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Tri-axial forces at the seat and backrest during whole-body fore-and-aft vibration

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Abstract

The fore-and-aft, lateral and vertical forces on a seat and a backrest have been investigated with 12 male subjects exposed to random fore-and-aft whole-body vibration (0.25–10 Hz) at four vibration magnitudes (0.125, 0.25, 0.625, and 1.25 $\mathrm{m\,s^{-2}}$ rms). Subjects sat in each of four sitting postures having varying foot heights, so as to produce differing thigh contact with the seat.

The fore-and-aft forces on the seat depended on whether the feet were supported on a footrest: peaks were found at two frequencies when the feet were not supported, compared to only one peak when the feet were supported. The fore-and-aft forces at the backrest were high, with their peak magnitudes correlated with subject mass. Vertical forces were high on the seat but not on the backrest. Lateral forces were relatively low on both the seat and the backrest. In all directions, forces on the seat and the backrest showed a nonlinear behaviour.

In comparison with a previous study undertaken with no backrest, it was found that the backrest reduced forces on the seat at low frequencies (in the fore-and-aft and vertical directions) but increased these forces at high frequencies.

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1. Introduction

Exposure of the body to oscillatory motion in one direction can give rise to forces (called cross-axis forces) in another direction. Appreciable cross-axis forces in the fore-and-aft direction have been reported on the seat and backrest during exposure of subjects to vertical vibration [1–3]. There are also high vertical cross-axis forces on the seat during exposure to fore-and-aft vibration [4]. The high cross-axis forces suggest that there is two-dimensional movement of the seated human body when it is exposed to single-axis vibration in either the vertical or fore-and-aft direction.

The use of a backrest has been found to affect the apparent mass of the body during fore-and-aft vibration (e.g. Ref. [5]), and both the apparent mass and fore-and-aft cross-axis apparent mass during exposure to vertical vibration [3]. While three vibration modes were found in the fore-and-aft apparent masses of subjects sitting without a backrest, only one vibration mode was evident in the apparent mass calculated from forces measured at the seat and backrest when there was also motion applied to the back [5]. During vertical vibration, the frequency of the principal resonance around 5 Hz increased when using a backrest [3,6]. Also with vertical vibration, there are significant differences in the fore-and-aft cross-axis apparent mass measured on a seat with and without a backrest in a maximum thigh contact posture and in a feet hanging posture [3]. Transmissibilities to the head during vertical and fore-and-aft vibration are also modified, especially for motions in the mid-sagittal plane, when a backrest is used [7,8].

Although backrests modify the vibration responses of the seated body, there are no known studies of the forces on backrests during horizontal (i.e. fore-and-aft or lateral) vibration. The present study investigated tri-axial (i.e. fore-aft, lateral and vertical) forces at the seat and the back during fore-and-aft whole-body vibration. It was expected that considerable forces would be found in the fore-and-aft direction on the seat and backrest. It was also anticipated that high forces would be found in the vertical direction on the seat, with low vertical forces on the backrest and low lateral forces on both the seat and backrest. It was hypothesised that the addition of a backrest would modify the fore-aft, lateral and vertical forces previously measured on a seat without a backrest [4].

2. Apparatus, experimental design and analysis

2.1. Apparatus

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 with a rigid vertical backrest and an adjustable footrest (to give different foot heights) were mounted on the platform of the vibrator (Fig. 1). A force plate (Kistler 9281 B) capable of measuring forces in three directions simultaneously was secured to the supporting surface of the seat in order to measure forces in the vertical, fore-and-aft and lateral directions. Another force plate (Kistler Z 13053) was bolted to the backrest so as to measure forces at the back in the fore-and-aft direction (see Fig. 1). The forces at the back in the vertical and lateral directions were also measured for one subject using the Kistler 9281 B force platform. A description of the force plates can be found in [2]. Signals

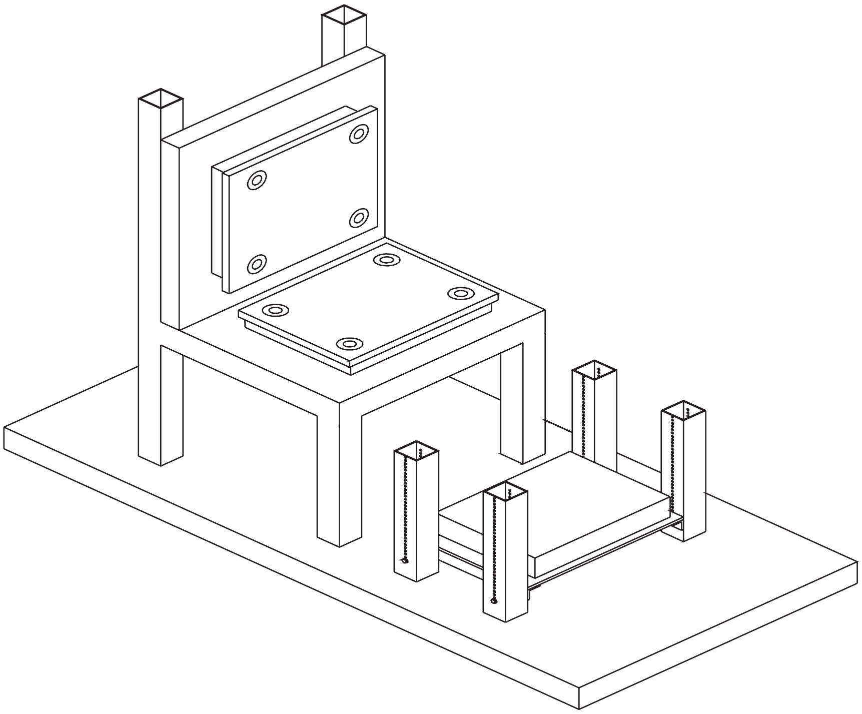

Fig. 1. The seat and the force measurement locations.

from the force platforms were amplified using Kistler 5007 charge amplifiers. Acceleration in the fore-and-aft direction was measured at the centre of the force platforms using piezo-resistive accelerometers (Entran EGCSY-240D-10). The signs of the fore-and-aft acceleration and fore-and-aft forces on both the seat and backrest 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 sampled 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

Twelve male subjects, with average age 30.8 years (range 24–47 years), weight 76.1 kg (range 63–103 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 0.25–10 Hz. Four different sitting postures were used (Fig. 2). The four postures were the same as those previously investigated by Nawayseh and Griffin [3]: (i) 'feet hanging' with no foot support, (ii) feet supported with 'maximum thigh contact' (i.e. heels just in contact with the 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 postures were achieved solely by

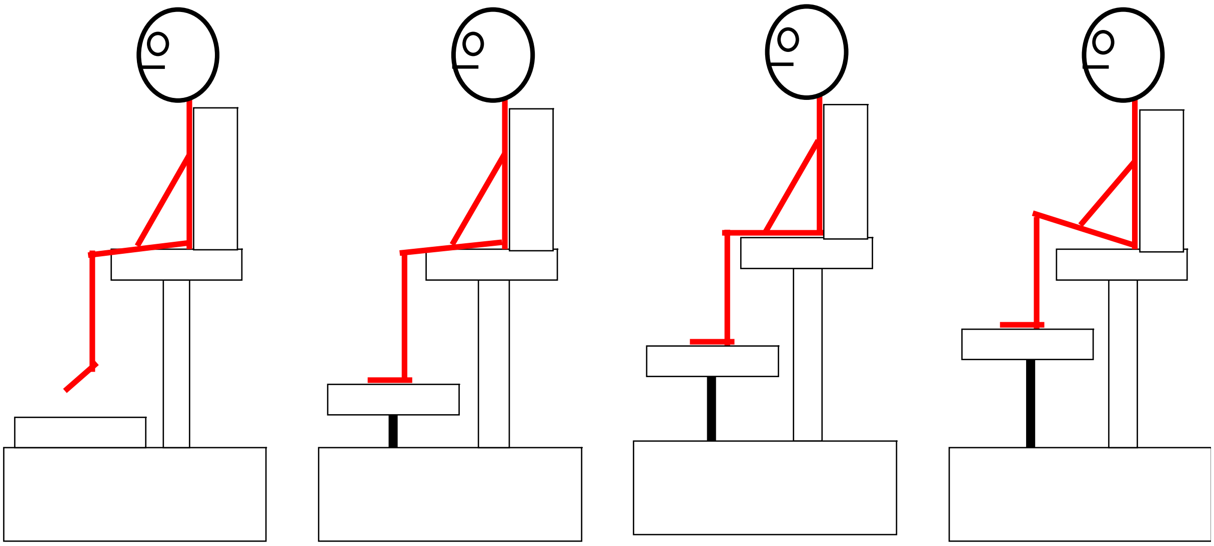

Fig. 2. Schematic diagrams of the four sitting postures: (a) feet hanging; (b) maximum thigh contact; (c) average thigh contact; and (d) minimum thigh contact.

altering the height of the footrest. The footrest was exposed to the same fore-and-aft vibration as the seat.

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

2.3. Analysis

The data are partly presented as apparent masses in the fore-and-aft direction, calculated from the fore-and-aft force and fore-and-aft acceleration at the seat and backrest. The forces in the vertical and lateral directions measured on the seat for 12 subjects, and on the back for one subject, were related to the acceleration measured on the seat or backrest in the fore-and-aft direction using the concept of 'cross-axis apparent mass'. The apparent mass and the cross-axis apparent mass were calculated using the cross-spectral density (CSD) method with frequency resolution of 0.195 Hz:

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

where $M(\omega)$ is the apparent mass (or the cross-axis apparent mass), $S_{af}(\omega)$ is the CSD between the force and the acceleration, and $S_{aa}(\omega)$ is the power spectral density (PSD) of the acceleration.

