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Effect of seat surface angle on forces at the seat surface during whole-body vertical vibration

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Abstract

Twelve male subjects have been exposed to whole-body vertical random vibration so as to investigate the effect of seat surface angle, vibration magnitude and contact with a backrest on the 'vertical apparent mass' (calculated from forces normal to the seat surface and vertical acceleration) and 'fore-and-aft cross-axis apparent mass' (calculated from forces parallel to the seat surface and vertical acceleration). At each of four seat surface angles (0°, 5°, 10°, and 15°), the subjects were exposed to four vibration magnitudes (0.125, 0.25, 0.625, and 1.25 $\mathrm{m\,s^{-2}}$ rms) in the frequency range 0.25–15 Hz.

The 'vertical apparent mass' and 'fore-and-aft cross-axis apparent mass' on the seat surface suggested resonances in the vicinity of 5 and 4 Hz, respectively. At all seat angles, both with and without a backrest, the resonance frequency in the 'vertical apparent mass' was greater than the resonance frequency in the 'fore-and-aft cross-axis apparent mass'. Within subjects, the two resonance frequencies were not correlated in any condition. Seat angles up to 15° had a negligible effect on the 'vertical apparent mass' but a considerable effect on the 'fore-and-aft cross-axis apparent mass' on the seat surface, where 'cross-axis apparent mass' increased with increasing seat angle. At all seat angles, increasing the vibration magnitude decreased the resonance frequency in both directions. The least significant decrease in resonance frequency with increasing vibration magnitude occurred in the 'fore-and-aft cross-axis apparent mass' at the maximum seat angle of 15°. At low frequencies, the backrest reduced the forces in both directions, with the reduction greatest in the 'fore-and-aft' direction. The 'fore-and-aft cross-axis apparent mass' at resonance was correlated with subject mass and subject stature.

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1. Introduction

Measures of biodynamic responses to vibration, including the mechanical impedance and apparent mass, are widely available in the literature (e.g. Refs. [1–5]). Such measures assist the construction of biodynamic models of the human body, which may advance understanding of human responses to vibration. Mechanical dummies may be constructed from such information and used as substitutes for human subjects in seat testing.

The human body shows a highly nonlinear response to vibration. A common finding is a reduction in the principal resonance frequency of both the apparent mass of the body and the transmissibility to different locations on the spine with increases in vibration magnitude (e.g. Refs. [2,6–8]). With random vibration, Fairley and Griffin [2] reported a decrease in the apparent mass resonance frequency from 6 to 4 Hz with, an increase in vibration magnitude from 0.25 to $2.0\,\mathrm{m\,s^{-2}}$ rms. Using sinusoidal vibration, Hinz and Seidel [6] reported a decrease in the apparent mass resonance frequency from 4.5 to 4 Hz when they increased the vibration magnitude from 1.5 to $3.0\,\mathrm{m\,s^{-2}}$ rms. Mansfield et al. [7] reported a similar nonlinear phenomenon when using random vibration, repeated shocks, and combinations of random vibration and repeated shocks. Matsumoto and Griffin [8] measured the transmissibility of the human body to the head, the pelvis and six locations on the spine (T1, T5, T10, L1, L3, L5) in three orthogonal axes in the sagittal plane at five vibration magnitudes. They observed the nonlinear phenomenon at most measurement locations. For example, when the vibration magnitude increased from 0.125 to $2.0\,\mathrm{m\,s^{-2}}$ rms, the resonance frequency in the vertical transmissibility to L3 reduced from 6.25 to 4.75 Hz.

The upper body posture also affects response to vibration (e.g. Refs. [2,9]). Both of these studies showed an increase in the principal resonance frequency of the human body when subjects changed their upper body posture from slouched (or relaxed) to erect, suggesting an increase in body stiffness. Mansfield and Griffin [10] studied the effect of vibration magnitude on apparent mass and seat-to-pelvis pitch transmissibility in nine sitting postures. They concluded that 'changes in vibration magnitude (from 0.2 to $2.0\,\mathrm{m\,s^{-2}}$ rms) resulted in greater changes in apparent mass and seat-to-pelvis transmissibility than changes in posture'.

The response of the body to vibration may also be modified by seating conditions: the presence of a footrest (stationary or moving in phase with the seat), contact with a backrest, backrest angle, and seat squab angle may affect response to vibration by either redistributing body mass or changing the sitting posture [2,11–13]. Fairley and Griffin [2] noticed that apparent mass at low frequencies increased with increased height of a stationary footrest, in contrast to decreased apparent mass with increased height of a footrest moving in phase with the seat. Nawayseh and Griffin [11] found that fore-and-aft cross-axis apparent mass (the ratio of the fore-and-aft force on the seat to vertical acceleration) depended on support for the lower legs on a moving footrest.

The apparent mass of the body, and the transmissibility to the head and the spine, are affected by the presence of a backrest. The backrest reduces the apparent mass at low frequencies and increases the resonance frequency and the apparent mass at frequencies above resonance, suggesting increased body stiffness [2,14,15]. Paddan and Griffin [16] found an increase in the vertical and fore-and-aft seat-to-head transmissibility at resonance when a backrest was used during vertical vibration. Magnusson et al. [12] studied the effect of backrest inclination on the transmission of vertical vibration through the lumbar spine. They reported that the backrest inclination attenuated the vertical vibration at the fourth lumbar vertebra compared to a no backrest condition, but the attenuation was small in the resonance region (4–6 Hz range). They also reported an increase in fore-and-aft vibration at the fourth lumbar vertebra when a backrest (with angles of 110° and 120°) was used relative to a no backrest condition.

Although the supporting surfaces of vehicle seats are often inclined, most studies of the dynamic responses of the body have involved horizontal supporting seat surfaces. In a study of the effect of seat inclination on both seat transmissibility and the apparent mass of the body, Wei and Griffin [13] found that increasing seat inclination from 0° to 20° decreased seat cushion transmissibility at frequencies below 6 Hz and increased seat transmissibility above 6 Hz. Subject vertical apparent mass decreased with increasing seat angle at frequencies below 5.5 Hz, although the change was generally small.

