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Non-linear dual-axis biodynamic response to fore-and-aft whole-body vibration

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Abstract

Seated subjects have participated in two experiments with fore-and-aft whole-body vibration to investigate dynamic responses at the seat and footrest in the direction of vibration and in other directions. In the first experiment, 12 males were exposed to fore-and-aft random vibration (0.25–20 Hz) at four magnitudes (0.125, 0.25, 0.625, and 1.25 m s^{-2} rms) while sitting on a seat with no backrest in four postures with varying foot heights to produce differing thigh contact with the seat (feet hanging, feet supported with maximum thigh contact, feet supported with average thigh contact, and feet supported with minimum thigh contact). In the second experiment, six subjects were exposed to three vibration magnitudes (0.125, 0.25, 0.625 m s^{-2} rms) in the average thigh contact posture, both with and without a rigid backrest. Forces were measured in the vertical, fore-and-aft, and lateral directions on the supporting seat surface (in the first experiment) and in the fore-and-aft and vertical directions at the footrest (in the second experiment).

On the seat, there were three vibration modes in the fore-and-aft apparent mass on the seat at frequencies below 10 Hz in all postures (around 1 Hz, between 1 and 3 Hz, and between 3 and 5 Hz); large vertical forces were dependent on foot support while lateral forces were relatively small. At the feet, the fore-and-aft apparent mass showed a resonance between 3 and 5 Hz, which increased in frequency and magnitude when a backrest was used. The fore-and-aft vibration produced high vertical forces at the footrest. At frequencies below resonance, the backrest reduced vertical and fore-and-aft forces at the footrest. On the seat and the footrest, the forces showed a nonlinear characteristic that varied between postures.

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The presence of appreciable vertical forces indicate that during fore-and-aft excitation the body moved in two dimensions. It is concluded that forces in directions other than the direction of excitation should be taken into account when considering biodynamic responses to fore-and-aft whole-body vibration.

1. Introduction

Horizontal vibration can be dominant in some vehicles (e.g. tractors, earth-moving machines and trains [1,2]). However, few studies have reported biodynamic responses of the human body to horizontal vibration.

Some measures of the driving point response of the seated body to horizontal vibration have been reported (e.g. Refs. [3–6]). There is some inconsistency in the modes reported to be associated with horizontal vibration, but three vibration modes have been suggested. The first is below 1 Hz, the second is between 1 and 3 Hz, and the third has a resonance around 5 Hz. Only Fairley and Griffin [3] investigated frequencies below 1 Hz and, hence, only their study reported a mode below 1 Hz.

Human response to horizontal vibration depends on sitting posture. When using a backrest, Fairley and Griffin [3] found only a vibration mode at 3.5 Hz in the fore-and-aft direction and at 1.5 Hz in the lateral direction, compared to two modes without a backrest. Holmlund and Lundström [4] noticed a decrease in the frequency of the 5 Hz mode when subjects changed from an erect to a relaxed posture.

With an increase in vibration magnitude, in both the fore-and-aft and lateral directions, Fairley and Griffin [3] noticed a decrease in the resonance frequency of the second mode, but not the first mode. Holmlund and Lundström [4] noticed the same effect on the frequency of the second mode (they did not measure the first mode), but only in the fore-and-aft direction. Mansfield and Lundström [6] reported a decrease in the frequency of both the second and third modes with an increase in vibration magnitude.

The human body has been shown to move in two dimensions when exposed to vertical vibration [7–9]. The mechanisms responsible for this cross-axis effect, and characteristics of the forces in directions other than the direction of vibration are otherwise unreported.

This paper reports two experimental studies in which tri-axial forces at the seat and dual-axis forces at the footrest were measured during whole-body fore-and-aft vibration. It was hypothesised that significant forces would be found in the fore-and-aft and vertical directions on the seat and footrest, but with less force in the lateral direction. It was also hypothesised that the response at the feet would depend on the body posture and that forces at both the seat and the feet would be nonlinear.

2. Apparatus, experimental design and analysis

2.1. Apparatus

Two separate experiments were conducted to measure the dynamic responses at the seat and the feet of seated subjects. In both experiments, subjects were exposed to fore-and-aft whole-body vibration using an electro-hydraulic vibrator capable of producing peak-to-peak displacements of 1 m. A rigid seat and an adjustable footrest (to give different foot heights) were mounted on the platform of the vibrator. A force plate (Kistler 9281 B) capable of measuring forces in three directions simultaneously was secured to the supporting surface of the seat (in the first experiment) and the feet (in the second experiment) in order to measure forces in the vertical, fore-and-aft, and lateral directions. The force plate ($600 \times 400 \times 20$ mm) consisted of four tri-axial quartz piezoelectric transducers of the same sensitivity located at the four corners of a rectangular aluminium plate. Signals from the force platform were amplified using Kistler 5007 charge amplifiers. Acceleration was measured at the centre of the force platform in each experiment using piezo-resistive accelerometers (Entran EGCSY-240D-10). The signs of the fore-and-aft acceleration and fore-and-aft force were positive in the forward direction. In the vertical direction, the force was positive in the upward direction. The signals from the accelerometers and the force transducers were acquired at 200 samples per second via 67 Hz anti-aliasing filters with an attenuation rate of 70 dB in the first octave.

2.2. *Experimental design*

2.2.1. *First experiment*

Twelve male subjects with average age 31.1 years (range 24–47 years), weight 77.5 kg (range 63–106 kg), and stature 1.79 m (range 1.68–1.91 m) were exposed to random fore-and-aft vibration with an approximately flat constant bandwidth acceleration power spectrum over the frequency range 0.25–20 Hz. Four different sitting postures were used (Fig. 1). The four postures, achieved solely by altering the height of the adjustable footrest, were: (i) 'feet hanging' with no foot support, (ii) feet supported with 'maximum thigh contact' (i.e. heels just in contact with the

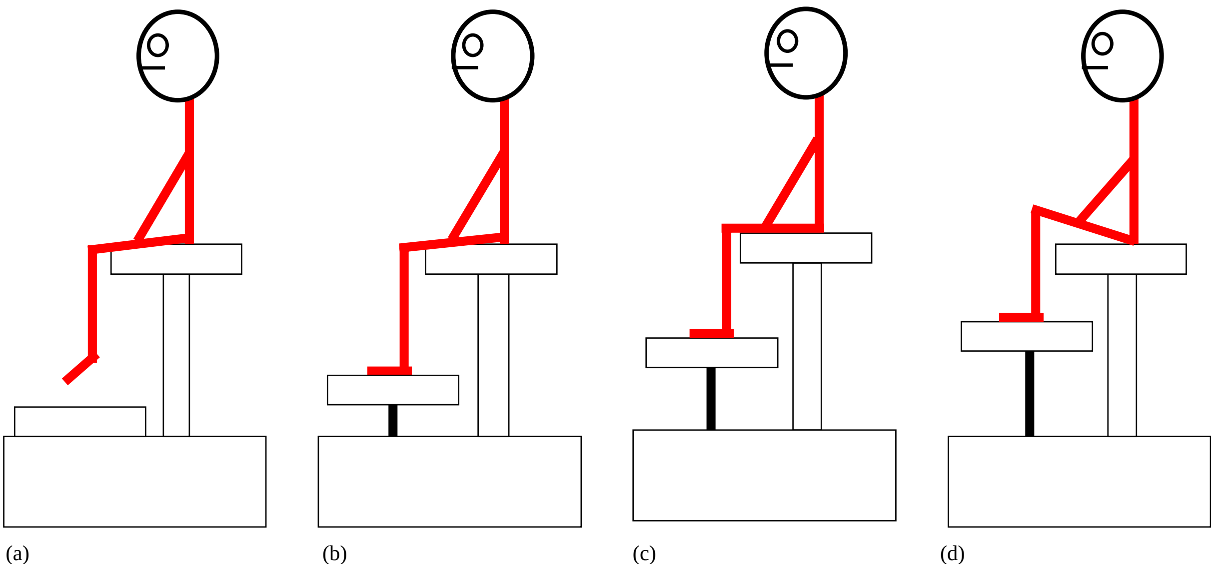

Fig. 1. Schematic diagrams of the four sitting postures: (a) feet hanging; (b) maximum thigh contact; (c) average thigh contact; (d) minimum thigh contact.

footrest), (iii) 'average thigh contact' (i.e. upper legs horizontal, lower legs vertical and supported on the footrest), and (iv) 'minimum thigh contact' (i.e. the footrest 160 mm above the position with 'average thigh contact' in position (iii)). The footrest was supported on the vibrator platform and therefore exposed to the same fore-and-aft vibration as the seat. The subjects placed their hands in their laps. No backrest was used in the first experiment.

In each sitting posture, the 12 subjects were exposed to four vibration magnitudes (0.125, 0.25, 0.625, and 1.25 $m\,s^{-2}$ rms). The presentation of the four postures and the four vibration magnitudes was balanced across subjects. Each vibration exposure lasted 60 s.

2.2.2. Second experiment

Six male subjects with average age 28 years (range 21–38 years), weight 71.3 kg (range 56–87 kg), and stature 1.72 m (range 1.63–1.83 m) participated in the second experiment. Three vibration magnitudes were used (0.125, 0.250, 0.625 $m\,s^{-2}$ rms). The same frequency range (0.25–20 Hz) and duration (60 s) were used as in the first experiment. For each vibration magnitude, the subjects in this experiment adopted the average thigh contact posture (posture C in Fig. 1) with a backrest and without a backrest.

2.3. Analysis

In the first experiment, the forces were measured in the vertical, fore-and-aft and lateral directions on the seat. In the second experiment, the forces were measured in the fore-and-aft and vertical directions on the footrest. For the fore-and-aft direction, the forces are presented as apparent masses calculated from the fore-and-aft acceleration and the fore-and-aft force at either the seat or the footrest.

For the vertical and lateral directions, the forces were related to the fore-and-aft acceleration using the concept of 'cross-axis apparent mass'.

The apparent mass and the cross-axis apparent mass, were calculated using the cross spectral density method:

$$M(\omega) = \frac{S_{af}(\omega)}{S_{aa}(\omega)},$$

where $M(\omega)$ is the apparent mass (or the cross-axis apparent mass), $S_{af}(\omega)$ is the cross spectral density between the force and the acceleration, and $S_{aa}(\omega)$ is the power spectral density of the acceleration. In the fore-and-aft direction, the mass of the aluminium plate of the force platform 'above' the force transducers was subtracted from the total measured mass (mass of the subject and plate) in the frequency domain: the transfer function measured without a subject was subtracted from the transfer functions obtained when subjects were used.

3. Results

3.1. Responses on the seat

3.1.1. Response in the fore-and-aft direction

There was appreciable inter-subject variability in the magnitude of the fore-and-aft apparent mass in all postures (Fig. 2). In all postures, the average coefficient of variation (the average of the

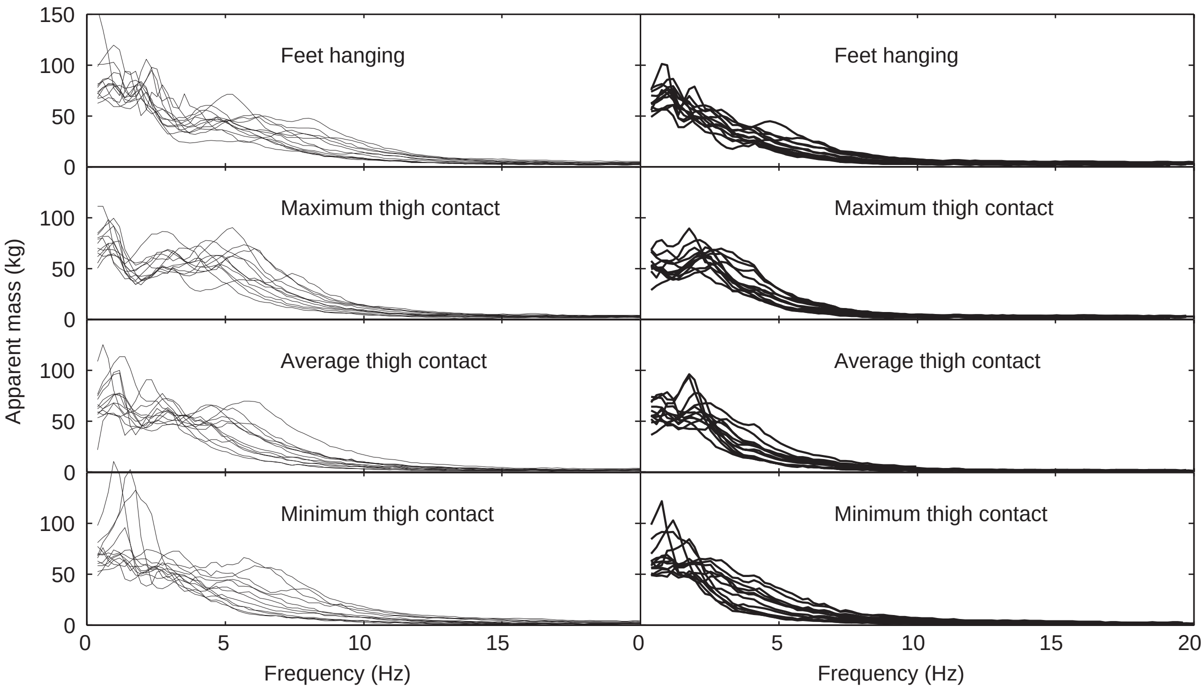

Fig. 2. Inter-subject variability in the fore-and-aft apparent mass at the seat for each posture at two vibration magnitudes. —, 0.125 m s^{-2} rms; —, 1.25 m s^{-2} rms.

ratios of the standard deviation to the mean calculated at each frequency) indicated greater variability at 0.125 m s^{-2} rms than at 1.25 m s^{-2} rms. The average coefficient of variation also showed greater inter-subject variability in the magnitude and the phase of the apparent mass in the minimum thigh contact posture than in the other postures.

