single frequency weighting can be used for all stimulus magnitudes. The results obtained in this study show a strong nonlinear characteristic in subjective responses to vertical continuous vibration and transient vibrations caused by different stimulus magnitudes. Fig. 13 compares the standardised frequency weightings (i.e., the W_k weighting in ISO 2631-1 [2] and the W_b weighting in BS 6841 [1]) with the median magnitude estimates of discomfort obtained with the continuous vibration in this study: the data presented in Fig. 4 were converted to dB with respect to the reference of 100.

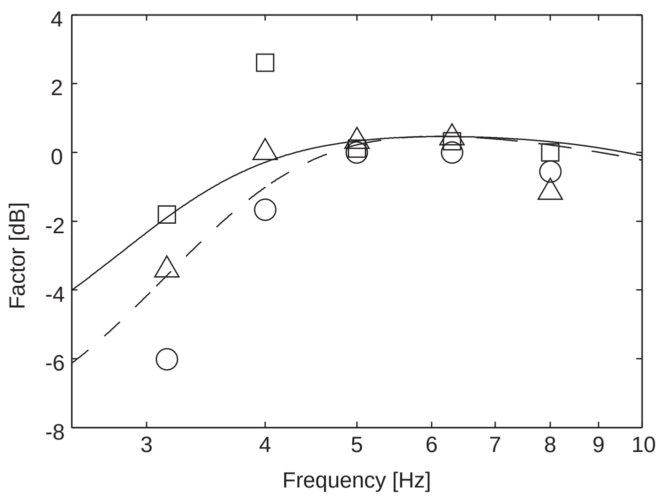

Fig. 13. Comparison between the standard frequency weightings (———; the W_k weighting in ISO 2631-1 [2]; – – –: the W_b weighting in BS 6841 [1]) and the median discomfort magnitude estimates obtained with the continuous vibrations, expressed in dB. ○: 0.5 m s^{-2} rms; △: 1.0 m s^{-2} rms; □: 2.0 m s^{-2} rms.

The figure implies that the nonlinearity observed in the subjective responses in this study is potentially important when considering frequency weightings for vertical vibration.

Nonlinear characteristics in driving point biodynamic responses to vertical whole-body vibration have been reported in several previous studies: the frequency of the resonance response reduces with increases in vibration magnitude (e.g. Refs. [12,14]). Previous studies have mainly used broad-band random vibration. When sinusoidal vibration has been used for the input stimuli, as in this study, it is usually not easy to identify resonance frequencies in the response due to the use of coarse frequency resolutions. However, evidence of the reduction of resonance frequency with increases in stimulus magnitude can be observed in other data with sinusoidal vibration: as stimulus magnitude increases, responses at frequencies lower than the resonance frequency increase and responses at frequencies higher than the resonance frequency decrease. This trend with sinusoidal vibration was observed in this study and previously by Matsumoto and Griffin [19].

5. Conclusions

Discomfort relative to that caused by 5.0 Hz vibration, and the driving-point dynamic responses normalised with respect to 5.0 Hz, were both influenced by vibration magnitude. When exposed to sinusoidal continuous vibration at 3.15 and 4.0 Hz, the relative discomfort and the normalised mechanical impedance and normalised apparent mass increased with increases in vibration magnitude from 0.5 to 2.0 $\mathrm{m\,s^{-2}}$ rms. There were correlations between the relative discomfort and the normalised mechanical impedance in the frequency range between 3.15 and 8.0 Hz. The correlations between relative discomfort and normalised mechanical impedance and normalised apparent mass increased when the data were restricted to the range 3.15 and 5.0 Hz.

With transient vibrations, discomfort and driving-point dynamic responses (nominal mechanical impedance and apparent mass) can be influenced by responses in frequency bands around the fundamental frequency of the input motion. The discomfort and nominal apparent mass may have been influenced by the resonance response of the body in the frequency range from 4.0 to 5.0 Hz, giving correlations between relative discomfort and normalised nominal apparent mass associated with the transient vibrations. Nominal mechanical impedance, having greater contributions from higher frequency components than nominal apparent mass, did not show positive correlations with the relative discomfort caused by transient vibrations.

Discomfort caused by vibration may be correlated with mechanical impedance and apparent mass in a frequency range where discomfort may be mainly attributed to motions of various parts within the body occurring almost in phase with each other, although the correlation does not necessarily imply a cause-effect relation. For higher frequencies, where independent local body motion may be the main source of discomfort, the dynamic responses of particular parts of the body may be more useful predictors of discomfort, but is the subject of other study.

The findings of the present study indicate that there are similar nonlinearities in the discomfort and the driving-point dynamic response associated with the principal body response to vertical vibration in the range 3.15–8 Hz. The nonlinearity in discomfort may be partially caused by the nonlinear dynamic response of the body and is sufficiently great to require consideration in methods of predicting discomfort caused by vertical whole-body vibration.

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