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Magnitude-dependence of equivalent comfort contours for fore-and-aft, lateral, and vertical vibration at the foot for seated persons

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ABSTRACT

Vibration at the feet can contribute to discomfort in many forms of transport and in some buildings. Knowledge of the frequency-dependence of discomfort caused by foot vibration, and how this varies with vibration magnitude, will assist the prediction of discomfort caused by vibration. With groups of 12 seated subjects, this experimental study determined absolute thresholds for the perception of foot vibration and quantified the discomfort caused by vibration at the foot. The study investigated a wide range of magnitudes (from the threshold of perception to levels associated with severe discomfort) over a wide range of frequencies (from 8 to 315 Hz in one-third octave steps) in each of the three orthogonal translational axes (fore-and-aft, lateral, and vertical). The effects of gender and shoes on absolute thresholds for the perception of vertical vibration at the foot were also investigated. Within each of the three axes, the vibration acceleration corresponding to the absolute thresholds for the perception of vibration, and also all contours showing conditions producing equivalent discomfort, were highly frequency-dependent at frequencies greater than about 40 Hz. The acceleration threshold contours were U-shaped at frequencies greater than 80 Hz in all three axes of excitation, suggesting the involvement of the Pacinian channel in vibration perception. At supra-threshold levels, the frequency-dependence of the equivalent comfort contours in each of the three axes was highly dependent on vibration magnitude. With increasing vibration magnitude, the conditions causing similar discomfort across the frequency range approximated towards constant velocity. Thresholds were not greatly affected by wearing shoes or subject gender. The derived frequency weightings imply that no single linear frequency weighting can provide accurate predictions of discomfort caused by a wide range of magnitudes of foot vibration.

1. Introduction

There are many situations in which the feet of the seated human body are exposed to vibration of a floor while there is also vibration at the seat (e.g., in buildings and in transport). Vibration of the feet may contribute to discomfort, annoyance, or interference with activities, with the sensations varying in strength according to the vibration magnitude, the vibration frequency, the direction of vibration, and the contact conditions with the vibrating surface.

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For the evaluation of fore-and-aft, lateral, and vertical vibration at the feet, International Standard 2631-1 [1] uses frequency weighting W_k, while British Standard 6841 [2] uses frequency weighting W_b. The W_b weighting was influenced by experimentally determined equivalent comfort contours at frequencies in the range 2.5–63 Hz for vibration of the feet at only one vibration magnitude, equivalent to 10 Hz vertical seat vibration at 0.8 ms^{-2} rms [3]. There appears to have been no investigation of whether vibration magnitude affects the frequency-dependence of discomfort caused by foot vibration.

It is intuitively obvious that increasing the magnitude of a vibration will increase the strength of sensations produced by the vibration. The relation between the physical magnitude of vibration stimuli and the consequent sensations can be expressed by Stevens' power law [4]

$$\psi = k\phi^n \tag{1}$$

where k is a constant and the exponent n describes the rate of growth of sensation, ψ, with increases in the vibration magnitude, φ. The exponent for each frequency determines the increase in vibration magnitude needed to increase the sensation by a given amount at that frequency. A frequency-dependence in the exponent indicates that the rate of growth of sensation varies with frequency, and means that the shapes of equivalent comfort contours will depend on the vibration magnitude.

The power law is sometimes written with an additive constant, $\varphi_{0,}$ representing the threshold of perception [5], 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 low magnitudes of hand-transmitted vibration [6].

Similar to the hand, the detection of vibration at the foot is thought to be mediated by four types of tactile receptor (Pacinian, NP I, NP II, and NP III channels), although the distribution and response of these receptors over the foot sole differs from their distribution and response over the glabrous skin of the hand [7]. Vibrotactile thresholds have been measured at specific locations on the foot [8–12]. The frequency-dependence of thresholds for the perception of vibration at the fingertip differs from that for the whole hand [13], so it may be expected that thresholds for the entire foot will differ from those determined at specific locations on the sole of the foot.

Investigations of gender differences in vibrotactile thresholds at the foot have tended to find that females are more sensitive to vibration than males in non-neuropathic populations (e.g., [14,15]) and in diabetic populations e.g., [16,17], although some studies have not found significant effects of gender (e.g., [9,18,19]). Vibration of a floor is usually experienced while wearing footwear (e.g., shoes) that might be expected to influence how vibration is perceived. There have been various studies of the dynamics of shoes, especially in the context of running shoes (e.g., [20,21]), but there is no known study of the effect of footwear on the perception of a foot resting on a vibrating surface.

This study was primarily designed to examine the effect of vibration magnitude (from the threshold of perception to magnitudes associated with discomfort and risks to health) on equivalent comfort contours for seated persons exposed to vibration at the foot in each of the three axes (fore-and-aft, lateral, and vertical axes) over the frequency range 8–315 Hz. It was hypothesised that, within each of the three axes, the frequency-dependence of vibration discomfort experienced at the foot would vary with vibration magnitude. Two experiments were conducted. Experiment 1a determined absolute thresholds for the perception of vibration at the foot in each of the three axes, while Experiment 1b examined the effect of footwear and gender on absolute thresholds for the perception of vertical foot vibration. Experiment 2 determined equivalent comfort contours for each of the three axes of foot vibration. The threshold contours were used in the determination of the equivalent comfort contours developed in Experiment 2 and are also compared with the frequency-dependence of the equivalent comfort contours.

2. Experiment 1: absolute thresholds

2.1. Method

2.1.1. Subjects

Three groups of 12 male subjects (Groups A, B, and C) participated in Experiment 1a, with one group for each axis of vibration. Two different groups of 12 subjects (Groups D and E) participated in Experiment 1b: Group D consisted of male subjects and Group E consisted of female subjects. All five groups of subjects (i.e., a total of 60 subjects) were aged between 19 and 30 years and were students or office workers with no history of occupational exposure to vibration. The characteristics of the subjects in each group are shown in Table 1. There were no significant differences in age between the five groups (Kruskal–Wallis, p=0.63) and there were no significant differences in weight or body stature between the four groups of males (Kruskal–Wallis, $p > 0.1$). The female group (i.e., Group E) had significantly less body weight and shorter body stature than the groups of males (i.e., Groups A, B, C, and D) (Mann–Whitney, $p < 0.01$).

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.

Table 1
Characteristics of five subject groups (12 subjects in each group). Medians (inter-quartile ranges).

