Available online at www.sciencedirect.com

SCIENCE @ DIRECT®

Journal of Sound and Vibration 277 (2004) 309–326

JOURNAL OF
SOUND AND
VIBRATION

www.elsevier.com/locate/jsvi

# Tri-axial forces at the seat and backrest during whole-body vertical vibration

N. Nawayseh, M.J. Griffin*

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

Received 4 March 2003; accepted 1 September 2003

---

## Abstract

During exposure of seated subjects to vertical whole-body vibration, forces in the fore-and-aft, lateral and vertical directions at the seat and backrest have been measured. The responses at the seat have been compared with those measured previously on a seat without a backrest. Twelve male subjects were exposed to random vertical vibration in the frequency range 0.25–20 Hz. The subjects sat on a rigid seat with a rigid backrest and were exposed to a 16 different conditions: four vibration magnitudes (0.125, 0.25, 0.625, and $1.25\,\mathrm{m\,s^{-2}}$ r.m.s.) and four sitting postures (with varying thigh contact with the seat). Although the excitation was vertical, considerable dynamic forces were found in the fore-and-aft direction on both the seat and the backrest. In the vertical direction on the backrest, and in the lateral direction on the seat and the backrest, the forces were low. At both the seat and the backrest, forces in all directions showed a non-linear behaviour. The presence of the backrest modified the forces on the seat in both the vertical and fore-and-aft directions: in all four postures there was an increase in the resonance frequency of the apparent mass when using the backrest. The effect of the backrest on fore-and-aft forces on the seat depended on whether the feet were supported or not. The results show the importance of considering the backrest when studying the response of the human body to whole-body vertical vibration.

© 2003 Elsevier Ltd. All rights reserved.

---

## 1. Introduction

Whole-body vibration can cause discomfort and interfere with activities and may cause back problems [1]. During vertical whole-body vibration, the human spine is alternately compressed and extended while bending and rocking. The axial and shear forces in the spine may be expected to influence the various effects of vibration, but are difficult to measure. Forces at the interfaces of

---

*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/$ - see front matter © 2003 Elsevier Ltd. All rights reserved.
doi:10.1016/j.jsv.2003.09.048

the body with the source of vibration (such as the seat and the backrest) reflect how the body moves during vibration and are relatively easy to measure. For example, forces in the vertical and fore-and-aft directions at the seat reflect two-dimensional movement of the body during vertical excitation [2,3].

Backrests affect the posture of the body by changing the spine curvature, which changes the geometry and stiffness of the body and the body's response to vibration [1]. With horizontal vibration, backrests may restrict body movements (at low frequencies) and may act as an additional source of vibration (at high frequencies), as reported by Fairley and Griffin [4].

A few studies have investigated the effect of a backrest on the vertical apparent mass of seated subjects (e.g., Refs. [5,6]). Fairley and Griffin [5] found that sitting with a backrest increased the resonance frequency of the body and increased the apparent mass at frequencies above resonance. Mansfield [6] also found an increase in the apparent mass above resonance when using a backrest but found no significant differences between the resonance frequencies with a normal upright posture and a back-on posture (i.e., the back in contact with the backrest).

Studies of the transmission of vertical seat vibration to various locations up the spine have been conducted using seats without a backrest (e.g., Ref. [7]). Because of practical limitations, studies with backrests have mainly measured transmissibility to the head (e.g., Ref. [8]) with a few studies reporting transmissibility to the pelvis [6]. Paddan and Griffin [8–11] studied the effect of a rigid backrest on seat-to-head transmissibility with six directions of excitation (vertical, fore-and-aft, lateral, roll, pitch and yaw) and six directions of head movement. With vertical excitation, they reported a decrease in inter-subject variability with a backrest but an increase in head vibration, especially in the mid-sagittal plane in the frequency range 5–10 Hz. They also reported a small lateral head motion during vertical and fore-aft excitation with back-on and back-off postures. Mansfield [6] reported an increase in pelvis rotation at resonance when a backrest was used, compared with an upright posture without backrest. He also mentions an increase in inter-subject variability with a backrest, opposite to that for seat-to-head transmissibility reported by Paddan and Griffin [8]. A minor effect of backrests, attenuating vibration at the third lumbar vertebra, was reported by Magnusson et al. [12].

Although some form of backrest is present on most seats, there appears to have been no study of the apparent mass measured at the back with any axis of vibration: fore-and-aft, lateral or vertical. The present study investigated forces at the seat and the backrest in three axes (vertical, fore-and-aft, and lateral) during whole-body vertical vibration. It was hypothesized that the backrest would modify the forces previously measured on the same seat without a backrest by Nawayseh and Griffin [3] and that although there would be appreciable forces in the vertical and fore-and-aft directions at the seat and backrest there would be small forces in the lateral direction.

## 2. Apparatus, experimental design and analysis

### 2.1. Apparatus

Subjects were exposed to random vertical vibration using an electro-hydraulic vibrator capable of producing a peak-to-peak displacement of 1 m. A rigid seat with a vertical rigid backrest was mounted on the platform of the vibrator. The backrest was fixed and not adjustable to subject height, and hence different subjects had different contact areas between the back and the backrest. An adjustable footrest (to give different foot heights) moved vertically in phase with the seat. Signals from a tri-axial force plate (Kistler 9281 B; 600 × 400 × 20 mm) and a single axis force plate (Kistler Z 13053; 600 × 400 × 47 mm) were amplified by Kistler 5007 charge amplifiers so as to measure the forces at the backrest and the seat. Vertical 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 digitized at 200 samples per second via 67 Hz anti-aliasing filters.

## 2.2. Experimental design

Twelve male subjects with average age 29.9 years (range 20–46 years), weight 77.2 kg (range 62–106 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 0.25–20 Hz. The duration of each exposure was 60 s.

Sixteen different conditions consisted of four vibration magnitudes (0.125, 0.25, 0.625, and 1.25 $\mathrm{m\,s^{-2}}$ r.m.s.) and four sitting postures. The four sitting postures were achieved by changing the height of an adjustable footrest while keeping the upper body in an upright posture so that any effect on the measurements would be due to a change in footrest height. The postures were: (i) ‘feet hanging’ with no foot support, (ii) feet supported with ‘maximum thigh contact’ (i.e., heels just in touch 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)). In each posture, the twelve subjects were exposed to four vibration magnitudes. The presentation of the four postures and the four vibration magnitudes was balanced across subjects. Fig. 1 shows a schematic diagram of the four postures, which are identical to those used in a previous study without a backrest by Nawayseh and Griffin [3].

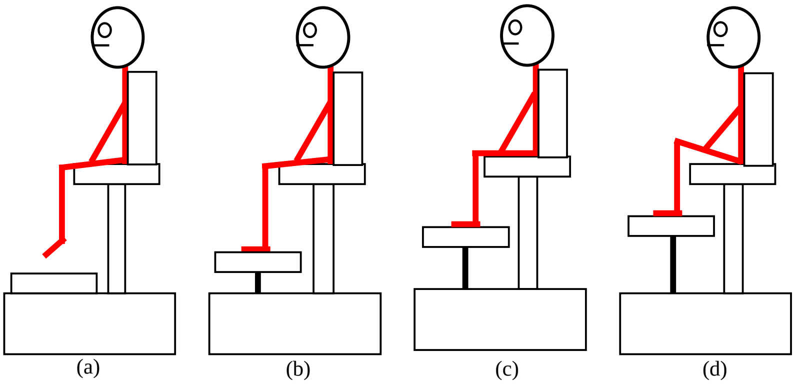

Fig. 1. Schematic diagrams of the four sitting postures: (a) feet hanging; (b) maximum thigh contact; (c) average thigh contact and (d) minimum thigh contact.

