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Equivalent comfort contours for fore-and-aft, lateral, and vertical whole-body vibration in the frequency range 1.0 to 10 Hz

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ABSTRACT
Standards assume vibration discomfort depends on the frequency and direction of whole-body vibration, with the same weightings for frequency and direction at all magnitudes. This study determined equivalent comfort contours from 1.0 to 10 Hz in each of three directions (fore-and-aft, lateral, vertical) at magnitudes in the range 0.1 to 3.5 ms^{-2} r.m.s. Twenty-four subjects sat on a rigid flat seat with and without a beanbag, altering the pressure distribution on the seat but not the transmission of vibration. The rate of growth of vibration discomfort with increasing magnitude of vibration differed between the directions of vibration and varied with the frequency of vibration. The frequency-dependence and direction-dependence of discomfort, therefore, depended on the magnitude of vibration. The beanbag did not affect the frequency-dependence or direction-dependence of vibration discomfort. It is concluded that different weightings for the frequency and direction of vibration are required for low and high magnitude vibration.

Practitioner summary: When evaluating whole-body vibration to predict vibration discomfort, the weightings appropriate to different frequencies and different directions of vibration should depend on the magnitude of vibration. This is overlooked in all current methods of evaluating the severity of whole-body vibration.

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Vibration discomfort; whole-body vibration; frequency weightings; direction weightings; vibration standards

1. Introduction

Whole-body vibration is experienced during transport by road or off-road vehicles, and by rail, air, and sea. The oscillations can cause discomfort as well as interfere with activities, impair health, or induce motion sickness.

For the prediction of the discomfort caused by the whole-body vibration of seated people, British Standard 6841 (British Standards Institution 1987) and International Standard 2631-1 (International Organization for Standardization 1997) suggest the vibration should be measured at three locations: on the supporting surface of the seat (in all six directions: fore-and-aft, lateral, vertical, roll, pitch, and yaw) and at the backrest and the feet (in all three translational directions: fore-and-aft, lateral, vertical). These vibrations are 'evaluated' by the root-mean-square (r.m.s.) or vibration dose value (VDV) after they have been weighted by frequency weightings assumed to reflect the frequency-dependence of the discomfort caused by vibration in each direction at each location. Many experimental studies have investigated how the vibration discomfort of seated people depends on the frequency of vertical seat vibration (e.g. Miwa 1967; Shoenberger and Harris 1971; Shoenberger 1975; Donati et al. 1983; Griffin, Parsons, and Whitham 1982a, Corbridge and Griffin 1986; Morioka and Griffin 2006; Zhou and Griffin 2014), the frequency of horizontal seat vibration (e.g. Miwa 1967; Donati et al. 1983; Griffin, Parsons, and Whitham 1982a, Corbridge and Griffin 1986; Morioka and Griffin 2006), the frequency of rotational seat vibration (e.g. Shoenberger 1979; Parsons and Griffin 1982; Beard and Griffin 2013), the frequency of vibration of the back (e.g. Morioka and Griffin 2010a; Basri and Griffin 2011) or the frequency of vibration of the feet (e.g. Morioka and Griffin 2010b). Although the frequency weightings in current standards are broadly consistent with the experimental findings available in the 1980s and 1990s, complications have become apparent due to the influence of relative motion between seat and feet

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(e.g. Jang and Griffin 2000), the inclination of backrests (e.g. Basri and Griffin 2013), effects of low frequency rotation (e.g. Beard and Griffin 2013), and the effects of mechanical shocks (e.g. Zhou and Griffin 2017).

Research subsequent to the publication of the standards has also uncovered nonlinearities in subjective responses to vibration that indicate the frequency-dependence of vibration discomfort changes with the magnitude of vibration. The nonlinearity can be understood through a power law (Stevens 1975) that relates the subjective magnitude, ψ, of a stimulus (e.g. the vibration discomfort) to the physical magnitude, ϕ, of the stimulus (e.g. the vibration acceleration) by:

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

where the exponent n represents the rate of growth of vibration discomfort as the physical magnitude of a vibration increases. Early investigations of the rate of growth of vibration discomfort did not report that it was dependent on the frequency of vibration. However, more recent studies at the University of Southampton have found that the rate of growth of discomfort, n, is not the same at all frequencies of vibration, or with all directions of vibration, or with all locations of input of vibration to the body (e.g. Morioka and Griffin 2006, 2010a, 2010b; Wyllie and Griffin 2007, 2009). This means that a vibration (with a specific frequency, direction, and location) can cause less discomfort than another vibration (with a different frequency, direction, or location) at low magnitudes but more vibration discomfort when the magnitudes of both vibrations are increased by the same percentage. This is not predicted by the frequency weightings in any current standard.

A potential explanation for the rate of growth of discomfort varying with the frequency and direction of vibration is that different frequencies and directions of vibration cause discomfort in different parts of the body. Perhaps increases in the magnitude of vibration, cause a greater increase in discomfort at some locations in the body than at other locations in the body.

The weightings in British Standard 6841 (British Standards Institution 1987) and International Standard 2631-1 (International Organization for Standardization 1997) were influenced by experimental studies that gave the frequency-dependence of vibration discomfort with moderate magnitudes of vibration that might be expected in some forms of transport (equivalent to the discomfort caused by 0.8 ms^{-2} r.m.s. vertical sinusoidal vibration at 10 Hz; Griffin, Parsons, and Whitham 1982b; Corbridge and Griffin, 1986). Much later, Morioka and Griffin (2006) found that the frequency-dependence of vibration discomfort caused by the fore-and-aft, the lateral, and the vertical vibration of seated people depends on the magnitude of vibration. Subsequent studies have reported a similar magnitude-dependence with other types of vibration excitation, but no study has explored how equivalent comfort contours in all three translational axes depend on the magnitude of vibration over the frequency range 1.0 to 10 Hz, even though these motions are often the dominant causes of vibration discomfort.

This paper reports an experimental study of the frequency-dependence of the rate-of-growth of vibration discomfort, the magnitude-dependence of equivalent comfort contours, and how the location of greatest vibration discomfort depends on the frequency and the direction of fore-and-aft, lateral, and vertical vibration of seated people. It was hypothesised that the rate of growth of discomfort would vary with the frequency of vibration and the direction of vibration. Due to these differences in the rate of growth of discomfort, equivalent comfort contours were expected to change shape with changes in the magnitude of vibration. It was also hypothesised that the location of greatest vibration discomfort would vary with the frequency, the direction, and the magnitude of vibration and the distribution of pressure over the seat surface.

2. Method

2.1. Subjects

The 24 subjects participating in the study were students or office workers at the University of Southampton: 12 males (21 to 40 years, 1.63 to 1.94 m in stature, and 65 to 130 kg in weight) and 12 females (19 to 38 years, 1.53 to 1.75 m in stature, and 45 and 78 kg in weight).

The experiment was approved by the Ethics Committee of the Faculty of Engineering and the Environment at the University of Southampton. Informed consent was given by the subjects who participated voluntarily.

2.2. Apparatus

Fore-and-aft, lateral, and vertical vibrations were produced by the six-axis vibration simulator in the Human Factors Research Unit of the Institute of Sound and Vibration Research. The simulator was controlled and monitored using a Servotest Pulsar system.

Subjects sat on a rigid seat (height: 0.56 m, width 0.50 m, and depth 0.50 m) with no backrest. They were supported either on the hard flat horizontal surface of the seat or on a 'bean bag' that distributed pressure over a larger area surrounding their ischial tuberosities. The 'bean bag' (height: 0.065 m, width: 0.41 m, and depth 0.45 m) was filled with small rigid plastic

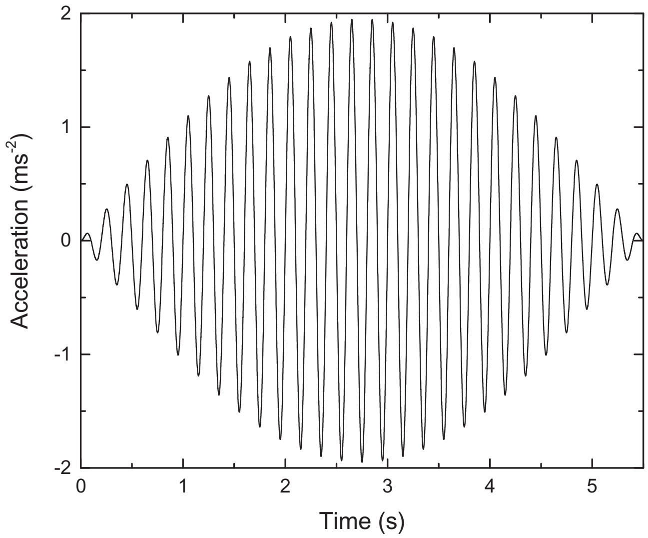

Figure 1. Example acceleration time history of a stimulus having a fundamental frequency of 5 Hz.

pellets and had a transmissibility of unity in all three axes over the range of frequencies investigated. The feet of the subjects were supported on the vibrating platform using a rigid horizontal footrest that was adjusted in height so that the lower surfaces of the thighs were in contact with the seat or the beanbag.