Experiment	Subject group	Vibration axis	Gender	Age (year)	Weight (kg)	Stature (cm)	Foot length (cm)	Foot width (cm)
Experiment 1a	A	Fore-and-aft	Male	25.5 (3.3)	68.0 (13.0)	179.5 (5.8)	26.8 (2.1)	9.7 (0.9)
	B	Lateral	Male	24.0 (3.3)	69.5 (9.3)	179.5 (2.9)	27.5 (1.9)	9.9 (0.8)
	C	Vertical	Male	24.5 (4.0)	74.5 (9.0)	178.0 (4.8)	27.8 (1.3)	10.3 (0.3)
Experiment 1b	D	Vertical	Male	23.0 (3.5)	70.0 (7.8)	178.0 (4.0)	26.5 (1.3)	9.4 (0.5)
	E	Vertical	Female	22.0 (4.5)	57.0 (8.0)	165.0 (6.5)	24.0 (0.8)	8.7 (0.5)
Experiment 2	A	Fore-and-aft	Male	25.5 (3.3)	68.0 (13.0)	179.5 (5.8)	26.8 (2.1)	9.7 (0.9)
	B	Lateral	Male	24.0 (3.3)	69.5 (9.3)	179.5 (2.9)	27.5 (1.9)	9.9 (0.8)
	D	Vertical	Male	23.0 (3.5)	70.0 (7.8)	178.0 (4.0)	26.5 (1.3)	9.4 (0.5)

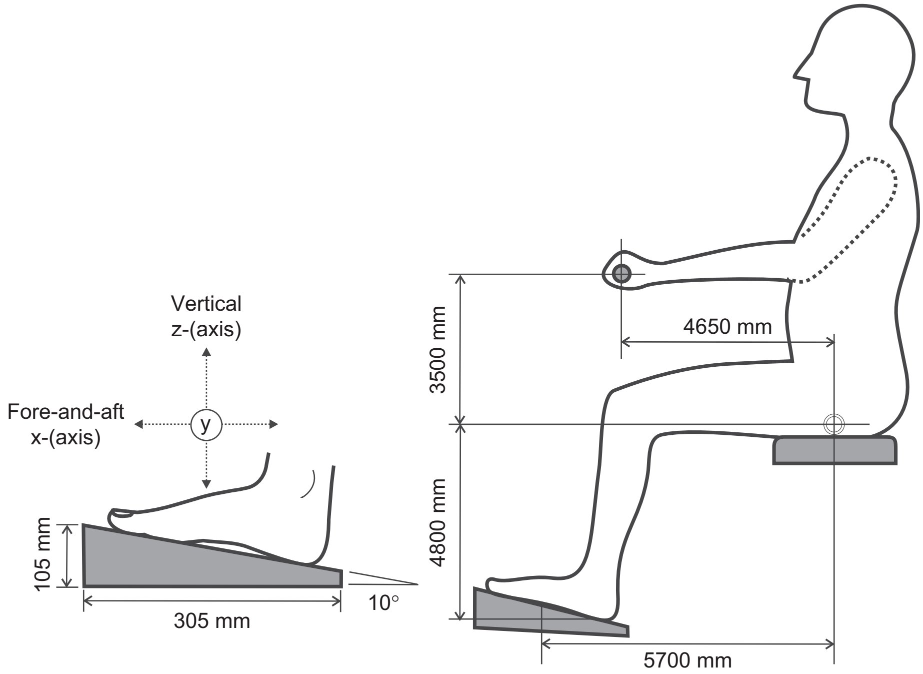

Fig. 1. The rigid footrest and foot posture. The subjects adopted a seated posture (not to scale). The vertical axis is aligned with gravity. The lateral axis is aligned with the coronal plane. Vibration stimuli were presented at the left foot only.

2.1.2. Apparatus

The subjects were seated on a stationary contoured wooden seat (250 × 50 mm) with their hands supported by two stationary cylindrical handles (100 mm length and 30 mm diameter) and their feet supported on two wooden footrests (30.5 × 10.5 mm with 10° inclination). One of the wooden footrests (for the left foot) was mounted rigidly via a metal plate to a vibrator system that varied according to the axis of excitation. Fore-and-aft and lateral vibration were produced by a trunnion-mounted electrodynamic vibrator (Derritron, VP75) that was connected to a slip table (Kimball Industries Inc., type 3089). Vertical vibration was produced by a different electrodynamic vibrator (Derritron, VP30). Fig. 1 shows a schematic diagram of the footrest and the foot posture.

With all stimuli, the cross-axis accelerations were less than 5% of the acceleration in the desired axis. Background vibration, mainly due to electrical noise at 50 Hz, was less than 0.008 $\mathrm{m\,s^{-2}}$ rms, and was not perceptible via the footrest.

The subjects were exposed to vibration at only one of their two feet (i.e., the left foot). For the non-exposed right foot, a stationary footrest with the same dimensions as the vibrating footrest was provided. The same body posture was adopted for all five groups of subjects.

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.

2.1.3. Procedure

In Experiment 1a, each of the three groups (Groups A, B, and C) took part in a 1 h session to determine perception thresholds for sinusoidal vibration of the left foot with either fore-and-aft, lateral or vertical excitation at the 17 preferred one-third octave centre frequencies between 8 and 315 Hz. Subjects wore normal clothes (without jackets or coats) and thin socks but no shoes. Their trousers were rolled up to the knee level so as to minimise any sensation due to movement of the trousers. In Experiment 1b, each of the two groups (Groups D and E) took part in two sessions on separate days to determine perception thresholds of the left foot for sinusoidal vertical vibration at the six preferred octave centre frequencies between 8 and 250 Hz: one session with a pair of shoes (also with socks) and another session with socks (without shoes). The order of the two sessions was balanced across subjects. The effect of shoes was examined only with vertical vibration because it was found in Experiment 1a that the foot was generally more sensitive to vertical vibration than horizontal (fore-and-aft or lateral) vibration over the frequency range investigated, and because vertical vibration is more common and any effect of shoes was expected to be more likely to occur with vertical vibration. The subjects in Groups D and E were individually provided with shoes that were identical apart from their size. The shoes were selected from a stock of nine different shoe sizes (from $4\frac{1}{2}$ to $11\frac{1}{2}$ in UK size) so as to fit their feet. The shoes were made of leather (outside) and man-made materials (inside) with rubber soles (17 mm thick at the front and 30 mm thick at the heel). The shoes had laces and covers to ankle level (130–170 mm in height in addition to the heel height).

The subjects were instructed to sit upright with comfortable postures with their eyes open and look straight ahead and with their hands on the stationary handles and their feet on the 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. All thresholds were determined for vibration of the left foot. Prior to the threshold tests, the skin temperature of the left foot was measured by means of a thermocouple placed between the foot and the wooden footrest. The threshold tests proceeded if the skin temperature was greater than 29 °C. The room temperature was maintained with the range 23 ± 2 °C.

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 (including 0.5 s cosine-tapered ends), 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 (25.9% 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 [22]. The order of presenting the test frequencies was randomized.

The experimental conditions for Experiments 1a and 1b are summarised in Table 2.