In most subjects, three vibration modes are apparent in the frequency range 0–10 Hz. The first vibration mode has a frequency around 1 Hz and is evident in all subjects in the feet hanging posture, the maximum thigh contact posture and the average thigh contact posture (although not at all vibration magnitudes), and in only six subjects of the twelve subjects in the minimum thigh contact posture (see Appendix A). The second mode has a peak in the frequency range 1–3 Hz and is apparent in the response of all subjects in all postures and most vibration magnitudes. The third mode occurs at frequencies between 3 and 5 Hz, and is evident in all subjects in the feet hanging posture, 11 subjects in the maximum thigh contact posture, eight subjects in the average thigh contact posture, and seven subjects in the minimum thigh contact posture (Appendix A).

The median magnitude and phase of the apparent mass showed a nonlinear response in all postures (Fig. 3). The apparent mass magnitudes at the frequencies of the three vibration modes and at higher frequencies (0.78, 2.15, 4.1, 6.05, 8.0 and 12.1 Hz) were used to quantify the nonlinearity. Above 6 Hz, statistical analysis using Wilcoxon matched-pairs signed ranks tests showed significant differences ($p<0.05$) in the apparent mass magnitudes measured at the four vibration magnitudes. Below 6 Hz, least nonlinearity was found in the average thigh contact posture and the minimum thigh contact posture at 2.15 Hz (Table 1).

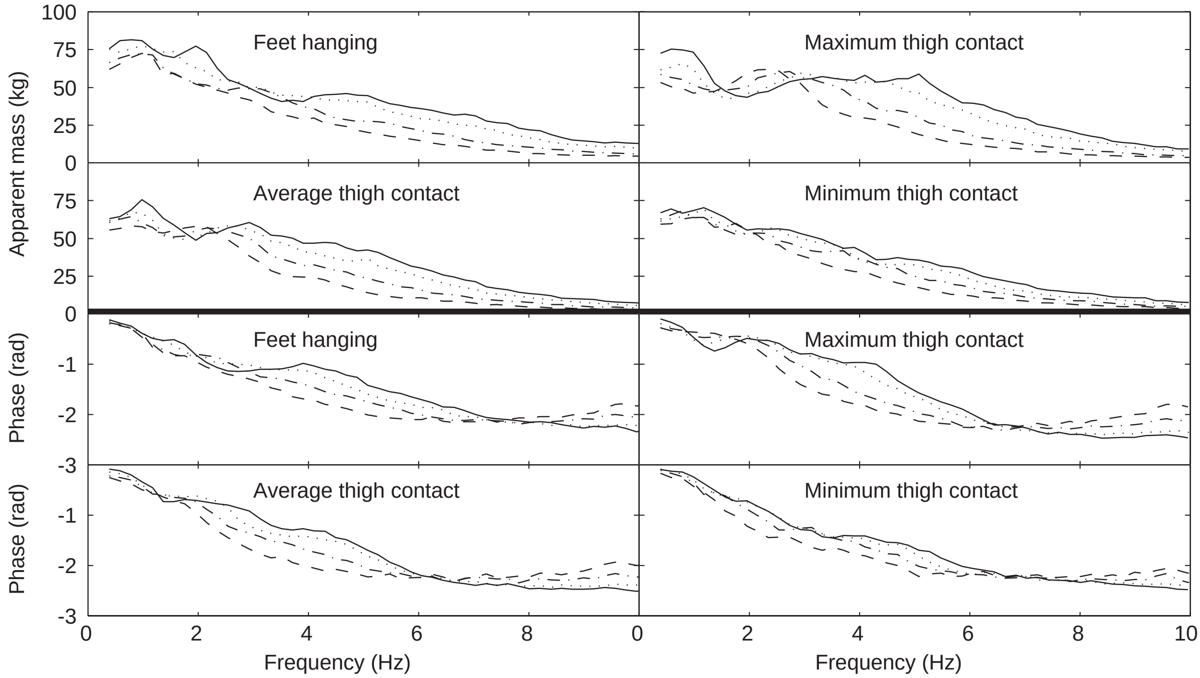

Fig. 3. Median fore-and-aft apparent mass and phase angle of 12 subjects at the seat: effect of vibration magnitude. —, 0.125 m s^{-2} rms; ……, 0.25 m s^{-2} rms; –·–·–·–, 0.625 m s^{-2} rms; – – – –, 1.25 m s^{-2} rms.

3.1.2. Responses in the vertical and lateral directions

Considerable vertical forces, represented as vertical cross-axis apparent mass, were found on the seat during fore-and-aft vibration (Fig. 4). The average coefficient of variation over the whole-frequency range indicated greater subjects variability at 0.125 m s^{-2} rms than at 1.25 m s^{-2} rms in all postures (see Fig. 4 and Appendix B). In the feet hanging posture, all subjects show a resonance frequency in the range 4–8 Hz. Eleven subjects show another resonance (although not at all vibration magnitudes) at a lower frequency (2–3 Hz). In the maximum thigh contact posture, vibration modes around 1 Hz, around 3 Hz and around 4–7 Hz can be identified (although all three modes are not visible for all subjects). In the average thigh contact posture and in the minimum thigh contact posture, most subjects showed modes with frequencies around 1 and 3 Hz, with a few showing a mode at a higher frequency.

Median data show that the vertical cross-axis apparent mass magnitudes tended to decrease with increasing vibration magnitude (Fig. 5). Statistical analysis using Wilcoxon matched-pairs signed ranks test showed that the change in the vertical cross-axis apparent mass with vibration magnitude depended on the frequency and the posture. For example, at four vibration magnitudes, there was no significant difference in the cross-axis apparent mass at either 0.78 or 2.15 Hz with the feet hanging posture. However, there was a significant difference in the cross-axis apparent mass obtained with the four vibration magnitudes at higher frequencies (Table 2).

At frequencies below about 5 Hz, the median vertical cross-axis apparent mass magnitudes tended to increase with increasing support for the feet (Fig. 6). However, at frequencies between 4 and 10 Hz, median results show the lowest cross-axis apparent mass in the average thigh contact

Table 1
Statistically significant differences between fore-and-aft apparent mass magnitudes

Posture	0.78 Hz	2.15 Hz	4.1 Hz	6.05 Hz	8.0 Hz	12.1 Hz	Total out of 36 possible combinations
Feet hanging	H1/H2 H1/H3 H1/H4 H2/H3	H1/H2 H1/H3 H1/H4 H2/H4	H1/H3 H1/H4 H2/H3 H2/H4 H3/H4	All combinations	All combinations	All combinations	31
Maximum thigh contact	Max1/Max2 Max1/Max3 Max1/Max4 Max2/Max3 Max2/Max4	Max1/Max2 Max1/Max3 Max1/Max4 Max2/Max3 Max2/Max4	Max1/Max4 Max2/Max3 Max2/Max4 Max3/Max4	All combinations	All combinations	All combinations	32
Average thigh contact	Av1/Av2 Av1/Av3 Av1/Av4 Av2/Av3 Av2/Av4	None	All combinations	All combinations	All combinations	All combinations	29
Minimum thigh contact	Min1/Min 4 Min2/Min4 Min3/Min4	Min1/Min 2	All combinations	All combinations	All combinations	All combinations	28

Comparisons shown where $p<0.05$; Wilcoxon matched-pairs signed ranks test: effect of vibration magnitude. H: feet hanging; Max: maximum thigh contact; Av: average thigh contact; Min: minimum thigh contact; vibration magnitudes: 1: 0.125; 2: 0.25; 3: 0.625; 4: 1.25 $m\,s^{-2}$ rms.

posture. At higher frequencies, the vertical cross-axis apparent mass is low in all postures. The phases of the vertical cross-axis apparent masses on the seat are also shown in Fig. 5. These phases can be understood by reference to the sign convention for the fore-and-aft acceleration and the vertical force mentioned in Section 2.1. For example, at 4.4 Hz, the median phase in the feet hanging posture at 0.125 $m\,s^{-2}$ rms is -3.14 rad. This means that, at this frequency, a forward acceleration produced a downward vertical force.

In all postures, the lateral cross-axis apparent masses were small relative to those in the vertical direction. The high inter-subject variability seen in the lateral direction was less at higher vibration magnitudes (Fig. 7). The response in the lateral direction shows a nonlinear characteristic with vibration magnitude (Fig. 8). The lateral cross-axis apparent masses are shown at frequencies below 10 Hz due to a lateral resonance in the system at about 13 Hz.

3.2. Responses at the feet

3.2.1. Response in the fore-and-aft direction

With and without a backrest, the inter-subject variability in the fore-and-aft apparent mass at the feet is shown in Fig. 9. There appears to be a resonance in the apparent mass at the feet in the

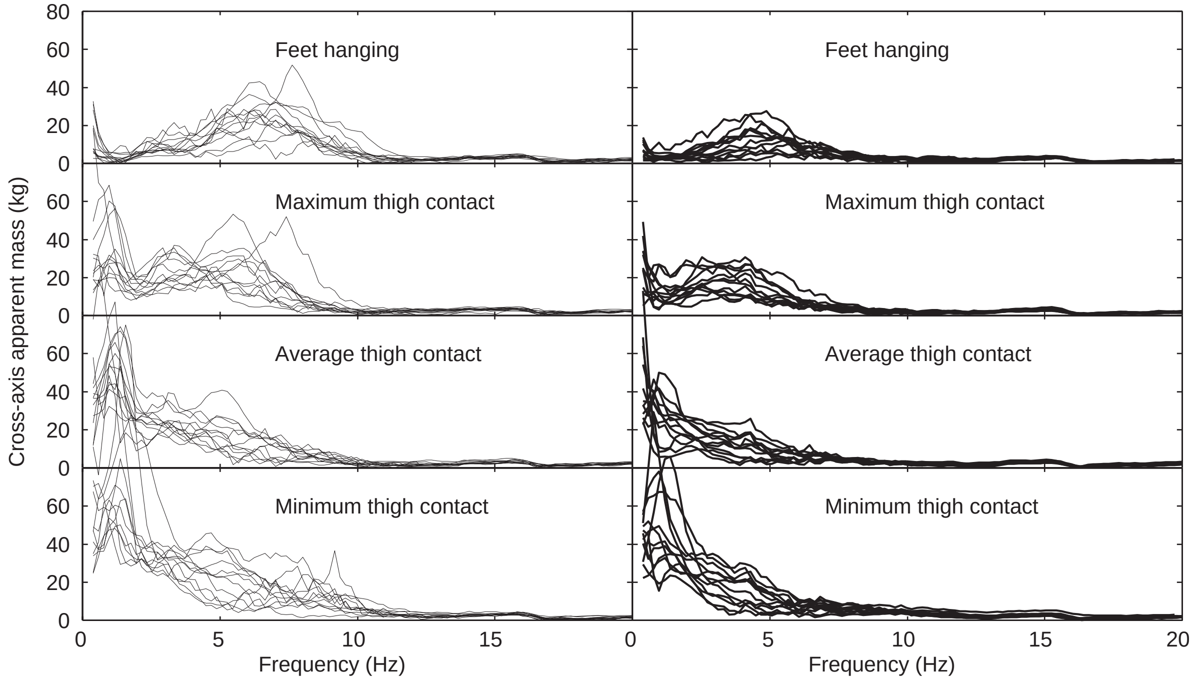

Fig. 4. Inter-subject variability in the vertical cross-axis apparent mass at the seat for each posture at two vibration magnitudes. —, 0.125 m s^{-2} rms; —, 1.25 m s^{-2} rms.

