RATE OF GROWTH OF VIBRATION DISCOMFORT WITH INCREASING MAGNITUDE OF FORE-AND-AFT, LATERAL, AND VERTICAL WHOLE-BODY VIBRATION IN THE FREQUENCY RANGE 1 TO 10 Hz

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Abstract

British and International standards provide frequency weightings to assist the prediction of the discomfort caused by fore-and-aft, lateral and vertical whole-body vibration. The practical application of the weightings assumes that the frequency-dependence and directional-dependence of vibration discomfort is independent of the magnitude of vibration. This will only be the case if the rate of growth of vibration discomfort with increasing magnitude of vibration is the same at all frequencies and in all three directions of vibration. With 24 subjects this study determined the rate of growth of vibration discomfort associated with translational vibration over the frequency range 1 to 10 Hz at unweighted magnitudes of vibration in the range of 0.09 to 3.5 $m.s^{-2}$ r.m.s. (weighted magnitudes in the range 0.088 to 0.70 $m.s^{-2}$ r.m.s.). The rate of growth of vibration discomfort showed large variations according to the frequency and direction of vibration and was generally greater for vertical vibration than for horizontal vibration.

1. Introduction

People are not perfect measurement tools. The level of vibration felt by a person depends on the frequency, magnitude, direction, and duration of the vibration (Griffin, 2007). It is therefore helpful to have a method of evaluating vibration to predict human response that takes into account these four attributes of vibration.

A British Standard (BSI 6841:1987) and an International Standard (ISO 2631-1:1997) define methods for evaluating human exposures to whole-body vibration. The evaluation method includes frequency weightings and direction multiplying factors to be applied to objectively measured acceleration at the seat pan, backrest, and feet so as to allow for expected human sensitivity to vibration of different frequencies in different directions at these three locations. The weightings were based on experimental studies of human responses to vibration and involve various assumptions.

The frequency weightings and axis multiplying factors were influenced by a series of studies of the frequency-dependence of discomfort caused by fore-and-aft, lateral, and vertical vibration at the seat pan, backrest, and feet (Griffin, Whitham and Parsons, 1982; Parsons and Griffin, 1982; Parsons *et al*., 1982; Griffin, Parsons and Whitman, 1982). The first paper reported an experiment with translational vibration at the seat pan in which 36 participants gave subjective judgements that allowed the construction of equivalent comfort contours in the three axes at the seat pan over the frequency range of 1 to 100 Hz (Griffin, Whitham and Parsons, 1982). These contours showed the

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vibration required to produce discomfort equivalent to that caused by 10-Hz vertical vibration with a magnitude of 0.8 ms^{-2} r.m.s. The weightings at low frequencies were refined using additional data from similar experimental studies (Corbridge and Griffin, 1986) and earlier research (see Griffin, 1990). Experimental equivalent comfort contours in each axis were then used to define frequency weightings that are now used in the standards to predict the relative discomfort of vibrations over a wide range of vibration magnitudes. For simplicity, the standardised frequency weightings initially corresponded to constant velocity, constant acceleration, and constant jerk over defined frequency ranges (asymptotic weightings). Later, the weightings were developed so as to be easily implemented in analogue and digital filters (realisable weightings).

Research completed subsequent to the publication of the standards has found that the frequency-dependence of human perception of vibration depends on the magnitude of vibration (e.g., Morioka and Griffin, 2006a; Wyllie and Griffin, 2009; Basri and Griffin, 2013). Although an equivalent comfort contour equivalent to a defined reference vibration will give a frequency weighting applicable to that degree of discomfort it will be less accurate for predicting the frequency-dependence of greater or lesser discomfort (Zhou and Griffin, 2014, 2016). As the vibration magnitude increases from the threshold of perception up to magnitudes causing appreciable discomfort, there are systematic changes in the frequency-dependence of vibration perception (Figure 1; Morioka and Griffin, 2006a). These experiments examined hypotheses with specific frequencies and magnitudes of vibration, leaving it desirable to obtain a better understanding of the dependence of the rate of growth of discomfort on the frequency and direction of low frequency whole-body vibration.

