Available online at www.sciencedirect.com

SCIENCE DIRECT®

Journal of Sound and Vibration 268 (2003) 503–523

JOURNAL OF SOUND AND VIBRATION

www.elsevier.com/locate/jsvi

Non-linear dual-axis biodynamic response to vertical whole-body vibration

N. Nawayseh, M.J. Griffin*

Human Factors Research Unit, Institute of Sound and Vibration Research, University of Southampton, Southampton SO17 1BJ, UK

Received 18 June 2002; accepted 18 November 2002

Abstract

Seated human subjects have been exposed to vertical whole-body vibration so as to investigate the non-linearity in their biodynamic responses and quantify the response in directions other than the direction of excitation. Twelve males were exposed to random vertical vibration in the frequency range 0.25–25 Hz at four vibration magnitudes (0.125, 0.25, 0.625, and 1.25 $\mathrm{m\,s^{-2}}$ r.m.s.). The subjects sat in four sitting postures having varying foot heights so as 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). Forces were measured in the vertical, fore-and-aft, and lateral directions on the seat and in the vertical direction at the footrest.

The characteristic non-linear response of the human body with reducing resonance frequency at increasing vibration magnitudes was seen in all postures, but to a lesser extent with minimum thigh contact. Appreciable forces in the fore-and-aft direction also showed non-linearity, while forces in the lateral direction were low and showed no consistent trend. Forces at the feet were non-linear with a multi-resonant behaviour and were affected by the position of the legs.

The decreased non-linearity with the minimum thigh contact posture suggests the tissues of the buttocks affect the non-linearity of the body more than the tissues of the thighs. The forces in the fore-and-aft direction are consistent with the body moving in two directions when exposed to vertical vibration. The non-linear behaviour of the body, and the considerable forces in the fore–aft direction should be taken into account when optimizing vibration isolation devices.

*Corresponding author. Tel.: +44-23-8059-2277; fax: +44-23-8059-2927.

E-mail address: m.j.griffin@soton.ac.uk (M.J. Griffin).

0022-460X/03/$ - see front matter
doi:10.1016/S0022-460X(03)00254-2

1. Introduction

When exposed to vertical vibration the human body exhibits various resonances, especially a resonance at about 5 Hz, seen as increased apparent mass and increased transmission of vibration to the body at this frequency. However, the biodynamic responses to whole-body vertical vibration depend on many factors, especially body posture (e.g., Refs. [1–6]) and vibration magnitude (e.g., Refs. [4,5,7–11]).

Posture affects the geometry of the body and the muscles that support the body. Fairley and Griffin [1], Kitazaki [2], and Holmlund et al. [3] concluded that an erect body posture increased mechanical impedance (or apparent mass) and increased the resonance frequency of the body relative to a relaxed posture. The transmission of vibration to the spine and to the head is also increased in an erect posture (e.g., Ref. [12]). These findings appear consistent with increased body stiffness in an erect posture.

Matsumoto and Griffin [4] found differences in the apparent mass characteristics measured using three standing postures (normal, leg bent, and standing on one leg). From measurements of transmissibility to the first and eighth thoracic vertebrae, to the fourth lumbar vertebrae, to the right and left iliac crests, and to the knee, the authors found that changing the posture of the legs changed the mechanisms that contributed to the principal resonance frequency of the body: in the normal standing posture, the transmissibilities to the fourth lumbar vertebra and to the iliac crests were similar to that of the apparent mass at low frequencies. In the leg bent posture, a pitching or bending mode of the upper body, together with a bending motion of the legs at the knees, appeared to contribute to the resonance frequency. When standing on one leg, rotational motion of the upper body about the hip joint may have contributed to the resonance frequency.

Muscle tension may also affect the responses of the body to vibration. For example, Fairley and Griffin [1] noticed an increase in the resonance frequency when subjects were instructed to tense their upper body muscles as much as possible.

Studies investigating the linearity of the apparent mass of the body have concluded that there is a ‘softening’ with increased vibration magnitude: the resonance frequency reduces at higher magnitudes of vibration (e.g., Refs. [1,5,7,9,10]). For example, an increase in the vibration magnitude from 0.125 to 2.0 $\mathrm{m\,s^{-2}}$ r.m.s. decreased the resonance frequency from 6.75 to 5.25 Hz in standing subjects [4] and reduced the resonance frequency from 6.4 to 4.75 Hz in sitting subjects [10].

Since standing and sitting postures both show a resonance at 5 Hz, which decreases in frequency with increasing vibration magnitude, it seems likely that there is a common mechanism. Some potential mechanisms would apply only when standing (e.g., response of feet tissue), some would apply only when sitting (e.g., response of tissue beneath the pelvis at the ischial tuberosities), and some would apply when both standing and sitting (e.g., movement of the viscera and muscle activity).

Several researchers have hypothesized that the tissues beneath the ischial tuberosities might contribute to the non-linearity (e.g., Refs. [13,14]). In an investigation of the effect of buttocks tissues on the non-linearity, Matsumoto and Griffin [9] instructed subjects to tense buttocks muscles to increase their stiffness. Using eight subjects at five vibration magnitudes (0.35, 0.5, 0.7, 1.0, and 1.4 $\mathrm{m\,s^{-2}}$ r.m.s.), they found the non-linearity decreased with increased muscle tension, implying that buttocks tissues may be partly responsible for the non-linearity.

A non-linearity has also been observed with seated subjects exposed to horizontal vibration [15–17]. Fairley and Griffin [15] measured the apparent mass during fore-and-aft and lateral vibration in the frequency range 0.25–20 Hz and observed two resonance frequencies at 0.7 Hz and between 1.5 and 3 Hz. However, only the second resonance frequency decreased with increase in vibration magnitude. In a later study, Mansfield and Lundström [16] measured the apparent mass in five different horizontal directions (0°, 22.5°, 45°, 67.5°, and 90° to the mid-sagittal plane) and found two resonance frequencies at 3 and 5 Hz and both decreased with increase in vibration magnitude. Holmlund and Lundström [17] reported an effect of vibration magnitude on the principal resonance frequency in the fore-and-aft direction and not in the lateral direction.

Almost all studies of the point response of the body (apparent mass or impedance) have been restricted to responses in the direction of the applied vibration. Measurements of acceleration on the body in the fore-and-aft direction (e.g., on the head, the abdomen, and the spine) caused by vertical vibration show appreciable movements in the fore-and-aft direction (e.g., Refs. [18–20]). Some biodynamic models predict non-vertical forces inside the body. In one experiment with vertical excitation, forces have been measured in the fore-and-aft direction on a seat excited in the vertical direction [9]. At resonance, it was found that the 'cross-axis apparent mass' (i.e., the ratio of the force in the fore-and-aft direction to the acceleration in the vertical direction), could reach up to 40% of the static masses of the subjects.

Understanding the mechanisms that produce the non-linear behaviour of the human body and the forces in directions other than the direction of excitation is important to improve the biodynamic modelling of humans' response to vibration. Such models are required to test the performance and response of vibration isolation devices (such as vehicle seats) that are influenced by the dynamic responses of the body and therefore vary with vibration magnitude.

This paper reports an experimental investigation of: (i) non-linearity in the responses of the seated human body to vertical vibration, and (ii) forces at the seat in directions other than the direction of excitation. It was hypothesized that decreasing the stiffness of the thighs, by raising the feet so as to increase the mass of the body supported on the ischial tuberosities, would decrease the non-linearity of the body. It was further hypothesized that there would be appreciable forces in the fore-and-aft direction and that these would also show a non-linear response. It was anticipated that forces on the seat in the lateral direction would be relatively small.

