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Journal of Sound and Vibration 298 (2006) 755–772
JOURNAL OF SOUND AND VIBRATION
www.elsevier.com/locate/jsvi

Magnitude-dependence of equivalent comfort contours for fore-and-aft, lateral and vertical whole-body vibration

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Received 3 May 2006; received in revised form 10 May 2006; accepted 8 June 2006
Available online 8 August 2006

Abstract

It is currently assumed that the same frequency weightings, derived from studies of vibration discomfort, can be used to evaluate the severity of vibration at all vibration magnitudes from the threshold of vibration perception to the vibration magnitudes associated with risks to health. This experimental study determined equivalent comfort contours for the whole-body vibration of seated subjects over the frequency range 2–315 Hz in each of the three orthogonal axes (fore-and-aft, lateral and vertical). The contours were determined at vibration magnitudes from the threshold of perception to levels associated with severe discomfort and risks to health.

At frequencies greater than 10 Hz, thresholds for the perception of vertical vibration were lower than thresholds for fore-and-aft and lateral vibration. At frequencies less than 4 Hz, thresholds for vertical vibration were higher than thresholds for fore-and-aft and lateral vibration. The rate of growth of sensation with increasing vibration magnitude was highly dependent on the frequency and axis of vibration. Consequently, the shapes of the equivalent comfort contours depended on vibration magnitude. At medium and high vibration magnitudes, the equivalent comfort contours were reasonably consistent with the frequency weightings for vibration discomfort in current standards (i.e. W_b and W_d). At low vibration magnitudes, the contours indicate that relative to lower frequencies the standards underestimate sensitivity at frequencies greater than about 30 Hz. The results imply that no single linear frequency weighting can provide accurate predictions of discomfort caused by a wide range of magnitudes of whole-body vibration.

1. Introduction

The EU Physical Agents Directive [1] requires the minimisation of risks from exposure to whole-body vibration. The Directive defines 'exposure action values' and 'exposure limit values' for fore-and-aft, lateral, and vertical vibration evaluated using frequency weightings defined in current standards. Dose–response relationships between whole-body vibration and injury have not been established, so it is optimistic to assume that the risk of injury can be estimated using any currently defined measure of vibration [2]. However, increases in vibration magnitude increase vibration discomfort and pain and can be assumed to increase the risks to health. In the absence of information to the contrary, the strength of sensation has been assumed to

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0022-460X/$ - see front matter
doi:10.1016/j.jsv.2006.06.011

reflect health risks, and knowledge of the relation between vibration and discomfort has greatly influenced the frequency weightings used to estimate risks, and the minimisation of the risks, from exposures to whole-body vibration.

The discomfort produced by whole-body vibration is dependent on several factors, including the frequency and the magnitude of the vibration [3]. The effect of the frequency of vibration on discomfort caused by whole-body vibration has been investigated by determining equivalent comfort contours for seated persons [4–12]. There is some consistency between these studies (e.g. the overall shape of equivalent comfort contours), but also inconsistencies that may partially be explained by the use of different experimental methods, different sitting postures, etc.

Previous studies have determined equivalent comfort contours over a range of vibration magnitudes, but they have not systematically explored whether vibration magnitude affects the frequency-dependence of the contours. Some of the differences between the contours obtained in the different studies may therefore arise from the different magnitudes of vibration that have been investigated. A magnitude-dependence in equivalent comfort contours for hand-transmitted vibration has been partly explained by mediation via different psychophysical channels at different vibration magnitudes [13]. The perception of whole-body vibration is more complex, involving several sensory systems (e.g., visual, vestibular, acoustic and somatosensory senses), and the mechanisms involved in the perception of whole-body vibration are less well understood than those involved in the perception of vibration applied to parts of the body.

The relation between physical stimuli and sensations is often expressed by Stevens' power law [14], in which the 'objective magnitude', φ, of the stimulus and the 'subjective magnitude', ψ, of the response are assumed to be related by a power function:

$$\psi = k\varphi^n. \tag{1}$$

The value of the exponent, n, is assumed to be constant for each type of stimulus. For typical magnitudes of vertical whole-body vibration, values of the exponent have been obtained at frequencies over frequency range 2–80 Hz [6,11,15–17]. Miwa [15] determined exponents for 5, 20 and 60 Hz and reported a reduction in the exponent with an increase in vibration magnitude, suggesting an exponent of 0.6 for vibration greater than 1.0 $\mathrm{ms^{-2}}$ rms and 0.46 for vibration less than 1.0 $\mathrm{ms^{-2}}$ rms. Jones and Saunders [16] found a mean exponent ranging from 0.88 to 0.99, but suggested that an exponent of 0.93 may be used to describe the response to whole-body vertical vibration from 5 to 80 Hz. Shoenberger and Harris [6] determined exponents for frequencies from 3.5 to 20 Hz and found that the exponent at 5 Hz was significantly greater than at 7, 15 and 20 Hz. Howarth and Griffin [11] investigated exponents for low magnitude (i.e., 0.04–0.4 $\mathrm{ms^{-2}}$ rms) vertical and lateral whole-body vibration over the frequency range 4–63 Hz and found no frequency dependence with vertical vibration but an increase with increasing frequency from 4 to 16 Hz with horizontal vibration.

A frequency-dependence in the exponent indicates that the rate of growth of sensation varies with frequency, and implies that the shapes of equivalent comfort contours depend on vibration magnitude. The currently available results are insufficient to define any such magnitude-dependence, partly due to the limited investigation of the rate of growth of sensation over the range of magnitudes from perception thresholds to magnitudes associated with severe discomfort and risks to health.

The power law is sometimes written with an additive constant, φ_0, representing the threshold of perception [18], assuming no sensation below the perception threshold:

$$\psi = k(\varphi - \varphi_0)^n. \tag{2}$$

The power law with the additive constant has proved useful in describing sensations caused by hand-transmitted vibration [13].

This paper reports an investigation of the effect of vibration magnitude (from the threshold of perception to magnitudes associated with discomfort and risks to health) on equivalent comfort contours over the frequency range 2–315 Hz for seated persons exposed to fore-and-aft, lateral and vertical whole-body vibration. It was hypothesised that, within each of the three axes, the frequency-dependence of vibration discomfort would vary with vibration magnitude.

The study comprised two experiments. The first experiment determined absolute threshold contours in each of the three translational axes (fore-and-aft, lateral and vertical). The second experiment determined the strength of sensation caused by whole-body vibration in each of the three axes and allowed the calculation of equivalent comfort contours.

2. Experiment 1: Perception thresholds

2.1. Method

2.1.1. Subjects

Three groups of male subjects participated in the study, with one group for each axis of vibration. The subjects in each group attended two experiments in which perception thresholds (Experiment 1) and judgements of the strength of sensation (Experiment 2) were determined in either the fore-and-aft, lateral, or vertical direction. All subjects were students or office workers with no history of occupational exposure to whole-body vibration. The three groups of 12 males (total of 36 subjects) were aged between 21 and 29 years with a mean age of 24.8 years (standard deviation, SD = 2.2), a mean stature of 177.3 cm (SD = 7.2) and a mean weight of 73.6 kg (SD = 9.6) participated. The characteristics of the subjects in each group are shown in Table 1. There were no significant differences in age, weight or body stature between the three groups (Mann-Whitney, $p > 0.1$) (Table 2).

During the tests, subjects were exposed to white noise at 75 dB(A) via a pair of headphones to prevent them hearing the vibration and to assist their concentration on the vibration by masking any distracting sounds.

Both experiments were approved by the Human Experimentation Safety and Ethics Committee of the ISVR, University of Southampton. Informed consent to participate in the experiments was given by all subjects.

2.1.2. Apparatus

A Derritron VP180LS vibrator was employed to generate vertical vibration at the seat. A Derritron VP 85 vibrator (coupled with a slip table, Kinball Industries, Inc.) was employed to generate fore-and-aft and lateral vibration at the seat.

