Response of the seated human body to whole-body vertical vibration: biodynamic responses to sinusoidal and random vibration
Zhou, Z. & Griffin, M. J. 2014 In : Ergonomics. 57, 5, p. 693-713 21 p.

Number of pages: 18

Number of Figures: 22

Number of Tables: 6

Number of References: 26

Response of the seated human body to whole-body vertical vibration: Biodynamic responses to sinusoidal and random vibration

Zhen Zhou and Michael J. Griffin

Human Factors Research Unit

Institute of Sound and Vibration Research

University of Southampton,

Southampton SO17 1BJ

England

Address for correspondence:

Professor Michael J Griffin

e-mail: M.J.Griffin@soton.ac.uk

Telephone: +44 (0)23 8059 2277

Facsimile: +44 (0)23 8059 2927

Abstract

The dependence of biodynamic responses of the seated human body on the frequency, magnitude, and waveform of vertical vibration has been studied in 20 males and 20 females. With sinusoidal vibration (13 frequencies from 1 to 16 Hz) at five magnitudes (0.1 to 1.6 ms^{-2} r.m.s.) and with random vibration (1 to 16 Hz) at the same magnitudes, the apparent mass of the body was similar with random and sinusoidal vibration of the same overall magnitude. With increasing magnitude of vibration, the stiffness and damping of a model fitted to the apparent mass reduced and the resonance frequency decreased (from 6.5 to 4.5 Hz). Male and female subjects had similar apparent mass (after adjusting for subject weight) and a similar principal resonance frequency with both random and sinusoidal vibration. The change in biodynamic response with increasing vibration magnitude depends on the frequency of the vibration excitation, but is similar with sinusoidal and random excitation.

Keywords: biodynamics; vibration magnitude; apparent mass; force; nonlinearity; frequency weighting.

Relevance of the findings for ergonomics practice

Biodynamic responses (e.g., body resonances) influence vibration discomfort and are studied with random vibration whereas psychological responses to vibration are studied with sinusoidal vibration. Vibration in transport includes both random and sinusoidal vibration. This study shows the frequency-dependence and magnitude-dependence of biodynamic responses are similar with random and sinusoidal vibration.

Running head: Biodynamic responses to vibration

1. Introduction

During whole-body vertical vibration, the resonance frequency evident in the vertical apparent mass of the human body decreases with increasing magnitude of vibration excitation, a phenomenon referred to as a biodynamic nonlinearity (Hinz and Seidel 1987, Fairley and Griffin 1989, Mansfield and Griffin 2000, Matsumoto and Griffin 2002, Nawayseh and Griffin 2003). With random vibration in the frequency range 1 to 20 Hz, Fairley and Griffin (1989) found that the principal resonance frequency in the vertical apparent masses of 60 seated subjects (24 men, 24 women and 12 children) decreased from about 6 Hz to about 4 Hz as the vibration magnitude increased from 0.25 to 2.0 ms^{-2} r.m.s. A second resonance in the vertical apparent mass, evident in the frequency range 8 to 12 Hz, has also been observed to reduce as the magnitude of vibration excitation increases (Fairley and Griffin 1989, Mansfield and Griffin, 2000).

When the seated body is excited by random vertical vibration there are significant forces on the seat in the fore-and-aft direction. These forces also show a nonlinear relationship to the vibration magnitude during random vertical excitation (Matsumoto and Griffin 2002a, 2002b, Nawayseh and Griffin 2003, Hinz *et al*. 2006).

There have been few studies of biodynamic nonlinearity during exposure to vertical sinusoidal vibration. The resonance frequency in the apparent mass averaged over four subjects decreased from 4.5 to 4 Hz as the magnitude of sinusoidal vertical vibration increased from 1.5 to 3.0 ms^{-2} r.m.s. (Hinz and Seidel 1987). Increasing the magnitude of sinusoidal vibration (over the range 0.5 to 2.0 ms^{-2} r.m.s.) increased the apparent mass at 3.15 Hz but decreased the apparent mass at 5.0, 6.3, and 8.0 Hz (Matsumoto and Griffin 2005).

During excitation by sinusoidal vibration, the dominant body motions occur at different locations in the body according to the frequency of the vibration excitation. During excitation by random vibration there is a more distributed movement of all parts of the body, with some parts experiencing more movement and other parts experiencing less movement than during excitation by any single frequency of sinusoidal vibration at the same acceleration magnitude. The nonlinearity observed in the apparent mass with random vibration does not identify which frequencies, or which movements, are associated with the nonlinearity. For example, nonlinearity observed at 16 Hz during random vibration may be caused by the 16-Hz vibration within the spectrum or it may be caused by the influence of vibration at another frequency. Although the vertical apparent mass of the human body has occasionally been measured with both sinusoidal and random vibration (e.g., Mansfield and Maeda, 2005) there has been little consideration of the nonlinearity in the apparent mass with different vibration waveforms.

Whereas biodynamic studies have mostly investigated responses to random vibration, studies of subjective reactions to vibration (e.g., judgements of vibration discomfort) have mostly investigated responses to sinusoidal vibration. The subjective studies have also observed nonlinearities (e.g., Matsumoto and Griffin 2005, Morioka and Griffin 2006, Subashi *et al.* 2009). In their working and leisure activities, people are exposed to non-sinusoidal vibration, so the applicability of the subjective studies (that employ sinusoidal vibration to obtain 'weightings' from the subjective judgements at each frequency) depends on an understanding of the nonlinearity, and whether the nonlinearity is similar with sinusoidal and non-sinusoidal vibration. Although the nonlinearity can have a large influence, the mechanisms responsible are not yet understood, so there are doubts as to the applicability to real environments of some of the findings from laboratory studies of human responses to sinusoidal vibration.

The effects of subject characteristics on the apparent mass of the body has been investigated in various studies (e.g., Fairley and Griffin 1989, Boileau *et al*. 1998, Paddan and Griffin 1998, Holmlund *et al*. 2000, Wang *et al*. 2004, Toward and Griffin 2011). Variability induced by differences in body mass, age, gender, height, and size among subjects are classified as inter-subject variability. In a group of 60 subjects, the principal resonance frequencies were found to be negatively correlated with the total body weights and static sitting weights of subjects divided by their sitting height (Fairley and Griffin 1989). In a group of 80 subjects, the principal resonance frequency in the vertical apparent mass was most consistently associated with age and with body mass index (BMI) (Toward and Griffin 2011). The only subject characteristic found to influence the biodynamic nonlinearity has been gender: the reduction in resonance frequency with increasing vibration magnitude was less in females than in males, but only when seated with a reclined rigid backrest (Toward and Griffin 2011). It was speculated that the difference in nonlinearity between the genders might have been caused by anatomical differences having a greater influence when supported by a reclined rigid backrest, consistent with the BMI affecting the resonance frequency in this posture.

Similar to biodynamic responses, subjective responses to vibration also depend on the magnitude of vibration excitation. Some nonlinearities in vibration discomfort (i.e., changes in the frequency-dependence of discomfort with changing magnitude of vibration excitation) appear to be associated with the nonlinearity in the biodynamic responses of human body (Matsumoto and Griffin 2005, Subashi *et al.* 2009, Zhou and Griffin 2014).

This study was primarily designed to compare the biodynamic non-linearity, as reflected in the vertical apparent masses and the fore-and-aft cross-axis apparent masses of seated people, during random and sinusoidal vertical vibration excitation. The nonlinearity was quantified by changes in the measured apparent masses, the principal resonance frequencies, and the parameters of a simple mathematical model of the vertical apparent mass. It was hypothesised that: (i) with both sinusoidal and random vibration, the equivalent stiffness and equivalent damping of the body would decrease with increasing magnitude of vibration excitation, and that there would be a corresponding reduction in the principal resonance frequencies of both the vertical apparent mass and the fore-and-aft cross-axis apparent mass; (ii) with both sinusoidal and random vibration, the principal resonance frequency in the vertical apparent mass would correlate with the principal resonance frequency in the fore-and-aft cross-axis apparent mass; (iii) at each magnitude of vibration, the different distributions of vibration in the body with random and sinusoidal vibration would result in different apparent masses measured with the two waveforms. In view of a reported difference in nonlinearity in males and females, the study had the subsidiary objective of comparing nonlinearity in males and females.

2. Method

2.1 Apparatus

A 1-metre stroke vertical electrohydraulic vibrator was employed to generate vertical vibration of a rigid flat seat. An accelerometer (Silicon Designs 2260-002) measured vertical acceleration and a force platform (Kistler 9281B) measured the vertical and fore-and-aft forces between the seat and subjects.

Sinusoidal vibration and random vibration were generated by a Servotest Pulsar system and acquired using an *HVLab* data acquisition and analysis system (version 1.0; University of Southampton, UK). The measured force and acceleration were acquired at 512 samples per second via 50-Hz anti-aliasing filters. The distortions of the sinusoidal acceleration waveforms were examined by fitting measured waveforms to the desired waveforms. For all sinusoidal waveforms, the difference, δ_a, between the measured and desired acceleration was calculated from:

$$\delta_a = \frac{\int (a_d(t) - a_m(t))^2 dt}{\int (a_d(t))^2 dt} \times 100\% \quad (1)$$

where $a_d(t)$ is the desired acceleration, and $a_m(t)$ is the measured acceleration. For the session of the experiment using low magnitude stimuli, the median difference between the measured acceleration waveform and the desired acceleration waveform (i.e., δa) was 1.7% (with a 5%-95% range from 0.43% to 5.5%). The distortions were less with the greater magnitude stimuli employed in the sessions with medium and high magnitudes (see below).

Subjects sat on the seat without making contact with the backrest (Figure 1). They rested their feet on a rigid footrest that was attached to the vibrator table.

FIGURE 1 ABOUT HERE

2.2 Subjects

Twenty male and twenty female subjects, students and staff at the University of Southampton, participated in the study. The subject characteristics are shown in Table 1.

TABLE 1 ABOUT HERE

Subjects were exposed to white noise at 65 dB(A) via a pair of headphones. During exposure to vibration, they closed their eyes to prevent vision influencing their reactions to the motion.

2.3 Experimental design

The experiment had three sessions conducted on different days. In each session, subjects were exposed to a series of vertical sinusoidal vibrations of 6-s duration, with the first and last second tapered by cosine functions. The sinusoidal motions were presented at each of 13 frequencies (1, 1.25, 1.6, 2, 2.5, 3.15, 4, 5, 6.3, 8, 10.0, 12.5 or 16 Hz) and at various magnitudes (including 0.1, 0.2, 0.4, 0.8 and 1.6 ms^{-2} r.m.s.). The order of presenting the vibration frequencies and vibration magnitudes was randomized.

At the end of the final session, subjects were exposed to random vertical vibration at five magnitudes (0.1, 0.2, 0.4, 0.8, and 1.6 ms^{-2} r.m.s.). The random vibration had an approximately flat constant bandwidth spectrum that was band-limited (Butterworth filter cut-off frequencies of 0.5 Hz and 18 Hz with 24 dB/octave attenuation rates). Each magnitude of random vibration was presented for 60 s. The order of presenting the magnitudes of random vibration was randomized.

The experiment was also designed to obtain the subjective responses of the subjects to the sinusoidal vibration stimuli. The subjective responses are reported separately (Zhou and Griffin, 2014). 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.

2.4 Analysis

With random vibration, the vertical apparent mass was calculated by the cross-spectral density method:

$$M(f) = S_{\mathrm{af}}(f)/S_{\mathrm{a}}(f) \quad (2)$$

where $M(f)$ is the apparent mass, is $S_{\mathrm{af}}(f)$ is the cross spectral density function between the vertical seat acceleration and the vertical force at the seat surface, and $S_{\mathrm{a}}(f)$ is the power-spectral density function of the vertical seat acceleration, all calculated using a frequency resolution of 0.25 Hz. The effect of the mass of the top plate on the force platform was eliminated by subtracting the vertical acceleration multiplied by the mass of the top plate of the force platform (i.e., 31.5 kg) from the measured vertical force. The fore-and-aft cross-axis apparent mass was calculated similarly, with $S_{\mathrm{af}}(f)$ the cross spectral density function between the vertical seat acceleration and the fore-and-aft force. A fore-and-aft mode in the response of the hydraulic vibrator impeded accurate measurement of fore-and-aft cross-axis apparent mass around 16 Hz, so all measures of fore-and-aft cross-axis apparent mass are limited to the range 1 to 12.5 Hz.

With sinusoidal vibration, the vertical apparent mass was calculated from the ratio of the r.m.s. values of the vertical seat acceleration and the vertical force at the seat surface after mass cancellation:

$$M_{\mathrm{zz}} = F_{\mathrm{z\text{-}rms}}/A_{\mathrm{z\text{-}rms}} \quad (3)$$

where M_{zz} is the vertical apparent mass, $F_{\mathrm{z\text{-}rms}}$ is the r.m.s. value of the vertical force at the seat surface, and $A_{\mathrm{z\text{-}rms}}$ is the r.m.s. value of the vertical seat acceleration. Mass cancellation was performed by subtracting the product of the mass of the top plate of the force platform and the vertical seat acceleration time history from the measured vertical force time history. The phase of the apparent mass was calculated from the maximum in the cross-correlation function between the force, after mass cancellation, and the acceleration.

With sinusoidal vibration, the fore-and-aft cross-axis apparent mass was calculated from the ratio of the r.m.s. values of the vertical seat acceleration and the fore-and-aft force at the seat:

$$M_{xz} = F_{\mathrm{x\text{-}rms}}/A_{\mathrm{z\text{-}rms}} \quad (4)$$

where M_{xz} is the cross-axis apparent mass, $F_{x\text{-rms}}$ is the r.m.s. value of the force at the seat in the fore-and-aft direction, and $A_{z\text{-rms}}$ is the r.m.s. value of the vertical seat acceleration.

To compare the apparent masses of males and females, the 'normalised apparent mass' of each subject was calculated by dividing their apparent mass by the modulus of their vertical apparent mass at 1 Hz. This gives a normalised vertical apparent mass of unity at 1 Hz.