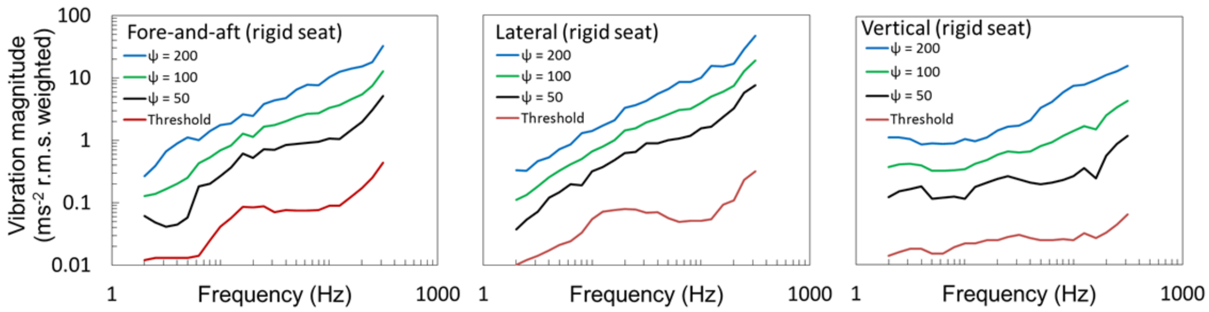

Figure 1 The frequency-dependence of thresholds for the perception of fore-and-aft, lateral, and vertical whole-body vibration compared to magnitude estimates of discomfort of 50, 150 and 300, where 100 is the discomfort caused by 20-Hz vibration at 0.5 ms^{-2} r.m.s. in the vertical direction and 1.0 ms^{-2} r.m.s. in the horizontal directions (Morioka and Griffin, 2006a).

The change in the frequency-dependence of vibration discomfort at different vibration magnitudes means that the rate of growth of vibration discomfort differs across the frequency range. The rate of growth also differs between directions of vibration (Morioka and Griffin, 2006a). Stevens' power law is used to relate the magnitude of human perception, ψ, to the physical magnitude, φ, of a stimulus:

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

where n is the 'rate of growth' of vibration discomfort and k is a constant. If values of n are the same at all frequencies of vibration, the equivalence determined at one magnitude of vibration (i.e. an equivalent comfort contour) is the same as that at a higher or lower magnitude of vibration. Equivalent comfort contours obtained at different degrees of discomfort would then be parallel and one frequency weighting can be expected to provide a good prediction of vibration discomfort for all magnitudes of vibration. The variation in the rate of growth of discomfort, n, with the frequency of vibration means that a different weighting is needed with different magnitudes of vibration. Differences in the rate of growth of discomfort between directions of vibration mean that a different axis multiplying factor will be needed at different magnitudes of vibration. The rate of growth of vibration discomfort is therefore of great importance.

This study was designed to determine the rate of growth of vibration discomfort for each of the three translational axes of seat vibration over the frequency range 1 to 10 Hz with frequency-weighted vibration magnitudes in the range 0.08 to 0.70 ms^{-2} r.m.s. It was hypothesised that the rate of growth would depend on frequency and the direction of the vibration.

2. Method

2.1. Subjects

Twenty four subjects, twelve male and twelve female students and office workers from the University of Southampton, participated in the study. Their characteristics are summarised in Table 1. The experiment was approved by the Ethics Committee of the Faculty of Engineering and the Environment at the University of Southampton (application number 19695).

Table 1 Medians and ranges of subject characteristics.

Gender	Age (years)	Stature (m)	Weight (kg)
Male	29 (21– 40)	1.82 (1.65 – 1.94)	75 (65 - 130)
Female	30 (19 - 38)	1.63 (1.53 -1.75)	61(45 -78)

2.2. Apparatus

Fore-and-aft, lateral, and vertical sinusoidal vibration was produced by a six-axis motion simulator in the Human Factors Research Unit of the Institute of Sound and Vibration Research at the University of Southampton (Figure 2).

A rigid seat with no backrest (seat-pan height 0.570 m, seat-pan depth 0.493 m) was mounted on the motion simulator. Subjects wore a loose lap belt and held an emergency stop button for safety. A rigid footrest was used if necessary so that the lower surfaces of the thighs were in contact with the seat surface and the heels of the subjects could rest on the footrest.

Simulator noise was masked by white noise at 65 dB (A) produced through headphones worn by the subjects. The experimenter was able to communicate to the subjects directly through the headphones via a microphone.

2.3. Motion Stimuli

Motion stimuli were generated using MATLAB (version 2012a) and *HVLab* toolbox (version 2). The sinusoidal stimuli were at the eleven preferred one-third octave centre frequencies from 1.0 to 10 Hz. The stimuli had durations of approximately 5.5 seconds, adjusted to n+0.5 cycles of oscillation (where n is an odd number). These stimuli were then modulated by a half sine envelope so that each

Figure 2 Experimental setup on the 6-axis simulator.

stimulus started and ended with zero displacement, zero velocity, and zero acceleration. An example stimulus is shown in Figure 3.

