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Magnitude-dependence of equivalent comfort contours for fore-and-aft, lateral and vertical hand-transmitted vibration

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Abstract

The strength of sensation produced by vibration applied to the glabrous skin of the hand varies with the magnitude, frequency, and direction of the vibration and the contact conditions. With groups of 12 subjects gripping a cylindrical handle, this experimental study investigated perception thresholds (in the frequency range 8–315 Hz) and the strength of sensation caused by each of the three axes of hand-transmitted vibration (in the frequency range 8–400 Hz) at vibration magnitudes from threshold up to levels associated with discomfort and injury. In all three axes, acceleration thresholds for the perception of vibration showed a U-shaped frequency-dependence with greatest sensitivity around 80–160 Hz. 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, equivalent sensation approximated towards constant velocity, whereas with decreasing magnitudes the sensation became similar to the absolute perception threshold. This magnitude-dependence of equivalent comfort contours suggests differential mediation of psychophysical channels responsible for perception at different vibration magnitudes. The results imply that no single linear frequency weighting can provide accurate predictions of subjective judgments of discomfort caused by hand-transmitted vibration.

1. Introduction

Vibration of the hand can arise from many sources, including self-induced oscillations, the movement of the hand over rough surfaces, the vibration of powered tools, and the vibration of surfaces in buildings and transport. If the vibration is of very low magnitude it may not be perceived, but vibration above the perception threshold results in sensations that vary in strength according to the point of contact, the vibration magnitude, the vibration frequency, and the direction of vibration.

Various studies of absolute thresholds for the perception of hand-transmitted vibration, including Miwa [1], Reynolds et al. [2], Brisben et al. [3] and Morioka, and Griffin [4] show U-shaped contours having maximum sensitivity to vibration acceleration at frequencies between 150 and 250 Hz. However, sensitivity to vibration varied between these studies, possibly due to the different conditions of each experiment, such as hand posture (i.e. gripping posture or a flat palm), psychophysical measurement method, grip force, and push force. For

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vibration at supra-threshold levels, equivalent comfort contours for the hand show reducing sensitivity to acceleration as the vibration frequency increases above about 16 Hz [1,2,5], contrasting with absolute thresholds that reduce with increasing frequency above about 16 Hz. The difference in the frequency-dependence of absolute thresholds and equivalent comfort contours for hand-transmitted vibration might be explained by the characteristics of receptors mediating sensations at threshold and supra-threshold levels.

Of four classes of mechanoreceptive afferent fibres in the glabrous skin of the hand, two are fast adapting (i.e. FA I and FA II fibres) and two are slow adapting (SA I and SA II fibres) [6]. Psychophysical studies of vibrotactile thresholds were initially thought to elicit responses from two types of sensory systems, often distinguished as Pacinian and non-Pacinian systems [7,8]. The Pacinian system has distinctive characteristics: spatial summation [9], temporal summation [10], and a dependence on skin temperature [11], and is associated with Pacinian corpuscles (i.e. FA II fibres) [12]. The non-Pacinian system includes the Meissner corpuscles, Merkel disks, and Ruffini endings (i.e. FA I, SAI and SA II fibres, respectively), some of which seem incapable of temporal or spatial summation and whose responses depend on stimulus gradients [7,8]. Later studies by Bolanowski et al. [13] and Gescheider et al. [14] demonstrated a four-channel model of vibrotactile perception by determining threshold responses of three tactile channels within the non-Pacinian system (NP I, NP II, and NP III channels corresponding to FA I, SA II, and SA I fibres, respectively) in the glabrous skin of the hand.

Studies of vibrotactile perception by Bolanowski, Gescheider, Verrillo, and co-workers [13–15] led to an understanding of the properties of the four information-processing channels in the glabrous skin by applying a small vibrating probe (varying from 0.1 to 2.9 cm^2) with a surround (usually 1 mm gap between the probe and the surround) to the fingertip or the thenar eminence to elicit, or isolate, responses from a particular tactile channel. Morioka and Griffin [4] extended this to the palmar area of the hand by examining the effect of contact area and contact location on thresholds of perception of vibration applied to the fingertip and the hand and concluded that thresholds for the perception of vibration applied to the whole area of the hand seemed to be mediated by the Pacinian, NP I and NP II channels with some influence of biodynamic responses. Morioka and Griffin [16] determined thresholds for the Pacinian, NP I and NP II channels using masking stimuli to isolate responses of a particular channel; they found masked thresholds for these channels less than 30 dB above the absolute thresholds of unmasked stimuli. However, it is not known how the various channels contribute to the strength of sensations at supra-threshold levels.

It is intuitively obvious that increasing vibration magnitude will increase the strength of sensation, but little is known about the rate at which the strength of sensation increases with increasing vibration magnitude. It is also unknown whether the frequency-dependence of sensation (i.e. the shape of equivalent comfort contours) depends on vibration magnitude. If the mechanoreceptive afferent fibres involved in sensations (e.g. discomfort) at magnitudes above perception thresholds were known, it may be possible to predict the effects of vibration frequency, vibration magnitude, and vibration axis on the discomfort caused by hand-transmitted vibration.

This study was conducted to assist the development of a method for predicting the perception of hand-transmitted vibration and the discomfort caused by hand-transmitted vibration, examining the effects of: (i) vibration frequency (over the range 8–400 Hz), (ii) vibration magnitude (from absolute thresholds to supra-threshold levels likely to be associated with significant discomfort), and (iii) vibration direction (i.e. fore-and-aft, lateral and vertical). Two experiments were designed to determine: (a) absolute threshold contours in each of the three axes and (b) equivalent comfort contours in each of the three axes.

2. Experiment 1: perception thresholds

Absolute thresholds of the perception of hand-transmitted vibration in each of the three axes were determined using sinusoidal vibration at preferred one-third octave centre frequencies between 8 and 315 Hz. It was hypothesized that thresholds would depend on vibration frequency and vibration direction, which reflect the sensitivity of Pacinian and non-Pacinian channels. Although the experiment was not designed to identify which tactile channels were responsible for vibration perception, it was expected that some inferences could be drawn from the correlations between thresholds obtained from subjects at different frequencies.

2.1. Method

2.1.1. Subjects

Twenty-four males aged between 22 and 27 years with a mean age of 25.3 years (standard deviation, SD = 1.8), a mean stature of 178.2 cm (SD = 5.8) and a mean weight of 72.8 kg (SD = 10.2) participated in the experiment. All subjects were students or office workers with no history of occupational exposure to hand-transmitted vibration. In 12 subjects (Group A), perception thresholds were determined in the fore-and-aft direction. In the other 12 subjects (Group B), perception thresholds were determined for lateral and vertical hand-transmitted vibration, with the axes studied on separate days. The characteristics of the subjects in each group are shown in Table 1. There were no significant differences in age, weight, body statue, and skin temperature between the two groups (Mann–Whitney, $p > 0.75$).