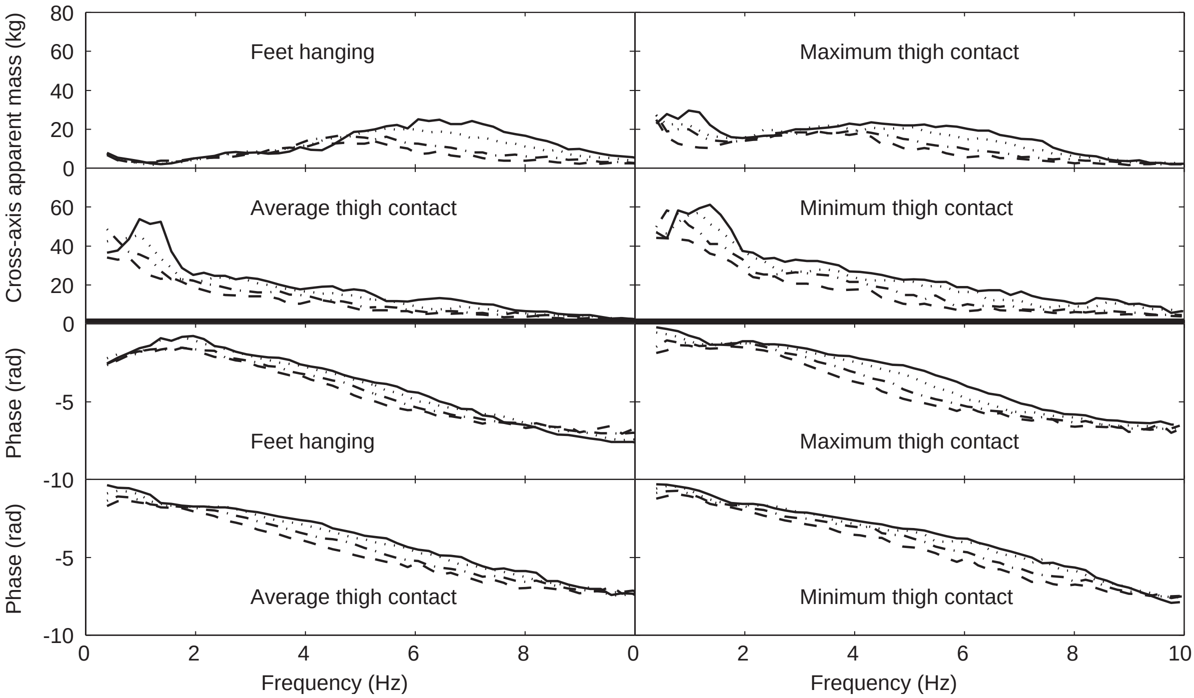

Fig. 5. Median vertical cross-axis apparent mass and phase angle of 12 subjects at the seat: effect of vibration magnitude. —, 0.125 m s^{-2} rms; ……, 0.25 m s^{-2} rms; –·–·–·–, 0.625 m s^{-2} rms; – – – –, 1.25 m s^{-2} rms.

Table 2
Statistically significant differences between the vertical cross-axis apparent mass magnitudes

	At 0.78 Hz	At 2.15 Hz	At 4.10 Hz	At 6.05 Hz	At 8.0 Hz	At 12.1 Hz	Total out of 36 possible combinations
Feet hanging	None	None	H1/H2	All combinations	All combinations	H1/H4 H2/H4 H3/H4	16
Maximum thigh contact	Max1/Max3 Max1/Max4 Max2/Max3 Max2/Max4 Max3/Max4	None	Max2/Max4	All combinations	All combinations	Max1/Max2 Max1/Max4 Max3/Max4	21
Average thigh contact	Av1/Av3 Av1/Av4 Av2/Av3 Av2/Av4	Av1/Av2 Av1/Av3 Av1/Av4	Av1/Av3 Av1/Av4 Av2/Av3 Av2/Av4 Av3/Av4	Av1/Av3 Av1/Av4 Av2/Av3 Av2/Av4 Av3/Av4	Av1/Av3 Av1/Av4 Av2/Av3 Av2/Av4 Av3/Av4	None	22
Minimum thigh contact	Min3/Min4	Min1/Min2 Min1/Min3 Min1/Min4 Min2/Min3 Min2/Min4	Min1/Min2 Min1/Min3 Min1/Min4 Min2/Min3 Min2/Min4	All combinations	All combinations	None	23

Comparisons shown where $p<0.05$; Wilcoxon matched-pairs signed ranks test: effect of vibration magnitude. H: feet hanging; Max: maximum thigh contact; Av: average thigh contact; Min: minimum thigh contact; vibration magnitudes: 1: 0.125; 2: 0.25; 3: 0.625; 4: 1.25 m s^{-2} rms.

frequency range 3–5 Hz (depending on the subject and vibration magnitude), both with and without the backrest (Figs. 10 and 11). The variation in apparent mass magnitude with change in vibration magnitude was investigated at six frequencies (0.78, 2.15, 4.1, 6.05, 8.0, and 12.1 Hz). Statistical analysis (Wilcoxon matched-pairs signed ranks test) showed that the change in apparent mass magnitude with vibration magnitude was dependent on the frequency: at some frequencies the effect of vibration magnitude on the apparent mass magnitude was clearer than at others (Table 3).

The backrest seemed to increase the median resonance frequency and the magnitude of the apparent mass at resonance, while decreasing the median apparent mass at frequencies below resonance (Fig. 12).

3.2.2. Response in the vertical direction

Variability between subjects in the vertical cross-axis apparent mass is shown in Fig. 13 for two vibration magnitudes and two sitting conditions. The figure also shows a resonance around 1 Hz when no backrest was used, but a resonance around 5 Hz when the backrest was used.

The response at the feet in the vertical direction depended on vibration magnitude (Figs. 14 and 15). As noticed in the fore-and-aft apparent mass measured at the feet, the variation in the vertical

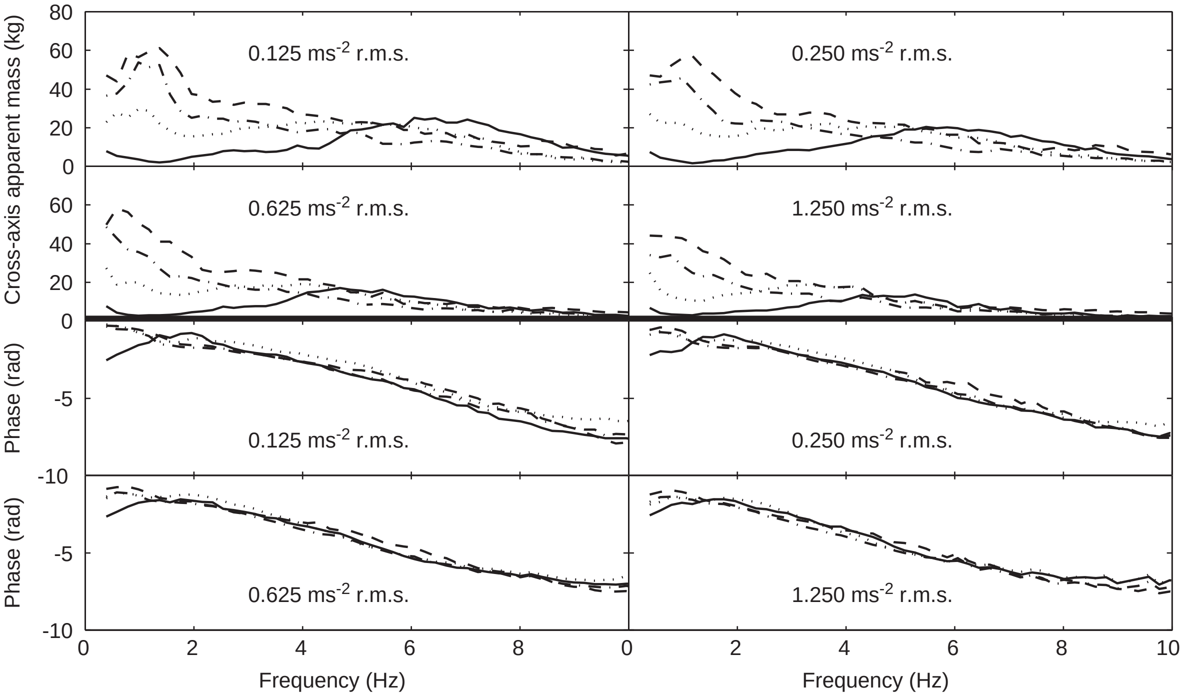

Fig. 6. Median vertical cross-axis apparent mass and phase angle of 12 subjects at the seat: effect of posture. —, feet hanging; ……, maximum thigh contact; –·–·–·–, average thigh contact; – – – –, minimum thigh contact.

cross-axis apparent mass at the feet with change in vibration magnitude was dependent on the frequency (Table 3).

Below 4 Hz, there was greater median vertical cross-axis apparent mass at the feet when subjects did not use the backrest (see Fig. 16). At the same vibration magnitude, there were statistically significant differences in the vertical cross-axis apparent masses measured with and without a backrest at 0.78, 2.15, 6.05, 8.0, and 12 Hz ($P<0.05$). No significant effect of backrest was found at 4.1 Hz.

4. Discussion

4.1. Validity of using linear techniques (cross-spectral density method)

Linear techniques, such as the cross-spectral density (CSD) method, are frequently used to analyse biodynamic responses of the human body to vibration, even though observations suggest that the human body responds nonlinearly. When using the CSD method, although a different response is found at different magnitudes, there is generally high coherency between the fore-and-aft acceleration and the fore-and-aft force at any one magnitude, possibly implying that the body behaves linearly at a vibration magnitude but differently at another magnitude. When the

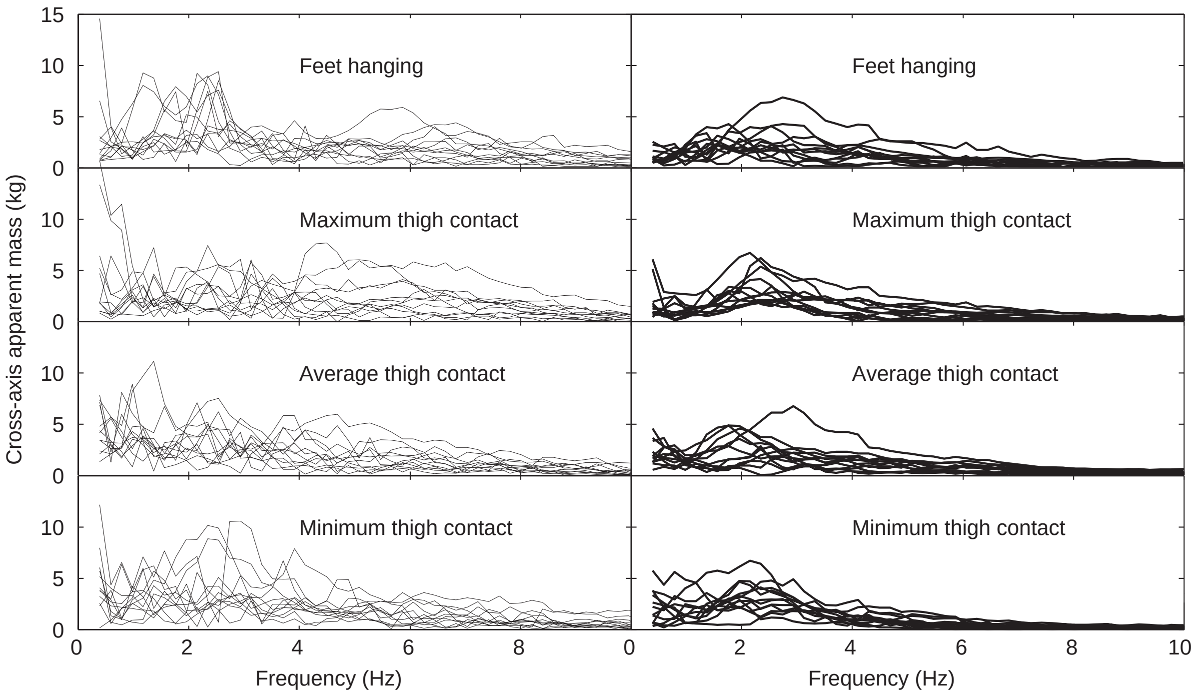

Fig. 7. Inter-subject variability in the lateral cross-axis apparent mass at the seat for each posture at two vibration magnitudes. —, 0.125 m s^{-2} rms; —, 1.25 m s^{-2} rms.

vibration magnitude changes, the human body might adjust to the new vibration magnitude (by postural change, muscular change or some other change), in which case the use of linear methods would be appropriate when analysing the response at one vibration magnitude. However, with current understanding, a nonlinear response when the body is exposed at only one vibration magnitude cannot be excluded. If the body may behave nonlinearly when exposed to a particular magnitude of vibration, it is of interest to compare the use of CSD method and the power spectral density (PSD) method for computing the apparent mass. Fig. 17 compares the fore-and-aft apparent mass of one subject at 0.625 m s^{-2} rms with the minimum thigh contact posture calculated using the CSD method (as described in Section 2.3) and the PSD method (from the square root of the ratio of the power spectral densities of force and acceleration). The figure also shows the vertical cross-axis apparent mass calculated using the CSD and PSD methods, as well as the coherency in the fore-and-aft direction and the vertical direction. The coherency was calculated after subtracting in the time domain the fore-and-aft force arising from the mass of the plate on which the subject sat from the total measured fore-and-aft force. In the fore-and-aft direction, the coherency was high in all conditions. In the vertical direction, the coherency was generally high, but dropped for some subjects at some frequencies. It may be seen that the CSD and PSD methods gave very similar results. This suggests that, whether or not the body behaves linearly at the vibration magnitudes investigated, the use of linear techniques in this study has not produced misleading findings.