To calculate the apparent masses of subjects in the fore-and-aft direction, the forces due to the masses of the aluminium plates of the force platforms 'above' the force transducers were subtracted from the total measured masses (mass of the subject and plate) in the frequency domain: the real and imaginary parts of the transfer function measured without a subject were subtracted from the real and imaginary parts of the transfer functions obtained with subjects. To calculate the coherency between fore-and-aft force and acceleration, the subtraction was performed in the time domain.

3. Results

3.1. Responses in the fore-and-aft direction

3.1.1. Response on the seat

High inter-subject variability was found in the responses of the 12 subjects, with a tendency towards less variability at higher vibration magnitudes (Fig. 3). In all postures, the average coefficient of variation, defined as the average of the ratios of the standard deviations to the means calculated at each frequency, showed a higher variability at $0.125\,\mathrm{m\,s^{-2}}$ rms than at $1.25\,\mathrm{m\,s^{-2}}$ rms.

In all postures, there was a peak in the fore-and-aft apparent mass on the seat in the frequency range 2–6 Hz (depending on the subject and vibration magnitude). An additional peak in the frequency range 1–2 Hz was found only in the feet hanging posture (Fig. 3). In all postures, both the median and the individual data showed a decreased resonance frequency and decreased apparent mass magnitude at resonance with increasing vibration magnitude (see Figs. 4 and 5)

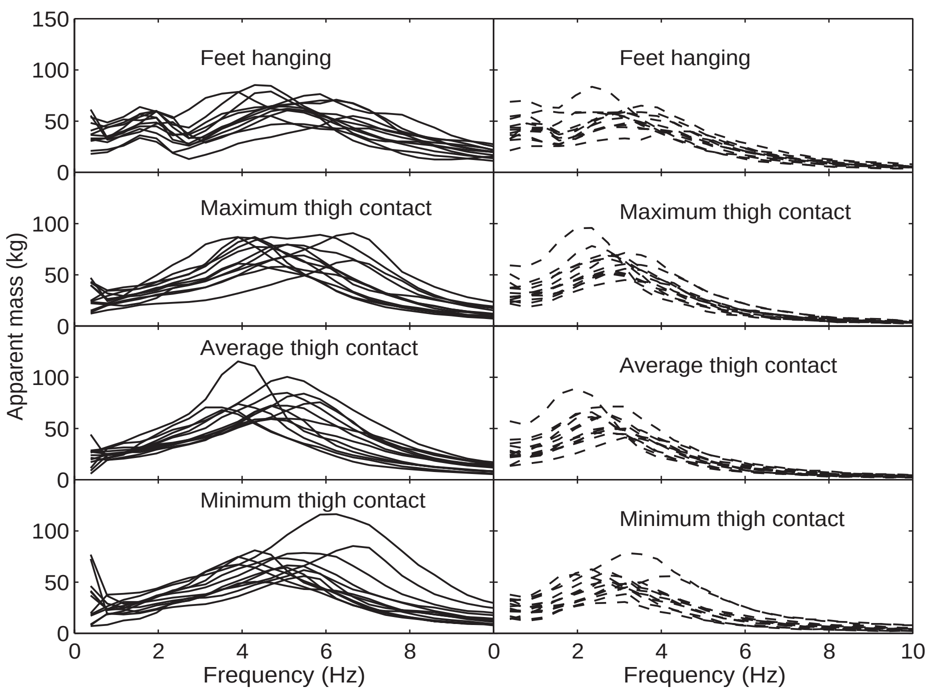

Fig. 3. Inter-subject variability in the fore-and-aft apparent mass on the seat for each posture at two vibration magnitudes. (—) $0.125\,\mathrm{m\,s^{-2}}$ rms; and (– – –) $1.25\,\mathrm{m\,s^{-2}}$ rms.

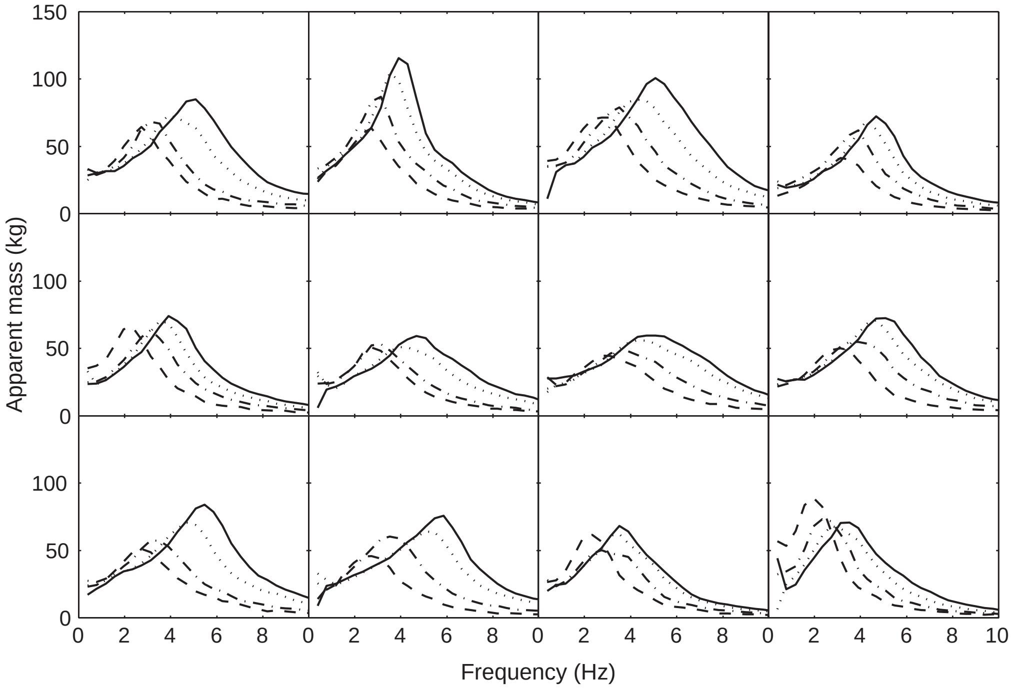

Fig. 4. Fore-and-aft apparent masses of 12 subjects measured on the seat in the average thigh contact posture at four vibration magnitudes. (—) 0.125 m s^{-2} rms; (⋯⋯) 0.25 m s^{-2} rms; (–·–·–) 0.625 m s^{-2} rms; and (– – –) 1.25 m s^{-2} rms.

except for subject 12 (Fig. 4). Statistical analysis showed significant differences ($p<0.05$) in the resonance frequencies (around 1–2 Hz in the feet hanging posture, and in the range 2–6 Hz in all postures) measured at the four vibration magnitudes. Subject posture did not affect the size of the change in the resonance frequency: there were no statistically significant differences between postures in the size of the change in the resonance frequency between the two lower vibration magnitudes (i.e. 0.125 and 0.25 m s^{-2} rms) and the two higher vibration magnitudes (i.e. 0.625 and 1.25 m s^{-2} rms).

A change of vibration magnitude also caused significant differences ($p<0.05$) in the magnitudes of the apparent mass at resonance, except between 0.25 and 0.625 m s^{-2} rms, between 0.25 and 1.25 m s^{-2} rms, and between 0.625 and 1.25 m s^{-2} rms in the feet hanging posture (for both peaks), and between 0.625 and 1.25 m s^{-2} rms in the maximum thigh contact posture and the average thigh contact posture.

At all vibration magnitudes, there were significant differences in the fore-and-aft apparent masses at resonance between the feet hanging posture and the maximum thigh contact posture ($p<0.05$), with the apparent mass magnitude at resonance higher in the maximum thigh contact posture than in the feet hanging posture. However, there were no significant differences in the fore-and-aft apparent mass between the maximum thigh contact posture, average thigh contact posture, and minimum thigh contact posture at any vibration magnitude, except between the maximum thigh contact posture and both the average thigh contact posture and the minimum thigh contact posture at 1.25 m s^{-2} rms.