2.3. Stimuli

Acceleration stimuli, at the 11 preferred one-third octave centre frequencies from 1.0 to 10 Hz, were generated using MATLAB (version 2012a) and *HVLab* toolbox (version 2). The transient stimuli (sinusoids modulated by a half sine) had $n + 0.5$ cycles of oscillation (where n is an odd number adjusted to give durations of approximately 5.5 s). This number of cycles allowed the signal to start and finish with zero displacement, zero velocity, and zero acceleration. An example stimulus is shown in Figure 1.

Each frequency of motion was presented at seven magnitudes with increments of 3 dB. At each frequency and in each of the three directions of motion (fore-and-aft, lateral, and vertical) the frequency-weighted magnitudes were 0.088, 0.125, 0.175, 0.25, 0.35, 0.50, and 0.70 m.s^{-2} r.m.s. These magnitudes were frequency-weighted so as to maintain a reasonable range of discomfort across the 11 frequencies and three directions of motion. The frequency weightings used were those in British Standard 6841 (British Standards Institution 1987) (i.e. W_b for vertical vibration and W_d for fore-and-aft and lateral vibration, with a unity axis multiplier in each direction). The unweighted vibration magnitudes are shown in Table 1.

2.4. Procedure

All subjects participated in two sessions on two separate days. The sessions lasted about 90 min with the same vibration stimuli and differed only in whether the 'bean bag' was placed on top of the rigid flat seat. With both seating conditions, all 231 stimuli were presented to each subject in an independently randomised order (between magnitude, frequency, and direction).

Subjects sat in comfortably upright postures on the rigid seat and they were asked to remain upright throughout the experiment with their eyes shut to eliminate visual cues. They were monitored by the experimenter to ensure they followed these instructions. Participants wore headphones delivering white noise at 65 dB(A) to mask sounds produced by the simulator, which were less than 51 dB(A), at the subjects' ears.

During each session, the subjects were given time to read the instructions, sign consent and health questionnaire forms, practice magnitude estimation by judging the lengths of lines and judging the discomfort caused by a few example vertical vibrations (to ensure they understood the magnitude estimation method), and then participate in the experiment.

The method of magnitude estimation was used by subjects to rate the vibration discomfort they experienced during each motion. At the beginning and the end of their practice with vertical vibration, the subjects received 0.25 ms^{-2} r.m.s. at 3.15 Hz (frequency–weighted) and were instructed that the discomfort they experienced should be rated as '100' and used as a starting point for all their subsequent judgements. This ensured they used 'convenient' numbers throughout the experiment. The written instructions explained that a rating of 50

Table 1. Unweighted acceleration magnitudes used in the study (ms^{-2} r.m.s.).

Fore-and-aft											
Frequency (Hz)	1.0	1.25	1.6	2.0	2.5	3.15	4.0	5.0	6.3	8.0	10
Magnitude 1	0.09	0.09	0.09	0.10	0.11	0.14	0.17	0.21	0.27	0.35	0.43
Magnitude 2	0.12	0.13	0.13	0.14	0.16	0.20	0.24	0.31	0.39	0.49	0.62
Magnitude 3	0.17	0.17	0.18	0.20	0.23	0.27	0.34	0.43	0.54	0.69	0.87
Magnitude 4	0.25	0.25	0.26	0.28	0.32	0.39	0.49	0.61	0.77	0.99	1.24
Magnitude 5	0.35	0.35	0.36	0.39	0.45	0.55	0.68	0.86	1.08	1.38	1.74
Magnitude 6	0.50	0.50	0.52	0.56	0.64	0.78	0.98	1.22	1.55	1.98	2.48
Magnitude 7	0.69	0.70	0.72	0.79	0.90	1.09	1.37	1.71	2.17	2.77	3.48
Lateral											
Frequency (Hz)	1.0	1.25	1.6	2.0	2.5	3.15	4.0	5.0	6.3	8.0	10
Magnitude 1	0.09	0.09	0.09	0.10	0.11	0.14	0.17	0.21	0.27	0.35	0.43
Magnitude 2	0.12	0.13	0.13	0.14	0.16	0.20	0.24	0.31	0.39	0.49	0.62
Magnitude 3	0.17	0.17	0.18	0.20	0.23	0.27	0.34	0.43	0.54	0.69	0.87
Magnitude 4	0.25	0.25	0.26	0.28	0.32	0.39	0.49	0.61	0.77	0.99	1.24
Magnitude 5	0.35	0.35	0.36	0.39	0.45	0.55	0.68	0.86	1.08	1.38	1.74
Magnitude 6	0.50	0.50	0.52	0.56	0.64	0.78	0.98	1.22	1.55	1.98	2.48
Magnitude 7	0.69	0.70	0.72	0.79	0.90	1.09	1.37	1.71	2.17	2.77	3.48
Vertical											
Frequency (Hz)	1.0	1.25	1.6	2.0	2.5	3.15	4.0	5.0	6.3	8.0	10
Magnitude 1	0.23	0.23	0.22	0.21	0.18	0.13	0.10	0.09	0.08	0.09	0.09
Magnitude 2	0.33	0.32	0.32	0.30	0.25	0.19	0.14	0.12	0.12	0.12	0.13
Magnitude 3	0.46	0.45	0.45	0.42	0.35	0.26	0.20	0.17	0.17	0.17	0.18
Magnitude 4	0.65	0.65	0.64	0.60	0.51	0.38	0.28	0.24	0.24	0.24	0.26
Magnitude 5	0.91	0.91	0.89	0.84	0.71	0.53	0.39	0.34	0.33	0.34	0.36
Magnitude 6	1.30	1.29	1.27	1.20	1.01	0.76	0.56	0.49	0.47	0.49	0.51
Magnitude 7	1.82	1.81	1.78	1.67	1.42	1.06	0.79	0.68	0.66	0.68	0.72

would mean their vibration discomfort was half of that caused by a motion judged as having a discomfort of 100, and that a rating of 200 would mean that their vibration discomfort was double that caused by a motion having a discomfort of 100.

After each motion, subjects were asked to indicate the body location where the vibration was most felt in the body using a body map. The 12 body locations (numbered from 0 to 11) were: 0: 'no discernible location'; 1: head; 2: neck; 3: shoulders; 4: chest; 5: arms; 6: lower abdomen; 7: ischial tuberosities, 8: lower thighs; 9: upper thighs; 10: legs; and 11: feet.

2.5. Analysis

For each frequency and direction of motion and every subject, the rate of growth of discomfort, n, and the constant, k, were determined by linear regression after a logarithmic transformation of Equation (1):

$$\log_{10}\psi = n\log_{10}\varphi + \log_{10}k \qquad (2)$$

Prior to the linear regressions, magnitude estimates from individual subjects were normalised to give a median value of 100 within a session, so data from different subjects could be combined to produce median equivalent comfort contours. The normalisation does not affect the rate of growth of discomfort, n, only the intercept, k. Normalised values of k are denoted by k'.

Equivalent comfort contours for selected levels of vibration discomfort (corresponding to magnitude estimates of 63, 80, 100, 125, and 160) were calculated using:

$$\varphi = 10^{\left((\log_{10}\psi)-(\log_{10}k')\right)/n} \qquad (3)$$

where ϕ is unweighted acceleration in ms^{-2} r.m.s.