The experiment was carried out in two sessions. In the first session, the tri-axial force platform was secured to the rigid backrest and the single-axis force platform was secured to the seat. In the second session, the force platforms were swapped between the seat and the backrest so that tri-axial forces on both the seat and backrest in the fore-and-aft, lateral and vertical directions could be obtained.

### *2.3. Analysis*

The data are partly presented as apparent masses in the vertical direction, calculated from the vertical force and vertical acceleration at the seat and backrest. The forces in the fore-and-aft and lateral directions on the seat and the backrest 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 method:

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

where, $M(\omega)$ is the apparent mass (or the cross-axis apparent mass), $S_{\mathrm{af}}(\omega)$ is the cross-spectral density between the force and the acceleration, and $S_{\mathrm{aa}}(\omega)$ is the power spectral density of the acceleration. The masses of the aluminium plates of the force platforms 'above' the force transducers (15 kg for the tri-axial force plate and 33 kg for the single axis force plate) were included in the forces measured in the vertical direction and hence mass cancellation was performed in order to remove the effect of these masses. Mass cancellation was performed in the time domain by subtracting the time history of the force on the aluminium plate (the mass of the plate multiplied by the measured acceleration time history) from the time history of the measured force.

Statistical analysis was performed using the non-parametric Wilcoxon matched-pairs signed ranks test.

## 3. Results

### *3.1. Static forces on the backrest*

The static forces that the backs of the subjects exerted on the backrest in the fore-aft direction in the four sitting postures were measured without vibration. The static forces were greater in the minimum thigh contact posture than in the feet hanging posture. The medians of the static forces were 42, 44.5, 52.5 and 79.5 N with inter-quartile ranges of 27, 19, 22, and 25.75 N for the feet hanging, maximum thigh contact, average thigh contact and minimum thigh contact postures, respectively. There were statistically significant differences ($p < 0.05$) in the static forces between postures, except between the feet hanging posture and the maximum thigh contact posture ($p = 0.82$). This seems reasonable since the maximum thigh contact posture is similar to the feet hanging posture except that the feet are just touching the footrest in the maximum thigh contact posture.

### 3.2. Response in the vertical direction (seat and backrest)

#### 3.2.1. Apparent mass at the seat

In both sessions, the vertical apparent mass was measured on the seat. The apparent masses of each of the 12 subjects measured in the first session were within 8% of those measured in the second session in all postures over the whole frequency range of interest (0.25–20 Hz). There were no significant differences in the resonance frequencies of the 12 subjects measured in the two sessions for any combination of posture and vibration magnitude.

Fig. 2 compares the vertical apparent masses of the 12 subjects measured at four vibration magnitudes in the average thigh contact posture in the second session using the tri-axial force platform. There was a decrease in both the first and the second resonance frequencies of the body with an increase in vibration magnitude. A very similar non-linearity was also evident in the other three postures (Fig. 3). Statistical analysis showed significant differences between the resonance frequencies of the apparent mass measured at different vibration magnitudes ($p < 0.05$; except between 0.125 and 0.25 m s$^{-2}$ r.m.s. in both the maximum thigh contact posture and the minimum thigh contact posture, and between 0.625 and 1.25 m s$^{-2}$ r.m.s. in the average thigh contact posture).

Further statistical analysis investigated 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 m s$^{-2}$ r.m.s.) and between the two higher vibration magnitudes (i.e., 0.625 and 1.25 m s$^{-2}$ r.m.s.). The results indicated no significant difference in the change of the resonance frequency between postures between the two lower vibration magnitudes and the two higher vibration magnitudes.

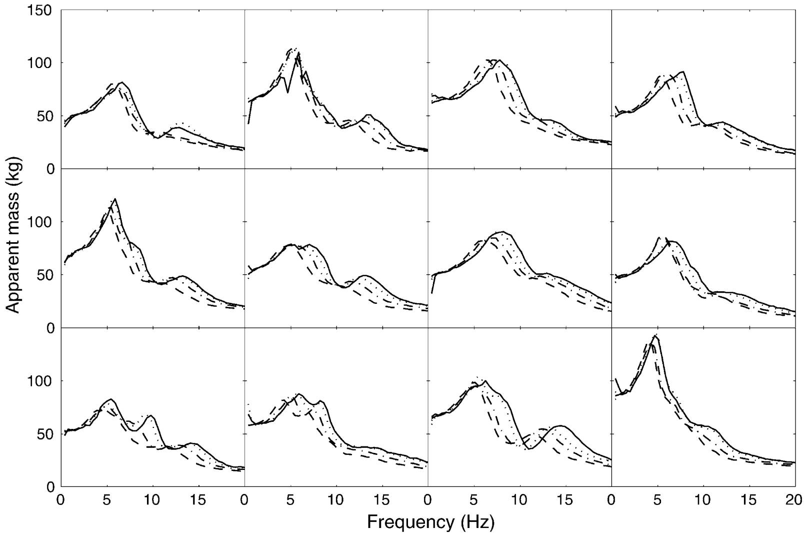

Fig. 2. Apparent masses of 12 subjects measured in the average thigh contact posture at four vibration magnitudes. ——, 0.125 m s$^{-2}$ r.m.s.; ·········, 0.25 m s$^{-2}$ r.m.s.; –· –· –, 0.625 m s$^{-2}$ r.m.s.; – – – –, 1.25 m s$^{-2}$ r.m.s.

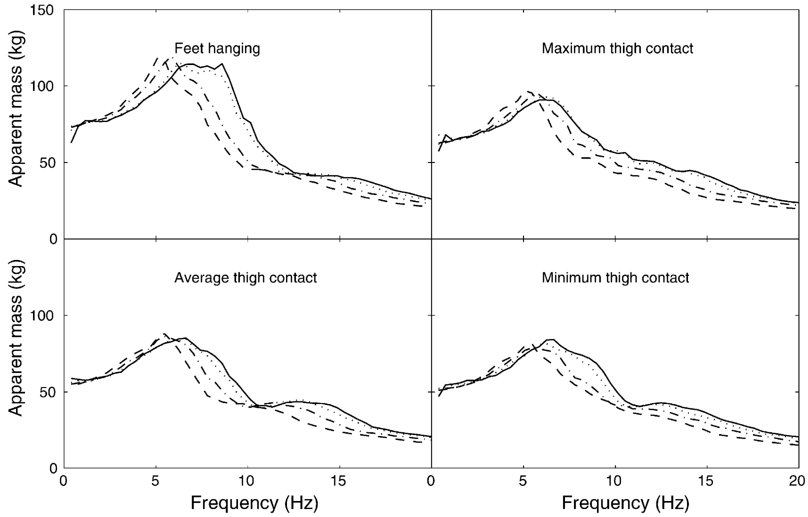

Fig. 3. Median apparent mass of twelve subjects in the vertical direction: Effect of vibration magnitude. ——, $0.125\,\mathrm{m\,s^{-2}}$ r.m.s.; ·········, $0.25\,\mathrm{m\,s^{-2}}$ r.m.s.; –· –· –, $0.625\,\mathrm{m\,s^{-2}}$ r.m.s.; ––––, $1.25\,\mathrm{m\,s^{-2}}$ r.m.s.