2. Apparatus, experimental design and analysis

2.1. Apparatus

Subjects were exposed to vertical 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 so as 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

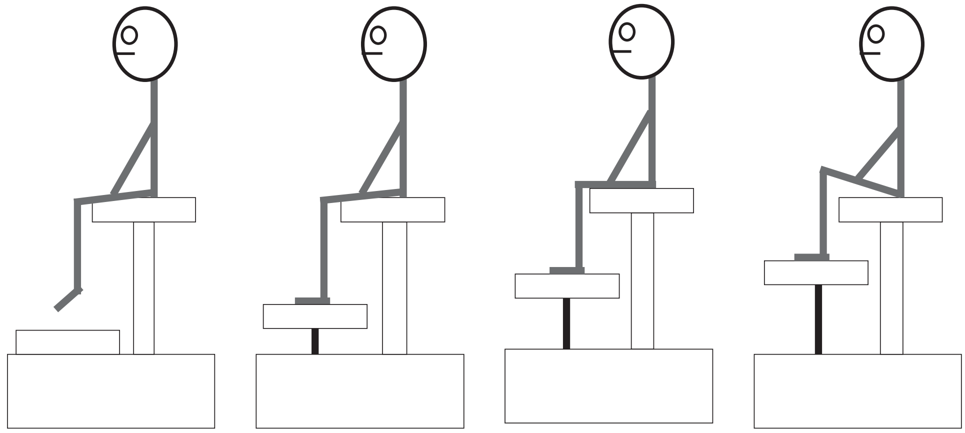

Fig. 1. Schematic diagrams of the four sitting postures: (a) feet hanging; (b) maximum thigh contact; (c) average thigh contact; (d) minimum thigh contact.

transducers of the same sensitivity located at the four corners of a rectangular aluminium plate. Another force platform (Kistler Z 13053; $600 \times 400 \times 47$ mm) was secured to the footrest so as to measure forces at the feet in the vertical direction. Signals from both force platforms were amplified using Kistler 5007 charge amplifiers. Acceleration was measured at the centre of both force platforms using piezo-resistive accelerometers (Entran EGCSY-240D-10). 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.

Four different foot heights, and hence four different sitting postures, were achieved using an adjustable footrest. The four postures were: (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 altering the height of the footrest. The footrest was exposed to the same vertical vibration as the seat. No backrest was used in this study. Fig. 1 shows a schematic diagram of the four postures.

2.2. Experimental design

Twelve male subjects with average age 31.4 years (range 20–47 years), weight 74.6 kg (range 57–106 kg), and stature 1.78 m (range 1.68–1.86 m), were exposed to random vertical vibration with an approximately flat constant bandwidth acceleration power spectrum over the frequency range 0.25–25 Hz. The duration of each exposure was 60 s.

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

2.3. Analysis

The measured data are partly presented as apparent masses in the vertical direction, calculated from the vertical force and vertical acceleration at the seat and footrest. The forces in the fore-and-aft and lateral directions were related to the acceleration measured on the seat in the vertical direction using the concept of cross-axis apparent mass. In both cases, the apparent mass and the cross-axis apparent mass, were calculated using the cross-spectral density (CSD) 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 CSD between the force and the acceleration, and $S_{aa}(\omega)$ is the power spectral density (PSD) of the acceleration. The aluminium plates of the force platforms 'above' the force transducers behaved as rigid bodies (giving constant mass and zero phase over the frequency range of interest) when tested with vertical vibration without a subject. Hence, the static masses of the plates of the force platforms (15 kg for the seat and 33 kg for the footrest) were subtracted from the real parts of the transfer functions measured in the vertical direction.

3. Results

3.1. Response in the vertical direction

The apparent mass data were used to present the results rather than the normalized apparent mass data in order to show the differences between the different postures. It was found that the medians of the normalized apparent masses of the individuals were mostly within 5% (a maximum of 10% at some frequencies) of the normalized median apparent masses.

The apparent masses of the 12 subjects were calculated for each posture and each vibration magnitude. Individual data were of a form similar to those previously published (e.g., Refs. [1,5]). A non-linearity was evident for all subjects in all postures. Fig. 2 shows the median apparent masses of the 12 subjects in the vertical direction at the seat in each posture and at each vibration magnitude. There is a clear decrease in the resonance frequency with an increase in vibration magnitude and a trend towards a reduction in the magnitude of the apparent mass at resonance with an increase in vibration magnitude. Table 1 shows the median resonance frequencies and median apparent masses at resonance for the 12 subjects. Statistical analysis showed significant reductions in the resonance frequencies with increases in vibration magnitudes for all postures ($p < 0.05$; Wilcoxon matched-pairs signed ranks) except between 0.125 and 0.25 $\mathrm{m\,s^{-2}}$ r.m.s. for the maximum thigh contact posture and for the minimum thigh contact posture (Table 2).

Further statistical analysis was conducted to investigate whether subject posture affected the size of the change in the resonance frequency between the two lower vibration magnitudes (i.e., 0.125 and 0.25 $\mathrm{m\,s^{-2}}$ r.m.s.) and between the two higher vibration magnitudes (i.e., 0.625 and 1.25 $\mathrm{m\,s^{-2}}$ r.m.s.). The results, shown in Table 3, indicate that the sizes of differences in the resonance frequencies obtained at the two lower vibration magnitudes did not depend on body posture. However, at the higher vibration magnitudes, there was a significant difference ($p < 0.05$)

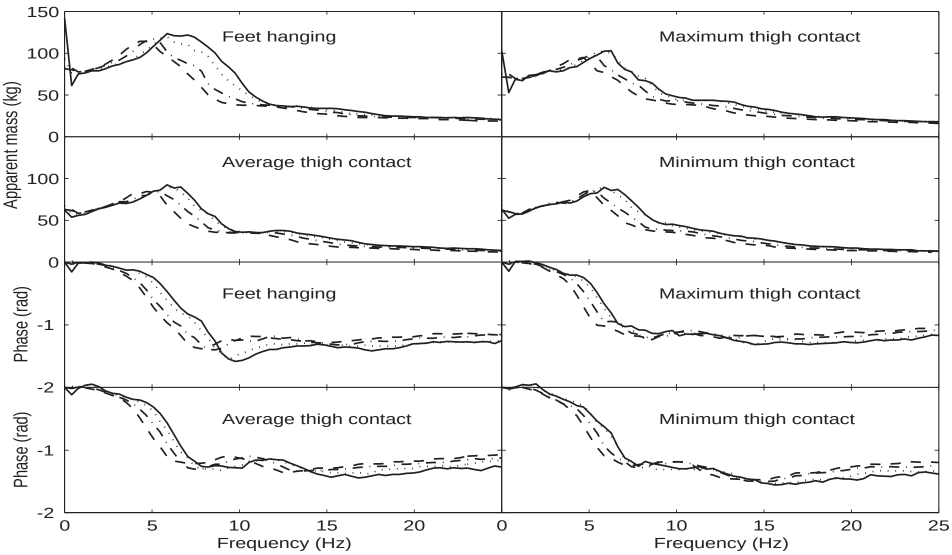

Fig. 2. Median apparent mass and phase angle of 12 subjects in the vertical direction: effect of vibration magnitude. ——, 0.125 m s^{-2} r.m.s.; · · · · ·, 0.25 m s^{-2} r.m.s.; – · – · –, 0.625 m s^{-2} r.m.s.; - - - - -, 1.25 m s^{-2} r.m.s.

