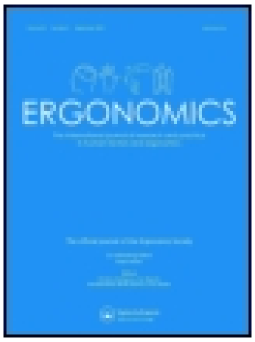

Ergonomics

ISSN: 0014-0139 (Print) 1366-5847 (Online) Journal homepage: http://www.tandfonline.com/loi/terg20

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To cite this article: Zhen Zhou & Michael J. Griffin (2016): Response of the seated human body to whole-body vertical vibration: discomfort caused by mechanical shocks, Ergonomics, DOI: 10.1080/00140139.2016.1164902

To link to this article: http://dx.doi.org/10.1080/00140139.2016.1164902

Accepted author version posted online: 22 Mar 2016.

Publisher: Taylor & Francis

Journal: *Ergonomics*

DOI: http://dx.doi.org/10.1080/00140139.2016.1164902

Number of pages: 12

Number of Figures: 12

Number of Tables: 0

Number of References: 20

Response of the seated human body to whole-body vertical vibration: discomfort caused by mechanical shocks

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Abstract

The frequency-dependence of discomfort caused by vertical mechanical shocks has been investigated with 20 seated males exposed to upward and downward shocks at 13 fundamental frequencies (1 to 16 Hz) and 18 magnitudes (±0.12 to ±8.3 ms^{-2}). The rate of growth of discomfort with increasing shock magnitude depended on the fundamental frequency of the shocks, so the frequency-dependence of equivalent comfort contours (for both vertical acceleration and vertical force measured at the seat) varied with shock magnitude. The rate of growth of discomfort was similar for acceleration and force, upward and downward shocks, and lower and higher magnitude shocks. The frequency-dependence of discomfort from shocks differs from that for sinusoidal vibrations having the same fundamental frequencies. This arises in part from the frequency content of the shock. Frequency weighting W_b in BS 6841:1987 and ISO 2631-1:1997 provided reasonable estimates of the discomfort caused by the shocks investigated in this study.

Key words: ride comfort; mechanical shocks; shock magnitude; force.

Practitioner summary

No single frequency weighting can accurately predict the discomfort caused by mechanical shocks over wide ranges of shock magnitude, but vibration dose values with frequency weighting W_b provide reasonable estimates of discomfort caused by shocks similar to those investigated in this study with peak accelerations well below 1 g.

1. Introduction

The prediction of discomfort caused by whole-body vibration and mechanical shock has applications in the design and operation of land, sea, and air transport and civil engineering structures (e.g., buildings and bridges). In standardised methods of evaluating the severity of vibration, the dependence of discomfort on the frequency of vibration is reflected in frequency weightings derived from studies of responses to sinusoidal vibration. There have been few studies of the applicability of the frequency weightings to non-sinusoidal vibration.

The relation between the physical magnitude of a stimulus and the sensations it produces may be expressed by Stevens' power law, in which the 'objective magnitude', φ, of the stimulus (e.g., acceleration or force) and the 'subjective magnitude', ψ, of the response (e.g., discomfort) are assumed to be related by a power function:

$$\Psi = k\,\varphi^{n} \qquad (2)$$

The exponent, n, indicates the rate of growth of sensation with increasing magnitude of vibration and is often assumed to be constant for each type of stimulus (Stevens, 1975). However, experimental studies with whole-body vibration have found that the rate of growth of discomfort differs according to the frequency of vibration (e.g., Matsumoto and Griffin, 2005; Morioka and Griffin, 2006; Zhou and Griffin, 2014a), the direction of vibration (e.g., Wyllie and Griffin, 2007, 2009; Subashi *et al*., 2009), body posture (e.g., Thuong and Griffin, 2011; Basri and Griffin, 2012, 2013), and the characteristics of shocks (e.g., Ahn and Griffin, 2008).

The dependence of the rate of growth of discomfort, n, on the frequency of vibration means the frequency-dependence of vibration discomfort depends on the magnitude of vibration. This is because a fixed percentage increase in the magnitude of vibration will produce a different percentage increase in discomfort at different frequencies. This is referred to as nonlinearity in subjective response and implies that frequency weightings should differ for low magnitude and high magnitude vibration. However, this is not reflected in current standards, where the same frequency weighting is used at all magnitudes (British Standards Institution, 1987; International Organization for Standardization, 1997). Considering the wide range of magnitudes experienced with mechanical shocks it is reasonable to question how well the vibration discomfort caused by mechanical shocks can be predicted using standardized frequency weightings derived from subjective responses to sinusoidal vibration.

Biodynamic studies show that the mechanical responses of the body are also nonlinear, with the resonance frequencies in the apparent mass of the body reducing as the magnitude of vibration increases (e.g., Fairley and Griffin, 1989; Mansfield and Griffin, 2000). Some of the nonlinearity in the biodynamic response is similar to some of the nonlinearity in the subjective response (Matsumoto and Griffin, 2005; Zhou and Griffin, 2014b).

For the evaluation of statistically stationary vibration, it is convenient to predict human responses to vibration from the root-mean-square of the frequency-weighted acceleration. However, because an 'average' measure is inappropriate for quantifying transients, including shocks, and the duration-dependence in r.m.s. averaging underestimates the severity of mechanical shocks, British Standard

6841 (1987) and International Standard 2631 (1997) suggest the severity of vibration containing mechanical shocks may be predicted from the vibration dose value:

$$\text{vibration dose value (VDV)} = \left[\int_{t=0}^{t=T} a_w^{\,4}(t)\,\mathrm{d}t \right]^{\frac{1}{4}} \tag{1}$$

where $a_w(t)$ is the frequency-weighted acceleration and T is the period during which a person is exposed. If the frequency-dependence implicit in the frequency weighting, and the fourth-power duration-dependence implicit in the vibration dose value, are appropriate for all magnitudes and all directions, shocks will produce similar discomfort when their vibration dose values are similar.

Using half-sine force inputs of various magnitudes and frequencies, the transient responses of single degree-of-freedom damped systems (four damping ratios from 0.05 to 0.4) were used by Ahn and Griffin (2008) to generate a wide range of vertical mechanical shocks (16 fundamental frequencies from 0.5 to 16 Hz, five peak magnitudes from ±0.28 to ±2.3 ms^{-2}, and a reversed direction shock). They found that the rate of growth of discomfort, n, reduced progressively with increases in the fundamental frequency of the shock up to about 8 Hz.

It might be expected that the direction of a shock (i.e., upward or downward) will have a large effect on discomfort, but more than one study has found that subjective responses to upward shocks are similar to subjective responses to downward shocks of the same magnitude and waveform. Using the transient response of single-degree-of-freedom damped systems to a step input (giving damped sine waves at fundamental frequencies of 1, 4, or 16 Hz, with damping ratios of 0.125, 0.250 and 0.707 and VDVs ranging from 0.6 to 4.0 $ms^{-1.75}$), no large differences were found in subjective responses to upward and downward shocks (Howarth and Griffin, 1991). Using the transient response of single degree-of-freedom damped systems to half-sine force inputs, Ahn and Griffin (2008) also found that equivalent comfort contours for upward shocks were similar to those for downward shocks.

Equivalent comfort contours have also been expressed in terms of force (e.g., Mansfield and Maeda 2005; Zhou and Griffin, 2014a). At 1, 2, and 4 Hz there was similar discomfort with similar force, whereas at frequencies greater than 4 Hz, there was increasing sensitivity to force with increasing frequency (at 8, 16, and 31.5 Hz in Mansfield and Maeda 2005). Zhou and Griffin (2014a) found that over 13 frequencies from 1 to 16 Hz the frequency-dependence of equivalent comfort contours were less dependent on vibration magnitude when expressed as force equivalent comfort contours than acceleration equivalent comfort contours. This suggests biodynamic nonlinearities cause some of the nonlinearity evident in equivalent comfort contours for vertical vibration.

The number of experimental studies that can be used to develop or confirm a procedure for predicting the discomfort caused by shocks is currently small. There are an infinite number of shock waveforms and only a few have been investigated. Although findings of the few previous studies are consistent with the use of the vibration dose value for predicting discomfort, the existence of nonlinearities of various forms suggests there will be limits to the applicability of the method. Further study is required to understand the factors influencing the discomfort caused by shocks and how that discomfort may be predicted.