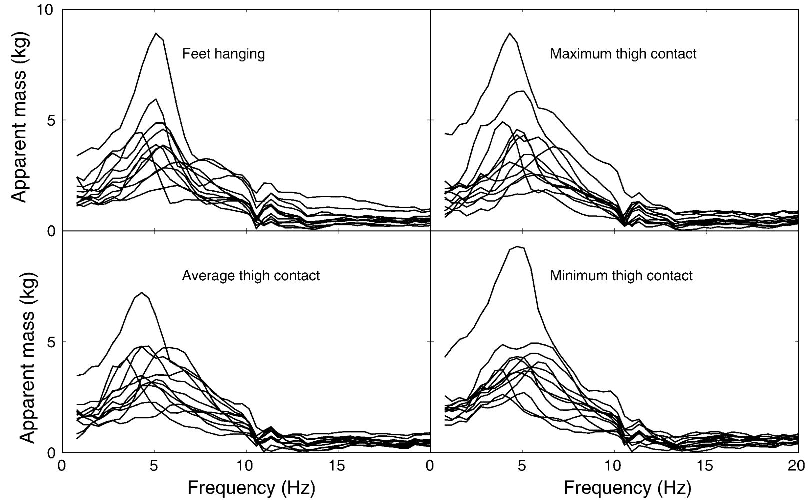

Fig. 4. Inter-subject variability in the apparent mass measured at the back in the vertical direction for each posture at $1.25\,\mathrm{m\,s^{-2}}$ r.m.s.

### *3.2.2. Apparent mass at the back*

Fig. 4 shows the inter-subject variability in the vertical apparent mass measured in four sitting postures at the backrest during exposure to $1.25\,\mathrm{m\,s^{-2}}$ r.m.s. There is high subject variability, with a resonance frequency in the vicinity of 5 Hz. The forces produced at the back in the vertical direction were small relative to those at the seat in the vertical direction.

Apparent masses at the backs of 12 subjects adopting the minimum thigh contact posture show resonance frequencies in the range 5–7 Hz (depending on the subject and vibration magnitude),

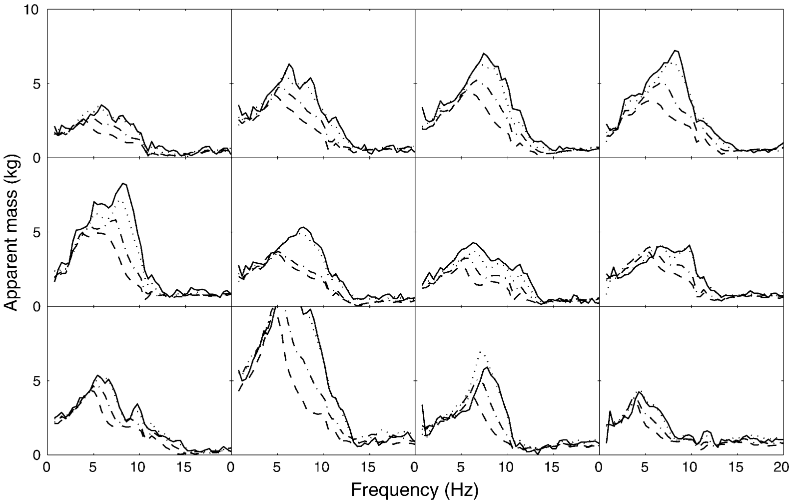

Fig. 5. Vertical apparent masses of 12 subjects measured at the back in the minimum thigh contact posture at four vibration magnitudes. ——, 0.125 m s$^{-2}$ r.m.s.; ········, 0.25 m s$^{-2}$ r.m.s.; –·–·–, 0.625 m s$^{-2}$ r.m.s.; ––––, 1.25 m s$^{-2}$ r.m.s.

with some subjects having two resonances in this range (Fig. 5). The second resonance appears more pronounced at low vibration magnitudes. There seemed to be a small effect of vibration magnitude on apparent mass at frequencies less than the principal resonance frequency and at high frequencies. At other frequencies, the vertical apparent mass measured at the back decreased with an increase in vibration magnitude. The resonance frequency also decreased with increasing vibration magnitude. The same effect was seen in all four postures (Fig. 6).

Statistical analysis showed significant reductions in the resonance frequencies with increases in vibration magnitudes for all postures ($p<0.05$; except between 0.125 and 0.25 m s$^{-2}$ r.m.s. in the average thigh contact posture). No significant differences were found between the apparent masses at resonance measured with 0.125 and 0.25 m s$^{-2}$ r.m.s. in any posture. In the feet hanging posture there were no significant differences between the apparent masses at resonance measured with 0.625 and 1.25 m s$^{-2}$ r.m.s.

Statistical analysis showed no significant difference between postures in the resonance frequencies of apparent mass in the vertical direction at the back at any vibration magnitude (except between the feet hanging posture and the maximum thigh contact posture at 0.25 m s$^{-2}$ r.m.s. and between the feet hanging posture and the average thigh contact posture at 1.25 m s$^{-2}$ r.m.s.). The apparent mass at resonance showed a statistically significant difference only between the average thigh contact posture and the minimum thigh contact posture at 0.625 m s$^{-2}$ r.m.s.

### *3.3. Response in the fore-and-aft direction*

#### *3.3.1. At the seat*

The cross-axis apparent masses of the 12 subjects measured in the fore-aft direction on the seat during vertical excitation show high values (Figs. 7 and 8). The principal resonance frequency, around 5 Hz, decreased with increasing vibration magnitude. A second resonance frequency,

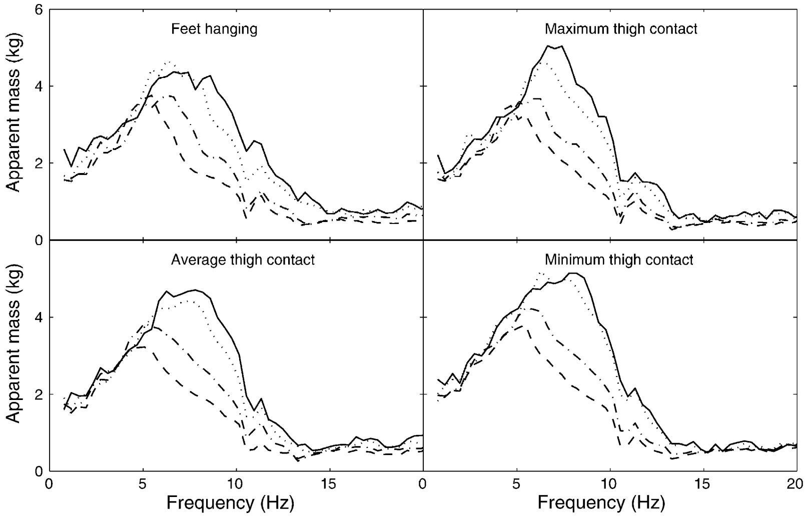

Fig. 6. Median apparent mass of twelve subjects measured at the back in the vertical direction: effect of vibration magnitude. ——, 0.125 m s$^{-2}$ r.m.s.; ·········, 0.25 m s$^{-2}$ r.m.s.; –· –· –, 0.625 m s$^{-2}$ r.m.s.; – – – –, 1.25 m s$^{-2}$ r.m.s.