Table 1
Median resonance frequencies and magnitudes of apparent mass at resonance for four postures at four vibration magnitudes

Vibration magnitude (m s^{-2} r.m.s.)	Resonance frequency (Hz), resonance magnitude (kg)			
	Feet hanging	Maximum thigh contact	Average thigh contact	Minimum thigh contact
0.125	5.85, 123.4	6.24, 103.1	5.85, 92.2	5.85, 89.5
0.250	5.85, 119.6	5.85, 102.3	5.85, 89.7	5.85, 89.5
0.625	5.07, 117.0	5.07, 98.4	5.46, 84.5	5.07, 85.3
1.25	4.68, 114.3	4.68, 95.1	4.68, 84.6	5.07, 85.6

in the size of the absolute change in the resonance frequencies between the feet hanging posture and the minimum thigh contact posture, and between the maximum thigh contact posture and the minimum thigh contact posture. The changes in the resonance frequencies between the two higher vibration magnitudes in the minimum thigh contact posture were less than those in the other two postures. The change in the magnitude of the apparent mass with change in vibration magnitude was further explored at three frequencies: (a) at resonance, (b) at a frequency below resonance (i.e., 3.12 Hz), and (c) at a frequency above resonance (i.e., 8.2 Hz). The results indicate that the non-linearity decreased when adopting the minimum thigh contact posture (Table 4).

At each vibration magnitude, the median apparent mass also depended on the posture. Like the median apparent masses shown in Fig. 3, the individual data showed a decrease over the whole frequency range when the thigh contact reduced. This is consistent with reduced thigh contact

Table 2
p values for differences in resonance frequencies of apparent mass: effect of vibration magnitude

Vibration magnitude ($m\,s^{-2}$ r.m.s.)	0.125	0.250	0.625	1.250
(a) Feet hanging				
0.125	—	0.014	0.014	0.002
0.250		—	0.005	0.002
0.625			—	0.002
1.250				—
(b) Maximum contact				
0.125	—	0.055	0.002	0.002
0.250		—	0.002	0.002
0.625			—	0.002
1.250				—
(c) Average contact				
0.125	—	0.027	0.002	0.002
0.250		—	0.002	0.002
0.625			—	0.004
1.250				—
(d) Minimum contact				
0.125	—	0.389	0.005	0.002
0.250		—	0.003	0.002
0.625			—	0.029
1.250				—

Table 3
p values for differences in the absolute change in resonance frequencies

(a) Lower vibration magnitudes (0.125 and 0.25 $m\,s^{-2}$ r.m.s.)	H1–H2	Max1–Max2	Av1–Av2	Min1–Min2
H1–H2	—	0.083	0.119	0.118
Max1–Max2			0.234	0.493
Av1–Av2			—	0.834
Min1–Min2				—
(b) Higher vibration magnitudes (0.625 and 1.25 $m\,s^{-2}$ r.m.s.)	H3–H4	Max3–Max4	Av3–Av4	Min3–Min4
H3–H4	—	0.414	0.931	0.014
Max3–Max4		—	0.720	0.021
Av3–Av4			—	0.166
Min3–Min4				—

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 $m\,s^{-2}$ r.m.s.

Table 4
Statistically significant differences between apparent mass magnitudes for four postures

	At the resonance frequency	Below resonance (3.12 Hz)	Above resonance (8.2 Hz)	Total out of 18 possible combinations
Feet hanging	H1/H2 H1/H3 H1/H4 H2/H3	H1/H2 H1/H3 H1/H4 H2/H3 H2/H4 H3/H4	H1/H3 H1/H4 H2/H3 H2/H4 H3/H4	15
Maximum thigh contact	Max2/Max3 Max2/Max4	Max1/Max3 Max1/Max4 Max2/Max4 Max3/Max4	Max1/Max4 Max2/Max3 Max2/Max4 Max3/Max4	10
Average thigh contact	Av1/Av3 Av2/Av3 Av2/Av4	Av1/Av4 Av2/Av4 Av3/Av4	Av1/Av3 Av1/Av4 Av2/Av3 Av2/Av4 Av3/Av4	11
Minimum thigh contact	Min1/Min4	Min2/Min4	—	2

Comparisons shown where $p < 0.05$; Wilcoxon matched-pairs signed ranks test. 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} r.m.s.

increasing the mass supported on the footrest and decreasing the mass supported on the seat. However, the resonance frequency of the apparent mass of the body was little affected by the posture, as shown in the median results and the statistical analysis in Table 5. There was no statistical significant difference in the resonance frequencies between the four postures except between the feet hanging posture and both the minimum thigh contact posture and the average thigh contact posture at 0.125 m s^{-2} r.m.s.

3.2. Response in the fore-and-aft direction

The fore-and-aft forces on the seat were related to the acceleration measured in the vertical direction using the cross-axis apparent mass concept. Fig. 4 shows the variability between subjects (inter-subject variability) in the fore-and-aft response measured at 1.25 m s^{-2} r.m.s. for the four postures. There were considerable forces on the seat in the fore-and-aft direction as a result of vibration applied in the vertical direction. In all postures, the resonance frequency is in the vicinity of 5 Hz, similar to that for the vertical apparent mass. There were high correlations between the resonance frequencies in the vertical response and the resonance frequencies of the fore-and-aft response. In all four postures the correlations were significant at the two higher vibration

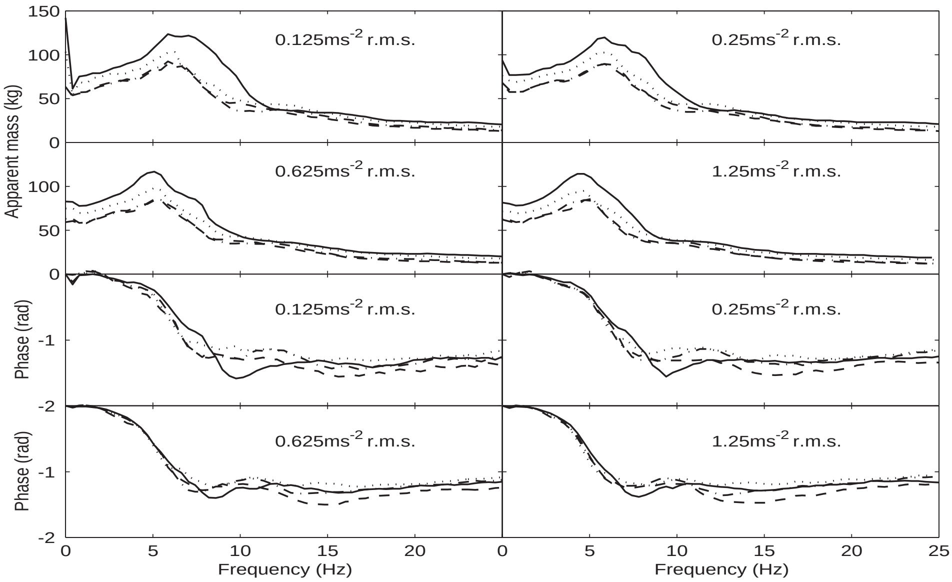

Fig. 3. Median apparent mass and phase angle of 12 subjects in the vertical direction: effect of posture. ——, feet hanging; · · · · ·, maximum thigh contact; – · – · –, average thigh contact; -----, minimum thigh contact.

magnitudes ($p<0.001$; Spearman rank correlation). However, the correlations were not statistically significant at the two lower magnitudes with the feet hanging or with the average thigh contact postures ($p>0.05$).

The resonance frequency apparent in the fore–aft forces decreased with increasing vibration magnitude, similar to the non-linearity in the vertical apparent mass (Fig. 5).

The cross-axis apparent mass in the fore-and-aft direction shows changes with posture: it seems that changing from a posture with no foot support to a posture in which the feet were more supported decreased the forces in the fore-and-aft direction. An exception is the minimum thigh contact posture where the forces were more than those with average thigh contact and slightly less, similar, or more than those with the maximum thigh contact posture, depending on the frequency (Figs. 4 and 5). There were no significant differences in the magnitude of the cross-axis apparent mass at resonance between the minimum and maximum thigh contact postures at any vibration magnitude ($p>0.1$).