This study was designed to investigate, for vertical shocks that are easily reproduced and have well-defined spectra, how the rate of growth of discomfort and equivalent comfort contours for both acceleration and force depend on the fundamental frequency of motion supporting the seated human body. It was hypothesized that the discomfort caused by mechanical shocks would depend on the fundamental frequency of the shock and the direction of the shock as well as the magnitude of the shock. Assuming part of the nonlinearity in subjective responses is caused by biodynamic nonlinearity, it was hypothesised that equivalent comfort contours expressed in terms of dynamic force would show less nonlinearity than equivalent comfort contours expressed in terms of acceleration.

2. Method

2.1 Apparatus

A 1-metre stroke vertical electrohydraulic vibrator generated vertical oscillation of a flat rigid seat. An accelerometer (Silicon Designs 2260-002) mounted on the seat measured acceleration in the direction of excitation. A force platform (Kistler 9281B) mounted on the seat measured force at the interface between the seat (i.e., top surface of the force platform) and the subject in the vertical direction. The effect of the mass of the top plate of the force platform was eliminated by subtracting from the measured vertical force the measured vertical acceleration multiplied by the mass of the top plate (i.e., 31.5 kg) in the time domain (i.e., mass cancellation). The vibrator was controlled by a Servotest Pulsar system that generated mechanical shocks. The resultant acceleration and force were acquired to a separate computer using an *HVLab* data acquisition and analysis system (version 1.0). The force and acceleration were acquired at 512 samples per second via 50-Hz anti-aliasing filters.

Subjects sat on the seat without making contact with the backrest (see Figure 1 in Zhou and Griffin, 2014a). They rested their feet on a footrest that was attached to the vibrator table. The footrest was adjusted so that the upper surfaces of the upper legs were horizontal.

2.2 Subjects

Twenty male subjects, students at the University of Southampton, participated in the study. The median subject age was 24.5 years (range 22 - 33 years), the median subject mass was 71.1 kg (range 48 - 107 kg), and the median stature was 1.75 m (range 1.65 - 1.97 m).

Subjects were exposed to white acoustic noise at 65 dB(A) via a pair of headphones. During exposure to shocks, subjects were asked to close their eyes to prevent vision affecting their reaction to the motion.

The experiment was approved by the Human Experimentation Safety and Ethics Committee of the Institute of Sound and Vibration Research at the University of Southampton. Informed consent to participate in the experiment was given by all subjects.

2.3 Shocks

To obtain the shock acceleration waveforms, sinusoidal waveforms with 1½ cycles were modulated by a half cycle sinusoid with a period three times longer than the period of the sinusoidal acceleration (Figure 1).

FIGURE 1 ABOUT HERE

The sinusoidal waveforms used to produce the shocks were at the 13 preferred one-third octave centre frequencies from 1.0 to 16 Hz. The study was conducted with a range of 'lower magnitude' shocks and a range of 'higher magnitude' shocks. With both ranges, and at each fundamental frequency, the shocks were presented at nine magnitudes with peak values adjusted to produce the same frequency-weighted vibration dose value, VDV, using the W_b frequency weighting in ISO 8041:2005. In the low magnitude session, the VDV at each frequency was in the range 0.05 to 0.315 $ms^{-1.75}$ (with peak magnitudes up to 1.3 ms^{-2} r.m.s.). In the high magnitude session, the VDV at each frequency was in the range 0.315 to 2.0 $ms^{-1.75}$ (with peak magnitudes up to 8.3 ms^{-2} r.m.s.). The 'W_b' weighting was used so that, in accord with BS 6841 (1987) and previous research, shocks with the same VDV would be expected to produce a similar degree of discomfort.

2.4 Experiment design

Subjects attended the experiment on two different days. They were exposed to the lower magnitude shocks on one day, and exposed to the higher magnitude shocks on the other day. On both days, subjects experienced 117 vertical shocks in the upward direction (an upward displacement as shown in Figure 1) in one session and 117 vertical shocks in the downward direction in another session over about 30 minutes. Half of the subjects began with upward shocks and the other half began with downward shocks. During all sessions, the shocks were presented in a completely random order. The four conditions are referred to as 'high magnitude upward', 'high magnitude downward', 'low magnitude upward', and 'low magnitude downward', where 'upward' and 'downward' refer to the displacement of the waveform (see Figure 1).

The method of absolute magnitude estimation was used to obtain subject judgements (Huang and Griffin, 2014). Subjects were asked to estimate the subjective magnitude (i.e., the discomfort) caused by each stimulus using any numerical value, but with greater values for greater discomfort. It was suggested that 100 would be a sensible median value. On both days, before the experiment commenced, the subjects practiced magnitude estimation by rating the lengths of lines drawn on paper and then practiced judging the discomfort caused by some of the shocks included in the experiment, so as to become familiar with the experimental procedure and the sensations produced by the range of stimuli used in the experiment. For each direction, after being exposed to 117 shocks, the subjects were also exposed to an additional shock at each of the 13 frequencies (at 0.125 $ms^{-1.75}$ VDV for low magnitude shocks and 0.8 $ms^{-1.75}$ VDV for high magnitude shocks) and asked to indicate the part of the body where they felt the shock produced the greatest discomfort .

The experiment was also designed to measure biodynamic responses to the same mechanical shocks. The biodynamic responses obtained from the acceleration and force time histories, and biodynamic models developed from these measures, are reported separately (Zhou and Griffin, 2016).

2.5 Analysis

Within each session, the subjective responses of each individual subject were normalised by dividing each magnitude estimate by the median of all 234 magnitude estimates obtained on that day (Stevens, 1971). This 'normalised' (or 'equalised') the data and placed the magnitude estimates of all subjects on a similar scale so that they could be compared and analysed using the same procedure.

To calculate the rate of growth of discomfort at each frequency, and subsequently calculate equivalent comfort contours, for each subject, at each fundamental frequency of shock, the relation between the vibration dose value, φ, and the individual magnitude estimate of discomfort, Ψ, was determined using Stevens' Power law (Morioka and Griffin, 2006; Zhou and Griffin, 2014a). Linear regression was performed at each frequency after logarithmic transformation of Equation (1) to:

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

The apparent mass of each subject was calculated by fitting the mass, *m*, the damping, *c*, and stiffness, *k*, of a single degree-of-freedom model to the measured force and acceleration time histories (Zhou and Griffin, 2016). The association between subjective responses and biodynamic responses was investigated by calculating correlations between the ratio of the vertical apparent masses at two frequencies and the ratio of the subjective responses at the same two frequencies. The ratios were calculated for all possible pairs of frequencies for all subjects when exposed to the middle magnitude of vibration in each of the two sessions.

To avoid making assumptions on the distribution of the data, non-parametric statistical tests were employed (Siegel and Castellan, 1988). The Friedman two-analysis of variance and the Wilcoxon matched-pairs signed ranks test were used to investigate differences between related samples.

3. Results

It was expected that the rate of growth of discomfort caused by mechanical shocks would depend on the frequency, direction, and magnitude of the shock. It was therefore hypothesized that the discomfort caused by mechanical shocks would depend on the fundamental frequency of the shock and the direction of the shock as well as the magnitude of the shock.

Assuming biodynamic nonlinearities contribute to the nonlinearity in subjective responses, it was hypothesised that the rate of growth of discomfort with increased dynamic force would show less dependence on the shock frequency than the rate of growth of discomfort with increased acceleration. Consequently, the nonlinearity in equivalent comfort contours expressed in terms of force was expected to be less than the nonlinearity expressed in terms of acceleration.

3.1 Rate of growth of discomfort with increasing acceleration and force

For all four conditions (i.e., low magnitude upward, low magnitude downward, high magnitude upward, and high magnitude downward), the exponent *n* in Stevens' power law for acceleration varied with the fundamental frequency of the shocks ($p<0.001$; Friedman), which means the frequency-dependence of discomfort caused by mechanical shocks depends on the magnitude of the shocks. There was no significant difference in the exponent, *n*, between upward and downward shocks, or between low magnitude and high magnitude shocks, at any frequency ($p>0.05$, Wilcoxon). Figure 2(a) shows the medians and inter-quartile ranges of the exponent, *n*, for acceleration at each frequency for high magnitude upward shocks.