The apparent mass obtained at the highest magnitude of vibration (i.e., 1.6 ms^{-2} r.m.s.) was expressed as a ratio of the apparent mass obtained at the lowest magnitude of vibration (i.e., 0.1 ms^{-2} r.m.s.) so as to quantify the nonlinearity, n, at each frequency:

$$n(f) = M(f)_{1.6} / M(f)_{0.1} \quad . \tag{5}$$

2.5 Curve fitting

To quantify the biodynamic nonlinearity, a one-degree-of-freedom parametric model (model 1b, Wei and Griffin, 1998, Figure 2) was used to fit the vertical apparent masses and phases (from 1 to 16 Hz) with both random and sinusoidal vibration so as to obtain the stiffness and damping of the model at each of the five magnitudes (i.e., 0.1, 0.2, 0.4, 0.8 and 1.6 ms^{-2} r.m.s.). It was assumed there was no mass transfer during vibration, and the masses m_1 and m_2 could be constrained to 15% and 85% of the sitting masses of subjects, in accord with the findings of Wei and Griffin (1998). The sitting masses were obtained from the measured apparent mass of each subject at 1 Hz.

FIGURE 2 ABOUT HERE

A constrained minimum error search command 'fmincon()' from the optimisation toolbox of MATLAB (version R2010a) was used for curve fitting. The target error, $E(f)$, was calculated by summing the squared errors in the modulus and phase at each frequency between the measured data and the fitted curve:

$$E(f) = \sum_N \left[M_m(f) - M_s(f)\right]^2 + \sum_N \left[PH_m(f) - PH_s(f)\right]^2 \tag{6}$$

where $E(f)$ is the overall target error between the fitted curve and measured apparent mass, N is the number of frequency points in the measured apparent mass (61 points for random vibration, 13 points for sinusoidal vibration corresponding to the frequency range 1-16 Hz), $M_m(f)$ and $PH_m(f)$ are the apparent mass modulus and phase of the model at each frequency, $M_s(f)$ and $PH_s(f)$ are the measured apparent mass modulus and phase. The initial guesses and bounds of the stiffness and damping were determined from published data where the parameters m_1, m_2, k_1, c_1 had been determined by fitting the model in the frequency domain to the apparent mass measured with random vibration (Wei and Griffin, 1998). In 24 male subjects, they found optimum stiffness and optimum damping in the ranges 29,409 to 77,829 Nm^{-1} and 675 to 2,345 Nsm^{-1}, respectively. Considering the variability between subjects, the lower and upper bounds of the stiffness and damping in the present study were set to 10,000 to 200,000 Nm^{-1} and 100 to 10,000 Nsm^{-1}, respectively. In order to avoid optimisation to local minima, different start points were used in a 'Global Search' algorithm in MATLAB (version R2010a).

A two-degree-degree-of-freedom parametric model (model 2b from Wei and Griffin, 1998) was also fitted to the measured apparent masses, with both constrained and un-constrained masses.

3. Results

3.1 Vertical apparent mass

Sinusoidal vibration

The principal resonance in the vertical apparent mass during sinusoidal vertical excitation was in the region of 5 Hz, but with variability within the 20 males and within the 20 females (Figure 3).

FIGURE 3 ABOUT HERE

With increasing magnitude of sinusoidal vibration, the phase lag of the apparent mass tended to increase (Figure 4).

FIGURE 4 ABOUT HERE

The resonance frequency in the vertical apparent mass reduced with increasing magnitude of sinusoidal excitation in both males and females (p<0.001 Friedman; Table 2). As the magnitude of sinusoidal vibration increased from 0.1 to 1.6 ms^{-2} r.m.s., the median resonance frequency evident in the modulus of the apparent mass decreased from 6.3 Hz to 4 Hz in both males and females.

TABLE 2 ABOUT HERE

Random vibration

The principal resonance in the vertical apparent mass during random vibration was also in the vicinity of 5 Hz, with variability within the males and within the females (Figure 5).

FIGURE 5 ABOUT HERE

With increasing magnitude of vibration, the modulus of the apparent mass shows nonlinearity with the resonance frequency decreasing with increasing magnitude of vibration (Table 2, Figure 6, and Figure 7). As the magnitude of random vibration increased from 0.1 to 1.6 ms^{-2} r.m.s., the median resonance frequency of the apparent mass decreased from 6.5 Hz to 4.5 Hz in males and decreased from 6.25 to 4.5 Hz in the females (p<0.001 for both males and females, Friedman). There were significant differences in the resonance frequency within both males and females with every increment in vibration magnitude (i.e., between 0.1 and 0.2 ms^{-2} r.m.s., between 0.2 and 0.4 ms^{-2} r.m.s., between 0.4 and 0.8 ms^{-2} r.m.s., between 0.8 and 1.6 ms^{-2} r.m.s.; Wilcoxon, p<0.005).

FIGURE 6 AND FIGURE 7 ABOUT HERE

With increasing magnitude of vibration excitation, the apparent mass at resonance showed a trend to decrease and then increase in the males (p=0.0189, Friedman) but increase in the females (p=0.00043, Friedman).

Comparing sinusoidal and random vibration

The median moduli and phases of the apparent mass measured with sinusoidal and random vibration were similar at all five magnitudes of vibration, for both males and females (Figures 8 and 9). After correction of *p*-values for multiple-comparisons, there were no significant differences at any frequency between the moduli or the phases of the apparent mass measured with sinusoidal and random vibration at the same r.m.s. magnitude.

FIGURE 8 AND FIGURE 9 ABOUT HERE

Effect of subject physical characteristics

There were no significant differences in the normalised vertical apparent mass between male and female subjects with either sinusoidal or random vibration at any of the five magnitudes of vibration at any frequency ($p>0.05$, Mann-Whitney U-test, Figures 10 and 11). There were also no significant differences in the resonance frequencies of the normalised apparent mass between males and females at any of the five magnitudes of vibration with either sinusoidal or random vibration ($p>0.05$, Mann-Whitney U-test).

FIGURE 10 AND FIGURE 11 ABOUT HERE

The biodynamic measurements (i.e., the apparent masses at different frequencies and the resonance frequency of the apparent mass) at each of the five magnitudes of random and sinusoidal vibration were compared with the physical characteristics of the 40 subjects (i.e., age, total-weight, sitting-weight, knee-height, sitting-height, body mass index). There was no significant correlation between subject age and any of the biodynamic measurements (i.e., apparent masses at different frequencies, resonance frequency of apparent mass) at any of the five vibration magnitudes ($p>0.05$, Kendall's τ_b correlation coefficient). There were significant positive correlations between total-weight, sitting-weight, knee-height, sitting-height, BMI and the apparent masses at 1, 10, and 16 Hz and also the resonance frequency ($p<0.05$, Kendall's τ_b correlation coefficient).

3.2 Fore-and-aft cross-axis apparent mass

Sinusoidal vibration

Similar to the vertical apparent mass, the principal resonance in the fore-and-aft cross-axis apparent mass during sinusoidal vertical excitation was in the region of 5 Hz, but with variability within the 20 males and within the 20 females (Figure 12).

FIGURE 12 ABOUT HERE

The modulus of the fore-and-aft cross-axis apparent mass varied with the magnitude of the vertical vibration excitation at all frequencies in the males and at all frequencies except 4 Hz in the females ($p<0.05$, Friedman; Figure 13).

FIGURE 13 ABOUT HERE

The median resonance frequencies in the fore-and-aft cross-axis apparent mass at resonance decreased from 6.3 to 4.0 Hz as the magnitude of vibration increased from 0.1 to 1.6 ms^{-2} r.m.s. in both the males and the females (p<0.001 Friedman; Table 2).

The median fore-and-aft cross-axis apparent mass at resonance also decreased as the vibration magnitude increased from 0.1 to 1.6 ms^{-2} r.m.s. in both males and females (Figure 13; p<0.001 Friedman).

Random vibration

The modulus of the fore-and-aft cross-axis apparent mass during random vibration also varied between subjects (Figure 14) and was highly dependent on the magnitude of vibration, with the frequency of the peak in the cross-axis apparent mass decreasing with increasing magnitude of vibration (Figure 15, Table 2).

FIGURES 14 AND 15 ABOUT HERE

The median resonance frequencies in the fore-and-aft cross-axis apparent mass at resonance decreased from 6.4 to 4.5 Hz as the vibration magnitude increased from 0.1 to 1.6 ms^{-2} r.m.s. in male subjects and decreased from 6.4 to 4.8 Hz in female subjects (Table 2). There were significant differences in the resonance frequency with every change of vibration magnitude (i.e., between 0.1 and 0.2 ms^{-2} r.m.s., between 0.2 and 0.4 ms^{-2} r.m.s., between 0.4 and 0.8 ms^{-2} r.m.s., between 0.8 and 1.6 ms^{-2} r.m.s.) in both males and females (p<0.05, Wilcoxon), except between 0.1 and 0.2 ms^{-2} r.m.s. in male subjects. The median fore-and-aft cross-axis apparent mass at resonance also decreased as the vibration magnitude increased from 0.1 to 1.6 ms^{-2} r.m.s. in both the males and females (Figure 15; p<0.001 Friedman).

Comparing sinusoidal and random vibration

The fore-and-aft cross-axis apparent mass shows small but systematic differences between sinusoidal and random excitation at most of the 12 frequencies, with greater apparent mass with sinusoidal excitation at the two lower magnitudes (i.e., 0.1 ms^{-2} r.m.s. and 0.2 ms^{-2} r.m.s.; Figure 16 and Table 3).

FIGURE 16 AND TABLE 3 ABOUT HERE

Effect of subject physical characteristics

There were no significant differences in the normalised cross-axis apparent masses of the males and females at any of the 12 frequencies at any of the five magnitudes of sinusoidal or random vibration (p>0.05, Mann-Whitney U-test; Figure 17). There were also no significant differences in the resonance frequencies of the normalised fore-and-aft cross-axis apparent mass between the males and females at any of the five magnitudes of vibration with either sinusoidal or random vibration (p>0.05, Mann-Whitney U-test).

FIGURE 17 ABOUT HERE

The fore-and-aft cross-axis biodynamic measurements (i.e., the fore-and-aft cross-axis apparent masses at different frequencies and the resonance frequency of the apparent mass) at each of the five magnitudes of random and sinusoidal vibration were also compared with the physical characteristics of the 40 subjects (i.e., age, total-weight, sitting-weight, knee-height, sitting-height, body mass index). There were significant positive correlations between total-weight, sitting-weight, knee-height, sitting-height, BMI and the apparent masses at 10 Hz and also at the resonance frequency (p<0.05, Kendall's τ_b correlation coefficient).

3.3 Comparing vertical apparent mass and fore-and-aft cross-axis apparent mass

There were no significant differences between the primary resonance frequencies in the vertical apparent mass and fore-and-aft cross-axis apparent mass with either random or sinusoidal vibration at any of the five magnitudes investigated (p>0.05, Wilcoxon). Over the 40 subjects, the resonance frequencies of the vertical apparent mass were correlated with the resonance frequencies of the fore-and-aft apparent mass with all five magnitudes of random vibration and with four magnitudes of sinusoidal vibration (i.e., except 0.4 ms^{-2} r.m.s.; Figure 18).

FIGURE 18 ABOUT HERE

3.4 Parameters of the one-degree-of-freedom model

Individual and median values of the stiffness, k, and damping, c, of the one degree-of-freedom model fitted to the apparent mass measured with vertical random and sinusoidal vibration at five magnitudes (0.1, 0.2, 0.4, 0.8 and 1.6 ms^{-2} r.m.s.) are shown in Tables 4 and 5. These values may be used to construct apparent mass models for each of the 20 males and 20 females used in this biodynamic study and the associated study of vibration discomfort (Zhou and Griffin, 2014).

TABLE 4 AND TABLE 5 ABOUT HERE

With both sinusoidal and random vibration, the stiffness, k, and the damping, c, decreased with increasing magnitude of vibration (p<0.001, Friedman). The stiffness decreased with each increment in magnitude, whereas the decrease in damping was not statistically significant between 0.1 and 0.2 ms^{-2} r.m.s. for sinusoidal vibration (p=0.78, Wilcoxon) or between 0.2 and 0.4 ms^{-2} r.m.s. for either waveform (p=0.22 for sinusoidal vibration; p=0.15 for random vibration).

Between sinusoidal vibration and random vibration there were no significant differences in the stiffnesses at the three lower magnitudes (p=0.058 at 0.1 ms^{-2} r.m.s., p=0.085 at 0.2 ms^{-2} r.m.s., p=0.076 at 0.4 ms^{-2} r.m.s., Wilcoxon). At two higher magnitudes, the stiffness was significantly greater with random vibration than with sinusoidal vibration (p=0.005 at 0.8 ms^{-2} r.m.s., p<0.001 at 1.6 ms^{-2} r.m.s.). The damping was significantly lower with sinusoidal vibration than with random vibration at all magnitudes except 0.2 ms^{-2} r.m.s. (p=0.053, Wilcoxon). The fitted parameters (both stiffness and damping) obtained with sinusoidal vibration and with random vibration were correlated (Table 6, Figures 19 and 20).

TABLE 6 ABOUT HERE

FIGURE 19 AND FIGURE 20 ABOUT HERE

Similar conclusions were obtained when fitting the two-degree-degree-of-freedom parametric model (model 2b from Wei and Griffin, 1998) to the measured vertical apparent masses of all individual subjects. When constraining the masses of the model (i.e., m, m_1, and m_2 to be 12%, 65%, and 23%

of the subject sitting mass), the stiffness k_1 and damping c_1 reduced as the magnitude of vibration increased, but the stiffness k_2 and damping c_2 (associated with the mass m_2) did not show a clear trend. When un-constraining the masses of the model, the stiffness k_1 reduced as the magnitude of vibration increased, but the stiffness k_2 and damping c_1 and c_2 did not show a clear trend.

4. Discussion

4.1 Nonlinearity in the vertical apparent mass

Nonlinearity in the vertical apparent mass is clearly evident with both the sinusoidal and the random vibration excitation. With sinusoidal vibration, as the magnitude of vibration increased from 0.1 to 1.6 ms^{-2} r.m.s., the median resonance frequency of the apparent mass decreased from 6.3 Hz to 4.0 Hz for both males and females. With random vibration, as the magnitude of vibration increased from 0.1 to 1.6 ms^{-2} r.m.s., the median resonance frequency of the apparent mass decreased from 6.5 Hz to 4.5 Hz in the males and from 6.25 Hz to 4.5 Hz in the females. This 'softening' behaviour of the apparent mass of the human body with increased vibration magnitude is similar to that found in previous studies of both the apparent mass of the body and the transmissibility to the spine (Fairley and Griffin 1989, Matsumoto and Griffin 2002a).