The human body moves in two dimensions (in the mid-sagittal plane) when exposed to vertical or fore-and-aft vibration [11,15,17–19]. High fore-and-aft forces have been found on the seat during vertical excitation and high vertical forces have been found during fore-and-aft excitation. The high cross-axis forces were attributed to pitching modes in the body. These measurements were obtained on a horizontal seat surface. There are no known measurements of the effects of seat surface angles or seat backrest angles on the vertical and fore-and-aft forces at the seat surface and the backrest.

Current biodynamic models are based on data from specific excitations and specific seating conditions, and are less applicable to other vibration magnitudes and other seating conditions. Only a few models take into account the movements and forces in directions other than the direction of excitation (i.e. the cross-axis forces, e.g. Refs. [20,21]). A biodynamic model of the response of the body to vibration should consider forces in all directions, the nonlinearity in the responses, the effects of body posture and the effects of seat configuration (e.g. footrest, backrest angle, seat squab angle, etc.).

This study investigated the effect of variations in seat surface angle on the ‘vertical apparent mass’ (calculated from the force normal to the seat surface and vertical acceleration) and ‘fore-and-aft cross-axis apparent mass’ (calculated from the force parallel to the seat surface and vertical acceleration) during exposure to whole-body vertical vibration. There is an evidence of a decrease in the nonlinearity in the vertical direction when tensing or stiffening the muscles of the ischial tuberosities [17]. However, it is not clear whether the stiffening in the axial, shear or both directions reduced the nonlinearity. In the present study, it was hypothesised that increasing seat surface angle would result in an increase in shear stiffness of tissue at the ischial tuberosities and that this increase in stiffness might affect the nonlinearity in the ‘vertical’ as well as in the ‘fore-and-aft’ direction. It was also hypothesised that there would be only small variations in the ‘vertical’ forces with variation in seat angles between 0° and 15°; assuming little change in body posture with these changes in seat angle, the vertical forces will vary with the cosine of the seat angle, which is close to unity for the angles employed. With a seat horizontal (i.e. at 0°), the fore-and-aft cross-axis apparent mass is mainly produced by the pitching modes of the upper body. However, with inclinations of 5°, 10°, and 15°, the ‘fore-and-aft cross-axis apparent mass’ has two main components: one is produced by the pitching movements of the body and the other by the force exerted on the mass of the body in the direction parallel to the seat surface. The latter was expected to increase with increasing seat surface inclination. The addition of a backrest was expected to reduce both the ‘vertical apparent mass’ and the ‘fore-and-aft cross-axis apparent mass’ at low frequencies.

2. Apparatus, experimental design and analysis

2.1. Apparatus

Subjects were exposed to whole-body vertical vibration using an electro-hydraulic vibrator capable of peak-to-peak displacements of 1 m. A rigid seat, with a flat supporting surface that could be adjusted to different angles, was mounted on the platform of the vibrator. The seat had a rigid flat vertical backrest, the bottom of which was level with the upper surface of the seat, while the top was 52 cm above the seat surface. When subjects were not using the backrest, they sat in an upright posture without their backs touching the backrest by leaving a gap between the back and the backrest. When the backrest was used, the subjects were asked to maintain full contact with the backrest. Subjects supported their feet on a footrest that was inclined by 45° and moved in phase with the seat (Fig. 1).

A tri-axial force platform (Kistler 9281 B) was used to measure the forces normal and parallel to the supporting seat surface (i.e. ‘vertical’ and ‘fore-and-aft’, respectively, Fig. 1). The force platform has been described elsewhere [11]. Signals from the force platform were amplified using charge amplifiers (Kistler 5007). Acceleration was measured in the vertical direction at the centre of the force platform using a piezo-resistive accelerometer (Entran EGCSY-240D-10). The acceleration and force were acquired at 200 samples per second via 67 Hz anti-aliasing filters, with an attenuation rate of 70 dB in the first octave. The duration of each vibration exposure was 60 s.

2.2. Experimental design

Twelve male subjects with an average age 30.9 years (range 24–47 years), weight 76.5 kg (range 65–103 kg), and stature 1.77 m (range 1.64–1.86 m) were exposed to random vertical vibration with an approximately flat constant bandwidth acceleration power spectrum over the frequency range 0.25–15 Hz.

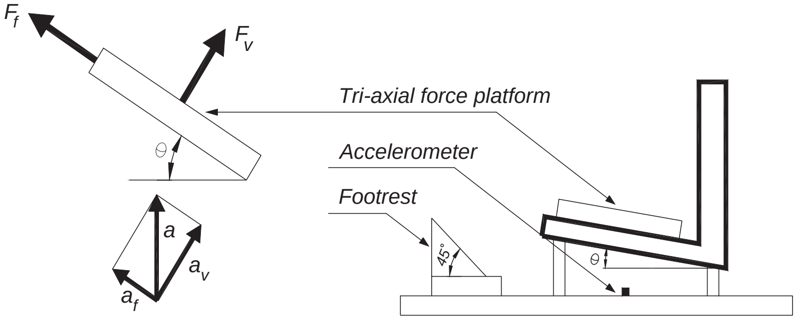

Fig. 1. Schematic diagram of the seat, force platform and accelerometer arrangements.

The experiment was conducted using four seat surface angles: 0°, 5°, 10°, and 15°. The subjects held an emergency STOP button with their hands in their laps. The subjects were instructed to stretch their legs forward and rest their feet on the inclined footrest. The footrest was moved toward the seat when the seat angle was increased, so as to maintain similar thigh contact with the seat in all conditions. With each seat angle, the 12 subjects were exposed to four vibration magnitudes (0.125, 0.25, 0.625, and $1.25\,\mathrm{m\,s^{-2}}$ rms), both with and without the vertical backrest. The presentation of the four seat angles and the four vibration magnitudes was balanced across subjects.