3.3. Response in the lateral direction

The lateral forces were calculated using the same cross-axis apparent mass concept: forces in the lateral direction were related to the seat acceleration in the vertical direction. Fig. 6 shows the inter-subject variability in cross-axis apparent mass when subjects were exposed to $1.25\,\mathrm{m\,s^{-2}}$ r.m.s. in the vertical direction. Fig. 7 shows the median cross-axis apparent masses of the 12 subjects in each posture and at each vibration magnitude. Both figures indicate that, in comparison with the forces in the vertical and fore-and-aft directions, the forces in the lateral direction were low during excitation with vertical vibration. Fig. 7 shows no clear effect of

Table 5
p values for differences between resonance frequencies of apparent mass: effect of the sitting posture

(a) $0.125\,\mathrm{m\,s^{-2}}$ r.m.s.	H1	Max1	Av1	Min1
H1	—	0.057	0.002	0.010
Max1		—	0.831	0.339
Av1			—	0.537
Min1				—

(b) $0.25\,\mathrm{m\,s^{-2}}$ r.m.s.	H2	Max2	Av2	Min2
H2	—	0.068	0.287	0.250
Max2		—	0.518	0.671
Av2			—	1.0
Min2				—

(c) $0.625\,\mathrm{m\,s^{-2}}$ r.m.s.	H3	Max3	Av3	Min3
H3	—	0.146	0.236	0.083
Max3		—	0.931	0.299
Av3			—	0.255
Min3				—

(d) $1.25\,\mathrm{m\,s^{-2}}$ r.m.s.	H4	Max4	Av4	Min4
H4	—	0.068	0.072	0.473
Max4		—	0.943	0.49
Av4			—	0.366
Min4				—

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: $1.25\,\mathrm{m\,s^{-2}}$ r.m.s.

vibration magnitude on the cross-axis apparent mass in the lateral direction. At some frequencies the cross-axis apparent mass in the lateral direction is low and only slightly in excess of the 'noise' measured with no subject (about 0.2 kg). Measurements are not shown at frequencies in excess of 10 Hz due to a lateral resonance in the system at about 13 Hz.

3.4. Response at the feet

The dynamic response at the feet was measured for the three postures in which the feet were supported on the footrest. In the maximum thigh contact posture, where the mass of the body supported on the footrest was least, one resonance frequency was found between 5 and 10 Hz. With average thigh contact and with minimum thigh contact, the responses were more complex and more than one resonance appeared for all subjects: at $1.25\,\mathrm{m\,s^{-2}}$ r.m.s. the average thigh contact posture showed two resonances (at 5 and 11 Hz), while the minimum thigh contact

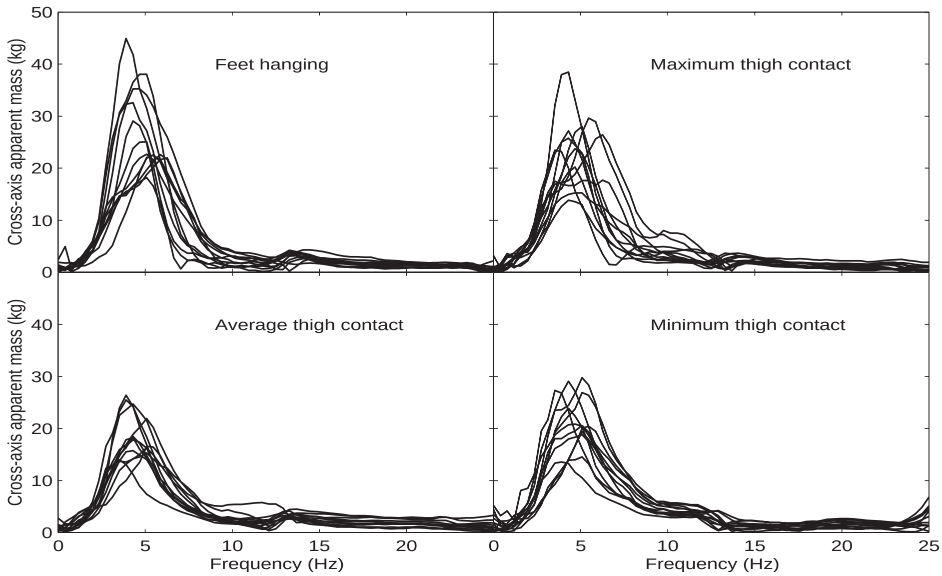

Fig. 4. Inter-subject variability in the cross-axis apparent mass in the fore-and-aft direction for each posture at $1.25\,m\,s^{-2}$ r.m.s.

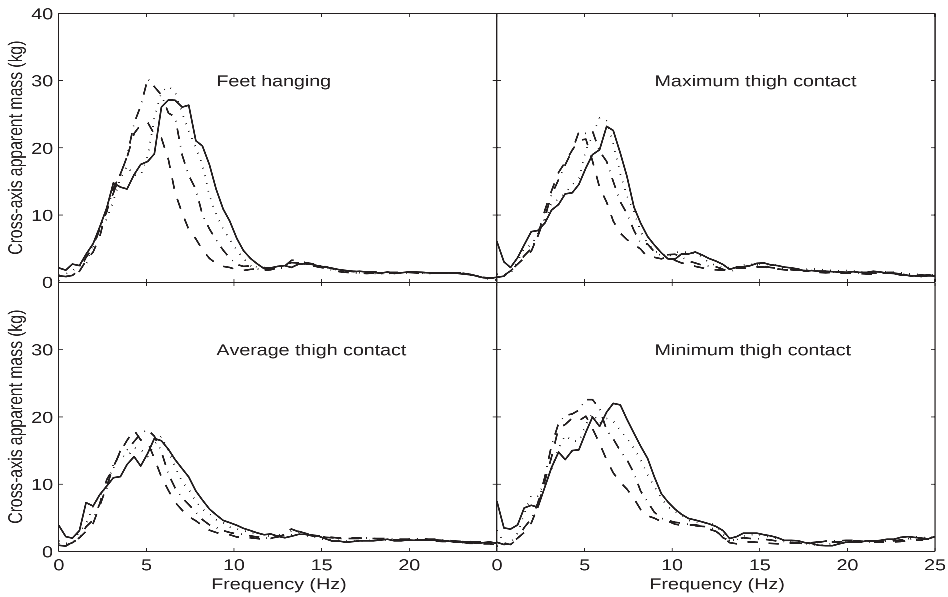

Fig. 5. Median cross-axis apparent masses of 12 subjects in the fore-and-aft direction: effect of vibration magnitude. ———, $0.125\,m\,s^{-2}$ r.m.s.; · · · · ·, $0.25\,m\,s^{-2}$ r.m.s.; – · – · –, $0.625\,m\,s^{-2}$ r.m.s.; - - - - -, $1.25\,m\,s^{-2}$ r.m.s.

posture showed three resonances (at 5, 7.5 and 11 Hz). Some subjects also showed a resonance around 14 Hz in both postures. This behaviour is clear in Fig. 8, which also shows the inter-subject variability in responses at the feet.