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 (25th to 75th percentiles) over the 12 subjects were determined at each frequency in each axis, and are shown in Fig. 2. There was no frequency-dependence in the acceleration

Table 2
Experimental conditions for Experiments 1a, 1b, and 2.

	Experiment 1a	Experiment 1b	Experiment 2
Axis	Fore-and-aft, lateral, and vertical	Vertical	Fore-and-aft, lateral, and vertical
Frequency (Hz)	8, 10, 12.5, 16, 20, 25, 31.5, 40, 50, 63, 80, 100, 125, 160, 200, 250, 315	8, 16, 31.5, 63, 125, 250	8, 10, 12.5, 16, 20, 25, 31.5, 40, 50, 63, 80, 100, 125, 160, 200, 250, 315
Duration of stimulus	2 s		
Psychophysical method	Staircase method (three-down one-up rule) with ‘yes–no’ procedure		Method of magnitude estimation
Gender	Male	Male and female	Male
Footwear	Without shoes	Without shoes and with shoes	Without shoes

perception thresholds at low frequencies: from 8 to 25 Hz with fore-and-aft excitation (Friedman p=0.267) or vertical excitation (Friedman, p=0.119), or from 8 to 40 Hz with lateral excitation (Friedman, p=0.353). A frequency-dependence of the acceleration thresholds was apparent at high frequencies, presenting slight U-shaped contours with greatest sensitivity to acceleration at about 100 Hz then a significant increase in the acceleration thresholds with each one-third octave step from 125 to 315 Hz with fore-and-aft and lateral excitation (Wilcoxon, $p < 0.01$) and with each one-third octave step from 200 to 315 Hz with vertical excitation (Wilcoxon $p < 0.01$). There were no systematic correlations between age and any of the measured thresholds.

The U-shaped acceleration threshold contours for all three axes of excitation at frequencies greater than 80 Hz (see Fig. 2) suggest the involvement of the Pacinian channel in the mediation of perception of vibration at the foot, as found in studies of absolute thresholds at the palm of the whole hand [6,23–24]. The perception thresholds for the foot determined in Experiment 1a have been compared with perception thresholds for the hand and the seat in Morioka and Griffin [25]; it was suggested that the thresholds at the hand, the foot, and the seat at frequencies greater than 80 Hz were mediated by the same psychophysical channel.

2.2.2. Thresholds between axes (effect of axis)

The thresholds differed significantly between the three axes of excitation (Kruskal–Wallis, $p < 0.05$) except at 63 and 80 Hz. At frequencies less than 50 Hz, the foot was most sensitive to vertical vibration: vertical thresholds were significantly lower than the lateral thresholds (Mann–Whitney, $p < 0.01$) and the fore-and-aft thresholds (Mann–Whitney, $p < 0.05$) except at 25 and 50 Hz (Mann–Whiney, $p > 0.05$). There were no differences between the lateral and the

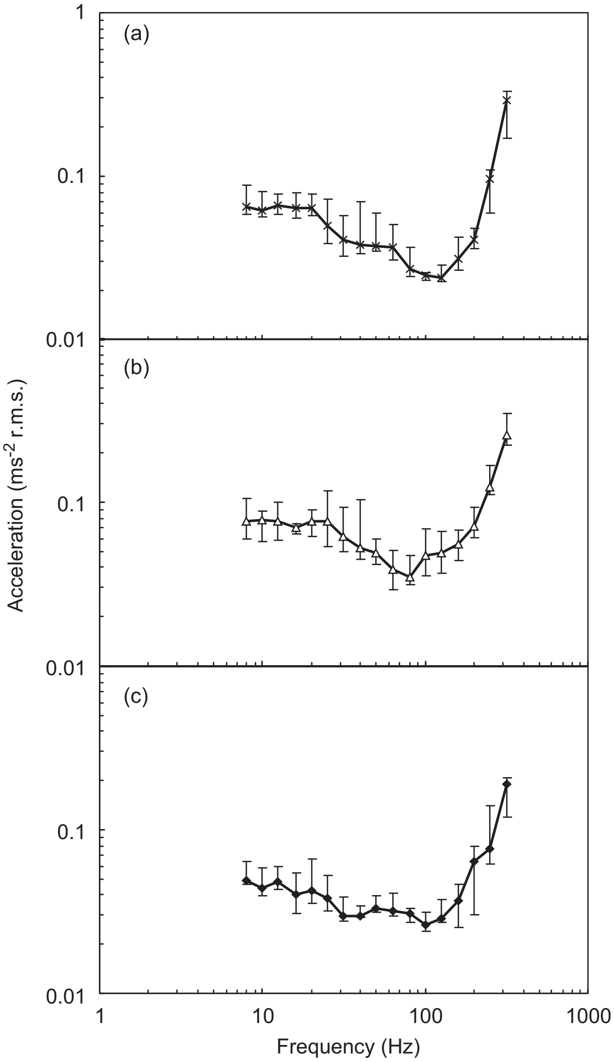

Fig. 2. Median absolute perception thresholds between 8 and 315 Hz: (a) fore-and-aft, (b) lateral, and (c) vertical. Error bars represent inter-quartile range.

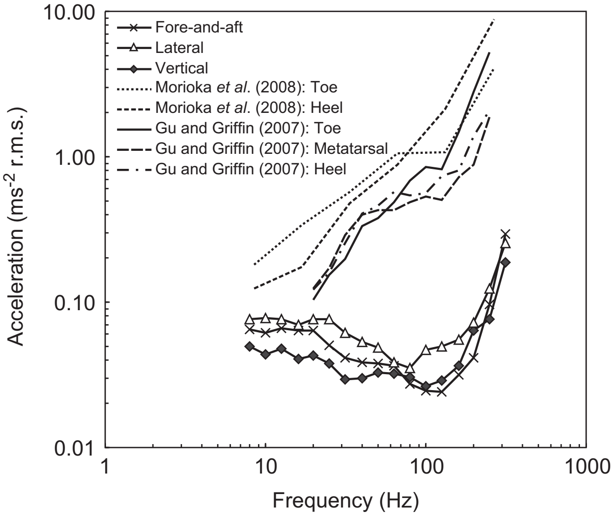

Fig. 3. Comparison of median perception threshold contours between the three axes. ×: fore-and-aft, △: lateral, ◆: vertical. The results were overlaid with median threshold contours from other studies using 6 mm diameter probe with a 2 mm gap.

fore-and-aft thresholds at frequencies less than 50 Hz (Mann–Whitney, $p > 0.05$), except at 31.5 Hz (Mann–Whitney, $p = 0.045$). At frequencies greater than 80 Hz, the foot was the least sensitive to lateral vibration: thresholds for lateral vibration were significantly higher than those for fore-and-aft vibration (Mann–Whitney, $p < 0.05$) except at 80 and 315 Hz (Mann–Whitney, $p > 0.1$) and higher than those for vertical vibration (Mann–Whitney, $p < 0.05$) except at 200 Hz (Mann–Whitney, $p = 0.16$). There were no significant differences between fore-and-aft and vertical thresholds at frequencies greater than 63 Hz (Mann–Whitney, $p > 0.1$). Greater sensitivity of the feet to vertical vibration than horizontal vibration has previously been reported by Parsons et al. [3] who determined equivalent comfort contours for the feet equivalent to vertical vibration of the seat at 0.8 ms^{-2} rms of 10 Hz.