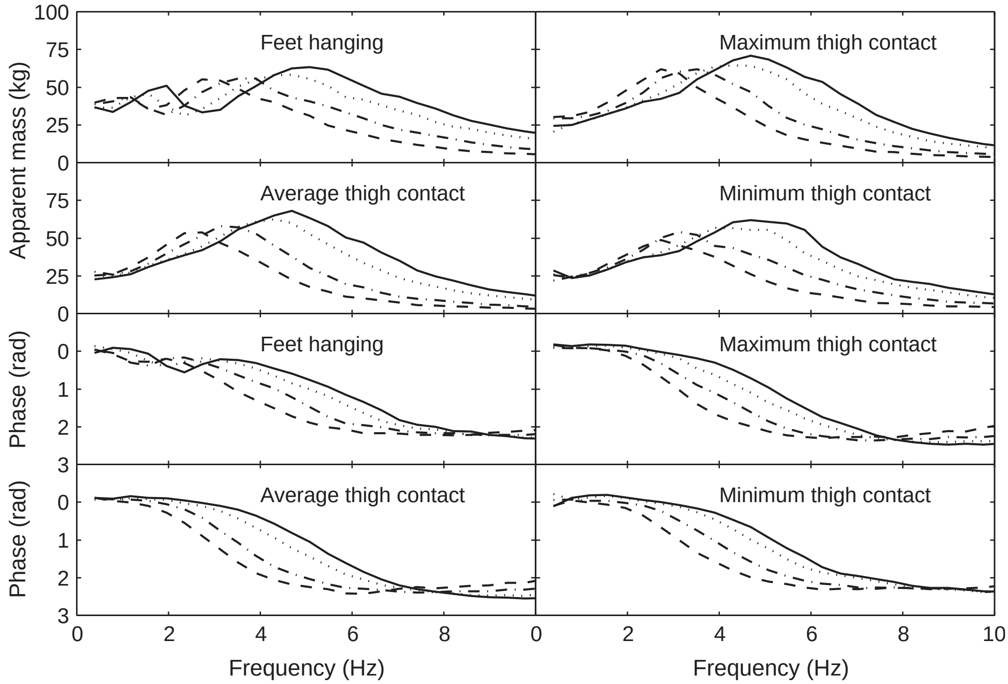

Fig. 5. Median apparent mass and phase angle of 12 subjects measured on the seat in the fore-and-aft direction: effect of vibration magnitude. (—) 0.125 m s^{-2} rms; (⋯⋯) 0.25 m s^{-2} rms; (–·–·–) 0.625 m s^{-2} rms; and (– – –) 1.25 m s^{-2} rms.

There was a trend for the resonance frequency to decrease with an increase in sitting mass (statistically significant at $p<0.05$ for more than 50% of the combinations of posture and vibration magnitude). The correlation between the sitting mass (and the total body mass) and the magnitude of the apparent mass at resonance depended on the support of the feet: when there was no support of the feet (i.e. feet hanging posture) or minimal support of the feet (maximum thigh contact posture), the correlation was significant at all vibration magnitudes. However, when the feet were supported (average thigh contact posture and minimum thigh contact posture), the correlation was not significant at any vibration magnitude.

3.1.2. Response at the backrest

The high subject variability in the fore-and-aft response on the seat was also present in the fore-and-aft response at the backrest (Fig. 6). In all sitting postures, there is a first peak with a frequency less than 2 Hz in most individual data. A second, clearer, peak is present in all individuals between 3 and 5 Hz, except for subject 11 in the feet hanging posture, average thigh contact posture and minimum thigh contact posture and for subject 12 in all postures where the second peak appeared below 3 Hz (Table 1). A third broad peak in the frequency range 4–7 Hz appeared in the responses of a few subjects. The first and third peaks were clearer at low vibration magnitudes than at high vibration magnitudes.

With a change in vibration magnitude, both the individual data and the median data showed changes in the fore-and-aft apparent mass measured at the back (Figs. 7 and 8). There were significant differences in the resonance frequency (between 3 and 5 Hz) at the four vibration

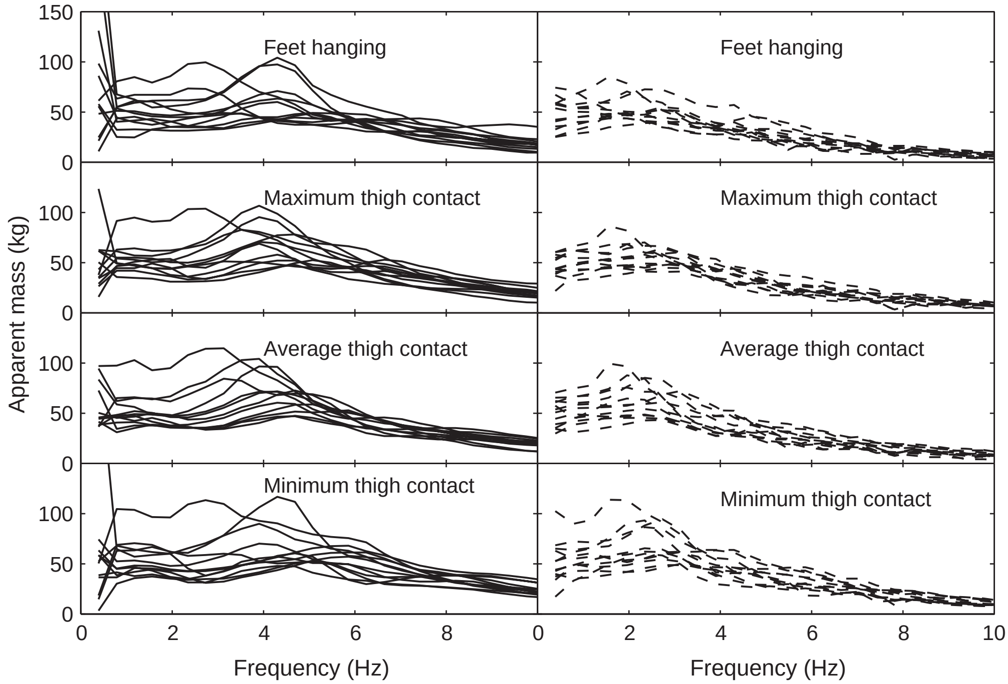

Fig. 6. Inter-subject variability in the fore-and-aft apparent mass at the back for each posture at two vibration magnitudes. (—) $0.125\,m\,s^{-2}$ rms; and (– – –) $1.25\,m\,s^{-2}$ rms.

Table 1
Peak frequencies and corresponding fore-and-aft apparent mass at the back measured at $0.25\,m\,s^{-2}$ rms. *f*: resonance frequency; *m*: magnitude at resonance; 1: first peak; 2: second peak; —: peak not clear

Subj. no.	Feet hanging				Maximum thigh contact				Average thigh contact				Minimum thigh contact			
	f_1 (Hz)	m_1 (kg)	f_2 (Hz)	m_2 (kg)	f_1 (Hz)	m_1 (kg)	f_2 (Hz)	m_2 (kg)	f_1 (Hz)	m_1 (kg)	f_2 (Hz)	m_2 (kg)	f_1 (Hz)	m_1 (kg)	f_2 (Hz)	m_2 (kg)
1	1.95	43.0	4.10	42.4	1.76	44.6	3.71	51.2	1.56	39.8	3.91	47.4	—	—	4.10	52.1
2	0.98	69.4	3.71	98.0	0.78	62.7	3.52	95.0	—	—	3.71	98.1	0.78	66.5	3.71	104
3	1.76	45.6	3.5	42.3	1.56	49.0	3.71	50.4	1.56	46.1	3.91	55.4	1.56	45.3	5.08	51.2
4	1.76	44.8	3.52	62.0	1.56	51.0	3.52	62.9	1.37	49.7	4.29	76.3	1.76	62.4	3.91	59.4
5	—	—	3.52	91.3	0.98	62.4	3.52	102	0.98	67.9	3.32	114	0.98	62.1	3.13	91.3
6	1.17	47.4	3.32	32.3	1.17	50.9	3.32	64.7	1.17	56.2	3.32	66.1	1.17	52.9	3.71	69.1
7	—	—	4.10	67.6	1.37	54.9	4.10	76.0	0.98	54.9	3.91	71.9	1.37	47.8	5.08	57.6
8	—	—	4.30	43.5	1.37	37.3	4.49	53.3	—	—	4.49	49.8	1.56	39.6	4.88	56.0
9	1.17	41.8	3.91	58.5	1.17	48.7	3.52	53.3	0.78	47.3	3.52	58.1	1.17	48.2	4.30	59.2
10	0.78	49.1	3.32	48.2	1.17	48.4	3.52	56.2	1.17	42.4	3.72	48.9	1.17	54.8	4.88	68.0
11	0.78	70.3	2.54	81.9	1.56	65.2	3.32	81.1	0.78	63.9	2.93	86.2	0.78	70.5	2.73	65.2
12	1.17	94.8	1.76	101	1.56	102	2.54	104	1.17	100	2.54	114	1.37	110	2.54	112

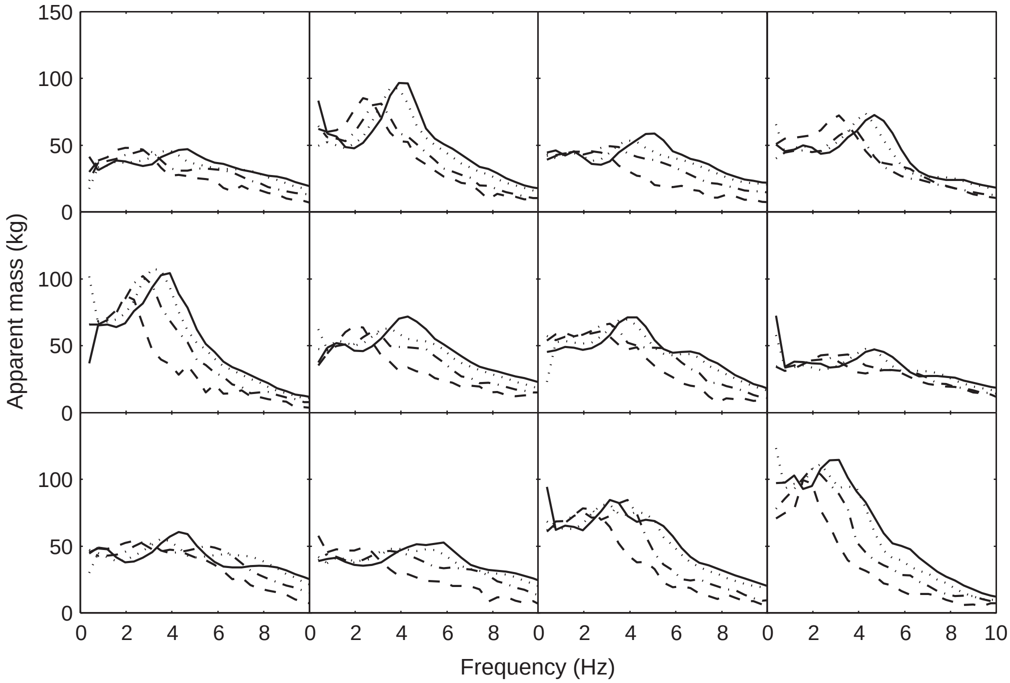

Fig. 7. Fore-and-aft apparent masses of 12 subjects measured at the back in the average thigh contact posture at four vibration magnitudes. (—) 0.125 $m s^{-2}$ rms; (⋯⋯) 0.25 $m s^{-2}$ rms; (–·–·–) 0.625 $m s^{-2}$ rms; and (– – –) 1.25 $m s^{-2}$ rms.