The nonlinearity is also evident in the phase of the apparent mass. With both vibration waveforms, the phase lag increased rapidly with increases in the frequency of the vibration excitation around the resonance frequency. As the vibration magnitude increased from 0.1 to 1.6 ms^{-2} r.m.s., there was a reduction in the frequency at which the phase started to increase. The changes in the phase of the apparent mass are consistent with the changes in the modulus of the apparent mass (Figures 4 and 6).

The mechanism responsible for the nonlinear biodynamic responses of the human body has been considered previously. It has been speculated that with increased magnitudes of vibration the thixotropic-like behaviour of the musculoskeletal structure reduces the dynamic stiffness of the body (Fairley and Griffin 1989). Both the stiffness, k, and the damping, c, of the one degree-of-freedom model reduced with increasing magnitude of both sinusoidal vibration and random vibration (Tables 4 and 5). The stiffness of such a model has been found to reduce with increasing magnitude of vibration in previous studies (e.g., Huang and Griffin 2006), and one study has reported a significant reduction in the damping (Toward and Griffin, 2010).

Nonlinearity along the vibration transmission path common to the spine and the abdomen allows the possibility that the nonlinearity might be caused by a combination of factors: a softening response of the buttocks tissue, a bending or buckling response of the spine (i.e., a geometric nonlinearity), and different muscular forces at different magnitudes of vibration (a doubling of vibration magnitude not resulting in a doubling of muscle activity) (Mansfield and Griffin 2000). The nonlinearity appears to decrease with voluntary increases in muscle tension around the buttocks, suggesting these tissues may be partly responsible for the nonlinearity (Matsumoto and Griffin 2002b). During vertical vibration excitation, nonlinearity in the apparent masses of seated subjects is slightly reduced when pressure on the tissues at the ischial tuberosities is increased, also consistent with these tissues being involved in the nonlinearity (Nawayseh and Griffin 2003). Other studies also suggest that passive thixotropy of soft tissues, rather than geometric nonlinearity or voluntary or involuntary muscular activity, is the most likely primary cause of the nonlinearity in biodynamic responses of the human body to whole-body vibration (Huang and Griffin 2008, Huang and Griffin 2009). The present study shows that the nonlinearity is similar with sinusoidal and random vibration, which suggests it is unlikely that changes in muscle activity are the principal cause of the nonlinearity.

By determining the parameters of a single degree-of-freedom model that fit the vertical apparent mass of the body at different magnitudes of vibration, the results can be applied to the specification of anthropodynamic dummies for replacing people when measuring seat transmissibility. In many situations the variation in apparent mass associated with the relevant range of vibration magnitudes is likely to be greater than the differences in apparent mass between a single degree-of-freedom model and a two degree-of-freedom model. It might therefore be argued that unless an anthropodynamic dummy is appropriately nonlinear, or the range of magnitudes of vibration is very narrow, there is no justification for developing an anthropodynamic dummy with more than a single degree-of freedom.

4.2 Nonlinearity in the fore-and-aft cross-axis apparent mass

There was similar nonlinear behaviour in the fore-and-aft cross-axis apparent mass as in the vertical apparent mass: a decrease in the resonance frequency with each increase in vibration magnitude (Figures 6 and 15). At all frequencies, and with both sinusoidal and random vibration at all magnitudes, the fore-and-aft cross-axis apparent mass was less than the vertical apparent mass (compare Figures 4 and 13, and Figures 6 and 15). However, it is clear that vertical excitation caused substantial fore-and-aft forces during both sinusoidal and random excitation, especially over the range 4 to 10 Hz.

Different mechanisms could be responsible for the non-linearity in the vertical apparent mass and the fore-and-aft cross-axis apparent mass. With random vertical vibration excitation at 1.7 ms^{-2} r.m.s. from 0.5 to 30 Hz, and measuring the motion of the head, spine, pelvis, and viscera in the mid-sagittal planes of eight subjects, Kitazaki and Griffin (1998) found separate vibration modes at 3.4 and 4.9 Hz produced by two different mechanisms. The mode at 3.4 Hz was a bending mode of the entire spine, with fore-and-aft motion of the pelvis in phase with fore-and-aft motion of the head. The mode at 4.9 Hz was the principal mode and in phase with a vertical visceral mode. Tensing the muscles of the tissues beneath the pelvis appears to affect the nonlinearity in the vertical direction but not the nonlinearity in the fore-and-aft direction (Matsumoto and Griffin 2002b), and increasing pressure on the tissue beneath the pelvis (sitting on a seat with minimum thigh contact) appears to reduce the nonlinearity in only the vertical direction (Nawayseh and Griffin 2003).

Although some studies have found differences suggestive of different mechanisms for nonlinearity in the vertical apparent mass and the fore-and-aft cross-axis apparent mass, in the present study, the primary resonance frequencies in the vertical apparent mass were highly correlated with the primary resonance frequency in fore-and-aft cross-axis apparent mass with both random vibration and sinusoidal vibration at each of the five magnitudes investigated (Figure 18). The correlation coefficients were greater with random vibration, consistent with the finer frequency resolution, and increased with increasing magnitude of vibration. In part, differences between the resonances in each direction may be due to difficulty in identifying the resonance frequency in some individuals (Figures 3, 5, 12, 14). Resonance frequencies in the fore-and-aft cross-axis apparent mass have also been found to be correlated with resonances in the vertical in-line apparent mass by Qiu and Griffin (2010).

4.3 Effect of vibration waveform on the apparent mass

Many previous studies have found nonlinearities in the apparent mass when using random vibration, including a reduction in the resonance frequency with increasing magnitude of vibration. This study shows that changes in the magnitude of sinusoidal vibration cause similar nonlinear changes. This is broadly consistent with changes in the frequency-dependence of subjective responses associated with increases in the magnitude of vibration excitation at some frequencies (e.g., Matsumoto and Griffin 2005, Subashi *et al*. 2009).

The energy in a random vibration is distributed across a range of frequencies whereas a sinusoidal vibration has energy concentrated at one frequency. For random and sinusoidal vibrations of the same r.m.s. acceleration, as in this study, at each frequency of the sinusoidal vibration the energy is greater than with random vibration of the same r.m.s. magnitude (Figure 21). Notwithstanding the large differences, the apparent masses obtained with the two very different waveforms of vibration are remarkably similar at all five magnitudes of acceleration (i.e., at 0.1, 0.2, 0.4, 0.8, and 1.6 ms^{-2} r.m.s.; Figures 8, 9 and 16). Superficially, the results may appear to suggest that the same apparent mass is obtained with very different waveforms (i.e., sinusoidal or random) when the r.m.s. magnitude of the vibration acceleration is the same.

FIGURE 21 ABOUT HERE

The non-linearity that is observed at any frequency may be presumed to arise from magnitude-dependent dynamic characteristics in a part of the body that influences the apparent mass with that frequency of vibration. The non-linearity in the apparent mass has been reported to be influenced more by some frequencies of vibration than by other frequencies of vibration (e.g., Toward 2002). In the present study, the ratio of the apparent masses obtained at the highest and the lowest magnitude at each frequency varied with the frequency of both the sinusoidal vibration and the random vibration (Figure 22). At frequencies less than 2.5 Hz, the ratio is close to unity, so the magnitude of vibration did not greatly affect the apparent mass, and the response of the human body is close to linear. At frequencies greater than about 2.5 Hz, the ratio differs from unity, indicating nonlinearity. A ratio greater than unity means the apparent mass is greater with higher magnitudes, whereas a ratio less than unity means the apparent mass is greater with lower magnitudes. As the magnitude of vibration increased, the apparent mass resonance frequency reduced, so the ratio was greater than unity at frequencies less than the resonance frequency (around 5 Hz) and less than unity at frequencies greater than the resonance frequency. Even though the distribution of vibration within the body differs greatly over the frequency range investigated here, it is clear from Figure 22 that nonlinearity influenced the apparent mass of the body at all frequencies greater than about 2.5 Hz. The median values of the model parameters (stiffness k and damping c; Tables 4 and 5) obtained by curve fitting to the measured vertical apparent masses of the individual subjects (males and females) were used to calculate the apparent mass of the one-degree-of-freedom model at the highest and lowest magnitudes with both sinusoidal and random vibration (Figure 22 (c)). At each frequency, the ratios of the apparent mass fitted from the single degree-of-freedom model at the highest and lowest magnitudes of vibration are close to the experimental data obtained with both sinusoidal vibration and random vibration. This means that, although the body is much more complex than a single degree-of-freedom model, a single degree-of-freedom model in which the stiffness and damping reduce with increasing magnitude of vibration can provide a useful prediction of the nonlinearity in the vertical apparent mass of the seated human body at all frequencies up to 16 Hz.

FIGURE 22 ABOUT HERE

A random vibration with a wider or a narrower bandwidth (or with a different spectral shape) than used in this study but with the same overall acceleration magnitude may be expected to produce a different apparent mass. The close similarity in the apparent mass obtained with sinusoidal and random vibration in the present study is therefore limited, to some extent, to random vibration with an approximately flat constant bandwidth acceleration spectrum within a bandwidth of approximately 1.0 to 16 Hz.

There is scope for improved understanding of the mechanisms involved in the non-linearity but, for practical purposes, the present results suggest that when the dominant interest is in biodynamic responses to vertical excitation at frequencies in the range 1 to 16 Hz, the apparent mass obtained with random vibration may be broadly similar to that with other waveforms, including sinusoidal vibration excitation, if the r.m.s. magnitudes of the acceleration are similar.

4.4 Effect of subject characteristic

The nonlinearity evident in the vertical apparent mass and the fore-and-aft cross-axis apparent mass obtained with both random and sinusoidal vibration was similar in males and females. There were no significant differences between males and females in their vertical apparent masses or their fore-and-aft cross-axis apparent masses (after normalisation to correct for subject mass) at any of the five vibration magnitudes (i.e., 0.1, 0.2, 0.4, 0.8 and 1.6 ms^{-2} r.m.s.). There were also no significant differences between males and females in the principal resonance frequencies in the vertical apparent mass or fore-and-aft cross-axis apparent mass for either random or sinusoidal vibration at any of the five vibration magnitudes. This finding is similar to Fairley and Griffin (1989) who concluded that the mean normalised apparent masses of men, women, and children are similar. After controlling for other factors (i.e., age and body mass index), the resonance frequencies in the vertical apparent masses of males and females have also been found to be similar with three different backrest conditions (i.e., sitting upright with no backrest, sitting upright with a rigid backrest, and sitting with a foam backrest reclined to 15°) (Toward and Griffin 2011). However, with a reclined rigid backrest the reduction in resonance frequency with increased vibration magnitude was significantly less in females than in males. It was suggested that the effects of anatomical differences between genders may be more pronounced when supported by a reclined rigid backrest.

The physical characteristics of the subjects (e.g., total-weight, sitting-weight, knee-height, sitting-height and BMI) were positively correlated with their vertical apparent masses at 1, 10 and 16 Hz, but there was no correlation with their resonance frequencies. Fairley and Griffin (1989) also found no statistically significant correlation between subject weight and the apparent mass resonance frequency, although seat-to-head transmissibility has been reported to be negatively correlated with subject weight and subject height (Griffin *et al*. 1982). In the present study there were no significant correlations between the ages of the 40 subjects and their measured biodynamic responses. In a study with 80 subjects, Toward and Griffin (2011) found the frequency of the principal resonance increased by 0.27 Hz per 10 years increase of age. Whereas the present study investigated subjects aged 22 to 41 years, Toward and Griffin investigated subjects aged 18 to 65 years and it seems that the principal influence of age occurred in their subjects who were older than about 40 years.

5. Conclusions

During vertical vibration excitation of the seated human body, the vertical apparent mass, the fore-and-aft cross-axis apparent mass, and the associated nonlinearity, are broadly similar with sinusoidal and random vibration. With both sinusoidal and random vibration, the principal resonance frequencies evident in the vertical apparent mass and the fore-and-aft cross-axis apparent mass are correlated and decrease as the magnitude of vibration excitation increases.

Both the stiffness and the damping of an equivalent single degree-of-freedom lumped parameter model of the body reduce with increasing magnitude of vibration excitation. Consequently, changes in the vertical apparent mass of the body with changes in the magnitude of vertical excitation depend on the frequency of the vibration excitation, with relatively little nonlinearity at frequencies less than about 2.5 Hz (where the apparent mass is little affected by stiffness or damping) but greater nonlinearity at higher frequencies (where the apparent mass is highly dependent on both stiffness and damping). It seems reasonable to expect that the changes in the stiffness and the damping are associated with some measure of relative motion at one or more location in the body. This relative motion will depend on the frequency of vibration, and so the nonlinearity in apparent mass obtained with random vibration may be expected, in general, to depend on the spectrum of the vibration excitation. The apparent mass of the body measured with the same magnitudes of random and sinusoidal vibration could therefore differ. However, for the spectrum of 1- to 16-Hz random vibration used in this study, the vertical apparent mass of the seated human body was similar to that with sinusoidal vibration of a similar magnitude, and there was similar nonlinearity with both waveforms (i.e., sinusoidal and random).

With both sinusoidal and random vibration there are no large or systematic differences between males and females in either their vertical apparent masses or their fore-and-aft cross-axis apparent masses after normalisation (i.e., correction for differences in sitting weight). There are also no large differences between males and females in the principal resonance frequencies evident in their vertical and fore-and-aft apparent masses during either random or sinusoidal vibration excitation.

References

Boileau, P.E., Wu, X. and Rakhe, S., 1998. Definition of a range of idealized values to characterize seated body biodynamic response under vertical vibration. *Journal of Sound and Vibration,* 215 (4), 841-862.

Fairley, T.E. and Griffin, M.J., 1989. The apparent mass of the seated human body: Vertical vibration. *Journal of Biomechanics,* 22 (2), 81-94.

Griffin, M.J., Whitham, E.M. and Parsons, K.C., 1982. Vibration and comfort. I: Translational seat vibration. *Ergonomics,* 25, 603-630.

Hinz, B., Bluthner, R., Menzel, G., Rutzel, S., Seidel, H. and Wolfel, H.P., 2006. Apparent mass of seated men—determination with single- and multi-axis excitation at different magnitudes. *Journal of Sound and Vibration,* 298 (3), 788-809.

Hinz, B. and Seidel, H., 1987. The nonlinearity of the human body's dynamic response during sinusoidal whole body vibration. *Industrial Health,* 25, 169-181.