The present thresholds for vibration of the entire foot can be compared with vibrotactile thresholds measured at specific locations over the sole of the foot. Gu and Griffin [11] determined vibrotactile thresholds at the big toe, the ball of the foot (between the first and second metatarsal bones), and the heel over the frequency range 20–250 Hz. Morioka et al. [12] compared vibrotactile thresholds at four body locations (i.e. the fingertip, volar forearm, large toe and heel) over the frequency range 8–250 Hz with two contact conditions. These two studies employed a 6 mm diameter vibrating probe with a 2 mm gap and the von Békésy method for determining thresholds. The median thresholds are compared with the present results in Fig. 3. It is evident that absolute thresholds of the whole foot (present results) are much lower thresholds than thresholds determined at small areas of the foot, particularly at frequencies greater than about 20 Hz. The greatly increased sensitivity to vibration when exposed to vibration of the whole foot may be partially explained by spatial summation [26]: thresholds mediated by the Pacinian channel are lower with larger areas of stimulation.

The use of different psychophysical methods may also have contributed to the lower thresholds in the present study. According to Morioka and Griffin [27], the von Békésy method ('yes–no' method with continuous stimulation) is likely to produce higher thresholds than the 'yes–no' method with intermittent stimulation employed in the present study.

2.2.3. *Effect of gender on thresholds*

Fig. 4 (top graphs) shows the effect of gender on median absolute acceleration thresholds (and the inter-quartile ranges) for vertical excitation with and without shoes. With shoes, the males tended to produce lower thresholds than the females, but with the difference statistically significant only at 31.5 Hz (Mann–Whitney, $p = 0.039$). When barefoot, the males seemed more sensitive to vertical vibration (i.e., had lower thresholds) than the females at 125 Hz (Mann–Whitney, $p = 0.02$), whereas the females were more sensitive than the males at 8 Hz (Mann–Whitney, $p = 0.002$). It has been suggested that the effect of gender on thresholds may be confounded by the effect of stature—there is evidence of lower thresholds in smaller persons and Bergenheim et al. [16] and Maser et al. [17] have reported that gender differences disappear when sensory thresholds are adjusted for stature. The present results show the opposite trends for the effect of gender at 8 and 125 Hz (without shoes), suggesting the shorter stature of females could not fully explain their higher thresholds, particularly those at 125 Hz. The lower thresholds at the higher frequencies in males would be consistent with a greater pressure at the feet with the heavier males increasing their sensitivity relative to the lighter females—increased pressure at the point of contact with vibration tends to reduce Pacinian thresholds (e.g., [28,29]).

2.2.4. *Effect of footwear on thresholds*

Acceleration thresholds are compared with and without shoes in Fig. 4 (bottom graphs). Perception thresholds were not affected by wearing shoes at any frequency except at 63 Hz in the males (Group D) and at 250 Hz in the females (Group E)

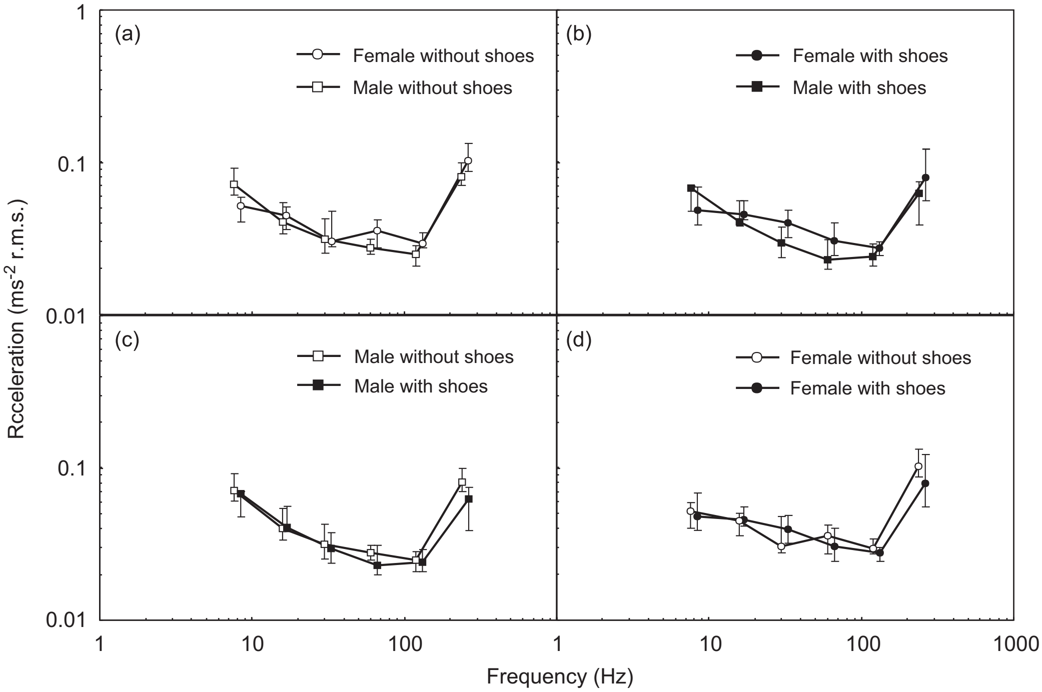

Fig. 4. Effect of gender and footwear on absolute perception thresholds. Median data with inter-quartile range. (a) Without shoes, (b) with shoes, (c) male, and (d) female.

where the thresholds were slightly lower when wearing boots (Wilcoxon, $p < 0.05$). Any increased sensitivity when wearing shoes might be attributed to increased area of contact with vibration (contact via the upper part of the foot as well as the sole), reducing thresholds mediated via the Pacinian channel due to spatial summation (e.g. [26]).

3. Experiment 2: equivalent comfort contours

3.1. Method

3.1.1. Subjects

Three groups of male subjects (Groups A, B, and D) participated in Experiment 2, with one group for each axis of vibration (i.e., fore-and-aft, lateral, or vertical excitation, respectively). The subjects who participated in Experiment 1a 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 method, were the same as employed in Experiment 1.