A rigid wooden seat (250 mm × 180 mm) manufactured in-house had a contoured surface to provide contact with the ischial tuberosities (see Fig. 1). The arrangement was designed to achieve resonance frequencies greater than 315 Hz with minimum cross-axis vibration (less than 10%). Two single-axis piezo-electric accelerometers (Model 355B03, PCB Piezotronics) were employed. An accelerometer inside the centre of the wooden seat was orientated to be sensitive to acceleration in the direction of excitation. Accelerometers mounted on the surface of the seat were orientated to measure cross-axis motions of the seat. Background vibration, due to electrical noise at 50 Hz, was less than 0.008 ms^{-2} rms, and was not perceptible via the seat.

Sinusoidal vibration was generated and acquired using *HVLab* Data Acquisition and Analysis Software (version 3.81) via a personal computer with anti-aliasing filters (TechFilter) and analogue-to-digital and digital-to-analogue converters (PCL-818). The signals were generated at 5000 samples per second and passed through 600 Hz low-pass filters. The stimulus parameters and the psychophysical measurement procedures were computer-controlled.

A stationary footrest (30.5 mm × 10.5 mm with 10° of inclination) and stationary cylindrical handles (100 mm length with 30 mm diameter) were provided. There was no backrest.

Table 1
Characteristics of subjects for each group who participated in the two experiments

	Fore-and-aft	Lateral	Vertical
Age (year)	24.5 (2.5)	23.6 (2.5)	24.8 (2.2)
Weight (kg)	71.2 (9.5)	73.4 (9.0)	76.1 (10.3)
Stature (cm)	175.6 (7.2)	176.8 (5.9)	179.8 (8.2)
Sitting height (cm)	91.4 (5.1)	90.0 (9.2)	92.6 (3.8)

Mean (standard deviation).

Table 2
Median exponents (n), constants (k) and thresholds (φ_0) for each of three axes (x = fore-and-aft, y = lateral, and z = vertical)

Frequency	Stevens power law with additive constant, Eq. (2)								
	Exponent (n)			Constant (k)			Threshold (φ_0)		
	x	y	z	x	y	z	x	y	z
2	0.948	0.635	0.626	706.15	406.07	185.91	0.012	0.010	0.014
2.5	0.668	0.763	0.697	376.70	470.54	185.10	0.013	0.012	0.016
3.15	0.499	0.742	0.751	244.57	354.57	192.13	0.013	0.014	0.018
4	0.461	0.932	0.897	209.94	361.08	227.98	0.013	0.017	0.018
5	0.468	0.876	0.669	190.24	269.34	212.76	0.013	0.021	0.015
6.3	0.805	0.953	0.687	197.61	233.94	215.97	0.014	0.024	0.015
8	0.711	0.716	0.702	156.71	165.50	215.48	0.025	0.033	0.019
10	0.735	0.935	0.624	131.98	147.03	193.55	0.041	0.054	0.022
12.5	0.854	0.907	0.814	118.44	123.23	203.19	0.057	0.072	0.022
16	0.956	0.954	0.827	79.85	100.07	181.80	0.086	0.076	0.025
20	0.896	0.826	0.776	89.80	74.35	149.93	0.084	0.079	0.025
25	0.830	0.801	0.757	66.05	70.76	136.11	0.087	0.077	0.028
31.5	0.762	0.882	0.697	64.85	55.87	136.52	0.071	0.069	0.030
40	0.802	0.753	0.600	57.10	54.98	127.67	0.077	0.070	0.027
50	0.694	0.741	0.489	54.80	49.65	110.59	0.075	0.056	0.025
63	0.646	0.666	0.462	53.15	48.05	102.78	0.075	0.049	0.025
80	0.668	0.696	0.424	51.59	44.76	93.11	0.077	0.051	0.026
100	0.611	0.744	0.413	48.29	35.97	85.98	0.089	0.051	0.025
125	0.558	0.617	0.448	48.67	36.97	78.76	0.089	0.054	0.032
160	0.612	0.745	0.379	39.44	26.57	85.31	0.125	0.093	0.027
200	0.673	0.840	0.464	31.78	18.66	64.80	0.171	0.109	0.033
250	0.792	0.857	0.515	20.48	11.29	52.99	0.252	0.231	0.044
315	0.746	0.758	0.535	14.87	10.75	45.47	0.436	0.319	0.065

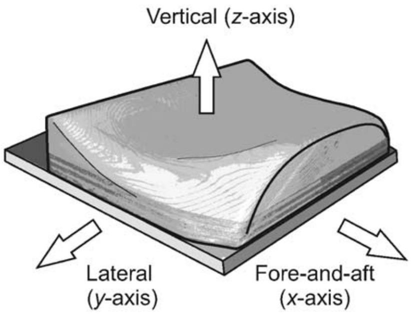

Fig. 1. The contoured rigid seat and axes of vibration. The wooden seat dimensions (250 mm × 180 mm, maximum height = 50 mm, minimum height = 33 mm).

2.1.3. Procedure

The subjects were instructed to sit upright with comfortable postures with their eyes open and looking straight ahead and with their hands on the stationary handles and their feet on the stationary footrests. The positions of the handles and the footrests were fixed relative to the seat. Their thighs were approximately horizontal and level with the seat, their feet were approximately 400 mm apart, and their forearms were approximately horizontal and level with the handles.

Absolute thresholds of the perception of whole-body vibration in each of the three axes were determined using sinusoidal vibration at each of the 23 preferred one-third octave centre frequencies between 2 and 315 Hz. The stimuli were 2.0 s in duration, including 0.5 s cosine-tapered ends.

An up-down (staircase) algorithm was employed to determine thresholds in conjunction with the three-down one-up rule. A single test stimulus was presented, 2.0 s in duration, with a cue light illuminated during this period. The task of subjects was to indicate whether they perceived the vibration stimulus or not. They responded saying 'yes' or 'no'. The vibration stimulus increased in magnitude by 2 dB (25.8% increment) after a negative ('no') response from a subject and decreased in magnitude by 2 dB after three consecutive positive ('yes') responses.

The procedure for determining a threshold was terminated after six reversals: a point where the stimulus magnitude reversed direction at either a peak or a trough. The threshold was calculated from the mean of the last two peaks and the last two troughs, omitting the first two reversals, as suggested by Levitt [19]. Thresholds within an axis were measured in a single session. The order of presenting the test frequencies was randomised.

2.1.4. Statistical analysis

Statistical analysis of the threshold data was performed using non-parametric tests because threshold data are not expected to be normally distributed. To examine the effect of vibration frequency (related samples), the Friedman two-way analysis of variance and the Wilcoxon matched-pairs signed ranks tests were applied. The effect of axis (independent samples), was examined using the Kruskal–Wallis and Mann–Whitney U tests.

2.2. Results and discussion

2.2.1. Thresholds within axes (effect of frequency)

The median absolute thresholds and the inter-quartile ranges (25–75th percentiles) over the 12 subjects were determined at each frequency in each axis, and are shown in Fig. 2. Within each axis, the acceleration perception thresholds varied significantly with vibration frequency (Friedman, $p<0.001$), with an overall trend of increasing thresholds with increasing frequency over the range investigated (from 2 to 315 Hz). The shapes of the threshold contours determined in the present study are broadly similar to those reported from previous studies [5,20], although sensitivity varies between the studies. Vertical thresholds obtained by Miwa [5] were somewhat lower than those determined by Parsons and Griffin [20] and in the present study, which might be explained by the different method used to determine thresholds: Miwa [5] used a two-interval forced-choice method in which the subjects chose which of two stimuli they felt, whereas Parsons and Griffin [20] and the present study employed 'yes–no' methods in which subjects responded if they felt the vibration stimulus. Morioka and Griffin [21] compared vibrotactile thresholds at the fingertip obtained with three different psychophysical methods, including a two-interval forced-choice method and a 'yes–no' method and found lower thresholds with the two-interval forced-choice method. In addition, differences in thresholds between the studies may be attributed to differences in body posture or body support, particularly at low frequencies. Although Miwa [5] and Parsons and Griffin [20] employed a stationary footrest (with no backrest) as in the present study, the surface of their seat was large enough to contact the buttocks and thighs, whereas the seat used in the present study did not contact the thighs. The absence of contact with the thighs in the present study may have reduced sensitivity to low-frequency vertical seat vibration.