magnitudes ($p<0.05$), except between 0.25 and 0.625 $m s^{-2}$ rms in all postures and between 0.125 and 0.625 $m s^{-2}$ rms in the minimum thigh contact posture. The median phases are also shown in Fig. 8. These phases can be understood by reference to the sign convention for the fore-and-aft acceleration and the fore-and-aft force at the backrest (Section 2.1).

There were positive correlations between both the sitting mass (weight supported on the seat) and the total body mass and the magnitude of the first peak and the second peak (appearing at about 1 and 4 Hz, respectively, $p<0.05$) in all 16 conditions (combination of four postures and four vibration magnitudes). There was no significant correlation between the sitting masses of the subjects and either the first resonance frequency or the second resonance frequency ($p>0.1$) except marginally between the second resonance frequency and the sitting masses of the subjects in the minimum thigh contact posture ($p = 0.078$). The statures (i.e. standing heights) of the subjects were not correlated with either the first or the second resonance frequencies or the apparent masses at resonance in any posture except marginally correlated with the second resonance frequency in the feet hanging posture ($p = 0.064$).

3.2. Responses in the vertical direction

3.2.1. Response on the seat

The vertical forces on the seat were related to the acceleration measured in the fore-and-aft direction using the concept of 'cross-axis apparent mass'. For the four sitting postures, Fig. 9

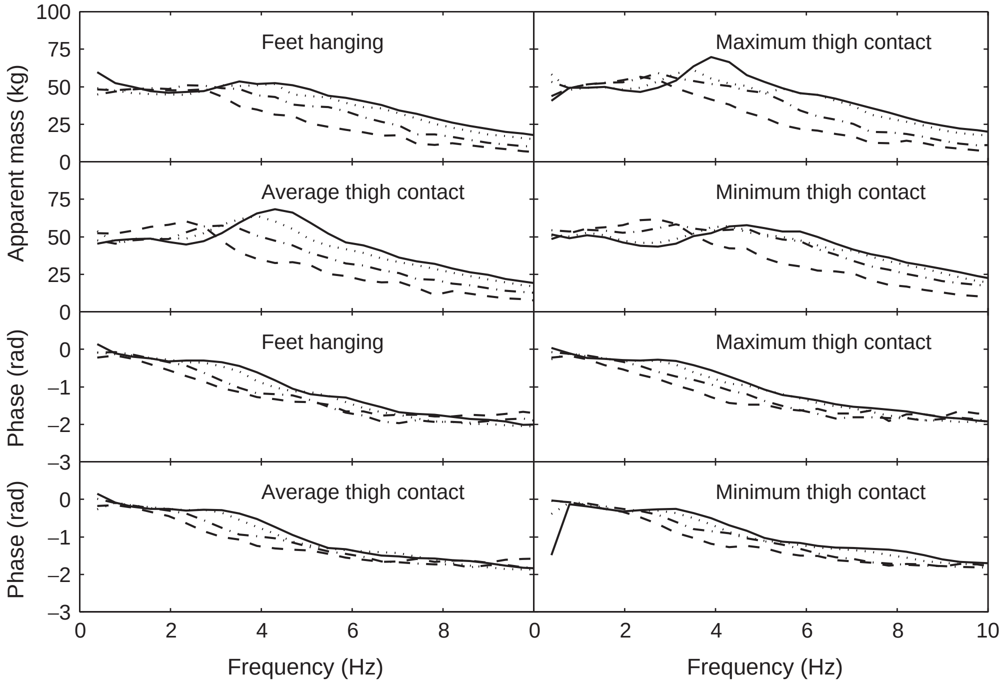

Fig. 8. Median fore-and-aft apparent mass and phase angle at the back of 12 subjects: Effect of vibration magnitude. (—) 0.125 m s^{-2} rms; (······) 0.25 m s^{-2} rms; (–·–·–) 0.625 m s^{-2} rms; and (– – –) 1.25 m s^{-2} rms.

shows the variability between subjects in the vertical responses measured with fore-and-aft excitation at 0.125 and 1.25 m s^{-2} rms. In all postures, the median resonance frequencies were in the range 6–8 Hz, depending on vibration magnitude. A trough can be seen around 5 Hz, where coherency also dropped (see Figs. 15 and 16 in Section 4.1).

The resonance frequency and, generally, the cross-axis apparent mass at resonance, decreased with increasing vibration magnitude, following the same nonlinear behaviour found in the fore-and-aft response (Figs. 10 and 11). There were significant differences in the resonance frequencies measured with the four vibration magnitudes ($p<0.05$), except between 0.125 and 0.25 m s^{-2} rms in the maximum thigh contact posture and between 0.625 and 1.25 m s^{-2} rms in both the maximum thigh contact posture and the average thigh contact posture. There were also differences in the cross-axis apparent mass at resonance measured at the four vibration magnitudes ($p<0.05$), except between 0.125 and 0.25 m s^{-2} rms in both the average thigh contact posture and the minimum thigh contact posture, and between 0.625 and 1.25 m s^{-2} rms in the average thigh contact posture ($p<0.05$).

At resonance, the minimum thigh contact posture gave a greater vertical cross-axis apparent mass than the other three postures. There was no significant difference in the vertical cross-axis apparent mass at resonance between the feet hanging posture, maximum thigh contact posture, and average thigh contact posture at any vibration magnitude ($p>0.05$). There were significant differences between these three postures and the minimum thigh contact posture at all four vibration magnitudes. There were no significant differences in resonance frequencies between postures at any vibration magnitude ($p>0.05$).

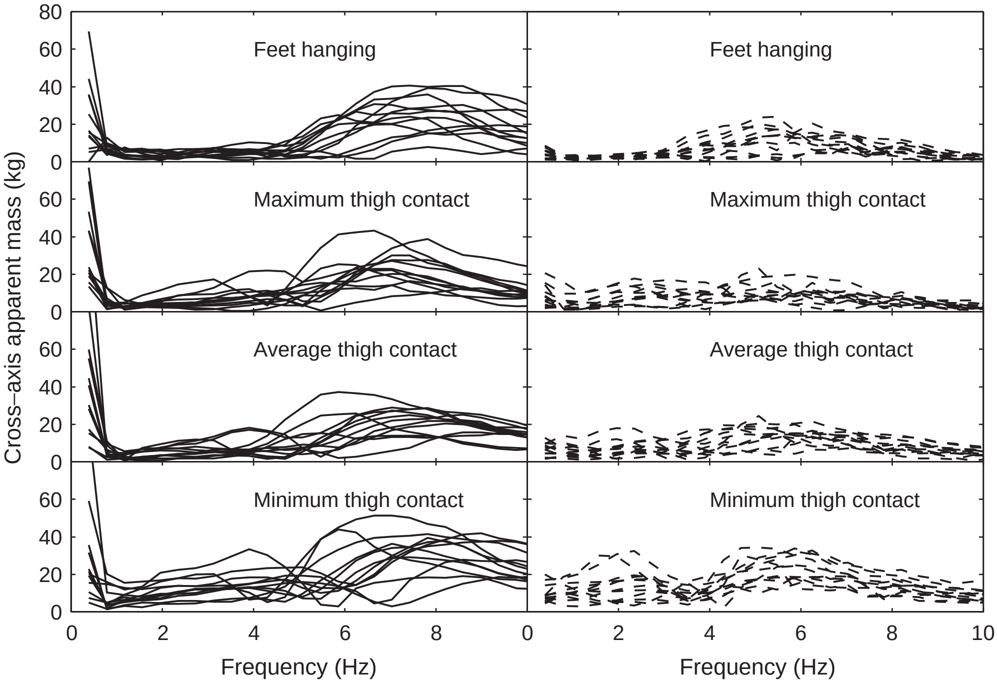

Fig. 9. Inter-subject variability in the vertical cross-axis apparent mass on the seat for each posture at two vibration magnitudes. (—) 0.125 m s^{-2} rms; and (– – –) 1.25 m s^{-2} rms.

3.2.2. Response at the backrest

The force in the vertical direction at the back was measured for one subject in the four sitting postures and at three vibration magnitudes (0.125, 0.25, and 0.625 m s^{-2} rms). The vertical cross-axis apparent mass at the back was low and, mostly, did not exceed 3 kg at a resonance appearing between 5 and 7 Hz, depending on the vibration magnitude (Fig. 12). In all postures, the resonance frequency decreased with increasing vibration magnitude.