The vibration stimuli were presented at seven magnitudes at increments of 3 dB. 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. To maintain a reasonable range of discomfort throughout the experiment, after frequency weighting in accord with British Standard 6841:1987 (W_b for vertical vibration and W_d for fore-and-aft and lateral vibration, with a unity axis multiplying factor) the range of frequency-weighted magnitudes was the same at every frequency and in all three axes.

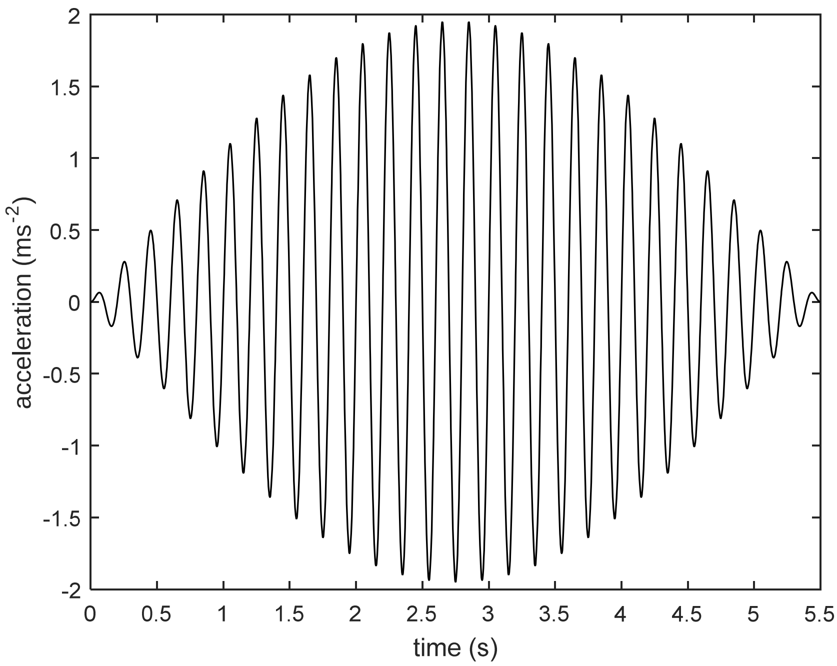

Figure 3 Example stimulus at 5 Hz.

2.4. Procedure

Subjects attended one session lasting approximately 90 minutes, which included reading instructions, signing a consent form, practice, and participating in the experiment. Practice consisted of judging the length of lines on paper and judging vibration discomfort when exposed to thirteen vertical vibrations (over the range of frequencies and magnitudes they would experience in the experiment).

During the experiment, the subjects were instructed to close their eyes to eliminate any influence of the visual perception of motion from their judgements. They were instructed to sit comfortably and maintain an upright posture.

Subjects rated the vibration discomfort caused by each of the motions using the method of absolute magnitude estimation. They were encouraged to give a rating of 100 for the first motion they experienced (3.15 Hz at 0.25 ms^{-2} r.m.s. frequency-weighted vertical vibration) and were required to rate the discomfort caused by all subsequent motions relative to the discomfort caused by the first motion. It was explained that a rating of 50 would mean the discomfort was half that caused by the first motion and a discomfort of 200 would mean the vibration discomfort was double that caused by the first motion. The order of presenting the motion stimuli was randomised independently in frequency, direction, and magnitude for each subject.

2.5. Analysis

Using Stevens' power law, the rate of growth of discomfort, *n,* and the constant, *k*, were determined at each frequency for every subject by linear regression after logarithmic transformation of Equation 1:

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

where n represents the slope (rate of growth of discomfort) and k represents the intercept of the linear regression between $\log_{10} \psi$ and $\log_{10} \varphi$.

The hypotheses were tested using non-parametric statistics in SPSS (version 22). To quantify differences between related samples, the Friedman two-way analysis of variance and the Wilcoxon matched-pairs signed ranks were used. The Mann-Whitney U test was employed to test for differences between independent samples. The probabilities shown are not adjusted for multiple comparisons.

3. Results

3.1. Within directions of vibration

The medians and inter-quartile ranges of the rates of growth of discomfort (i.e., the exponent n) at each frequency of vibration are shown for fore-and-aft, lateral, and vertical vibration in Figure 4. In each of the directions the rate of growth of vibration discomfort depended on the frequency of vibration ($p<0.001$ in all three directions; Friedman).