2.3. Analysis

The components of acceleration in the directions normal and parallel to the seat surface (a_v and a_f in Fig. 1) could be used with the forces measured normal and parallel to the seat surface to calculate a 'normal apparent mass' and a 'parallel cross-axis apparent mass'. However, with the seat angle changing, the magnitude of acceleration in these directions also changed during the experiment. The 'vertical apparent masses' at different seat angles and the 'fore-and-aft cross-axis apparent masses' measured with different seat angles will therefore have varied due to the combined effects of changing the seat surface angle and the nonlinearity of the body. An alternative analysis is for the force measured normal to the seat surface, F_v, to be resolved into vertical and fore-and-aft components, and the force measured parallel to the seat surface, F_f, to be resolved into vertical and fore-and-aft components so as to calculate resultant forces in the vertical and fore-and-aft directions. However, given the nonlinearity of the human body, this simple resolving and adding of force components may be suspect. It was therefore decided to directly compare the measured forces (i.e. the forces normal and parallel to the seat surface) with the applied vertical acceleration.

The forces measured normal to the seat surface (F_v) and parallel to the seat surface (F_f) were analysed relative to the vertical acceleration (see Fig. 1), producing two frequency response functions: one normal to the seat surface (i.e. 'vertical apparent mass') and the other parallel to the seat surface ('fore-and-aft cross-axis apparent mass'). The two frequency response functions were calculated using the cross-spectral density method:

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

where, $M(\omega)$ is the 'vertical apparent mass' (or 'fore-and-aft cross-axis apparent mass'), in kg, $S_{af}(\omega)$ is the cross-spectral density between the force measured normal (or parallel) to the seat surface and the applied vertical acceleration, and $S_{aa}(\omega)$ is the power spectral density of the applied vertical acceleration. Before calculating $M(\omega)$, mass cancellation was needed to remove the effect of the mass of the aluminium plate of the force platform (15 kg) mounted 'above' the force cells. The force produced by the aluminium plate of the force platform in the direction normal to the seat surface ($15\,\mathrm{kg} \times a\cos\theta$, Fig. 1) was subtracted in the time domain from the force measured normal to the seat surface, F_v. The force produced by the aluminium plate in the direction parallel to the seat surface ($15\,\mathrm{kg} \times a\sin\theta$) was subtracted in the time domain from the force measured in the direction parallel to the seat surface, F_f. The coherency between the force and acceleration was calculated after mass cancellation in the time domain and found to be above 0.96 over the whole frequency range for the 'vertical apparent mass' and above about 0.85 over the whole frequency range for the 'fore-and-aft cross-axis apparent mass', except in the region 5–7 Hz where a trough was evident in the data (see Section 3.2).

Data analysis was performed using SPSS (versions 10). Non-parametric statistical methods were used throughout: the Friedman analysis of variance was used to test for differences between multiple conditions, the Wilcoxon matched-pairs signed ranks test was used to test for differences between pairs of conditions, Spearman's rank correlation was used to investigate associations between variables.

3. Results

3.1. *'Vertical apparent mass'*

The 'vertical apparent masses' of 12 subjects (obtained from the force normal to the seat surface and the vertical applied acceleration) measured at 1.25 m s^{-2} rms with four seat angles are shown in Fig. 2. All subjects and all seat angles showed a similar response characteristic: the modulus increased with increasing frequency up to a peak in the vicinity of 5 Hz, and then decreased with increasing frequency. The phase lag between the vertical acceleration and the 'vertical' force was zero at very low frequencies and increased up to 1.5 rad in the resonance area, with no big change at higher frequencies.

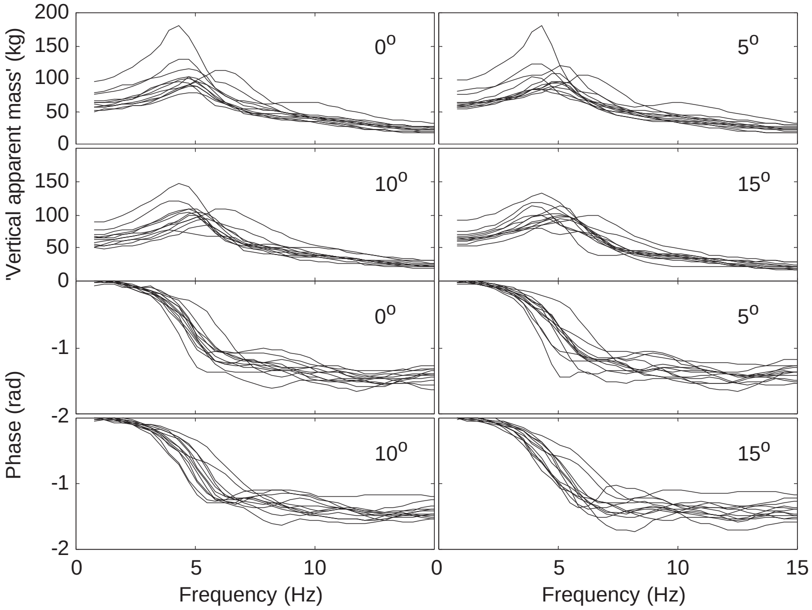

Fig. 2. Inter-subject variability in the 'vertical apparent masses' measured at 1.25 m s^{-2} rms with four different seat angles and no backrest.

The coefficient of variation (defined as the ratio of the standard deviation to the mean) showed that at all seat angles and with all vibration magnitudes, the inter-subject variability was greatest around the resonance frequency.

3.1.1. *Effect of vibration magnitude*

With all seat angles, the ‘vertical apparent mass’ showed a nonlinear characteristic (Fig. 3): statistically significant differences were found between the resonance frequencies at the different vibration magnitudes ($p<0.05$), except between 0.125 and 0.25 m s^{-2} rms, with seat angles of 5° and 15°. Further statistical analysis was conducted to investigate whether the seat angle 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} rms) and between the two higher vibration magnitudes (i.e. 0.625 and 1.25 m s^{-2} rms). The results indicate that the sizes of differences in the resonance frequencies obtained at the two lower vibration magnitudes and the sizes of differences in the resonance frequencies obtained at the two higher vibration magnitude did not depend on the seat angle (Friedman, $p>0.7$).