3.1.3. Procedure

Subjects adopted the same sitting posture as specified for Experiment 1. The subjects judged the discomfort caused by sinusoidal vibration of the left foot (without shoes but with socks) with each of the three axes of excitation (fore-and-aft, lateral, and vertical) at the 17 preferred one-third octave centre frequencies between 8 and 315 Hz. The stimuli lasted 2.0 s, including 0.5 s cosine-tapered ends. The motions varied in velocity from 0.002 to 0.126 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 were determined by preliminary experimentation and are shown in Fig. 6.

The method of magnitude estimation [4] was employed to determine judgements of discomfort caused by the vibration. Pairs of motions, a 2 s reference motion followed by a 2 s test motion, were presented with a 1.0 s interval. The reference motion was fixed with a frequency of 50 Hz and a magnitude of 5.0 ms^{-2} rms The reference motion and the test motion had the same direction of excitation (i.e., either fore-and-aft, lateral, or vertical). 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’. For each subject, 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 judgement. They were instructed to indicate ‘no sensation’ if the test stimulus was not perceived. A small cue light was illuminated during the presentation periods of both the reference stimulus and the test stimulus.

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. Every subject received all the vibration stimuli in one axis of excitation during a single session lasting approximately one hour, with short breaks every 30 to 35 pairs.

A few stimuli at low magnitudes were not perceived by all subjects. Any stimulus not felt by a subject was excluded from the analysis of that 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. To investigate the overall 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. To investigate the trends in the rates of growth of sensation between the axes of excitation, Mann–Whitney test was applied for independent measures.

3.2. Results and discussion

3.2.1. Growth of sensation

For each frequency of vibration and axis of excitation, the relationships between the vibration magnitudes, φ, and the corresponding sensation magnitudes of each of the 12 subjects, 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 of the same subjects for the appropriate frequency and direction of excitation as determined in Experiment 1a. Linear regression was performed at each frequency after transforming Eq. (2) to

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

This technique has been employed in previous studies (e.g., [6]) where it was shown that the coefficient of determination, R^2, obtained using the power law with the additive constant is mostly higher than determined using Stevens’ power law without the additive constant.

For each of the three axes of excitation, the median rates of growth of sensation, *n*, determined using Stevens’ power law with an additive constant (Eq. (2)) are shown in Fig. 5. Within each axis, the rate of growth of sensation varied with the frequency of vibration (Friedman, $p<0.001$). With fore-and-aft vibration, the exponent values (rates of growth of sensation) did not change significantly between any combination of frequencies over the ranges 8–40 Hz or 40–315 Hz (Friedman, $p>0.05$), but exponents at frequencies greater than 40 Hz were significantly lower than exponents at frequencies less than 40 Hz (Wilcoxon, $p<0.05$). With lateral vibration, the exponent values were independent of frequency over the ranges 8–20 Hz and 63–315 Hz (Friedman, $p>0.05$). With vertical vibration, the exponent values were independent of frequency over the ranges 8–12.5 Hz and 16–315 Hz (Friedman, $p>0.05$), with exponents at frequencies greater than 20 Hz significantly lower than those at frequencies less than 20 Hz (Wilcoxon, $p<0.05$). Kitazaki [30] reported driving point apparent masses of the foot of seated subjects in response to vertical vibration with primary resonance frequencies around 7–15 Hz, coinciding with the frequencies having the three highest exponents for vertical vibration (i.e., 8, 10, and 12.5 Hz). Shoenberger and Harris [31] and Morioka and Griffin [32] found greater exponents at resonance

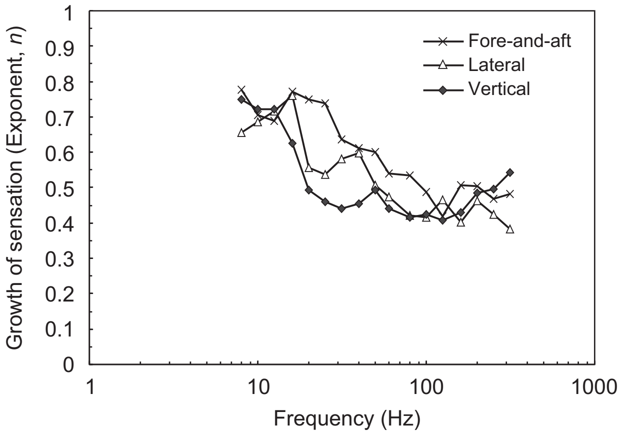

Fig. 5. Rates of growth of sensation (median exponent, *n*, from 12 subjects) as a function of vibration frequency from 8 to 315 Hz for three directions (determined with Eq. (2)). × : fore-and-aft, △: lateral, and ◆: vertical.

frequencies for whole-body vibration, but the reason for any association between the rate of growth of sensation and resonances frequencies is not yet clear. Between the three axes, the rates of growth of sensation with vertical excitation were less than those for fore-and-aft excitation at frequencies between 20 and 31.5 Hz (Mann–Whitney, $p<0.01$) and less than that for lateral excitation at 16 Hz (Mann–Whitney, $p=0.02$). There were no significant differences in the rates of growth of sensation between fore-and-aft and lateral excitation. There were no systematic associations between the rates of growth (i.e. the exponents) and the anthropometric characteristics of the subjects.

3.2.2. Equivalent comfort contours

Equivalent comfort contours were determined by calculating the vibration acceleration, φ , corresponding to the subjective magnitude, ψ (varying from 25 to 300 in steps of 25, where 100 is equivalent to sensation caused by 5.0 ms^{-2} rms at 50 Hz in the same axis) at each vibration frequency (from 8 to 315 Hz) using Eq. (2) (see Fig. 6). The corresponding median exponents (n), constants (k), and thresholds (φ_0) used to create equivalent comfort contours are shown in Table 3. The equivalent comfort contours illustrate the vibration magnitudes required to produce the same strength of sensation across the frequency range. Each contour provides information on which frequencies produced greater discomfort (a lower acceleration at a particular frequency indicates that greater discomfort is caused by acceleration at that frequency).