3.3. Response in the lateral direction (at the seat and the backrest)

The lateral cross-axis apparent masses measured on the seat and backrest were low in all postures (Figs. 13 and 14). On the seat, increasing the vibration magnitude decreased the resonance frequency in the lateral cross-axis apparent mass from about 5 Hz to around 2–3 Hz.

4. Discussion

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

Linear techniques, such as the CSD method are frequently used to analyse biodynamic responses of the human body to vibration, even though observations suggest that the human body

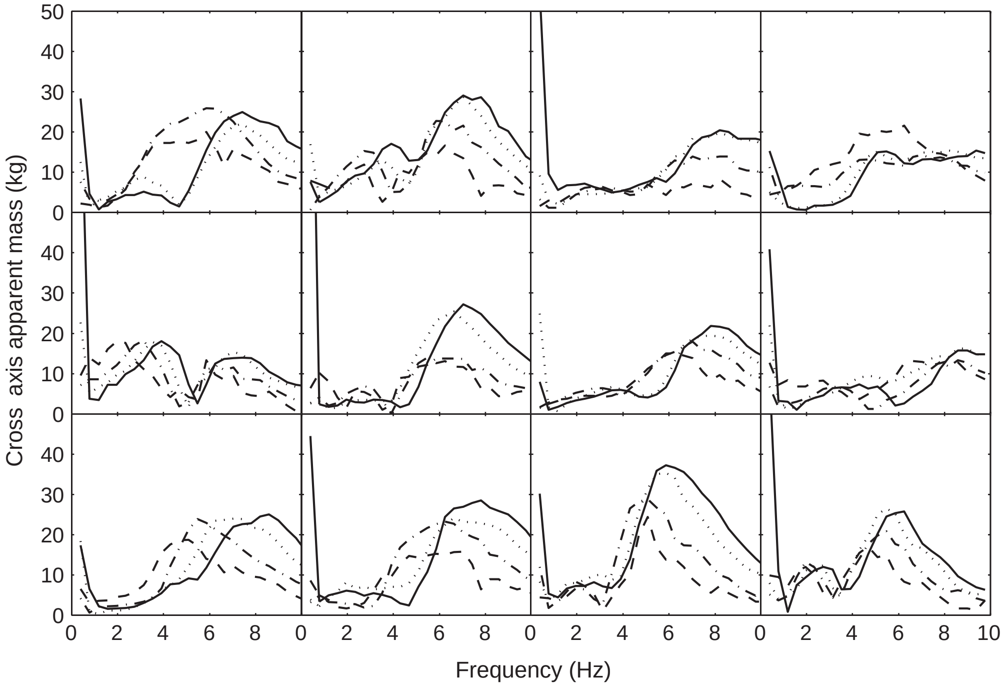

Fig. 10. Vertical cross-axis apparent masses of 12 subjects measured on the seat in the average thigh contact posture at four vibration magnitudes. (—) 0.125 m s^{-2} rms; (⋯⋯) 0.25 m s^{-2} rms; (–·–·–) 0.625 m s^{-2} rms; and (– – –) 1.25 m s^{-2} rms.

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 measured on the seat or at the backrest at any one magnitude. This has sometimes been assumed to imply that the body behaves approximately linearly at any specific vibration magnitude but differently at another magnitude: when the 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, a nonlinear response when the body is exposed at only one vibration magnitude is also likely. If the body may behave nonlinearly when exposed to a particular magnitude of vibration, it is of interest to compare the use of the CSD method and the PSD method for computing the apparent mass. Fig. 15 compares the fore-and-aft apparent mass of one subject measured on the seat and backrest at 0.25 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 on the seat 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 subtraction, where applicable, in the time domain the fore-and-aft force arising from the mass of the force plate (on the seat or the backrest) 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 lower and there were some

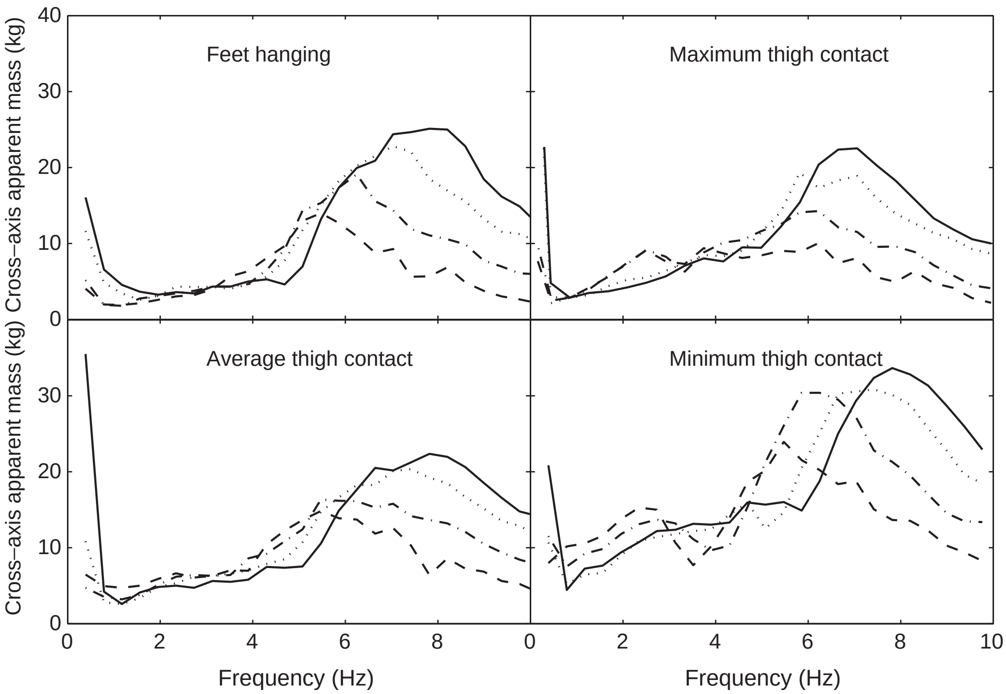

Fig. 11. Median vertical cross-axis apparent mass of 12 subjects measured on the seat: effect of vibration magnitude. (—) 0.125 m s^{-2} rms; (⋯⋯) 0.25 m s^{-2} rms; (–·–·–) 0.625 m s^{-2} rms; and (– – –) 1.25 m s^{-2} rms.

differences between the results obtained using the CSD and PSD methods, consistent with a nonlinearity in the body response (Figs. 15 and 16).

It may be seen that the CSD and PSD methods gave very similar results in the fore-and-aft direction (direction of vibration excitation). 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. In the vertical direction, the trends found with both methods, as well as the peaks and troughs, were similar, although there are some differences in the magnitudes of the vertical cross-axis apparent mass. This indicates the need for further investigation of the nonlinearity, but the principal findings reported here from the use of linear methods appear relevant.

4.2. Response in the fore-and-aft direction

Changing foot height may change the posture of the upper-body and, hence, the biodynamic responses of the body to vibration. However, in all conditions, of this experiment the subjects were instructed to keep the same upper-body posture (upright upper-body with full contact of the back with the backrest). Any differences in the responses between the different conditions are therefore assumed to be primarily due to the extent to which the thighs were in contact with the seat and not other changes in body posture.

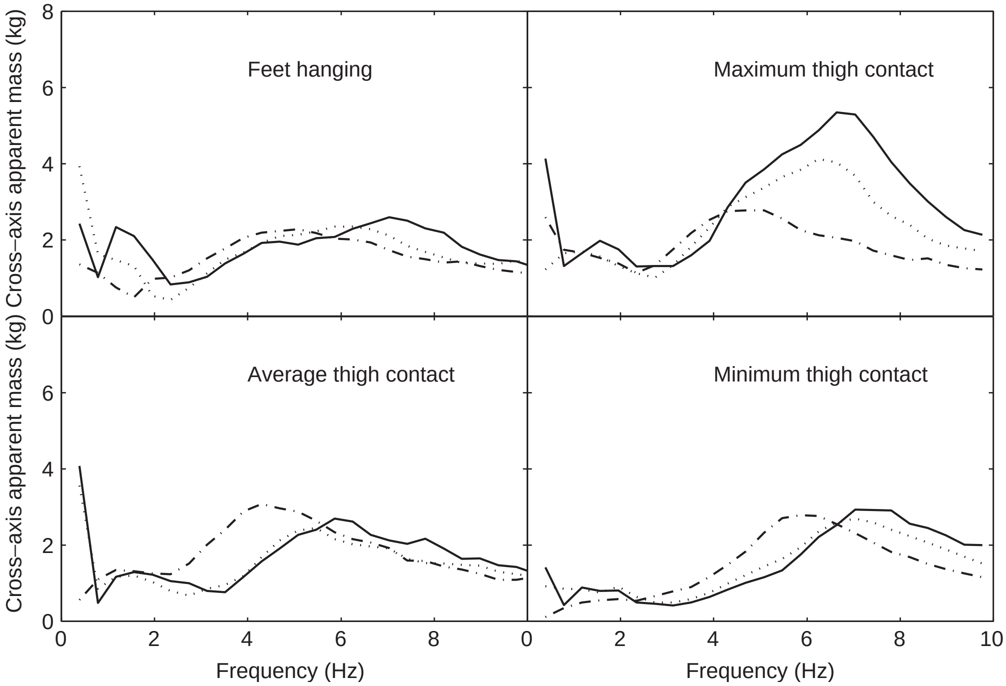

Fig. 12. Vertical cross-axis apparent mass of one subject measured at the back at three vibration magnitudes. (—) $0.125\,m\,s^{-2}$ rms; (⋯⋯) $0.25\,m\,s^{-2}$ rms; and (–·–·–) $0.625\,m\,s^{-2}$ rms.