The effect of vibration magnitude on the ‘vertical apparent mass’ magnitude at resonance was clearer at low seat angles: statistically significant differences were found in the ‘vertical apparent mass’ at resonance measured at the different vibration magnitudes only when the seat angle was 0° or 5° (Friedman, $p<0.05$). At 0°, significant differences in the apparent mass magnitude at resonance were found between 0.125 and 0.25, between 0.625 and 1.25 m s^{-2} rms, and between 0.25 and 0.625 m s^{-2} rms (Wilcoxon, $p<0.05$). At 5°, significant differences were found between 0.125 and 0.625 m s^{-2} rms and between 0.25 and 0.625 m s^{-2} rms (Wilcoxon, $p<0.05$). Where

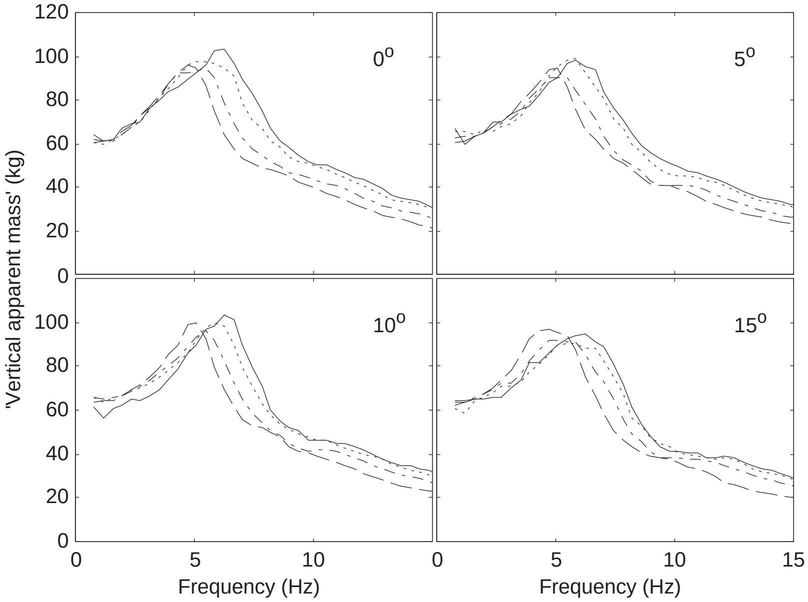

Fig. 3. Effect of vibration magnitude on median ‘vertical apparent masses’ of 12 subjects measured without a backrest: ———, 0.125 m s^{-2} rms; ……… , 0.25 m s^{-2} rms; –·–·–·–, 0.625 m s^{-2} rms; – – – –, 1.25 m s^{-2} rms.

there were differences, the magnitude at resonance at the lower vibration magnitude was higher than the magnitude at the higher vibration magnitude.

The median resonance frequencies and the median ‘vertical apparent masses’ at resonance obtained with the four vibration magnitudes and the four seat angles are shown in Table 1.

3.1.2. Effect of seat angle

At all vibration magnitudes, the ‘vertical apparent masses’ were similar at each of the four seat angles (Figs. 4 and 5). There were no statistically significant differences in the resonance frequencies, or the magnitudes at resonance, with changing seat surface angle at any vibration magnitude (Friedman, $p > 0.1$). There were also no significant differences between the ‘vertical

Table 1
Median resonance frequencies and magnitudes at resonance of the ‘vertical apparent mass’ for four seat angles at 0.125, 0.250, 0.625 and 1.25 m s^{-2} rms (without backrest)

Seat angle (deg)	Resonance frequency (Hz)				Magnitude at resonance (kg)			
	0.125	0.250	0.625	1.250	0.125	0.250	0.625	1.250
0	6.25	5.47	5.47	4.69	103.4	97.6	94.3	95.8
5	5.86	5.86	5.47	5.08	97.9	99.1	90.1	94.8
10	6.25	5.86	5.47	5.08	103.4	99.9	96.4	99.5
15	6.25	5.47	4.69	4.69	94.8	90.7	92.0	96.6

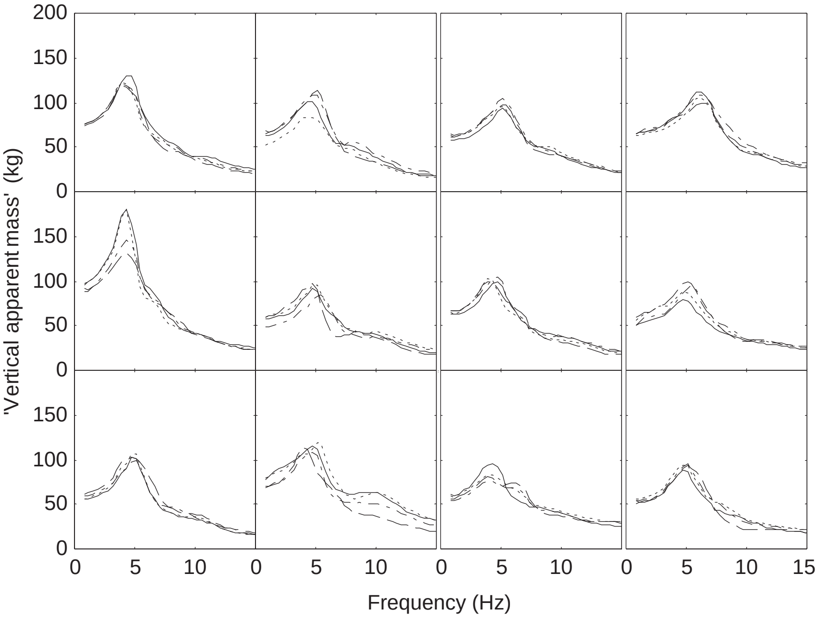

Fig. 4. ‘Vertical apparent masses’ of 12 subjects measured at 1.25 m s^{-2} rms without a backrest: ———,0°; ………, 5°; –·–· 10°; – – – –, 15°.