For all four conditions (i.e., low magnitude upward, low magnitude downward, high magnitude upward, and high magnitude downward), the exponent, *n*, for force also varied with the fundamental frequency of the shocks ($p<0.001$, Friedman). Similar to the exponent for acceleration, at each frequency there was no significant difference in the exponent between upward and downward shocks, or between low magnitude and high magnitude shocks ($p>0.05$, Wilcoxon). Figure 2(b) shows the medians and inter-quarter ranges of the exponent, *n*, for force at each frequency for high magnitude upward shocks.

FIGURE 2 ABOUT HERE

There were no significant differences in the exponent, *n*, between acceleration and force with either direction of shock or either magnitude of shock, at any of the 13 frequencies ($p>0.05$ Wilcoxon).

3.2 Acceleration and force equivalent comfort contours

Equivalent comfort contours were determined for each subject by calculating the vibration magnitude, φ, corresponding to nine subjective magnitudes, ψ, from 40 to 250 at each fundamental frequency of shock (from 1 to 16 Hz) using equation 1. The magnitude of vibration (either acceleration or force) was expressed using the vibration dose value (with no frequency weighting). The equivalent comfort contours show the magnitudes of the 1½-cycle shocks required to produce the same strength of sensation as the fundamental frequencies of the shocks varied from 0.5 to 16 Hz. Each shock contained a spectrum of frequencies around the fundamental frequency of the shock: so the equivalent comfort contours differ in shape from equivalent comfort contours for sinusoidal vibration that are dominated by response to a single frequency.

With both directions of shock and both magnitudes of shock, the acceleration equivalent comfort contours for all sensation magnitudes (i.e., ψ from 40 to 250) varied with the fundamental frequency of the shock ($p<0.0001$, Friedman; Figure 3). The acceleration contours become progressively flatter as the shock magnitude increases. For the lower magnitudes, the acceleration equivalent comfort contours tend to reduce (i.e., the shocks are more uncomfortable) as the fundamental frequency increases from 1 to 5 Hz, and then remain roughly constant to 16 Hz.

FIGURE 3 ABOUT HERE

Equivalent comfort contours for force also varied with the fundamental frequency of the shocks for both directions of shock and both magnitudes of shock ($p<0.0001$, Friedman; Figure 4). Generally, the equivalent comfort contours for force reduce as the fundamental frequency of the shocks increases from 1 to 16 Hz.

FIGURE 4 ABOUT HERE

3.3 Effect of shock direction

Equivalent comfort contours for upward and downward shocks are compared for acceleration and force in Figure 5. There was no evidence of a consistent difference in the median magnitude estimates for upward and downward shocks at either low or high magnitudes (p>0.05, Wilcoxon).

FIGURE 5 ABOUT HERE

3.4 Location of discomfort

Most discomfort was generally felt in either the buttocks or the thighs (Figure 6). As the shock magnitude increased, the location of most discomfort tended to move from the lower-body to the upper-body.

FIGURE 6 ABOUT HERE

3.5 Association between relative discomfort and normalised apparent mass

After adjustment for multiple comparisons, there was no clear pattern of statistically significant correlations between the relative apparent mass and the relative subjective response between any pair of frequencies for either upward or downward shocks of either low or high magnitude.

4. Discussion

4.1 Vibration discomfort caused by acceleration

The rate of growth of discomfort (the exponent n in Stevens' Power Law) varied with the fundamental frequency of the shocks, tending to reduce as the fundamental frequency increased from 1 to 10 Hz (Figure 2a). This is consistent with Ahn and Griffin (2008) who found the exponent reduced as the frequency increased from 0.5 to 8 Hz. In both studies there is a hint of an increase in the exponent as the frequency increases further to 16 Hz (Figure 7).

FIGURE 7 ABOUT HERE

The rates of growth of discomfort obtained with vertical shocks in this study can be compared with those obtained previously using vertical sinusoidal vibration (Zhou and Griffin, 2014a). It may be seen that the exponents are greater with sinusoidal vibration over the frequency range 2.5 to 5 Hz. All the factors influencing the rate of growth are not known, but the present findings show that the waveform can have a large effect, possibly because the shocks excited the body at frequencies both higher and lower than their fundamental frequency, and significant discomfort was sometimes caused by a frequency other than the fundamental frequency of the shock. There is scope for greater understanding of how shock waveform influences discomfort and the rate of growth of discomfort as the magnitude of a shock increase.

Because the rate of growth of discomfort (i.e., the exponent n) for acceleration varied with the frequency of the vibration (Figure 2a), the shapes of the equivalent comfort contours varied with the magnitude of the shocks (i.e., the acceleration equivalent comfort contours are not parallel, as seen in Figure 3).

Expressed in terms of vibration dose values, the magnitudes of the shocks used by Ahn and Griffin (2008) are similar to those employed in the high magnitude session of the present study. Their equivalent comfort contours (obtained with various damping ratios and with both upward and downward shocks but different waveforms to those in the present study) are compared with the equivalent comfort contours for the high magnitude upward and downward shocks in the present study (Figure 8). Although the shock waveforms (and therefore the frequency content of the shocks) differed, the equivalent comfort contours have similar characteristics, especially for shocks produced with a high damping ratio (i.e., ζ=0.4).

FIGURE 8 ABOUT HERE

The equivalent comfort contours for shocks have been compared with those previously obtained for sinusoidal vibration by normalising each contour to unity at 1 Hz (Figure 9). For both shocks and sinusoidal vibration, greater magnitudes tend to be needed to produce vibration discomfort at the lower frequencies (less than about 5 Hz) than at higher frequencies. At the higher frequencies, greater magnitudes are required from shocks than from sinusoidal vibration to cause similar discomfort, assuming the discomfort is similar at 1 Hz.

FIGURE 9 ABOUT HERE

There are several reasons why the equivalent comfort contours for shocks differ from those for sinusoidal vibration. The sinusoidal contours were obtained with 6-s periods of motion and were expressed in terms of r.m.s. values and, because the duration was the same at all frequencies, the ratio between r.m.s. values and vibration dose values does not depend on the frequency of the vibration. The shock contours were obtained using shocks whose duration reduced with increasing frequency and are expressed in terms of vibration dose values. If the time-dependency in the vibration dose value is appropriate, the effect of differing durations will have been nulled by comparing the contours in terms of vibration dose values, as in Figure 9.

Whereas the sinusoidal vibrations were dominated by a single frequency, all the shocks contained energy at frequencies both greater than and less than their fundamental frequency (Figure 10). With shocks having fundamental frequencies less than about 5 Hz, the presence of the higher frequencies will have heightened sensitivity, and therefore lowered the equivalent comfort contours at the lower frequencies. With shocks having fundamental frequencies greater than about 4 Hz, the presence of some energy at lower frequencies will have reduced sensitivity and so raised the equivalent comfort contours for shocks at these higher frequencies.

FIGURE 10 ABOUT HERE

The four equivalent comfort contours for shocks in Figure 9 differ according to the shock magnitude. The nonlinearity in equivalent comfort contours for both shocks and sinusoidal vibration is another reason why equivalent comfort contours for shocks differ from those for sinusoidal vibration.

According to BS 6841:1987 and ISO 2631-1:1997, shocks with the same frequency-weighted VDV should produce broadly similar discomfort. The median subjective responses obtained with shocks having the same W_b-weighted VDV over the full range of fundamental frequencies (1 to 16 Hz) and over the full range of shock magnitudes (0.05 to 2 $ms^{-1.75}$) are shown in Figure 11. Although some of the contours are flat (as expected if the frequency-weighted VDV provides a good prediction), some are not. The contours are consistent with the need for different frequency weightings at different magnitudes if shocks are to be evaluated over a wide range of magnitudes. Separate analysis (not shown) confirmed that the W_b-weighted VDV contours in Figure 9 are more flat than equivalent contours obtained using unweighted VDV, r.m.s., or peak values.

FIGURE 11 ABOUT HERE

4.2 Vibration discomfort caused by force

Similar to the exponent for acceleration, the rate of growth of sensation for force varied with frequency (Figure 2b). The minimum exponent tended to be around 10 Hz and so the force equivalent comfort contours show the greatest spread around 10 Hz (Figure 4).