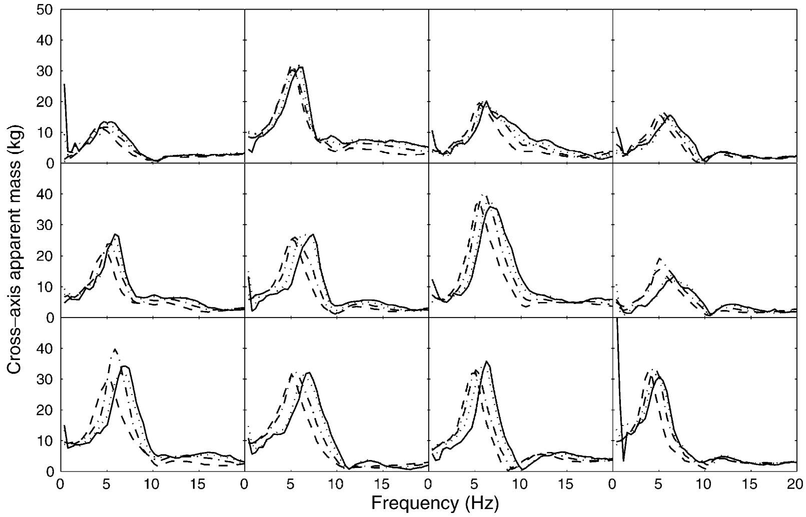

Fig. 7. Fore-and-aft cross-axis apparent masses of 12 subjects measured on the seat in the minimum thigh contact posture at four vibration magnitudes. ——, 0.125 m s$^{-2}$ r.m.s.; ·········, 0.25 m s$^{-2}$ r.m.s.; –· –· –, 0.625 m s$^{-2}$ r.m.s.; – – – –, 1.25 m s$^{-2}$ r.m.s.

between 10 and 15 Hz, is also clear in most of the individual data (in the posture shown in Fig. 7 and in the other three postures).

There were significant differences between the principal resonance frequencies measured at the four vibration magnitudes in all postures (except between 0.125 and 0.25 m s$^{-2}$ r.m.s. in the feet hanging posture and in the minimum thigh contact posture). Statistical analysis showed no

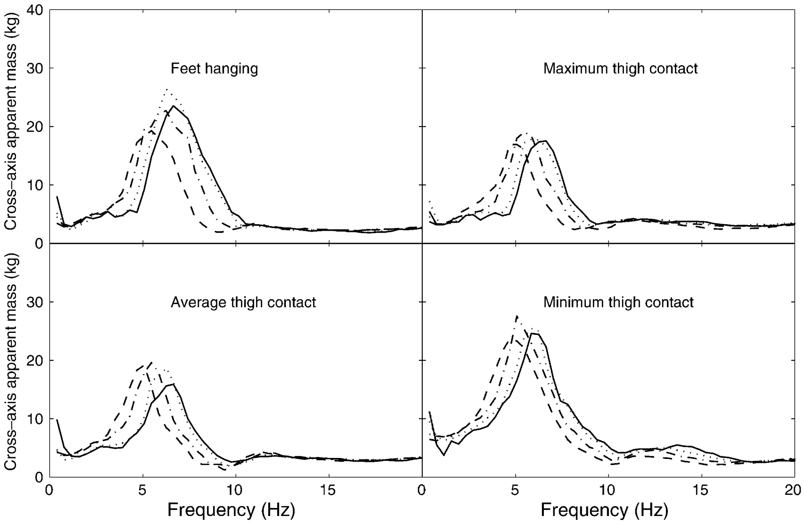

Fig. 8. Median fore-and-aft cross-axis apparent mass of 12 subjects measured on the seat: effect of vibration magnitude. ——, 0.125 m s$^{-2}$ r.m.s.; ………, 0.25 m s$^{-2}$ r.m.s.; –· –· –, 0.625 m s$^{-2}$ r.m.s.; ––––, 1.25 m s$^{-2}$ r.m.s.

significant differences ($p > 0.05$) between the cross-axis apparent mass at resonance (except between 0.125 and 1.25 m s$^{-2}$ r.m.s., between 0.25 and 1.25 m s$^{-2}$ r.m.s. and between 0.625 and 1.25 m s$^{-2}$ r.m.s. in the feet hanging posture, and between 0.625 and 1.25 m s$^{-2}$ r.m.s. in the maximum thigh contact posture, average thigh contact posture and minimum thigh contact posture).

There were no statistically significant differences in the cross-axis apparent mass at resonance between the feet hanging posture and the minimum thigh contact posture at any vibration magnitude. Similarly, there were no significant differences between the average thigh contact posture and the maximum thigh contact posture.

### 3.3.2. *At the backrest*

The cross-axis apparent mass in the fore-aft direction at the backrest showed high inter-subject variability in all postures, especially at frequencies below 10 Hz (Fig. 9). Some subjects showed a first resonance frequency in the range 2–3 Hz, but all subjects showed a higher resonance frequency, in the range 5–10 Hz depending on the subject and vibration magnitude, with a few subjects showing two resonance frequencies in the 5–10 Hz range (Figs. 10 and 11).

The fore-aft cross-axis apparent mass at the back is non-linear. Statistical analysis showed significant differences between the resonance frequencies (around 5 Hz) measured at four vibration magnitudes (except between 0.125 and 0.25 m s$^{-2}$ r.m.s. in the feet hanging posture). There were significant differences in the fore-aft cross-axis apparent mass at resonance between 0.125 and 0.625 m s$^{-2}$ in the maximum thigh contact posture and between 0.125 and 0.25 m s$^{-2}$ and 0.125 and 1.25 m s$^{-2}$ in the minimum thigh contact posture.