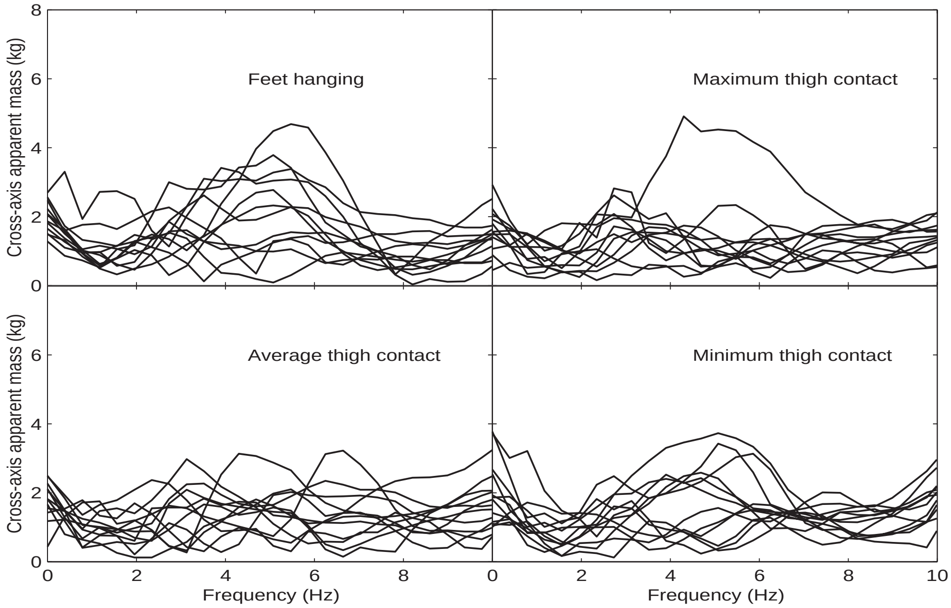

Fig. 6. Inter-subject variability in the cross-axis apparent mass in the lateral direction for each posture at $1.25\,m\,s^{-2}$ r.m.s.

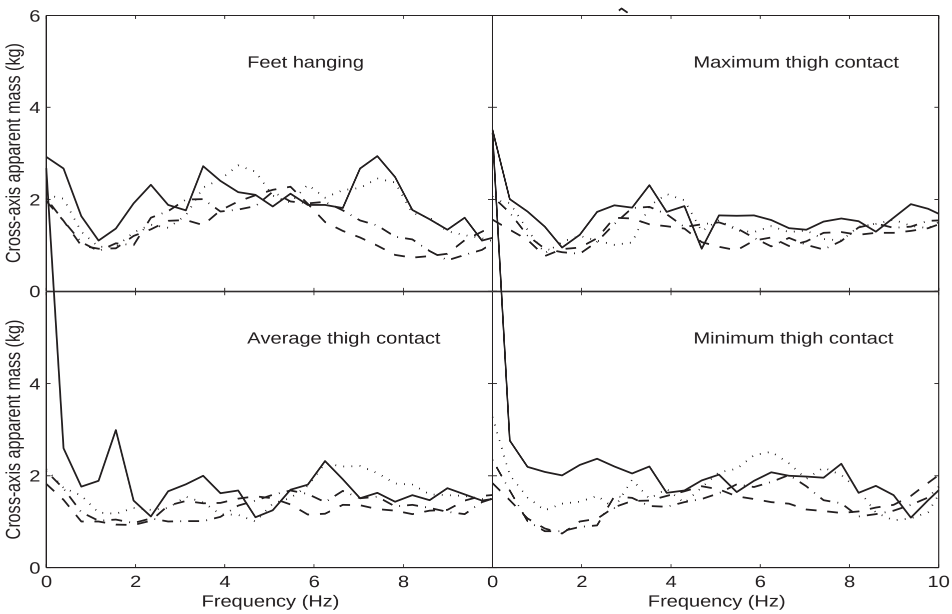

Fig. 7. Median cross-axis apparent mass of 12 subjects in the lateral direction: effect of vibration magnitude. ———, $0.125\,m\,s^{-2}$ r.m.s.; · · · · ·, $0.25\,m\,s^{-2}$ r.m.s.; – · – · –, $0.625\,m\,s^{-2}$ r.m.s.; -----, $1.25\,m\,s^{-2}$ r.m.s.

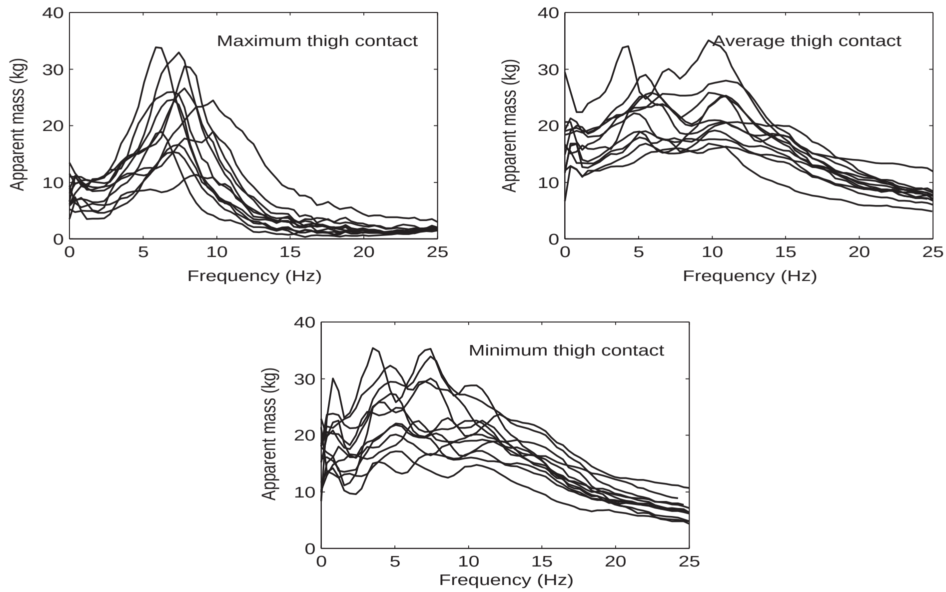

Fig. 8. Inter-subject variability in the apparent mass at the feet in the vertical direction for each posture at $1.25\,\mathrm{m\,s^{-2}}$ r.m.s.

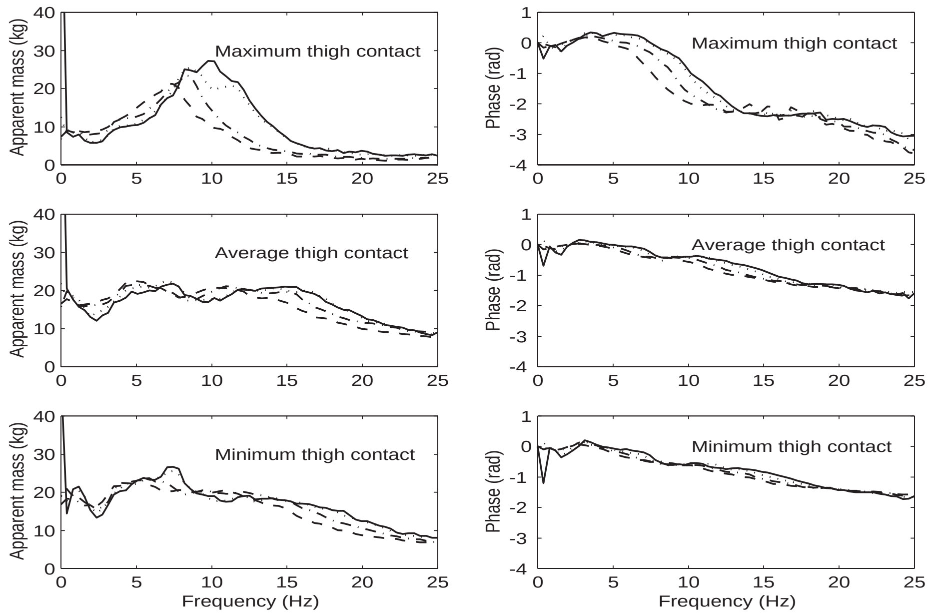

Fig. 9. Median apparent mass and phase angle at the feet of 12 subjects in the vertical direction: effect of vibration magnitude. ———, $0.125\,\mathrm{m\,s^{-2}}$ r.m.s.; · · · · ·, $0.25\,\mathrm{m\,s^{-2}}$ r.m.s.; – · – · –, $0.625\,\mathrm{m\,s^{-2}}$ r.m.s.; -----, $1.25\,\mathrm{m\,s^{-2}}$ r.m.s.