Thresholds at adjacent frequencies were tested for differences. With fore-and-aft vibration, the threshold contours exhibited approximately constant acceleration between 2 and 6.3 Hz (Wilcoxon, $p>0.1$); a significant increase (almost constant velocity) from 6.3 to 16 Hz (Wilcoxon, $p<0.01$), constant acceleration between 16 and 125 Hz (Wilcoxon, $p>0.05$) except between 80 and 100 Hz (Wilcoxon, $p=0.041$); a significant increase (almost constant velocity) from 125 to 315 Hz (Wilcoxon, $p<0.05$). With lateral vibration, thresholds exhibited a trend broadly similar to that with fore-and-aft vibration: constant acceleration between 2 and 3.15 Hz (Wilcoxon, $p>0.05$); a significant increase (almost constant velocity) from 3.15 to 12.5 Hz (Wilcoxon, $p<0.05$), except between 4 and 5 Hz (Wilcoxon, $p=0.48$); no significant change in threshold between 12.5 and 125 Hz (Wilcoxon $p>0.05$); a significant increase (almost constant velocity) from 125 to 31.5 Hz (Wilcoxon, $p<0.05$). The thresholds for vertical vibration showed a different pattern from the horizontal thresholds: a significant increase from 2 to 2.5 Hz (Wilcoxon, $p=0.002$), followed by no change in acceleration thresholds between 2.5 and 4 Hz (Wilcoxon, $p>0.1$), then a significant trough in thresholds at 5 and 6.3 Hz within the frequency range 4–10 Hz; constant acceleration between 10 and 200 Hz (Wilcoxon, $p>0.05$); a significant increase (almost constant velocity) from 200 to 315 Hz (Wilcoxon, $p<0.05$). Although the criteria for

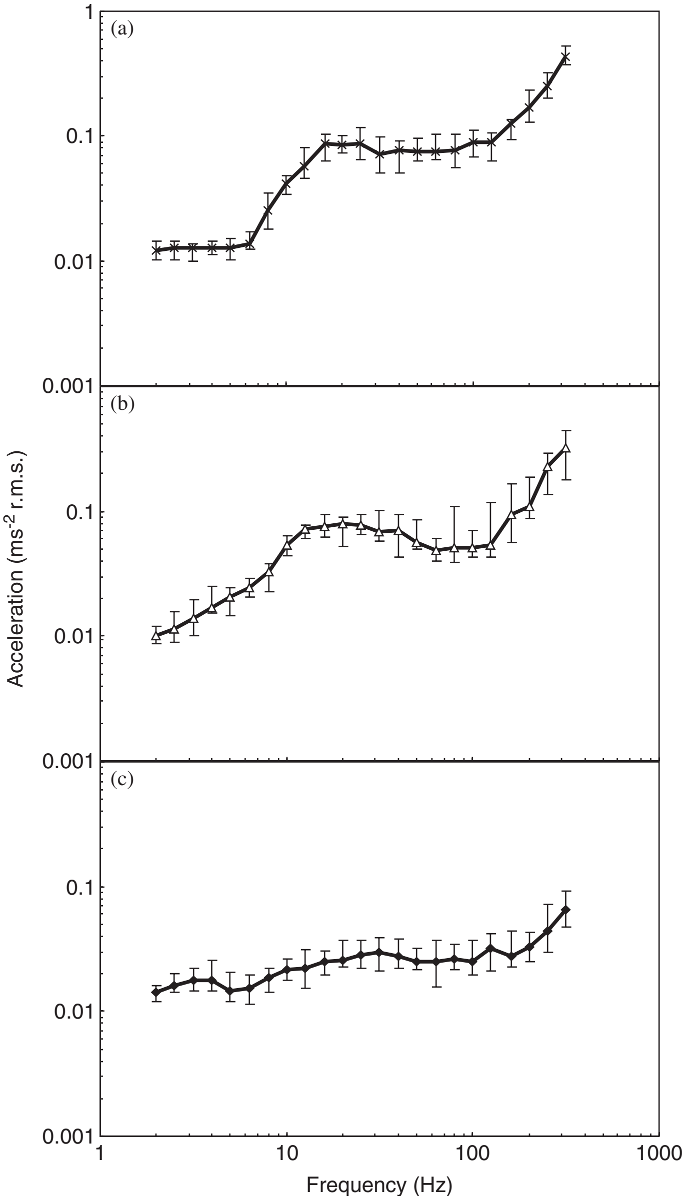

Fig. 2. Median absolute perception thresholds between 2 and 315 Hz: (a) fore-and-aft, (b) lateral, (c) vertical. Error bars represent inter-quartile range.

significance in the above p-values were not adjusted for pair-wise multiple comparisons for repeated measures, it may be speculated from the trends in the results that changes in sensitivity to vibration reflected changes in the sensory systems responsible for detecting vibration, such as visual, vestibular, acoustic, and somatosensory senses. Griffin [3] suggested that the high-frequency thresholds arose from various end organs in the muscles, on the bones and near the surface of the body, whereas the low-frequency thresholds were likely to be associated with vision, the vestibular system, and other cues to movement such as relative motion between the seat and footrest.

There was a tendency for negative correlations between thresholds and body stature (i.e. standing height), with the correlations significant with lateral vibration at 2 Hz (Spearman, $p = 0.013$) and with vertical vibration at 2 and 2.5 Hz (Spearman, $p < 0.05$). This trend was consistent with the finding by Corbridge and

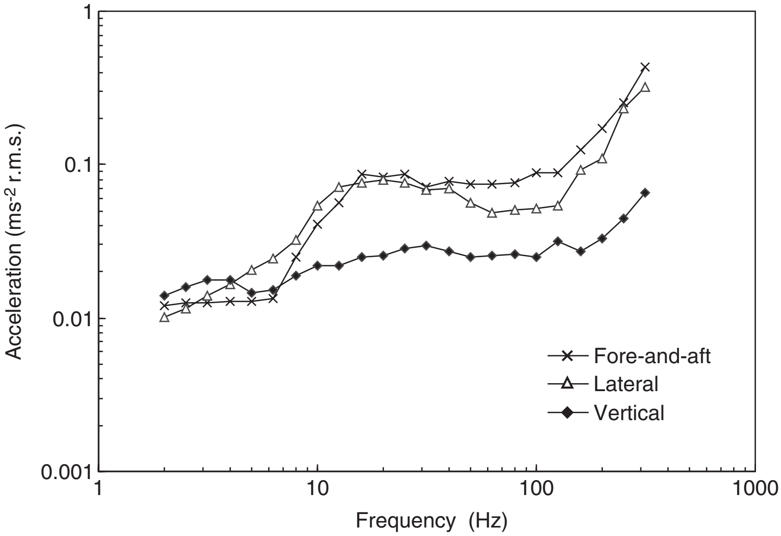

Fig. 3. Median perception threshold contours for the three axes. ×: fore-and-aft, △: lateral, and ♦: vertical.

Griffin [8], in which taller male subjects with longer legs were more sensitive to low-frequency vertical vibration at frequencies less than 2 Hz.

2.2.2. Thresholds between axes (effect of axis)

The median absolute thresholds in the three axes (i.e. fore-and-aft, lateral, and vertical) are compared in Fig. 3. The thresholds differed significantly between the three axes at all frequencies (Kruskal–Wallis, $p<0.05$) except at the lowest frequency of 2 Hz (Kruskal–Wallis, $p = 0.067$).

To allow for multiple-comparisons between the three axes, the significance criterion for two independent samples (Mann–Whitney tests) reported below were adjusted to $p = 0.05/3$ (0.017). At frequencies greater than 10 Hz, the body was most sensitive to vertical vibration: vertical thresholds were significantly lower than fore-and-aft thresholds and lateral thresholds at all frequencies between 10 and 315 Hz (Mann–Whitney, $p<0.017$). In contrast, at frequencies less than 3.15 Hz, sensitivity to vertical vibration was less than sensitivity to fore-and-aft vibration (Mann–Whitney, $p<0.017$). The greater sensitivity to vertical vibration than horizontal vibration at high frequencies may be explained, at least partially, by greater transmission of high-frequency vertical vibration to the head [22,23].