Holmlund, P., Lundström, R. and Lindberg, L., 2000. Mechanical impedance of the human body in vertical direction. *Applied Ergonomics,* 31 (1), 415-422.

Huang, Y. and Griffin, M.J., 2006. Effect of voluntary periodic muscular activity on nonlinearity in the apparent mass of the seated human body during vertical random whole-body vibration. *Journal of Sound and Vibration,* 298 (3), 824-840.

Huang, Y. and Griffin, M.J., 2008. Nonlinear dual-axis biodynamic response of the semi-supine human body during vertical whole-body vibration. *Journal of Sound and Vibration,* 312 (1-2), 296-315.

Huang, Y. and Griffin, M.J., 2009. Nonlinearity in apparent mass and transmissibility of the supine human body during vertical whole-body vibration. *Journal of Sound and Vibration,* 324 (1-2), 429-452.

Kitazaki, S. and Griffin, M.J., 1997. A modal analysis of whole-body vertical vibration, using a finite element model of the human body. *Journal of Sound and Vibration,* 200 (1), 83-103.

Mansfield, N.J. and Griffin, M.J., 2000. Non-linearities in apparent mass and transmissibility during exposure to whole-body vertical vibration. *Journal of Biomechanics,* 33 (8), 933-941.

Mansfield, N.J. and Maeda, S., 2005. Comparison of the apparent mass of the seated human measured using random and sinusoidal vibration. *Industrial Health,* 43, 233-240.

Matsumoto, Y. and Griffin, M.J., 2002a. Effect of muscle tension on non-linearities in the apparent masses of seated subjects exposed to vertical whole-body vibration. *Journal of Sound and Vibration,* 253 (1), 77-92.

Matsumoto, Y. and Griffin, M.J., 2002b. Non-linear characteristics in the dynamic responses of seated subjects exposed to vertical whole-body vibration. *Journal of Biomechanical Engineering,* 124 (5), 527-532.

Matsumoto, Y. and Griffin, M.J., 2005. Nonlinear subjective and biodynamic responses to continuous and transient whole-body vibration in the vertical direction. *Journal of Sound and Vibration,* 287, 919-937.

Morioka, M. and Griffin, M.J., 2006. Magnitude-dependence of equivalent comfort contours for fore-and-aft, lateral and vertical whole-body vibration. *Journal of Sound and Vibration,* 298 (3), 755-772.

Nawayseh, N. and Griffin, M.J., 2003. Non-linear dual-axis biodynamic response to vertical whole-body vibration. *Journal of Sound and Vibration,* 268 (3), 503-523.

Paddan, G.S. and Griffin, M.J., 1998. A review of the transmission of translation seat vibration to the head. *Journal of Sound and Vibration,* 215 (4), 863-882.

Qiu, Y. and Griffin, M.J., 2010. Biodynamic responses of the seated human body to single-axis and dual-axis vibration. *Industrial Health,* 48, 615-627.

Subashi, G.H.M.J., Nawayseh, N., Matsumoto, Y. and Griffin, M.J., 2009. Nonlinear subjective and dynamic responses of seated subjects exposed to horizontal whole-body vibration. *Journal of Sound and Vibration,* 321 (1-2), 416-434.

Toward, M.G.R., 2002. Apparent mass of the human body in the vertical direction: Effect of input spectra. *37th United Kingdom Conference on Human Response to Vibration.* Department of Human Sciences, Loughborough University.

Toward, M.G.R. and Griffin, M.J., 2010. A variable parameter single degree-of-freedom model for predicting the effects of sitting posture and vibration magnitude on the vertical apparent mass of the human body. Industrial Health 2010, 48, 654–662.

Toward, M.G.R. and Griffin, M.J., 2011. The transmission of vertical vibration through seats: Influence of the characteristics of the human body. *Journal of Sound and Vibration,* 330 (26), 6526-

6543.

Wang, W., Rakheja, S. and Boileau, P.E., 2004. Effect of sitting postures on biodynamic response of seated occupants under vertical vibration. *International Journal of Industrial Ergonomics,* 34 (4), 289-306.

Wei, L. and Griffin, M.J., 1998. Mathematical models for the apparent mass of the seated human body exposed to vertical vibration. *Journal of Sound and Vibration,* 212 (5), 855-874.

Zhou, Z. and Griffin, M.J., 2014. Response of the seated human body to whole-body vertical vibration: Discomfort caused by sinusoidal vibration. *Ergonomics,* submitted.

Table 1 Characteristics of 20 males and 20 females: medians (range).

	Age (years)	Weight (kg)	Stature (cm)	Sitting height* (cm)
Males	26.5 (22-41)	70.5 (48-107)	173 (165-202)	90 (78-102)
Females	23.5 (20-30)	55.8 (45-72)	165 (149 - 183)	86 (80-92)

* from surface of seat to vertex of head

Table 2 Resonance frequencies and apparent masses at resonance with sinusoidal and random vibration at five magnitudes (0.1, 0.2, 0.4, 0.8, and 1.6 ms^{-2} r.m.s.). (Medians of individual values of the resonance frequencies and apparent masses at resonance from 20 males and 20 females)

Direction		Vertical apparent mass				Fore-and-aft cross-axis apparent mass			
Vibration		Sinusoidal		Random		Sinusoidal		Random	
	Magnitudes (ms^{-2} r.m.s.)	Males	Females	Males	Females	Males	Females	Males	Females
Resonance Frequency (Hz)	0.1	6.3	6.3	6.5	6.3	6.3	6.3	6.4	6.4
	0.2	6.3	5.0	6.1	5.9	6.3	6.3	6.3	5.9
	0.4	5.0	5.0	5.8	5.5	5.0	5.0	6.0	5.5
	0.8	5.0	5.0	5.0	5.0	5.0	5.0	5.3	5.1
	1.6	4.0	4.0	4.5	4.5	4.0	4.0	4.5	4.8
Apparent mass at resonance (kg)	0.1	92.5	71.5	99.4	74.3	59.8	49.9	59.1	49.3
	0.2	95.1	69.4	95.8	74.5	58.7	46.2	56.4	41.7
	0.4	87.3	68.9	91.7	73.8	56.6	48.4	54.7	47.6
	0.8	93.3	75.1	93.0	74.2	48.8	45.7	50.2	38.8
	1.6	94.9	74.6	93.5	79.8	40.6	33.1	45.5	36.2

Table 3 Statistical significance of differences in fore-and-aft cross-axis apparent mass between sinusoidal vibration excitation and random vibration excitation at 12 frequencies (Wilcoxon matched-pairs signed-ranks test).

Frequency (Hz)	Males (ms^{-2} r.m.s.)					Females (ms^{-2} r.m.s.)				
	0.1	0.2	0.4	0.8	1.6	0.1	0.2	0.4	0.8	1.6
1	***	***	-	**	**	***	***	-	-	-
1.25	***	**	-	-	**	***	**	-	-	-
1.6	**	**	-	-	**	**	**	**	-	**
2	***	***	-	-	-	***	**	**	-	**
2.5	***	**	-	-	-	***	**	-	-	-
3.15	***	-	-	-	-	***	**	-	-	-
4	-	-	-	-	-	***	-	**	-	-
5	-	-	-	-	**	-	-	-	-	-
6.3	**	-	-	-	-	-	-	-	-	-
8	-	-	-	-	***	***	**	-	-	-
10	***	**	-	-	**	***	***	-	-	-
12.5	***	***	-	-	***	***	**	-	-	-

*: p<0.05, **: p<0.01, ***:p<0.005; -: p>0.05

Table 4 Individual and median stiffness (k, Nm^{-1}) of the single degree-of-freedom model fitted to the apparent mass with vertical random and sinusoidal vibration at five magnitudes (0.1, 0.2, 0.4, 0.8, and 1.6 ms^{-2} r.m.s.).

		Sinusoidal (ms^{-2} r.m.s.)					Random (ms^{-2} r.m.s.)				
Subject	Gender	0.1	0.2	0.4	0.8	1.6	0.1	0.2	0.4	0.8	1.6
1	F	87173	74026	63118	46489	38097	103809	90465	78638	61728	48089
2	F	76639	72133	56852	48308	43190	68109	70477	63002	52332	43630
3	F	69204	72179	52799	51656	35634	84670	79316	69267	60808	49673
4	F	80776	74301	61140	58884	46666	74545	72721	55785	46601	42305
5	F	85515	72767	64004	43300	41903	91257	84105	69202	59256	49822
6	F	81486	81612	61559	59158	53961	88585	73492	58019	50632	41794
7	F	75004	68611	65734	41654	33572	83130	82174	58286	47827	42049
8	F	81412	73177	62020	54992	48062	76439	63147	51531	39944	38108
9	F	49553	40964	38371	28765	27054	76179	63443	56337	43426	34929
10	F	73564	69018	47719	48663	45954	83368	74901	68102	53739	48515
11	F	88640	73799	61929	51643	41914	142505	133300	109502	80766	65168
12	F	77567	69007	59913	44590	38010	78298	69778	58290	49828	41950
13	F	64062	59764	46501	35484	35889	83889	84497	78091	58191	38578
14	F	57082	46012	48786	34366	28963	64516	50064	41949	35453	31012
15	F	81285	77829	80233	60793	51722	94183	87490	79463	65571	57137
16	F	77247	58670	52733	39927	31311	72062	58506	50717	38705	34525
17	F	64681	57030	51737	41421	35924	78744	74999	62827	50094	40575
18	F	68914	58199	42005	36705	32278	64714	60347	49649	43497	38079
19	F	53884	48005	34220	33945	27680	55761	52231	47003	40368	35004
20	F	111856	86146	96683	68034	53247	103483	99927	85227	71261	61792
21	M	73180	73122	92126	49264	42599	66310	55209	45634	32716	27290
22	M	82619	72752	58613	43362	35049	83887	68182	60282	43406	36002
23	M	105319	100113	75443	64953	52456	83730	84653	74881	64719	58109
24	M	119433	102761	81525	63130	53721	106386	95681	89723	69560	55499
25	M	86698	77896	65998	49207	42088	86261	80744	62514	50639	41747
26	M	123712	107229	92324	79009	66208	110111	101947	89663	78632	64167
27	M	90497	101008	91906	77021	63161	95636	82727	84406	68614	62838
28	M	72188	70833	58624	43754	35357	70217	68932	57678	43843	35742
29	M	53074	54773	49325	29151	26258	78611	61530	39395	34473	30390
30	M	83871	84261	60885	49250	42670	75497	78223	63445	53093	45245
31	M	87290	76434	53942	60994	53541	78352	69083	53660	47217	43892
32	M	109955	108955	88882	64624	54008	134328	112336	95099	82454	57179
33	M	83876	68727	58520	43340	33802	83826	74617	63271	54958	43415
34	M	80176	65044	61851	48953	39709	111149	105423	90826	73874	62447
35	M	77940	76542	67486	45687	35607	84336	78016	68872	50532	44071
36	M	85092	84278	69286	66700	56286	132079	122207	109504	85517	73413
37	M	75045	80406	50443	43315	34900	64516	57849	50019	41272	36906
38	M	103790	94949	75544	65902	51541	94176	90641	73599	60527	53738
39	M	107662	100896	75165	48879	40625	143048	124174	103655	71503	62363
40	M	107996	101537	81496	63316	53686	132920	129397	112953	94088	81177
Median		81349	73488	61705	48916	41909	83857	78120	63358	52713	43761

Table 5 Individual and median damping (c, Nsm^{-1}) of the single degree-of-freedom model fitted to the apparent mass with vertical random and sinusoidal vibration at five magnitudes (0.1, 0.2, 0.4, 0.8 and 1.6 ms^{-2} r.m.s.).

Subject	Gender	Sinusoidal (ms^{-2} r.m.s.)					Random (ms^{-2} r.m.s.)				
		0.1	0.2	0.4	0.8	1.6	0.1	0.2	0.4	0.8	1.6
1	F	1344	1261	1447	1183	859	1648	1600	1608	1367	1227
2	F	2508	2443	1810	1673	1343	2469	2501	2370	1831	1466
3	F	1491	1598	1496	1192	1451	1449	1348	1407	1417	1294
4	F	1547	1763	1675	1618	1420	1712	1682	1654	1619	1494
5	F	1421	1300	1638	942	1253	1604	1638	1544	1453	1335
6	F	2986	2677	1845	1818	1565	2286	2123	1802	1613	1291
7	F	1455	1374	1466	1562	1421	1967	2041	1884	1744	1446
8	F	1647	1792	1401	1447	1273	1464	1487	1422	1347	1164
9	F	1589	1161	1335	1101	934	1816	1707	1709	1515	1188
10	F	1293	1760	1313	1556	1326	1720	1818	1760	1674	1522
11	F	2111	1653	2603	1101	1006	1544	1556	1594	1570	1423
12	F	2171	2256	1715	1200	1149	1554	1519	1515	1436	1284
13	F	1842	1682	1685	1563	920	2183	1980	2142	1938	1467
14	F	1521	1691	1620	1236	1048	1626	1671	1510	1409	1265
15	F	1857	1717	1947	1398	1266	1664	1674	1640	1522	1447
16	F	1786	1537	1215	1094	808	1795	1539	1416	1160	983
17	F	1150	1162	1361	1223	935	1817	1735	1685	1505	1290
18	F	1800	1565	1397	1293	1095	1964	1770	1660	1509	1298
19	F	1624	1622	1426	1437	1313	1924	1756	1652	1473	1306
20	F	2146	2475	2048	1704	1017	2432	2304	2060	1984	1586
21	M	1142	1648	1404	961	1238	1265	1241	1271	1179	1036
22	M	1559	2499	2126	1347	1050	1460	1591	1575	1459	1225
23	M	2112	2325	1988	1887	1321	2792	2515	2438	2163	1876
24	M	1084	1581	1286	1435	1523	1736	1647	1822	1684	1327
25	M	1508	1420	1420	1447	1283	1678	1842	2001	1922	1643
26	M	2522	1722	1958	1646	1725	2212	1903	1979	1779	1598
27	M	1612	1716	1772	1562	1478	1995	1979	1804	1704	1472
28	M	788	832	758	764	590	848	987	1129	1119	973
29	M	1282	999	1263	861	755	1989	1207	1357	1226	1168
30	M	1001	1121	1674	1197	1157	1550	1546	1537	1492	1326
31	M	1237	1124	1089	1290	995	1225	1101	1116	1042	1001
32	M	1242	1089	1311	1171	1239	1222	1082	1260	1249	1063
33	M	1153	1065	1144	845	866	1353	1273	1276	1251	1124
34	M	1347	1425	1567	792	723	2209	2252	2119	1750	1375
35	M	894	1195	1286	1111	780	1353	1440	1443	1275	1176
36	M	1201	1235	1259	1174	1184	2178	2154	2362	1916	1648
37	M	1585	1798	948	987	973	1306	1336	1224	1086	989
38	M	1828	1820	2394	1679	1305	2181	2162	1990	1707	1397
39	M	2511	1998	1729	1562	1353	2058	1960	1884	1286	1217
40	M	2463	1880	1241	1450	1291	2713	2857	2725	2397	1964
Median		1553	1635	1456	1292	1211	1728	1678	1653	1507	1302

Table 6 Kendall's correlation coefficient τ_b between the model parameters (i.e., stiffness and damping) obtained with random vibration and sinusoidal vibration.