Fig. 12 indicates that below 3 Hz and above 10 Hz, there was little effect of posture on fore-aft cross-axis apparent mass at the back. However, around the resonance frequency, the fore-and-aft cross-axis apparent mass increased with increasing contact between the back and the backrest (see

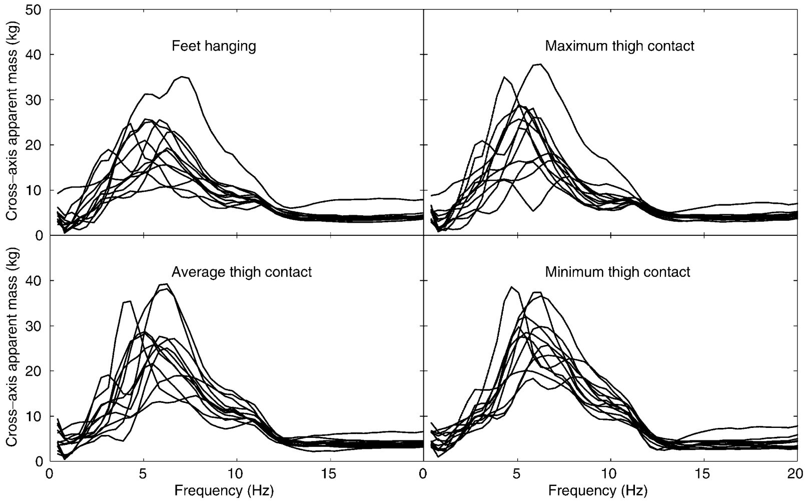

Fig. 9. Inter-subject variability in the fore-and-aft cross-axis apparent mass measured at the back for each posture at $1.25\,\mathrm{m\,s^{-2}}$ r.m.s.

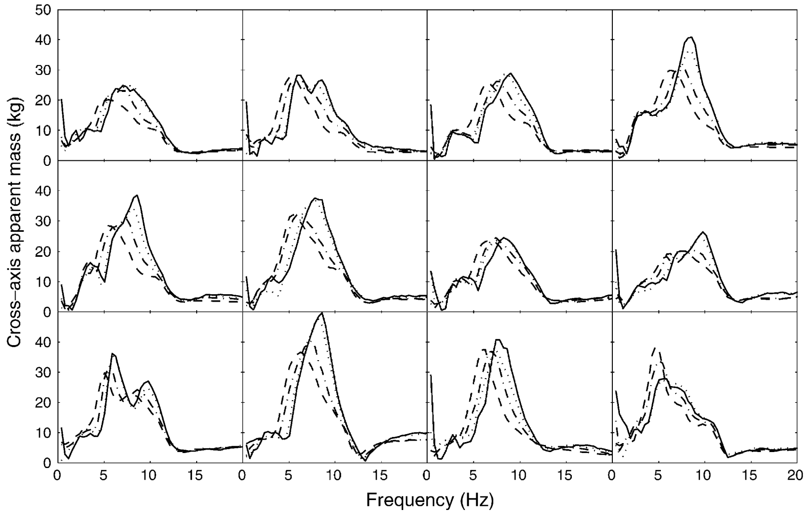

Fig. 10. Fore-and-aft cross-axis apparent masses of 12 subjects measured at the back in the minimum thigh contact posture at four vibration magnitudes. ——, $0.125\,\mathrm{m\,s^{-2}}$ r.m.s.; ·········, $0.25\,\mathrm{m\,s^{-2}}$ r.m.s.; –· –· –, $0.625\,\mathrm{m\,s^{-2}}$ r.m.s.; – – – –, $1.25\,\mathrm{m\,s^{-2}}$ r.m.s.

Section 3.1). Statistically significant differences were found in the magnitude of the fore-aft cross-axis apparent mass at resonance between the minimum thigh contact posture and both the feet hanging posture and the maximum thigh contact posture at all vibration magnitudes. Significant differences were also found between the average thigh contact posture and the feet hanging posture at all vibration magnitudes.

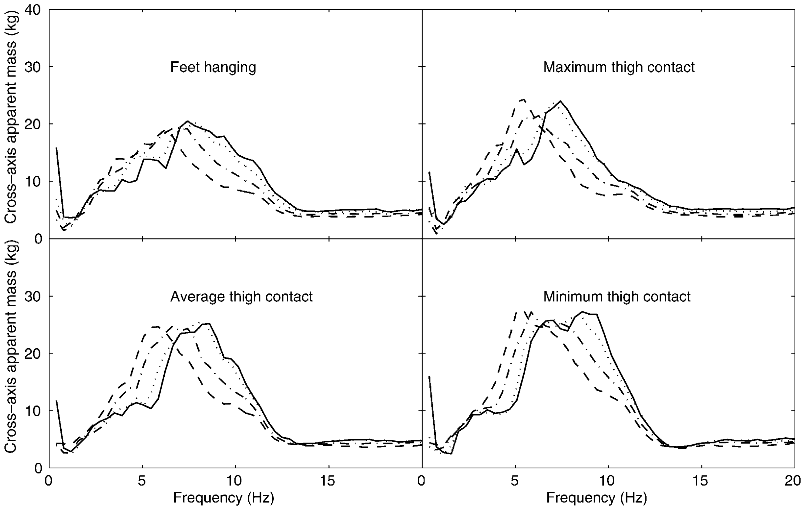

Fig. 11. Median fore-and-aft cross-axis apparent mass of 12 subjects measured at the back: effect of vibration magnitude. ——, 0.125 m s$^{-2}$ r.m.s.; ·········, 0.25 m s$^{-2}$ r.m.s.; –· –· –, 0.625 m s$^{-2}$ r.m.s.; – – – –, 1.25 m s$^{-2}$ r.m.s.

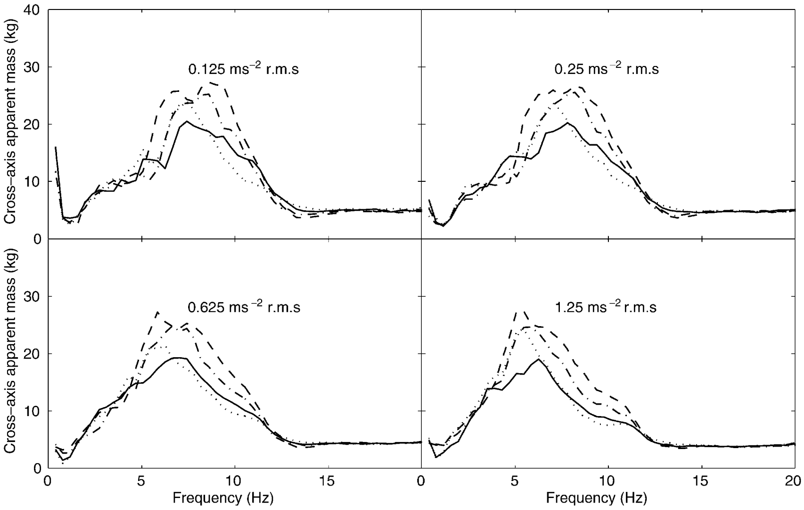

Fig. 12. Median fore-and-aft cross-axis apparent mass of twelve subjects measured at the back: effect of posture. ——, feet hanging; ·········, maximum thigh contact; –· –· –, average thigh contact; – – – –, minimum thigh contact.

### 3.4. Response in the lateral direction at the seat and backrest

The median lateral cross-axis apparent mass at the seat and backrest were small in all postures and at all vibration magnitudes (Figs. 13 and 14). Although the forces are small, the cross-axis apparent mass tends to decrease with increasing vibration magnitude, showing the same non-linear behaviour apparent in other axes.