Skin temperatures of the hand were measured at the beginning of each session using an *HVLab* Tactile Aesthesiometer (by means of thermocouples). The tests only proceeded if the skin temperature was greater than 29 °C; the subjects warmed their hands if the temperature was below this criterion. The room temperature was maintained at 21 ± 2 °C. During the tests, the subjects were exposed to white noise at 75 dB(A) via a pair of headphones to prevent them from hearing the vibration, although no audible noise was generated by any of vibration stimuli used in the experiment. This white noise was also to assist their concentration on the vibration by masking any distracting sounds.

This experiment (and Experiment 2) was approved by the Human Experimentation Safety and Ethics Committee of the ISVR, University of Southampton. Informed consent to participate in the experiment was given by all subjects.

2.1.2. Apparatus

Subjects were exposed to hand-transmitted vibration via a 30 mm diameter rigid smooth cylindrical wooden handle mounted on a Derritron VP30 electrodynamic vibrator (for fore-and-aft and lateral vibration), or a Derritron VP 4 electrodynamic vibrator (for vertical vibration). The vibration was measured during the experiment by means of piezoelectric accelerometers attached to the handle. Cross-axis motions were less than 5% of the magnitude in the generated axis. Background vibration due to electrical noise at 50 Hz was less than 0.008 m s^{-2} rms, and was not perceptible via the hand.

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.

The subjects were instructed to grasp the handle lightly and comfortably. Their forearms were horizontal and level with the vibrating handle (no armrest) during the measurements. The vertical vibration transmitted to the hand through the handle was perpendicular to the long axis of the handle, the lateral vibration was

Table 1
Characteristics of subjects who participated in the Experiments 1 and 2

	Experiment 1		Experiment 2		
	z	y and x	z	y	x
	Group A	Group B	Group C	Group D	Group E
Age (year)	25.4 (1.9)	25.3 (1.8)	24.5 (1.7)	23.9 (2.5)	26.3 (2.8)
Weight (kg)	72.2 (10.1)	73.5 (10.7)	75.6 (9.9)	71.3 (5.3)	70.7 (9.3)
Stature (cm)	178.7 (6.4)	177.8 (5.4)	178.8 (3.6)	180.0 (5.4)	177.2 (7.0)
Hand length (cm)	19.0 (0.7)	19.1 (0.8)	19.5 (0.7)	19.1 (0.6)	19.2 (1.0)

z = fore-and-aft, y = lateral, and x = vertical, mean (standard deviation).

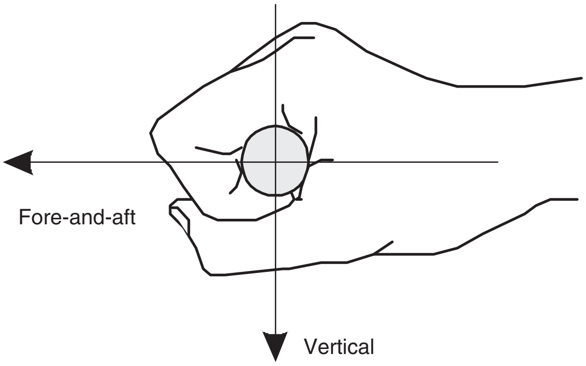

Fig. 1. Hand posture and axis of vibration. The lateral axis is defined as parallel to the handle axis.

parallel to the long axis of the handle and the fore-and-aft vibration was perpendicular to the vertical and fore-and-aft axes; the hand posture and axes of vibration are shown in Fig. 1.

2.1.3. Procedure

The 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. A cue light was 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 intensity by 2 dB (25.8% increment) after a negative ('no') response from a subject and decreased in intensity by 2 dB after three consecutive positive ('yes') responses.

The threshold determination was terminated after six reversals: a point where the stimulus level 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 [17].

Threshold measurements within one axis were performed in one session. The order of presenting the 17 preferred one-third octave centre frequencies between 8 and 315 Hz was randomized.

2.2. Results and discussion

2.2.1. Thresholds within an axis (effect of frequency)

The median absolute thresholds and the inter-quartile range (25th–75th percentiles) of the 12 subjects were determined at each frequency in each axis, as shown in Fig. 2. Within each axis, the acceleration perception thresholds were highly dependent on vibration frequency (Friedman, $p<0.001$), presenting U-shaped contours with greatest sensitivity to acceleration around 80–160 Hz. The results are broadly similar to the perception threshold contours for hand-transmitted vibration determined in other studies [1–4].

A subject having a high threshold at one frequency would be expected to have high thresholds at another frequency mediated by the same tactile channel. Consequently, if the same tactile channel is involved, thresholds will tend to be correlated between frequencies. There were high correlations between thresholds at frequencies greater than 20 Hz for vertical vibration (51 of 78 combinations being statistically significant; Spearman $r^2>0.6$, $p<0.05$) and at frequencies greater than 12.5 Hz for lateral vibration (89 out of 105 combinations being significant; Spearman $r^2>0.6$, $p<0.05$). With fore-and-aft vibration, there were high correlations between thresholds at frequencies between 20 and 100 Hz (17 out of 27 combinations being significant; Spearman $r^2>0.58$, $p<0.05$) and between 160 and 315 Hz (four out of six combinations being significant; Spearman $r^2>0.6$, $p<0.05$).

The highly correlated perception thresholds in particular frequency ranges (frequencies greater than 20 Hz for vertical and fore-and-aft vibration and frequencies greater than 12.5 Hz for lateral vibration) might imply the involvement of the Pacinian channel (FA II fibres). Morioka and Griffin [4] demonstrated spatial summation at frequencies greater than 16 Hz when increasing the contact area from the fingertip and the