Magnitude (ms^{-2} r.m.s.)	stiffness		damping	
	τ_b	*p*-value	τ_b	*p*-value
0.1	0.54	<0.001	0.42	<0.001
0.2	0.45	<0.001	0.37	<0.001
0.4	0.45	<0.001	0.32	<0.005
0.8	0.49	<0.001	0.48	<0.001
1.6	0.58	<0.001	0.36	<0.001

Figure 1 Experiment setup.

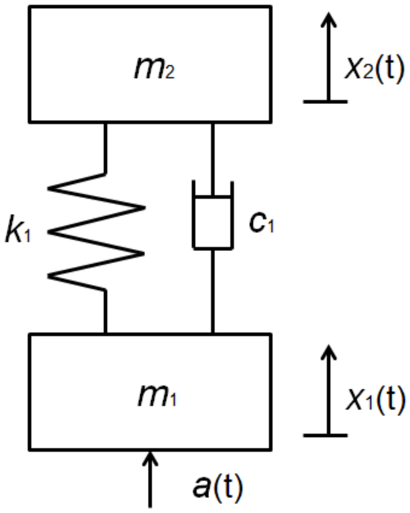

Figure 2 Single-degree-of-freedom model.

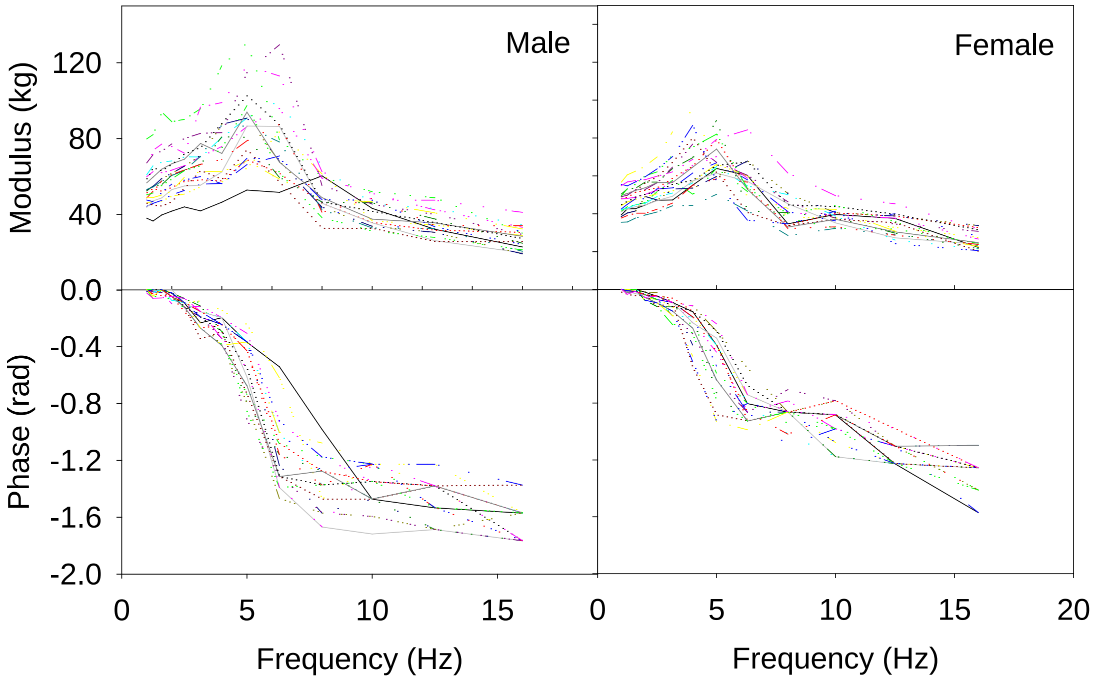

Figure 3 Inter-subject variability in the vertical apparent masses of 20 male and 20 female subjects exposed to sinusoidal vertical vibration at 0.4 ms^{-2} r.m.s.

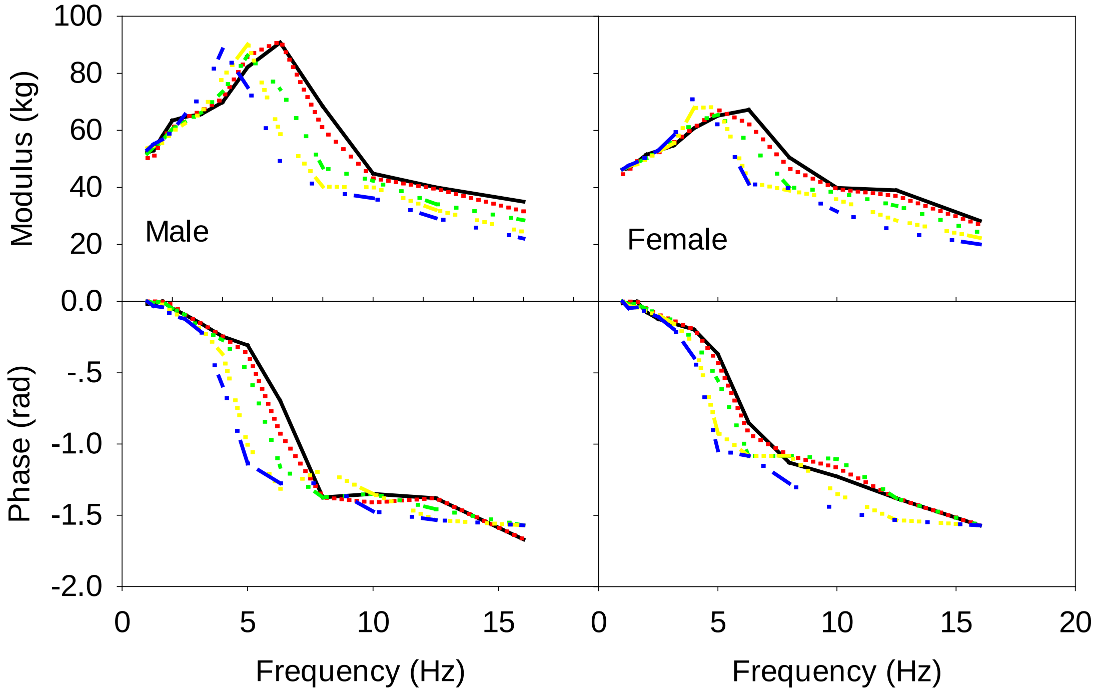

Figure 4 Median modulus and phase of apparent mass for subjects exposed to sinusoidal vibration at five different magnitudes of random vibration (—— 0.1 ms^{-2} r.m.s., ● ● ● 0.2 ms^{-2} r.m.s., — — — 0.4 ms^{-2} r.m.s., — ● ● — 0.8 ms^{-2} r.m.s., — — — 1.6 ms^{-2} r.m.s.). Median values for 20 males and 20 females.

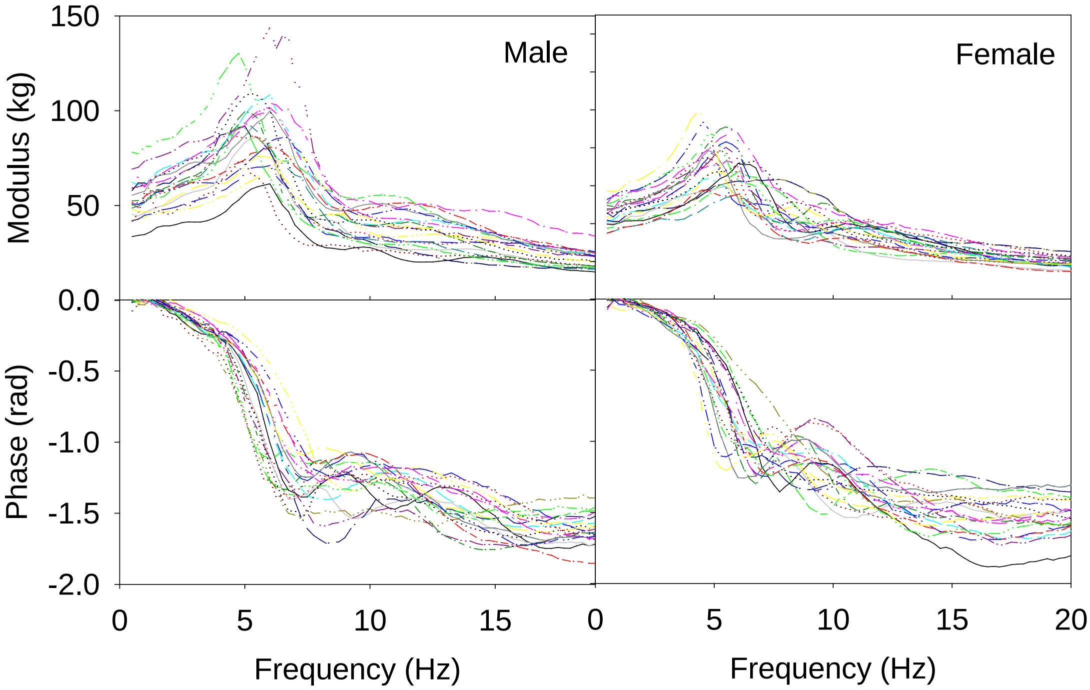

Figure 5 Inter-subject variability in the vertical apparent masses of 20 male and 20 female subjects exposed to random vertical vibration at 0.4 ms^{-2} r.m.s.

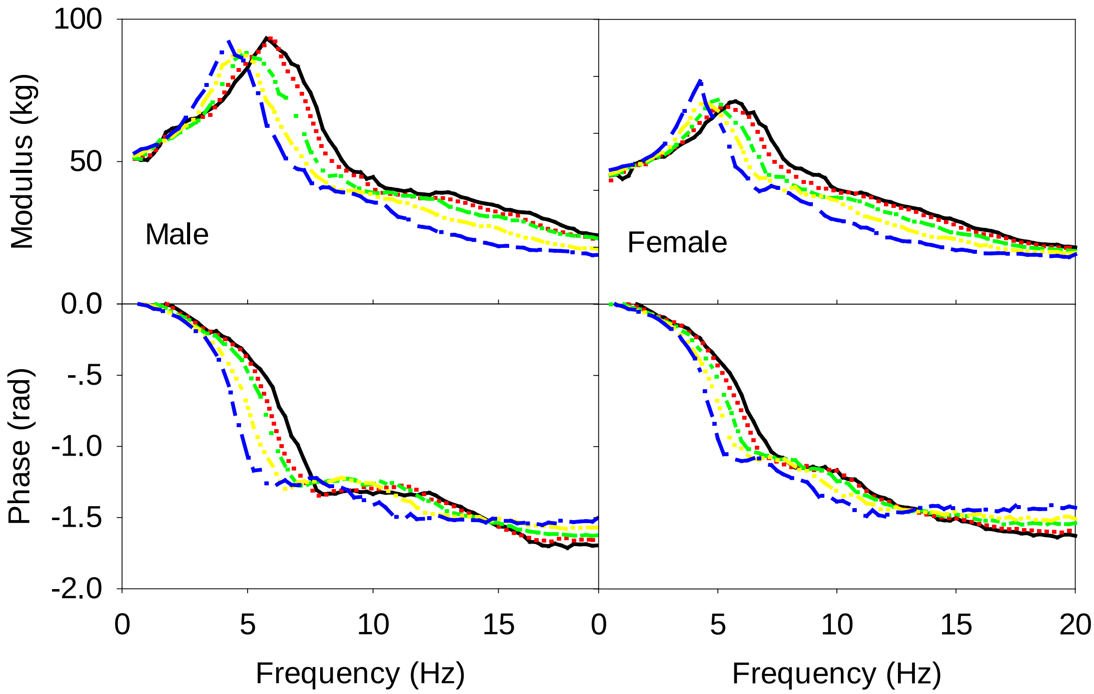

Figure 6 Median modulus and phase of apparent mass for subjects exposed to random vibration at five different magnitudes of random vibration (——— 0.1 ms^{-2} r.m.s., • • • 0.2 ms^{-2} r.m.s., — — — 0.4 ms^{-2} r.m.s., — • • — 0.8 ms^{-2} r.m.s., — — — 1.6 ms^{-2} r.m.s.). Median values for 20 males and 20 females.