Thresholds for fore-and-aft and lateral vibration were similar across the frequency range, except between 4 and 6.3 Hz where fore-and-aft thresholds were lower than lateral thresholds (Mann–Whitney, $p<0.017$). Similar thresholds for fore-and-aft and lateral vibration of seated subjects across the range 2–100 Hz (apart from 16 Hz) have also been reported by Parsons and Griffin [20].

3. Experiment 2: Equivalent comfort contours

3.1. Method

3.1.1. Subjects

Three groups of male subjects participated in the study, with one group for each axis of vibration (i.e. fore-and-aft, lateral or vertical axis). The subjects who participated in Experiment 1 also took part in Experiment 2. The characteristics of the subjects in each group are shown in Table 1.

3.1.2. Apparatus

All apparatus, including the signal generation and signal acquisition, were the same as employed in Experiment 1.

3.1.3. Procedure

Subjects adopted the same sitting posture as specified in Experiment 1. The subjects judged the discomfort caused by sinusoidal whole-body vibration in each of the three axes (fore-and-aft, lateral and vertical) at the 23 preferred one-third octave centre frequencies between 2 and 315 Hz. The stimuli lasted 2.0 s, including 0.5 s cosine-tapered ends. The motions varied in velocity from 0.02 to 1.25 ms^{-1} rms in 3 dB steps. The range of stimulus magnitudes varied between the axes, so as to ensure that the stimuli were above the absolute perception thresholds but not likely to be considered excessively unpleasant. The acceleration ranges of the test stimuli are shown in Fig. 4.

The method of magnitude estimation [14] was employed to determine judgements of discomfort caused by the vibration. Pairs of motions, a 2 s reference motion and a 2 s test motion, were presented with a 1.0 s interval. The reference motion was fixed with a frequency of 20 Hz and a magnitude of 0.5 ms^{-2} rms for vertical (z-axis) vibration, and a frequency of 20 Hz and a magnitude of 1.0 ms^{-2} rms for horizontal vibration (in the x- and y-axis). The subjects were asked to assign a number representing the discomfort of the test motion relative to the discomfort of the reference motion, assuming the discomfort of the reference motion corresponded to '100'. The order of presenting the magnitudes and frequencies of the test motions was completely random. Subjects were able to ask for a pair of stimuli to be repeated if they were unsure of their judgment. They were instructed to indicate 'no sensation' if the test stimulus was not perceived. A small cue light was illuminated during the presentation of the reference and the test stimuli.

Prior to commencing the experiment, subjects practiced magnitude estimation by judging the lengths of lines drawn on paper and by judging a few selected vibration stimuli. This provided an opportunity to check that they understood the procedure and also familiarised them with the type of vibration stimuli. Each subject received all the vibration stimuli in one axis of excitation in a single session, with short breaks every 35 pairs.

There were a few stimuli at low magnitudes that were not perceived by all subjects. The stimuli not felt by a subject were not included in the analysis of the subject's judgements.

3.1.4. Statistical analysis

Statistical analysis of the rate of growth of sensation was performed using the same non-parametric tests as described for Experiment 1.

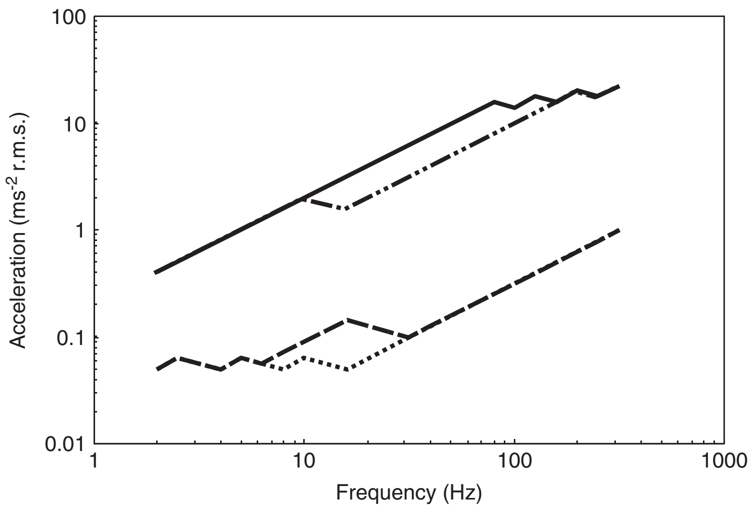

Fig. 4. Range of vibration magnitudes used for the method of magnitude estimation in Experiment 2. ———: horizontal axis upper limit, — · · —: vertical axis upper limit, — — —: horizontal axis lower limit, and ···········: vertical axis lower limit.

3.2. Results and discussion

3.2.1. Growth of sensation

For each frequency and axis, the relationships between the vibration magnitudes, φ, to which the 12 subjects were exposed and their median sensation magnitudes, ψ, were determined using Stevens' Power law with an additive constant representing the threshold (Eq. (2)). The constant, φ_0, was taken from the median perception threshold from the same subjects for the appropriate frequency and direction of excitation as determined in Experiment 1. Linear regression was performed at each frequency (see Fig. 5 for examples) transforming Eq. (2) to

$$\log_{10}\psi = n\log_{10}(\varphi - \varphi_0) + \log_{10}k. \tag{3}$$

As can be seen in Fig. 5, there was evidence of a curvilinear relationship when the data were plotted on log–log coordinates for sensation magnitude as a function of vibration magnitude, showing a steeper slope (i.e. greater rate of growth of sensation) at low magnitudes, especially at low frequencies approximately between 10 and 20 Hz where the stimulus magnitudes employed in the experiment were closer to the perception threshold. This curvilinear relationship was also apparent in the results of Howarth and Griffin [11], who used low magnitude stimuli (i.e. 0.04–0.4 ms^{-2} rms) at frequencies from 4 to 63 Hz. Although the present results did not allow a complete examination of the curvilinear relationship at high frequencies, the use of the additive constant seemed to improve the representation of sensation magnitudes. The subjective magnitude functions

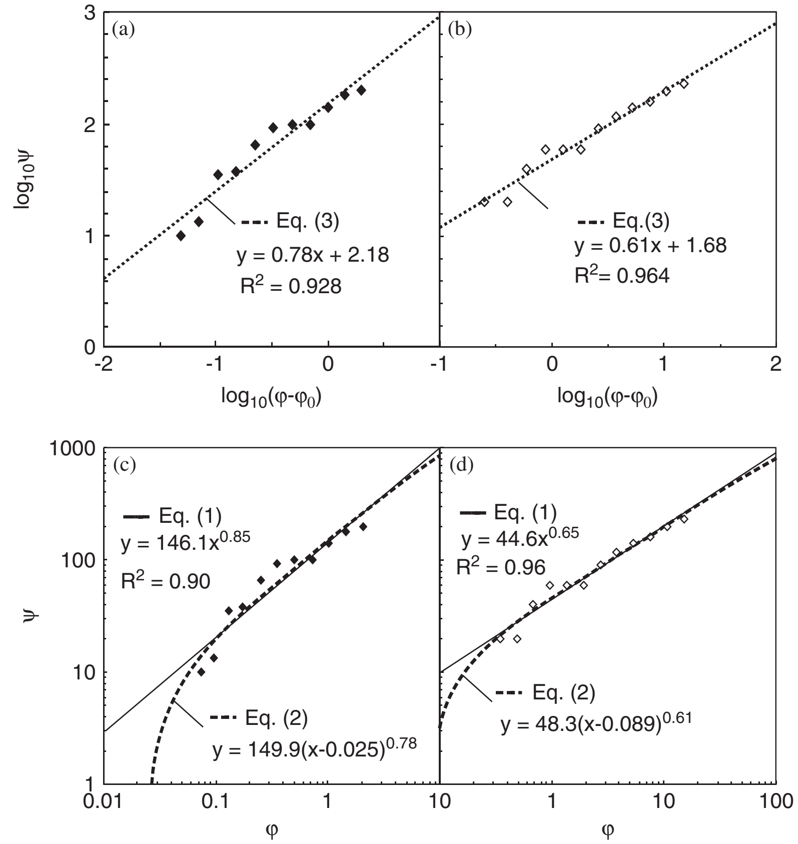

Fig. 5. Examples of linear regression for: (a) 20 Hz responses to vertical vibration and (b) 100 Hz responses to fore-and-aft vibration using Eq. (3). The data are then converted into sensation magnitudes, ψ, as a function of vibration magnitude, φ, for: (c) 20 Hz (vertical) and (d) 100 Hz (fore-and-aft). The values of the additive constant, φ_0, represent the median thresholds determined in Experiment 1, which are 0.025 ms^{-2} rms for vertical vibration at 20 Hz and 0.089 ms^{-2} rms for fore-and-aft vibration at 100 Hz. ——: Eq. (1), ----: Eq. (2) and ·········: Eq. (3).

