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Journal of Sound and Vibration 314 (2008) 357–370
JOURNAL OF SOUND AND VIBRATION
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Absolute thresholds for the perception of fore-and-aft, lateral, and vertical vibration at the hand, the seat, and the foot

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Received 23 November 2006; received in revised form 15 November 2007; accepted 20 December 2007
Handling Editor: C. Morfey
Available online 20 February 2008

Abstract

Oscillatory motions of handles, seats, and floors produce complex patterns of sensations in the body with the detection of these motions dependent on the sensitivity of the body to the applied vibration. This study examined the effect of input location (the hand, the seat, and the foot) and vibration frequency (8–315 Hz at the hand and foot; 2–315 Hz at the seat) on absolute thresholds for the perception of vibration in each of three axes (fore-and-aft, lateral, and vertical). Perception thresholds were determined with 96 males aged 20–29 years divided into eight groups of 12 subjects; each group received vibration at either the hand, the seat, or the foot in one of the three axes (one group experienced both lateral and vertical vibration at the hand). A frequency dependence in the thresholds was apparent for each of the three directions at each of the three locations; U-shaped acceleration threshold contours at frequencies greater than 80 Hz suggest the same psychophysical channel-mediated high-frequency thresholds at the hand, the seat, and the foot. Among the nine axes, sensitivity was greatest for vertical vibration at the seat at frequencies between 8 and 80 Hz, whereas sensitivity was greatest for vertical vibration at the hand at frequencies greater than 100 Hz. Absolute thresholds for the perception of vibration at the hand, the seat, and the foot are not consistent with the relevant frequency weightings in current standards.

1. Introduction

In transport, at workplaces, and during leisure and domestic activities, vibration is felt via the hands, the seat, the back, and the feet. Discomfort, annoyance, or interference with activities may occur if the vibration exceeds the threshold for the perception of the vibration. When there is more than one vibration input to the body (e.g. at the hands, the seat, and the feet), the sensation is most easily detected at the location with greatest sensitivity. Knowledge of differences in the thresholds of perception for vibration between the hand, the seat, and the feet should assist the identification of sources of disturbance caused by vibration.

Thresholds for the perception of vibration have been determined in studies of hand-transmitted vibration [1–5] and in studies of whole-body vibration with seated [6–9] and standing subjects [6,7]. However, there has been little investigation of perception thresholds for the foot resting on a vibrating surface. The thresholds of

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0022-460X/$ - see front matter
doi:10.1016/j.jsv.2007.12.036

hand-transmitted vibration and whole-body vibration reported in previous studies are not easily compared, partly due to the use of different experimental techniques (e.g. different ranges of frequency, different psychophysical methods, different sitting postures, etc.).

The detection of hand-transmitted vibration mainly involves the somatosensory mechanoreceptive (tactile) channels, often classified as Pacinian (P) and non-Pacinian (NP) channels. The P channel is associated with Pacinian corpuscles (FA II) that provide sensations at high frequencies of vibration (e.g. >40–50 Hz) and summate over the stimulus duration and over the excitation area, known as 'temporal summation' and 'spatial summation', respectively [10,11]. The NP channels include the Meissner corpuscles, Merkel disks, and Ruffini endings (i.e. FA I, SA I, and SA II, respectively), and show enhanced sensitivity with increasing stimulus gradients at frequencies less than about 40 Hz [12,13]. With vibrotactile stimuli (vibration perceived at the fingertip or thenar eminence of the hand), a four-channel model of vibrotactile perception has been proposed [14,15]. For vibration applied over the entire hand, the identification of the channels responsible for the detection of hand-transmitted vibration has been attempted by Morioka and Griffin [16] who concluded that at least three channels (Pacinian, NP I, and NP II channels) may be involved in detecting hand-transmitted vibration. For the detection of whole-body vibration, several sensory systems are expected to be involved, including the visual, vestibular, auditory, and somatosensory senses [17].

This study was designed to determine differences in the perception of vibration at the hand, the seat, and the feet while these body parts are in contact with vibrating surfaces in a manner similar to that in transport, work, leisure, and domestic activities. Absolute thresholds for perception of vibration were determined to examine the effects of vibration frequency (8–315 Hz for the hand and foot; 2–315 Hz for the seat), vibration direction (fore-and-aft, lateral, and vertical), and input location (the hand, the seat, and the foot) on absolute thresholds for the perception of vibration. There was no backrest and so thresholds were not influenced by the vibration of a surface in contact with the back. The perception thresholds have been presented previously for hand-transmitted vibration [18] and whole-body vibration [19], in experimental studies determining equivalent comfort contours. In this paper, the frequency dependence of vibration perception thresholds at the seat and foot is compared with those at the hand, so as to assist understanding of the mechanisms involved in the detection of vibration at different body locations.

2. Methods

2.1. Subjects

The experiment was carried out with a total of 9 conditions (3 axes $\times$ 3 body locations). Each experimental condition was completed within a session lasting about 1 h. Eight groups of 12 males (total of 96) aged between 20 and 29 years participated in the experiment. Subjects in each group attended a single experimental session determining perception thresholds for fore-and-aft, lateral, or vertical vibration either at the hand, seat, or foot (except subjects in Group B attended sessions with both lateral and vertical vibration at the hand). All subjects were students or staff of the University of Southampton, with no history of occupational exposure to the whole-body vibration or the hand-transmitted vibration. The characteristics of the subjects in each group are shown in Table 1. There were no significant differences in age, body weight, or stature between the eight groups (Kruskal–Wallis, $p>0.5$).

During the experiments, 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.

The experiment was 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 the subjects.