The data were analysed using non-parametric statistics in SPSS (version 22). The Friedman two-way analysis of variance and the Wilcoxon matched-pairs signed ranks indicated differences between related samples. The Mann–Whitney U test was used for differences between independent samples. The Cochran-Q test was used to investigate differences in body locations associated with greatest discomfort for related samples and the McNemar change test was used to investigate changes in body location between magnitudes.

3. Results

The median rates of growth, n, and the constants, k', for each frequency of vibration in each of the three axes of vibration when sitting on the rigid seat are shown in Table 2.

3.1. Rate of growth of vibration discomfort

3.1.1. Within directions of vibration

Within each of the three directions of vibration, and with both seating conditions, the rate of growth of vibration discomfort, n, was highly dependent on the frequency of the vibration ($p<0.001$; Friedman; Figure 2). Over the frequency range 1 to 10Hz, the percentage change in the rate of growth of discomfort was less with vertical vibration than with either fore-and-aft or lateral vibration.

3.1.2. Between directions of vibration

At all eleven frequencies, and with both seating conditions, the rate of growth of vibration discomfort differed across the three directions of vibration ($p<$ 0.05, Friedman).

Without the beanbag, there was no statistically significant difference in the rate of growth of vibration discomfort between fore-and-aft and lateral vibration ($p>$ 0.05, Wilcoxon), except at 1.6 Hz and 2.5 Hz ($p=$ 0.004 and $p=$ 0.002, respectively, Wilcoxon). With the beanbag, there was no statistically significant difference in the rate of growth between fore-and-aft and lateral vibration ($p>$ 0.05, Wilcoxon), except at 4 Hz and 5 Hz ($p=$ 0.022 and $p=$ 0.005, respectively, Wilcoxon).

Without the beanbag, the rate of growth of vibration discomfort was significantly greater with vertical vibration than with either fore-and-aft or lateral vibration ($p<$ 0.02, Wilcoxon; Figure 2), except between vertical and fore-and-aft vibration from 1.6 to 2.5 Hz and between vertical and lateral vibration from 1.6 to 2.0 Hz (Figure 2). With the beanbag, the rate of growth of vibration discomfort was also significantly greater with vertical vibration than with either fore-and-aft or lateral vibration ($p<$ 0.04, Wilcoxon), except between vertical and fore-and-aft vibration at 1.25 Hz and from 2.0 to 2.5 Hz and between vertical and lateral vibration from 1.25 to 2.0 Hz, and at 6.3 Hz and 10 Hz.

Table 2. Median exponents, n, and constants, k' for each of the three axes for the rigid seat.

	Fore-and-aft		Lateral		Vertical	
Frequency (Hz)	k'	n	k'	n	k'	n
1.0	189	0.54	165	0.53	107	0.87
1.25	160	0.42	180	0.63	109	0.75
1.6	163	0.57	241	0.76	104	0.69
2.0	178	0.62	194	0.60	107	0.69
2.5	182	0.68	177	0.48	113	0.68
3.15	172	0.51	140	0.37	133	0.72
4.0	148	0.36	137	0.39	191	0.70
5.0	131	0.34	117	0.38	187	0.69
6.3	112	0.41	114	0.31	167	0.45
8.0	107	0.30	110	0.28	210	0.67
10.0	101	0.36	111	0.32	188	0.59

3.1.3. Between seating conditions

Over all 11 frequencies and the three directions of vibration, the rate of growth of vibration discomfort was not significantly affected by whether subjects sat with or without the beanbag ($p>$ 0.05, Wilcoxon; Figure 3), except with fore-and-aft vibration at 10 Hz ($p=$ 0.012, Wilcoxon) and with vertical vibration at

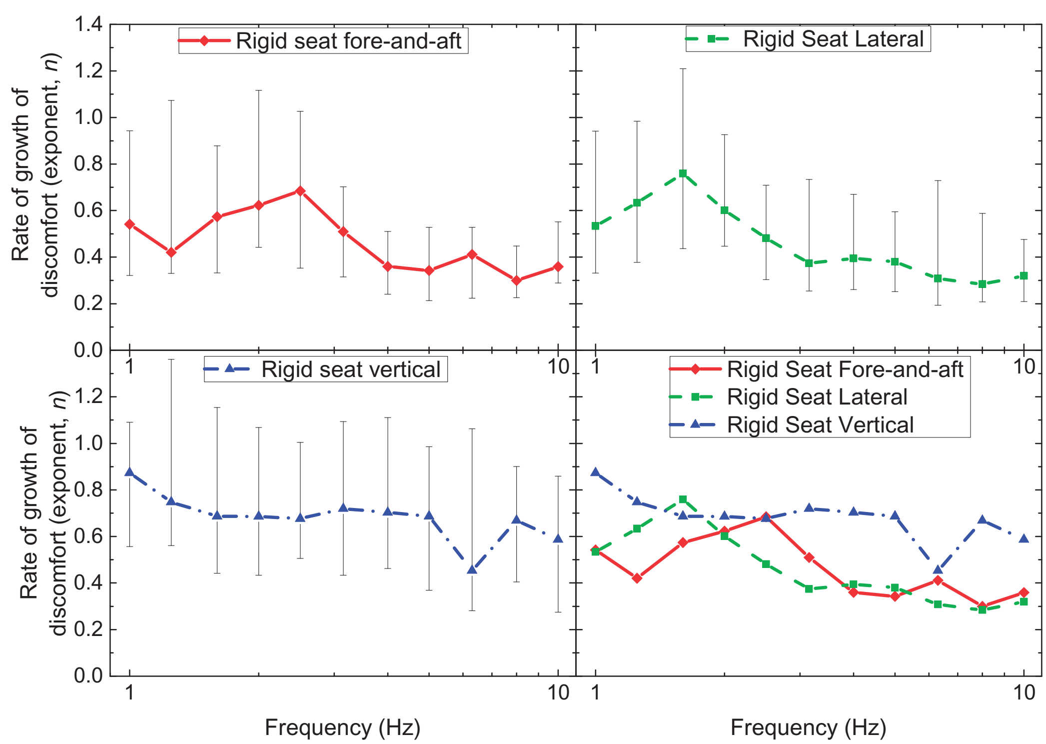

Figure 2. Rates of growth of vibration discomfort, n, for fore-and-aft vibration (top left), lateral vibration (top right), and vertical vibration (bottom left), and all three directions of vibration (bottom right) when sitting on a rigid seat without a backrest. Medians and inter-quartile ranges for 24 subjects.

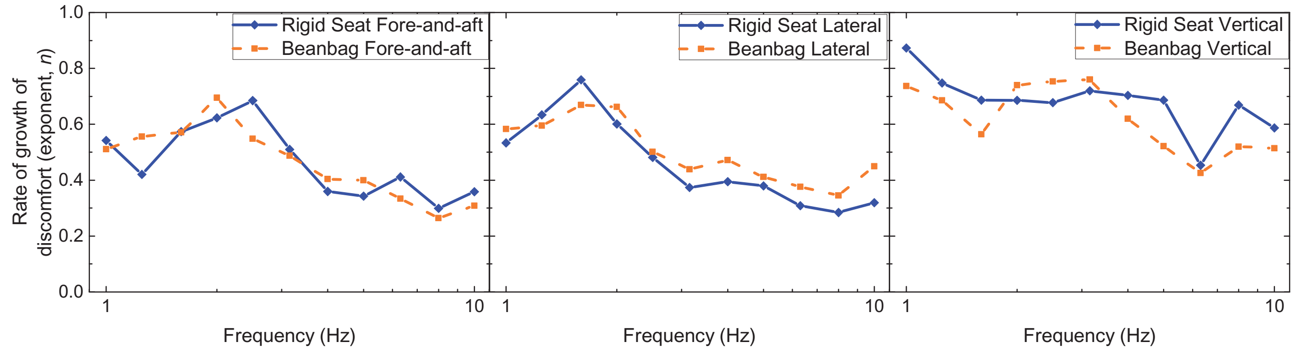

Figure 3. Rates of growth of vibration discomfort, n, for fore-and-aft vibration (left), lateral vibration (centre), and vertical vibration (right) when sitting without a backrest on either a rigid seat or a beanbag. Median values for 24 subjects.