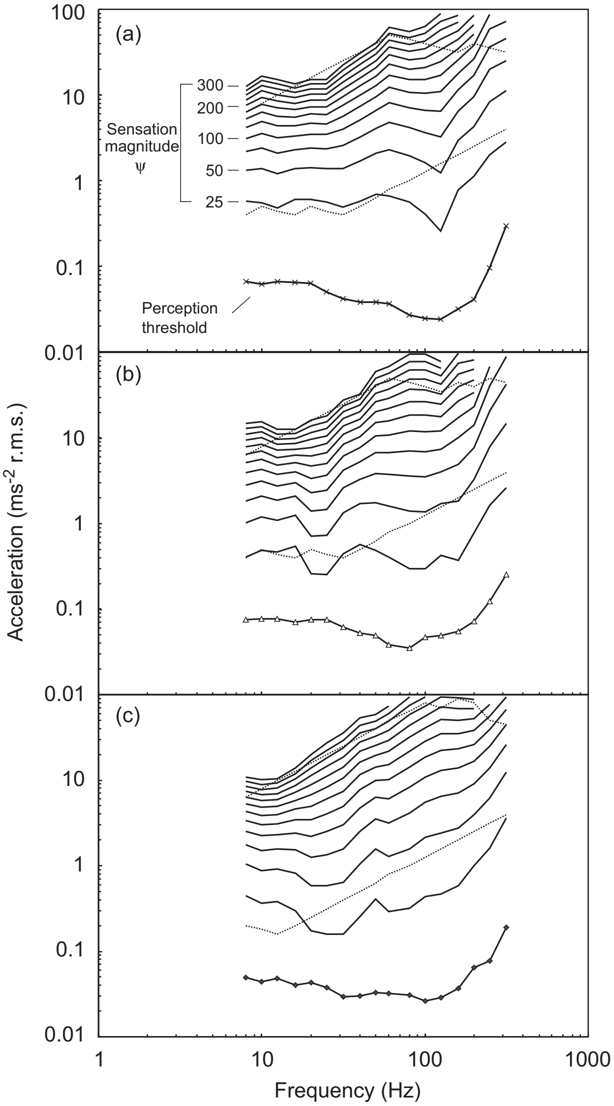

Fig. 6. Equivalent comfort contours for sensation magnitudes from 25 to 300 relative to a vibration magnitude of 5.0 ms^{-2} rms at 50 Hz from Eq. (2): (a) fore-and-aft, (b) lateral, and (c) vertical. Median absolute perception threshold contours for each axis as determined in the Experiment 1a are also 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).

Table 3
Median exponents (n), constants (k), and thresholds (φ_0) for each of three axes (x=fore-and-aft, y=lateral, and z=vertical).

	Stevens’ power law with additive constant, Eq. (2)								
	Exponent (*n*)			**Constant (*k*)**			**Threshold (φ_0)**		
Frequency	***x***	***y***	***z***	***x***	***y***	***z***	***x***	***y***	***z***
8	0.776	0.657	0.750	42.044	51.558	50.489	0.065	0.076	0.049
10	0.704	0.686	0.722	41.448	46.206	57.016	0.062	0.077	0.044
12.5	0.689	0.715	0.722	45.941	49.329	55.796	0.066	0.077	0.048
16	0.771	0.762	0.626	40.458	43.752	58.318	0.064	0.070	0.040
20	0.748	0.555	0.494	39.701	64.417	68.187	0.064	0.076	0.043
25	0.738	0.538	0.459	40.747	63.052	66.176	0.050	0.076	0.038
31.5	0.637	0.582	0.441	41.677	43.471	62.001	0.041	0.061	0.030
40	0.613	0.599	0.455	36.821	37.042	49.442	0.038	0.053	0.030
50	0.601	0.506	0.493	32.389	38.063	40.626	0.038	0.049	0.033
63	0.540	0.475	0.440	32.389	40.300	45.352	0.037	0.039	0.032
80	0.536	0.420	0.415	35.132	43.944	41.812	0.027	0.035	0.031
100	0.487	0.417	0.425	39.994	44.648	36.358	0.025	0.047	0.026
125	0.417	0.466	0.409	46.100	39.418	35.067	0.024	0.049	0.029
160	0.506	0.402	0.429	29.147	39.710	32.554	0.031	0.055	0.037
200	0.503	0.464	0.484	24.160	29.161	25.876	0.041	0.072	0.064
250	0.469	0.423	0.496	18.535	20.946	20.319	0.096	0.124	0.077
315	0.481	0.382	0.542	15.922	17.989	12.853	0.292	0.256	0.189

As it can be seen in Fig. 6, within each axis the overall shapes of the equivalent comfort contours depended on vibration magnitude, except for low frequencies where the equivalent comfort contours at frequencies less than about 30 Hz for the fore-and-aft, and lateral axes, and less than about 16 Hz for the vertical axis, are relatively independent of vibration magnitude. At higher frequencies, the equivalent comfort contours tended towards contours with constant velocity (i.e. acceleration increasing in proportion to frequency) as the sensation magnitude increased. As expected, the contours tend towards the absolute perception threshold as the sensation magnitudes decrease. The shapes of the equivalent comfort contours for fore-and-aft and lateral vibration were similar, except for increased sensitivity to low magnitudes of lateral acceleration (less than 3 $\mathrm{ms^{-2}}$ rms) between 20 and 31.5 Hz.

The shapes of the comfort contours obtained in the present study show reasonable agreement with the contours determined by Parsons et al. [3] when compared at similar levels of acceleration (Fig. 7). With fore-and-aft vibration at low frequencies (less than 20 Hz, the present equivalent comfort contours show constant acceleration (flat response to acceleration) whereas those determined by Parsons et al. [3] show decreased sensitivity to acceleration with decreasing frequency from 16 to 4 Hz. The increased sensitivity at low frequency fore-and-aft excitation in the present study may have arisen from different foot postures (the present study employed a footrest with 10° inclination, whereas Parsons et al. employed a flat footrest). Fore-and-aft vibration of the foot on the inclined footrest would have transmitted some vibration to the knee and thigh, which may have increased sensitivity to vibration.

Miwa [33] determined an equivalent comfort contour for vertical acceleration of the left foot at frequencies in the range 8–400 Hz and found a flat contour between 8 and 16 Hz that increased steeply with increasing frequency (by 12 dB per octave) at frequencies greater than 16 Hz, differing from the present study where the slope is only about 6 dB per octave above 16 Hz (Fig. 7). It might be speculated that with subjects using the method of adjustment in Miwa’s study there may have been sufficient exposure to high magnitudes of vibration to decrease sensitivity to high frequencies due to temporary threshold shifts.