had lower slopes when using an additive constant than when using Stevens' power law without the additive constant. Moreover, the coefficients of determination, R^2, determined using the power law with the additive constant are mostly higher (20 out of 23 frequencies) than those determined with Stevens' power law without the additive constant. A similar trend was found by Morioka and Griffin [13] with hand-transmitted vibration.

For each of the three axes, the median rates of growth of sensation, n, determined using Stevens' Power law with an additive constant (Eq. (2)) are shown in Fig. 6. Within each axis, the rates of growth of sensation varied with vibration frequency (Friedman, $p < 0.001$).

To illustrate general trends in the rates of growth of sensation over frequencies, the Wilcoxon matched-pairs signed ranks test was applied with the significance criteria in the p-values not adjusted for pair-wise multiple comparisons for repeated measures. With fore-and-aft vibration, the exponent was lowest at 5 Hz (0.47) while the 2 Hz exponent (0.95) was significantly higher than that at other frequencies between 2.5 and 5 Hz (Wilcoxon, $p < 0.05$). With vertical vibration, the 4 Hz exponent (0.9) was significantly higher than that any other frequency between 2 and 10 Hz (Wilcoxon, $p < 0.05$). There was no obvious trend in the exponents for lateral vibration at frequencies less than 16 Hz, apart from frequencies between 2 and 10 Hz (Wilcoxon, $p = 0.05$). The findings seem partially consistent with the hypothesis of Shoenberger and Harris (1971) that the greatest exponents will occur at the whole-body resonance frequency; they determined exponents for vertical vibration at 3.5, 5, 7, 9, 11, 15, and 20 Hz and found that the exponent at 5 Hz (1.04) was significantly greater than that at 7, 15, and 20 Hz. The primary resonance frequencies for fore-and-aft, lateral and vertical whole-body vibration (without backrest) are in the region of 2.5, 2.0, and 4.0 Hz, respectively [24,25], which more-or-less coincide with the maximum exponent for fore-and-aft vibration (at 2 Hz) and the maximum exponent for vertical vibration (at 4 Hz) in the present study. In the lateral direction, the study of Fairley and Griffin [25] had subjects with feet close together whereas in the present study the feet were further apart—this may have increased the resonance frequency of the body in the lateral direction in the present study and so a maximum exponent for lateral vibration in the 4–6 Hz range may also be associated (in some undefined way) with the biodynamic responses of the body during vibration.

There was a tendency towards a decreased rate of growth of sensation as the frequency increased from 16 to 100 Hz: with fore-and-aft vibration, 16 of 36 combinations of exponents for two frequencies were significantly reduced at the higher frequency (Wilcoxon, $p < 0.05$); for lateral vibration 20 out of 36 combinations of two frequencies were reduced (Wilcoxon, $p < 0.05$); for vertical vibration 25 out of 36 combinations of two frequencies were reduced (Wilcoxon, $p < 0.05$). However, at frequencies between 125 and 315 Hz, there was an inverse trend (an increased rate of growth of sensation with increasing frequency) which was significant

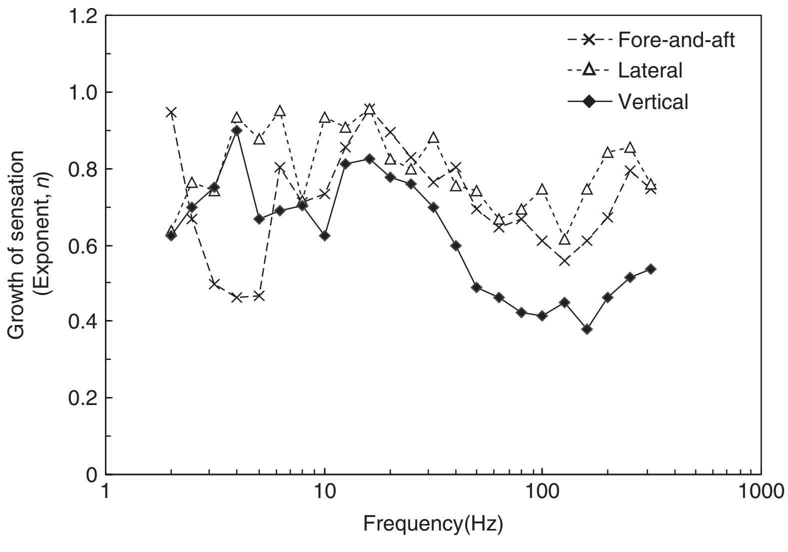

Fig. 6. Rates of growth of sensation (median exponent, n, from 12 subjects) as a function of vibration frequency from 2 to 315 Hz for three directions (determined with Eq. (2)). ×: fore-and-aft, △: lateral, and ♦: vertical.

between 125 and 160 Hz for fore-and-aft vibration (Wilcoxon, $p = 0.019$), significant between 125 and 200 Hz for lateral vibration (Wilcoxon, $p = 0.006$), and significant between 160 and 250 Hz and 160 and 315 Hz for vertical vibration (Wilcoxon, $p < 0.05$). There was no significant difference in the rate of growth between 250 and 315 Hz in any of the three axes. No combinations of exponents for two frequencies showed a significant increase in the rate of growth with increasing frequency. Other studies have found little evidence of a frequency-dependence in the exponent within the frequency range from 16 to 80 Hz, but no study has investigated exponents for whole-body vibration at frequencies greater than 80 Hz. Miwa [15] determined the exponent for vertical and horizontal vibration at 5, 20, and 60 Hz and found no difference between the frequencies. Jones and Saunders [16] also found no significant difference in the exponent for vertical vibration in the frequency range 5–80 Hz, although the mean exponents showed a slight decrease with increasing frequency from 10 Hz (slope of 0.96) to 80 Hz (slope of 0.9). Howarth and Griffin [11] found relatively high exponent values and no frequency-dependence for either vertical or lateral vibration at frequencies between 16 and 63 Hz, but for lateral vibration there was a tendency for the exponent to increase (from 0.68 to 1.99) with increasing frequency from 4 to 16 Hz. They explained the increase in the slope with frequency as an effect of magnitude rather than frequency: greater slopes may have arisen from lower subjective magnitudes that fell on the steeper section of the curve. The magnitude range employed by Jones and Saunders [16] (0.35–1.41 $\mathrm{ms^{-2}}$ rms from 5 to 80 Hz) and Howarth and Griffin [11] (0.04–0.4 $\mathrm{ms^{-2}}$ rms from 4 to 63 Hz) show little overlap, whereas the present study almost covered both magnitude ranges. The comfort contours determined from the present study were derived from curvilinear regression (Stevens' power law with an additive constant for the threshold), whereas others have employed linear regression (Stevens' power law without a constant representing the threshold). The subjective magnitudes determined by Howarth and Griffin [11] probably fell into the lower section of the curve (where the slope is greater) while the subjective magnitudes determined by Jones and Saunders [16] probably fell into the higher section of the curve (where the slope is reduced). This is consistent with Jones and Saunders finding lower exponents than Howarth and Griffin. A greater mean exponent found by Howarth and Griffin for lateral vibration than vertical vibration at frequencies from 16 to 63 Hz is consistent with the difference between axes found in the present study.