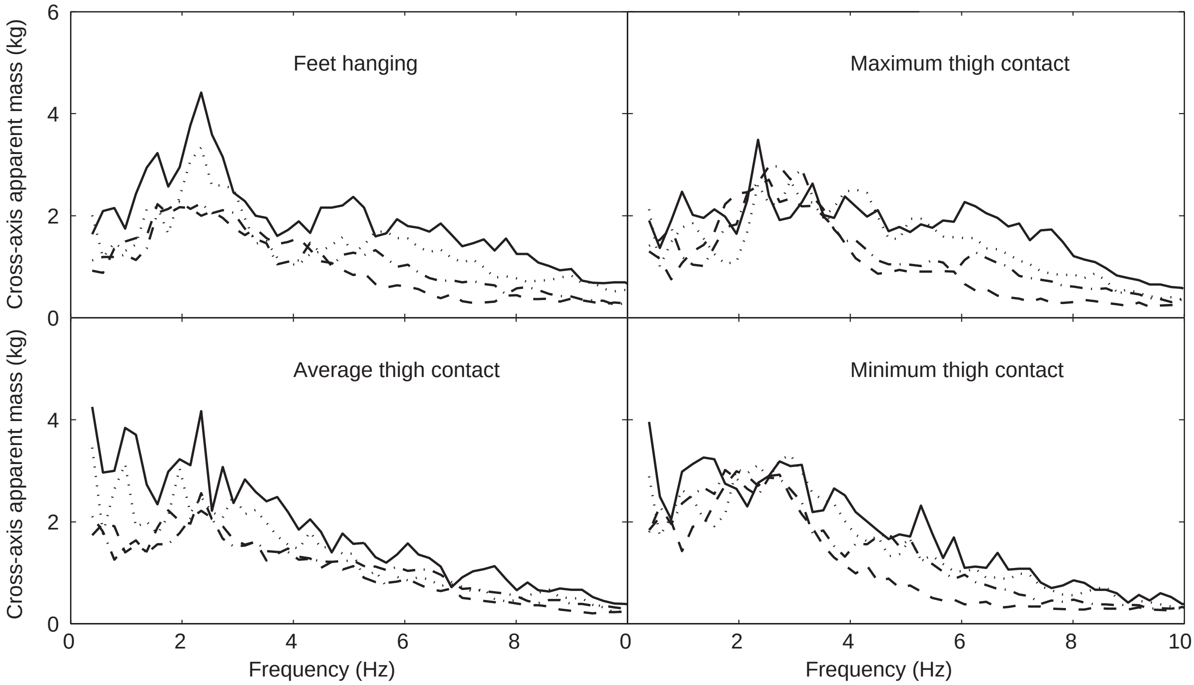

Fig. 8. Median lateral cross-axis apparent mass of 12 subjects at the seat: effect of vibration magnitude. —, 0.125 m s^{-2} rms; ……, 0.25 m s^{-2} rms; –·–·–·–, 0.625 m s^{-2} rms; – – – –, 1.25 m s^{-2} rms.

4.2. Response in the fore-and-aft direction

More than one resonance, high subject variability and a nonlinearity in the fore-and-aft apparent mass are consistent findings in previous studies. Three vibration modes were found in the present study (around 1 Hz, between 1 and 3 Hz and between 3 and 5 Hz). Fairley and Griffin [3] reported modes similar to the first and second modes found here, but no third mode. Holmlund and Lundström [4] and Mansfield and Lundström [6] only investigated frequencies above 1 Hz; Holmlund and Lundström reported mainly one mode, similar to the second mode in this study, while Mansfield and Lundström reported modes similar to the second and third modes found here.

Some of the differences in apparent mass between studies may be due to the use of different vibration magnitudes and waveforms, different sitting postures, and whether the feet were moving in phase with the seat or supported on a stationary footrest. The angle between the upper leg and lower leg, as well as the height of the footrest with respect to the seat, may also have contributed to differences between the studies.

In the present study, vibration magnitude affected the visibility of the third vibration mode above 3 Hz: the third mode was mainly evident at low vibration magnitudes, diminishing with increasing vibration magnitude as the apparent mass decreased in that region. Fairley and Griffin [3] used a minimum vibration magnitude of 0.5 m s^{-2} rms, compared to 0.125 m s^{-2} rms in the present study and 0.25 m s^{-2} rms in the study reported by Mansfield and Lundström [6].

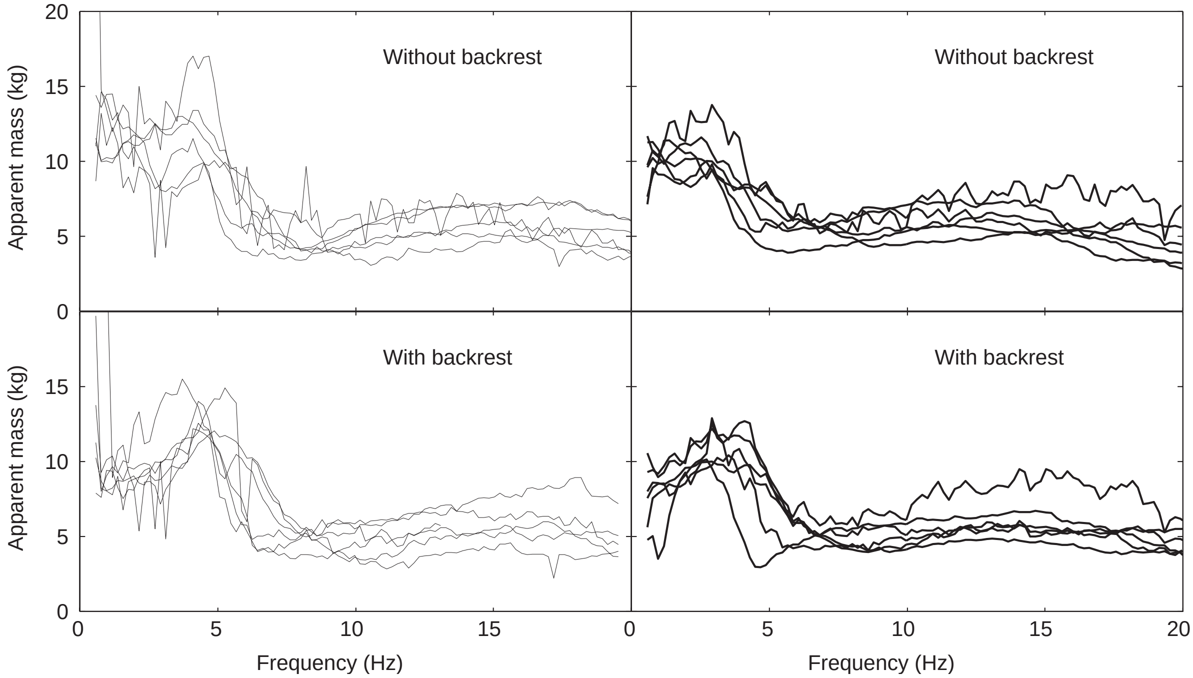

Fig. 9. Inter-subject variability in the fore-and-aft apparent mass at the feet for two postures at two vibration magnitudes. —, $0.125\,\mathrm{m\,s^{-2}}$ rms; —, $0.625\,\mathrm{m\,s^{-2}}$ rms.

Although, Holmlund and Lundström [4] used vibration magnitude as low as $0.25\,\mathrm{m\,s^{-2}}$ rms, they employed sinusoidal vibration where the energy at each frequency would have been higher than when using broad-band random vibration at the same overall vibration magnitude. Fairley [10] compared the vertical apparent mass of the body at $1.0\,\mathrm{m\,s^{-2}}$ rms using random vibration over the range 1.5–20 Hz and a frequency sweep. There was a reduced resonance frequency with the sinusoidal vibration, consistent with the expected nonlinearity and offering an explanation of the difference between the results obtained in this study with random vibration at $0.25\,\mathrm{m\,s^{-2}}$ rms and those obtained by Holmlund and Lundström with sinusoidal vibration of the same magnitude. Mansfield and Lundström suggested that placing the hands on the knees, or in the laps, might have damped the third mode, but this may be excluded since subjects in the present study also placed their hands in their laps.

In contrast to the present study, where an adjustable footrest was used, all previous studies have used a fixed distance between the seat surface and the footrest. If the range of subject heights was wide, the previous studies would have been a mixture of results from the four postures used in the present study (perhaps excluding the feet hanging posture). Neither Fairley and Griffin [3] nor Mansfield and Lundström [6] reported the heights of their subjects. In the Holmlund and Lundström [4] study, the subject heights were in the range 167–188 cm. The mixture of postures resulting from using the same seat with different subject sizes may have increased inter-subject variability and increased the difficulty of comparing results from the different studies: in the present study, there were statistically significant differences in apparent masses obtained with different postures.

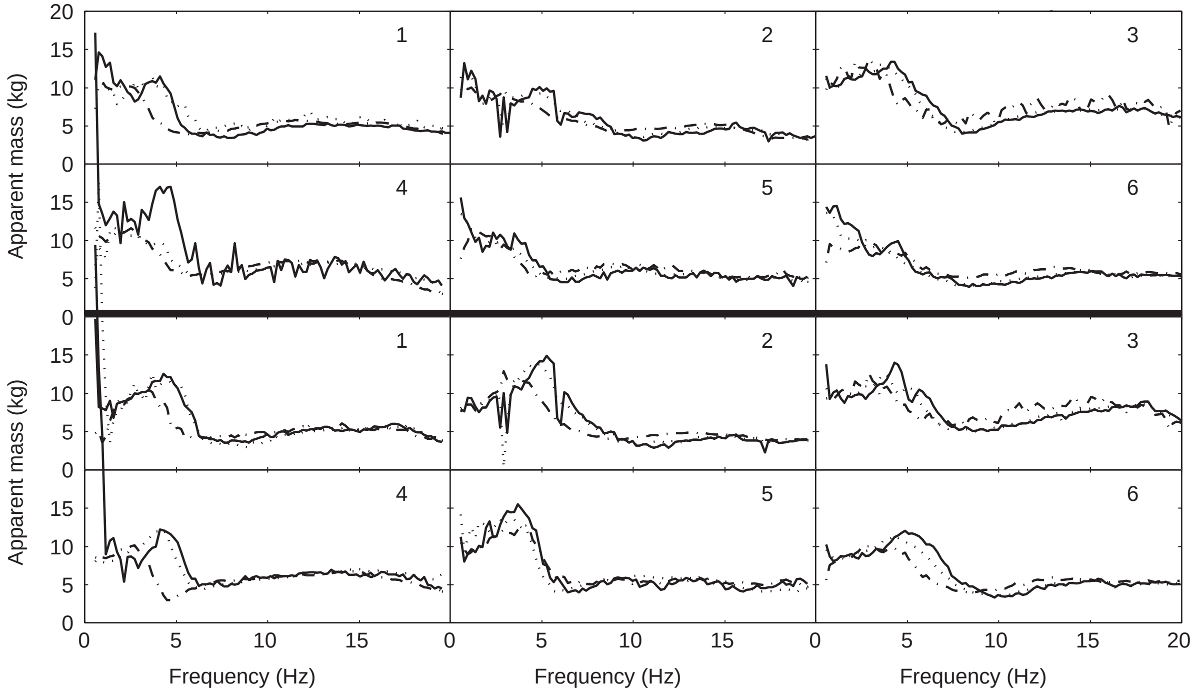

Fig. 10. Fore-and-aft apparent masses at the feet of six subjects. —, 0.125 m s^{-2} rms; ……, 0.25 m s^{-2} rms; –·–·–·–, 0.625 m s^{-2} rms. First two rows of figures without backrest; second two rows with backrest.