The response on the seat in the fore-and-aft direction showed a dependency on the status of the feet: when the feet were not supported there were two resonance frequencies, compared to one resonance frequency when the feet were supported. In comparison with studies using vertical vibration (e.g. Ref. [2]), supporting the feet on a footrest moving in phase with the seat tended to reduce the apparent mass measured on the seat (due to the reduced mass on the seat) without changing the shape of the response.

The responses measured in the four postures in the present study can be compared with the responses measured in the same postures without a backrest (Fig. 17; [4]). The comparison is shown at $0.125\,m\,s^{-2}$ rms for the median of the 11 subjects who participated in both the present study and in the previous study without a backrest. Without a backrest, there was evidence of three modes, irrespective of whether the feet were supported (Fig. 17). When a backrest was used, there were two modes in the feet unsupported posture (i.e. feet hanging) but only one mode when the feet were supported. The fore-and-aft forces decreased at low frequencies and increased at high frequencies (see Fig. 17) when the backrest was used. The results with the other vibration magnitudes showed the same trend.

The one mode in the fore-and-aft apparent mass when the feet were supported is consistent with the single mode found by Fairley and Griffin [5] with $1.0\,m\,s^{-2}$ rms in a feet supported posture. Fairley and Griffin, who reported only two modes (at 0.7 and 1.5–3 Hz) without a backrest, suggested that the single mode found when using a backrest might be associated with the second mode measured without backrest. However, a third mode found above 3 Hz without a

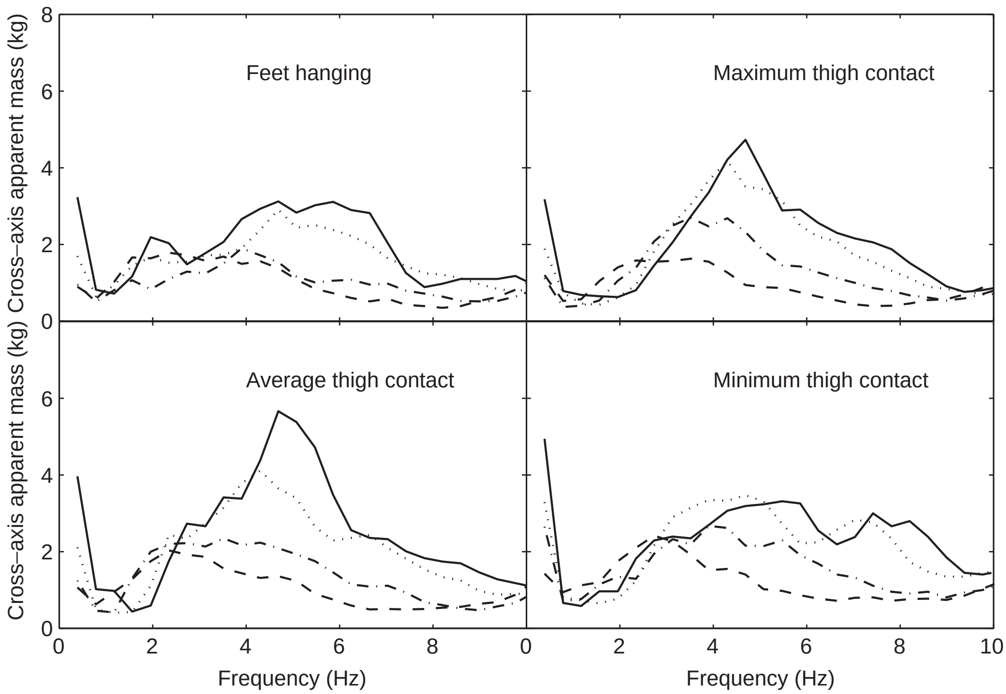

Fig. 13. Median lateral cross-axis apparent mass of 12 subjects measured on the seat: effect of vibration magnitude. (—) 0.125 m s^{-2} rms; (⋯⋯) 0.25 m s^{-2} rms; (–·–·–) 0.625 m s^{-2} rms; and (– – –) 1.25 m s^{-2} rms.

backrest [4,9] was more pronounced at low vibration magnitudes (0.125 and 0.25 m s^{-2} rms) than at high vibration magnitudes. This, together with the results in the feet hanging posture (where two modes were found when using a backrest, see Fig. 17) suggest that the second mode in the feet hanging posture and the single mode in the other postures when using a backrest may be associated with the third mode found without a backrest.

High forces were found in the fore-and-aft direction at the backrest. With a backrest, the 'total apparent mass' of the body can be calculated from the sum of the forces measured at the seat and the backrest. Although this summation may be applicable where the human body behaves linearly in response to vibration (e.g. at very low frequencies, below 1 Hz), it is not applicable at higher frequencies where the body behaves nonlinearly and the superposition principle will not apply. The apparatus used by Fairley and Griffin [5] was designed to combine the force at the back with that on the seat (a vertical flat backrest was welded to the top plate of the force platform mounted on the seat, so giving measurements of forces transmitted to the body from both the seat and the back). This would explain the higher apparent mass obtained by Fairley and Griffin than measured on the seat in the present study. Fairley and Griffin found an increase in their measure of apparent mass at frequencies above 0.8 Hz when the body made contact with the backrest.

The increased apparent mass when using a backrest is similar to the increased head motion (in vertical, fore-aft, lateral, pitch, roll, and yaw axes) when subjects use a backrest during exposure to translational or rotational whole-body vibration [7–8,10,11]. Clearly, the backrest can be a source of vibration transmission to the body and so reduction in the vibration on a backrest may

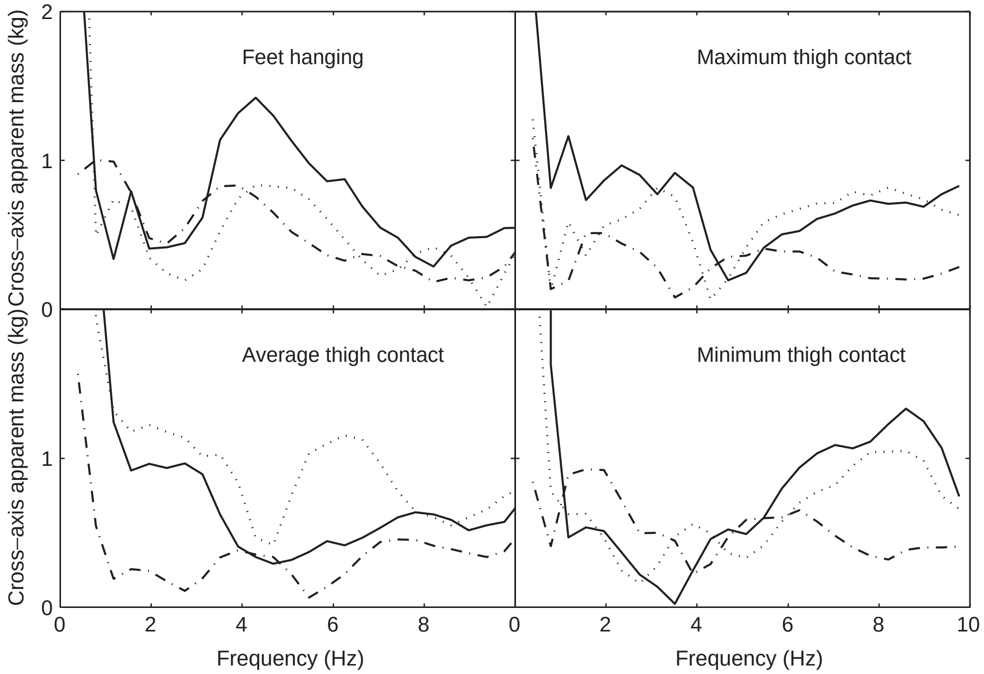

Fig. 14. Lateral cross-axis apparent mass of one subject measured at the back at three vibration magnitudes. (—) $0.125\,m\,s^{-2}$ rms; (······) $0.25\,m\,s^{-2}$ rms; and (–·–·–) $0.625\,m\,s^{-2}$ rms.

reduce some adverse human responses to vibration. However, with the non-rigid seats used in many vehicles the forces at the seat and backrest will not be in phase (unlike this study) and the vibration at the seat and backrest may be expected to combine in a phase-dependent manner. Furthermore, at low frequencies, a backrest may provide postural stability and reduce some effects of vibration, even though there is an increased apparent mass when using a backrest.

The correlation between the sitting mass (or the total body mass) of the subject and the apparent mass on the seat at resonance was found to depend on the support of the feet: significant correlations were found with feet hanging and maximum thigh contact postures while insignificant correlations were found with average thigh contact and minimum thigh contact postures. It seems that the response on the seat in the fore-and-aft direction depends on the foot posture in a complex manner that not only changes the shape of the response but also affects the correlations.

The significant correlations between the masses of subjects and the apparent masses measured at the back at resonance in all conditions are similar to the high correlation between sitting mass and vertical apparent mass at resonance during vertical vibration (e.g. Refs. [6,12]). The way that fore-and-aft vibration is applied to the back resembles the way vertical vibration is applied to the seat: both applied forces are normal to the body, in contrast to the shear force applied by the seat during fore-and-aft vibration.