With hand-transmitted vibration, similar to the present study, a progressive decrease in the exponent has been found as the frequency increases from 20 Hz in each of the three axes [13]. At frequencies greater than about 16 Hz, subject judgements of whole-body vibration are unlikely to have been influenced by visual or vestibular stimulation, so it may be speculated that their judgements arose from stimulation of the somatosensory system, which is also responsible for the perception of hand-transmitted vibration. Although different channels of the somatosensory system may be involved in the perception of whole-body vibration and hand-transmitted vibration, the similar trends in the exponents (apart from frequencies greater than 125 Hz) suggests some similarities. An understanding of the frequency-dependence and axis-dependence of the exponent awaits further study.

3.2.2. *Equivalent comfort contours*

Equivalent comfort contours were determined by calculating the vibration acceleration, φ, corresponding to each subjective magnitude, ψ (varying from 25 to 300 in steps of 25, where 100 is equivalent to 1.0 $\mathrm{ms^{-2}}$ rms at 20 Hz for fore-and-aft and lateral vibration, or 0.5 $\mathrm{ms^{-2}}$ rms at 20 Hz for vertical vibration) at each vibration frequency (from 2 to 315 Hz) using Eq. (2) and are shown in Fig. 7. The equivalent comfort contours illustrate the vibration magnitudes required to produce the same strength of sensation across the frequency range. They provide information on which frequencies produced greater discomfort (a lower acceleration at a particular frequency indicates greater discomfort at that frequency).

The overall shapes of the equivalent comfort contours differ between axes of vibration. For horizontal vibration, sensitivity to acceleration is generally greatest at the lowest frequency, 2 Hz, and decreases progressively with increasing frequency. For vertical vibration, sensitivity to acceleration tends to be greatest between approximately 5 and 10 or 20 Hz, with only a gradual decrease in sensitivity as the frequency increases further, although with a more rapid reduction as the frequencies increases above 100 Hz, depending on the magnitude of the vibration. The shapes of the comfort contours obtained in the present study show reasonable agreement with the contours from other studies, particularly at frequencies greater than about 5 Hz [5,6,8,9,16,26,27], notwithstanding the use of different methodologies. The similarity between equivalent

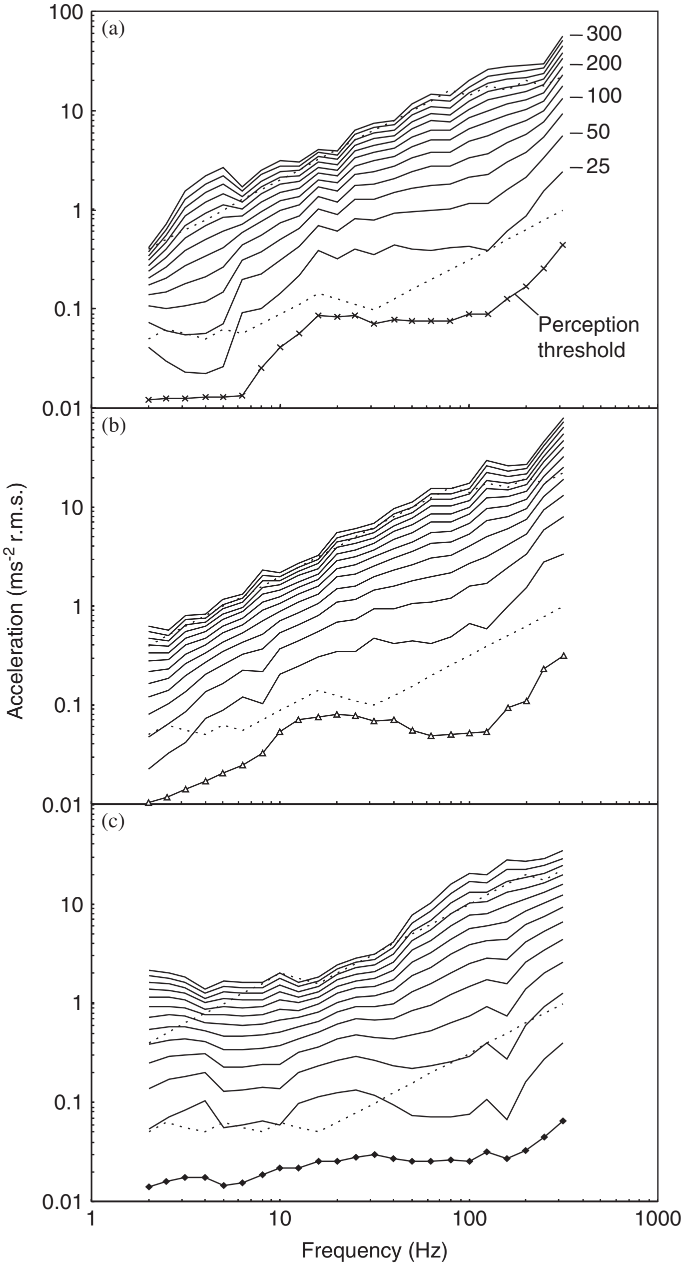

Fig. 7. Equivalent comfort contours for sensation magnitudes from 25 to 300 relative to a vibration magnitude of 1.0 ms^{-2} rms (fore-and-aft and lateral vibration) or 0.5 ms^{-2} rms (vertical vibration) at 20 Hz from Eq. (2): (a) fore-and-aft, (b) lateral, (c) vertical. Median absolute perception threshold contours for each axis as determined in Experiment 1 are also shown (solid line with symbols). Dotted lines indicate the range of stimuli investigated in this study (equivalent comfort contours beyond these lines were determined by extrapolation of the regression lines).

comfort contours in the fore-and-aft and lateral directions in the present study is consistent with the results of Miwa [5] and Griffin et al. [9]. At frequencies less than about 4 Hz, some studies have produced contours with approximately constant acceleration for horizontal vibration, but contours with increased acceleration (i.e. decreased sensitivity) with decreasing frequency for vertical vibration [5,8,9,26,28]. This differs somewhat from the present findings but may be explained by differences in the seating arrangements between studies. The stationary footrests and stationary handles employed in the present study are likely to have increased sensitivity at low frequency due to producing relative movement between the seat and feet and between the seat and hands. Jang and Griffin [29] investigated discomfort caused by phase differences between the seat and the feet in the vertical vibration. It was found that discomfort increased when the phase differences at the seat and the feet increased at frequencies less than about 4 Hz. The effect was greatest at low magnitudes and reflected in greater exponents when the relative motion (caused by phase differences between the seat and the feet) was greatest. The absence of thigh contact with the seat in the present study (due to the small size of the seat) may also have altered sensitivity to low-frequency vibration. Miwa [5] and Griffin et al. [9] employed stationary footrests, while Dupuis et al. [28], Donati et al. [26] and Corbridge and Griffin [8] employed footrests that moved with the seat. None of these studies employed stationary handles, except Dupuis et al. [28] who provided a stationary guide wheel (steering wheel) to support the hands and arms of the subjects.

As a result of the change in the exponent with frequency, the shapes of the equivalent comfort contours depend on vibration magnitude. With increasing sensation magnitude, the comfort contours approximate contours corresponding to constant velocity (i.e. acceleration increasing in proportion to frequency) within the frequency range 2–315 Hz for horizontal vibration and within the frequency range 16–315 Hz for vertical vibration. With decreasing sensation magnitudes, the contours become similar to the absolute perception thresholds. This is particularly notable at frequencies greater than about 20 Hz where the frequency-dependence of sensitivity to vibration changes from approximately constant velocity at high magnitudes to, very roughly, constant acceleration at low magnitudes. This magnitude-dependence changes the relative discomfort produced by stimuli. For example, 4 ms^{-2} rms fore-and-aft vibration produced more than double of strength of sensation at 20 Hz than at 100 Hz, whereas 0.4 ms^{-2} rms, fore-and-aft vibration produced a similar strength of sensation at 20 and 100 Hz. The magnitude-dependence of the contours is less pronounced with lateral vibration than with the other two axes of vibration.