With vertical sinusoidal whole-body vibration, force equivalent comfort contours have been found to be less nonlinear than acceleration equivalent comfort contours (Zhou and Griffin, 2014a). However, in the current study with mechanical shocks there were no differences in the exponent, *n*, between acceleration and force with either direction of shock or with lower or higher magnitude shocks at any of the 13 frequencies. This might be partially explained by the mechanical shocks having energy at all frequencies and not only at their fundamental frequencies, as shown in Figure 10.

Force equivalent comfort contours for shocks are compared with force equivalent comfort contours previously obtained for sinusoidal vibration (both normalised to unity at 1 Hz) in Figure 12. The comparison is broadly similar to that shown for acceleration in Figure 9, although the contours differ less.

FIGURE 12 ABOUT HERE

4.3 Association between subjective responses and biodynamic responses

An association between subjective responses and biodynamic responses might allow biodynamic measurements to be used to predict subjective responses. With sinusoidal vibration, distinct patterns of positive correlations have been found between the ratios of the apparent mass at pairs of frequencies and the ratios of subjective responses at these frequencies (Zhou and Griffin, 2014a). Such correlations were not found in the present study with mechanical shocks. Again, this may be explained by the mechanical shocks having components at frequencies other than the fundamental frequencies of the shocks. The present findings do not allow any useful prediction of individual discomfort from the biodynamic responses of individuals, as measured with acceleration and force at the surface of the supporting seat.

5. Conclusions

For vertical whole-body mechanical shocks, the rate of growth in discomfort with increases in both acceleration and force depends on the fundamental frequency of the shock, but with no large difference in the rate of growth in discomfort between force and acceleration or between upward and downward shocks at the magnitudes investigated (peak unweighted accelerations at magnitudes up to about 8 ms^{-2} in the frequency range 1.0 to 16 Hz).

The frequency-dependence of the discomfort of seated people exposed to vertical shocks differs from that for sinusoidal vibration having the same fundamental frequencies. This arises for several reasons including the frequency content of the shocks. For the 1½-cycle shocks investigated here, there was greatest sensitivity to acceleration at frequencies between about 5 and 12.5 Hz, but with a frequency-dependence that varied with the magnitude of the shock. No single frequency weighting can accurately predict the discomfort caused by either vibration or mechanical shock over a large range of magnitudes, but frequency weighting W_b as defined in current standards provided a reasonable estimate of the relative discomfort caused by the shocks investigated in this study.

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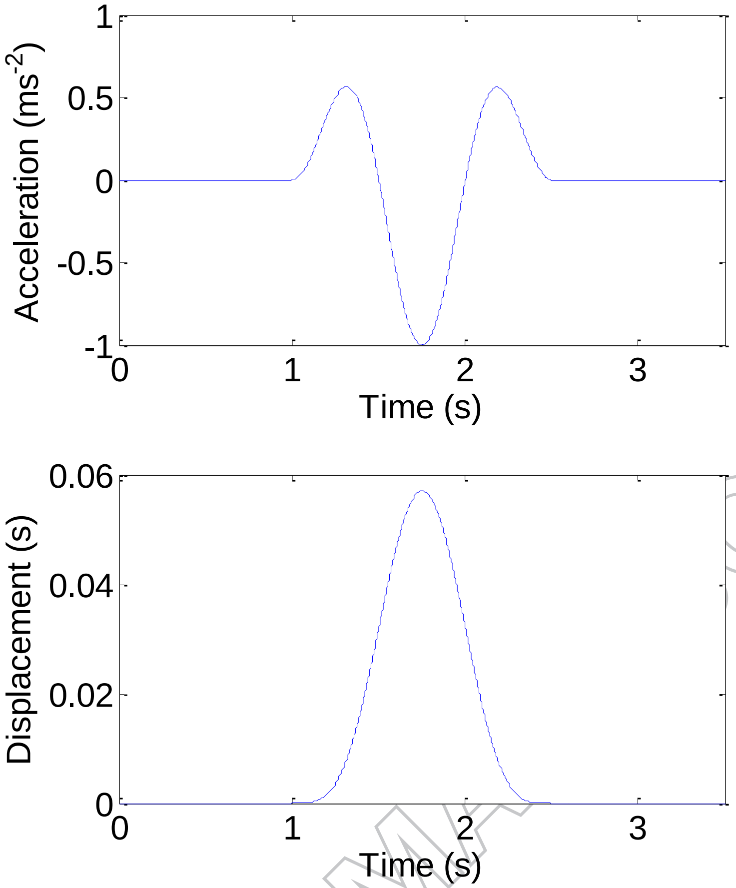

Figure 1 Example acceleration and displacement waveforms of the shocks used in the study.

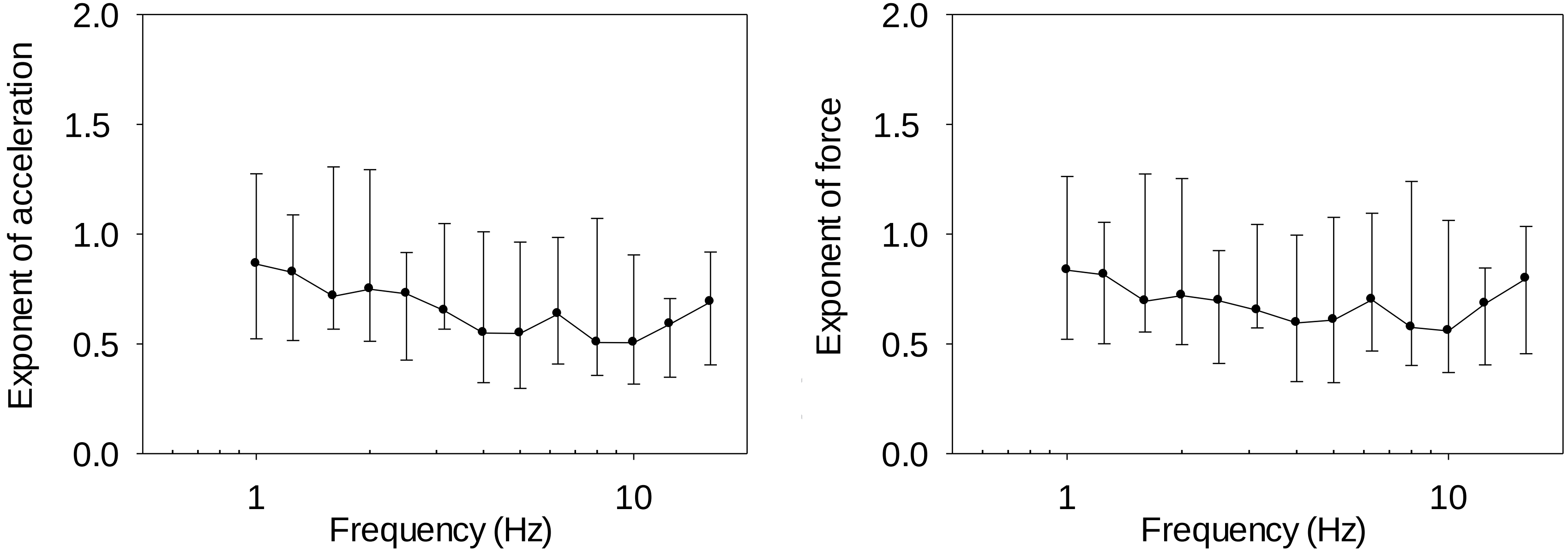

Figure 2 The rate of growth of discomfort, *n*, for vertical vibration acceleration (left) and force (right) with higher magnitude upward shocks. Medians and inter-quartile ranges for 20 subjects.