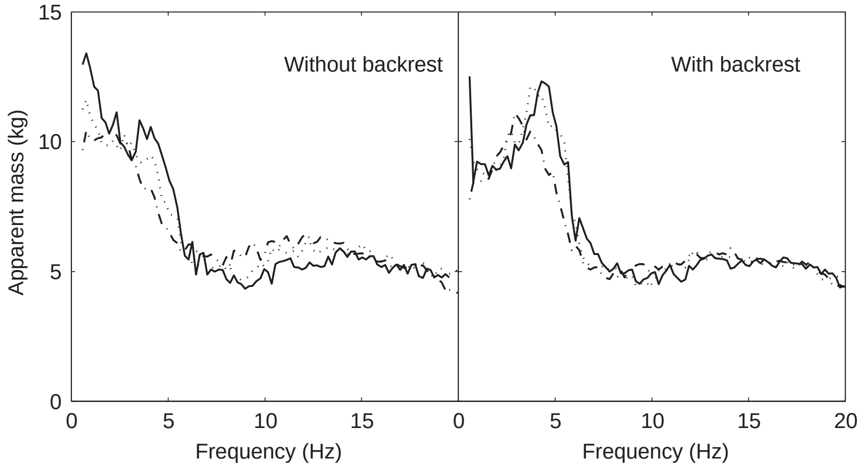

Fig. 11. Median fore-and-aft apparent masses at the feet of six subjects: effect of vibration magnitude. —, 0.125 m s^{-2} rms; ……, 0.25 m s^{-2} rms; –·–·–·–, 0.625 m s^{-2} rms.

Another difference between studies is whether the footrest moved with the seat (as in this study and in Ref. [3]) or was stationary (as in Refs [4,6]). Different forces on the seat should be expected with a moving footrest and a stationary footrest, due to different phases between the seat and the feet.

Table 3
Statistically significant differences between the fore-and-aft apparent mass magnitudes at the feet, and between the vertical cross-axis apparent mass magnitudes at the feet

	Fore-and-aft		Vertical	
	Without backrest	With backrest	Without backrest	With backrest
At 0.78 Hz	WO1/WO3	—	WO1/WO3 WO2/WO3	—
At 2.15 Hz	—	—	WO1/WO2	—
At 4.10 Hz	WO1/WO2 WO1/WO3 WO2/WO3	W1/W3 W2/W3	WO1/WO3 WO2/WO3	W1/W3
At 6.05 Hz	—	—	WO2/WO3	W1/W2 W1/W3
At 8.00 Hz	—	—	WO1/WO3 WO2/WO3	W1/W3 W2/W3
At 12.1 Hz	WO1/WO2 WO1/WO3	W2/W3	—	W1/W2

Comparisons shown where $p<0.05$; Wilcoxon matched-pairs signed ranks test: effect of vibration magnitude. WO: without backrest; W: with backrest; vibration magnitudes: 1: 0.125; 2: 0.25; 3: 0.625 m s^{-2} rms.

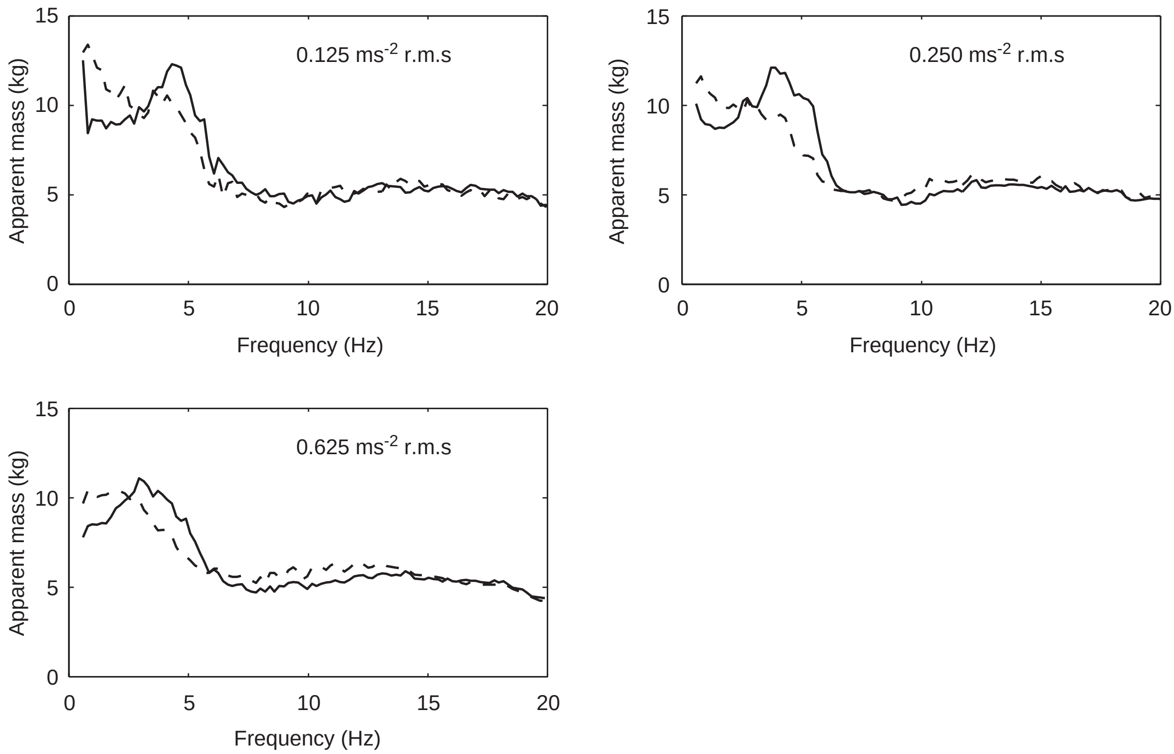

Fig. 12. Median fore-and-aft apparent masses at the feet of six subjects: effect of backrest. —, with backrest; – – – –, without backrest.

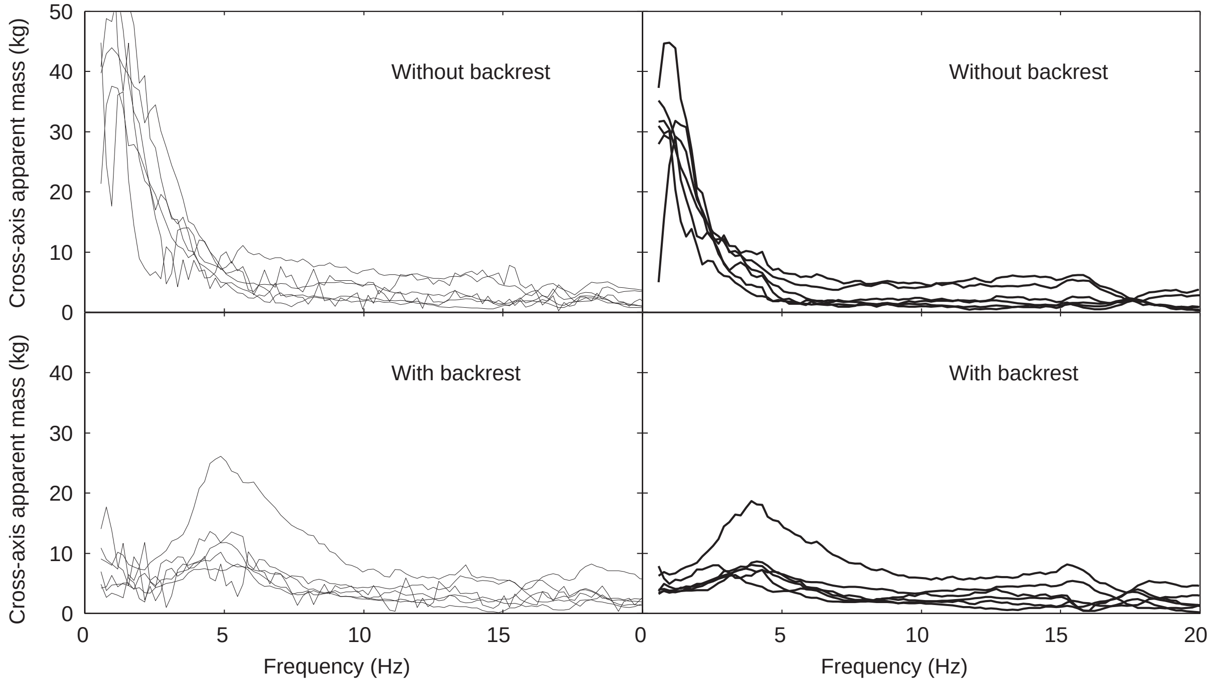

Fig. 13. Inter-subject variability in the vertical cross-axis apparent mass at the feet for two postures at two vibration magnitudes. —, $0.125\,\mathrm{m\,s^{-2}}$ rms; —, $0.625\,\mathrm{m\,s^{-2}}$ rms.

With a stationary footrest, forces measured on the seat might be affected by the height of the footrest, as found with vertical vibration by Fairley and Griffin [11]. With a decrease in the height of a stationary footrest, they reported a decrease in the apparent mass on the seat at low frequencies, as opposed to the increase in apparent mass with a decrease in the height of a footrest that moved in phase with the seat (e.g. Ref. [8]). Although the difference has only been reported for vertical vibration, it might be wise to assume that the results obtained with a moving footrest at low frequencies (below 1 Hz) in the present study and in Fairley and Griffin [3] may not be the same as those with a stationary footrest.

All relevant previous studies [3,4,6] reported a decrease in the resonance frequency of the second mode with an increase in vibration magnitude. Mansfield and Lundström [6] also reported a decrease in the third mode resonance frequency with an increase in vibration magnitude. Fairley and Griffin [3] (the only previous study to measure the first mode) found no effect of vibration magnitude on the resonance frequency of this mode. With an increase in vibration magnitude, although Mansfield and Lundström reported an increase in the apparent mass magnitude at resonance for the second mode, Holmlund and Lundström [4] reported a decrease in the magnitude of the mechanical impedance at resonance, and over the whole frequency range. None of the previous studies provided evidence that the apparent changes were statistically significant. In the present study, the change in the magnitude of the fore-and-aft apparent mass with a change in vibration magnitude was used as a measure of the nonlinearity, because not all subjects showed

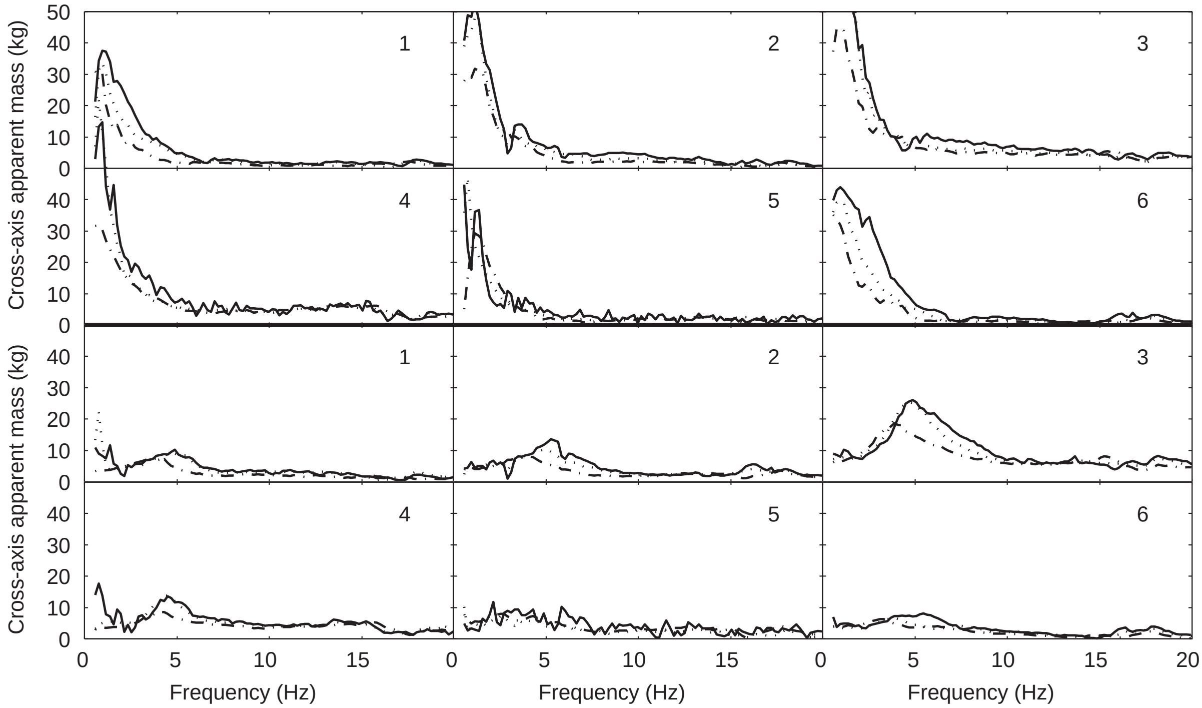

Fig. 14. Vertical cross-axis apparent masses at the feet of six subjects. —, 0.125 $m s^{-2}$ rms; ……, 0.25 $m s^{-2}$ rms; –·–·–·–, 0.625 $m s^{-2}$ rms. First two rows of figures without backrest; second two rows with backrest.

clear resonances at all vibration magnitudes (see Table 1). The nonlinear response in the fore-and-aft direction depended on the height of the footrest and the vibration frequency.