2.2. Apparatus

Vibration stimuli were presented separately at the hand, the seat or the foot via rigid surfaces. There was no backrest. The direction of the generated vibration was either fore-and-aft, lateral, or vertical in accord with the gravitational (i.e. geocentric) coordinate system (Fig. 1). Two piezoelectric accelerometers (DJ Birchall,

Table 1
Characteristics of the eight subject groups (12 subjects per group): mean (standard deviation)

Vibration location	Vibration axis	Subject group	Age (year)	Weight (kg)	Stature (cm)
HAND	Fore-and-aft	A	25.4 (1.9)	72.2 (10.1)	178.7 (6.4)
HAND	Lateral	B	25.3 (1.8)	73.5 (10.7)	177.8 (5.4)
HAND	Vertical	B	25.3 (1.8)	73.5 (10.7)	177.8 (5.4)
SEAT	Fore-and-aft	C	24.5 (2.5)	71.2 (9.5)	175.6 (7.2)
SEAT	Lateral	D	23.6 (2.5)	73.4 (9.0)	176.8 (5.9)
SEAT	Vertical	E	24.8 (2.2)	76.1 (10.3)	179.4 (8.3)
FOOT	Fore-and-aft	F	25.0 (2.5)	69.9 (11.0)	176.7 (7.8)
FOOT	Lateral	G	24.7 (2.2)	70.3 (6.8)	178.8 (5.9)
FOOT	Vertical	H	24.9 (2.2)	73.1 (7.2)	177.1 (4.8)

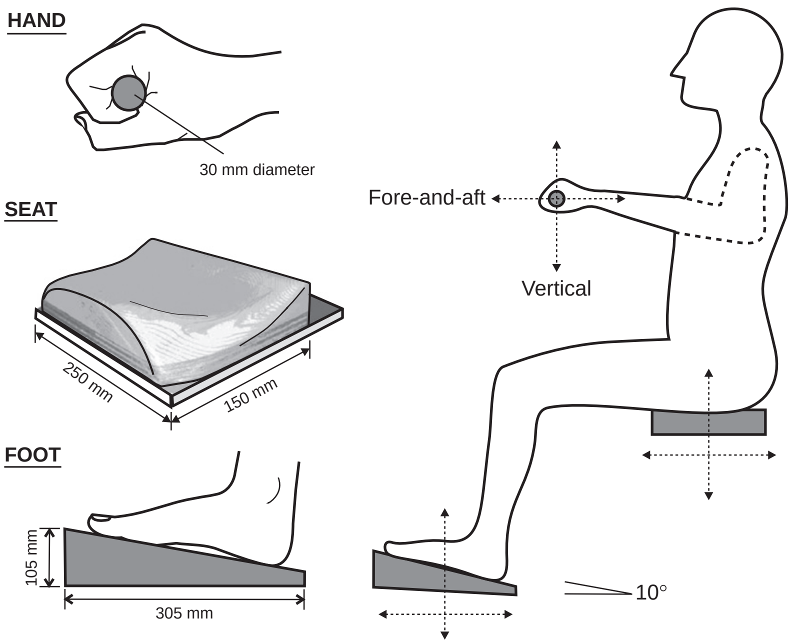

Fig. 1. The rigid handle, the contoured rigid seat and the rigid footrest and body posture adopted by the subjects. The lateral axis is defined as parallel to the handle axis.

model A/20/T at the handle and the footrest; PCB Electronics, model 355B03 at the seat) were mounted on each of the vibrating surfaces so as to monitor the excitation as well as the greatest expected cross-axis motion.

For vibration of the hand, a rigid cylindrical handle (100 mm in length, 30 mm in diameter) was mounted rigidly to the vibrator (Derritron VP30 for fore-and-aft or lateral vibration, Derritron VP4 for vertical vibration). Cross-axis acceleration was less than 5% of the magnitude in the desired axis.

For vibration at the seat, a rigid wooden seat (250 mm × 150 mm) was mounted to a vibrator (Derritron VP85 via Kimball slip table for fore-and-aft and lateral vibration, Derritron VP180 for vertical vibration). The seat had a contoured surface to provide contact with the ischial tuberosities (Fig. 1). The arrangement was designed to achieve resonance frequencies greater than 315 Hz with minimum cross-axis vibration (generally less than 5%, less than 10% at frequencies greater than about 160 Hz).

For vibration of the foot, a wooden footrest (30.5 mm × 10.5 mm with 10° inclination) was mounted rigidly to the vibrator (Derritron VP75 via Kimball slip table for fore-and-aft and lateral vibration, Derritron VP30 for vertical vibration). Cross-axis accelerations were less than 5% of the magnitude in the desired axis.

Background vibration, mainly due to electrical noise at 50 Hz, was less than 0.008 $m\,s^{-2}$ rms, and was not perceptible via the handle, the seat, or the footrest.

The subjects were exposed to vibration at only one of their two hands or at only one of their two feet. For the non-exposed hand or foot, a stationary handle, and footrest with the same dimensions as the vibrating handle and footrest were provided so that the same body posture was adopted among the eight groups of subjects (see Fig. 1).

Sinusoidal vertical 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.

2.3. Stimuli and procedure

Absolute thresholds for the perception of vibration were determined using sinusoidal acceleration at each of the 17 preferred one-third octave centre frequencies between 8 and 315 Hz for hand and foot vibration and the 23 preferred one-third octave centre frequencies between 2 and 315 Hz for seat vibration. The frequency ranges were determined partly by practical limitations, partly from the results of preliminary experimentation, and partly by considering the various practical applications of the thresholds at each location of contact. The stimuli were 2.0 s in duration, including 0.5-s cosine-tapered ends.