In the fore-and-aft direction, the rate of growth of discomfort decreased with increasing frequency greater than about 2.5 Hz and was significantly greater at frequencies less than 3.15 Hz than at frequencies greater than 3.15 Hz ($p<0.05$, Wilcoxon), except for comparisons between 1.25 Hz and 10 Hz ($p=0.051$, Wilcoxon) and 3.15 Hz and 10 Hz ($p=0.052$, Wilcoxon).

In the lateral direction, the rate of growth of vibration discomfort also decreased with increasing frequency greater than about 1.6 Hz and was significantly greater at frequencies less than 2.0 Hz than at frequencies greater than 2.0 Hz ($p<0.05$, Wilcoxon), except for the comparison between 1.0 and 10 Hz ($p=0.051$, Wilcoxon).

In the vertical direction, the rate of growth of vibration discomfort reduced with increasing frequency with significant differences between frequencies less than 1.6 Hz and frequencies greater than 4 Hz ($p<0.05$, Wilcoxon).

3.2. Between directions of vibration

At all frequencies, there was a significant difference in the rate of growth of discomfort over the three directions of vibration ($p<0.05$, Friedman). However, the rate of growth of vibration discomfort did not differ between the two horizontal directions ($p>0.05$, Wilcoxon), except at 1.6 Hz and 2.5 Hz ($p=0.004$ and $p=0.002$, respectively, Wilcoxon).

The rate of growth of vibration discomfort in the vertical direction was significantly greater than in either of the two horizontal directions ($p<0.02$, Wilcoxon), except from 1.6 to 2.5 Hz between vertical and fore-and-aft vibration and from 1.6 to 2.0 Hz between vertical and lateral vibration (see Figure 4).