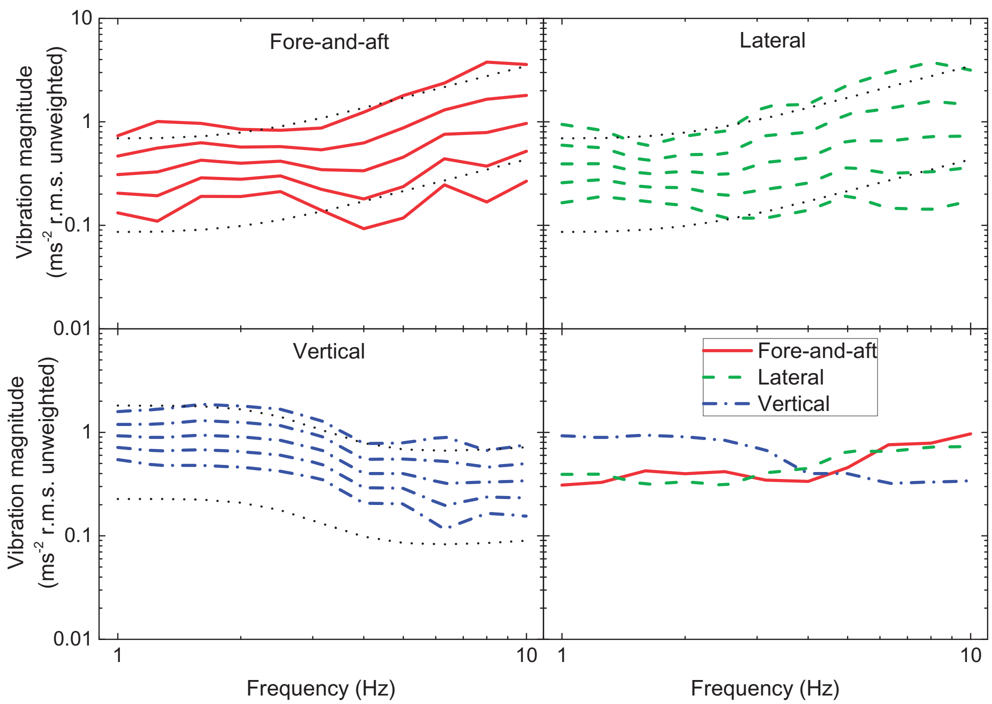

Figure 4. Equivalent comfort contours for fore-and-aft, lateral and vertical vibration for subjective magnitudes from 63 to 160 relative to 0.25 ms^{-2} r.m.s. weighted vertical vibration at 3.15 Hz. Ranges of stimuli employed in the study shown by dotted lines (….). Bottom right graph compares equivalent comfort contours between the three directions for a subjective magnitude of 100.

1.25 and 8 Hz ($p =$ 0.024 and .021, respectively, Wilcoxon). With 33 comparisons, these three differences could be considered the result of chance.

3.2. Equivalent comfort contours

3.2.1. Within directions of vibration

Equivalent comfort contours were determined by calculating values of the vibration acceleration, ϕ, corresponding to five subjective magnitudes, ψ: 63, 80, 100, 125, and 160 (where ψ = 100 is equivalent to the discomfort caused by 3.15-Hz vertical vibration at 0.25 ms^{-2} r.m.s. weighted, 0.38 ms^{-2} unweighted).

In all three directions and at all five subjective magnitudes, the levels of the equivalent comfort contours were highly dependent on the frequency of vibration ($p <$ 0.001, Friedman). With all three directions of vibration, the discomfort caused by acceleration was almost independent of the frequency of vibration at frequencies less than about 2 or 3 Hz. As the frequency increased to 10 Hz, the vibration magnitude required to produce the same degree of discomfort progressively increased for the two directions of horizontal vibration but decreased for vertical vibration (Figure 4).

With less percentage change in the rate of growth of discomfort with vertical vibration, the equivalent

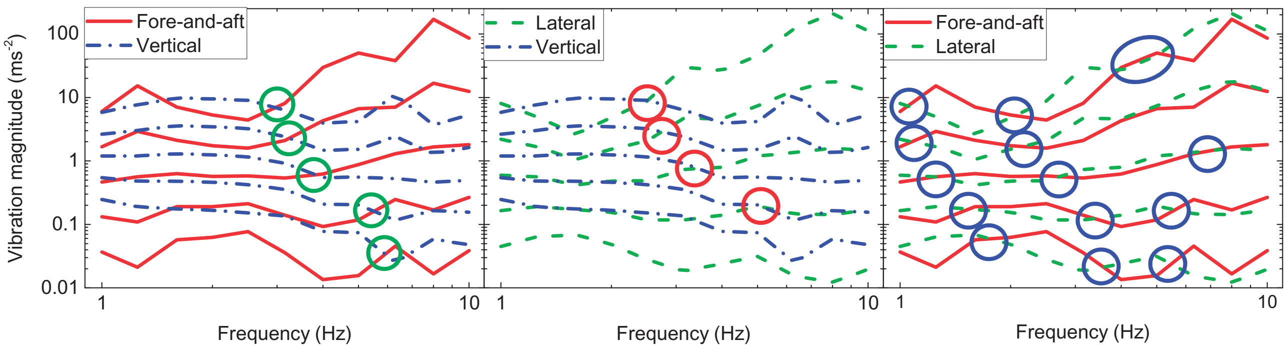

Figure 5. Comparisons of equivalent comfort contours between axes for subjective magnitudes from 63 to 160 in the fore-and-aft (red), lateral (green) and vertical (blue) directions, relative to a vibration magnitude of 0.25 ms^{-2} r.m.s. vertical vibration at 3.15 Hz, without beanbag. Circles show systematic changes in the frequencies of the cross-overs between pairs of equivalent comfort contours in different axes. Median data from 24 subjects.

comfort contours for vertical vibration were less affected by the magnitude of the vibration than the equivalent comfort contours for horizontal vibration. Nevertheless, with all three directions of vibration, the greater rate of growth of discomfort at lower frequencies caused closer equivalent comfort contours: less change in the magnitude of vertical vibration was needed with the lower frequencies to produce the same change in vibration discomfort. The rate of growth of discomfort was generally greater with vertical vibration, so less change in magnitude was needed with vertical vibration than with horizontal vibration to produce the same change in discomfort.

3.2.2. Between directions of vibration

Equivalent comfort contours for fore-and-aft, lateral, and vertical acceleration are compared for subjective magnitudes of 63, 80, 100, 125, and 160 in Figure 4.

With all five subjective magnitudes, there was significantly greater sensitivity to lateral vibration than to fore-and-aft vibration at 1.6 and 2.0 Hz ($p < 0.02$, Wilcoxon) and with subjective magnitudes of 63 and 80 at 2.5 Hz ($p < 0.02$, Wilcoxon). There was significantly greater sensitivity to fore-and-aft vibration than to lateral vibration with all subjective magnitudes at 4.0 Hz ($p < 0.05$, Wilcoxon), and at 3.15 Hz with subjective magnitudes of 100 and greater ($p < 0.01$, Wilcoxon).

Previous research has suggested a 'crossover' between sensitivity to vertical vibration and horizontal vibration at 3.15 Hz, with fore-and-aft and lateral vibration giving more discomfort at frequencies less than 3.15 Hz and vertical vibration giving more discomfort at frequencies greater than 3.15 Hz (Griffin and Whitham 1977). In this study, the frequency of the crossover between fore-and-aft vibration and vertical vibration decreased with increasing magnitude of vibration (Figure 5). With a subjective magnitude of 63 (without the beanbag), the crossover frequency was between 5 and 6.3 Hz: subjects were more sensitive to fore-and-aft vibration than to vertical vibration at all frequencies less than 5 Hz ($p < 0.001$, Wilcoxon) and more sensitive to vertical vibration than to fore-and-aft vibration at frequencies greater than 6.3 Hz ($p < 0.05$, Wilcoxon). With subjective magnitudes of 80 and 100, the frequency at which there was no significant difference between sensitivity to fore-and-aft and vertical vibration was 5 Hz. With subjective magnitudes of 125 and 160, the frequency at which there was no significant difference reduced to 4 Hz.