Table 6
Statistically significant differences between apparent mass magnitudes at the feet for three postures

	At 3.1 Hz	At 5.1 Hz	At 8.2 Hz	At 12.1 Hz	Total out of 24 possible combinations
Maximum thigh contact	Max1/Max3 Max1/Max4 Max2/Max3 Max2/Max4 Max3/Max4	Max1/Max3 Max1/Max4 Max2/Max3 Max2/Max4 Max3/Max4	Max2/Max4 Max3/Max4	Max1/Max2 Max1/Max3 Max1/Max4 Max2/Max3 Max2/Max4 Max3/Max4	18
Average thigh contact	Av1/Av3 Av1/Av4 Av2/Av3 Av2/Av4 Av3/Av4	Av1/Av2 Av1/Av3 Av1/Av4 Av2/Av3 Av2/Av4	Av1/Av3	Av1/Av4 Av2/Av4 Av3/Av4	14
Minimum thigh contact	Min1/Min3 Min1/Min 4 Min2/Min4	—	Min2/Min4	—	4

Comparisons shown where $p < 0.05$; Wilcoxon matched-pairs signed ranks test. 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} r.m.s.

The three postures show some non-linear behaviour in the response at the feet (Fig. 9). The median resonance frequency in the maximum thigh contact posture reduced from 9.75 to 7.02 Hz when the vibration magnitude increased from 0.125 to 1.25 m s^{-2} r.m.s. However, statistical analysis (Table 6) showed that the non-linearity decreased when the feet were more supported. It is also clear that the phase lag between acceleration and force at the feet was greater when the feet were less supported.

4. Discussion

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

Biodynamic responses of the human body to vibration are frequently analyzed using linear techniques, such as the CSD method, even though observations suggest that the human body responds non-linearly. When using the CSD method, although a different response is found at different magnitudes, there is generally high coherency between the vertical acceleration and the vertical force at any one magnitude, possibly implying that the body behaves linearly at a 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

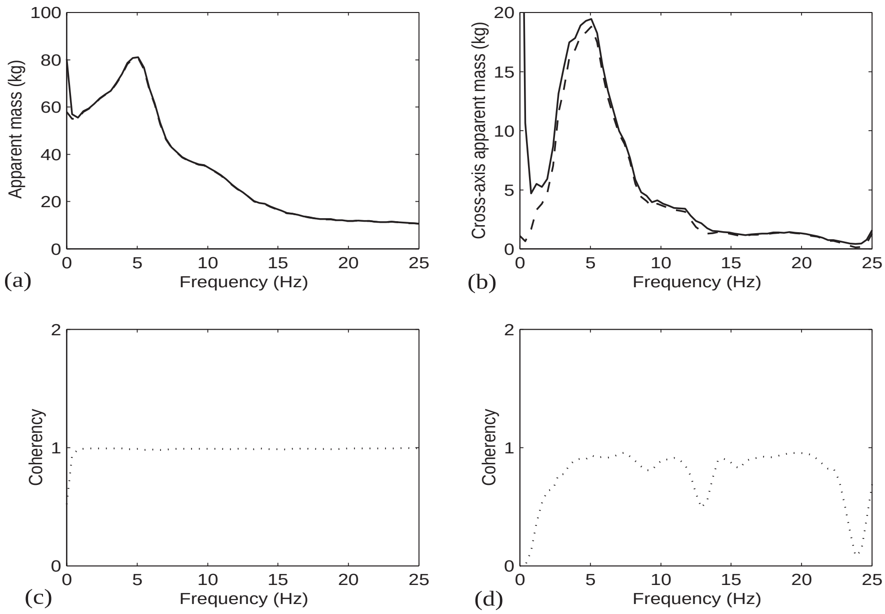

Fig. 10. Apparent mass, cross-axis apparent mass, and coherences of one subject at $1.25\,\mathrm{m\,s^{-2}}$ r.m.s. with the minimum thigh contact posture. (a) apparent mass in the vertical direction, (b) cross-axis apparent mass in the fore-and-aft direction, (c) coherency in the vertical direction, (d) coherency in the fore-and-aft direction. ——, PSD method; - - - - -, CSD method; · · · · ·, coherency.

appropriate when analyzing the response at one vibration magnitude. However, with current understanding, a non-linear response when the body is exposed at only one vibration magnitude cannot be excluded. If the body may behave non-linearly when exposed to a particular magnitude of vibration, it is of interest to compare the use of CSD method and the PSD method for computing the apparent mass. Fig. 10 shows the apparent mass of one subject at $1.25\,\mathrm{m\,s^{-2}}$ r.m.s. 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 fore-and-aft cross-axis apparent mass calculated using the CSD and PSD methods as well as the coherency in the vertical and the fore-and-aft directions. The coherency was calculated after subtracting in the time domain the vertical force arising from the mass of the plate on which the subject sat from the total measured force. It may be seen that the CSD and PSD methods gave very similar apparent masses. This suggests that, whether or not the body behaves linearly at the vibration magnitudes investigated, the use of linear techniques has not produced misleading findings.

4.2. Response in the vertical direction

In all of the postures investigated, the apparent mass of the human body showed a principal resonance in the vicinity of 5 Hz and a second resonance in the range 7–14 Hz. Both resonances decreased with an increase in vibration magnitude, showing a 'non-linearity' as noticed previously (e.g., Refs. [1,4,5,7]). Some subjects exhibited a principal resonance frequency as high as 8.6 Hz, which is higher than previously reported. This high value occurred at the lowest vibration magnitude ($0.125\,\mathrm{m\,s^{-2}}$ r.m.s.), which is lower than used in previous studies.

The precise manner in which the resonance of the body occurs is not yet known. Studies have investigated the parts of the body that cause, or contribute to, the resonance frequency by measuring the transmissibility to specific locations and comparing the results to the resonance frequency of the whole-body (e.g., Refs. [5,19,21]). Hagena et al. [21] measured vertical transmissibilities from the platform of a shaker to vibration at the head, the seventh cervical vertebra, the sixth thoracic vertebra, the first, fourth and fifth lumbar vertebrae and the sacrum with both seated and standing subjects. They found that the transmissibility to each of the measurement locations increased at about 4 Hz, which led them to conclude that the entire body has a resonance at about 4 Hz. Mansfield and Griffin [5] found that the vertical transmissibility to the spine, posterior superior iliac spine and iliac crest have a resonance frequency similar to that found in the apparent mass and concluded that the peaks in the transmissibilities and apparent mass are produced by the same mechanisms. Matsumoto and Griffin [19] illustrated the movement of the upper bodies of seated subjects at the principal resonance frequency using transmissibilities from vertical seat vibration to vertical, fore-and-aft, and pitch vibration at eight locations on the body (at the first, fifth and tenth thoracic vertebrae, at the first, third and fifth lumbar vertebrae, at the pelvis, and at the head). They concluded that more than one vibration mode may contribute to the principal resonance frequency of the human body but that bending and rocking modes of the spine may contribute to the resonance frequency of the apparent mass. A pitch mode of the pelvis, which might have been accompanied by axial and shear deformation of the pelvis tissue, was noticed close to the resonance frequency. In a later study in which the vertical and the fore-and-aft transmissibilities were modelled, Matsumoto and Griffin [14] suggested that bending or buckling of the vertebral column probably made a minor contribution to the resonance frequency and that the major contribution may come from deformation of the tissue beneath the pelvis and the vertical motion of the viscera. The presence of different modes at and around the resonance frequency may suggest that these modes are closely coupled with each other due to the heavy damping of the body.

