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Thresholds for the perception of fore-and-aft, lateral and vertical vibration by seated persons

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Vibration experienced in transport and in buildings can yield discomfort or annoyance if the vibration exceeds the threshold for vibration perception. Knowledge of thresholds makes it possible to determine which frequencies and directions of low magnitude vibration give rise to perception. The effect of vibration frequency (2 to 315 Hz) on absolute thresholds for the perception of whole-body vibration has been determined experimentally with 12 seated persons for each of the three axes of excitation (fore-and-aft, lateral and vertical). The frequency-dependence of the thresholds differed between the three axes. At frequencies, greater than 10 Hz, sensitivity was greatest for vertical vibration. At frequencies less than 3.15 Hz, sensitivity was greatest for fore-and-aft vibration. In all three axes, the acceleration threshold contours at frequencies greater than 80 Hz were U-shaped, suggesting the same psychophysical channel mediated high frequency thresholds for fore-and-aft, lateral and vertical vibration. It is shown that the frequency-dependencies of absolute thresholds for the perception of whole-body vibration are not consistent with the frequency weightings used in current standards.

1 Introduction

In transport and buildings, people can experience discomfort or annoyance if the magnitude of a vibration exceeds the absolute threshold for the perception of the vibration. Absolute thresholds for the perception of whole-body vibration by seated persons have been determined over the frequency range from 0.5 to 300 Hz for vertical vibration [1-4], lateral vibration [1, 2], and fore-and-aft vibration [1, 2]. However, no previous study has determined thresholds over this range at all preferred one-third octave centre frequencies or investigated statistically the differences between thresholds in the three axes.

The objectives of this study were to examine: (i) the effect of vibration frequency, and (ii) the effect of vibration direction on absolute thresholds for the perception of whole-body vibration by seated persons.

2 Methods

2.1 Subjects

Perception thresholds were determined with 36 males aged between 20 and 29 years. Twelve subjects in each of three groups attended a single experimental session during which perception thresholds were determined for fore-and-aft, lateral or vertical vibration presented at the seat (with no backrest). There were no significant differences in age, body weight or stature between the three groups of subjects (Kruskal-Wallis, $p>0.5$).

During the experimental sessions, 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.

2.2 Apparatus

Vibration stimuli were presented via a rigid wooden seat (250 mm x 150 mm) mounted to a vibrator (a Derritron VP85 via a Kimball slip table for fore-and-aft and lateral vibration, a Derritron VP180LS for vertical vibration). The seat had a contoured surface to provide contact around the ischial tuberosities (Fig.1). Two piezoelectric accelerometers (PCB Electronics, model 355B03 at the seat) were mounted on the vibrating surfaces so as to monitor the excitation as well as the greatest expected cross-axis motion. The arrangement achieved resonance frequencies greater than 315 Hz and low cross-axis vibration (generally less than 5%, less than 10% at frequencies greater than about 160 Hz). Background vibration, mainly due to electrical noise at 50 Hz, was less than 0.008 ms^{-2} r.m.s., and was not perceptible via the seat.

The hands and feet of the subjects rested on rigid cylindrical handles (100 mm in length, 30 mm in diameter) and rigid footrests (30.5 mm x 10.5 mm with 10-degree inclination), respectively. This resulted in approximately the same body posture for all 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.

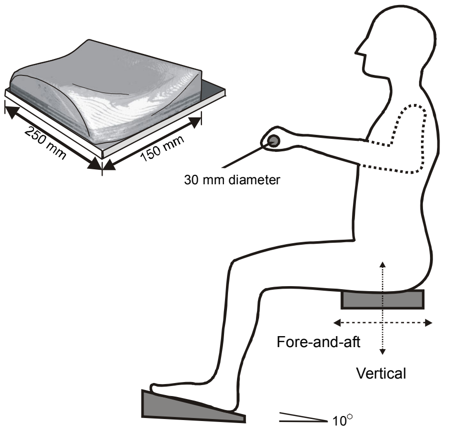

Fig.1 The rigid seat and the body posture. The rigid handles and the rigid footrests were stationary.