With increasing magnitude of vibration, there was a similar reduction in the frequency of the crossover in sensitivity between lateral vibration and vertical vibration (Figure 5). With a subjective magnitude of 63, the crossover frequency was at 5 Hz: subjects were more sensitive to lateral vibration at all frequencies less than 5 Hz ($p < 0.005$, Wilcoxon) and more sensitive to vertical vibration at all frequencies greater than 5 Hz ($p < 0.05$, Wilcoxon), except at 10 Hz ($p = 0.219$). With a subjective magnitude of 80, subjects were more sensitive to lateral vibration at 5 Hz and lower frequencies and more sensitive to vertical vibration at 6.3 Hz and higher frequencies, with significant differences at all frequencies ($p < 0.05$). For a subjective magnitude of 100, the frequency at which there was no significant difference was 4 Hz. For a subjective magnitude of 125, subjects were more sensitive to lateral vibration at 3.15 Hz and lower frequencies and more sensitive to vertical vibration at 4 Hz and higher frequencies, with significant differences at all frequencies ($p < 0.05$). With a magnitude estimate of 160, the frequency at which there was no significant difference reduced to 3.15 Hz.

There were similar trends in relative sensitivity to vibration in the three axes when subjects sat on the beanbag.

3.3. Between seating conditions

Subjects judged discomfort with and without the beanbag cushion on separate days, so magnitude estimates of discomfort do not directly indicate whether there were any overall differences in vibration discomfort between the two seating conditions. However, the frequency-dependence of discomfort and the direction-dependence of discomfort can be compared between the two seating conditions.

The variable '*k*' in Equation (1) reflects the frequency-dependence and direction-dependence of subject estimates of vibration discomfort. For example, irrespective of the rate of growth of vibration discomfort (i.e. *n*), the value of *k′* gives the subjective magnitude, ψ, when the vibration magnitude is 1.0 ms^{-2} r.m.s. If changes to the distribution of force between the beanbag and the subjects affected the frequency-dependence or direction-dependence of discomfort caused by vibration, the ratio of the value of *k′* with and without the beanbag would vary with the frequency or the direction of vibration.

Over the 11 frequencies within each of the three directions of vibration, the ratio of the value of *k′*, with and without the beanbag, varied over the range from 0.83 to 1.27. After adjusting for 11 multiple comparisons within each direction, the ratio was only statistically significant with 5-Hz lateral vibration where the ratio was 0.83 ($p = 0.01$). For this combination of frequency and direction, the finding suggests subjects were more sensitive to lateral vibration when sitting on the beanbag. However, this finding could be due to chance and it is noted that the ratio was close to 1.0 at adjacent frequencies.

The effect of the beanbag on the direction-dependence of vibration discomfort was investigated at each frequency by comparing the ratio of *k′*-values between sitting with and without the beanbag between all three possible pairs of directions. These ratios varied between 0.73 and 1.22. After adjusting for multiple comparisons, none of the ratios showed a statistically significant effect of the beanbag. It is concluded that the direction-dependence of vibration discomfort was not affected by the beanbag at any of the 11 frequencies.

3.4. Body location

The principal locations of discomfort identified by subjects when sitting on the rigid seat during exposure to fore-and-aft, lateral, and vertical vibration at 'low' magnitudes (0.088 ms^{-2} r.m.s., weighted) and 'high' magnitudes (0.70 ms^{-2} r.m.s., weighted) are shown in Figure 6. The corresponding locations when sitting on the beanbag are shown in Figure 7.

3.4.1. Effect of frequency of vibration

With fore-and-aft vibration, the areas of the body in contact with vibration (the ischial tuberosities and lower thighs) became progressively more dominant locations of discomfort as the frequency of low magnitude vibration increased from 1.0 to 10 Hz in both seating conditions ($p < 0.01$, Cochran Q). There was a corresponding statistically significant reduction in the dominance of vibration discomfort in the lower and upper torso as the frequency of fore-and-aft high magnitude vibration increased from 1 to 10 Hz ($p < 0.02$, Cochran Q).

With lateral vibration, the areas of the body in contact with vibration also became more dominant locations of discomfort as the frequency of low magnitude vibration increased from 1.0 to 10 Hz with both seating conditions ($p < 0.01$, Cochran Q). There was a corresponding reduction in the discomfort experienced at the head as the frequency increased ($p < 0.05$, Cochran Q) with no reports of discomfort at the head with frequencies greater than 3.15 Hz.

With high magnitude vertical vibration without the beanbag, the head, neck and shoulders were dominant sources of discomfort at lower frequencies (1.0 to 4 Hz) but not at higher frequencies ($p < 0.001$, Cochran Q).

With the higher frequencies of vibration, the legs and feet were frequently identified as dominant locations of discomfort, particularly with higher magnitudes of vibration, but in no condition were the feet and lower legs identified as the location of greatest discomfort by the majority of subjects.

3.4.2. Effect of magnitude of vibration

Increases in the magnitude of vertical vibration caused a large increase in reports of dominant discomfort in the chest and shoulders, and reduced reports of dominant discomfort around the ischial tuberosities and lower thighs (Figures 6 and 7). For the purposes of statistical analysis, reports of dominant discomfort in the shoulders or chest were combined and reports of dominant discomfort at the ischial tuberosities or