The parts of the body contributing to the principal resonance frequency of the body can also be identified by varying the properties of the parts of the body in a mathematical model and observing the changes to the resonance frequency. For example, Kitazaki and Griffin [22] used a finite element model and found that a shift in the apparent mass resonance associated with altering body posture could be achieved by changing the axial stiffness of the buttocks tissue. This implies that the buttocks tissues might be partly responsible for the resonance frequency.

The differences in the apparent masses between the four postures (as shown in Fig. 3) arise because with the feet hanging the whole of the body mass is supported on the seat. Increasing the height of the footrest increased the mass of the body supported on the footrest and decreased the mass supported on the seat. Hence, the minimum thigh contact posture exhibited the lowest apparent mass. However, this change in the distribution of mass between the footrest and the seat had little or no effect on the resonance frequency of the body. The absence of a significant change in the resonance frequency with the changes in posture in this study could suggest that the principal resonance frequency depends on the motion of the upper body regardless of the changes at the thighs and the legs. This hypothesis might be supported by the similarity of the resonance frequencies between the standing and the sitting positions measured in previous studies (e.g., Refs. [23,24]).

An alternative explanation for the resonance frequency being independent of the postures studied here could be that changing from one posture to another not only changed the distribution of the subject mass on the seat and the footrest but also changed the stiffness of the thighs. This may have maintained the same proportional contribution of the mass and the stiffness to the resonance frequency in the four postures.

A non-linear response of the human body to vibration has been found in transmissibility measurements to various parts of the body (e.g., Refs. [2,10,25]) as well as in mechanical impedance and apparent mass measurements. In the present study, where only apparent mass was measured, the extent of the non-linearity differed between the four postures: a finding that may assist the identification of the mechanisms that cause non-linearity. The position of the feet changed the degree to which the thighs were in contact with the seat and also changed the pressure on tissues beneath the pelvis. For example, changing from the maximum thigh contact posture to the minimum thigh contact posture increased the mass supported on the footrest, reduced the mass supported on the seat and reduced the area of contact at the seat, so increasing the pressure on the pelvis tissue and increasing the stiffness of these tissues. Sandover [26] noticed an increase in the resonance frequency of the body from 4 to 6 Hz when two 25 mm cubes were placed under the ischial tuberosities, implying an increase in the stiffness of these tissues by increasing the pressure on them. An increase in the stiffness of the tissues of the ischial tuberosities might be the reason for a decrease in the non-linearity in the minimum thigh contact posture: a previous study found decreased non-linearity when the buttocks were tensed [9]. This is also consistent with previous suggestions that deformation of tissues beneath the pelvis contribute to the non-linearity of the body in response to vibration [9,13,25].

It has been suggested that involuntarily muscle activity may contribute to the non-linearity of the human body in response to vibration. Matsumoto and Griffin [9] reported less clear non-linear characteristics in the apparent masses of seated subjects when involuntary muscle activity was reduced by controlling muscle tension in the abdomen and the buttocks. It was reported by some subjects in the present study that maintaining an upright upper body posture with minimum thigh contact was more difficult than with the other three postures. Subjects may have used their muscles to keep the required upright posture and hence reduced the effect of involuntarily changes in muscle tension during vibration. This may be another reason for the reduced non-linearity in the minimum thigh contact posture.

In all postures, the apparent masses at very low frequencies were equal to the static masses of the subjects supported on the seat. At all frequencies, increasing the footrest height decreased the apparent mass of the body measured at the seat due to the increased mass supported at the feet. However, this seems to be only true for a footrest vibrating in phase with the seat. Fairley and Griffin [1] found a dramatic effect of the height of a stationary footrest on the apparent mass of the body at low frequencies where the apparent mass did not tend toward the static mass on the seat but decreased with a decrease in the height of the footrest. The authors attributed this observation to relative movement between the feet and the seat.

4.3. Response in the fore-and-aft direction

The forces measured in the fore-and-aft direction are consistent with the only previous study [9] to have quantified these forces. The individual data in the present study showed that, at resonance, the cross-axis apparent mass in the fore-and-aft direction could reach up to 60% of the static mass of the subject. Matsumoto and Griffin [9] did not observe the clear peaks apparent in this study around 5 Hz, possibly due to the different conditions in which the feet of their subjects rested on a stationary footrest. A two-dimensional motion is consistent with the fore-and-aft and pitch transmissibilities measured on the body during vertical vibration [19,21] and the high shear forces at the third lumbar vertebra predicted by Fritz [27] for a biomechanical model of responses to vertical vibration.

The high forces measured in the fore-and-aft direction might be attributed to some combination of bending or rotational modes of the upper thoracic and cervical spine at the principal resonance frequency or a bending mode of the lumbar and lower thoracic spine, as found by Kitazaki and Griffin [22] at a mode close to the principal resonance. The fore-and-aft and pitch transmissibilities from vertical seat vibration to six locations on the spine, the head and the pelvis reported by Matsumoto and Griffin [19] showed high values around the resonance frequency especially at the head and the first thoracic vertebra. The forces measured in the fore-and-aft direction in this study may be assumed to be associated with the motions found by Kitazaki and Griffin [22] and Matsumoto and Griffin [19], but their full explanation must await an improved biodynamic model of the linear and non-linear motions of the body.

It was expected that postures with less foot support would produce greater forces in the fore-and-aft direction due to increased free movement of the body. This was true for all postures except with minimum thigh contact, which showed forces more than those found with average thigh contact and similar or more than those found with maximum thigh contact. It seems that with minimum thigh contact it was easy for the body to pivot around the pelvis with a pitching motion that was translated into forces in the fore-and-aft direction.

When a driver is exposed to multi-axis vibration in a vehicle, there will be two fore-and-aft force components contributing to the total force in the fore-and-aft direction on the seat surface. One component of force comes from the reaction of the body to fore-and-aft seat vibration. The other component comes from fore-and-aft forces arising from the responses of the body to vertical vibration, as shown in this study. Since magnitudes of vertical vibration can often be much greater than magnitudes of fore-and-aft vibration, the contribution to the total fore-and-aft force from the component caused by vertical vibration may be significant. In which case, this force may appreciably enhance (or cancel) the fore-and-aft force arising from fore–aft vibration. The prediction of the fore-and-aft transmissibilities of seat cushions may need to take this additional force into account.

The well-known non-linearity in the apparent mass of the body in the vertical direction was also evident in the cross-axis apparent mass measured in the fore-and-aft direction. However, in the fore-and-aft direction the non-linearity was less with average thigh contact than with the other three postures. This may imply that the mechanisms that affected the non-linearity in the vertical direction had a different effect on the non-linearity in the fore-and-aft direction: increasing the pressure on the tissue beneath the pelvis in the minimum thigh contact posture reduced the non-linearity in the vertical direction only. This is consistent with the result of Matsumoto and Griffin

[9] who showed that tensing the muscles of the tissue beneath the pelvis had an effect on the non-linearity in the vertical direction but not the fore-and-aft direction. Since tensing the buttocks muscles in the Matsumoto and Griffin study is assumed to have increased the stiffness of the tissue beneath the pelvis in the vertical and the fore-and-aft direction, it may be hypothesized that neither the axial nor the shear deformation of the buttocks tissue affects the non-linearity found in the fore-and-aft response.

4.4. Response in the lateral direction

Forces measured in the lateral direction were small compared to those in the fore-and-aft direction. The lower forces in the lateral direction than in the fore–aft direction are presumably the consequences of the symmetry of the human body either side of the mid-sagittal plane. The centre of gravity of the seated human body is in the mid-sagittal plane but forward of the ischial tuberosities where the vibration enters the upper body. This makes it easier for the body to pitch around the lateral axis than to roll around the fore-and-aft axis of the body.