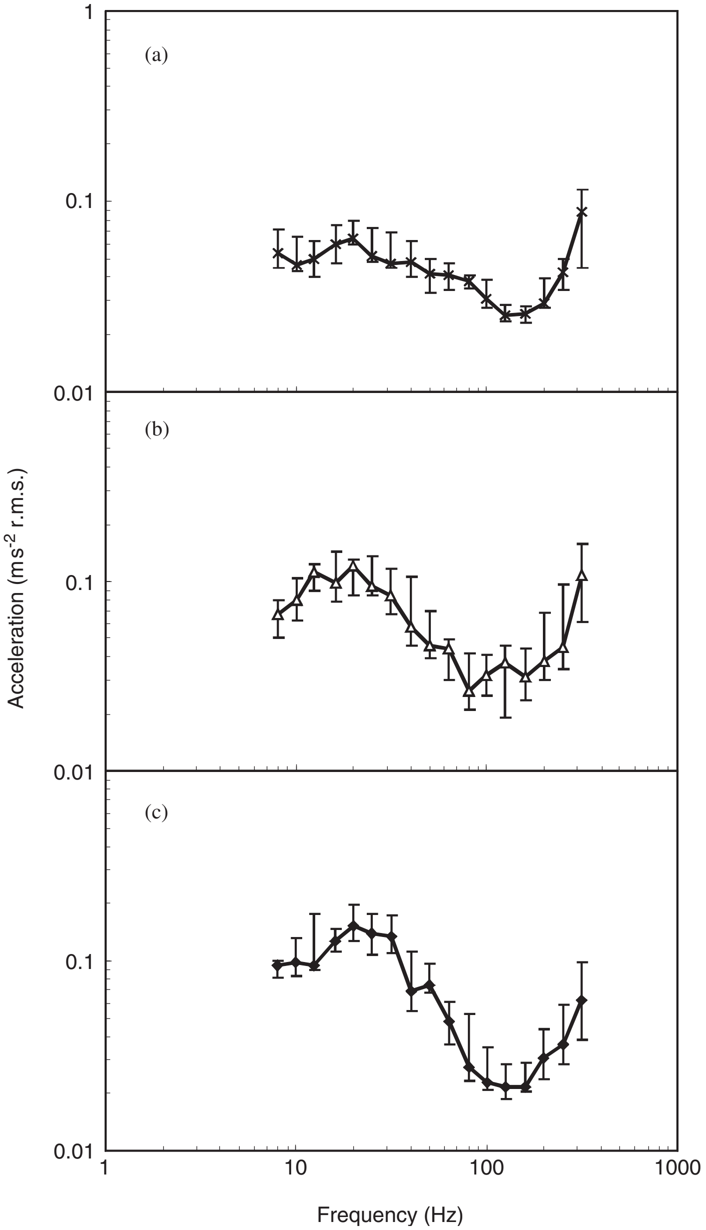

Fig. 2. Median absolute perception thresholds between 8 and 315 Hz: (a) fore-and-aft, (b) lateral, and (c) vertical. Error bars represent inter-quartile range.

whole area of the hand, suggesting that thresholds for the detection of vibration applied to the whole hand at frequencies greater than about 16 Hz are likely to have been mediated by the Pacinian channel (FA II fibres). Morioka [18] determined perception thresholds for hand-transmitted vibration at frequencies between 4 and 250 Hz when holding a steering wheel and found a slope of approximately −12 to −14 dB per doubling of frequency at frequencies between 16 and 250 Hz and approximately −5 dB per doubling of frequency between 4 and 16 Hz when expressed in displacement. The slope of the threshold contour for Pacinian channel (FA II) between 15 and 200 Hz has been suggested to be approximately −12 dB per octave when expressed in displacement [7,9,13,14,19]. The Meissner's corpuscles (FA I) respond with a slope of about −5.0 dB per octave between about 3 and 35 Hz [13,15]. The previous results are consistent with the present results, suggesting perception thresholds at frequencies greater than about 20 Hz for vertical and fore-and-aft

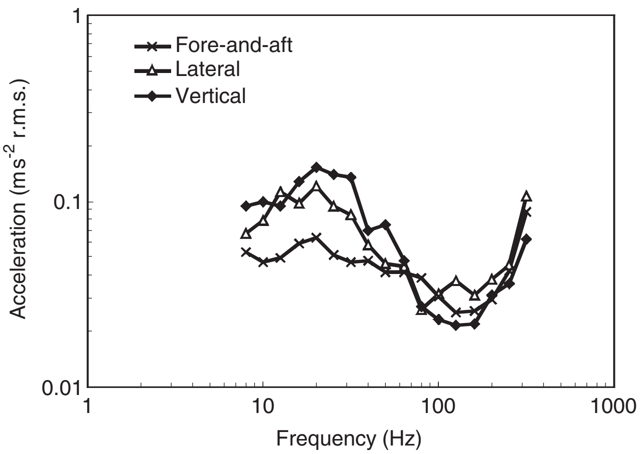

Fig. 3. Median perception threshold contours overlaid between the three axes. $\times$: fore-and-aft, $\triangle$: lateral, and $\blacklozenge$: vertical.

vibration, and greater than about 12.5 Hz for lateral vibration, were predominantly mediated by Pacinian corpuscles (FA II), while perception thresholds at lower frequencies were mediated by one of the other psychophysical channels, such as Meissner corpuscles (FA I).

There were few correlations between vibrotactile thresholds and skin temperature, age, body size, or hand and finger size, and no systematic correlations were found.

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. At frequencies greater than 63 Hz, there were no differences between the fore-and-aft and vertical thresholds (Mann–Whitney, $p>0.1$) or between the fore-and-aft and lateral thresholds (Mann–Whitney, $p>0.2$). However, vertical thresholds were significantly lower than lateral thresholds at frequencies greater than 125 Hz (Wilcoxon, $p<0.05$). An increased sensitivity to vertical vibration relative to vibration in other axes is also present in the thresholds reported by Reynolds et al. [2]: at frequencies greater than about 125 Hz, mean vertical thresholds and mean fore-and-aft thresholds were lower than mean lateral thresholds with a palm grip condition, although no statistical results were presented. The mechanism responsible for the difference in thresholds between axes is not known, but the similarity in the shapes of threshold contours suggests a difference in sensitivity within the Pacinian channel when vibration occurs perpendicular or parallel to the surface of the skin.

At low frequencies, less than 50 Hz, the hand was most sensitive to fore-and-aft vibration: thresholds were significantly lower in the fore-and-aft direction than in the vertical direction at frequencies less than 50 Hz (Mann–Whitney, $p>0.04$) and significantly lower in the fore-and-aft direction than in the lateral direction at frequencies between 10 and 25 Hz (Mann–Whitney, $p<0.005$). Thresholds were generally lower in the lateral direction than in the vertical direction at frequencies less than 31.5 Hz (Wilcoxon, $p<0.03$), except at 10 and 12.5 Hz (Wilcoxon, $p>0.2$). Low frequency vibration caused movements of the arm and elbow, which may have enhanced the detection of hand-transmitted vibration, particularly in the fore-and-aft direction.

3. Experiment 2: equivalent comfort contours

In this experiment, the rates of growth in vibration sensation with increasing vibration magnitude were determined at frequencies between 8 and 400 Hz, so as to produce equivalent comfort contours for vibration in each of the three axes. The rate of growth in sensation with increasing magnitude has been determined using Stevens' power law [20], which describes the relationship between the psychophysical magnitude, ψ, and the physical magnitude, φ, of a stimulus:

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

where k is a constant, and the exponent n describes the rate of change of sensation, ψ, with vibration magnitude, φ. There is some evidence of a frequency-dependence of the value of the exponent, n. Stevens [21] found a greater exponent at 60 Hz (exponent of 0.95) than at 120 Hz (exponent of 0.83) when vibration was applied to the fingertip (without a surround). Verrillo and Capraro [22] examined the combined effects of a surround and vibration frequency on the exponent and observed a greater exponent at 60 Hz (exponent of 0.45 at the fingertip) than at 250 Hz (exponent of 0.40 at the fingertip) when there was no surround around a vibrating contactor, while no differences in the exponent were found between the two frequencies (exponent of 0.46 and 0.44 for 60 and 250 Hz, respectively) with a surround. The results led them to a theory in which the slope is determined by the number of activated fibres; the greater the number of activated fibres the lower the slope. This theory was used by Verrillo et al. [23] to explain steeper slopes in older subjects than in younger subjects at 250 Hz: they suggested that the increased slope was due to a loss of tactile sensitivity due to aging, analogous to 'loudness recruitment' observed in the auditory system.