Few studies have determined equivalent comfort contours for low magnitudes of vibration. Howarth and Griffin [11] determined contours from power functions for vertical and lateral vibration at magnitudes between 0.04 and 0.4 ms^{-2} rms within the frequency range 4–63 Hz and Bellmann et al. [12] determined equivalent comfort contours for vertical vibration of magnitudes between 0.03 to 0.32 ms^{-2} rms within the frequency range 12.5–63 Hz. The comfort contours determined by Howarth and Griffin [11] and Bellmann et al. [12] are similar to those in the present study at similar magnitudes, and confirm the 'flattening' of comfort contours at low magnitudes of whole-body vibration.

4. General discussion

In each of the three axes, the perception threshold contours and the equivalent comfort contours indicate that sensitivity to whole-body vibration is highly dependent on vibration frequency. This confirms the need for some means of taking account of changes in sensitivity with frequency (e.g., a frequency weighting). British Standard 6841 [30] advocates the use of frequency weighting W_d for the evaluation of x- and y-axis whole-body vibration and frequency weighting W_b for the evaluation of z-axis whole-body vibration. The W_d frequency weighting for horizontal acceleration is independent of frequency (a slope of 0 dB per octave) between 0.5 and 2 Hz, and inversely proportional to frequency (i.e., −6 dB per octave) between 2 and 80 Hz, indicating greatest sensitivity to acceleration at frequencies between 0.5 and 2 Hz [30]. The W_b frequency weighting for vertical acceleration is independent of frequency (0 dB per octave) between 0.5 and 2 Hz, increases in proportion to frequency (+6 dB per octave) between 2 and 5 Hz, independent of frequency (0 dB per octave) between 5 and 16 Hz, and decreases inversely proportional to frequency (−6 dB per octave) between 16 and 80 Hz, indicating greatest sensitivity to acceleration at frequencies between 5 and 16 Hz [30]. The W_d and W_b frequency weightings were derived from equivalent comfort contours determined by Griffin et al. [10] over the frequency range 1–100 Hz and by Corbridge and Griffin [8] over the range 0.5–5 Hz.

The equivalent comfort contours for fore-and-aft and lateral vibration determined in Experiment 2 have been inverted and normalised to have a value of unity at 2 Hz and overlaid with the W_d frequency weighting (Fig. 8). The equivalent comfort contours for vertical vibration have been similarly inverted and normalised to have a value of unity at 5 Hz and overlaid with the W_b frequency weighting (Fig. 8). Both weightings have been extrapolated to frequencies greater than 80 Hz. The frequency weightings implied by the present results are in broad agreement with the appropriate frequency weighting in the standard (i.e., W_d or W_b), although

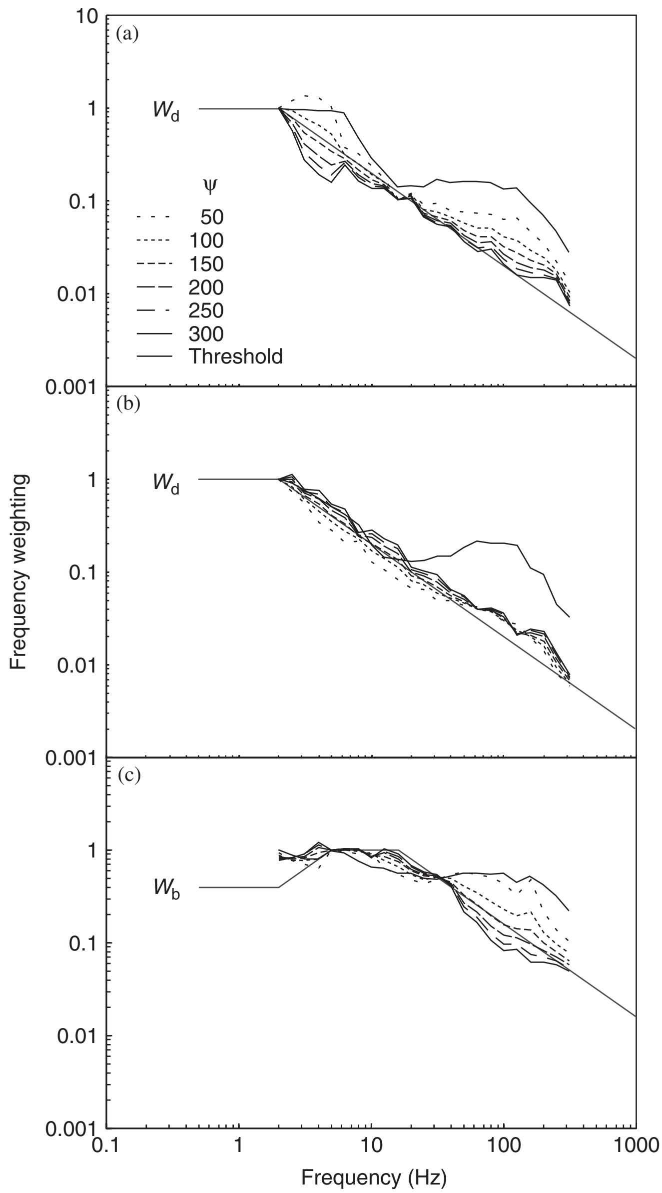

Fig. 8. Effect of vibration magnitude on frequency weightings (inverted equivalent comfort contours normalised at 2 Hz for fore-and-aft and lateral vibration and normalised at 5 Hz for vertical vibration): (a) fore-and-aft, (b) lateral, (c) vertical. A sensation magnitude of 100 is equivalent to the discomfort produced by 1.0 ms^{-2} rms (fore-and-aft and lateral vibration) or 0.5 ms^{-2} rms (vertical vibration) at 20 Hz. The results are compared with the frequency weightings from BS 6841 [30]. ············: 50, ······: 100, ----: 150, — —: 200, — · —: 250, ——: 300, ——: threshold.

there is a tendency for the standardised frequency weightings to underestimate discomfort at frequencies greater than about 30 Hz (or, conversely, the frequency weightings W_d or W_b overestimate the sensations caused by the lower frequencies).

International Standard 2631 [31] uses frequency weighting W_k for the evaluation of some types of vertical vibration—weighting W_k was based on the preference of some committee members rather than experimental evidence. If frequency weighting W_k were used for evaluating vertical vibration at the seat, the underestimate of human sensitivity at higher frequencies is greater than when using frequency weighting W_b—consistent with the widespread use of W_b for predicting comfort in the automotive and rail industries (e.g. ISO 2631-4 [32]).

Moreover, the underestimate of human sensitivity to high-frequency vibration is greater at lower sensation magnitudes (i.e. vibration magnitudes closer to perception thresholds). For vertical vibration at frequencies less than 5 Hz, the present results differ from the W_b frequency weighting, but this may be explained by the relative movement between the seat and the feet arising from the use of a stationary footrest: decreased sensitivity to vertical vibration is expected if the relative movement between the seat and feet was reduced by the seat and the feet having the same vertical movement.

For assessing the health effects of whole-body vibration, the current EU Physical Agents Directive [1] for vibration defines an 'exposure limit value' and 'exposure action value', corresponding to 0.5 and 1.15 ms^{-2} rms for 8 h daily exposures expressed as root-mean-square (rms) or vibration dose value (VDV). With both methods (i.e. rms and VDV), the exposure limit value and exposure action value increase with reductions in the daily exposure duration. For 10 min exposures, the rms exposure action value and the rms limit value are 3.5 and 8.0 ms^{-2} rms, respectively, whereas the VDV exposure action value and exposure limit value are 1.3 and 3.1 ms^{-2} rms, respectively. There are only a few studies of equivalent comfort contours at such high vibration magnitudes. Magid et al. [33] determined contours for human tolerance (for a short time, 2 and 3 min) of vertical vibration at frequencies from 3 to 20 Hz. They found greatest sensitivity at frequencies between 4 and 8 Hz corresponding to about 5, 10 and 20 ms^{-2} rms for 3 and 2 minute and short time exposures, respectively. Their contours suggest a relatively high sensitivity to frequencies in the 4–8 Hz range (roughly as in ISO 2631, 1974), compared with the present and other studies with lower magnitudes (about 0.5 and 2.0 ms^{-2} rms) where greatest sensitivity is at frequencies over a broader range of frequencies between about 5 and 16 Hz. The Magid et al. [33] studies suggest that the magnitude-dependence of equivalent comfort contours may occur at magnitudes greater than those studied here.