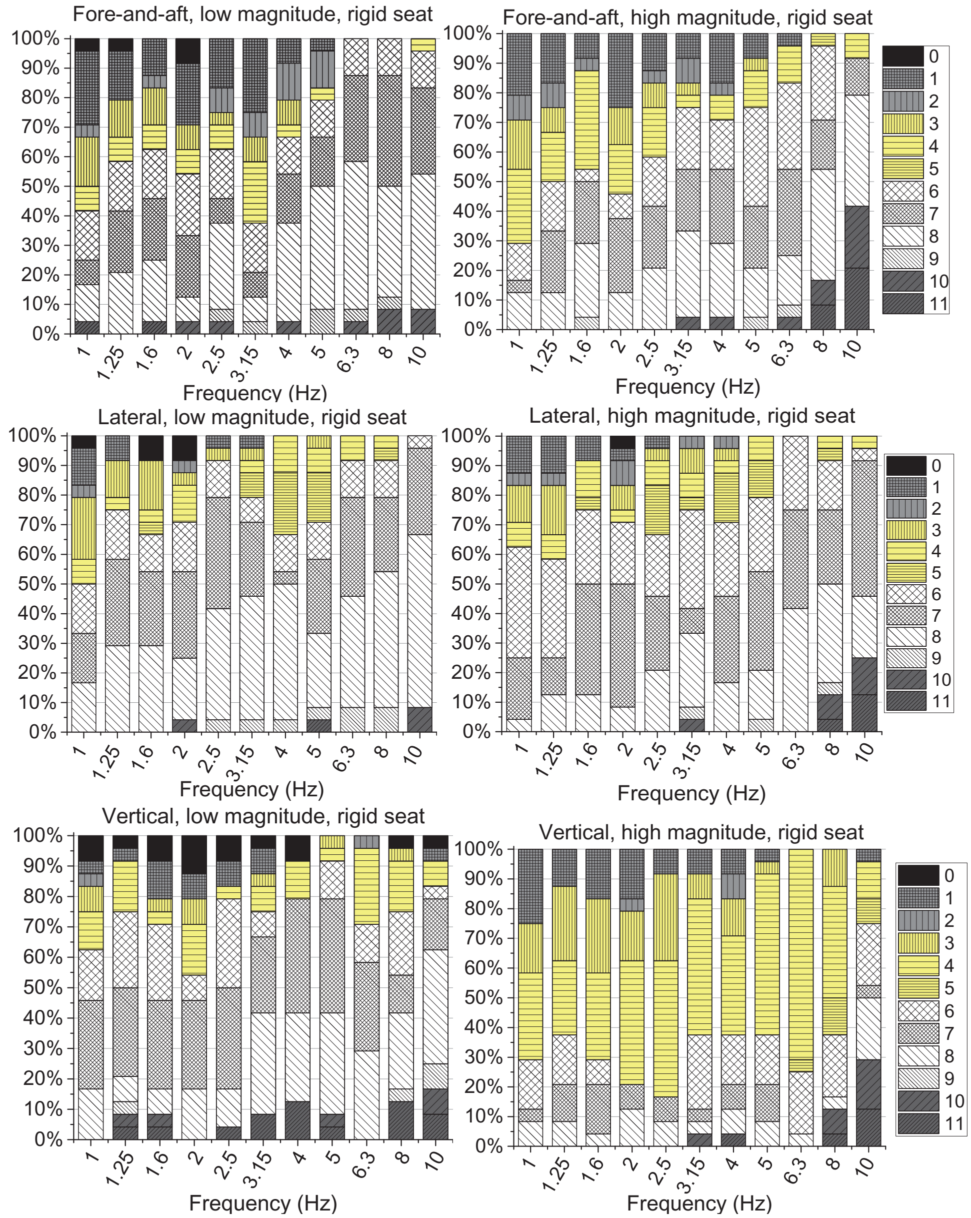

Figure 6. Reported body locations of most discomfort in each axis of vibration, at 'low' magnitudes (0.088 ms^{-2} r.m.s., weighted) and 'high' magnitudes (0.70 ms^{-2} r.m.s., weighted) with a rigid seat. Body locations – 0: 'no discernible location'; 1: head; 2: neck; 3: shoulders; 4: chest; 5: arms; 6: lower abdomen; 7: ischial tuberosities, 8: lower thighs; 9: upper thighs; 10: legs; and 11: feet.

lower thighs were combined. With the rigid seat, when the vibration magnitude increased from 'low' to 'high', reports of dominant discomfort in the shoulders or chest were significantly increased at frequencies from 1.0 to 6.3 Hz and reports of dominant discomfort around the ischial tuberosities or lower thighs were reduced at 1.0 Hz and from 2.5 to 8 Hz (Table 3). With the beanbag, when the vibration magnitude increased from 'low' to 'high', reports of dominant discomfort in the shoulders or chest were significantly increased at frequencies from 1.6 to 6.3 Hz and reports of discomfort around the ischial tuberosities or lower thighs were reduced at 2.0 Hz and from 3.15 to 6.3 Hz (Table 3).

With fore-and-aft and lateral vibration, the range of magnitudes of vibration included in the study had no statistically significant effect on the location of discomfort at any frequency of vibration.

3.4.3. Effect of beanbag

The beanbag had little effect on the location of dominant discomfort with any of the three directions of vibration at any frequency (compare Figures 6 and 7).

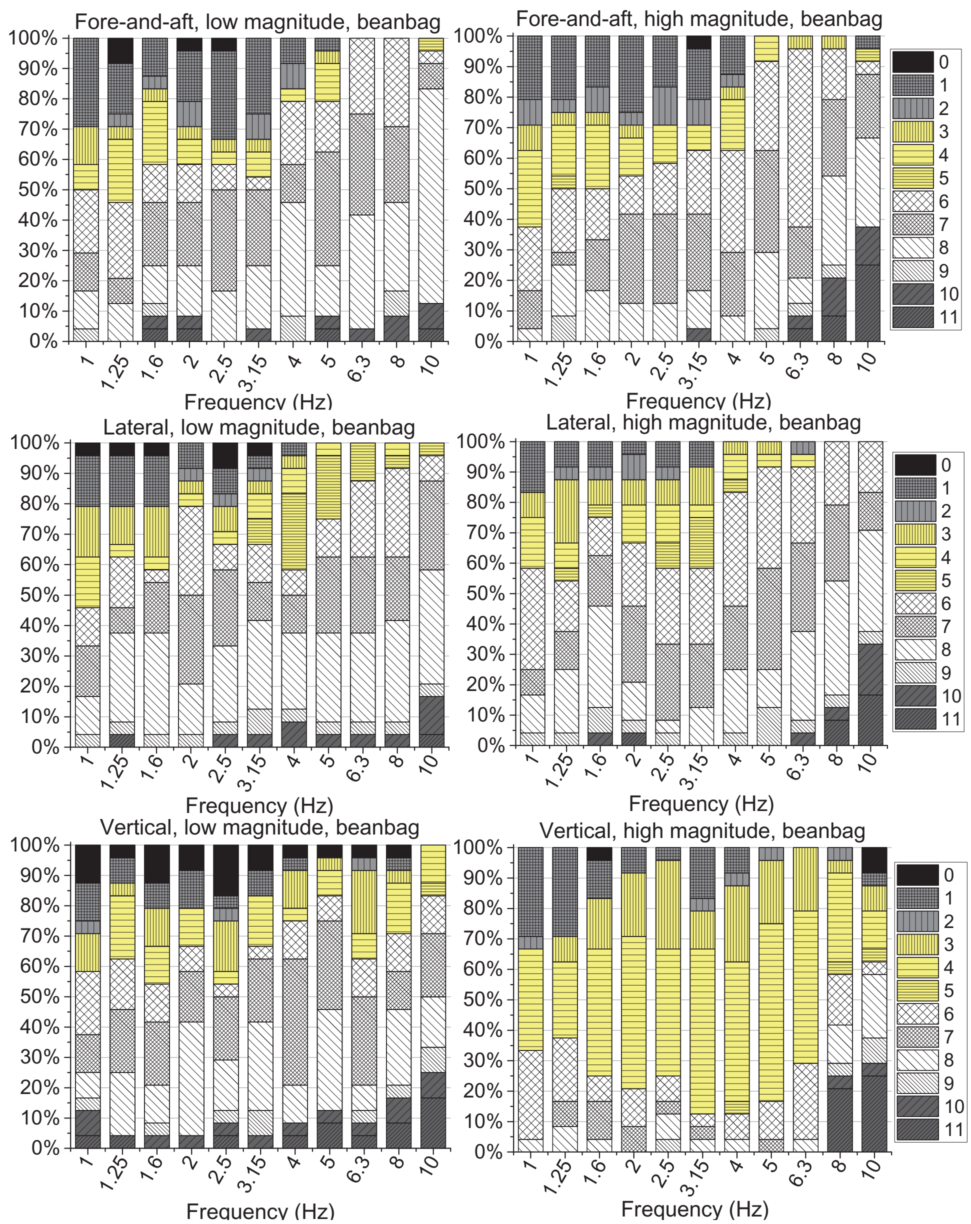

Figure 7. Reported body locations of most discomfort in each axis of vibration, at 'low' magnitudes (0.088 ms^{-2} r.m.s., weighted) and 'high' magnitudes (0.70 ms^{-2} r.m.s., weighted) when sitting on the beanbag. Body locations – 0: 'no discernible location'; 1: head; 2: neck; 3: shoulders; 4: chest; 5: arms; 6: lower abdomen; 7: ischial tuberosities, 8: lower thighs; 9: upper thighs; 10: legs; and 11: feet.

Contrary to expectations, the ischial tuberosities were not less dominant locations of discomfort when the beanbag distributed the pressure to a larger area ($p >$ 0.05, McNemar).

4. Discussion

4.1. Rate of growth of discomfort

The rate of growth of vibration discomfort varied over the frequency range (1.0 to 10 Hz) within all three axes of vibration (fore-and-aft, lateral, and vertical) and differed between these axes of vibration. This means that the shapes of the equivalent comfort contours (and corresponding frequency weightings) will change with changing magnitude of vibration and the relative discomfort caused by vibration in each axis will change as the magnitude of vibration changes.

A vibration with a greater rate of growth of vibration discomfort becomes a more important source of discomfort as the vibration magnitudes increase. Referring to Figure 2, as the magnitudes of horizontal vibration increase, fore-and-aft vibration around 2.5 Hz and lateral vibration around 1.6 Hz will become more

Table 3. The effect of magnitude of vertical vibration on the location of dominant discomfort (*p*-values; McNemar test): ↑ statistically significant increase in reports of discomfort at these locations with increasing magnitude of vibration; ↓ statistically significant decrease in reports of discomfort at these locations with increasing magnitude of vibration.