An up-down (staircase) algorithm was employed to determine thresholds in conjunction with a three-down one-up rule. A single test stimulus, 2.0 s in duration, was presented 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 3 dB (41.3% increment) after a negative ('no') response from a subject and decreased in magnitude by 3 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 [20]. The order of presenting the test frequencies was randomised. The absolute thresholds determined in this study are expressed in terms of the root-mean-square acceleration (i.e. $m\,s^{-2}$ rms), which is the preferred method of quantifying human exposure to vibration in relevant International Standards [21–23]. Since all the thresholds were determined with sinusoidal vibration, the acceleration thresholds can easily be converted to peak displacement, as sometimes used in psychophysical research.

Skin temperature of the hands and feet were measured at the beginning and end of each session using an *HVLab* Tactile Aesthesiometer (by means of thermocouples). The threshold test was allowed to proceed if the skin temperature is higher than 29 °C at the hands and higher than 23 °C at the feet.

The subjects were instructed to maintain their body posture during the threshold tests: sitting upright with comfortable postures with their eyes open, looking straight ahead with their hands on the handles and their feet on the footrests. The upper surfaces of their upper legs were approximately horizontal, their feet were approximately 400 mm apart, and their forearms were approximately horizontal and level with the handles. Subjects were instructed to grasp the handles with forces that they felt most comfortable, but ensuring that much of the glabrous skin of the hand was in contact with the handle. The subjects wore normal clothes (without jackets or coats) and thin socks but not shoes. Their trousers were rolled up to the knee level so as to minimise any sensation due to movements of the trousers. Any loose sleeves of the subjects were also rolled up to the elbow level for the same reason.

2.4. 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 and the effect of body location (independent samples), was examined using the Kruskal–Wallis and Mann–Whitney U tests. For the case of comparing the thresholds between the fore-and-aft and vertical vibration at the hand (related samples), the Wilcoxon-matched-pairs signed ranks test was applied.

The statistical results were not adjusted for multiple comparisons. The significance criteria for two independent samples and two dependent samples were set at $p = 0.05$.

3. Results

3.1. Effect of frequency

The median absolute thresholds and the inter-quartile range (25–75th percentiles) of the 12 subjects determined for the hand, the seat, and the foot in each of the three axes of vibration (fore-and-aft, lateral, and vertical) are presented as a function of vibration frequency in Fig. 2. Threshold contours determined from other studies are overlaid for comparison.

With vibration at the hand, the acceleration perception thresholds in all three axes were highly dependent on vibration frequency (Friedman, $p<0.001$), presenting U-shaped contours with greatest sensitivity to acceleration around 80–160 Hz. Within each of the axes, there was no significant difference in sensitivity between each one-third octave step from 16 to 31.5 Hz in the fore-and-aft axis (Wilcoxon, $p>0.05$), from 10 to

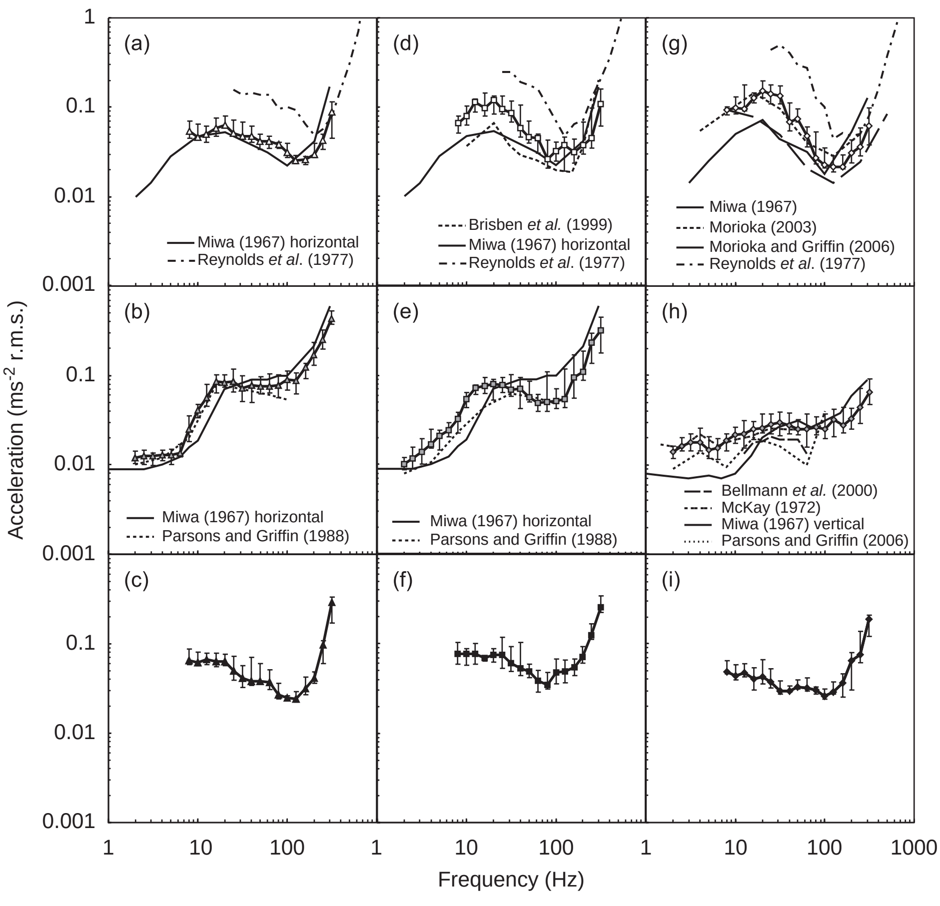

Fig. 2. Median absolute thresholds at each of the three axes at the hand (a, d, and g), at the seat (b, e, and h) and at the foot (c, f, and i), overlaid with threshold contours from other studies. (a, b, and c) Fore-and-aft, (d, e, and f) lateral, (g, h, and i) vertical. Error bars represent inter-quartile range.