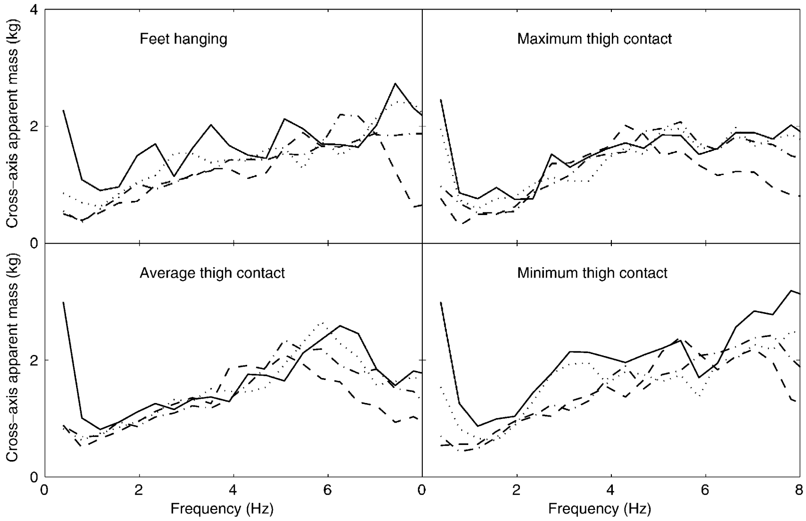

Fig. 13. Median lateral cross-axis apparent mass of 12 subjects measured on the seat: effect of vibration magnitude. ——, 0.125 m s$^{-2}$ r.m.s.; ·········, 0.25 m s$^{-2}$ r.m.s.; –· –· –, 0.625 m s$^{-2}$ r.m.s.; –––– , 1.25 m s$^{-2}$ r.m.s.

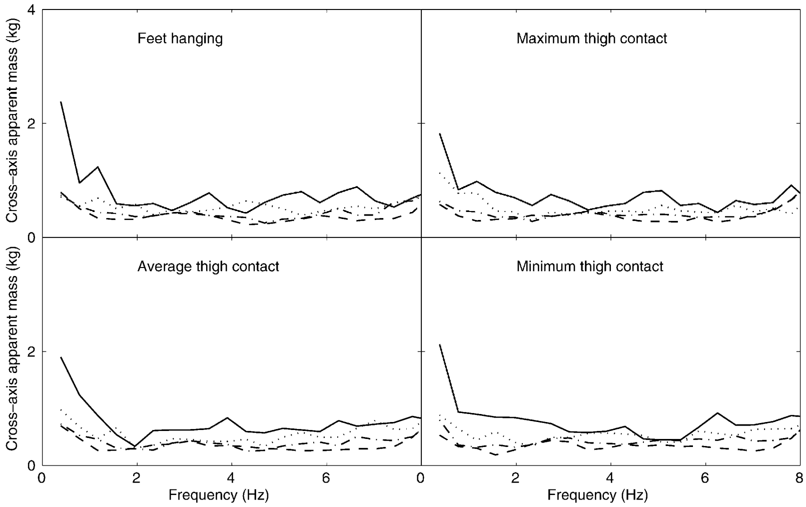

Fig. 14. Median lateral cross-axis apparent mass of 12 subjects measured at the back: effect of vibration magnitude. ——, 0.125 m s$^{-2}$ r.m.s.; ·········, 0.25 m s$^{-2}$ r.m.s.; –· –· –, 0.625 m s$^{-2}$ r.m.s.; –––– , 1.25 m s$^{-2}$ r.m.s.

### *3.5. Correlation with body characteristics*

The resonance frequency and apparent mass at resonance in the vertical direction at the back, and the resonance frequency and cross-axis apparent mass in the fore-and-aft direction at the back measured at 1.25 m s$^{-2}$ r.m.s. were investigated to determine whether they were correlated with body characteristics (mass, sitting mass, height and ratio of mass to height) or the static force measured at the back. In the vertical direction at the back, positive correlations were found between the body characteristics and the magnitudes at resonance as well as between the static force and the magnitude at resonance, although these were statistically significant only for the body mass ($p = 0.036$) and the sitting mass ($p = 0.007$) in the average thigh contact posture. The increased correlation with the sitting masses, as opposed to the total masses, of the subjects suggests that the upper-body caused the correlation in this posture. There were generally negative correlations, although not statistically significant, between the body characteristics and the resonance frequencies of the vertical apparent mass at the back.

Correlations between the resonance magnitudes of the fore-aft cross-axis apparent mass at the back and the body characteristics were, generally, positive although statistically significant only with the heights of the subjects in the average thigh contact posture ($p = 0.011$). There was also a negative correlation, although significant only in the feet hanging posture ($p = 0.002$), between the masses of the subjects and their resonance frequencies for fore-and-aft cross-axis apparent mass at the back.

## 4. Discussion

### 4.1. Response in the vertical direction (on the seat and backrest)

The apparent masses measured on the seat in the vertical direction were compared with those obtained without a backrest by Nawayseh and Griffin [3]. The median apparent masses of 11 of the same subjects used in the two studies with and without a backrest at 1.25 m s$^{-2}$ r.m.s. are shown in Fig. 15. At low frequencies (less than 4 Hz), statistically significant differences were found between the apparent masses measured with backrest and the apparent masses measured without backrest in all postures (first column, Table 1). At frequencies above about 4 Hz, the difference in the apparent mass measured with and without a backrest was significant in some frequency ranges and insignificant in others (Table 1). The effect of the backrest on the apparent mass is more pronounced when the contact between the body and the backrest increased as the feet were raised to the average thigh contact posture and the minimum thigh contact postures (see last two columns in Table 1).

Since the human body moves as a rigid body at very low frequencies, the vertical forces measured on the seat without a backrest may be expected to be the same as the vector addition of the vertical forces measured on the seat and the backrest when using the backrest. This hypothesis was tested in all postures at 0.78 Hz and 0.25 m s$^{-2}$ r.m.s. In all postures, there were no significant differences ($p > 0.05$) between the apparent mass measured on the seat without a backrest and the apparent mass obtained from adding the forces on the seat and backrest in the vertical direction at 0.78 Hz at 0.25 m s$^{-2}$ r.m.s.

The median results show a tendency for the resonance frequency to increase with the use of a backrest (Fig. 15). This increase in the resonance frequency was explained previously (e.g., Ref. [5]) as an increase in body stiffness when in contact with a backrest. Statistical analysis showed significant difference ($p < 0.05$) in the resonance frequency of the apparent mass measured at 1.25 m s$^{-2}$ r.m.s. with and without a backrest in all sitting postures, except in the minimum

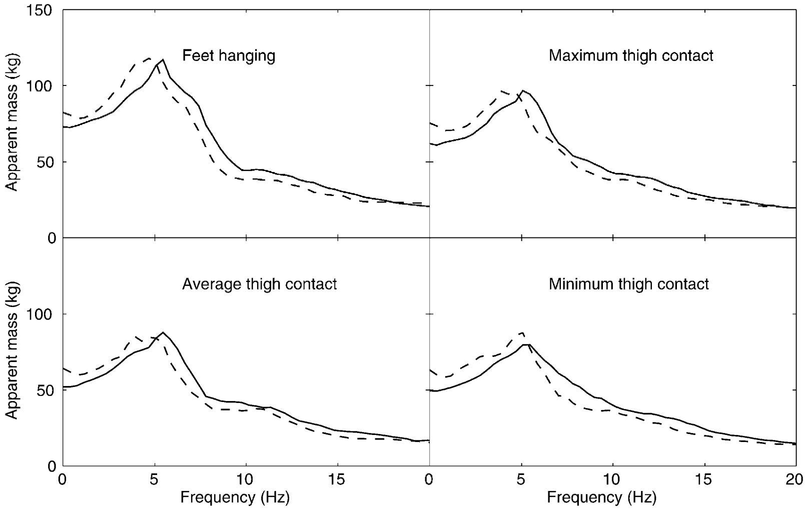

Fig. 15. Median vertical apparent mass of 11 subjects measured on the seat at 1.25 m s$^{-2}$ r.m.s. in four sitting postures: effect of backrest. ——, with backrest; – – – –, without backrest.