4. General discussion

For the evaluation of vibration at the feet in all the three axes, British Standard 6841 [2] advocates the use of frequency weighting W_b, while International Standard 2631 [1] advocates the use of frequency weighting W_k. The W_b frequency weighting 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 [2]. The W_k frequency weighting provides greatest sensitivity to acceleration at frequencies between 4 and 12.5 Hz [1]. The equivalent comfort contours determined in Experiment 2 have been inverted and normalised to have a value of unity at 8 Hz and overlaid with the W_b and the W_k frequency weightings (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 frequency weightings in the standards (i.e., W_b or W_k) at sensation magnitudes greater than 200 (where 100 is equivalent to the discomfort produced by 5.0 $\mathrm{ms^{-2}}$ rms at 50 Hz). At lower sensation magnitudes there is a tendency for the standardised frequency weightings to underestimate human sensitivity to foot

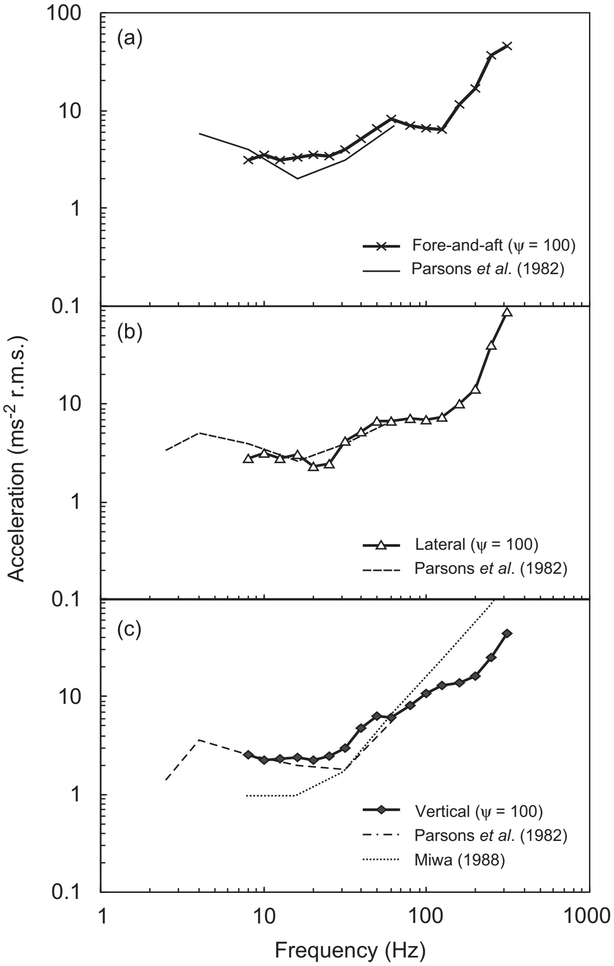

Fig. 7. Equivalent comfort contours for sensation magnitudes of 100 relative to a vibration magnitude of 5.0 ms^{-2} rms at 50 Hz in comparison with Parsons et al. (1982). (a) fore-and-aft, (b) lateral, and (c) vertical.

vibration at frequencies greater than about 20 Hz (or, conversely, the frequency weightings W_b or W_k overestimate the sensations caused by frequencies less than 20 Hz). The underestimate of human sensitivity at higher frequencies is greater with the W_k weighting than the W_b weighting. Although this indicates that W_b is more appropriate than W_k, neither weightings accurately represents human sensitivity at the foot at low vibration magnitudes. The magnitude-dependence of the equivalent comfort contours demonstrated in the present study means that no single linear frequency weighting can provide an accurate prediction of subjective judgements of discomfort caused by foot vibration over a wide range of vibration frequencies and magnitudes.

The frequency weightings for the three axes of foot vibration in this study (Experiment 2) are compared in Fig. 9 for low, medium, and high vibration magnitudes (equivalent to sensation magnitudes of 50, 100, 200, and 300, relative to 5.0 ms^{-2} rms at 50 Hz), assuming a unity weighting at 8 Hz for each axis (as in ISO 2631 [1] and BSI 6841 [2]). The magnitude-dependence of the frequency-weightings can be seen to be broadly similar in the three axes. The frequency weightings appropriate for sensation magnitudes of 50 and 100 show a greater weighting than the W_b and W_k weightings at frequencies greater than 16 Hz for all three axes, with increased weighting around 100 Hz for horizontal vibration. Experiment 2 did not directly investigate the equivalence of vibration discomfort between the three axes, so Fig. 9 does not reflect the relative sensitivity between the axes. Parsons et al. [3] concluded that vertical vibration produces more discomfort than horizontal vibration, warranting a 60% greater multiplying factor for vertical vibration than that for horizontal axis (i.e. 0.4 versus 0.25) in ISO 2631 [1] and BS 6841 [2].

The magnitude-dependence of the equivalent comfort contours determined in the present study may be explained by different psychophysical channels being responsible for discomfort of the foot at different vibration magnitudes. For the hand, anatomically similar to the foot [7], it has been concluded that individual thresholds for FA II, FA I, and SA II fibres (Pacinian, NP I, and NP II channels, respectively) lie within a 30 dB range above absolute thresholds from a study of masked thresholds for the hand applied to a rigid flat plate vibrating in the vertical direction [34]. In Fig. 6, the U-shaped portions of

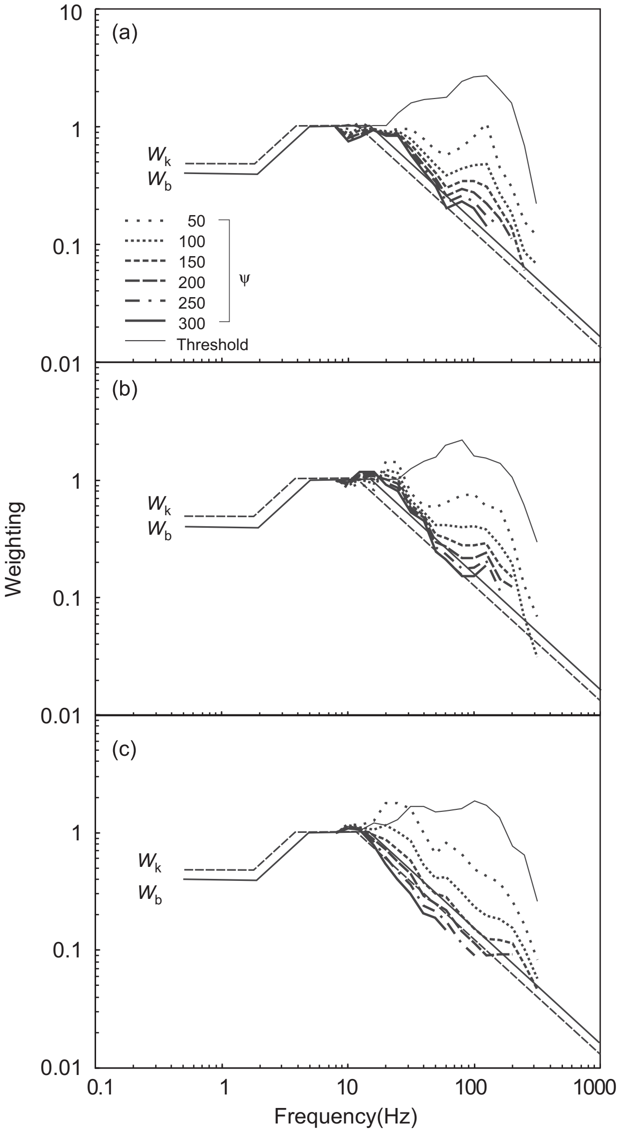

Fig. 8. Effect of vibration magnitude on frequency weightings (inverted equivalent comfort contours normalised at 8 Hz: (a) fore-and-aft, (b) lateral, and (c) vertical. A sensation magnitude of 100 is equivalent to the discomfort produced by 5.0 ms^{-2} rms at 50 Hz. The results are compared with the frequency weightings, W_b (BS 6841, 1987) and W_k (ISO 2631-1, 1997). ⋯⋯: 50, ▪▪▪▪▪▪: 100, – – –: 150, ▬ ▬: 200, ▬ · ▬ :250, ▬▬▬: 300, and ——: threshold.

the comfort contours at high frequencies (between 50 and 200 Hz) diminish as the vibration magnitude increases above about 1 or 2 ms^{-2} rms, which may be a sign of another channel being excited. Similar trends were observed in a similar study of equivalent comfort contours for hand-transmitted vibration [6]. Although thresholds for individual channels responsible for vibration discomfort in the foot are unknown, it seems likely that vibration of the foot at supra-threshold levels often excites more than one psychophysical channel.