Verrillo et al. [23] also identified breaks in the slopes of magnitude estimation curves, demonstrating a change in the rate of increase in sensation above the threshold of the NP II channel (determined with a 0.008 cm^2 contactor). This suggested that the activity of more than one psychophysical channel contributed to the slope found by magnitude estimation.

The power law is sometimes written with an additive constant, $\varphi_{0,}$ representing the threshold [24], assuming no sensation below the perception threshold:

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

The threshold, $\varphi_{0,}$ has proved useful in describing thermal sensation, brightness, and loudness [20]. However, it has not been investigated whether a threshold constant is appropriate when describing sensations caused by vibration stimuli.

This experiment was designed to determine equivalent comfort contours for various vibration magnitudes of hand-transmitted vibration in each of three axes, testing two hypotheses: (i) the rate of growth of sensation depends on vibration frequency, assuming more than one psychophysical channel is activated within the range of frequencies and magnitudes and (ii) use of an additive constant representing the perception threshold (i.e. Eq. (2)) will improve the representation of the growth of sensation magnitudes.

3.1. Method

3.1.1. Subjects

Thirty-six male healthy volunteers aged between 21 and 31 years, with a mean age of 24.9 years, (standard deviation, SD = 2.5), a mean stature of 178.7 cm (SD = 5.5) and a mean weight of 72.5 kg (SD = 8.5) participated in the experiment. All subjects were students or office workers with no history of occupational exposure to hand-transmitted vibration. They were divided into three groups (i.e. Groups C, D, and E) for the determination of the strength of sensation caused by fore-and-aft, lateral and vertical axes, respectively (see Table 1 for characteristics of the subjects). There were no significant differences in age, weight, body stature or skin temperature between the three groups (Kruskal–Wallis, $p > 0.1$).

During the tests, the subjects were exposed to white noise at 75 dB(A) via a pair of headphones. This white noise was partly to mask any audible noise generated by vibration stimuli and partly to assist their concentration on the vibration by masking any distracting sounds. The vibration stimuli used in the experiment did not produce audible noise, apart from vibration at 250, 315 and 400 Hz. Some stimuli at these frequencies generated audible noise (particularly at magnitudes greater than about 10 $m\,s^{-2}$ rms) and may not have been masked by the 75 dB(A) white noise. Subjects were instructed to judge the vibration, ignoring any audible noise.

3.1.2. Apparatus

All apparatus, including the signal generation and signal acquisition, were the same as employed in Experiment 1, except a Derritron VP30 electrodynamic vibrator was used to deliver all vibration to the hand.

3.1.3. Procedure

Judgments of discomfort caused by hand-transmitted vibration were determined using the method of magnitude estimation [20]. A set of two motions, reference motion and test motion, were created; each motion lasted 2.0 s with an interval of 1.0 s between the motions. The motions had 0.5 s cosine-tapered ends. The reference motion was $5.0\,\mathrm{m\,s^{-2}}$ rms at 50 Hz in the axis being investigated. The test motions were randomly selected from the 18 preferred one-third octave centre frequencies in the range 8–400 Hz. The test motions varied in velocity from 0.002 to $0.126\,\mathrm{m\,s^{-1}}$ rms in 3 dB steps. The minimum acceleration of the test motions was $0.16\,\mathrm{m\,s^{-2}}$ rms (corresponding to $0.002\,\mathrm{m\,s^{-1}}$ rms at 12.5 Hz) to ensure that the stimuli were above the absolute thresholds of the subjects. The task of the subjects was to assign a number that represented the discomfort of the test motion relative to the discomfort of the reference motion, assuming the discomfort caused by the reference motion corresponded to '100'. Each subject received a total of 211 pairs of two motions (reference and test motions) in a session, with short breaks in every 35 pairs (the last set consisted of 36 pairs). The order of presenting the test motions was randomized. The subjects were allowed to ask for a repeat of a pair of stimuli, if they were unsure of their judgment. The subjects were instructed to indicate 'no sensation' if the test stimulus was not perceived. A cue light was illuminated during the presentation of the reference and the test stimuli.

Prior to the magnitude estimation test, two practice tasks were presented to each subject in order to familiarize them with the procedure and the vibration stimuli: (i) magnitude estimation of line lengths and (ii) magnitude estimation of vibration with a few selected vibration test stimuli.

3.2. Results and discussion

3.2.1. Growth of sensation

The relationship between sensation magnitude, ψ, and vibration magnitude, φ, for each frequency was initially determined by linear regression using Stevens' Power law without the additive constant representing the threshold, as shown in Eq. (1). The median rates of growth of sensation, n, from 12 subjects for each direction are shown in Fig. 4 and were less than 1.0 at every frequency and in each of the three axes: a doubling of vibration magnitude resulted in less than a doubling of sensation magnitudes. It is also seen that the n values became progressively lower as the frequency increased from 20 to 400 Hz, indicating that for the same percentage change in vibration magnitude there was a smaller change in the strength of sensation at higher frequencies. The frequency-dependence in the rate of growth of sensation was statistically significant within each of the three axes (Friedman, $p<0.001$). There were no significant differences within the frequency range 8–12.5 Hz in the vertical and lateral axes (Wilcoxon, $p>0.05$) or within the frequency range 8–40 Hz in the fore-and-aft axis (Friedman, $p=0.30$). There was no significant difference in n value between the three axes at any frequencies (Friedman, $p>0.09$).

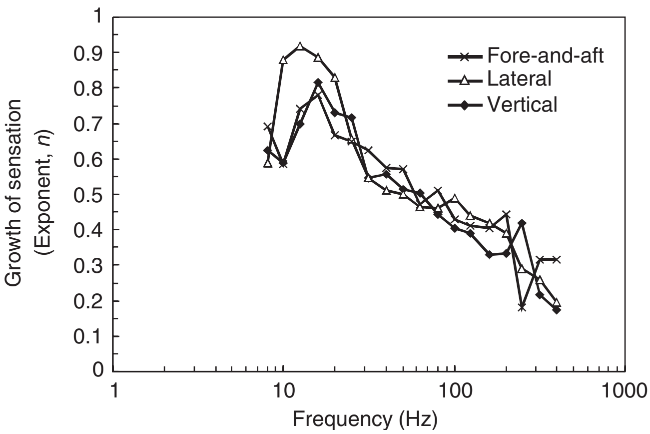

Fig. 4. Growth of sensation (median exponent, n, from 12 subjects) as a function of frequency from 8 to 400 Hz for three directions (determined with Eq. (1)). $\times$: fore-and-aft, $\triangle$: lateral, and $\blacklozenge$: vertical.