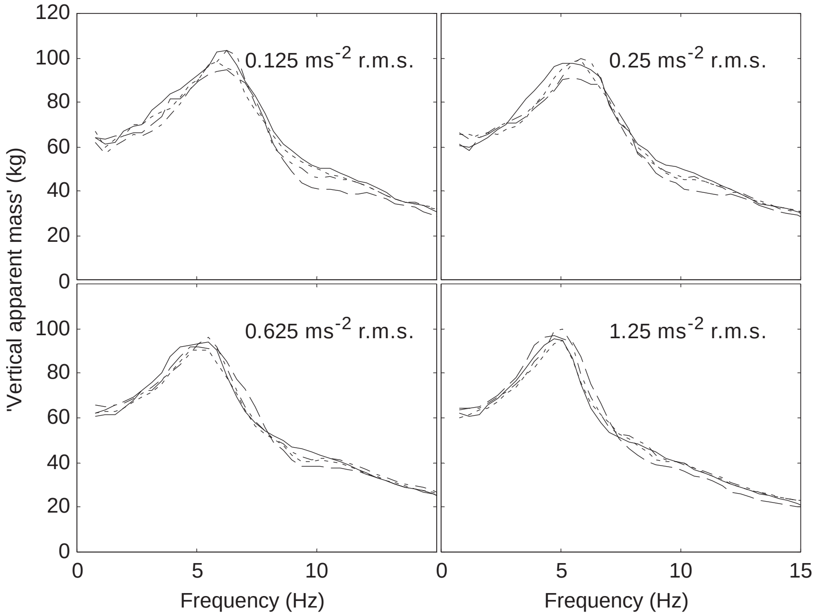

Fig. 5. Effect of seat angle on median 'vertical apparent masses' of 12 subjects measured without a backrest:. ———,0°; ………, 5°; –·–·–, 10°; – – – –, 15°.

apparent masses' measured with 0° and the 'vertical apparent masses' measured with 5°, 10°, or 15° at any frequency (0.25–15 Hz, $p>0.1$).

3.1.3. *Effect of backrest*

At each seat angle and at all vibration magnitudes, the 'vertical apparent masses' measured without a backrest were compared to those measured with a backrest (Figs. 6 and 7). There was no statistically significant difference between the resonance frequencies of the 'vertical apparent mass' measured with a backrest and the resonance frequencies of the 'vertical apparent mass' measured without a backrest when using seat angles of 0°, 5° or 10° at any vibration magnitude ($p>0.05$). However, with a seat angle of 15°, there were statistically significant differences between the resonance frequencies of the 'vertical apparent mass' measured with a backrest and the resonance frequencies of the 'vertical apparent mass' measured without a backrest, except with a vibration magnitude of $0.125\,\mathrm{m\,s^{-2}}$ rms Table 2 shows the median resonance frequencies and median 'vertical apparent mass' magnitudes at resonance measured in all conditions with a backrest.

Over the whole frequency range, the backrest tended to reduce the 'vertical apparent mass' at low frequencies and increase the 'vertical' apparent mass at high frequencies (see Fig. 7). The effect of the backrest on the 'vertical apparent mass' over the whole frequency range (obtained with $1.25\,\mathrm{m\,s^{-2}}$ rms) is shown in Table 3. The table shows a greater effect of the backrest at small seat angles than at large seat angles.

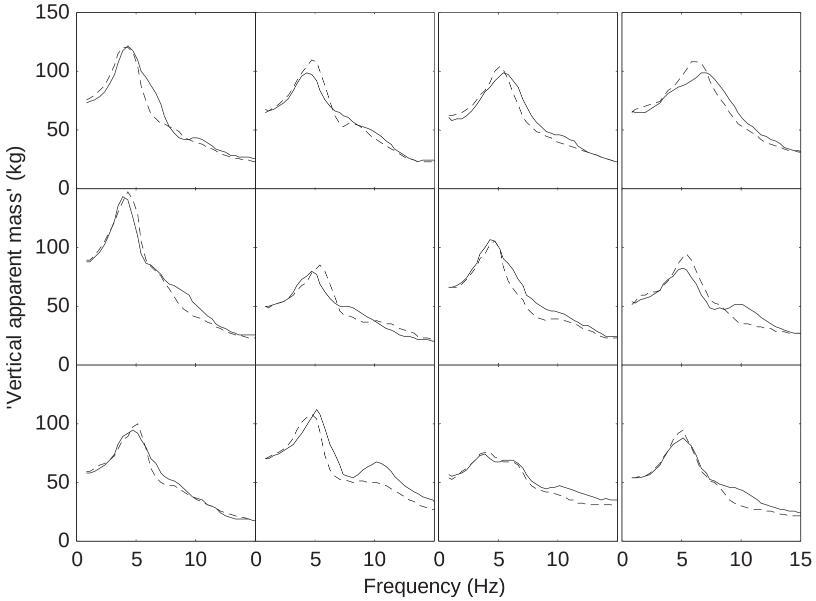

Fig. 6. Effect of backrest on 'vertical apparent masses' of 12 subjects measured at 1.25 m s^{-2} rms with seat angle of 10°: ———, with backrest; – – – – , without backrest.

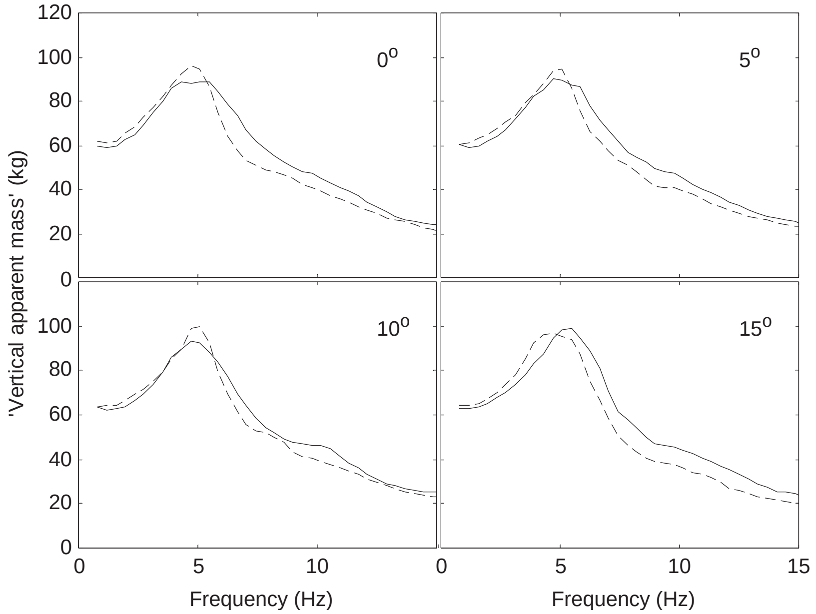

Fig. 7. Effect of backrest on median 'vertical apparent masses' of 12 subjects measured at 1.25 m s^{-2} rms: ———, with backrest; – – – –, without backrest.