Rigid seat, locations 3 or 4 (shoulders or chest)										
1.0	1.25	1.6	2.0	2.5	3.15	4.0	5.0	6.3	8.0	10
0.031↑	0.021↑	0.001↑	0.021↑	0.000↑	0.006↑	0.008↑	0.000↑	0.001↑	0.092	1.000
Rigid seat, locations 7 or 8 (ischial tuberosities or lower thighs)										
1.0	1.25	1.6	2.0	2.5	3.15	4.0	5.0	6.3	8.0	10
0.008↓	0.344	0.219	0.070	0.016↓	0.002↓	0.002↓	0.002↓	0.001↓	0.021↓	0.092
Beanbag seat, locations 3 or 4 (shoulders or chest)										
1.0	1.25	1.6	2.0	2.5	3.15	4.0	5.0	6.3	8.0	10
0.227	0.754	0.039↑	0.001↑	0.000↑	0.000↑	0.000↑	0.000↑	0.006↑	0.453	0.687
Beanbag seat, locations 7 or 8 (ischial tuberosities or lower thighs)										
1.0	1.25	1.6	2.0	2.5	3.15	4.0	5.0	6.3	8.0	10
0.219	0.146	0.289	0.007↓	0.146	0.002↓	0.000↓	0.000↓	0.008↓	0.070	0.388

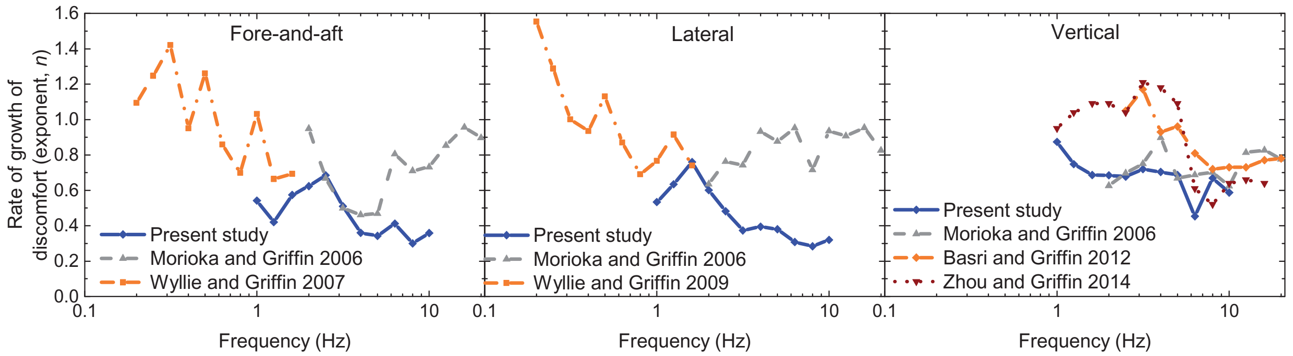

Figure 8. Rates of growth of vibration discomfort, *n*, for fore-and-aft, lateral and vertical whole-body vibration for a rigid seat without a backrest reported in various studies.

important sources of vibration discomfort. Relative to horizontal vibration, vertical vibration will increase in importance as a source of discomfort as the magnitude of vibration increases at frequencies greater than about 3 Hz.

The median rates of growth of discomfort found in this study varied over an approximately 2:1 range, from about 0.4 to 0.8. A vibration with a rate of growth of 0.4 must increase in magnitude by a factor of four to produce the percentage increase in vibration discomfort achieved by only doubling the magnitude of a vibration with a rate of growth of 0.8. The variations in the rate of growth of vibration discomfort over frequencies and directions can therefore have a large effect of the relative importance of different frequencies and directions of vibration in causing vibration discomfort.

There are various potential causes for a frequency-dependence and direction-dependence in the rate of growth of discomfort. The rate of growth is likely to depend on the location in the body where the vibration causes greatest discomfort, with increased discomfort in the upper torso (location 4) during higher magnitudes of vertical vibration partially explaining the greater rate of growth of discomfort with vertical vibration at frequencies greater than about 3 Hz. A similar explanation has been offered for differences in the rate of growth of discomfort between vertical vibration at the feet and vertical vibration at the seat (Jang and Griffin 2000). Local peaks and troughs in the frequency-dependence of the rate of growth of vibration discomfort may arise from the biodynamic nonlinearities of the body that cause the frequency of greatest response to reduce as the vibration magnitude increases (Matsumoto and Griffin 2005; Subashi et al. 2009).

The rate of growth of discomfort has varied between studies (Figure 8). Potential reasons for the variation between studies include different seats employed (flat or contoured), different footrest conditions (stationary or moving with the seat), the amount of thigh contact, and whether the subjects' eyes were open or closed. The current study tried to prevent secondary cue's from influencing subject judgements by requiring eyes to be closed and masking the noise from the vibrating platform. Future studies should investigate what factors apart from the frequency and magnitude of vibration influence the rate of growth of discomfort.

Over the frequency range 1.0 to 10 Hz, the rate of growth of vibration discomfort varies more for vibration in the horizontal directions than for vibration in the vertical direction. Among potential causes for this difference are the different mechanisms involved in producing sensations, including changes in the location of the principal vibration discomfort in the body with changing frequency and changing direction of vibration.

4.2. Equivalent comfort contours

4.2.1. Within directions of vibration

With both fore-and-aft and lateral vibration, the acceleration equivalent comfort contours show little dependence on the frequency of vibration at the lower magnitudes (around 0.1 to 0.2 ms^{-2} r.m.s.) but reduced sensitivity to the higher frequencies with greater magnitudes of vibration (Figure 4).

The frequencies of greatest vibration discomfort caused by fore-and-aft and lateral acceleration appear to reduce with increasing magnitude of vibration and occur at a higher frequency for fore-and-aft vibration than for lateral vibration, consistent with Subashi et al. (2009). With low magnitudes of vertical acceleration, vibration discomfort increases with increasing frequency up to about 6.3 Hz, whereas the increase occurs up to only about 4 or 5 Hz at the higher magnitudes, consistent with Matsumoto and Griffin (2005) and Zhou and Griffin (2014).

4.2.2. Between directions of vibration

The relative sensitivity to fore-and-aft and lateral vibration depends on the magnitude of vibration, but at the magnitudes used in this study there was greater sensitivity to lateral vibration around 1.6 to 2 Hz and greater sensitivity to fore-and-aft vibration around 3.15 to 4 Hz (Figure 5).

Currently, both British Standard 6841 (British Standards Institution 1987) and International Standard 2631-1 (International Organization for Standardization 1997) indicate that unweighted vertical acceleration causes greater discomfort than unweighted horizontal vibration at frequencies greater than 3.15 Hz and less discomfort than unweighted horizontal vibration at frequencies less than 3.15 Hz. This study shows that the effect of vibration magnitude on the shapes of the equivalent comfort contours causes the frequency of the crossover between sensitivity to vertical and horizontal vibration to change with the magnitude of vibration (Figure 5). At low magnitudes, the frequency of the crossover was as high as 6.3 Hz, but this reduced with increasing magnitude of vibration and was not always the same for fore-and-aft and lateral vibration.

4.3. Body locations showing greatest discomfort

With fore-and-aft and lateral vibration, the location of greatest discomfort was at, or close to, the interface between the occupant and the seat (i.e. locations 6/7/8). The likely cause of the discomfort being located here is shearing between the seat surface and the occupant, and weak transmission of vibration to the upper body. Because of the shearing, less motion was transferred to the torso of the body and so the location of discomfort did not change much with a change in magnitude.

With vertical vibration at the lower magnitudes, the location of greatest discomfort was spread across all possible locations but with a tendency towards greatest discomfort at the interface with the seat surface. At the higher magnitudes of vertical vibration, the location of greatest discomfort moved towards the upper body. This suggests the rate of growth of discomfort differed between body areas, with lower rates of growth of discomfort in peripheral areas and higher rates of growth of discomfort in central areas of the body. Consequently, vibration discomfort was located predominantly in the central parts of the body with higher magnitudes of vertical vibration but distributed more uniformly with lower magnitudes of vertical vibration.

The locations of discomfort in the body caused by fore-and-aft, lateral, and vertical whole-body vibration when sitting on a flat rigid seat with feet supported on a stationary footrest have been investigated previously (Whitham and Griffin 1978). With fore-and-aft and lateral vibration, the areas of most discomfort were in the area of the lower abdomen and the buttocks, with greatest discomfort at the ischial tuberosities. With vertical vibration in the range of 4 to 16 Hz, greatest discomfort was in the upper parts of the body, consistent with the current study. Whitham and Griffin used a vibration magnitude of 1.0 $m.s^{-2}$ (unweighted), so at frequencies less than 4 Hz the magnitude was close to the middle magnitude used in the current study. With 2-Hz vertical vibration, they found discomfort fairly evenly distributed over body locations, similar to the lower magnitudes of vibration in the current study.