Table 1
Ranges of frequencies where there was, or was not, a statistically significant difference between the vertical apparent mass measured on the seat with and without backrest

| Posture | Frequency range (Hz) | | Out of 52 frequencies | |
|---|---|---|---|---|
| | Significant difference | Non-significant difference | Significant difference | Non-significant difference |
| Feet hanging | 0.39–4.29<br>7.02–9.75<br>12.09–14.04 | 4.68–6.63<br>10.14–11.70<br>14.43–20.0 | 25 | 27 |
| Maximum thigh contact | 0.39–4.29<br>7.02–14.04 | 4.68–6.63<br>14.43–20.0 | 30 | 22 |
| Average thigh contact | 0.39–4.68<br>5.85–13.65 | 5.07–5.46<br>14.04–20.0 | 33 | 19 |
| Minimum thigh contact | 0.39–4.68<br>7.02–18.33 | 5.07–6.63<br>18.72–20.0 | 42 | 10 |

thigh contact posture. In the minimum thigh contact posture, and when not using a backrest, the subjects needed to tense their muscles to keep the upright posture.

Significant correlations ($p \leqslant 0.03$) were found between the resonance frequencies measured with a backrest and the resonance frequencies measured without a backrest in all postures and at all vibration magnitudes, except at $0.125\,\mathrm{m\,s^{-2}}$ r.m.s. in the feet hanging posture and at 0.25 and $0.625\,\mathrm{m\,s^{-2}}$ r.m.s. in the minimum thigh contact posture. Significant correlations ($p \leqslant 0.047$) were also found between the apparent mass at resonance measured with and without a backrest, except at 0.125 and $0.25\,\mathrm{m\,s^{-2}}$ r.m.s. in the feet hanging posture. These correlations may be used to predict the resonance frequency and apparent mass at resonance that would be obtained with a backrest in studies conducted without a backrest.

The vertical apparent masses measured at the back were small and varied across subjects from 5 kg to 10 kg in the frequency range 5–7 Hz. This peak is at a frequency similar to the peak in the vertical transmissibility to the spine (to T1, T6, T11, L3, and S2) and the pelvis [7,13]. The vertical forces measured at the back arise from the vertical force applied at the backs of the subjects by the vertical movement of the backrest as well as from the pitch movement, expansion and contraction of the upper body produced by the vertical oscillation of the body. If the backrest had been stationary, only a friction force would have been produced to oppose the motion in the vertical direction. If an inclined backrest had been used, vertical force on the backrest would have arisen from the mass of the parts of the upper body supported on the backrest as well as from the pitching movements of the upper body. In this case, the total vertical force on the backrest would depend on the phase between the forces produced by the mass on the backrest and the forces produced by the upper body pitching modes.

The high variability between subjects in the vertical apparent mass at the back could be attributed to several factors. As was seen in Section 3.5, there were positive correlations between the total masses and the sitting masses of the subjects and the magnitude of the vertical apparent mass measured at the back. Although no significant correlations were found between the heights of the subjects and the magnitude at resonance of the apparent mass at the back, the location of the point of contact between the back and the backrest could be a source of variability.

In all four postures there was a decrease in the resonance frequencies of the apparent masses of the body with an increase in vibration magnitude. With a backrest, statistical analysis showed no effect of posture on the non-linearity—as opposed to the reduced non-linearity in the minimum thigh contact posture when no backrest was used [3]. Matsumoto and Griffin [2] found that increased muscle tension reduce the non-linearity of the body. Possibly, without a backrest, the subjects tensed their muscles to maintain the upright posture in the minimum thigh contact posture but did not need the same muscle tension when a backrest was used.

No significant difference was found in the absolute change in resonance frequency with and without a backrest in any of the cases mentioned above. This means that, although the backrest seemed to increase the stiffness of the body and shift the resonance frequency to higher values, it did not affect the non-linearity of the body. Comparing this with the results of Matsumoto and Griffin mentioned above, one might conclude that the non-linearity is affected by the stiffness of only particular parts of the body.

### *4.2. Response in the fore-and-aft direction (seat and backrest and comparison with no backrest)*

The high forces in the fore-and-aft direction on the seat are consistent with the results of Matsumoto and Griffin [2] and Nawayseh and Griffin [3] obtained without a backrest. These forces may be attributed to rotational modes of the upper body segments. The first resonance frequency, between 5 and 8 Hz, changed with a change of vibration magnitude. The second resonance (a small peak between 10 and 15 Hz) is consistent with a rotational mode of the pelvis and the lower upper-body (T11-L3) found using a biodynamic model with rotational capabilities [14]. The origin of this peak may be the same as that of the small peak in the vertical apparent mass of seated person in the same frequency range.

As was found by Nawayseh and Griffin [3] without a backrest, the feet hanging posture and the minimum thigh contact posture gave the highest forces in the fore-and-aft direction on the seat, possibly due to greater pitching motions in these two postures.

The forces on the seat in the fore-and-aft direction (cross-axis apparent masses) with a backrest were compared with those obtained by Nawayseh and Griffin [3] without a backrest (Fig. 16). Statistical analysis showed significant differences in the cross-axis apparent masses at resonance measured with and without a backrest at every vibration magnitude only in the feet hanging posture and in the maximum thigh contact posture ($p<0.05$). The presence of the backrest restrained the upper body and helped in reducing the pitching motion that was difficult to reduce without a backrest, especially when the feet were not supported.