The rate of growth of sensation was also determined using the power law with an additive constant (i.e. Eq. (2)). The constant, φ_0, was taken from the median perception threshold for the appropriate frequency and direction of excitation determined in Experiment 1. The constants, φ_0, for 400 Hz vibration in the fore-and-aft, lateral, and vertical directions were estimated from linear extrapolation of the median thresholds (in log–log form) obtained with 250 and 315 Hz vibration in Experiment 1, giving 0.186, 0.262, and 0.109 m s^{-2} rms, respectively. Linear regression was performed at each frequency (see Fig. 5 for examples) transforming Eq. (2) to:

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

Values of the exponent, n, determined from the median sensation magnitudes of the 12 subjects for each direction using the power law with and without an additive constant have been compared and are shown in Table 2. Generally, there are lower n values when using an additive constant than when using Stevens' power law without the additive constant. However, the difference between the two exponents is small: the inter-quartile-range of exponents obtained with Stevens' power law is greater than the difference between the two exponents. There were no significant differences between the two exponents at any frequency in any of the three axes (Wilcoxon, $p>0.05$) except at 250 Hz in the lateral axis (Wilcoxon, $p = 0.041$). However, the correlation coefficients, R^2, determined when using the power law with an additive constant are mostly higher than those determined with Stevens' power law without the additive constant (at 47 of the 54 conditions). This indicates that the additive constants representing the thresholds improved the representation of sensation magnitudes of hand-transmitted vibration.

The slopes of the subjective magnitude functions for 63 and 250 Hz vertical vibration, 0.45 and 0.41, respectively (0.48 and 0.46 for the average of the three axes), are reasonably consistent with values obtained in other research. Stevens [21] obtained slopes of 0.5 and 0.34 for 60 and 250 Hz vibration at the fingertip with a 6 mm diameter contactor without a surround. Verrillo and Chamberlain [25] obtained a slope of 0.40 for 250 Hz fingertip vibration without surround. Verrillo and Capraro [22] found slopes of 0.45 and 0.40 for 60

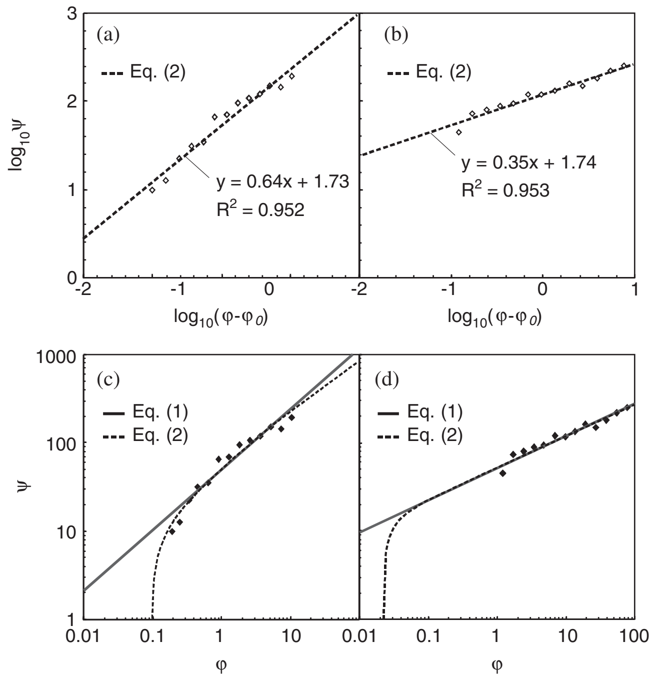

Fig. 5. Examples of linear regression for: (a) 12.5 Hz and (b) 100 Hz data in the vertical axis using Eq. (2). The data are then converted into sensation magnitudes, ψ, as a function of vibration magnitudes, φ, for: (c) 12.5 Hz and (d) 100 Hz. $\varphi_0 = 0.095$ m s^{-2} rms (12.5 Hz), 0.023 m s^{-2} rms (100 Hz) (median thresholds determined in Experiment 1). —: Eq. (1) and - - - -: Eq. (2).

Table 2
Comparison of median exponents for each of three axes between Eqs. (1) and (2)

Frequency	Stevens power law Eq. (1)									Power law with additive constant Eq. (2)					
	Median exponent			IQR of exponent			R^2			Median exponent			R^2		
	z	y	x	z	y	x	z	y	x	z	y	x	z	y	x
8	0.75	0.68	0.62	0.42	0.29	0.21	0.92	0.94	0.94	0.71	0.63	0.56	0.94	0.96	0.96
10	0.70	0.86	0.60	0.39	0.16	0.64	0.94	0.95	0.94	0.66	0.79	0.57	0.95	0.97	0.95
12.5	0.78	0.92	0.65	0.32	0.31	0.46	0.94	0.91	0.94	0.74	0.80	0.64	0.95	0.95	0.95
16	0.75	0.85	0.73	0.23	0.37	0.33	0.92	0.91	0.97	0.71	0.78	0.73	0.93	0.93	0.96
20	0.67	0.81	0.66	0.31	0.25	0.38	0.91	0.86	0.95	0.64	0.75	0.64	0.92	0.90	0.94
25	0.64	0.66	0.66	0.39	0.17	0.27	0.90	0.88	0.91	0.62	0.63	0.61	0.91	0.90	0.93
31.5	0.65	0.50	0.60	0.24	0.21	0.27	0.88	0.94	0.91	0.64	0.48	0.56	0.89	0.95	0.93
40	0.62	0.52	0.52	0.32	0.24	0.28	0.91	0.92	0.93	0.61	0.51	0.51	0.92	0.93	0.94
50	0.53	0.44	0.47	0.20	0.25	0.26	0.92	0.94	0.91	0.52	0.43	0.46	0.93	0.94	0.92
63	0.55	0.44	0.45	0.32	0.16	0.20	0.97	0.94	0.93	0.54	0.44	0.45	0.97	0.94	0.93
80	0.48	0.46	0.38	0.32	0.23	0.19	0.96	0.97	0.96	0.48	0.45	0.38	0.96	0.97	0.96
100	0.45	0.45	0.35	0.26	0.24	0.12	0.99	0.97	0.95	0.44	0.45	0.35	0.99	0.97	0.95
125	0.39	0.46	0.36	0.12	0.34	0.22	0.92	0.97	0.96	0.39	0.46	0.36	0.92	0.97	0.96
160	0.35	0.41	0.32	0.19	0.10	0.14	0.93	0.97	0.98	0.34	0.40	0.32	0.93	0.97	0.98
200	0.39	0.35	0.29	0.21	0.22	0.29	0.87	0.83	0.83	0.38	0.35	0.29	0.87	0.83	0.83
250	0.53	0.44	0.41	0.44	0.28	0.31	0.85	0.92	0.87	0.53	0.44	0.41	0.86	0.92	0.87
315	0.23	0.32	0.32	0.19	0.30	0.29	0.45	0.81	0.85	0.22	0.31	0.32	0.45	0.81	0.85
400	0.39	0.32	0.14	0.59	0.33	0.44	0.88	0.80	0.43	0.39	0.32	0.14	0.88	0.80	0.43

IQR of exponent from Eq. (1) is also shown. R^2 values are the medians of the R^2 value from individual subjective judgments at each frequency. z = Fore-and-aft, y = lateral, and x = vertical.

and 250 Hz vibration applied to the fingertip with a 6 mm diameter probe without a surround. In the present study, there is a systematic decrease in the rate of growth of sensation as the frequency increased above 16 Hz in the vertical and lateral axes and above 50 Hz in the fore-and-aft axis (Fig. 4). This appears consistent with the theory of Verrillo and Capraro [22], based on an increased number of activated fibres with increased vibration frequency.