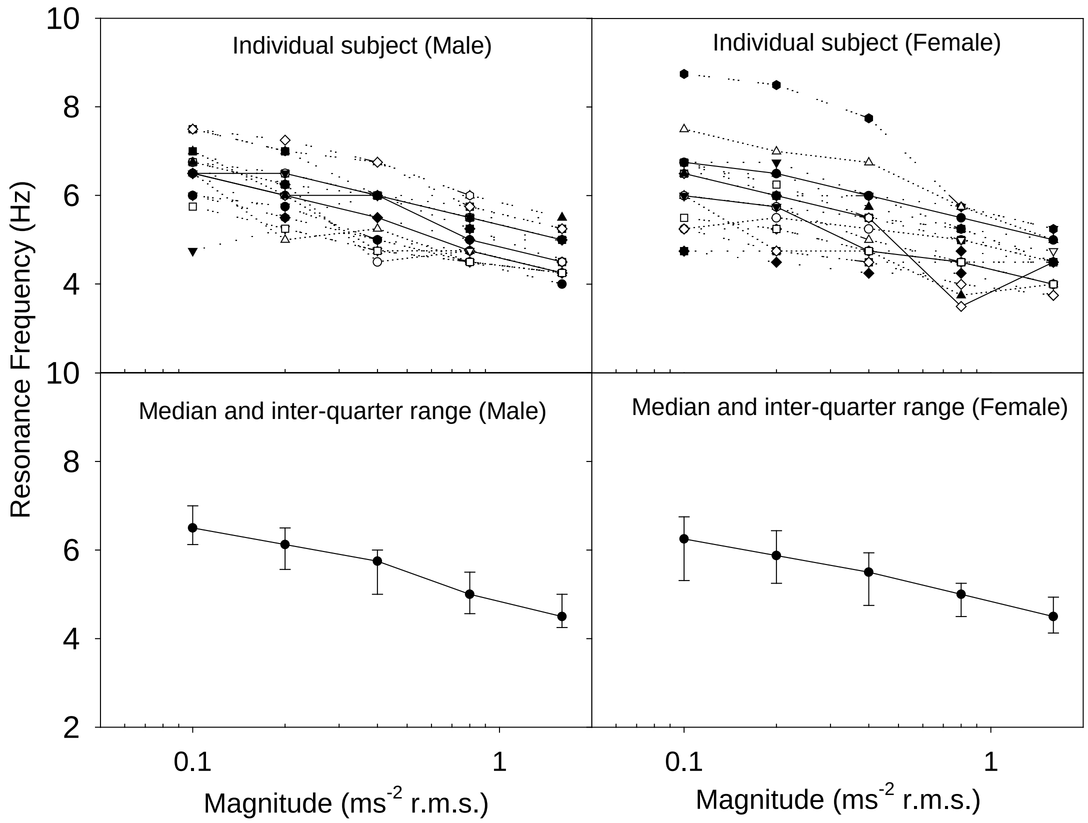

Figure 7 Individual (top) and median and inter-quarter range (bottom) of resonance frequencies for 20 males and 20 females exposed to random vibration at five magnitudes (0.1, 0.2, 0.4, 0.8 and 1.6 ms^{-2} r.m.s.)

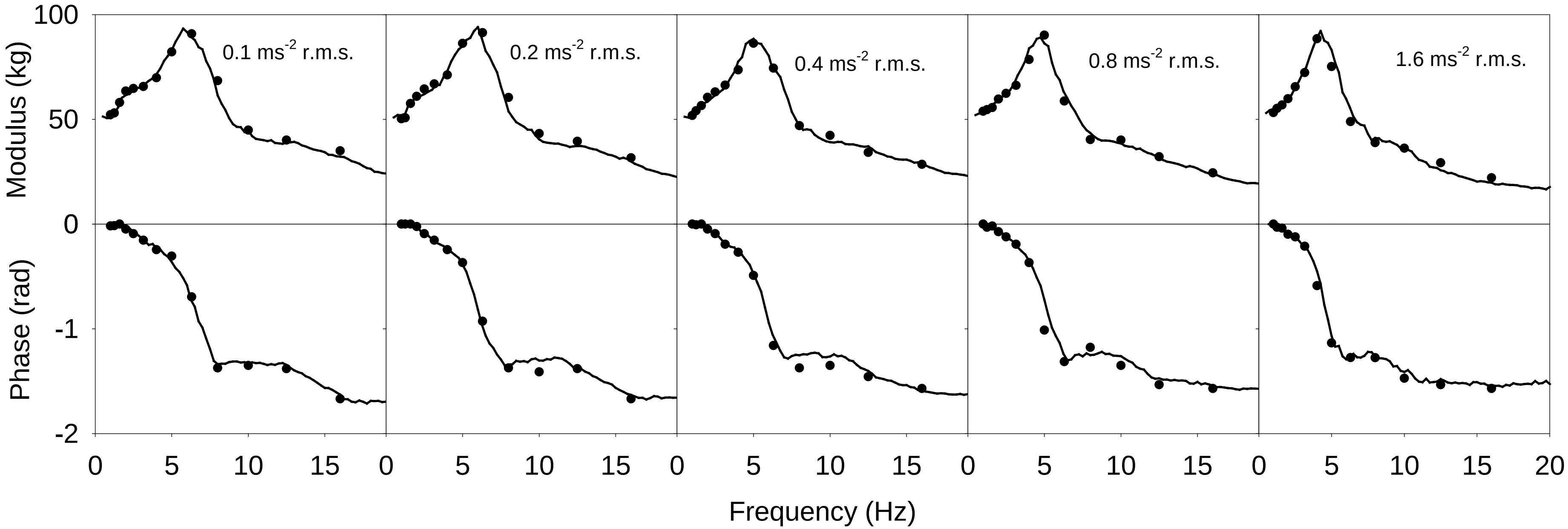

Figure 8 Comparison of the modulus and phase of the apparent mass between sinusoidal vibration and random vibration at five vibration magnitudes (median values for 20 males).

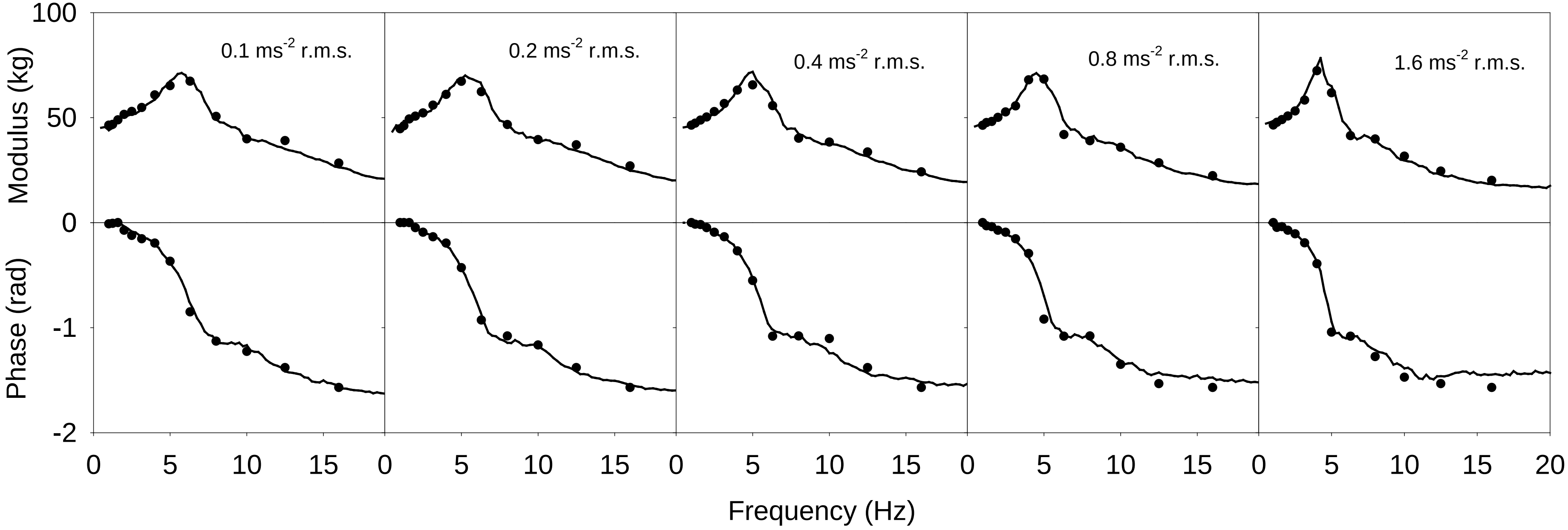

Figure 9 Comparison of the modulus and phase of the apparent mass between sinusoidal vibration and random vibration at five vibration magnitudes (median values for 20 females).

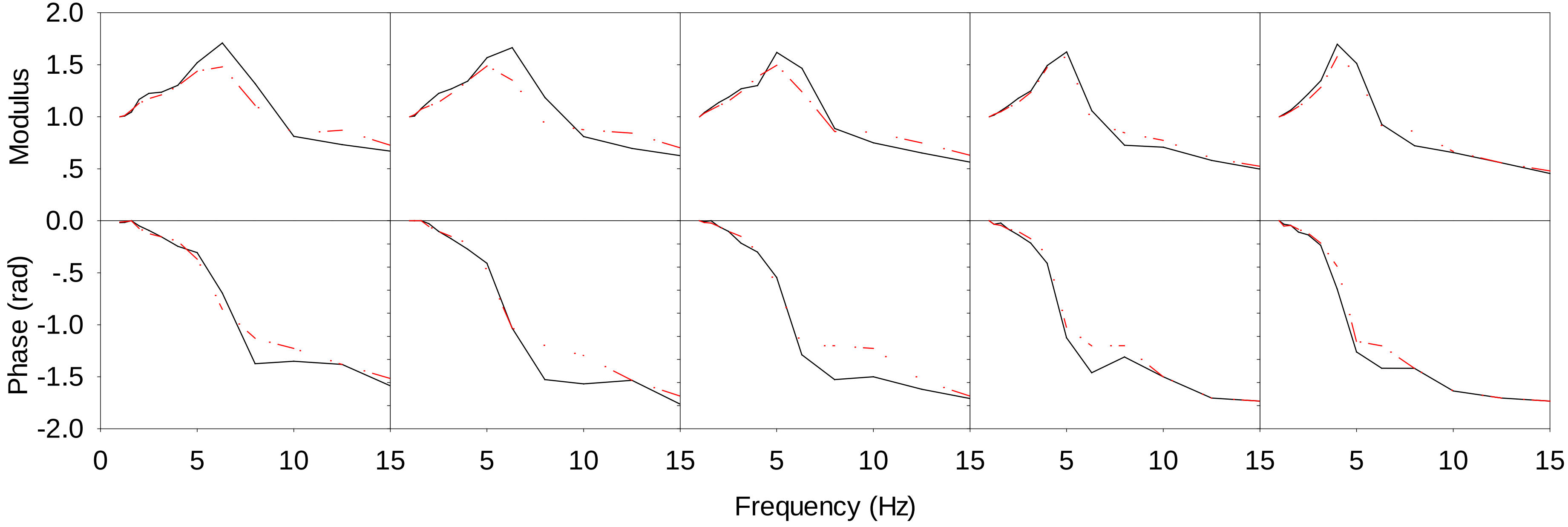

Figure 10 Comparison the modulus of the normalised vertical apparent mass between male and female subjects for sinusoidal vibration at five magnitudes (from left to right: 0.1, 0.2, 0.4, 0.8 and 1.6 ms^{-2} r.m.s.). Median values for 20 males (——) and 20 females (– – –).

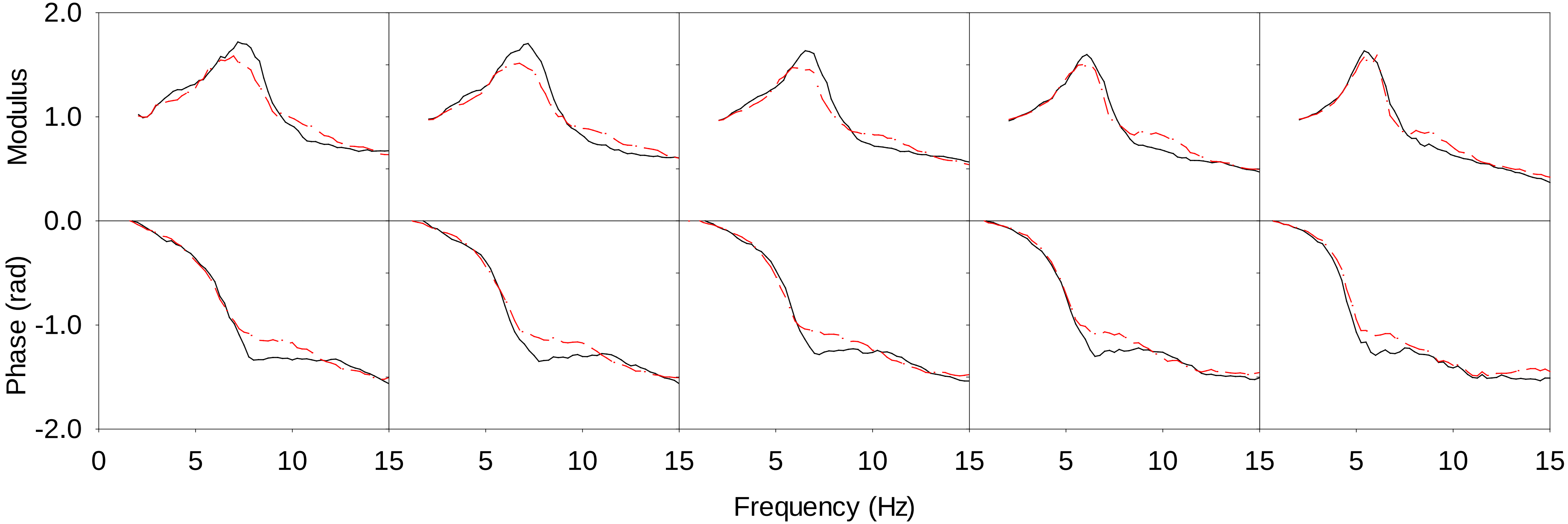

Figure 11 Comparison the modulus of the normalised vertical apparent mass between male and female subjects for sinusoidal vibration at five magnitudes (from left to right: 0.1, 0.2, 0.4, 0.8 and 1.6 ms-2 r.m.s.). Median values for 20 males (——) and 20 females (— — —).

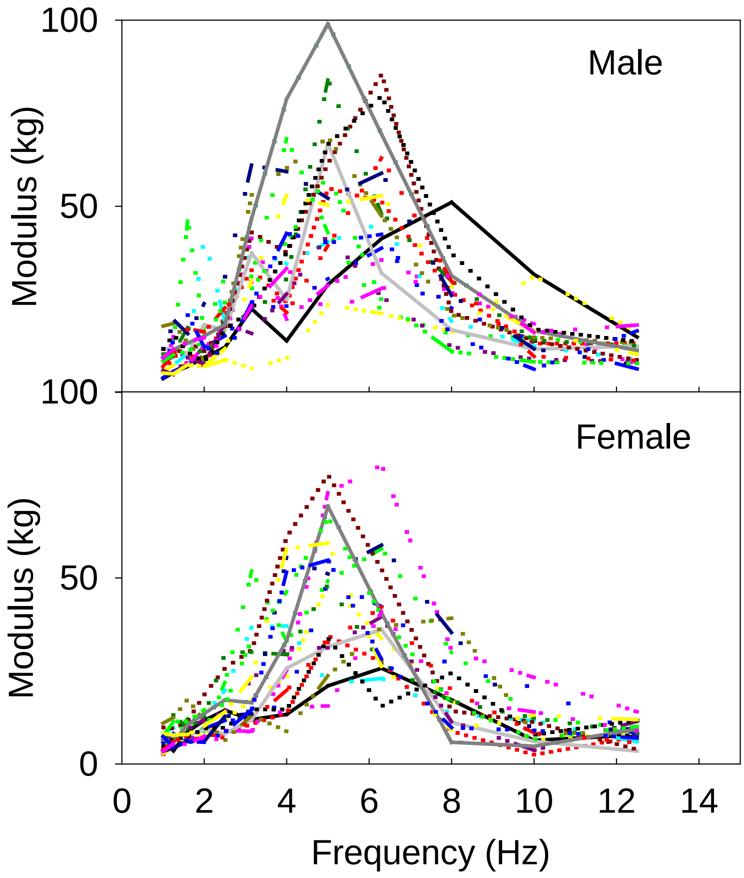

Figure 12 Inter-subject variability in the fore-and-aft cross-axis apparent masses of 20 male and 20 female subjects exposed to sinusoidal vertical vibration at 0.4 ms^{-2} r.m.s.