The magnitude-dependence of the equivalent comfort contours demonstrated in the present results imply that no single linear frequency weighting can provide an accurate prediction of subjective judgements of discomfort caused by whole-body vibration over a range of vibration frequencies and magnitudes from threshold to levels associated discomfort and injury.

The frequency weightings calculated for the three axes of vibration are compared in Fig. 9 for low, medium, and high vibration magnitudes (equivalent to subjective magnitudes of 50, 100, 200, and 300), assuming a unity weighting at 2 Hz for horizontal vibration and a unity weighting at 5 Hz for vertical vibration (as in BSI 6841 [30]). Experiment 2 did not directly investigate the equivalence of vibration discomfort between the three axes, but the weightings as drawn are consistent with equal sensitivity to whole-body horizontal and vertical vibration at 3.15 Hz [30,31]. At any sensation magnitude, vertical vibration will have the greatest weighting among the three axes at frequencies greater than about 4 Hz. There was a similar, although not identical, pattern with perception thresholds for the three axes: at frequencies greater than 10 Hz thresholds determined in Experiment 1 were lower for vertical vibration (Fig. 3).

It seems likely that the variations in subjective judgements with vibration frequency, axis, and magnitude will have been influenced by body dynamics, with greater discomfort arising when there was greater transmission of vibration to the body. Griffin et al. [9] found strong correlations between equivalent comfort contours and seat-to-head transmissibilities for vertical vibration at preferred one-third octave centre frequencies from 1 to 100 Hz. However, the equivalent comfort contours are not a simple reflection of the transmissibility of the body: there was greater discomfort with high frequencies (greater than 10 Hz) than predicted from the reciprocal of the seat-to-head transmissibility.

Increased transmission of vibration to the body is reflected in the apparent mass of the body. When seated on a rigid flat surface with no backrest, the apparent mass of the body shows a first major resonance with vertical excitation at about 5 Hz and a second resonance in the region of 10 Hz [24]. In the fore-and-aft and lateral directions there are resonances at about 1.5 and 3 Hz [25]. The present results show greatest subjective response to vertical vibration around 5–10 Hz and greatest sensitivity to horizontal vibration around 2 Hz, suggesting that the increased discomfort around these frequencies was associated with resonance of the body.

Non linearity in biodynamic responses to vertical vibration have been demonstrated in various studies (e.g. Refs. [24,34,35]), with greater vibration magnitudes producing reductions in the principal resonance frequency of the apparent mass. This non linear biodynamic response may explain the magnitude-dependence of the comfort contours at low frequencies in the present results. Matsumoto and Griffin [36] examined the effect of vibration magnitude on both subjective and biodynamic responses to continuous and transient whole-body

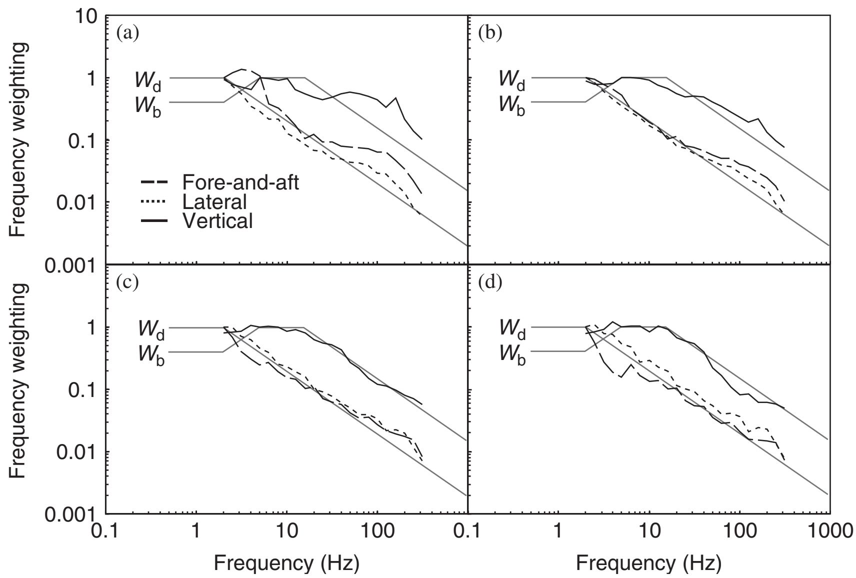

Fig. 9. Effect of axis of vibration excitation on frequency weightings (inverted equivalent of comfort contours normalised at 2 Hz for fore-and-aft and lateral vibration and at 5 Hz for vertical vibration) for sensation magnitudes of: (a) 50, (b) 100, (c) 200 and (d) 300. A sensation magnitude of 100 is the equivalent discomfort produced by 1.0 ms^{-2} rms (fore-and-aft and lateral vibration) or 0.5 ms^{-2} rms (vertical vibration) at 20 Hz. The results are compared with the frequency weightings from BS 6841 [30]. ----: fore-and-aft, ······: lateral, ——: vertical.

vertical vibration in the frequency range 3.15–8.0 Hz at three magnitudes (0.5, 1.0 and 2.0 ms^{-2} rms). With increasing vibration magnitude, they found significant increases in discomfort at 3.15 and 4.0 Hz relative to a reference vibration at 5.0 Hz, with the increases correlated with changes in the mechanical impedance of the body at these frequencies, suggesting the nonlinearities in discomfort were partly caused by the nonlinear dynamic response of the body. The magnitude-dependence of comfort contours at high frequencies (greater than about 30 Hz) cannot currently be explained by this phenomenon.

5. Conclusions

When seated on a rigid surface with no backrest, thresholds for the perception of whole-body vibration in each of the three axes (i.e. fore-and-aft, lateral and vertical) were highly dependent on vibration frequency, but with an overall trend of increasing acceleration thresholds with increasing frequency from 2 to 315 Hz. At frequencies greater than 10 Hz, thresholds for vertical vibration were lower than those for horizontal vibration, whereas at frequencies less than 4 Hz, thresholds for vertical vibration were higher than those for horizontal vibration. Thresholds for fore-and-aft and lateral vibration were similar over the frequency range investigated.

The rates of growth of sensation within each of three axes of vibration (i.e. the exponent in Stevens' Power law when using an additive constant), were also dependent on vibration frequency. With low frequencies of fore-and-aft and vertical vibration, the greatest exponent was obtained around the principal resonance frequency of the body, whereas with high frequencies (16–315 Hz) the dependence of the rate of growth of sensation on vibration frequency was similar to that for hand-transmitted vibration.

Over the frequency range 2–315 Hz, the equivalent comfort contours showed maximum sensitivity to acceleration between 5 and 10 Hz for vertical vibration, and at 2 Hz for both fore-and-aft and lateral vibration. Where comparison is possible, the present contours are consistent with contours obtained in previous studies. However, the present results show a magnitude-dependence in the equivalent comfort contours, particularly with fore-and-aft and vertical vibration. At low vibration magnitudes, the equivalent comfort contours have a similar frequency-dependence to perception thresholds. With increasing vibration magnitude, the equivalent comfort contours approximate to contours of constant velocity within the frequency range 2–315 Hz for horizontal vibration and within the frequency range 16–315 Hz for vertical vibration. The results are consistent with knowledge of biodynamic responses to whole-body vibration.

The frequency weightings derived from the equivalent comfort contours are reasonably consistent with the frequency weightings in current standards (W_b and W_d as in BS6841 [30]), while suggesting more sensitivity at frequencies greater than about 30 Hz. However, the magnitude-dependence in the equivalent comfort contours means that no single linear frequency weighting can provide accurate predictions of subjective judgements of discomfort caused by whole-body vibration.

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