The mode between 1 and 2 Hz seen in the fore-and-aft apparent mass on the seat in the feet hanging posture disappeared when the feet were supported. This mode might be associated with the second mode reported by Nawayseh and Griffin [4] between 1 and 3 Hz in all sitting postures

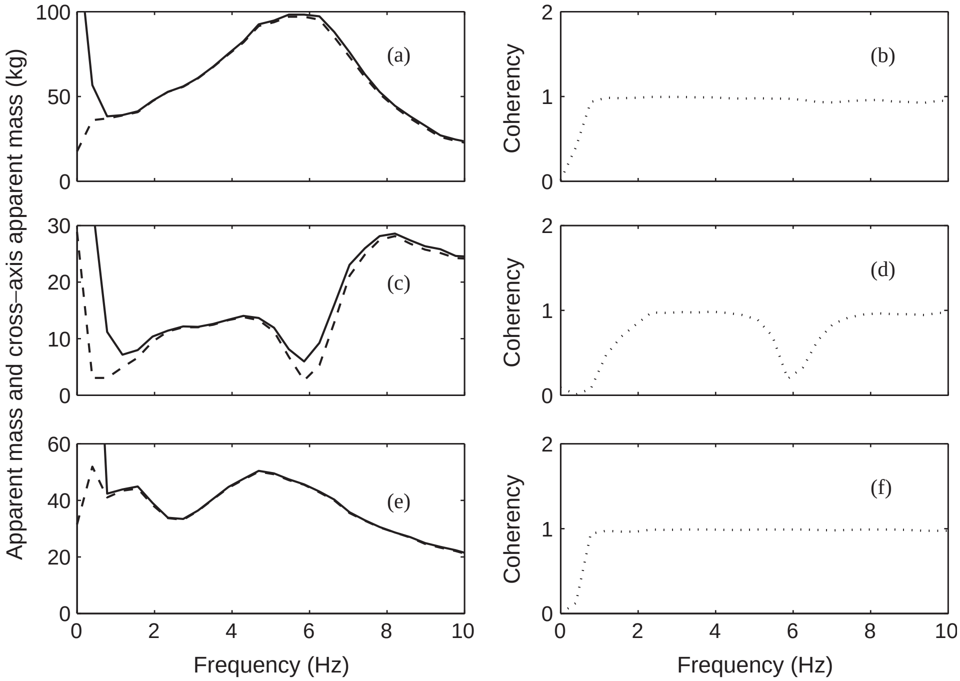

Fig. 15. Apparent masses, cross-axis apparent mass, and coherences of one subject at $0.25\,m\,s^{-2}$ rms with the minimum thigh contact posture. (a,b) Fore-and-aft apparent mass on the seat, (c,d) vertical cross-axis apparent mass on the seat, (e,f) fore-and-aft apparent mass at the backrest. (—) PSD method; (– – –) CSD method; and (⋯⋯) coherency.

(i.e. feet hanging, maximum thigh contact, average thigh contact and minimum thigh contact) when no backrest was used (see feet hanging posture in Fig. 17 and Ref. [4]). At a similar frequency, Matsumoto and Griffin [13] found a pitching mode in the pelvis and the upper body during vertical vibration. Kitazaki and Griffin [14] reported an out-of-phase fore-and-aft motion of the head and pelvis at about 1 and 2 Hz caused by bending deformation of the spine during vertical vibration. When using a backrest, a 1–2 Hz peak is also pronounced in measures of the transmissibility of fore-and-aft seat vibration to fore-and-aft head vibration [8]. Although the feet were supported, when no backrest was used the rotational modes were clearer, consistent with the upper body being free to pitch. However, when the subjects leant on a backrest, the presence of a backrest together with the foot support reduced the freedom of the body to pitch forward and backward. However, this was not the case with the feet hanging posture where the body still has some degree of freedom to pitch. This might explain the presence of the 1–2 Hz mode in all sitting postures when no backrest was used and in the feet hanging posture when a backrest was used. A mode in a similar frequency range was also found in the fore-and-aft apparent mass at the back in all postures. The mode measured at the back at 1–2 Hz might be associated with a pitching mode also seen at the head in this frequency range, as reported by Paddan and Griffin [8].

The body movements responsible for the peaks appearing in the fore-and-aft apparent mass on the seat and backrest, as well as the causes of the nonlinearity, are not yet well established. The resonance in the vicinity of 4 Hz in the fore-and-aft apparent mass on the seat could reflect a

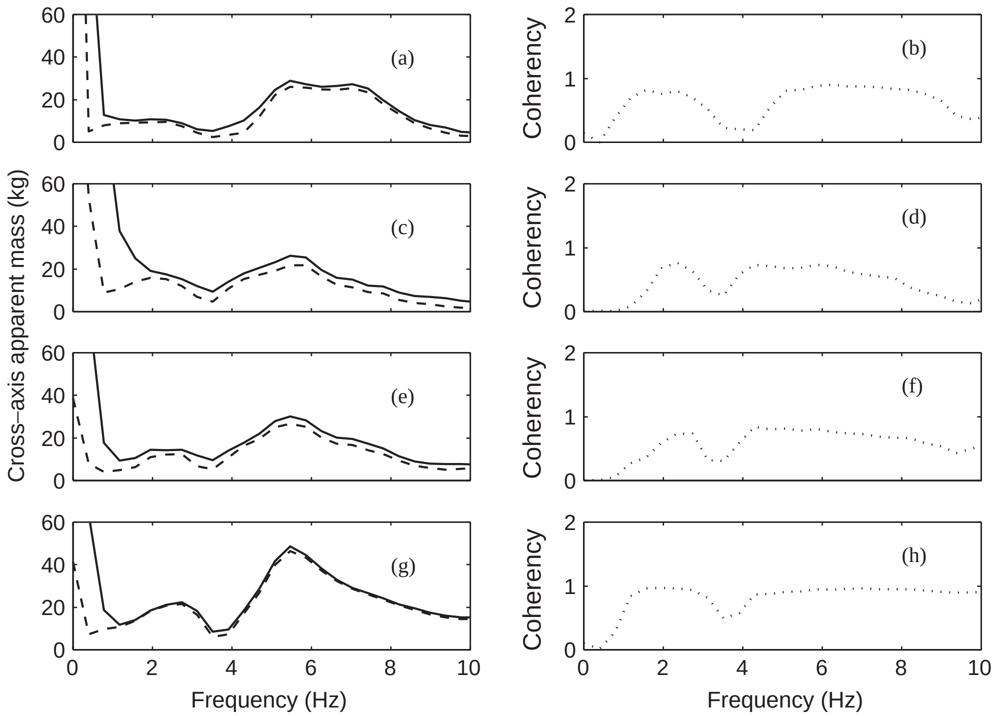

Fig. 16. Vertical cross-axis apparent mass and coherences of one subject at $0.25\,m\,s^{-2}$ rms with four different sitting postures. (a,b) Feet hanging, (c,d) maximum thigh contact, (e,f) average thigh contact, (g,h) minimum thigh contact. (—) PSD method; (– – –) CSD method; and (⋯⋯) coherency.

response of the tissues of the buttocks. Kitazaki and Griffin [14] noticed shear deformation of buttocks tissue beneath the pelvis and fore-and-aft movement of the pelvis in the range 4–6.5 Hz. The peaks in the fore-and-aft apparent mass could also be the result of bending modes in the spine or a pitching mode of the pelvis (the spine and the pelvis appear to have rotational modes at these frequencies, [15,16]). The mechanisms producing the resonance frequencies and the nonlinearity are gradually being uncovered from measures of the transmissibilities to different locations on the body and measures of the apparent mass, both allowing the gradual development of improved biodynamic models (see e.g. Refs. [13,14,17]).

4.3. Response in the vertical and lateral directions

On the seat and backrest, vertical forces (presented as cross-axis apparent masses) indicated a resonance between 5 and 8 Hz, decreasing in frequency with increasing vibration magnitude. However, the magnitudes of these forces were only considerable on the seat. Matsumoto and Griffin [1] and Nawayseh and Griffin [2,3] found considerable forces on the seat in the fore-and-aft direction during vertical excitation, which were attributed to rotational modes of different parts of the upper body. If a segment of the upper body has a pitch mode during vertical excitation, the same mode may be expected during fore-and-aft excitation. The rotational modes