31.5 Hz in the lateral axis (Wilcoxon, $p>0.05$) and from 12.5 to 31.5 Hz in the vertical axis (Wilcoxon, $p>0.05$). There was a significant increase in sensitivity with each one-third octave step from 31.5 to 80 Hz in the fore-and-aft and lateral axes (Wilcoxon, $p<0.05$, except between 50 and 80 Hz in the fore-and-aft axis and between 40 and 50 Hz in the lateral axis) and from 31.5 to 100 Hz in the vertical axis (Wilcoxon, $p<0.05$, except between 40 and 50 Hz). There was a significant decrease in sensitivity with each one-third octave step from 160 to 315 Hz (Wilcoxon, $p<0.05$, except between 160 and 200 Hz in the lateral axis and between 200 and 250 Hz in the vertical axis).

With vibration at the seat, the acceleration perception thresholds also depended on vibration frequency (Friedman, $p<0.001$) with a general trend towards higher thresholds with increasing frequency over the range investigated (2–315 Hz). With fore-and-aft vibration, there was no significant change in the acceleration threshold for all combinations of pairs of frequencies between 2 and 6.3 Hz (Wilcoxon, $p>0.05$, except the combination between 2 and 6.3 Hz), then a significant increase in thresholds with each one-third octave step from 6.3 to 16 Hz (Wilcoxon, $p<0.01$), followed by no change in the acceleration threshold between 16 and 125 Hz (Wilcoxon, $p>0.05$, except between 16 and 40 Hz, between 40 and 100 Hz, and between 80 and 100 Hz), and a significant increase in acceleration thresholds at frequencies greater than 125 Hz (Wilcoxon, $p<0.05$). With lateral vibration, there was a significant increase in threshold with each one-third octave step from 3.15 to 12.5 Hz (Wilcoxon, $p<0.05$, except between 4 and 5 Hz), followed by no change in the acceleration threshold between 16 and 125 Hz (Wilcoxon, $p>0.05$, except combinations of 63 Hz with 16–40 Hz), and a significant increase in acceleration thresholds at frequencies >125 Hz (Wilcoxon, $p<0.05$). With vertical vibration, there was a marginally non-significant change in acceleration thresholds between 16 and 200 Hz (Friedman $p = 0.052$), but a significant increase in acceleration thresholds with each one-third octave step from 200 to 315 Hz (Wilcoxon, $p<0.05$).

With vibration at the foot, there was no frequency dependence in the acceleration perception thresholds at low frequencies: from 8 to 25 Hz in the fore-and-aft axis (Friedman $p = 0.267$) and the vertical axis (Friedman, $p = 0.119$), from 8 to 40 Hz in the lateral axis (Friedman, $p = 0.353$). A frequency dependence was apparent at high frequencies, presenting a slight U-shaped contour with a greatest sensitivity at about 100 Hz then a significant increase in the acceleration thresholds with each one-third octave step from 125 to 315 Hz in the fore-and-aft and lateral axes (Wilcoxon, $p<0.01$) and with each one-third octave step from 200 to 315 Hz in the vertical axis (Wilcoxon $p<0.01$).

There were no systematic correlations between age and any of the measured thresholds. There was a tendency for negative correlations between thresholds at the seat and body stature (i.e. standing height), which were statistically significant at 125 Hz with fore-and-aft vibration (Spearman, $p = 0.029$), at 2 Hz with lateral vibration (Spearman, $p = 0.013$), and at 2 and 2.5 Hz with vertical vibration (Spearman, $p<0.05$), suggesting that taller subjects had lower thresholds for whole-body vibration.

3.2. *Effect of axis*

The median absolute thresholds for the perception of vibration in the three axes (i.e. fore-and-aft, lateral, and vertical) were compared within each location of excitation (i.e. at the hand, the seat, and the foot) and are shown in Fig. 3.

At low frequencies (<50 Hz), the hand was most sensitive to fore-and-aft vibration: the fore-and-aft thresholds were significantly lower than the vertical thresholds at frequencies less than 50 Hz (Mann–Whitney, $p<0.05$) and significantly lower than the lateral thresholds at frequencies between 10 and 25 Hz (Mann–Whitney, $p<0.05$). The lateral thresholds were generally lower than the vertical thresholds at frequencies less than 31.5 Hz (Wilcoxon, $p<0.05$), except at 10 and 12.5 Hz (Wilcoxon, $p>0.2$). At frequencies greater than 63 Hz, there were no significant 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 the lateral thresholds at frequencies greater than 125 Hz ($p<0.05$).

With seat vibration, the thresholds differed significantly between the three axes (Kruskal–Wallis, $p<0.05$), except at the lowest frequency of 2 Hz (Kruskal–Wallis, $p = 0.067$). At frequencies, greater than 10 Hz, the body was most sensitive to vertical vibration: vertical thresholds were significantly lower than fore-and-aft