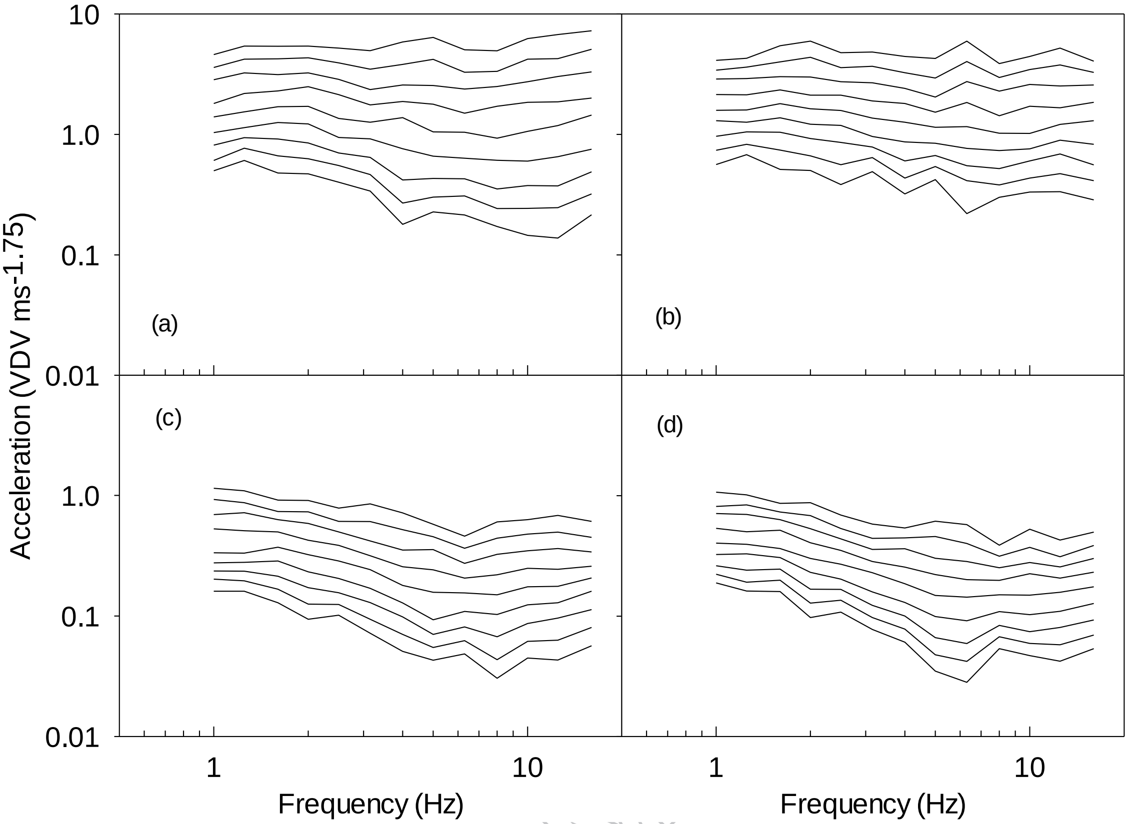

Figure 3 Acceleration equivalent comfort contours for shocks: (a) higher magnitude upward shocks; (b) higher magnitude downward shocks; (c) lower magnitude upward shocks; (d) lower magnitude downward shocks. Contours are for subjective magnitudes, ψ, of 40, 50, 63, 80, 100 125, 160, 200 and 250. Vibration dose values for acceleration without frequency weighting. Median values from 20 subjects.

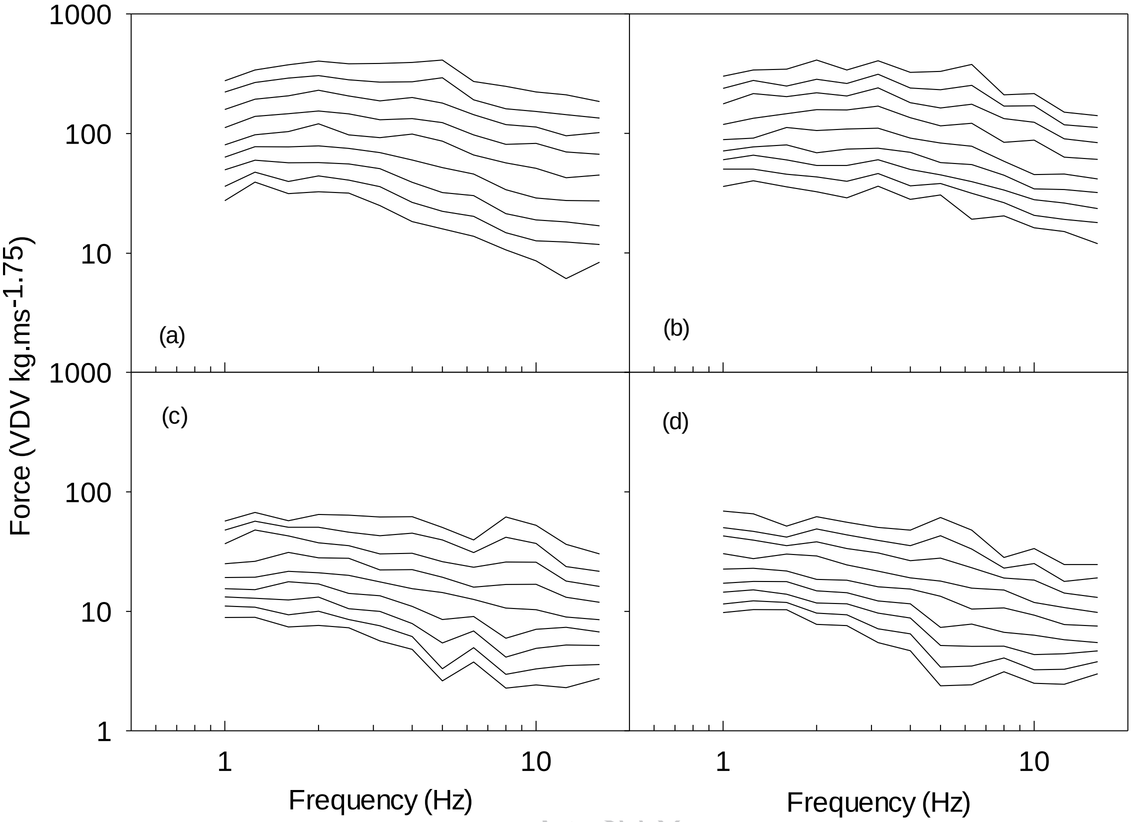

Figure 4 Force equivalent comfort contours for shocks: (a) higher magnitude upward shocks; (b) higher magnitude downward shocks; (c) lower magnitude upward shocks; (d) lower magnitude downward shocks. Contours are for subjective magnitudes, ψ, of 40, 50, 63, 80, 100 125, 160, 200 and 250. Vibration dose values for force without frequency weighting.