An additional explanation for differences in modes between studies is that because not all modes are at the same frequency in all subjects, they become 'smeared out' by averaging when calculating a mean or median response.

4.3. Responses in the vertical and lateral directions

High vertical forces on the seat, but low lateral forces, are consistent with unpublished data mentioned by Holmlund and Lundström [12]. The results are also similar to the high fore-and-aft forces and low lateral forces arising from vertical vibration [8,9].

In the present study, within the range 4–7 Hz, individual vertical cross-axis apparent mass was up to 70% of the static subject mass in the feet hanging posture. At frequencies below 5 Hz, the vertical cross-axis apparent mass increased with increasing support for the feet, and reached up to 100% of the static mass of some subjects in the minimum thigh contact posture (Fig. 6). The magnitudes of the vertical cross-axis apparent mass were then similar to the fore-and-aft apparent mass. For example, in the minimum thigh contact posture, the median vertical cross-axis apparent mass was 64% of the fore-and-aft apparent mass at 5 Hz and 86% of the fore-and-aft apparent mass around 1.0 Hz. This is consistent with a ratio of 1.3 to 1 between shear and

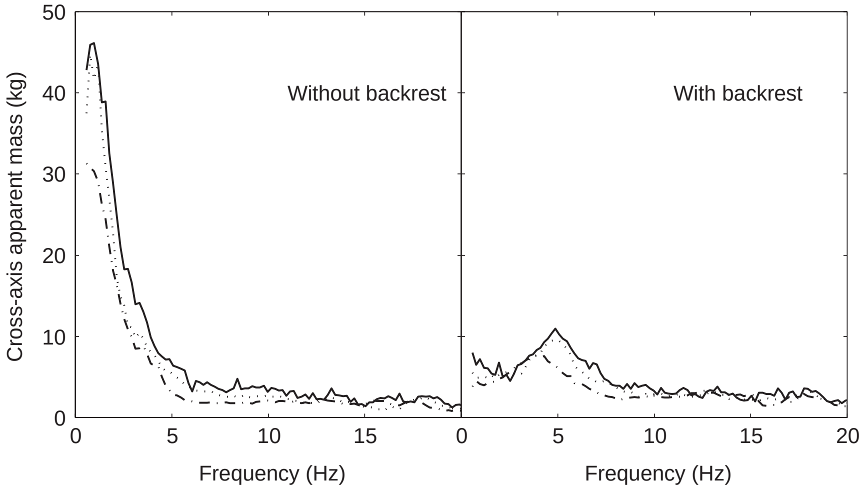

Fig. 15. Median vertical cross-axis apparent masses at the feet of six subjects: effect of vibration magnitude. —, $0.125\,m\,s^{-2}$ rms; ……, $0.25\,m\,s^{-2}$ rms; –·–·–·–, $0.625\,m\,s^{-2}$ rms.

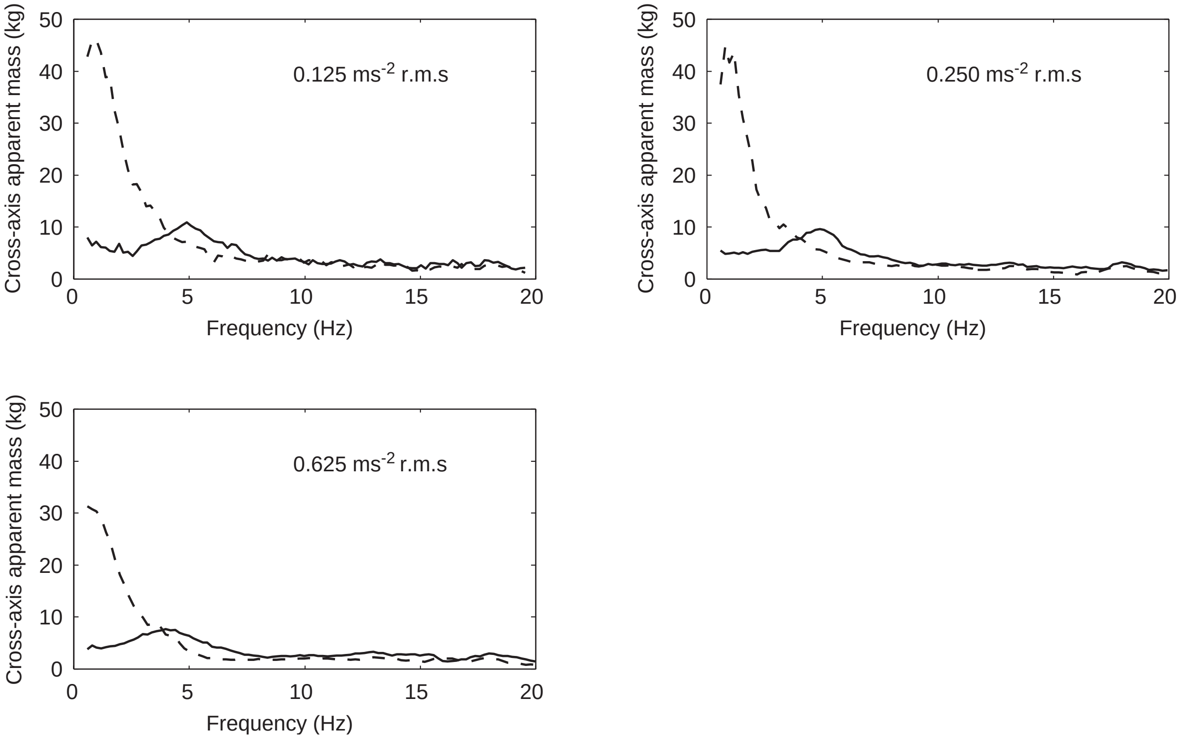

Fig. 16. Median vertical cross-axis apparent masses at the feet of six subjects: effect of backrest. —, with backrest; – – – –, without backrest.

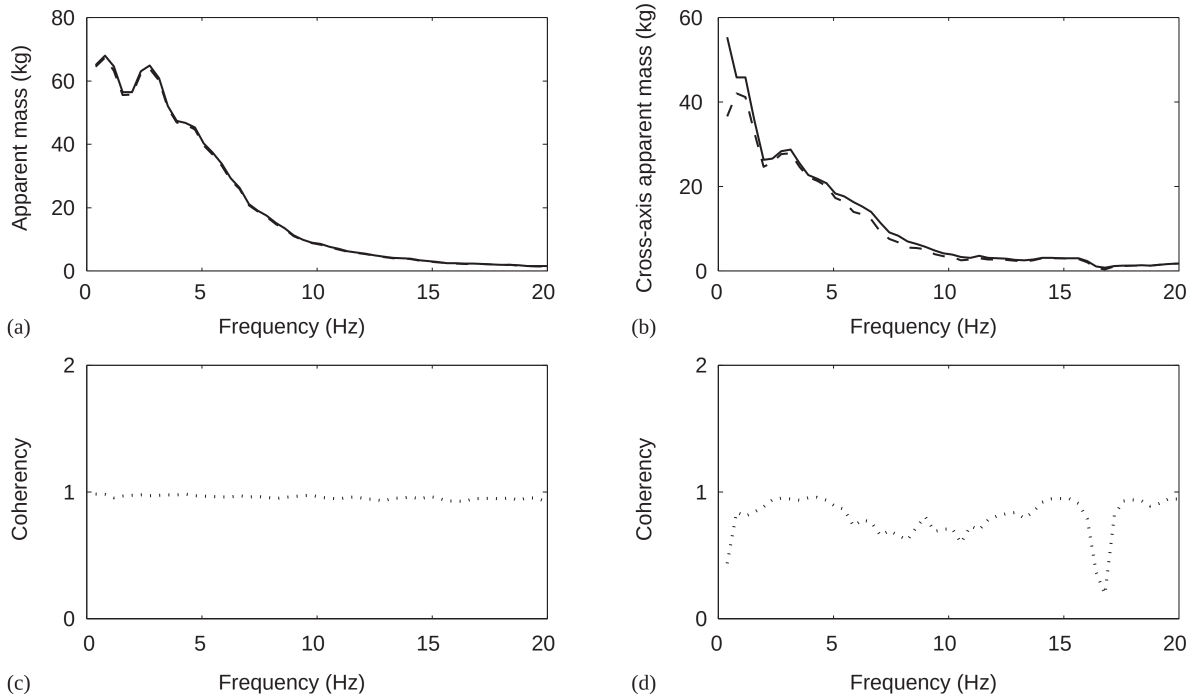

Fig. 17. Apparent mass, cross-axis apparent mass, and coherences of one subject at 0.625 m s^{-2} rms with the minimum thigh contact posture. (a) Apparent mass in the fore-and-aft direction, (b) cross-axis apparent mass in the vertical direction, (c) coherency in the fore-and-aft direction, (d) coherency in the vertical direction. —, PSD method; – – – –, CSD method; ……, coherency.

compressive forces predicted by Fritz [13] for a biomechanical model of responses to fore-and-aft vibration.

Using the same conditions as in this study, but with vertical vibration, Nawayseh and Griffin [8] and Nawayseh and Griffin [9] found high fore-and-aft forces on the seat with a peak at about 5 Hz in all four postures. The high forces were attributed to bending and rotational modes in the upper body. Only the vertical forces measured with the feet hanging posture in the present study are similar to the fore-and-aft forces obtained by Nawayseh and Griffin [8] and Nawayseh and Griffin [9] during vertical vibration. When the feet were supported, there were high vertical forces at frequencies lower than 5 Hz, which might have masked the peak in the vertical cross-axis apparent mass at 5 Hz in some subjects. Any swinging of the feet when they are not supported might primarily affect fore-and-aft forces on the seat. When the feet are supported on a footrest, the subjects may stabilise their body by exerting greater force on the footrest when moving forward and greater force on the seat when moving backward. Some subjects reported difficulty in preventing themselves from sliding on the seat when the body was less supported and said they needed to push down on the footrest to prevent sliding.

At 2 and 5 Hz, the vertical forces may have been caused by modes similar to the fore-and-aft forces presented by Nawayseh and Griffin [8] for vertical vibration. With the feet hanging, the response in the vertical direction resembles transmissibilities from fore-and-aft seat vibration to vertical and pitch vibration at the head, where resonances around 2 Hz and between 6 and 10 Hz have been reported [14]. Using a biodynamic model with rotational capability, Matsumoto and Griffin [15] obtained three pitch modes: around 2.5 Hz (pitching motion of the pelvis together with a bending mode of the spine), 5.7 Hz (bending of the spine) and 8.6 Hz (bending in the spine). From experimental data with vertical seat vibration, Matsumoto and Griffin [16] also determined rotational modes in the range 5–7 Hz for pitch motion of the head and motion of first thoracic vertebra. Since the pitch modes occur in the mid-sagittal plane (the x–z) plane, it is reasonable that the same rotational modes are obtained during vertical and fore-and-aft vibration. However, a full explanation of the forces in the vertical direction must await experimental studies of transmissibility from fore-and-aft seat vibration to parts of the body and the development of biodynamic models describing the motion of the human body caused by fore-and-aft excitation.

4.4. *Response at the feet*

Previous studies (e.g. Refs. [8,17]) found that during vertical vibration, the response at the feet is complex, with multiple resonances that vary with posture. Kitazaki [17] compared the response of the feet with whole-body vertical vibration with the response when only the feet were excited. There were similar response characteristics in both conditions, but the apparent mass of the feet during whole-body vibration was higher than when only the feet were excited. This indicates that some of the forces measured at the feet came from forces transmitted from the upper body down the legs to the feet. No previous study has reported biodynamic responses at the feet with horizontal vibration.