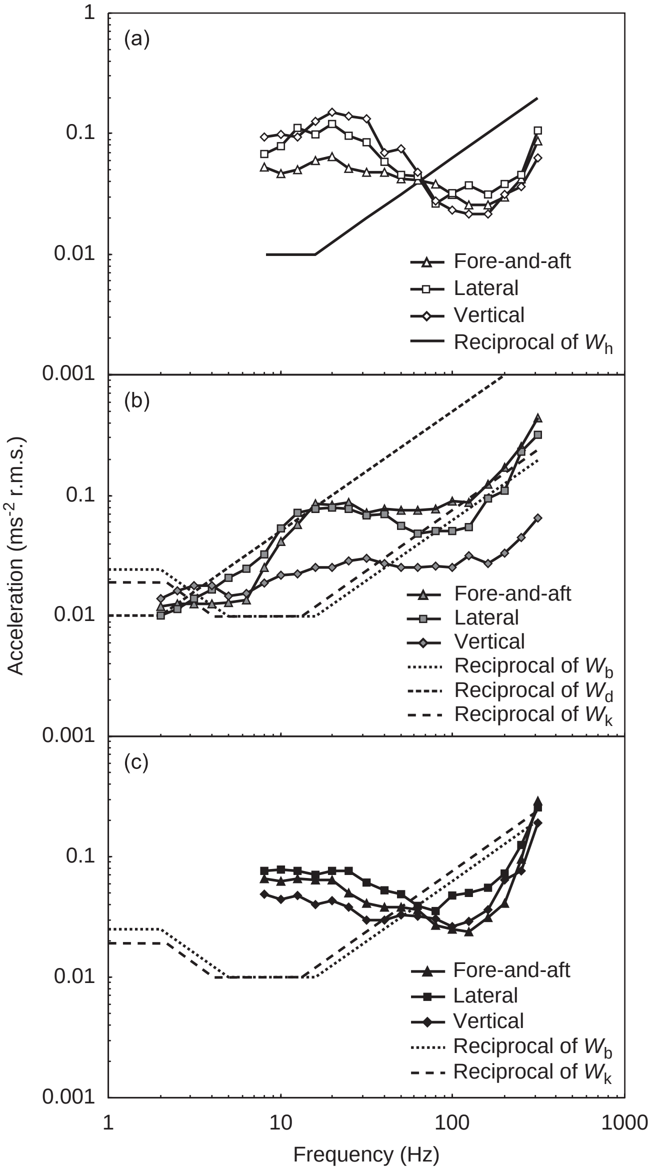

Fig. 3. Comparison of median perception threshold contours between the three axes: (a) hand, (b) seat, and (c) foot. The reciprocals of W_h (—), W_b (⋯⋯), W_d (- - - -), and W_k (– – –) frequency weightings normalised to 0.01 m s^{-2} rms (and extrapolated) are overlaid.

thresholds and lateral thresholds at all frequencies between 10 and 315 Hz (Mann–Whitney, $p<0.01$). In contrast, at frequencies less than 3.15 Hz, sensitivity to vertical vibration was less than sensitivity to fore-and-aft vibration (Mann–Whitney, $p<0.05$).

With foot vibration, the thresholds differed significantly between the three axes (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 less 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 fore-and-aft thresholds at frequencies <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, $p>0.1$).

3.3. Effect of location

The median absolute thresholds at the three input locations (i.e. the hand, the seat, and the foot) are compared within axes in Fig. 4.

With fore-and-aft vibration, there was a statistically significant effect of input location at all frequencies investigated (Kruskal–Wallis, $p<0.05$, except at 40 Hz, $p=0.158$). Sensitivity to fore-and-aft vibration was the greatest at the seat at 8 Hz (Mann–Whitney, $p<0.01$) but least at frequencies greater than 40 Hz

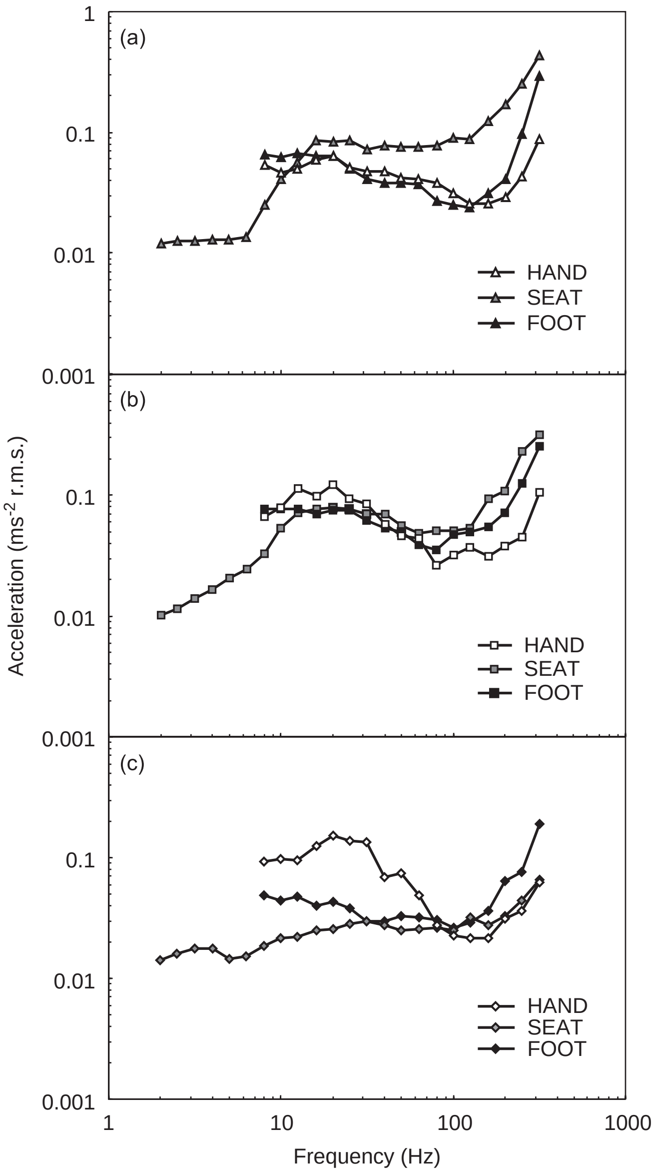

Fig. 4. Comparison of median perception threshold contours between the hand, the seat and the foot: (a) fore-and-aft, (b) lateral, and (c) vertical.

(Mann–Whitney, $p<0.05$, except between the hand and the seat at 40 Hz, $p = 0.052$). At frequencies between 16 and 160 Hz, thresholds of fore-and-aft vibration at the hand and the foot did not differ significantly (Mann–Whitney, $p>0.05$, except at 100 Hz, $p = 0.008$), but thresholds for hand vibration were significantly lower than those for foot vibration at frequencies greater than 200 Hz (Mann–Whitney, $p<0.05$).