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 5.0 m s^{-2} rms at 50 Hz), for each vibration frequency (from 8 to 400 Hz) using Eq. (2) and are shown in Fig. 6. The corresponding median exponents (n), constants (k), and thresholds (φ_0) for creating the equivalent comfort contours (Fig. 6) 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. They provide information on which frequencies produced greater discomfort (a lower acceleration at a particular frequency indicates greater discomfort at that frequency).

It can be seen that, in each axis, the shapes of the equivalent comfort contours depend on vibration magnitude. With increasing sensation magnitudes, the comfort contours approximate contours corresponding to constant velocity (i.e. acceleration increasing in proportion to frequency). With decreasing sensation magnitudes, the contours become similar to the absolute perception threshold. Sensitivity to vibration acceleration decreased with increasing frequency (from 8 to 400 Hz) at high acceleration magnitudes (greater than about 2.0 m s^{-2} rms) but sensitivity increased with increasing vibration frequency (from 20 to 100 Hz) at low acceleration magnitudes (less than about 2.0 m s^{-2} rms). For example, 10 m s^{-2} rms, hand-transmitted vibration produced a greater strength of sensation at 20 Hz than at 100 Hz, whereas 1.0 m s^{-2} rms, hand-transmitted vibration produced a similar or greater strength of sensation at 100 Hz than at 20 Hz. The magnitude-dependence of the contours is more pronounced with vertical vibration than with horizontal

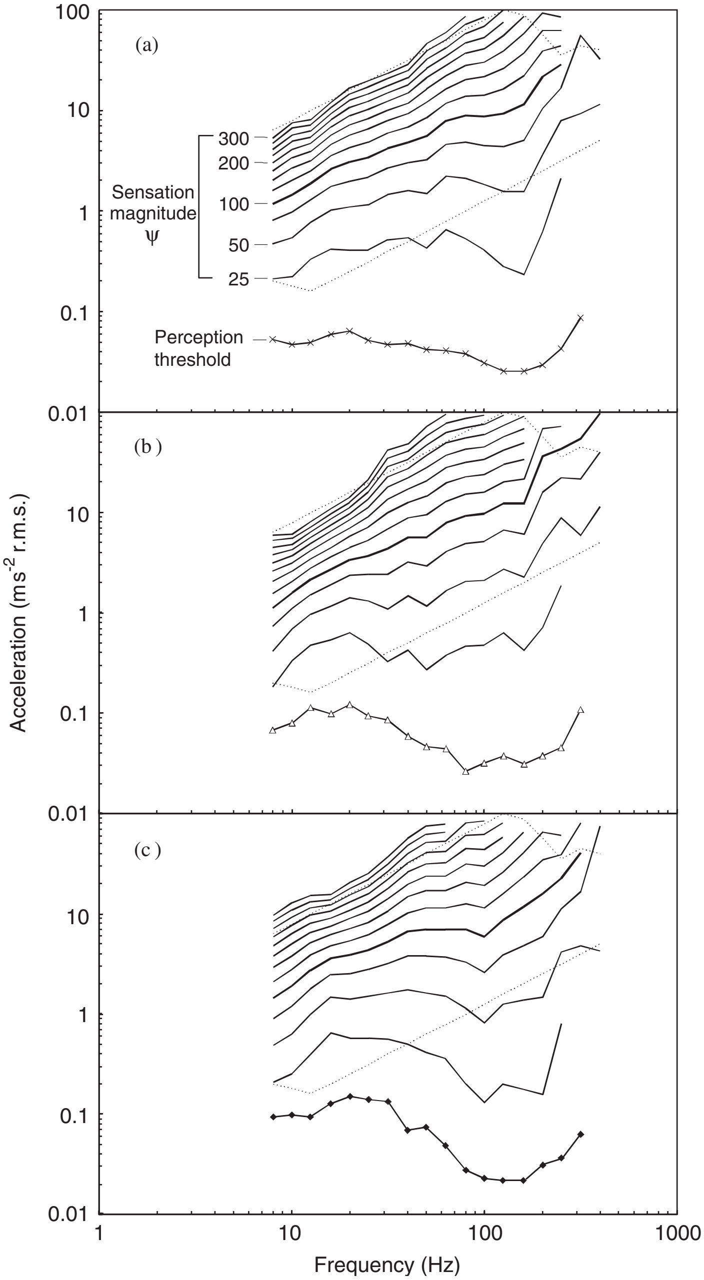

Fig. 6. Equivalent comfort contours for sensation magnitudes, at interval 25 from 25 to 300 relative to vibration magnitude of $5.0\,\mathrm{m\,s^{-2}}$ rms at 50 Hz, based on Eq. (2): (a) fore-and-aft, (b) lateral, and (c) vertical. Median absolute perception threshold contours for each axis determined 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).

vibration. As surmised with the perception thresholds determined in Experiment 1, the frequency-dependence of the comfort contours may be evidence of different psychophysical channels being responsible for magnitude estimates at different frequencies. Since the shape of the threshold contour and comfort contours below about $1\,\mathrm{m\,s^{-2}}$ rms are similar, it can be suggested that the strength of sensation of hand-transmitted vibration at low magnitudes was probably predominantly mediated by the Pacinian channel (FA II) at frequencies greater than about 20 Hz. At frequencies less than about 20 Hz, one of the other channels, probably the NP I channel (FA I), mediated discomfort at low vibration magnitudes.

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

Frequency	Stevens power law with additive constant, Eq. (2)								
	Exponent (n)			Constant (k)			Threshold (φ_0)		
	z	y	x	z	y	x	z	y	x
8	0.710	0.630	0.558	92.087	97.949	84.333	0.053	0.067	0.094
10	0.661	0.788	0.565	79.104	73.097	71.450	0.047	0.079	0.098
12.5	0.743	0.804	0.636	64.003	56.938	53.703	0.050	0.113	0.095
16	0.708	0.781	0.734	51.547	47.098	40.050	0.059	0.097	0.126
20	0.644	0.748	0.644	49.238	41.333	43.112	0.064	0.121	0.152
25	0.621	0.625	0.614	47.195	44.555	41.286	0.051	0.095	0.140
31.5	0.637	0.482	0.559	40.281	49.831	40.050	0.047	0.085	0.134
40	0.614	0.509	0.509	38.309	41.620	38.282	0.048	0.058	0.069
50	0.521	0.431	0.460	41.011	47.610	40.926	0.042	0.046	0.074
63	0.542	0.439	0.448	32.779	40.682	42.170	0.041	0.045	0.048
80	0.481	0.454	0.375	35.245	36.392	48.195	0.038	0.026	0.027
100	0.443	0.450	0.345	38.539	35.934	54.075	0.031	0.032	0.023
125	0.386	0.456	0.359	42.374	31.827	46.345	0.025	0.037	0.022
160	0.345	0.404	0.322	43.072	36.333	45.394	0.026	0.031	0.022
200	0.384	0.348	0.287	30.521	28.741	45.082	0.029	0.038	0.031
250	0.528	0.437	0.409	16.908	19.311	27.925	0.042	0.045	0.036
315	0.224	0.313	0.323	30.458	28.807	30.200	0.088	0.107	0.062
400	0.387	0.318	0.140	19.498	23.259	40.926	0.186	0.262	0.109