With and without a backrest, the fore-and-aft apparent mass at the feet showed a peak in the frequency range 3–5 Hz. At the same vibration magnitude, the resonance frequency and the apparent mass at resonance increased when using a backrest (Fig. 12), showing a similar trend to the effect of a backrest on the apparent mass of seated subjects during fore-and-aft vibration (Fairley and Griffin [3]). At frequencies below resonance, the fore-and-aft apparent mass at the feet is less with a backrest than without a backrest, showing another trend similar to the effect of a backrest on the fore-and-aft apparent mass of seated subjects [3,18]. This shows that the response at the feet is affected by the posture of the upper body: when a subject leans against a backrest, the upper body is restrained from swaying backward and forward, so reducing the force on the legs arising from the motion.

The vertical cross-axis apparent mass at the feet also depended on the presence of a backrest. The high vertical cross-axis apparent mass at the feet at low frequencies (Fig. 13) is consistent with the explanation for the high forces in the vertical direction on the seat: the subjects may have applied forces in the vertical direction on the footrest when they pitched forward and applied vertical forces on the seat when they pitched backward. The decrease in the vertical forces at low frequencies at the feet when using a backrest is similar to the decrease in the vertical forces measured at the seat when a backrest was used during fore-and-aft vibration [18].

5. Conclusion

The apparent mass responses of seated subjects to fore-and-aft vibration suggest three modes: a mode around 1 Hz, a mode between 1 and 3 Hz, and a mode between 3 and 5 Hz. The three modes varied between subjects, and depended on the vibration magnitude and the sitting posture.

Fore-and-aft vibration caused considerable vertical forces at the seat and at the footrest. The vertical forces are assumed to arise from pitching of all or parts of the upper body. At the seat and at the footrest, the vertical forces were influenced by sitting posture: with increasing height of the footrest, the vertical forces on the seat increased at low frequency; when a backrest was used, the vertical forces on the footrest decreased at low frequencies.

On the seat and the footrest, the dynamic responses in all directions showed a nonlinear behaviour. The extent of the nonlinearity depended on the posture, the vibration frequency, measurement location and direction.

Appendix A

Peak frequencies in apparent masses of 12 subjects are given in Tables 4–7.

Table 4
Peak frequencies in the apparent masses of 12 subjects adopting the feet hanging posture and exposed to horizontal vibration at four vibration magnitudes

Subject	Vibration magnitude ($m s^{-2}$ rms)	Mode 1 (below 1 Hz)	Mode 2 (between 1 and 3 Hz)	Mode 3 (above 3 Hz)
1	0.125	0.39	1.95	3.91
	0.250	0.78	1.56, 2.73	4.49
	0.625	0.98	2.54	—
	1.250	—	1.17, 1.95	—
2	0.125	0.98	1.76, 2.54	4.69, 6.25, 8.00
	0.250	0.98	2.34	4.10
	0.625	0.59	1.17	5.27
	1.250	0.78	—	4.69
3	0.125	0.98	2.15	3.13, 6.05
	0.250	0.98	1.95, 2.73	5.47
	0.625	0.59	1.17, 2.73	4.69
	1.250	—	1.17, 2.34	—
4	0.125	0.78	1.95	4.49, 7.23
	0.250	0.78	1.56, 2.34	7.23
	0.625	0.59	1.17, 2.15	6.25
	1.250	0.98	2.15	5.66
5	0.125	0.98	2.34	4.49
	0.250	0.78	1.76	3.32
	0.625	0.98	—	3.32
	1.250	—	1.17	—
6	0.125	0.98	1.95	4.69
	0.250	0.98	1.76	3.71
	0.625	—	1.37	—
	1.250	—	1.17	—

Table 4 (*continued*)

Subject	Vibration magnitude ($m\,s^{-2}$ rms)	Mode 1 (below 1 Hz)	Mode 2 (between 1 and 3 Hz)	Mode 3 (above 3 Hz)
7	0.125	0.78	1.95	5.08, 7.81
	0.250	0.78	1.56	4.30
	0.625	0.59	1.17, 2.93	
	1.250	0.98	2.54	
8	0.125	0.78	2.15	4.69
	0.250	0.78	2.15	5.08
	0.625	—	1.17, 2.73	—
	1.250	—	1.17, 2.73	—
9	0.125	0.98	2.34	4.69, 5.86
	0.250	0.98	1.95	5.08
	0.625	—	1.17	3.32
	1.250	—	1.17	—
10	0.125	—	1.17, 1.76	5.08
	0.250	—	1.17	—
	0.625	0.98	—	—
	1.250	0.98	—	—
11	0.125	0.59	1.76	4.30
	0.250	—	1.17, 2.54	3.52
	0.625	0.98	1.95, 2.73	—
	1.250	0.78	1.76	—
12	0.125	0.39	1.37, 2.73	3.52
	0.250	0.39	1.37, 2.34	—
	0.625	0.98	2.15	—
	1.250	0.78	1.95	—

Frequency resolution is 0.195 Hz.

Table 5
Peak frequencies in the apparent masses of 12 subjects adopting the maximum thigh contact posture and exposed to horizontal vibration at four vibration magnitudes

Subject	Vibration magnitude ($m\,s^{-2}$ rms)	Mode 1 (below 1 Hz)	Mode 2 (between1 and 3 Hz)	Mode 3 (above 3 Hz)
1	0.125	0.78	2.73	4.88
	0.250	0.39	2.93	—
	0.625	—	2.73	—
	1.250	—	2.34	—
2	0.125	0.98	2.54	4.30
	0.250	0.78	2.34	4.10
	0.625	—	—	3.13
	1.250	—	2.73	—

Table 5 (*continued*)

Subject	Vibration magnitude ($m\,s^{-2}$ rms)	Mode 1 (below 1 Hz)	Mode 2 (between1 and 3 Hz)	Mode 3 (above 3 Hz)
3	0.125	0.98	2.93	5.66
	0.250	0.59	2.93	5.08
	0.625	0.78	2.73	4.10
	1.250	—	2.93	—
4	0.125	—	1.17, 2.73	5.47, 7.42
	0.250	0.78	2.93	5.47
	0.625	—	2.34	4.88
	1.250	—	2.34	4.30
5	0.125	0.78	2.93	4.69
	0.250	0.78	2.93	—
	0.625	0.59	2.34	—
	1.250	0.98	1.95	—
6	0.125	0.78	1.95	4.88
	0.250	0.78	—	4.10
	0.625	0.78	—	3.13
	1.250	—	2.34	—
7	0.125	0.78	2.54	5.27
	0.250	0.59	2.73	4.88
	0.625	—	—	4.10
	1.250	—	2.93	—
8	0.125	0.98	—	3.13, 5.27
	0.250	0.98	—	3.13, 4.69
	0.625	0.78	—	3.13
	1.250	0.78	2.54	—
9	0.125	0.98	—	3.13, 6.05
	0.250	0.39	—	3.13, 5.08
	0.625	0.78	—	3.13
	1.250	0.78	2.15, 2.93	—
10	0.125	0.78	2.54	3.91
	0.250	0.98	2.93	3.52
	0.625	0.78	2.34	—
	1.250	0.78	1.76	—
11	0.125	0.59	2.34	3.32
	0.250	0.78	2.34	3.52
	0.625	—	2.54	—
	1.250	—	2.15	—
12	0.125	0.39	2.73	—
	0.250	0.39	2.34	—
	0.625	—	2.15	—
	1.250	0.78	1.76	—

Frequency resolution is 0.195 Hz.

Table 6
Peak frequencies in the apparent masses of 12 subjects adopting the average thigh contact posture and exposed to horizontal vibration at four vibration magnitudes

Subject	Vibration magnitude ($m\,s^{-2}$ rms)	Mode 1 (below 1 Hz)	Mode 2 (between1 and 3 Hz)	Mode 3 (above 3 Hz)
1	0.125	0.98	2.93	—
	0.250	0.78	2.34	—
	0.625	0.59	2.34	—
	1.250	—	1.95	—
2	0.125	—	1.37, 2.34	4.88
	0.250	—	1.17, 2.15	4.69
	0.625	0.59	—	—
	1.250	—	—	—
3	0.125	—	1.17, 2.93	5.86
	0.250	0.98	2.93	5.08
	0.625	0.59	2.73	4.69
	1.250	—	2.54	—
4	0.125	—	1.17, 2.54	4.69
	0.250	0.98	2.73	4.88
	0.625	0.78	2.15	—
	1.250	0.78	2.15	—
5	0.125	—	1.17, 2.93	—
	0.250	0.78	2.73	—
	0.625	0.78	2.15	—
	1.250	0.98	1.76	—
6	0.125	0.98	—	4.49
	0.250	0.98	—	3.91
	0.625	—	2.73	—
	1.250	—	1.17, 2.54	—
7	0.125	0.98	—	4.30
	0.250	0.78	—	4.10
	0.625	0.59	2.34	—
	1.250	0.59	1.95	—
8	0.125	0.78	—	3.13, 5.08
	0.250	0.78	2.93	4.49
	0.625	—	—	3.32
	1.250	0.78	—	3.13
9	0.125	—	1.17, 2.93	5.47
	0.250	0.98	2.93	5.08
	0.625	0.78	2.34	—
	1.250	0.78	1.76	4.10
10	0.125	0.98	—	3.52
	0.250	0.98	2.54	—
	0.625	0.78	2.15	—
	1.250	0.98	—	—

Table 6 (*continued*)

Subject	Vibration magnitude ($m\,s^{-2}$ rms)	Mode 1 (below 1 Hz)	Mode 2 (between1 and 3 Hz)	Mode 3 (above 3 Hz)
11	0.125	—	2.73	—
	0.250	0.39	2.54	—
	0.625	—	2.15	—
	1.250	—	1.76	—
12	0.125	0.59	2.34	—
	0.250	0.39	1.95	—
	0.625	—	1.76	—
	1.250	0.78	1.76	—

Frequency resolution is 0.195 Hz.

Table 7
Peak frequencies in the apparent masses of 12 subjects adopting the minimum thigh contact posture and exposed to horizontal vibration at four vibration magnitudes

Subject	Vibration magnitude ($m\,s^{-2}$ rms)	Mode 1 (below 1 Hz)	Mode 2 (between1 and 3 Hz)	Mode 3 (above 3 Hz)
1	0.125	0.78	2.54	—
	0.250	0.59	2.40	—
	0.625	0.59	2.34	—
	1.250	—	1.76	—
2	0.125	—	1.76	5.27
	0.250	—	1.56	4.88
	0.625	—	1.17	3.91
	1.250	—	1.17	4.30
3	0.125	—	1.37	3.32, 6.04
	0.250	0.98	2.93	4.88
	0.625	0.78	2.73	—
	1.250	—	1.17, 2.54	—
4	0.125	—	1.17, 2.54	4.88
	0.250	—	1.17, 2.34	4.69
	0.625	0.98	2.15	—
	1.250	0.98	—	—
5	0.125	—	1.56	3.32
	0.250	—	1.37	3.32
	0.625	—	1.17	3.32
	1.250	—	1.17	—
6	0.125	—	—	—
	0.250	0.98	2.15	3.71
	0.625	0.78	1.95	3.32
	1.250	0.78	2.73	—

Table 7 (*continued*)

Subject	Vibration magnitude ($m\,s^{-2}$ rms)	Mode 1 (below 1 Hz)	Mode 2 (between1 and 3 Hz)	Mode 3 (above 3 Hz)
7	0.125	—	—	—
	0.250	0.78	2.15	3.32
	0.625	0.78	2.34	3.91
	1.250	0.78	2.54	—
8	0.125	—	—	—
	0.250	—	1.56, 2.73	5.47
	0.625	—	1.38, 2.73	—
	1.250	—	1.17, 2.93	—
9	0.125	—	1.56	—
	0.250	—	1.17	—
	0.625	—	1.17,2.93	—
	1.250	0.78	1.95	—
10	0.125	0.98	—	—
	0.250	—	1.17, 2.54	—
	0.625	0.78	1.95	—
	1.250	—	1.17	—
11	0.125	—	2.15	—
	0.250	—	2.34	—
	0.625	—	1.76	—
	1.250	—	1.76	—
12	0.125	0.98	2.73	—
	0.250	0.98	2.34	—
	0.625	0.78	2.15	—
	1.250	0.78	1.76	—

Frequency resolution is 0.195 Hz.

Appendix B

Peak frequencies and magnitudes in the vertical cross-axis apparent masses of 12 subjects are given in Tables 8–11.