With lateral vibration, the thresholds between 25 and 63 Hz did not differ significantly among the three locations (hand, seat, and foot). Between the three locations, the seat was more sensitive to lateral vibration at 8 and 10 Hz (Mann–Whitney, $p<0.05$). The hand was less sensitive to lateral vibration than the seat and foot at 12.5, 16, and 20 Hz (Mann–Whitney, $p<0.05$), but more sensitive than the seat and foot at frequencies greater than 100 Hz (Mann–Whitney, $p<0.05$).

With vertical vibration, at frequencies less than 63 Hz, the thresholds differed significantly between the three input locations (Kruskal–Wallis, $p<0.01$); sensitivity to vertical vibration was greater at the seat than at the hand at frequencies less than 63 Hz (Mann–Whitney, $p<0.01$) and at the foot at frequencies less than 25 Hz (Mann–Whitney, $p<0.05$). At frequencies between 80 and 160 Hz, there were no differences in vertical thresholds between the three locations (Kruskal–Wallis, $p>0.05$). At frequencies greater than 200 Hz, sensitivity to vertical vibration at the foot was least (Mann–Whitney, $p<0.05$).

4. Factors influencing the measured perception thresholds

In the present studies, forces between the body and the sources of vibration were not controlled at specific values but the subjects were instructed to maintain specific body postures (sitting upright with their feet supported while grasping handles with forces that they felt most comfortable). Variations in force or pressure at the point of contact with vibration may alter perception thresholds. For the Pacinian channel, the threshold of perception for vibration of a small circular probe applied at the fingertip or the thenar eminence decreases with increasing force [24,25]. However, the contact conditions are very different when vibration is applied to the whole hand.

Brisben et al. [3] determined perception thresholds for the hand using a 32-mm diameter cylinder applied at the distal phalanx of the third digit or at the distal part of the palm and found no significant effect of variations in contact force (from 0.05 to 0.1 N) for either 40- or 300-Hz thresholds. Morioka and Griffin [5] determined perception thresholds for the whole distal finger in contact with a flat vibrating surface with two contact forces (1 and 5 N) and found that the five-fold increase in contact force increased 125-Hz thresholds by 65%, unlike the decrease in thresholds found in studies with small contact areas [24,25]. Morioka and Griffin [5] also investigated the effect of contact area and contact location over the hand for perception thresholds at frequencies between 16 and 125 Hz by progressively extending the contact area from the distal finger to the whole hand while maintaining a constant contact force of 5 N. The thresholds at all frequencies decreased (by up to a factor of five) with increases in the contact area from the distal finger to the whole hand. It seems likely that for the variability usually present in practical situations the variations in contact force will have less influence on perception thresholds than variations in the location of contact and the area of contact with vibration.

In the present study, the area of contact with the vibrating surfaces inevitably differed between the three body locations investigated (i.e. at the hand, the seat, and the foot). For the Pacinian channel, a 3 dB decrease in thresholds is expected per doubling of contact area due to 'spatial summation' [10]. The differences in thresholds between the body locations found in the present study cannot be explained by spatial summation since sensitivity to vibration at frequencies greater than 40 Hz was not greatest at the seat, despite this excitation having the largest contact area.

Variations in vibrotactile sensitivity over the body surface have been investigated by Wilska [26] using a cylindrical piece of wood (1.0 cm^2 in area) over the frequency range from 25 to 1280 Hz. The results showed that the hand was the region most sensitive to vibration whereas the gluteal region was the least sensitive. This differs from the present findings and suggests that thresholds for the perception of vibration at the hand, the seat, and the feet may not be adequately predicted from the thresholds obtained using small areas of skin excitation.

In the present studies, the vibration was transmitted into the body so that, as in transport, at workplaces, and during leisure and domestic activities, there was movement of body parts and not only the excitation of a small area on the body surface. While fundamental studies of vibrotactile sensitivity have uncovered the influences of some factors influencing vibration thresholds (e.g. effects of contact area and contact location), they do not yet provide sufficient understanding to either explain or accurately predict thresholds for the perception of vibration in practical situations.

5. Discussion

The ways in which the perception thresholds in the present results depend on the frequency of vibration are broadly similar to those determined in other studies with vibration of the hand [1–5] and the seat [6–9], as seen in Fig. 2. The higher thresholds for hand-transmitted vibration from Reynolds et al. [2] may be partly due to the use of different psychophysical methods. The present study employed a staircase method in conjunction with a 'yes–no' procedure in which subjects responded if they felt the intermittent vibration stimulus, whereas Reynolds et al. [2] asked the subjects to adjust the magnitude of the continuous vibration stimulus until they determined that the sensation produced by the vibration was 'just barely perceptible'. Miwa [1,6], Brisben et al. [3], Morioka and Griffin [5] and McKay [9] employed a two-alternative forced-choice method (Bellmann et al. [8] employed a three-alternative forced-choice method) in which the subjects chose which of two stimuli they felt. A comparison of vibrotactile thresholds at the fingertip obtained with three different psychophysical methods, including a two-interval forced-choice method and a 'yes–no' method, found significantly lower thresholds with the two-interval forced-choice method [27].

Differences in thresholds between the studies may also be attributed to differences in body posture or body support. For low-frequency vibration of the seat, a stationary footrest is expected to increase sensitivity compared to footrest moving with the seat, due to increased relative motion between the seat and the footrest, as found by Jang and Griffin [28]. Although Miwa [6] and Parsons and Griffin [7] employed a stationary footrest (with no backrest) as in the present study, the surfaces of their seats were large enough to contact the buttocks and thighs, whereas the seat used in the present study did not contact the thighs. The absence of thigh contact in the present studies may have reduced sensitivity to low frequency vertical seat vibration in this study and slightly raised the low-frequency thresholds.