In a study with vertical vibration and no backrest, middle magnitudes produced discomfort primarily in the buttocks and lower thighs at low frequencies (2.5 to 4.0 Hz) but, as the frequency increased above 5.0 Hz, there was increased discomfort in the lower and upper back, although the buttocks and the lower thighs remained the primary location of discomfort (Basri and Griffin 2012). At the highest magnitude investigated, discomfort was mostly located at the buttocks at 2.5 and 3.15 Hz, with increasing discomfort at the lower back and upper back as the frequency increased to 6.3 Hz. Discomfort at the buttocks and lower thighs increased from 8.0 to 10 Hz. This is reasonably consistent with the current study where increasing the magnitude of vertical direction changed the location of greatest discomfort from the interfaces between the subject and the seat (ischial tuberosities and thighs) to more central parts of the body (lower abdomen and chest).

In a later study, at the higher magnitudes and at frequencies greater than 1.0 Hz, there was some discomfort in the head as well as in the central parts of the body (Basri and Griffin 2013). As frequencies increased, the head became a less important location for discomfort in favour of the upper back and the lower back. At 8.0 and 10 Hz, the locations of greatest discomfort lowered to the buttocks and the lower thighs. This is also in reasonable agreement with the current study, which found some discomfort at the head decreasing with frequency increasing from 1.0 to 4.0 Hz, the chest becoming a greater location of discomfort with increasing frequency up to 6.3 Hz, and the lower abdomen, thighs, and legs becoming more uncomfortable at 8.0 and 10 Hz.

The location of greatest discomfort has also been found in the lower part of the body with lateral vibration and in the upper body with vertical vibration by Griefahn and Bröde (1999).

4.4. Effect of beanbag

There were no systematic differences in the rates of growth of discomfort in any of the three directions between sitting with and without the beanbag. Similarly, there was little effect of the beanbag on the equivalent comfort contours.

Acceleration measured on the beanbag with a sit-pad indicated that it was rigid over the frequency range used in this study, so it is reasonable for it not to affect the rates of growth of discomfort or the equivalent comfort contours. However, prior to the experiment it was hypothesised that without the beanbag there would be more reports of the location of dominant discomfort at the ischial tuberosities, because of increased pressure around the ischial tuberosities. The absence of any large effect suggests that the findings from many previous studies with rigid flat seat surfaces are not restricted to only those seating conditions.

4.5. Implications for methods of evaluating whole-body vibration with respect to vibration discomfort

Similar to some previous studies (e.g. Morioka and Griffin 2006; Wyllie and Griffin 2007, 2009; Basri and Griffin 2012; Zhou and Griffin 2014) this study found that the rate of growth of vibration discomfort depended on the frequency of vibration. There was a frequency-dependence of the rate of growth of vibration discomfort with fore-and-aft, lateral, and vertical whole-body vibration and, at each frequency, the rate of growth differed between the directions of vibration. This means the optimum frequency weightings for vibration discomfort, and the optimum multiplying factors to represent relative sensitivity to each direction of vibration depend on the magnitude of vibration.

The finding of different equivalent comfort contours for fore-and-aft and lateral vibration suggests it is inappropriate to evaluate vibration in these two directions using the same frequency weighting. However, the larger difference is between these contours and the standardised frequency weighting W_d (Figure 9).

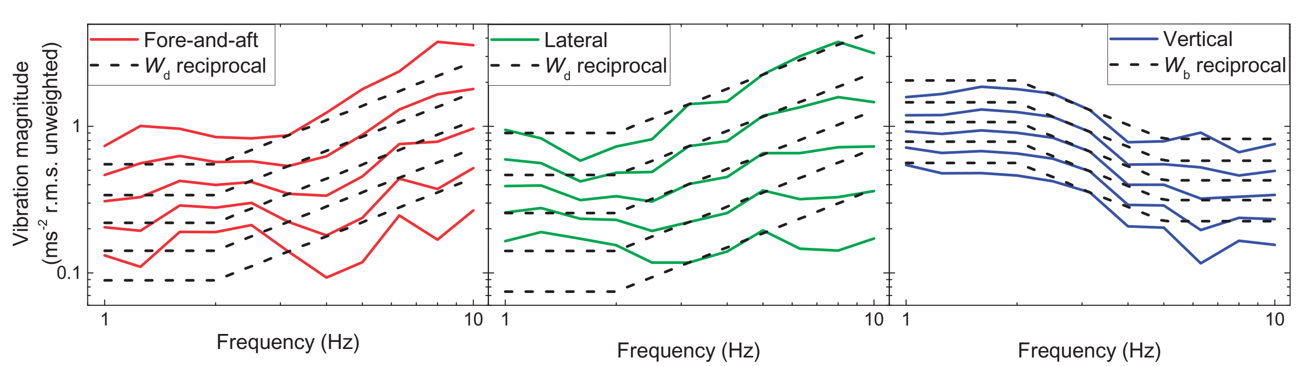

Figure 9. Equivalent comfort contours for subjective magnitudes from 63 to 160 in the fore-and-aft, lateral, and vertical directions, relative to 0.25 ms^{-2} r.m.s. weighted vertical vibration at 3.15 Hz. Contours compared with the reciprocals of the asymptotic versions of frequency weightings W_d and W_b for horizontal and vertical vibration, respectively. The reciprocal weightings have been adjusted to be equal to the equivalent comfort contours at 3.15 Hz.

This weighting will tend to underestimate the discomfort caused by low magnitudes of higher frequencies of vibration, as reported previously by Morioka and Griffin (2006), but it is more appropriate when predicting the discomfort of higher magnitudes of fore-and-aft or lateral vibration. So although there are consistent differences between the equivalent comfort contours for fore-and-aft and lateral vibration, the differences due to the change in the frequency-dependence with changing magnitude of vibration merit greater consideration.

For the conditions investigated here, the rate of growth of vibration discomfort is greater for all directions of vibration at low frequencies and generally greater with vertical vibration than horizontal vibration. Consequently, the shapes of equivalent comfort contours, and the equivalence between directions of vibration, change as the magnitude of vibration changes. These differences are not reflected in the standards that recommend the use of the same frequency weightings and the same axis multiplying factors for predicting the discomfort caused by all magnitudes of vibration.

5. Conclusions

The rate-of-growth of vibration discomfort with increasing magnitude of fore-and-aft, lateral, or vertical vibration is highly dependent on the frequency of the vibration and depends on the direction of the vibration. Equivalent comfort contours therefore have a frequency-dependence that depends on the magnitude of vibration and the relative contributions of fore-and-aft, lateral, and vertical vibration to discomfort depend on the magnitude of vibration.

With all directions of vibration, but especially horizontal vibration (fore-and-aft and lateral), the frequency-dependence of the acceleration required to cause similar discomfort becomes more marked as the magnitude of vibration increases. At the higher magnitudes of vibration studied here, the frequency-dependence of discomfort is consistent with frequency weighting W_b (for vertical vibration) and frequency weighting W_d (for horizontal vibration), although there are systematic differences in the frequency-dependence of discomfort caused by fore-and-aft and lateral vibration.

During horizontal vibration, greatest discomfort is experienced at the interfaces between the body and the seat, consistent with shearing of tissues around the ischial tuberosities. During vertical vibration, greater discomfort is experienced towards the central and upper parts of the body as the magnitude of vibration increases. Widening the distribution of pressure over the surface of a rigid flat seat with a bean-bag had no effect on the rate of growth of vibration discomfort, or the frequency-dependence of vibration discomfort, or the locations of greatest discomfort.

Differences in the magnitude-dependence of the frequency-dependence of vibration discomfort and the relative discomfort caused by vertical and horizontal vibration are not reflected in the currently standardised frequency weightings. To better coincide with the frequency-dependence and the direction-dependence of the discomfort caused by whole-body vibration it may be appropriate to develop different weightings for low magnitude and high magnitude vibration.

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