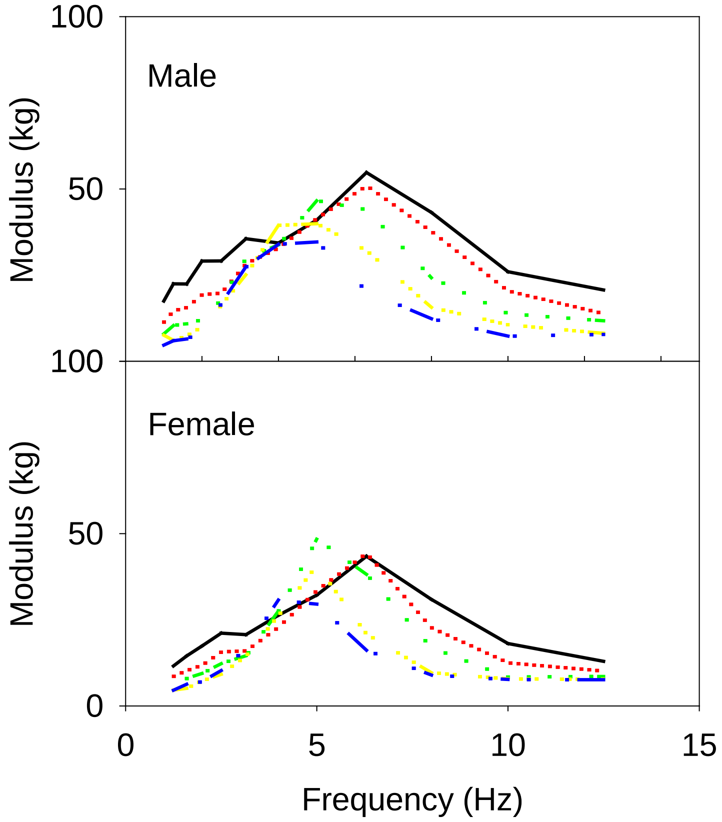

Figure 13 Modulus of the fore-and-aft cross-axis apparent mass with sinusoidal vibration at five different magnitudes (—— 0.1 ms^{-2} r.m.s., ······ 0.2 ms^{-2} r.m.s., — · — 0.4 ms^{-2} r.m.s., — — 0.8 ms^{-2} r.m.s., ▬▬ 1.6 ms^{-2} r.m.s.). (Medians of the measured apparent masses of 20 males and 20 females)

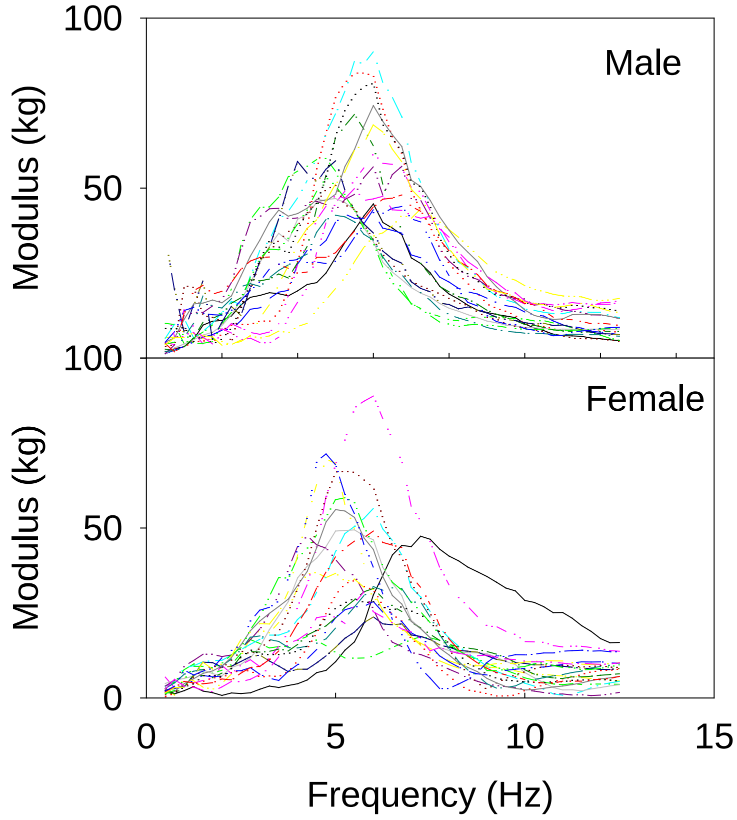

Figure 14 Inter-subject variability in the fore-and-aft cross-axis apparent masses of 20 male and 20 female subjects exposed to random vertical vibration at 0.4 ms^{-2} r.m.s.

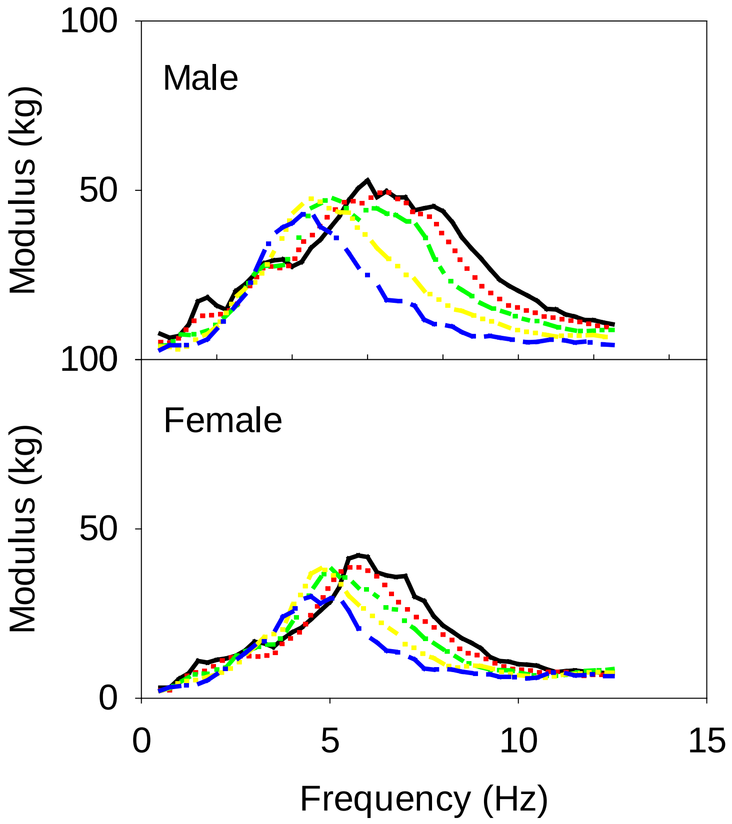

Figure 15 Modulus of the fore-and-aft cross-axis apparent mass with random vibration at five vibration magnitudes (——— 0.1 ms^{-2} r.m.s., • • • 0.2 ms^{-2} r.m.s., — — — 0.4 ms^{-2} r.m.s., — • • — 0.8 ms^{-2} r.m.s., — — — 1.6 ms^{-2} r.m.s.). (Medians of the measured apparent masses of 20 males and 20 females)

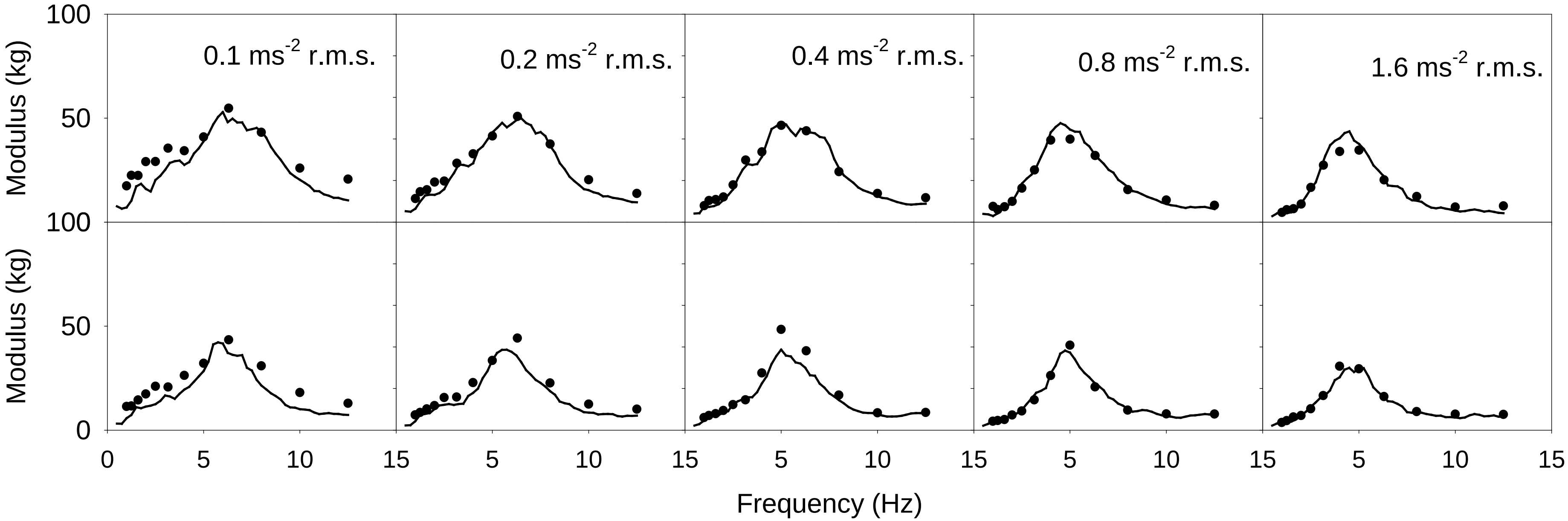

Figure 16 Comparison the modulus of the fore-and-aft cross-axis apparent mass between sinusoidal and random vibration for males (upper) and females (lower) at five vibration magnitudes. Median values for 20 males and 20 females.

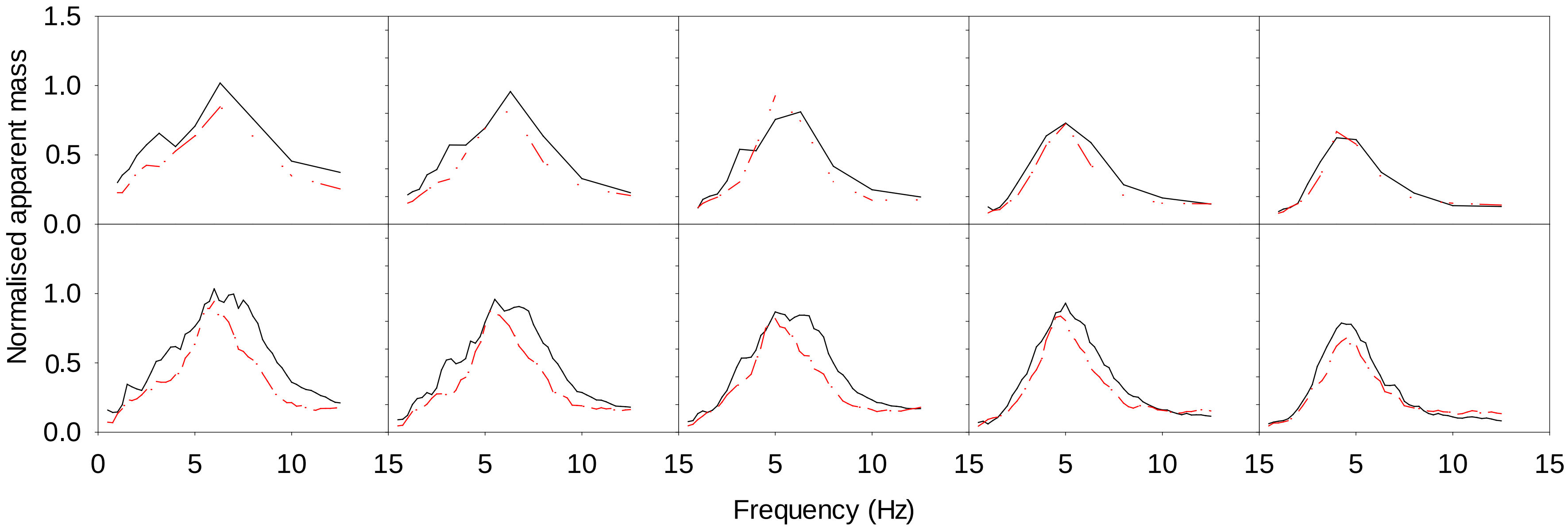

Figure 17 Comparison the modulus of the normalised fore-and-aft cross-axis apparent mass between male and female subjects for sinusoidal vibration (upper figures) and random vibration (lower figures) at five magnitudes (from left to right: 0.1, 0.2, 0.4, 0.8 and 1.6 ms^{-2} r.m.s.). Median values for 20 males (——) and 20 females (— — —).