The detection of hand-transmitted vibration is thought to involve Pacinian (P) and non-Pacinian (NP) channels. The U-shaped acceleration threshold contour at the hand suggests some involvement of the Pacinian channel mediating perception of the stimuli, as found in other studies of vibrotactile thresholds [12,13]. The results are also consistent with the involvement of the Pacinian channel in the detection of vertical hand-transmitted vibration at frequencies greater than about 20 Hz [5]. The similar shape to the threshold contour obtained for the hand, the seat and the foot at frequencies greater than approximately 80 Hz suggests the same channel (i.e. P channel) mediated the perception of the vibration stimuli at threshold for all three locations. Some vibration stimuli may have been felt as a result of shear strain in the tissues exciting a tactile channel. Westling and Johansson [29] 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. It was found that most SA II fibres (NP II channel) were excited by skin deformation or stretch caused by grip forces and load forces while grasping the object, suggesting that the SA II fibres play a role in regulating force coordination. Further investigation is required to improve understanding of the mechanisms involved in the detection of the various directions of vibration at all locations over the body.

The detection of low-frequency vibration may be influenced by sensory systems other than the Pacinian channel. Hand-transmitted vertical vibration at frequencies less than about 20 Hz is likely to be detected via the non-Pacinian (NP) channels [5]. Whole-body vibration can be detected by vision, and vestibular, and acoustic senses [17]. The present study required subjects to keep their eyes open and look ahead during the threshold measurements, which may have allowed some visual cues for some subjects and lowered thresholds at low frequencies, possibly below about 5 Hz. The extent and location of somatosensory detection of whole-body vibration in the seated body may be dependent on the transmission of vibration within the body. When seated on a rigid flat surface with no backrest, the apparent mass of the body shows a first resonance with vertical excitation at about 5 Hz (e.g. Ref. [30]), and resonances around 1.5 and 3 Hz with fore-and-aft and lateral excitation (e.g. Ref. [31]). Whitham and Griffin [32] found maximum sensitivity to vertical vibration acceleration in the range 4–16 Hz, with discomfort experienced in the upper torso and head, whereas with fore-and-aft and lateral vibration of seated subjects, sensitivity to acceleration decreased with increasing frequency and discomfort was mainly experienced at the ischial tuberosities.

For predicting various effects of vibration (e.g. perception, discomfort, annoyance, health risks, interference with activities), current standards advocate the use of frequency weightings. High gain at some frequency in a weighting indicates high sensitivity to vibration relative to other frequencies, whereas low gain indicates low sensitivity relative to other frequencies. Frequency weightings for comfort can be derived from the reciprocals of equivalent comfort contours since where low magnitudes are required to produce discomfort a high weighting is appropriate. The frequency weighting W_h is used to evaluate the severity of hand-transmitted vibration in each of the three orthogonal axes (i.e. x-, y-, z-axes) (ISO 5349-1 [21]). Fore-and-aft and lateral seat vibration are evaluated using W_d in both British Standard [22] and International Standard [23], while vertical seat vibration is evaluated using W_b in British Standard [22] and either W_b or W_k in International Standard [23]. Vibration in each of the three orthogonal axes (i.e. x, y, z axes) at the foot is evaluated using W_b in British Standard [22] and either W_b or W_k in International Standard [23]. For evaluating the effect of vibration on human comfort, International Standard [23] allows the use of W_b as an acceptable approximation to W_k, which has slightly greater weighting at frequencies less than 5 Hz and less weighting at frequencies greater than 12.5 Hz. The W_k weighting was based on the personal preference of some committee members, whereas W_b was based on equivalent comfort contours at vibration magnitudes well in excess of absolute thresholds for the perception of vibration. The experimentally determined thresholds are compared with the reciprocals of the W_h, W_b, W_k, and W_d frequency weightings in Fig. 3. It is evident that the threshold contours for the hand, the seat, and the foot do not match the shapes of the reciprocals of either W_h, W_b, or W_d. The differences indicate that the frequency weightings will greatly underestimate human perception of high-frequency vibration at the hand, the seat, and the foot or, conversely, overestimate the perception of low frequencies.

For prediction of the perception of vibration by seated persons, British Standard 6841 [22] and International Standard 2631 [23] state that fifty percents of alert, fit persons can just detect a weighted vibration with a peak magnitude of approximately 0.015 m s^{-2}, with an inter-quartile range of responses from about 0.01 to 0.02 m s^{-2} peak. If the standards provided appropriate predictions of the perception of vibration, the experimentally determined thresholds (in peak acceleration) multiplied by the appropriate frequency weighting at each frequency should produce values close to 0.015 m s^{-2} at all frequencies and in all three axes. Fig. 5 shows the experimentally determined thresholds for seated subjects after frequency weighting by W_d (for fore-and-aft and lateral vibration) and by W_b (for vertical vibration). The weighted thresholds are not constant at $\pm$0.015 m s^{-2}. Frequency weighting W_d gives a reasonable prediction of sensitivity to lateral vibration at frequencies between 2 and 31.5 Hz, but greatly underestimates sensitivity at frequencies greater

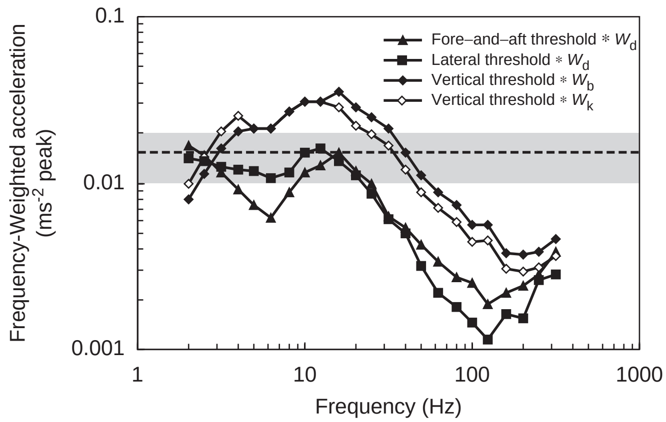

Fig. 5. Frequency-weighted median perception thresholds (m s^{-2} peak) for each of the three axes of vibration at the seat. Frequency weightings (i.e. W_b, W_d, and W_k) for frequencies >100 Hz were extrapolated. ▲: W_d weighted fore-and-aft threshold, ■: W_d weighted lateral threshold, ♦: W_b weighted vertical threshold, ◇: W_k weighted vertical threshold. ----- (with grey zone): predicted perception threshold of vibration experienced by seated persons according to British Standard 6841 [22].