Table 2
Median resonance frequencies and magnitudes at resonance of the 'vertical apparent mass' for four seat angles at 0.125, 0.250, 0.625 and 1.25 m s^{-2} rms (with backrest)

Seat angle (deg)	Resonance frequency (Hz)				Magnitude at resonance (kg)			
	0.125	0.250	0.625	1.250	0.125	0.250	0.625	1.250
0	6.25	6.25	5.86	5.08	97.3	94.9	89.0	89.1
5	7.03	6.25	5.08	4.69	97.9	91.2	90.6	89.8
10	5.86	5.86	5.47	4.69	97.3	95.4	95.8	93.4
15	5.86	5.86	5.47	5.47	98.0	93.8	93.2	98.8

Table 3
Ranges of frequencies where there was, or was not, a statistically significant difference in the 'vertical apparent mass' measured with and without a backrest at 1.25 m s^{-2} rms

Seat angle (deg)	Frequency range (Hz)		Out of 39 frequencies	
	Significant difference	Non-significant difference	Significant difference	Non-significant difference
0	0.39–15.0	—	39	—
5	1.17–4.30 6.25–15.0	0.39–0.78 4.69–5.86	33	6
10	1.56–2.73 4.69–5.08 7.03–12.50 14.84–15.0	0.39–1.17 3.12–4.30 5.47–6.64 12.89–14.45	23	16
15	5.86–15.0	0.39–5.47	25	14

3.2. *'Fore-and-aft cross-axis apparent mass'*

With all seat angles, the 'fore-and-aft cross-axis apparent masses' (obtained from the force measured parallel to seat surface and the vertical applied acceleration) had magnitudes comparable to the 'vertical apparent mass'. The 'fore-and-aft cross-axis apparent mass' increased with increasing frequency up to a peak in the vicinity of 4 Hz, after which the 'fore-and-aft cross-axis apparent mass' reduced to a trough (Fig. 8). The inter-subject variability was the greatest between 5 and 7 Hz, where the trough occurred with all seat angles and all vibration magnitudes. The coefficient of variation in the 5–7 Hz region decreased with increasing seat angle. Consequently, the average coefficient of variation over the whole frequency range decreased with increasing seat angle: the average coefficient of variation decreased by about 25% when the seat angle was increased from 0° to 15° at 0.125 m s^{-2} rms and by about 30% when the seat angle was increased from 0° to 15° at 1.25 m s^{-2} rms.

The resonance frequencies of the 'fore-and-aft cross-axis apparent masses' were tested for correlation with the resonance frequencies of the 'vertical apparent masses'. In none of the 16 conditions (four seat angles and four vibration magnitudes) was there a significant correlation

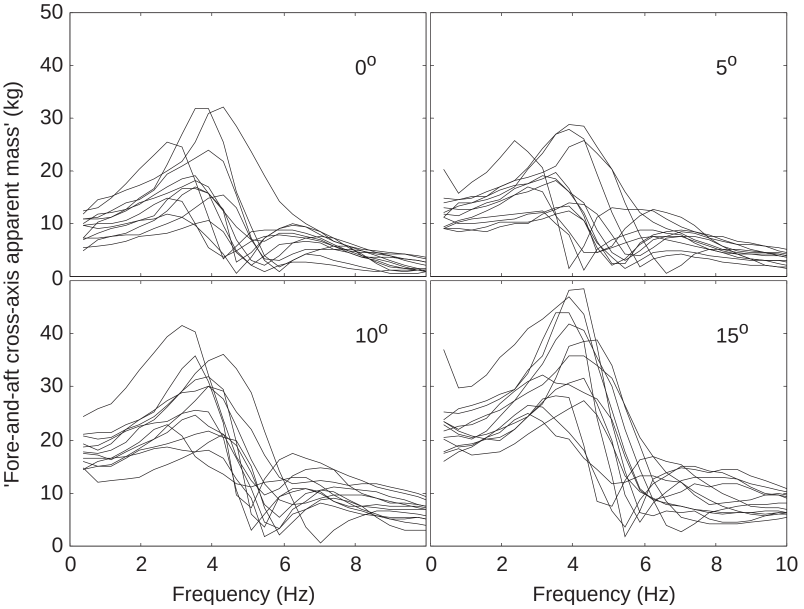

Fig. 8. Inter-subject variability in the 'fore-and-aft cross-axis apparent mass' measured at 1.25 m s^{-2} rms with four different seat angles and no backrest.

between the resonance frequencies measured in the 'fore-and-aft' and 'vertical' directions (Spearman, $p > 0.1$).

At all angles and at all vibration magnitudes, subject mass and subject stature were correlated with the magnitude of the 'fore-and-aft cross-axis apparent mass' at resonance ($p < 0.01$, Spearman), but they were not correlated with the resonance frequency of the 'fore-and-aft cross-axis apparent mass'.

3.2.1. Effect of vibration magnitude

The effect of vibration magnitude on the resonance frequency of the 'fore-and-aft cross-axis apparent mass' decreased with increasing seat angle (Fig. 9 and Table 4): Table 4 indicates that the least effect of vibration magnitude on the resonance frequency occurred with the seat inclined at 15°. For the 'fore-and-aft cross-axis apparent mass' at resonance, there were no statistically significant differences between the different vibration magnitudes at any seat angle (Friedman, $p > 0.05$), except between 0.125 and 1.25 m s^{-2} rms at 15° (Wilcoxon, $p < 0.05$). Table 5 shows the changes of the median resonance frequency and median magnitude at resonance with changes in vibration magnitude.