A nonlinear biodynamic response of the foot might partly explain the magnitude-dependence of the comfort contours at low frequencies (less than about 30 Hz) in the present results where the frequencies with greatest sensitivity tended to reduce as the vibration magnitude increased. Kitazaki [30] found that the resonance frequencies of the feet decreased from 9, 13, and 35 Hz to 8, 12, and 33 Hz when the magnitude of vertical vibration increased from 0.3 to 1.0 ms^{-2} rms. A similar nonlinearity in the apparent mass at the feet has been reported with both vertical vibration of the feet [35] and fore-and-aft vibration of the feet [36] during simultaneous exposure to the same axis of vibration at the seat: with both axes, increases in the vibration magnitude decreased the principal resonance frequency of the apparent mass. The magnitude-dependence of the equivalent comfort contours at high frequencies (i.e. greater than about 30 Hz) cannot be explained by this biodynamic nonlinearity.

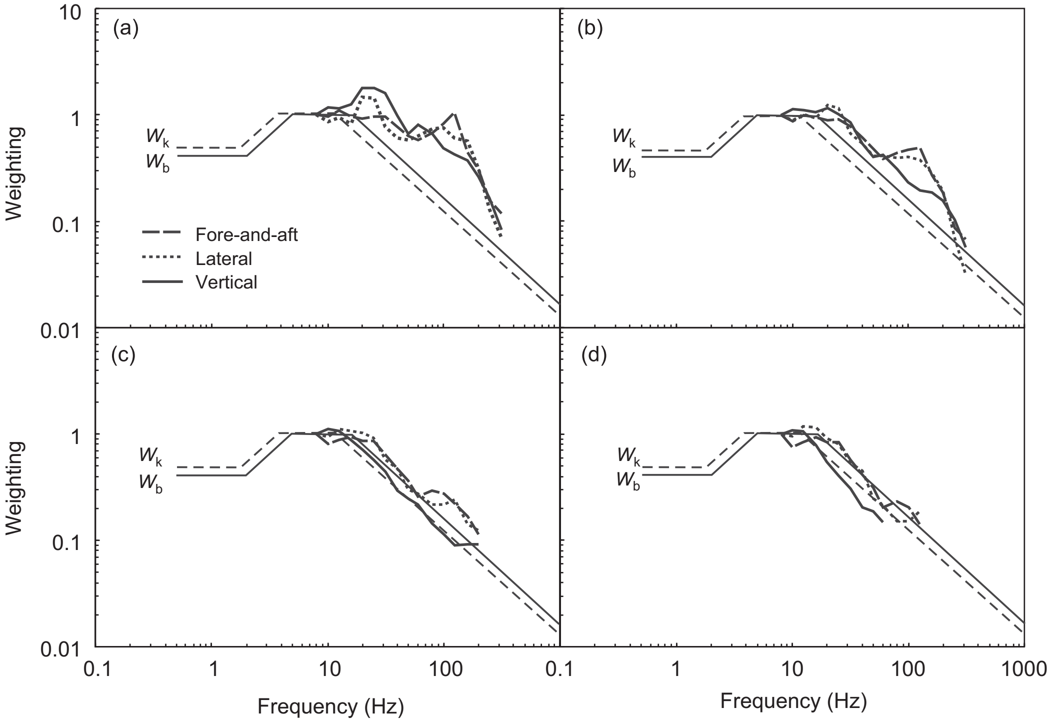

Fig. 9. Effect of axis of vibration excitation on frequency weightings (inverted equivalent of comfort contours normalised at 8 Hz for sensation magnitudes of: (a) 50, (b) 100, (c) 200, and (d) 300. A sensation magnitude of 100 is the equivalent discomfort produced by 5.0 ms^{-2} rms at 50 Hz. The results are compared with the frequency weightings W_b (BS 6841, 1987) and W_k (ISO 2631-1, 1997). ———: fore-and-aft, ▪▪▪▪▪▪: lateral, and ▬▬▬: vertical.

5. Conclusions

When the foot of a seated person rests on a vibrating surface, absolute thresholds for the perception of vibration acceleration in each of the three axes (i.e. fore-and-aft, lateral, and vertical) have a U-shaped frequency-dependence with greatest sensitivity to acceleration at frequencies greater than 80 Hz, suggesting an involvement of the Pacinian channel. Absolute thresholds for the perception of vertical vibration of the foot were lower than those for the perception of fore-and-aft and lateral vibration at frequencies less than 50 Hz. There was no large or simple influence of gender on the perception of vibration at the foot: when barefoot, males produced lower thresholds than females at 125 Hz, but the opposite was observed at 8 Hz. Thresholds were not greatly affected by wearing shoes.

Over the frequency range 8–315 Hz, the frequency-dependence of equivalent comfort contours for foot vibration in each of the three axes is dependent on vibration magnitude. At low magnitudes, equivalent comfort contours have a similar shape to the absolute threshold. With increasing magnitudes of vibration, the equivalent comfort contours tend towards contours with constant velocity. The magnitude-dependence of the equivalent comfort contours suggests that more than one psychophysical channel is responsible for discomfort caused by vibration applied to the foot over the range of frequencies and magnitudes investigated. A nonlinear biodynamic response to vibration of the foot may partly explain the magnitude-dependence of equivalent comfort contours at low frequencies (less than 30 Hz).

The equivalent comfort contours are broadly consistent with the W_b and W_k frequency weightings employed in current standards, but only at relatively high vibration magnitudes (those producing discomfort double that caused by 5.0 ms^{-2} rms at 50 Hz) and at frequencies greater than 16 Hz. At lower magnitudes, the W_b and W_k frequency weightings underestimate sensitivity to foot vibration at frequencies greater than 16 Hz. The magnitude-dependence of the equivalent comfort contours implies that no single linear frequency weighting can provide accurate predictions of discomfort caused by vibration of the foot.

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