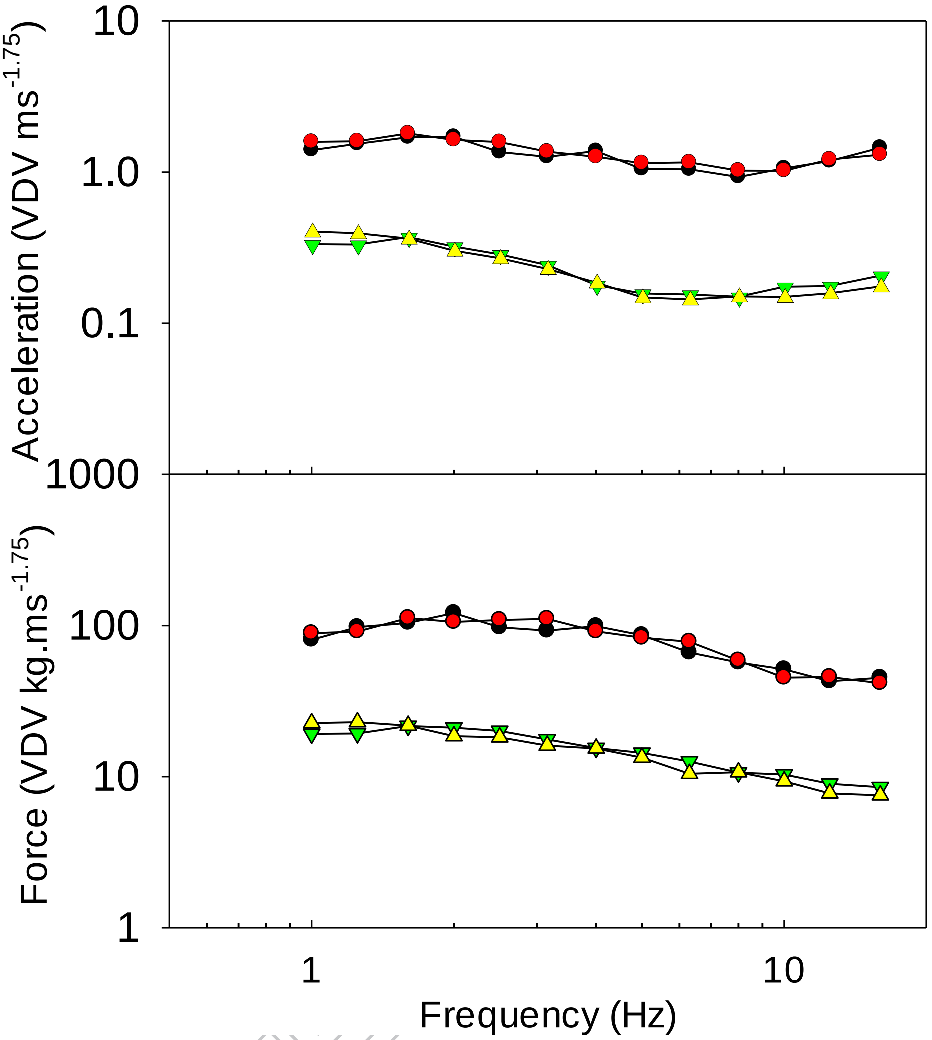

Figure 5 Comparison of median equivalent comfort contours for upward and downward shocks: acceleration (upper figure) and force (lower figure); ●: higher magnitude upward shocks; ●: higher magnitude downward shocks; ▼: lower magnitude upward shocks; ▲: lower magnitude downward shocks. Median equivalent comfort contours from 20 subjects for ψ = 100.

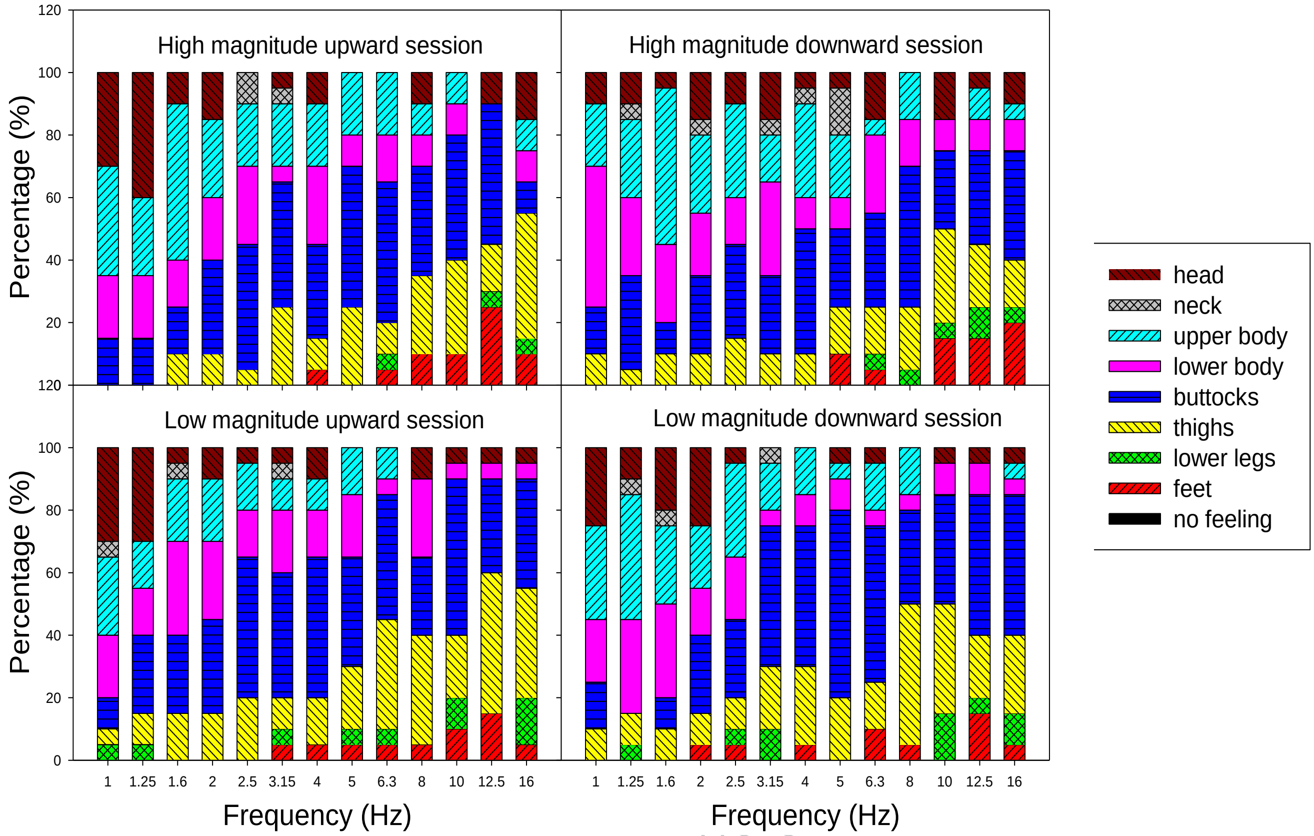

Figure 6 Locations of discomfort arising from exposure to vertical shocks: lower magnitude shocks (lower figures), higher magnitude shocks (upper figures); upward shocks (left figures); downward shocks (right figures).

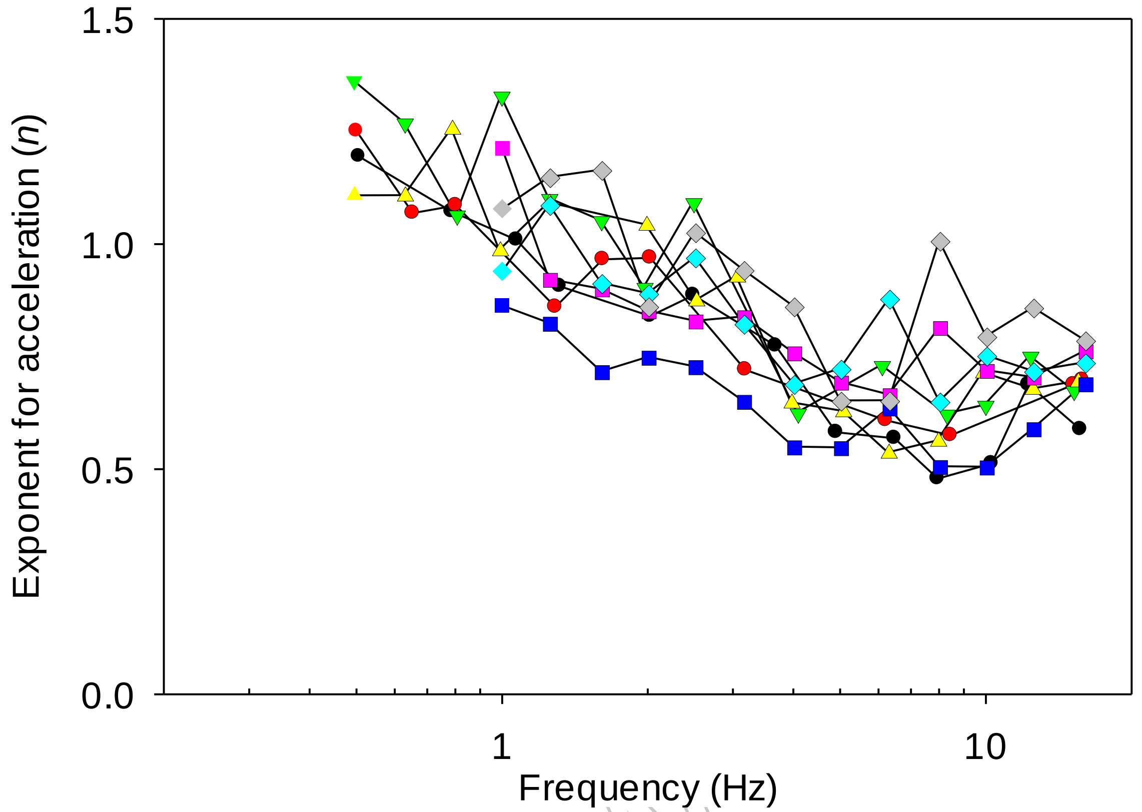

Figure 7 Comparison of rate of growth of discomfort, *n*, in two studies with shocks: present study and Ahn and Griffin (2008):●: Ahn and Griffin (2008) ζ =0.1; ●: Ahn and Griffin (2008) ζ =0.2; ▼: Ahn and Griffin (2008) ζ =0.4 ;▲: Ahn and Griffin (2008) ζ =0.4(r); ■:Present study (higher magnitude upward shocks); ■:Present study (higher magnitude downward shocks); ♦: Present study (lower magnitude upward shocks); ♦:Present study (lower magnitude downward shocks).