Table 8
Peak frequencies and magnitudes in the vertical cross-axis apparent masses of 12 subjects adopting the feet hanging posture and exposed to horizontal vibration at four vibration magnitudes. f: frequency; mag: magnitude

Subject	Vibration magnitude ($m\,s^{-2}$ rms)	f1, mag1	f2, mag2	f3, mag3
1	0.125	2.93, 8.2	4.88, 18.6	9.18, 14.8
	0.250	2.93, 8.7	4.49, 11.6	8.59, 14.1
	0.625	—	4.10, 7.9	7.42, 6.24
	1.250	3.52, 7.2	—	—

Table 8 (*continued*)

Subject	Vibration magnitude ($m\,s^{-2}$ rms)	f1, mag1	f2, mag2	f3, mag3
2	0.125	3.71, 13.6	6.45, 43.1	—
	0.250	2.92, 9.5	5.47, 33.5	—
	0.625	—	4.88, 21.2	—
	1.250	—	4.30, 18.3	—
3	0.125	3.13, 7.7	7.42, 21.0	—
	0.250	3.13, 7.7	7.23, 15.5	—
	0.625	2.93, 7.3	—	—
	1.250	—	6.05, 5.8	—
4	0.125	2.93, 7.2	7.62, 51.8	—
	0.250	2.93, 13.0	7.23, 29.3	—
	0.625	2.93, 13.0	4.88, 18.6	—
	1.250	—	4.30, 18.5	—
5	0.125	2.34, 13.7	6.05, 36.2	—
	0.250	1.95, 8.5	5.66, 31.9	—
	0.625	—	5.08, 30.1	—
	1.250	—	4.88, 27.6	—
6	0.125	2.54, 7.2	5.86, 28.4	—
	0.250	—	5.66, 24.8	—
	0.625	—	5.47, 17.6	—
	1.250	—	4.10, 17.9	—
7	0.125	—	6.05, 12.8	7.81, 16.4
	0.250	—	4.88, 12.4	7.23, 16.8
	0.625	—	—	6.25, 12.7
	1.250	—	3.52, 9.5	5.47, 12.2
8	0.125	2.93, 6.7	6.45, 24.8	—
	0.250	—	5.08, 16.4	—
	0.625	—	5.66, 12.0	—
	1.250	—	5.66, 10.3	—
9	0.125	2.73, 8.9	7.03, 32.3	—
	0.250	2.54, 7.1	6.84, 28.1	—
	0.625	—	5.47, 20.8	—
	1.250	—	5.27, 14.0	—
10	0.125	2.93, 17.7	6.25, 28.1	—
	0.250	—	5.08, 26.3	—
	0.625	—	4.49, 19.3	—
	1.250	—	4.30, 14.5	—
11	0.125	2.73, 10.1	7.03, 22.8	—
	0.250	—	5.86, 18.6	—
	0.625	—	4.69, 11.8	—
	1.250	2.15, 5.7	4.69, 10.0	—
12	0.125	1.37, 9.5	5.27, 28.9	—
	0.250	3.71, 18.9	5.66, 26.2	—
	0.625	—	3.91, 25.3	—
	1.250	—	4.10, 25.6	—

Frequency resolution is 0.195 Hz.

Table 9
Peak frequencies and magnitudes in the vertical cross-axis apparent masses of 12 subjects adopting the maximum thigh contact posture and exposed to horizontal vibration at four vibration magnitudes. f: frequency; mag: magnitude

Subject	Vibration magnitude (m s^{-2} rms)	f1, mag1	f2, mag2	f3, mag3
1	0.125	0.98, 26.2	3.71, 21.8	—
	0.250	—	3.71, 18.5	—
	0.625	—	2.93, 15.6	—
	1.250	—	2.54, 16.8	—
2	0.125	0.98, 60.4	2.93, 27.2	5.47, 53.3
	0.250	0.78, 53.5	2.73, 25.9	5.27, 47.0
	0.625	—	—	4.30, 34.9
	1.250	—	—	4.10, 30.7
3	0.125	0.98, 22.5	3.13, 19.9	—
	0.250	0.98, 15.8	3.13, 18.6	5.66, 16.9
	0.625	—	3.32, 15.5	—
	1.250	—	3.32, 13.0	—
4	0.125	1.17, 56.3	3.32, 35.6	7.42, 52.1
	0.250	0.98, 45.0	3.13, 30.8	6.64, 34.7
	0.625	—	2.73, 37.6	5.66, 27.6
	1.250	—	2.54, 30.6	—
5	0.125	0.98, 68.5	3.32, 33.4	5.86, 35.4
	0.250	0.98, 51.3	2.93, 33.8	4.88, 32.3
	0.625	0.98, 31.3	2.54, 29.3	4.10, 28.9
	1.250	0.98, 26.8	1.95, 29.1	4.10, 27.2
6	0.125	0.98, 29.7	—	5.66, 29.7
	0.250	0.78, 25.3	—	5.08, 28.0
	0.625	0.98, 21.1	—	4.10, 22.6
	1.250	—	—	4.10, 22.2
7	0.125	0.98, 20.0	—	5.08, 22.5
	0.250	0.78, 16.8	3.13, 14.65	4.88, 22.4
	0.625	0.59, 15.3	—	4.10, 19.8
	1.250	0.78, 11.6	3.13, 18.4	—
8	0.125	1.17, 27.8	3.52, 16.9	5.66, 27.3
	0.250	0.98, 21.5	—	5.08, 21.2
	0.625	0.78, 19.2	—	4.10, 17.4
	1.250	0.78, 9.8	—	4.30, 11.2
9	0.125	0.98, 31.7	3.32, 36.9	5.66, 31.4
	0.250	0.98, 20.1	3.13, 32.4	4.88, 28.8
	0.625	0.98, 19.0	—	4.69, 26.4
	1.250	0.78, 12.6	—	4.30, 24.2
10	0.125	1.17, 34.9	3.71, 21.4	4.3, 25.5
	0.250	0.98, 36.8	3.32, 23.3	—
	0.625	0.98, 24.9	2.73, 18.7	—
	1.250	—	—	—

Table 9 (*continued*)

Subject	Vibration magnitude (m s^{-2} rms)	f1, mag1	f2, mag2	f3, mag3
11	0.125	—	3.91, 25.3	—
	0.250	—	3.71, 24.2	—
	0.625	—	3.32, 18.9	—
	1.250	—	2.15, 14.6	—
12	0.125	—	2.93, 35.7	—
	0.250	—	2.34, 31.0	—
	0.625	—	2.15, 30.6	—
	1.250	—	1.95, 26.7	—

Frequency resolution is 0.195 Hz.

Table 10
Peak frequencies and magnitudes in the vertical cross-axis apparent masses of 12 subjects adopting the average thigh contact posture and exposed to horizontal vibration at four vibration magnitudes. f: frequency; mag: magnitude

Subject	Vibration magnitude (m s^{-2} rms)	f1, mag1	f2, mag2	f3, mag3
1	0.125	0.98, 48.4	2.93, 23.5	—
	0.250	0.78, 34.2	2.34, 22.5	—
	0.625	—	2.54, 12.7	—
	1.250	—	2.15, 11.4	—
2	0.125	1.37, 74.2	2.54, 39.5	5.08, 40.8
	0.250	1.17, 63.7	2.54, 34.4	4.88, 37.1
	0.625	0.78,53.2	—	4.30, 31.2
	1.250	—	—	—
3	0.125	1.17, 60.2	3.32, 21.6	6.25, 15.7
	0.250	0.98, 41.0	3.32, 17.3	—
	0.625	0.59, 25.3	2.93, 13.9	—
	1.250	—	2.34, 9.65	—
4	0.125	1.17, 65.9	3.13, 35.4	—
	0.250	1.17, 68.8	2.93, 33.4	—
	0.625	0.78, 50.5	—	—
	1.250	0.78, 46.5	—	—
5	0.125	1.17, 87.1	—	—
	0.250	0.98, 69.1	2.73, 32.4	—
	0.625	0.98, 58.7	2.54, 27.4	—
	1.250	0.98, 50.1	—	—
6	0.125	1.17, 44.1	—	4.88, 27.3
	0.250	0.98, 40.3	—	5.08, 24.2
	0.625	0.98, 30.0	—	4.10, 23.0
	1.250	0.59, 31.7	—	—
7	0.125	0.98, 53.2	—	4.88, 16.7
	0.250	0.98, 48.0	—	—

Table 10 (*continued*)

Subject	Vibration magnitude (m s^{-2} rms)	f1, mag1	f2, mag2	f3, mag3
	0.625	0.59, 47.2	—	—
	1.250	—	—	—
8	0.125	0.98, 41.3	3.32, 19.8	—
	0.250	0.98, 43.3	3.52, 16.8	—
	0.625	—	—	—
	1.250	1.37, 26.5	—	—
9	0.125	1.37, 71.9	3.13, 39.5	—
	0.250	0.98, 58.4	3.32, 30.5	—
	0.625	1.17, 43.2	2.93, 28.4	—
	1.250			
10	0.125	1.37, 53.3	—	—
	0.250	1.17, 40.9	2.93, 25.3	—
	0.625	0.98, 37.2	—	—
	1.250	0.98, 41.7	—	—
11	0.125	—	2.15, 28.2	—
	0.250	—	2.54, 27.8	—
	0.625	—	2.34, 18.1	—
	1.250	—	1.75, 17.6	—
12	0.125	—	2.15, 27.2	—
	0.250	—	2.34, 29.8	—
	0.625	—	1.95, 25.7	—
	1.250		1.56, 22.2	—

Frequency resolution is 0.195 Hz.

Table 11
Peak frequencies and magnitudes in the vertical cross-axis apparent masses of 12 subjects adopting the minimum thigh contact posture and exposed to horizontal vibration at four vibration magnitudes. f: frequency; mag: magnitude

Subject	Vibration magnitude (m s^{-2} rms)	f1, mag1	f2, mag2	f3, mag3
1	0.125	0.98, 63.2	2.15, 32.4	—
	0.250	0.98, 47.1	2.93, 23.7	—
	0.625	0.78, 36.6	2.54, 18.8	—
	1.250	1.37, 23.4	—	—
2	0.125	1.76, 108.1	—	4.10, 37.1
	0.250	1.56, 132.9	—	4.49, 42.6
	0.625	1.17, 82.4	—	—
	1.250	0.98, 67.4	—	—
3	0.125	1.37, 85.0	3.32, 39.4	—
	0.250	1.17, 67.1	3.32, 28.7	—
	0.625	0.98, 46.4	2.93, 29.3	—
	1.250	1.17, 32.8	—	—

Table 11 (*continued*)

Subject	Vibration magnitude (m s^{-2} rms)	f1, mag1	f2, mag2	f3, mag3
4	0.125	1.17, 71.0	2.73, 41.0	—
	0.250	1.17, 81.0	2.34, 39.7	—
	0.625	0.98, 81.9	—	—
	1.250	0.98, 78.3	—	—
5	0.125	1.56, 155.3	3.32, 33.7	—
	0.250	1.37, 122.3	—	—
	0.625	1.17, 105.2	—	—
	1.250	1.37, 86.1	—	—
6	0.125	1.17, 48.2	2.15, 32.1	—
	0.250	0.98, 46.9	2.34, 30.6	4.88, 33.4
	0.625	—	3.32, 31.1	—
	1.250	—	2.73, 25.5	—
7	0.125	1.17, 60.55	3.13, 37.0	—
	0.250	1.17, 56.7	3.32, 36.3	—
	0.625	0.78, 57.8	—	—
	1.250	0.98, 49.4	—	—
8	0.125	1.37, 50.2	—	—
	0.250	1.56, 48.6	—	—
	0.625	1.56, 42.5	—	—
	1.250	1.37, 34.6	—	—
9	0.125	1.56, 63.9	—	4.69, 45.9
	0.250	1.56, 49.6	—	4.30, 40.9
	0.625	1.17, 41.8	—	—
	1.250	1.17, 39.0	—	—
10	0.125	0.98, 53.7	—	7.81, 28.5
	0.250	1.17, 57.5	—	7.03, 23.6
	0.625	0.78, 58.2	—	—
	1.250	1.17, 41.4	—	—
11	0.125	—	2.54, 41.8	—
	0.250	—	2.34, 32.6	—
	0.625	1.56, 27.6	—	—
	1.250	1.76, 29.8	—	—
12	0.125	0.98, 134.9	—	—
	0.250	0.98, 129.3	—	—
	0.625	0.78, 113.1	—	—
	1.250	0.78, 109.4	—	—

Frequency resolution is 0.195 Hz.

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