4.5. Response at the feet

Only a few studies have investigated the biodynamic response of the feet to vibration. Kitazaki [28] studied the response of the feet to vertical vibration at $1.0\,\mathrm{m\,s^{-2}}$ r.m.s. With subjects sitting in an inclined rigid seat with an inclined backrest but with knees at angle of 90°, he found resonance frequencies at about 5, 7.5, and 12 Hz, similar to those found in this study at $1.25\,\mathrm{m\,s^{-2}}$ r.m.s. with the minimum thigh contact posture. In the study by Kitazaki, the 12 Hz resonance frequency disappeared when the subjects changed the knee angle from 90° to 110°. In this study, the 7.5 Hz resonance disappeared when the subjects adopted the average thigh contact posture.

The forces measured at the feet in this study were due to the point impedance of the feet but may also have arisen from forces transmitted from the upper body down the legs. Kitazaki [28] compared the response of the feet with whole-body vibration with their 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.

In the present study, the non-linearity in the responses at the seat were also apparent in the apparent mass measured at the feet. A similar finding was reported by Kitazaki [28]: the resonance frequencies of the feet decreased when the vibration magnitude increased. A non-linearity has also been observed in the vertical direction at the feet of standing subjects and in the fore-and-aft transmissibility to the knees of standing subjects adopting a bent knee posture [4]. The non-linearity in the response of the feet may be partly due to the deformation of tissues of the feet, similar to the hypothesized deformation of the tissues under the pelvis. This proposition is supported by the decrease in non-linearity of both the upper body and the feet in the minimum thigh contact posture, where the tissues under the pelvis and the feet may have been stiffer due to increased forces at both locations. The non-linearity might alternatively, or additionally, have arisen from bending motions of the joints or as a reflection of the non-linearity that takes place in the upper body.

The phase lag between the force and the acceleration measured at the feet was less when there was more mass of the body supported on the footrest. One of the possible explanations for this is that the stiffness of the feet tissues might have increased when the feet were more supported.

5. Conclusion

Varying degrees of non-linearity of the human body have been observed in response to vertical vibration with four postures differing in the degree of thigh contact with the seat, with least non-linearity in a posture having least thigh contact. The results imply little effect of thigh stiffness on the non-linear behaviour but are consistent with the buttocks tissue affecting the non-linearity. Compressing the tissue beneath the ischial tuberosities in this posture may have increased the tissue stiffness and reduced the non-linearity.

Forces on the seat in the fore-and-aft direction, produced by vibration of the seat in the vertical direction were high and varied with posture. Forces in the lateral direction were relatively small. The study confirms that the human body has appreciable movements in two dimensions when exposed to vertical vibration. The two-dimensional movement should be considered when modelling non-vertical vibration isolation devices, including seats.

The feet showed a complex response with multiple resonances that varied with posture: both the position of the feet and the upper body affected the forces measured at the feet.

References

[1] T. Fairley, M.J. Griffin, The apparent mass of the seated human body: vertical vibration, Journal of Biomechanics 22 (1989) 81–94.
[2] S. Kitazaki, Application of experimental modal analysis to the human whole-body vibration, United Kingdom Informal Group Meeting on Human Response to Vibration, Institute of Sound and Vibration Research, University of Southampton, Southampton, UK, 28–30 September, 1992.
[3] P. Holmlund, R. Lundström, L. Lindberg, Whole-body vibration. Mechanical impedance of human body in the vertical direction, United Kingdom Informal Group Meeting on Human Response to Vibration, Silsoe, Bedford, UK, 18–20 September 1995.
[4] Y. Matsumoto, M.J. Griffin, Dynamic response of the standing human body exposed to vertical vibration: influence of posture and vibration magnitude, Journal of Sound and Vibration 212 (1998) 85–107.
[5] N.J. Mansfield, M.J. Griffin, Non-linearities in apparent mass and transmissibility during exposure to whole-body vertical vibration, Journal of Biomechanics 33 (2000) 933–941.
[6] R.R. Coermann, The mechanical impedance of the human body in sitting and standing positions at low frequencies, Human Factors 4 (1962) 227–253.
[7] B. Hinz, H. Seidel, The nonlinearity of the human body's dynamic response during sinusoidal whole-body vibration, Industrial Health 25 (1987) 169–181.
[8] M.J. Griffin, Handbook of Human Vibration, Academic Press Limited, London, 1990.
[9] Y. Matsumoto, M.J. Griffin, Effect of muscle tension on non-linearities in the apparent masses of seated subjects exposed to vertical whole-body vibration, Journal of Sound and Vibration 253 (2002) 77–92.
[10] Y. Matsumoto, M.J. Griffin, Non-linear characteristics in the dynamic responses of seated subjects exposed to vertical whole-body vibration, Journal of Biomechanical Engineering 124 (2002) 527–532.
[11] S.D. Smith, Modelling differences in the vibration response characteristics of the human body, Journal of Biomechanics 33 (2000) 1513–1516.

[12] M.J. Griffin, Vertical vibration of seated subjects: effect of posture, vibration level and frequency, Aviation Space and Environmental Medicine 46 (1975) 269–276.
[13] S. Kitazaki, Modelling Mechanical Responses to Human Whole-Body Vibration, Ph.D. Thesis, University of Southampton, 1994.
[14] Y. Matsumoto, M.J. Griffin, Modelling the dynamic mechanisms associated with the principal resonance of the seated human body, Clinical Biomechanics 16 (2001) 31–44.
[15] T. Fairley, M.J. Griffin, The apparent mass of the seated human body in the fore-and-aft and lateral directions, Journal of Sound and Vibration 139 (1990) 299–306.
[16] N.J. Mansfield, R. Lundström, The apparent mass of the human body exposed to non-orthogonal horizontal vibration, Journal of Biomechanics 32 (1999) 1269–1278.
[17] P. Holmlund, R. Lundström, Mechanical impedance of the human body in the horizontal direction, Journal of Sound and Vibration 215 (1998) 801–812.
[18] S. Kitazaki, M.J. Griffin, Resonance behaviour of the seated human body and effects of posture, Journal of Biomechanics 31 (1998) 143–149.
[19] Y. Matsumoto, M.J. Griffin, Movement of the upper-body of seated subjects exposed to vertical whole-body vibration at the principal resonance frequency, Journal of Sound and Vibration 215 (1998) 743–762.
[20] M.M. Panjabi, G.B.J. Anderson, L. Jorneus, E. Hult, L. Mattsson, In vivo measurements of spinal column vibrations, Journal of Bone Joint Surgery Incorporated A 68 (1986) 695–702.
[21] F.W. Hagena, C.J. Wirth, J. Piehler, W. Plitz, G.O. Hofmann, T. Zwingers, In vivo experiments on the response of the human spine to sinusoidal Gz-vibration, AGARD Conference Proceedings 378 (1985) 1–12.
[22] S. Kitazaki, M.J. Griffin, A modal analysis of whole-body vertical vibration using a finite element model of the human body, Journal of Sound and Vibration 200 (1997) 83–103.
[23] T. Miwa, Mechanical impedance of human body in various postures, Industrial Health 13 (1975) 1–22.
[24] Y. Matsumoto, M.J. Griffin, Comparison of biodynamic responses in standing and seated human bodies, Journal of Sound and Vibration 238 (2000) 691–704.
[25] N.J. Mansfield, Non-linear Dynamic Response of the Seated Person to Whole-Body Vibration, Ph.D. Thesis, University of Southampton, 1998.
[26] J. Sandover, Modelling human responses to vibration, Aviation Space and Environmental Medicine 49 (1978) 335–339.
[27] M. Fritz, Description of the relation between the forces acting in the lumbar spine and whole-body vibrations by means of transfer functions, Clinical Biomechanics 15 (2000) 234–240.
[28] S. Kitazaki, The apparent mass of the foot and prediction of floor carpet transfer function, United Kingdom Group Meetingon Human Response to Vibration, University of Southampton, Southampton, UK, 17–19 September, 1997.