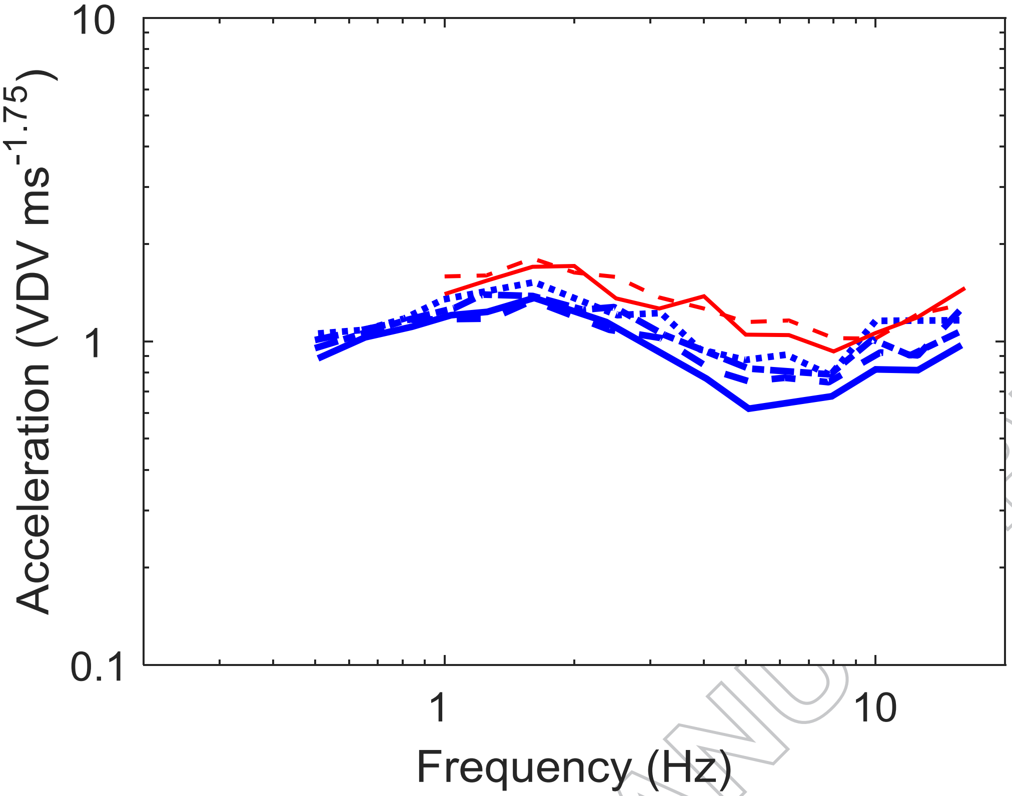

Figure 8 Frequency-dependence of equivalent comfort contours for acceleration: ——: Ahn and Griffin (2008) ζ=0.1; — —: Ahn and Griffin (2008) ζ=0.2; —•—: Ahn and Griffin (2008) ζ=0.4; • • •: Ahn and Griffin (2008) ζ=0.4(r); ——: Present study (high magnitude upward); — —: Present study (high magnitude downward). Vibration dose values for acceleration without frequency weighting.

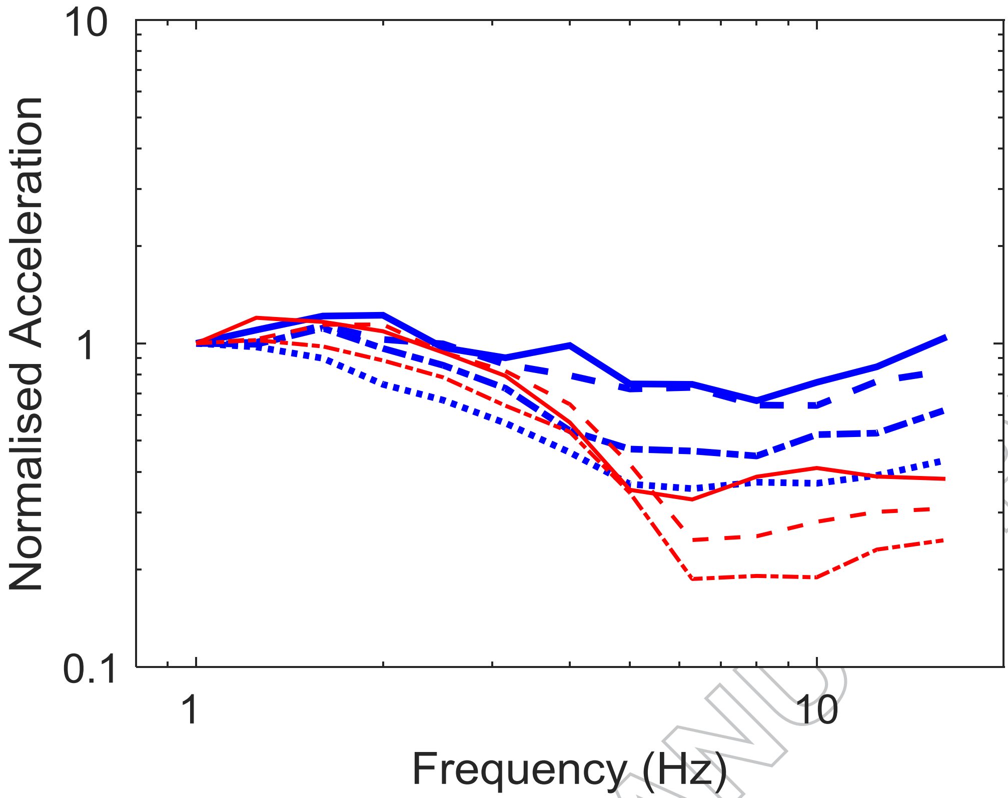

Figure 9 Comparison of acceleration equivalent comfort contours for shocks in the present study with equivalent comfort contours for sinusoidal vibration (from Zhou and Griffin, 2014). Values are normalised to unity at 1 Hz (The shock equivalent comfort contours are based on VDV, and the sinusoidal equivalent comfort contours are based on r.m.s. values). Shocks: ——: higher magnitude upward shocks; — —: higher magnitude downward shocks; —•—: lower magnitude upward shocks; • • • : lower magnitude downward shocks. Sinusoidal vibration: ——: higher magnitude sinusoidal vibration; — —: medium magnitude sinusoidal vibration; —•—: lower magnitude sinusoidal vibration.