Table 2
Median perception thresholds (m s^{-2} rms) determined for each of the nine axes (three axes at the hand, the seat and the foot)

Frequency	Hand			Seat			Foot		
	Fore-and-aft	Lateral	Vertical	Fore-and-aft	Lateral	Vertical	Fore-and-aft	Lateral	Vertical
2				0.012	**0.010**	0.014			
2.5				0.013	**0.012**	0.016			
3.15				**0.013**	0.014	0.018			
4				**0.013**	0.017	0.018			
5				**0.013**	0.021	0.015			
6.3				**0.014**	0.024	0.015			
8	0.053	0.067	0.094	0.025	0.033	**0.019**	0.065	0.076	0.049
10	0.047	0.079	0.098	0.041	0.054	**0.022**	0.062	0.077	0.044
12.5	0.050	0.113	0.095	0.057	0.072	**0.022**	0.066	0.077	0.048
16	0.059	0.097	0.126	0.086	0.076	**0.025**	0.064	0.070	0.040
20	0.064	0.121	0.152	0.084	0.079	**0.025**	0.064	0.076	0.043
25	0.051	0.095	0.140	0.087	0.077	**0.028**	0.050	0.076	0.038
31.5	0.047	0.085	0.134	0.071	0.069	**0.030**	0.041	0.061	**0.030**
40	0.048	0.058	0.069	0.077	0.070	**0.027**	0.038	0.053	0.030
50	0.042	0.046	0.074	0.075	0.056	**0.025**	0.038	0.049	0.033
63	0.041	0.045	0.048	0.075	0.049	**0.025**	0.037	0.039	0.032
80	0.038	**0.026**	0.027	0.077	0.051	**0.026**	0.027	0.035	0.031
100	0.031	0.032	**0.023**	0.089	0.051	0.025	0.025	0.047	0.026
125	0.025	0.037	**0.022**	0.089	0.054	0.032	0.024	0.049	0.029
160	0.026	0.031	**0.022**	0.125	0.093	0.027	0.031	0.055	0.037
200	**0.029**	0.038	0.031	0.171	0.109	0.033	0.041	0.072	0.064
250	0.042	0.045	**0.036**	0.252	0.231	0.044	0.096	0.124	0.077
315	0.088	0.107	**0.062**	0.436	0.319	0.065	0.292	0.256	0.189

Bold text indicates the lowest thresholds at each frequency.

than about 31.5 Hz, with an error as much as a factor of 10. Frequency weighting W_d is less accurate with fore-and-aft vibration. Frequency weighting W_b overestimates sensitivity to vertical vibration at frequencies between about 8 and 30 Hz but underestimates sensitivity at frequencies greater than about 63 Hz, if frequency weighting W_k were used in place of W_b, the underestimate of sensitivity is even greater at high frequencies. For seated subjects, perception thresholds for vertical acceleration have little dependence on frequency, with the median threshold in the range 0.01–0.03 m s^{-2} rms at frequencies between 2 and 100 Hz (see Table 2). Consequently, unweighted acceleration is a more accurate, and sometimes more convenient, measure for predicting whether vertical seat vibration will be perceived.

When the hands, the seat, and the feet are exposed to vibration simultaneously, it may be assumed that vibration will be most perceptible at the location with the greatest sensitivity. The median perception thresholds for all the nine conditions (three directions at the hand, the seat, and the foot) determined in this study are shown in Table 2 and indicate the greatest sensitivity (lowest thresholds) at each frequency. It is seen that vertical vibration at the seat is likely to provide the greatest sensitivity among the nine axes at frequencies between 8 and 80 Hz, whereas vertical vibration at the hand is likely to produce greatest sensitivity among the nine axes at frequencies greater than 100 Hz. In practice, the hands, the seat, and the feet are usually exposed to different levels of vibration in different frequency ranges. For example, seats amplify some low frequencies of vibration and attenuate high-frequency vibration, so further increasing the probability of detecting seat vibration at low frequencies but hand (or foot) vibration at high frequencies.

6. Conclusions

Perception thresholds for vibration of the hand, the seat, and the foot are highly frequency dependent. Sensitivity to vibration also differs between the three locations. Thresholds for the hand suggest that at frequencies greater than about 20 Hz, perception is mediated by the Pacinian channel. A similar frequency dependence for thresholds at the hand, the seat, and the foot suggests the Pacinian channel may mediate thresholds in all three axes at frequencies greater than about 80 Hz. The perception of vibration at frequencies less than about 20 Hz may involve other tactile channels and other sensory systems, including vision.

Among the nine axes, sensitivity is greatest for vertical vibration at the seat at frequencies between 8 and 80 Hz, whereas sensitivity is greatest for vertical vibration at the hand at frequencies greater than 100 Hz.

The relevant frequency weightings (e.g. W_h, W_b, or W_k, and W_d) in current standards are not consistent with absolute thresholds for the perception of vibration at the hand, the seat, and the foot. The unweighted acceleration is a better predictor than weighted acceleration of whether vertical vibration of seated subjects will be felt.

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