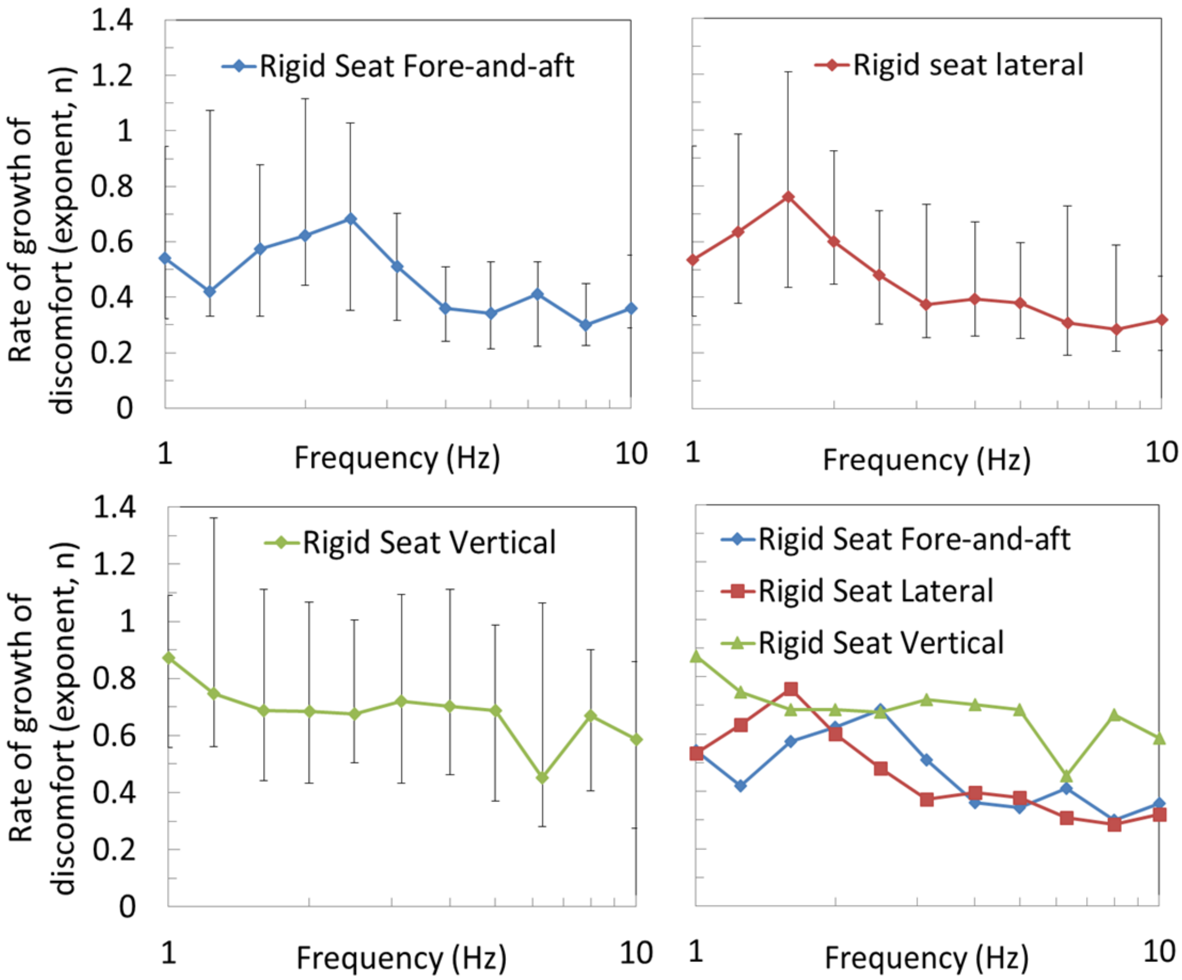

Figure 4 Rate of growth of vibration discomfort, *n*, for fore-and-aft vibration (top left), lateral vibration (top right), and vertical vibration (bottom left), and all three directions of vibration (bottom right) when sitting on a rigid seat without a backrest. Median values and inter-quartile ranges for 24 subjects.

3.3. Effect of gender

In all three axes there was generally a greater rate of growth of vibration discomfort in males than in females (Figure 5).

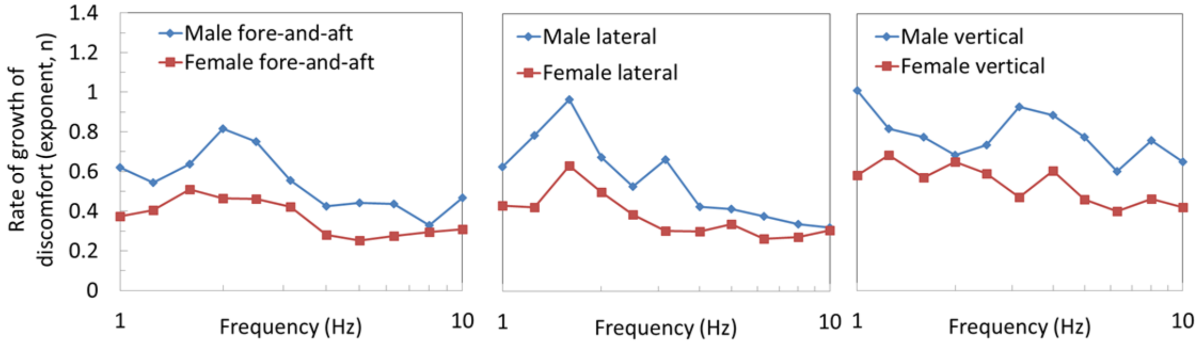

Figure 5 Rate of growth of vibration discomfort, *n*, for fore-and-aft vibration, lateral vibration, and vertical vibration with a rigid seat without a backrest for male (blue) and female (red) subjects. Median values for 12 males and 12 females.

Differences in the rate of growth of vibration discomfort between male and female subjects were tested for statistical significance in each direction and at each frequency using the Mann-Whitney U-test (Table 2).

Table 2 Statistical significance (*p* values) of differences between males and females in the rate of growth of vibration discomfort at each frequency and all three directions of vibration ($p<0.05$ shown in bold).

Frequency, Hz	1.00	1.25	1.60	2.00	2.50	3.15	4.00	5.00	6.30	8.0	10.0
Fore-and-aft	0.196	0.242	**0.042**	**0.009**	**0.011**	0.056	**0.005**	**0.005**	**0.014**	**0.049**	**0.025**
Lateral	0.185	**0.034**	0.079	**0.027**	0.065	**0.002**	0.207	0.069	**0.012**	0.124	0.196
Vertical	0.389	0.056	0.056	0.340	0.140	0.268	0.065	**0.036**	**0.007**	0.065	0.148

4. Discussion

It is reasonable to expect that the rate of growth of vibration discomfort will depend on the location of the body most excited by the vibration and the sensory system involved in the perception of motion at that location. The transmission of vibration through the body is highly dependent on the frequency and direction of the vibration so a frequency-dependent in the rate of growth of vibration discomfort is likely.