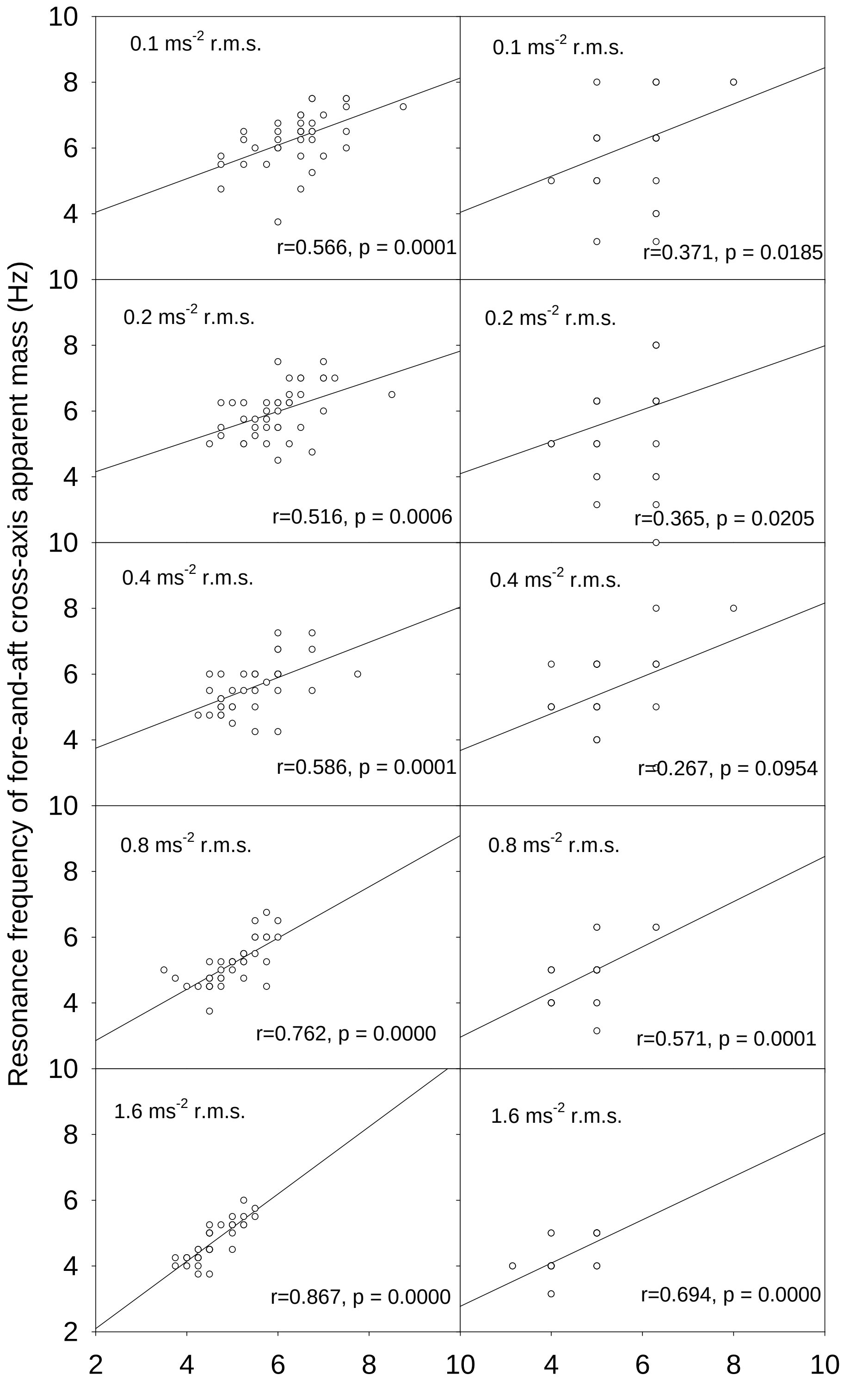

Figure 18 Correlation of resonance frequencies between the vertical apparent masses and the fore-and-aft apparent masses of 40 subjects exposed to random vibration (left) and sinusoidal vibration (right). Correlation coefficients r and p-values were obtained using Spearman rank correlation.

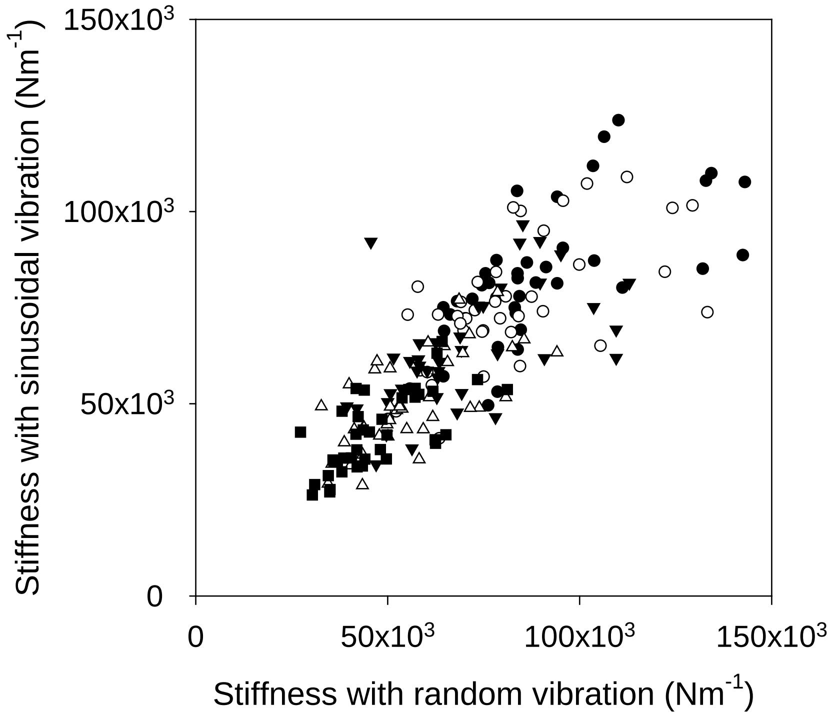

Figure 19 Correlation between the stiffnesses of an equivalent single degree-of-freedom model of biodynamic response to random vibration and biodynamic response to sinusoidal vibration (●: 0.1 ms^{-2} r.m.s.;○ : 0.2 ms^{-2} r.m.s.; ▼: 0.4 ms^{-2} r.m.s.; ∆: 0.8 ms^{-2} r.m.s.; ■: 1.6 ms^{-2} r.m.s.)

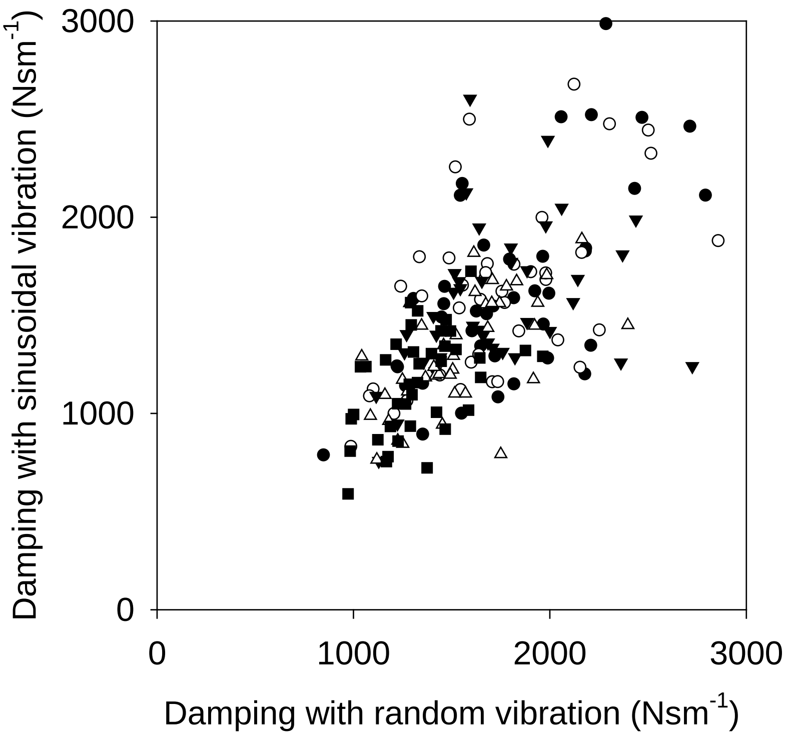

Figure 20 Correlation between the damping of an equivalent single degree-of-freedom model of biodynamic response to random vibration and biodynamic response to sinusoidal vibration (●: 0.1 ms^{-2} r.m.s.;○ : 0.2 ms^{-2} r.m.s.; ▼: 0.4 ms^{-2} r.m.s.; ∆: 0.8 ms^{-2} r.m.s.; ■: 1.6 ms^{-2} r.m.s.)

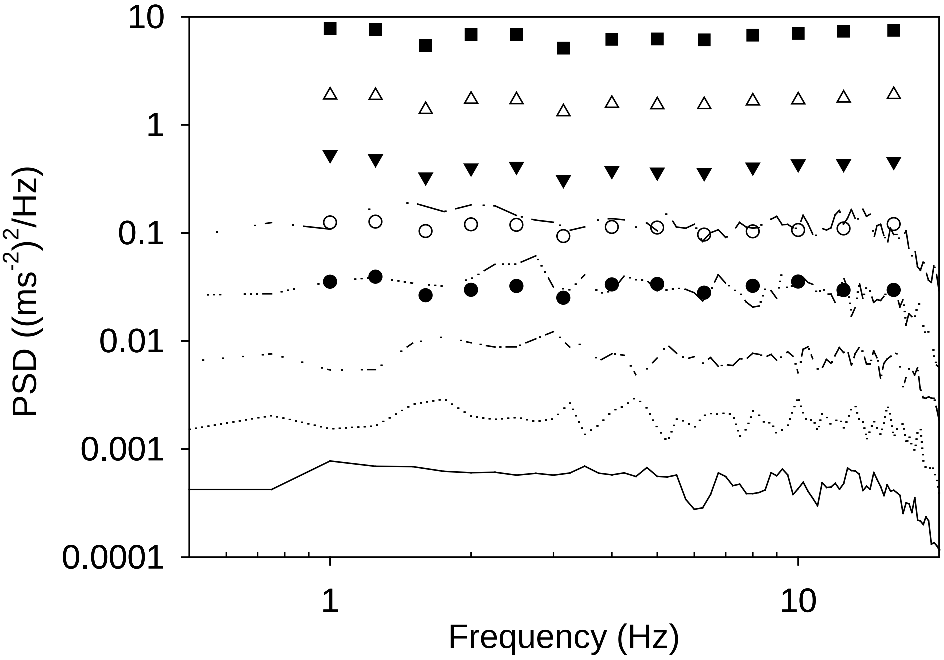

Figure 21 Comparison of acceleration power spectral densities between sinusoidal vibration (• 0.1 ms^{-2} r.m.s.; ○ 0.2 ms^{-2} r.m.s.; ▼ 0.4 ms^{-2} r.m.s.; ∆ 0.8 ms^{-2} r.m.s.; ■ 1.6 ms^{-2} r.m.s.) and random vibration (—— 0.1 ms^{-2} r.m.s., ⋯⋯ 0.2 ms^{-2} r.m.s., — — 0.4 ms^{-2} r.m.s., — ·· — 0.8 ms^{-2} r.m.s., —— —— 1.6 ms^{-2} r.m.s.) analysed with 0.25-Hz frequency resolution.

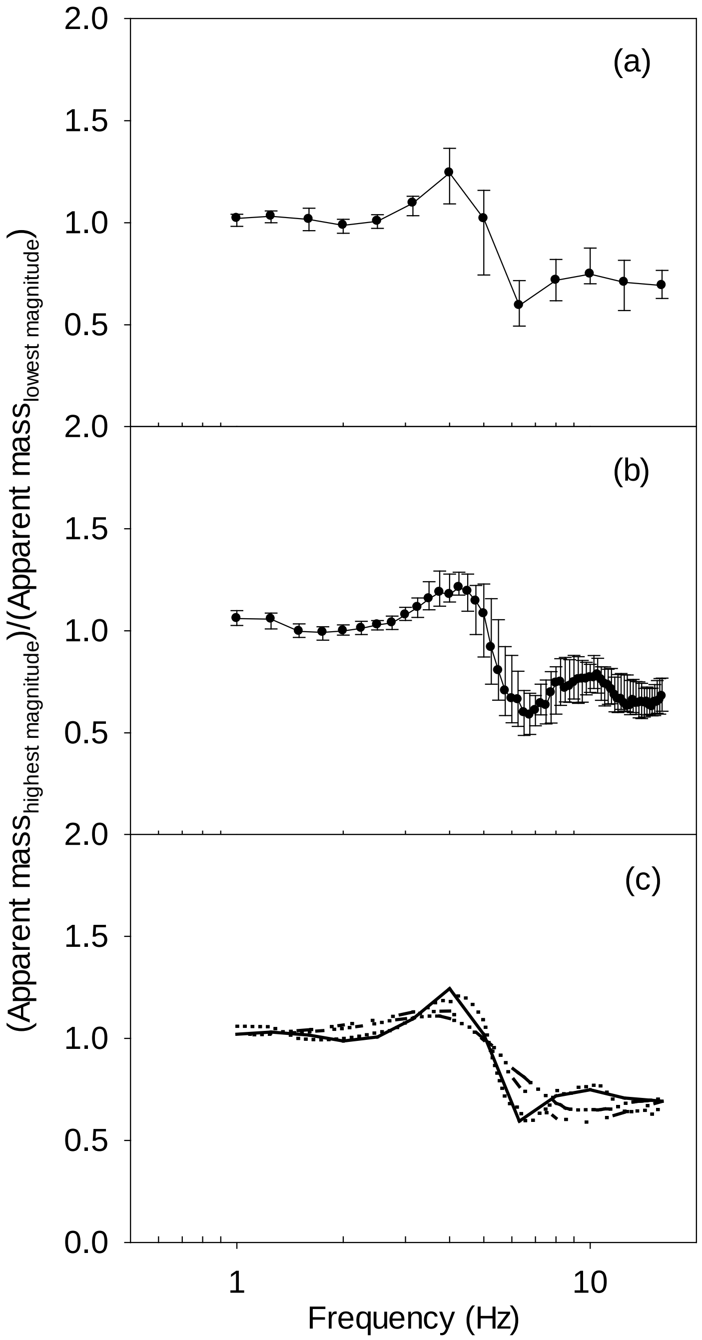

Figure 22 Ratios of apparent masses obtained at the highest and lowest magnitudes of vibration (i.e., 1.6 and 0.1 ms^{-2} r.m.s.): (a) sinusoidal vibration (medians and inter-quarter ranges for 40 subjects); (b) random vibration (medians and inter-quarter ranges for 40 subjects); (c) comparison of the median ratio from four conditions: measured sinusoidal vibration (──), measured random vibration (······), fitted sinusoidal vibration (─ ─) and fitted random vibration (─ · · ─).