3.2.2. Effect of seat angle

The resonance frequencies and the 'fore-and-aft cross-axis apparent mass' magnitude at resonance with different seat angles were compared at each vibration magnitude. No statistically significant difference in the resonance frequency was found between the different seat angles at any vibration magnitude (Friedman, $p > 0.05$). However, there were significant differences in the apparent mass magnitude at resonance between seat inclinations of 0°, 10°, and 15° at all

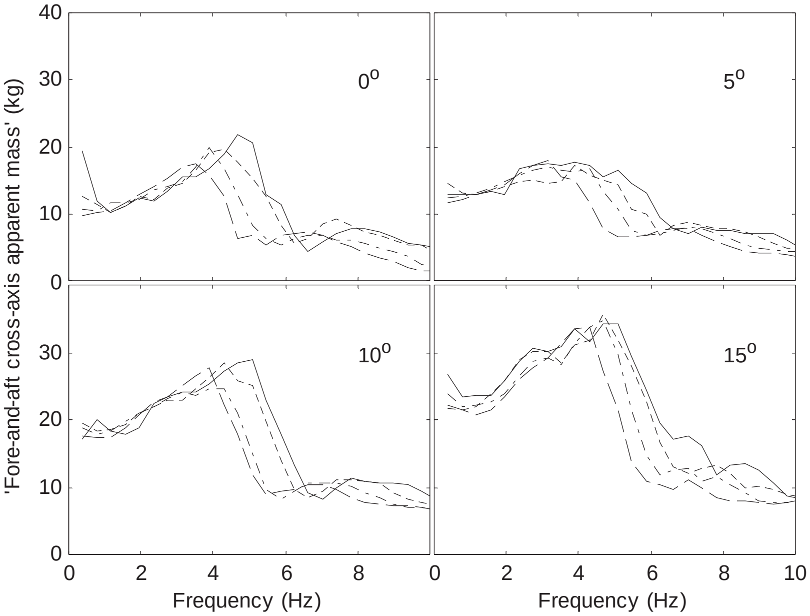

Fig. 9. Effect of vibration magnitude on median 'fore-and-aft cross-axis apparent mass' of 12 subjects measured without a backrest: ———, 0.125 m s^{-2} rms; ……… , 0.25 m s^{-2} rms; –·–·–·–, 0.625 m s^{-2} rms; – – – –, 1.25 m s^{-2} rms.

vibration magnitudes, but no significant difference in the magnitude at resonance between 0° and 5° at any vibration magnitude. There was also a significant difference between the magnitude of the 'fore-and-aft cross-axis apparent mass' measured with a 0° seat angle and the 'fore-and-aft cross-axis apparent mass' measured with 5°, 10° or 15° seat angle at all frequencies in the range 0.25–10 Hz (at a magnitude of 1.25 m s^{-2} rms) ($p < 0.05$), except in the range 2.73–7.03 Hz with seat angles of 0° and 5°. Between 5°, 10°, and 15°, the 'fore-and-aft cross-axis apparent mass' increased with increasing seat angle at frequencies below 5 Hz, although the greatest differences occurred in the resonance area (Fig. 10). Above 5 Hz, no significant differences were found in the 'fore-and-aft cross-axis apparent mass' between 10° and 15°. A similar trend was found with the other vibration magnitudes (Fig. 11).

3.2.3. Effect of backrest

The median resonance frequencies and magnitudes of the 'fore-and-aft cross-axis apparent mass' at resonance with a backrest are shown in Table 6. In comparison with Table 5 (where the median 'fore-and-aft cross-axis apparent mass' at resonance without a backrest are shown), there is a trend for the apparent mass magnitude at resonance to decrease when using a backrest. With all seat surface angles, the effect of the backrest was evident at low frequencies: there were statistically significant differences in the magnitude of the 'fore-and-aft cross-axis apparent mass' measured with and without a backrest only below about 6 Hz at 0.125 and at 0.25 m s^{-2} rms and below about 4 Hz at 0.625 and at 1.25 m s^{-2} rms (Figs. 12 and 13).

Table 4
Wilcoxon matched-pairs signed-ranks test for the resonance frequency of the 'fore-and-aft cross-axis apparent mass': effect of vibration magnitude

Vibration magnitude ($m\,s^{-2}$ rms)	0.125	0.250	0.625	1.250
(*a*) 0°				
0.125	—	**	***	***
0.250		—	***	***
0.625			—	**
1.250				—
(*b*) 5°				
0.125	—	ns	***	**
0.250		—	**	**
0.625			—	*
1.250				—
(*c*) 10°				
0.125	—	ns	**	**
0.250		—	ns	ns
0.625			—	ns
1.250				—
(*d*) 15°				
0.125	—	ns	ns	ns
0.250		—	ns	ns
0.625			—	**
1.250				—

*$p<0.1$, **$p<0.05$, ***$p<0.01$, ns: $p>0.1$

Table 5
Median resonance frequencies and magnitudes at resonance of the 'fore-and-aft cross-axis apparent mass' for four seat angles at 0.125, 0.250, 0.625 and 1.25 $m\,s^{-2}$ rms (without backrest)

Seat angle (deg)	Resonance frequency (Hz)				Magnitude at resonance (kg)			
	0.125	0.25	0.625	1.25	0.125	0.25	0.625	1.25
0	4.69	4.30	3.91	3.52	21.8	19.7	20.0	17.6
5	3.91	3.91	3.12	3.12	17.6	17.1	16.9	17.9
10	5.08	4.30	3.91	3.91	28.9	28.3	24.6	27.7
15	5.08	4.69	4.69	4.30	34.2	35.6	34.8	33.8

4. Discussion

4.1. 'Vertical apparent mass'

At all seat angles, the moduli and phases of the 'vertical apparent mass' were similar to the vertical apparent mass moduli and phases reported previously (e.g. [22,23]). The decrease in the

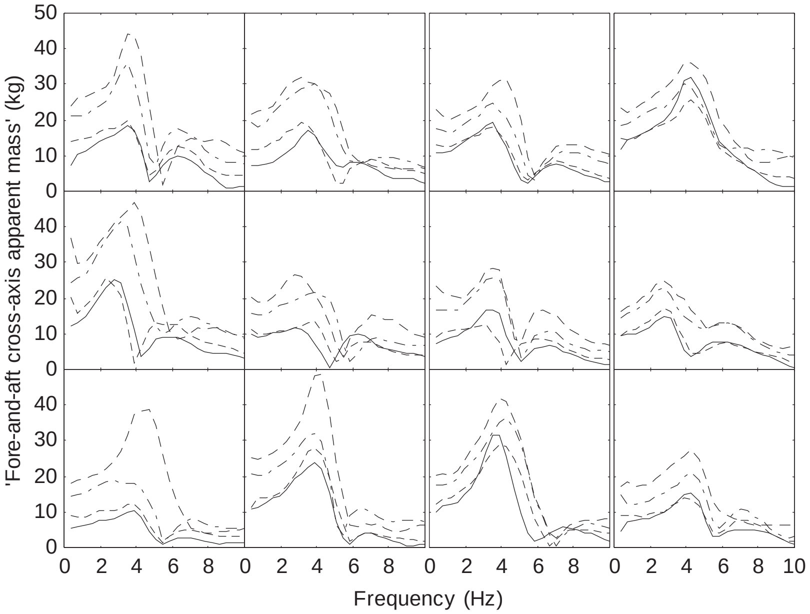

Fig. 10. 'Fore-and-aft cross-axis apparent masses' of 12 subjects measured at 1.25 m s^{-2} rms with no backrest: ———, 0°; ……… , 5°; –·–·–·–, 10°; – – – –, 15°.