Vibration discomfort will tend to be greater at the resonance frequencies of the body (because there is more vibration in the body at the resonance frequencies than at adjacent frequencies) but it does not automatically follow that the rate of growth of vibration discomfort will be greater at a resonance. However, the dominant low frequency resonances of the body (around 2 Hz in the horizontal directions and in the approximate range 5 to 10 Hz in the vertical direction) increase vibration in the 'central' parts of the body. One study has concluded that the location of perception varies with the magnitude of vibration with the discomfort caused by higher magnitudes of vibration more affected by vibration in the torso of the body (Jang and Griffin, 2000). So whereas the perception of low magnitudes may be perceived in other areas (e.g., tingling of the thighs resting on the seat) this is perceived as less important as the magnitude increases and significant sensations are experienced within the torso. This would be consistent with a greater rate of growth for vibration perceived in the torso than vibration perceived at the thighs, and the greater vibration around the resonance frequencies could result in a greater rate of growth for those resonances that involve the torso. This would be consistent with both the observed frequency-dependence of the rate of growth of vibration discomfort and the greater rate of growth for vertical vibration than horizontal vibration at the higher frequencies in the present study.

The frequency-dependence in the rate of growth of discomfort found at higher frequencies than those studied here (see Figure 1) and with hand-transmitted vibration and foot-transmitted vibration may be associated with the perception of vibration via different sensory channels (Morioka and Griffin, 2006a,b, 2010).

There are no known previous studies of differences in the rate of growth of vibration discomfort between males and females. The differences appear interesting and worthy of further investigation.

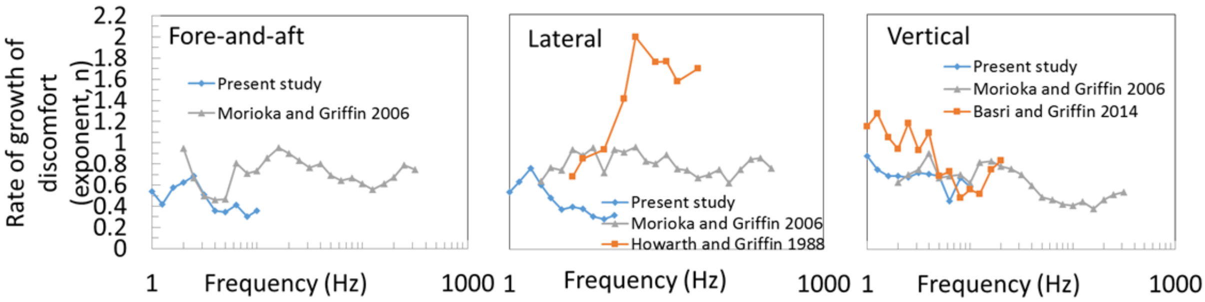

Figure 6 Rates of growth of vibration discomfort, *n*, for fore-and-aft, lateral and vertical whole-body vibration for a rigid seat without a backrest. Present study (blue) Morioka and Griffin (2006a) (grey), Howarth and Griffin (1988) (orange, lateral) and Basri and Griffin (2014) (orange, vertical).

The rate of growth of vibration discomfort has differed between studies (Figure 6). The differences may be associated with the magnitudes of vibration studied, the range of magnitudes in each study, and the postures of subjects (e.g. footrest and backrest conditions). For example, the stationary footrest employed in by Morioka and Griffin will have created greater relative displacement between the seat pan and feet during low frequency vibration. There may also be differences associated with having the eyes open or closed, the characteristics of the surface on which subjects sat, and the form of magnitude estimation employed: absolute magnitude estimation or relative magnitude estimation with either a vibration or noise reference. Future studies should investigate the factors influencing the rate of growth of vibration discomfort in addition to the frequency and direction of vibration.

The present and previous studies show that the rate of growth of discomfort is dependent on the frequency of vibration and also the direction of vibration. For the conditions investigated here, the rate of growth is greater at low frequencies and greater with vertical vibration, so people are more sensitive to changes in the magnitude of lower frequency vibration and vertical vibration. As a consequence, equivalent comfort contours and the equivalence between directions of vibration will change in shape as the magnitude of vibration changes. These differences are not reflected in 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 caused by fore-and-aft, lateral, and vertical whole-body vibration depends on the frequency of the vibration and the direction of the vibration. The relative vibration discomfort between frequencies and directions therefore depends on the magnitude of vibration. Current standards for predicting vibration discomfort overlook these magnitude-dependent effects of human sensitivity to the frequency and direction of whole-body vibration.

6. Acknowledgement

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