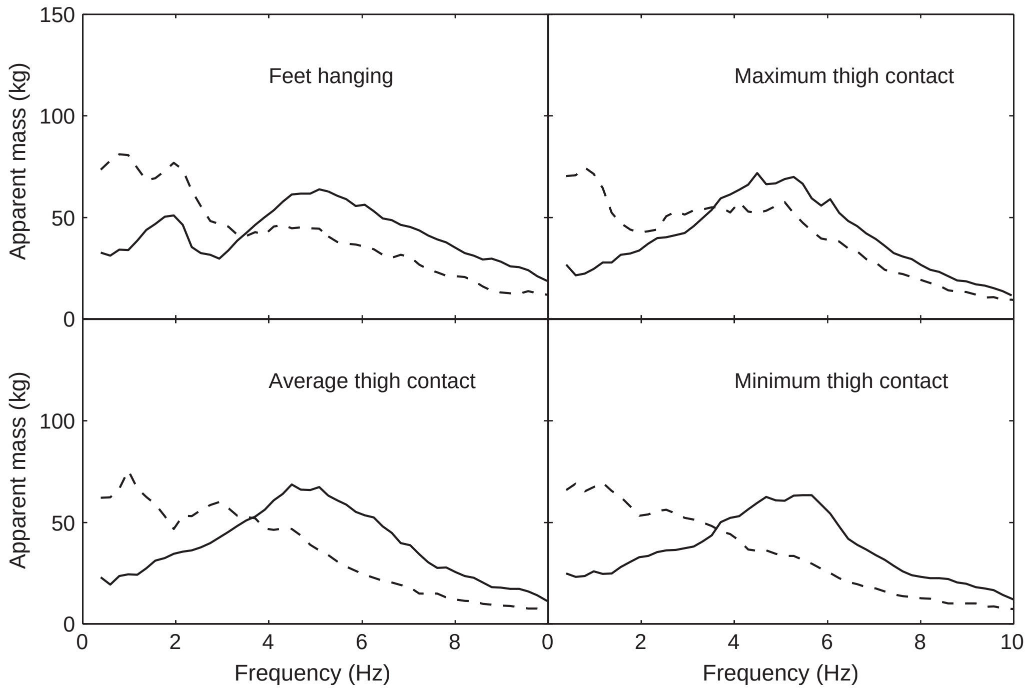

Fig. 17. Median fore-and-aft apparent masses of 11 subjects measured on the seat at $0.125\,m\,s^{-2}$ rms in four sitting postures: effect of backrest. (—) With backrest; and (– – –) without backrest.

in the mid-sagittal plane of the pelvis, the spine and the head seen in both transmissibility studies (e.g. Refs. [7,18]) and biodynamic models (e.g. Refs. [13,14]) could be responsible for both the vertical forces on the seat during fore-and-aft vibration and the fore-and-aft forces on the seat during vertical vibration. The low vertical forces at the backrest could be the result of some vertical motion of the spine accompanying the pitching mode of the pelvis, spine and upper body.

The vertical cross-axis apparent mass at resonance was greatest in the minimum thigh contact posture. Nawayseh and Griffin [2] found that without a backrest the fore-and-aft forces on the seat during vertical vibration were also greatest in the minimum thigh contact posture. In this posture the body is resting on a small area (around the ischial tuberosities) allowing easier pitching of the upper body in the minimum thigh contact posture than in the other postures.

The vertical cross-axis apparent masses measured on the seat in the present study were compared with those measured by Nawayseh and Griffin [4] without a backrest at $0.125\,m\,s^{-2}$ rms. The presence of the backrest shifted the resonance frequency to a higher frequency (see the feet hanging posture and the maximum thigh contact posture in Fig. 18), consistent with the backrest increasing the stiffness of the body (e.g. Ref. [6]). The results with the other vibration magnitudes showed the same trend. The high vertical forces on the seat at low frequencies with no backrest were explained by the subjects applying forces on the seat in the vertical direction when they sway backward, and applying a vertical force on the footrest when they sway forward (Fig. 18; [4]). The subjects in the present study did not apply a vertical force on the seat at low frequencies since the backrest restrained the body from swaying backward. The

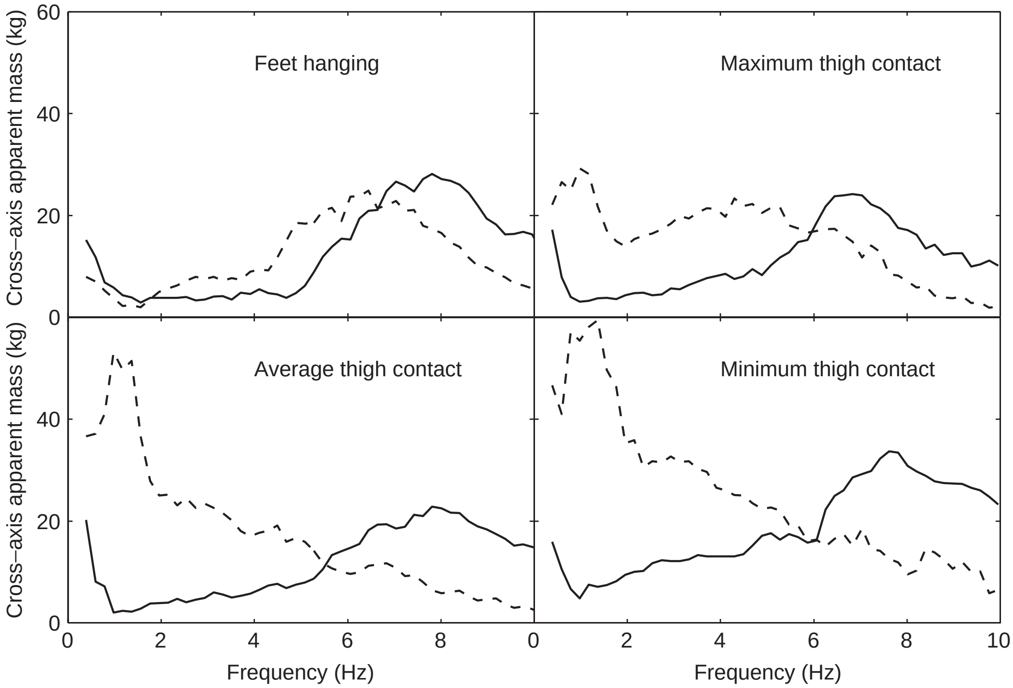

Fig. 18. Median vertical cross-axis apparent masses of 11 subjects measured on the seat at 0.125 m s^{-2} rms in four sitting postures: effect of backrest. (—) With backrest; and (– – –) without backrest.

increase in the vertical forces at high frequencies (Fig. 18) is not surprising given that the backrest transmits vibration to the body at high frequencies: the backrest increased the pitching motion of the upper body by applying a fore-and-aft force on the upper body.

There were low forces in the lateral direction on the seat and at the backrest. This is consistent with the body being roughly symmetrical about the mid-sagittal plane. The lateral forces on the seat, are slightly greater than those measured by Nawayseh and Griffin [4] on the seat without a backrest (Fig. 19). The slight increase in the lateral forces when using the backrest is consistent with a slight increase in the lateral motion of the head when a similar backrest was used [7,8].

5. Conclusion

Fore-and-aft vibration of subjects sitting in a rigid seat with a rigid flat vertical backrest resulted in high forces in the fore-and-aft and vertical directions on the seat and high forces in the fore-and-aft direction on the backrest. Lateral forces on the seat and backrest, and vertical forces at the backrest, are relatively small.

The characteristics of the fore-and-aft forces on the seat depended on whether the feet were supported on a footrest: two resonance frequencies were found when the feet were not supported compared to only one resonance frequency when the feet were supported. Forces in all directions on the seat and backrest showed nonlinear behaviour.

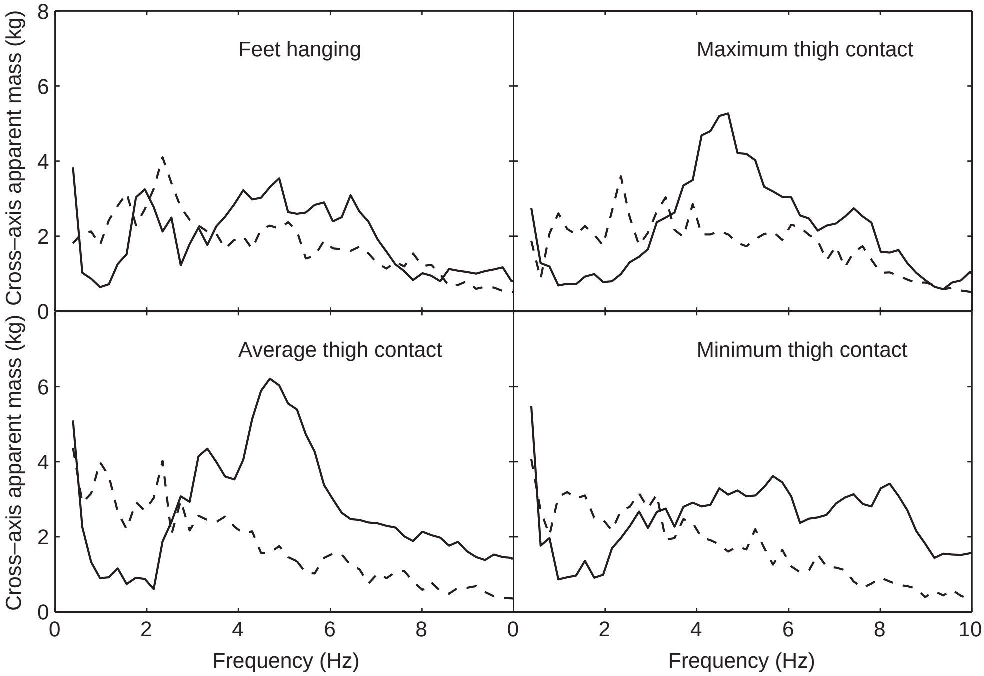

Fig. 19. Median lateral cross-axis apparent masses of 11 subjects measured on the seat at 0.125 m s^{-2} rms in four sitting postures: effect of backrest. (—) With backrest; and (– – –) without backrest.

In comparison with previous measurements with no back support, the backrest reduced forces in the fore-and-aft and vertical directions on the seat at low frequencies and increased forces at high frequencies.

The high fore-and-aft forces at the backrest confirm the need to consider the contribution of backrests to vibration of the body. The high vertical forces on the seat during fore-and-aft excitation suggest the need to take into account the forces appearing in directions other than the direction of excitation when designing vibration isolation devices.

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