The magnitude-dependence of the comfort contours might also be explained by different psychophysical channels being responsible for discomfort at different vibration magnitudes. A study of masked thresholds with the whole hand applied to a rigid flat plate vibrating in the vertical direction concluded that individual thresholds for FA II, FA I, and SA II fibres (Pacinian, NP I and NP II channels, respectively) lie within 30 dB above absolute thresholds [16]. This implies that vibration magnitudes 30 dB above thresholds will excite more than one psychophysical channel. In Fig. 6, the U-shaped portions of the comfort contours at high frequencies (between about 50 and 200 Hz) seem to diminish as the vibration magnitude increases above about 1 m s^{-2} rms With vertical vibration at 125 Hz, the threshold of the NP I channel (FA I) was found at approximately 1.0 m s^{-2} rms, with the Pacinian channel (FA II) mediating the perception of vibration below this magnitude [16]. While this suggests the involvement of several tactile channels over the range of vibration magnitudes and frequencies in the present experiment, it does not identify whether the sensation magnitudes at any one magnitude and frequency are produced by the mediation of a single channel or the combined mediation of two or more channels.

4. General discussion

In each of the three axes, both the perception threshold contours and the equivalent comfort contours suggest that sensitivity to hand-transmitted vibration greatly depends on vibration frequency. This confirms the need for some means of taking account of changes in sensitivity with frequency (i.e. a frequency weighting). International Standard [26] defines a single frequency weighting, W_h, for the evaluation of human exposure to hand-transmitted vibration in any axis. The W_h frequency weighting indicates greatest sensitivity to acceleration at frequencies between 8 and 16 Hz, with sensitivity to acceleration reducing in proportion to frequency from 16 to 1000 Hz. The W_h weighting was derived from equivalent comfort contours and absolute threshold contours determined by Miwa [1] over the frequency range 3–300 Hz with the hand pressing on a flat plate.

The equivalent comfort contours determined in Experiment 2 have been inverted and normalised to vibration acceleration at 8 Hz and overlaid with the frequency weighting W_h and are shown for each axis in

Fig. 7. For sensation magnitudes greater than 200 (producing at least twice the discomfort associated with $5\,\mathrm{m\,s^{-2}}$ rms at 50 Hz), at frequencies greater than 16 Hz, the frequency weightings implied by the present results show some similarity with the W_h frequency weighting: sensitivity decreases in proportion to vibration frequency (i.e. sensitivity independent of vibration frequency when measuring vibration velocity). However, for sensation magnitudes less than 100 (vibration producing less discomfort than $5\,\mathrm{m\,s^{-2}}$ rms at 50 Hz) the sensations caused by vibration at frequencies greater than about 50 Hz are underestimated by frequency

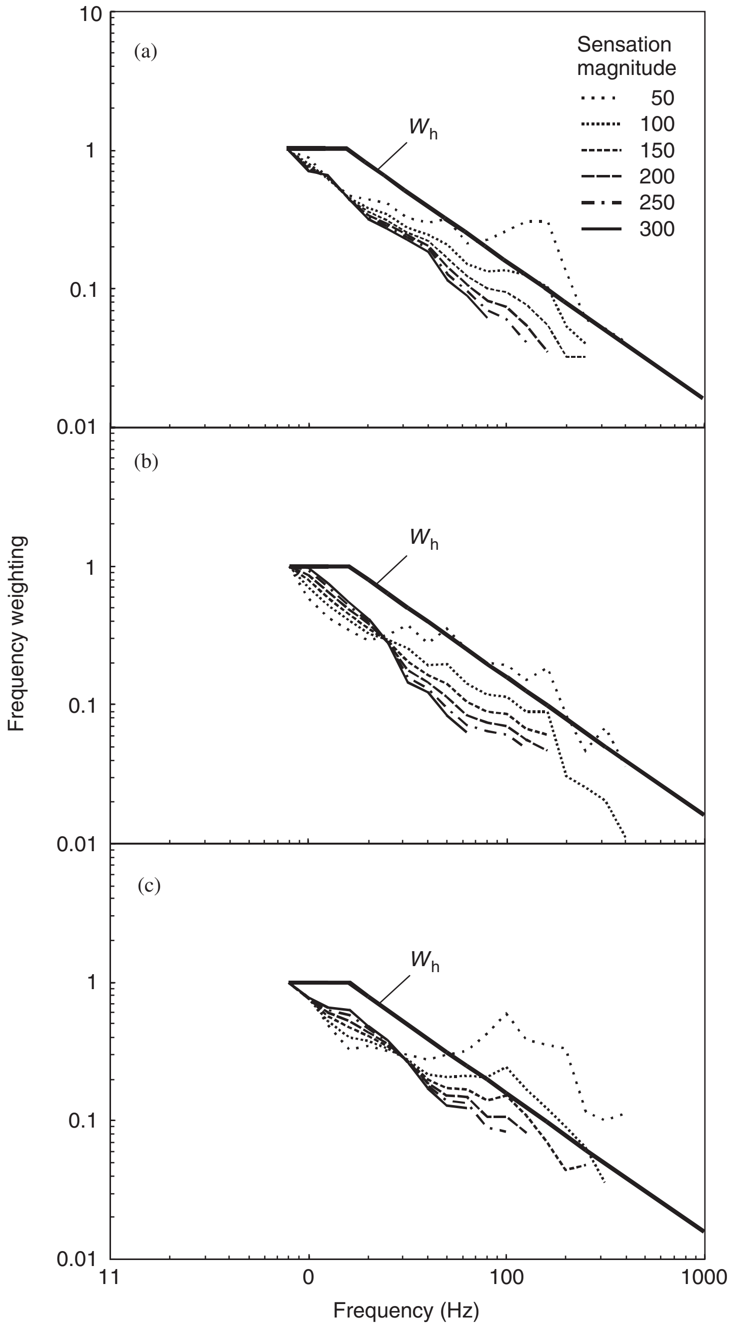

Fig. 7. Effect of magnitude on frequency weightings (inverted equivalent comfort contours normalized at 8 Hz): (a) fore-and-aft, (b) lateral, and (c) vertical. A sensation magnitude of 100 is equivalent to the discomfort caused by $5.0\,\mathrm{m\,s^{-2}}$ rms of 50 Hz. · · · · · · : 50, ⋯⋯: 100, - - - - -: 150, – –: 200, – · –: 250, and ——: 300.

weighting W_h (or, conversely, the frequency weighting W_h overestimates the sensations caused by lower frequencies). At all vibration magnitudes, the contours also show that, unlike the frequency weighting W_h which implies similar sensitivity to vibration acceleration from 8 to 16 Hz, sensation magnitudes progressively reduced with increasing frequency from 8 to 16 Hz. The comfort contours of Miwa [1] also show reduced sensitivity to acceleration with increasing frequency above 5 Hz, unlike the constant sensitivity between 8 and 16 Hz in frequency weighting W_h.