2.3 Stimuli and procedure

Absolute thresholds for the perception of vibration by the seated subjects were determined using sinusoidal acceleration at each of the 23 preferred one-third octave centre frequencies between 2 and 315 Hz. The stimuli were 2.0 seconds in duration, including 0.5-second cosine-tapered ends.

An up-down (staircase) algorithm was employed to determine thresholds in conjunction with a three-down oneup rule. A single test stimulus, 2.0 seconds in duration, was presented accompanied by a cue light. The task of the 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. The order of presenting the test frequencies was randomized.

The subjects were instructed to maintain their body postures 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.

3 Results

3.1 Effect of vibration frequency

The median absolute thresholds and the inter-quartile ranges (25th to 75th percentiles) of the 12 subjects determined 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.

The acceleration thresholds depended on vibration frequency (Friedman, $p<0.001$) with a general trend towards higher thresholds with increasing frequency over the range investigated (2 to 315 Hz).

With fore-and-aft vibration, there was no significant change in the acceleration threshold for any pair of frequencies between 2 and 6.3 Hz (Wilcoxon, $p>0.05$, except between 2 and 6.3 Hz), then a significant increase in the threshold with each one-third octave increase 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 to 40 Hz), and a significant increase in acceleration thresholds at frequencies greater than 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 $p=0.052$), and a significant increase in acceleration thresholds with each one-third octave step from 200 to 315 Hz (Wilcoxon, $p<0.05$).

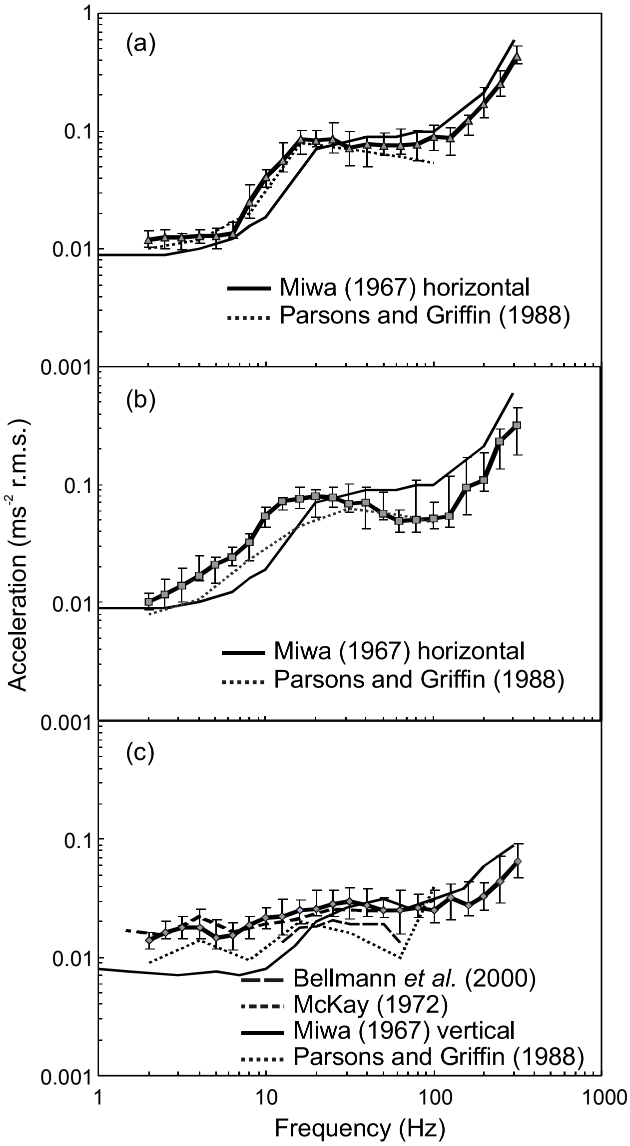

Fig.2. Median absolute thresholds in each of the three axes at the seat: (a) fore-and-aft, (b) lateral, and (c) vertical. Error-bars represent inter-quartile range.