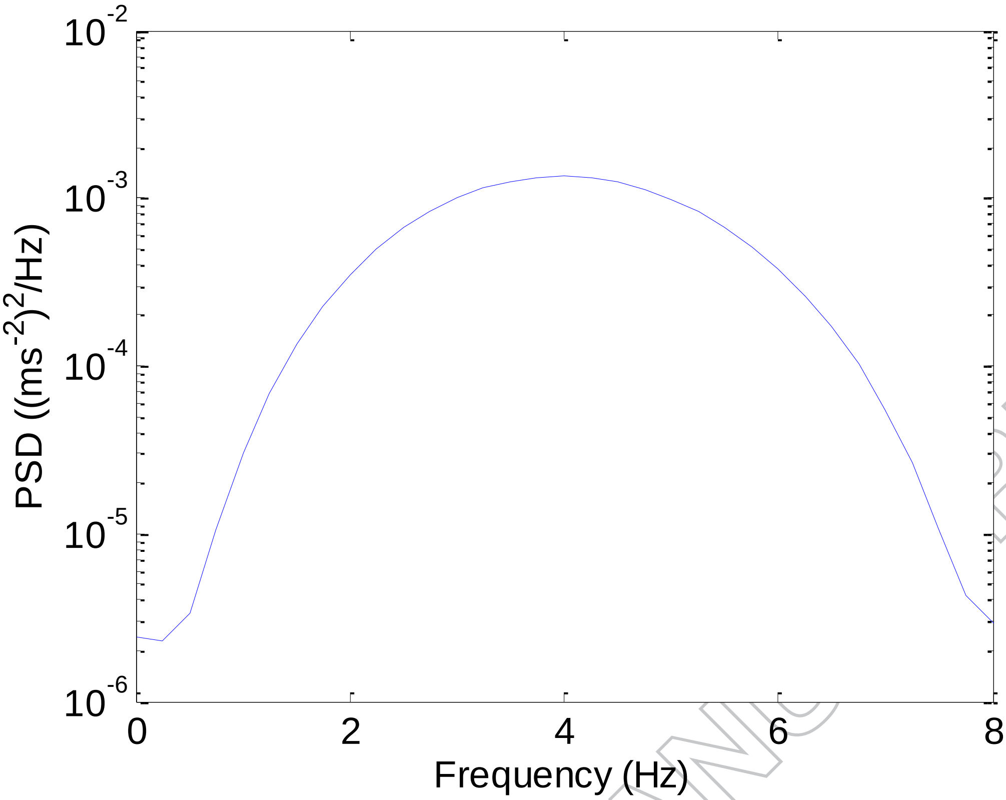

Figure 10 Example of spectrum of a 1½-cycle shock as used in this study (with a fundamental frequency of 4 Hz).

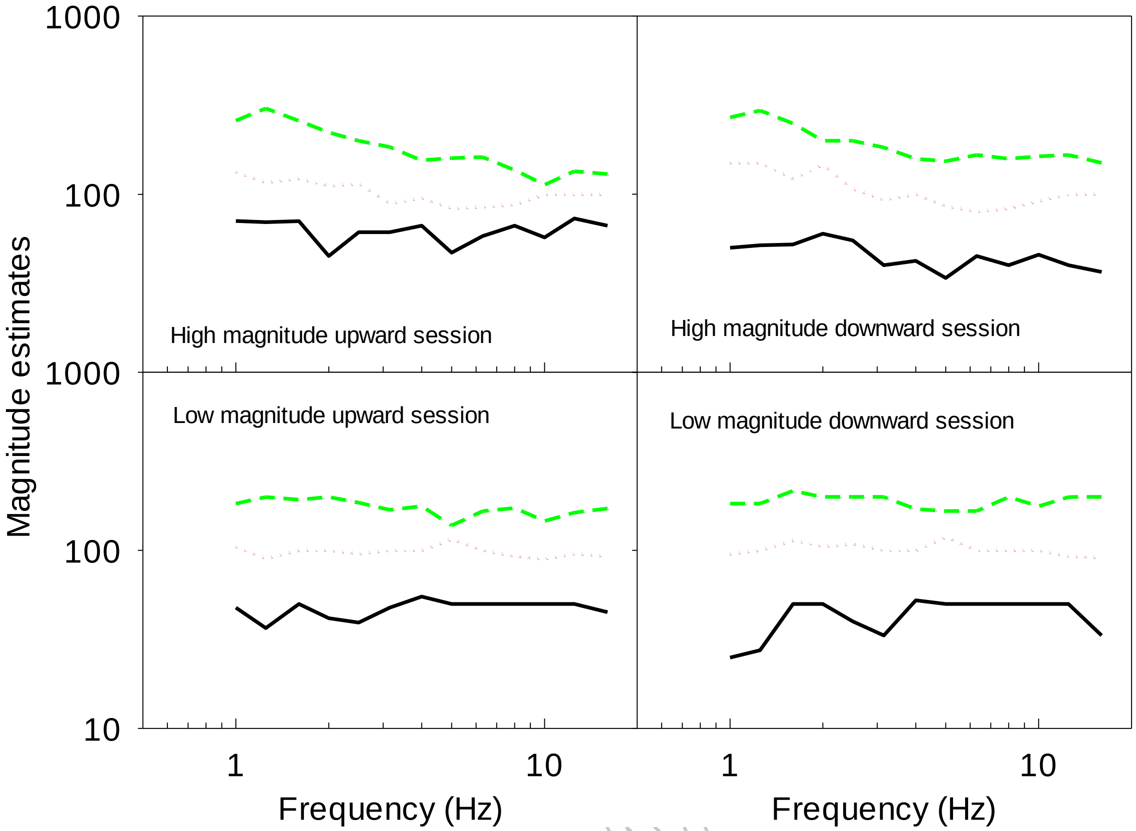

Figure 11 Magnitude estimates for shocks having the same frequency-weighted vibration dose values (using weighting W_b). Higher magnitude shocks: —— 0.315 $ms^{-1.75}$; ···: 0.8 $ms^{-1.75}$; — — —: 2.0 $ms^{-1.75}$; lower magnitude shocks: —— 0.05 $ms^{-1.75}$; ···: 0.125 $ms^{-1.75}$; — — —: 0.315 $ms^{-1.75}$. Median values from 20 subjects.

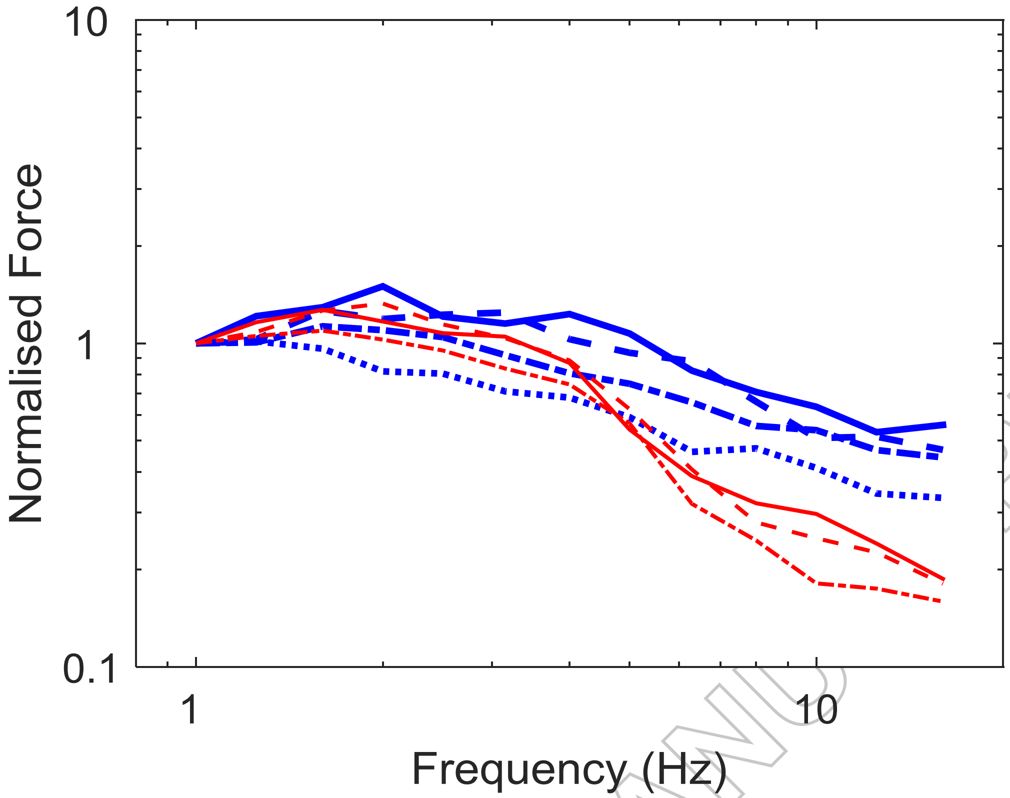

Figure 12 Equivalent comfort contours for force from the present study with mechanical shocks compared with equivalent comfort contours for sinusoidal vibration (from Zhou and Griffin, 2014). Values are normalised to unity at 1.0 Hz (The shock equivalent comfort contours are based on VDV, and the sinusoidal equivalent comfort contours are based on r.m.s. values). Shocks: ——: higher magnitude upward condition; — —: higher magnitude downward condition; —•—: lower magnitude upward condition; • • •: lower magnitude downward condition. Sinusoidal vibration: ——: high magnitude session; — —: medium magnitude session ; —•—: low magnitude session.