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

A direct comparison between the frequency weightings calculated for the three axes of vibration is shown in Fig. 8 for low, medium, and high vibration magnitudes (equivalent to subjective magnitudes of 50, 100, 200, and 300), assuming equal weight at 8 Hz. It can be seen that the frequency weightings do not differ greatly between the three axes, other than at sensation magnitudes less than 50 (less than half of the discomfort of 5 m s^{-2} rms at 50 Hz) where fore-and-aft vibration tends to have the greatest weighting at frequencies less than 40 Hz and vertical vibration has the greatest weighting at frequencies greater than 50 Hz. This trend is consistent with the perception thresholds in the three axes obtained in Experiment 1: at frequencies less than 50 Hz the hand was most sensitive to fore-and-aft vibration while at frequencies greater than 125 Hz the hand was more sensitive to vertical vibration than lateral vibration (Fig. 3). However, Experiment 2 did not directly investigate the equivalence of vibration discomfort between the three axes—the weightings in Fig. 8 are artificially adjusted to be identical at 8 Hz. The comparison of perception thresholds between the three axes in Fig. 3 implies that at low vibration magnitudes there will be a significant difference in discomfort between the three directions, especially at low frequencies, with appreciably greater discomfort in the fore-and-aft direction at frequencies less than about 50 Hz. Since the rates of growth in discomfort are similar in the three axes (Fig. 4) it follows that this difference will also apply at higher vibration magnitudes. Consequently, whatever frequency weighting is applicable to the three axes, it may be inappropriate to apply the same overall weighting to each of the three axes when evaluating hand-transmitted vibration occurring in the three axes.

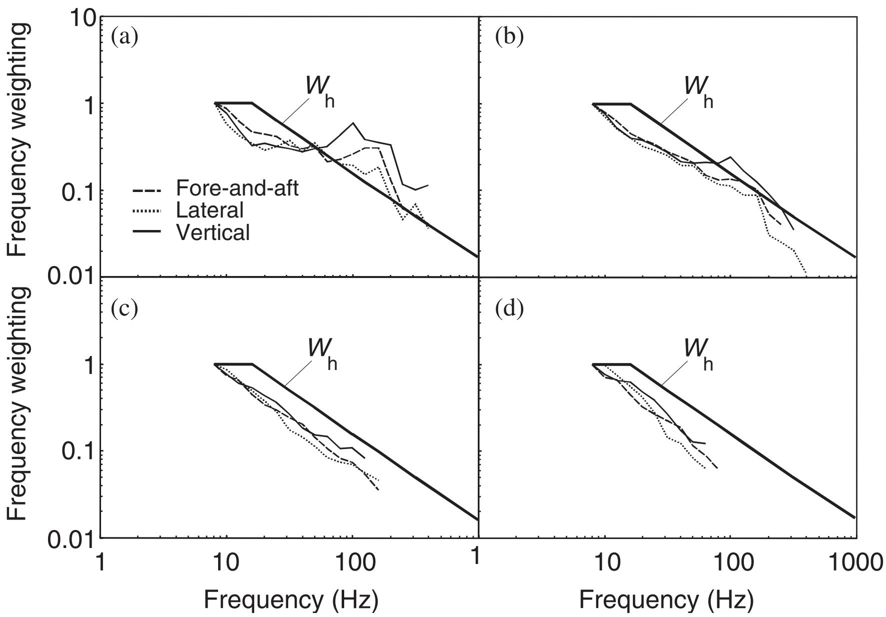

Fig. 8. Effect of vibration axis on frequency weightings (inverted equivalent of comfort contours normalized at 8 Hz) for sensation magnitudes of: (a) 50, (b) 100, (c) 200, and (d) 300 (a sensation magnitude of 100 is the equivalent discomfort produced by 5.0 m s^{-2} rms of 50 Hz). - - - - -: fore-and-aft, · · · · · ·: lateral, and ———: vertical.

Of four classes of mechanoreceptive afferent fibres in the glabrous skin of the hand (fast adapting FA I and FA II fibres and slow adapting SA I and SA II fibres), it seems certain that FA II fibres (i.e. Pacinian corpuscles, Pacinian channel) were involved in the mediation of low sensation magnitudes at high frequencies, as explained above. The FA I fibres (i.e. Meissner's corpuscles, NP I channel) may be suspected as being involved at low frequencies (less than about 20 Hz) because of the similarity in the shapes of the comfort contours with the threshold contours and the supposition that Meissner's corpuscles probably mediated thresholds at these frequencies. However, hand-transmitted vibration would cause some shear movement at the skin in contact with the vibrating handle, and so some sensations may have been mediated by the SA II fibres (i.e. Ruffini endings, NP II channel) that are thought to be sensitive to stretch [27]. Westling and Johansson [28] recorded impulses in single tactile units innervating the human glabrous skin while an object was lifted, positioned in space and replaced using a precision grip between the fingers and thumb. They found that most SA II fibres (Ruffini endings) were excited by skin deformation or stretch caused by grip forces and load forces while grasping the object, suggesting that the SA II fibres may play a role in regulating force coordination. The SA II fibres are also capable of mediating static stimuli and joint movements of the hand and elbow [6]. The SA II fibres, as well as the FA I and FA II fibres, may have contributed to the overall strength of sensation caused by hand-transmitted vibration, particularly with a posture of the hand grasping a handle.

5. Conclusions

When gripping a horizontal cylindrical handle, thresholds for the perception of hand-transmitted vibration in each of the three axes (i.e. fore-and-aft, lateral and vertical) are U-shaped with greatest sensitivity to acceleration in the range 80–160 Hz. At frequencies less than 50 Hz, thresholds are lowest for fore-and-aft vibration, while at frequencies greater than 125 Hz thresholds for vertical vibration are lower than thresholds for lateral vibration.

Within the frequency range 8–400 Hz in each of the three axes, the frequency-dependence of sensations produced by hand-transmitted vibration at supra-threshold levels is dependent on vibration magnitude. At low vibration magnitudes, the equivalent comfort contours have a similar shape to the perception threshold. With increasing vibration magnitude, equivalent comfort contours approximate to contours corresponding to constant velocity. The magnitude-dependence of the equivalent comfort contours suggests that a different psychophysical channel is responsible for discomfort at different vibration magnitudes. The frequency weightings corresponding to the equivalent comfort contours is only consistent with the W_h frequency weighting used in the current International Standard [26] at higher vibration magnitudes (those producing discomfort greater than that caused by $5.0\,\mathrm{m\,s^{-2}}$ rms at 50 Hz) and 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 subjective judgements of discomfort caused by hand-transmitted vibration.

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