3.2 Effect of vibration axis

The median absolute thresholds for the perception of vibration in the three axes (i.e., fore-and-aft, lateral and vertical) are compared in Fig.3.

The thresholds differed significantly between the three axes (Kruskal-Wallis, $p<0.05$), except at the lowest frequency of 2 Hz (Kruskal-Wallis, $p=0.067$). At frequencies, greater than 8 Hz, the body was most sensitive to vertical vibration: vertical thresholds were significantly lower than fore-and-aft thresholds and lateral thresholds at all frequencies between 10 and 315 Hz (Mann-Whitney, $p<0.01$). In contrast, at frequencies less than 3.15 Hz, sensitivity to vertical vibration was less than sensitivity to fore-and-aft vibration (Mann-Whitney, $p<0.05$).

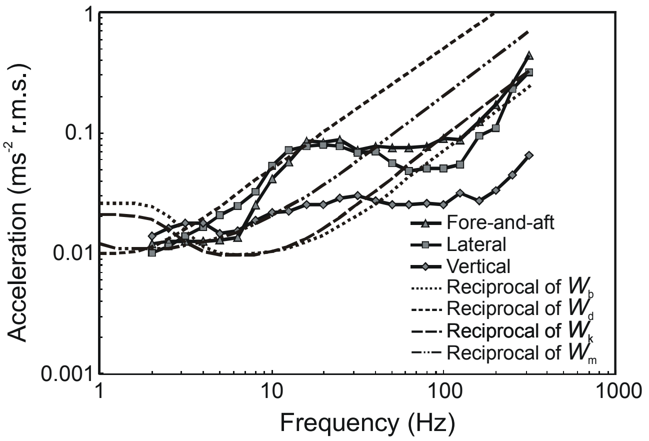

Fig.3. Comparison of median perception thresholds between the three axes for seated subjects. The reciprocal of W_b, W_d, W_k and W_m frequency weightings normalised to 0.01 ms^{-2} r.m.s. (and extrapolated) are overlaid.

4 Discussion

Some differences in thresholds between the present and previous studies may 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 a footrest moving with the seat, due to increased relative motion between the seat and the footrest, as found by Jang and Griffin [5]. Although Miwa [1] and Parsons and Griffin [2] 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 study may have reduced sensitivity to low frequency vertical seat vibration and slightly raised the low frequency thresholds.

The detection of vibration is thought to involve Pacinian (P) and non-Pacinian (NP) channels. The U-shaped acceleration threshold contour at high frequencies suggests some involvement of the Pacinian channel mediating perception of the stimuli, as found in other studies of vibrotactile thresholds [6-7]. The similar shape to the threshold contour obtained for the three axes at frequencies greater than approximately 80 Hz suggests the same channel (i.e., P channel) mediated the perception of the vibration stimuli for fore-and-aft, lateral and vertical vibration. Other tactile channels (NP channels) might be involved in the detection of low frequency vibration, although further investigation is required to improve understanding of the mechanisms involved in the detection of whole-body vibration.

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., [8]), and resonances around 1.5 and 3 Hz with fore-and-aft and lateral excitation (e.g. [9]). Whitham and Griffin [10] found maximum sensitivity to vertical vibration acceleration in the range 4 to 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 close to 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. Fore-and-aft and lateral seat vibration are evaluated using W_d in both British Standard 6841 [11] and International Standard 2631-1 [12], while vertical seat vibration is evaluated using W_b in British Standard 6841 [11] and either W_b or W_k in International Standard 2631-1 [12]. The frequency weighting W_k has slightly greater weighting than W_b 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. According to ISO2631-2 [13], the W_m frequency weighting may be used for the evaluation of fore-and-aft, lateral, and vertical vibration in buildings. The W_m weighting is formed from a combination of the W_g weighting (for *z*-axis vibration in ISO 2631, 1974) and the W_d weighting (for *x*- and *y*- axes) [14]. As seen in Fig.3, the W_m weighting does not fit perception thresholds for either vertical or horizontal vibration of seated persons. However, the W_m weighting is not too inappropriate for the horizontal perception thresholds of recumbent persons [14].