There were high forces (i.e., high fore-and-aft cross-axis apparent masses) at the back. Similar to the forces measured in the fore-and-aft direction on the seat, the fore-aft forces measured at the back may have arisen from rotational motions of some parts of the body caused by the vertical oscillation of the body (at the seat and at the backrest). The first resonance frequency, which appeared between 2 and 3 Hz, is consistent with a dominant upper-body pitch mode found in this frequency range by Matsumoto and Griffin [14]. It is also consistent with a peak found in the transmission of vertical seat vibration to fore-aft head vibration and in the transmission of vertical seat vibration to horizontal motion of the third lumbar vertebra [7,8,13]. A peak in the same frequency range was more pronounced in the fore-and-aft motion of the head during fore-and-aft seat vibration than during vertical seat vibration [9]. In the present study, a vertical force was applied by the backrest on the backs of the subjects; this may have caused the upper body to pitch,

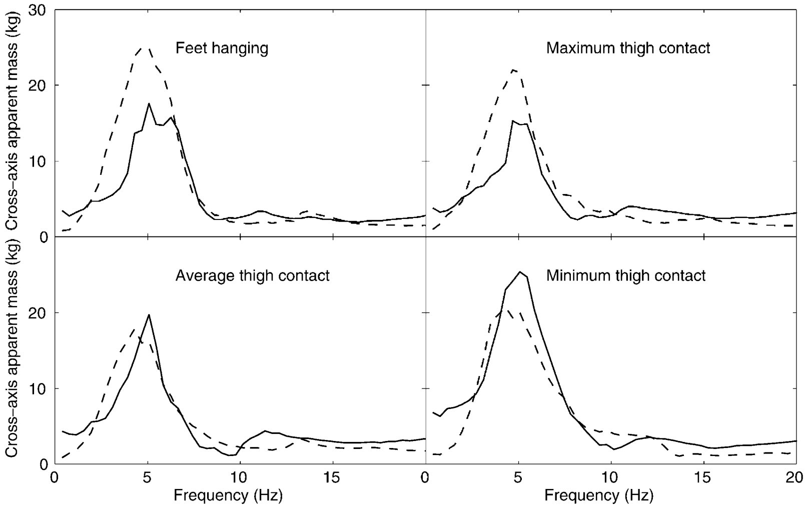

Fig. 16. Median fore-and-aft cross-axis apparent mass of 11 subjects measured on the seat at 1.25 m s$^{-2}$ r.m.s. in four sitting postures: effect of backrest. ——, with backrest; – – – –, without backrest.

producing a fore-aft vibration in the head-neck system. Similarly, pitch motion of the body resulting from vertical oscillation will have produced a horizontal force to the head-neck system. The second mode between 5 and 10 Hz in the present study is consistent with horizontal motions of the spine at this frequency (e.g., Ref. [13]).

The cross-axis apparent mass at the back in the fore-and-aft direction was greater when there was greater contact force between the backs of the subjects and the backrest (i.e., the minimum thigh contact posture). This trend for increased cross-axis apparent mass with increased static force is similar to the increase in apparent mass on the seat with heavier subjects. In postures where the feet were more supported on the footrest (and there was increased static force on the backrest) there would have been a force from the feet to react to the pitch movement during vibration, and so push the upper body against the backrest, which may have increased the dynamic force on the backrest in the fore-and-aft direction.

The oscillatory fore-and-aft forces at the back (caused by solely vertical vibration) may be a source of discomfort. Studies have shown that fore-aft oscillation of a backrest causes discomfort (e.g., Ref. [15]) but oscillatory force without motion has not been investigated.

### 4.3. Response in the lateral direction (seat and backrest and comparison with no backrest)

Lateral forces measured on the backrest and on the seat were small in comparison to the forces measured in the vertical and fore-and-aft directions. Furthermore, there were no large changes in forces at the seat with and without a backrest (see Fig. 17). The high inter-subject variability indicates that, although the human body is roughly symmetrical in the mid-sagittal plane, some roll or yaw oscillation may have occurred and produced a lateral force. This is consistent with measurements of the transmission of vertical seat vibration to lateral, roll, and yaw motion at the head [8].

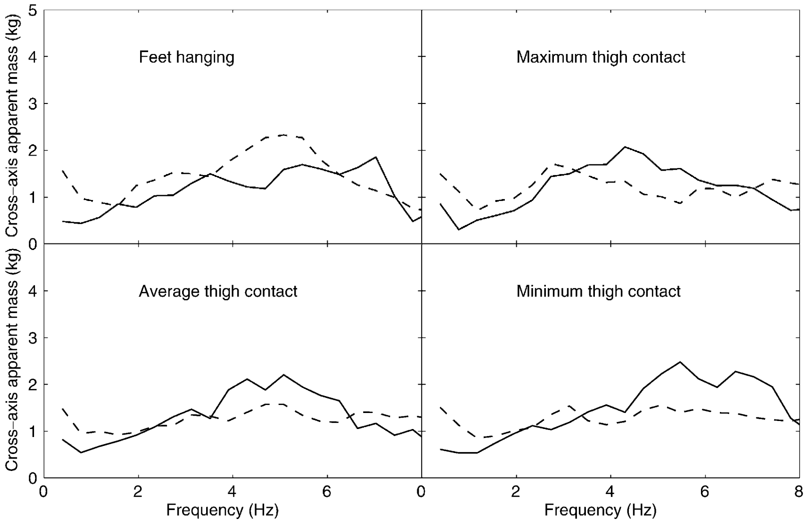

Fig. 17. Median lateral cross-axis apparent mass of 11 subjects measured on the seat at 1.25 m s$^{-2}$ r.m.s. in four sitting postures: effect of backrest. ——, with backrest; – – – –, without backrest.

The forces measured in this study were obtained with a rigid seat and a rigid backrest. Cushioned seats and backrests may modify the results. For example, whereas a rigid backrest tends to prevent movement at the back, a compliant backrest will allow fore-aft movement of the back.

## 5. Conclusions

During vertical whole-body vibration, in addition to vertical forces at the seat, there are high forces in the fore-and-aft direction on the seat and backrest. Forces in the lateral direction were small, as were forces in the vertical direction on the backrest. Forces in all directions showed a similar non-linear response characterized by decreases in resonance frequencies with increases in vibration magnitude. The presence of the backrest modified the forces in the fore-aft and vertical direction on the supporting seat surface. The forces at the backrest, as well as forces on the seat in directions other than the direction of excitation, should be considered in dynamic models of seat-person systems.

## References

[1] M.J. Griffin, *Handbook of Human Vibration*, Academic Press Limited, London, 1990.

[2] 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.

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

[4] 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.

[5] T. Fairley, M.J. Griffin, The apparent mass of the seated human body: vertical vibration, *Journal of Biomechanics* 22 (1989) 81–94.

[6] N.J. Mansfield, Non-linear Dynamic Response of the Seated Person to Whole-Body Vibration, Ph.D. Thesis, University of Southampton, Southampton, 1998.

[7] 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.

[8] G.S. Paddan, M.J. Griffin, The transmission of translational seat vibration to the head. I. Vertical seat vibration, *Journal of Biomechanics* 21 (1988) 191–197.

[9] G.S. Paddan, M.J. Griffin, The transmission of translational seat vibration to the head. II. Horizontal seat vibration, *Journal of Biomechanics* 21 (1988) 199–206.

[10] G.S. Paddan, M.J. Griffin, Transmission of roll and pitch seat vibration to the head, *Ergonomics* 37 (1994) 1513–1531.

[11] G.S. Paddan, M.J. Griffin, Transmission of yaw seat vibration to the head, *Journal of Sound and Vibration* 229 (2000) 1077–1095.

[12] M. Magnusson, M. Pope, M. Rostedt, T. Hansson, Effect of backrest inclination on the transmission of vertical vibrations through the lumbar spine, *Clinical Biomechanics* 8 (1993) 5–12.

[13] S. Kitazaki, Modelling Mechanical Responses to Human Whole-Body Vibration, Ph.D. Thesis, University of Southampton, 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] K.C. Parsons, M.J. Griffin, E.M. Whitham, Vibration and comfort III. Translational vibration of the feet and back, *Ergonomics* 25 (1982) 705–719.