The experimentally determined thresholds are compared with the reciprocals of the W_b, W_k, and W_d frequency weightings in Fig.3. It is evident that the threshold contours for the seat do not match the shapes of the reciprocals of either W_b, W_k, or W_d. The differences indicate that the frequency weightings will greatly underestimate human perception of high frequency vibration at the seat or, conversely, overestimate the perception of low frequencies.

For the prediction of the perception of vibration by seated persons, British Standard 6841 [11] and International Standard 2631-1 [12] state that fifty percents of alert, fit persons can just detect a weighted vibration with a peak acceleration of approximately 0.015 ms^{-2}, with an inter-quartile range from about 0.01 to 0.02 ms^{-2} peak. If the standards provide appropriate predictions of the absolute thresholds of vibration perception, the experimentally determined thresholds (in peak acceleration) multiplied by the appropriate frequency weighting at each frequency should produce a value close to 0.015 ms^{-2} at all frequencies and in all three axes. Fig. 4 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 ±0.015 ms^{-2}. Frequency weighting W_d gives a reasonable prediction of sensitivity to lateral vibration at frequencies between about 2 and 31.5 Hz, but greatly underestimates sensitivity at frequencies greater than about 31.5 Hz, with an error as much as a factor of 10 at 100 Hz. Frequency weighting W_d is less appropriate for fore-and-aft vibration at low frequencies. 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 is used in place of W_b, the underestimate of sensitivity is even greater at high frequencies.

For seated subjects, absolute thresholds for the perception of vertical acceleration have little dependence on frequency, with the median threshold in the range 0.01 to 0.03 ms^{-2} r.m.s. at frequencies between 2 and 100 Hz (see Fig.3). Consequently, unweighted acceleration is a more accurate, and sometimes more convenient, measure for predicting whether vertical seat vibration will be perceived.

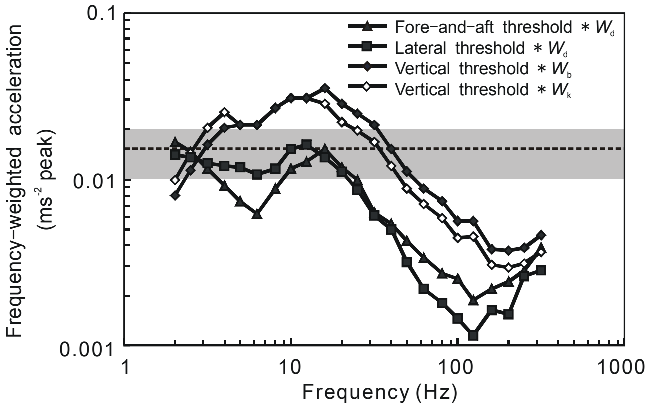

Fig.4. Frequency-weighted median perception thresholds (ms^{-2} peak) for each of the three axes of vibration at the seat. Frequency weightings greater than 100 Hz were extrapolated. ----- (with grey zone) represents inter-quartile of the predicted perception threshold for vibration experienced by seated persons according to British Standard 6841 [11] and ISO 2631-1 [12]. Figure from Morioka and Griffin [15]

5 Conclusions

The frequency-dependencies of the absolute thresholds for the perception of seat vibration differ between the three axes. At frequencies, greater than 10 Hz, sensitivity is greatest for vertical vibration, whereas at frequencies less than 3.15 Hz, sensitivity is greatest for fore-and-aft vibration. In all three axes, the acceleration threshold contours at frequencies greater than approximately 80 Hz were U-shaped, suggesting the same psychophysical channel mediated high frequency thresholds for fore-and-aft, lateral and vertical vibration. The perception of vibration at frequencies less than about 20 Hz may involve other tactile channels and other factors, including relative motion due to stationary footrests and handles. The frequency-dependencies of absolute thresholds for the perception of whole-body vibration are not consistent with the frequency weightings used in current standards. For the vertical vibration of seated subjects, the unweighted acceleration provides a more accurate prediction of whether the vibration will be felt than the frequency-weighted acceleration.

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