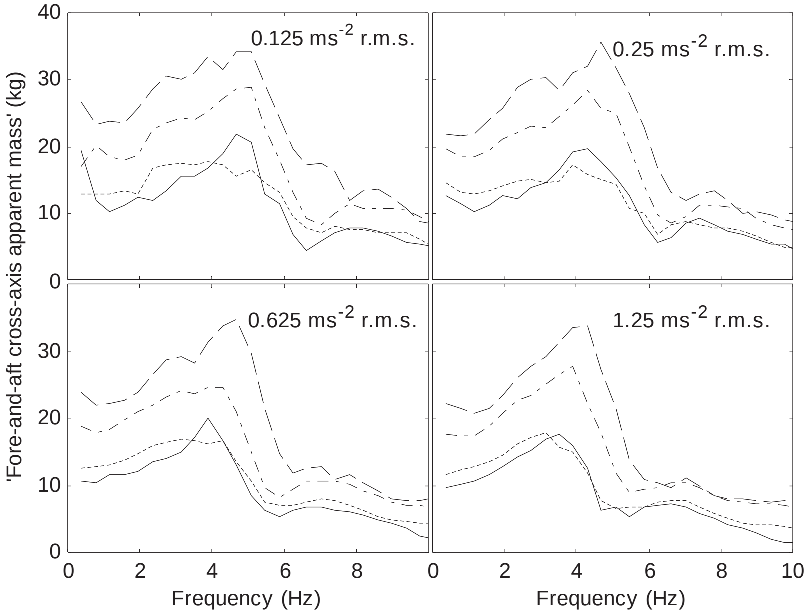

Fig. 11. Effect of seat angle on median 'fore-and-aft cross-axis apparent masses' of 12 subjects measured without a backrest: ——— , 0°; ………, 5°; –·–·–·–, 10°; – – – –, 15°.

Table 6
Median resonance frequencies and magnitudes at resonance of the 'fore-and-aft cross-axis apparent mass' for four seat angles at 0.125, 0.250, 0.625 and 1.25 m s^{-2} rms (with backrest)

Seat angle (deg)	Resonance frequency (Hz)				Magnitude at resonance (kg)			
	0.125	0.25	0.625	1.25	0.125	0.25	0.625	1.25
0	4.69	5.47	4.30	4.30	8.2	9.4	7.3	8.1
5	5.47	4.69	4.30	3.91	9.09	9.09	7.68	7.49
10	5.08	5.08	3.91	3.12	17.94	16.76	12.69	11.6
15	4.69	5.08	3.12	3.52	20.52	19.28	14.10	13.36

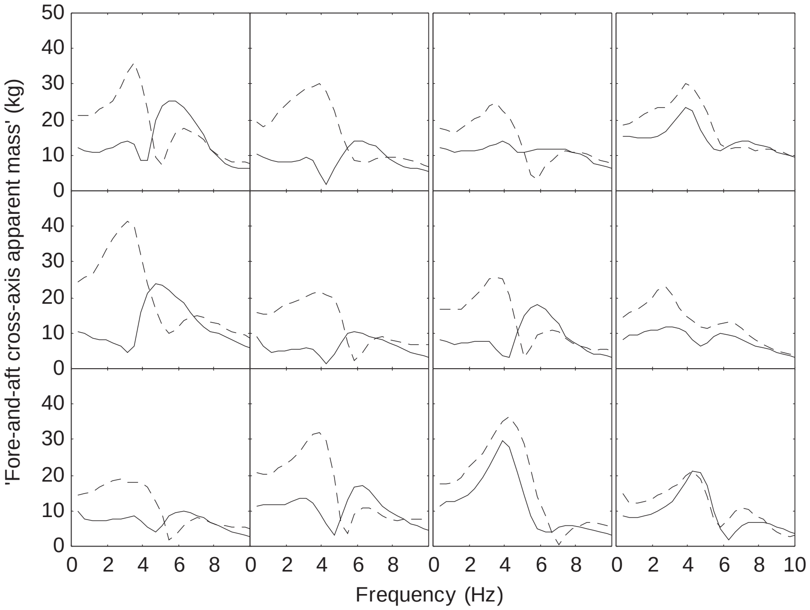

Fig. 12. Effect of backrest on 'fore-and-aft cross-axis apparent masses' of 12 subjects measured at 1.25 m s^{-2} rms with seat angle of 10°. ———, with backrest; – – – –, without backrest.

inter-subject variability (decrease in the average coefficient of variation) with an increase in vibration magnitude is consistent with that noticed by Mansfield and Griffin [10], where they found a higher average coefficient of variation over the frequency range 1–20 Hz at 0.2 m s^{-2} rms than at 1.0 or 2.0 m s^{-2} rms in seven out of nine postures.

The nonlinearity observed here in the 'vertical apparent mass' with all seat angles (the decrease in the resonance frequency of the body with the increase in vibration magnitude) is consistent with the decrease in the resonance frequency, with an increase in vibration magnitude found previously in measures of apparent mass and mechanical impedance (e.g. Refs. [6,11,17]) and in measures of transmissibility to different parts of the body (e.g. Refs. [8,24]) when horizontal supporting seat surfaces were used. The mechanisms that cause the decrease in the resonance frequency with an increase in vibration magnitude are not known, but some suggestions have been offered.

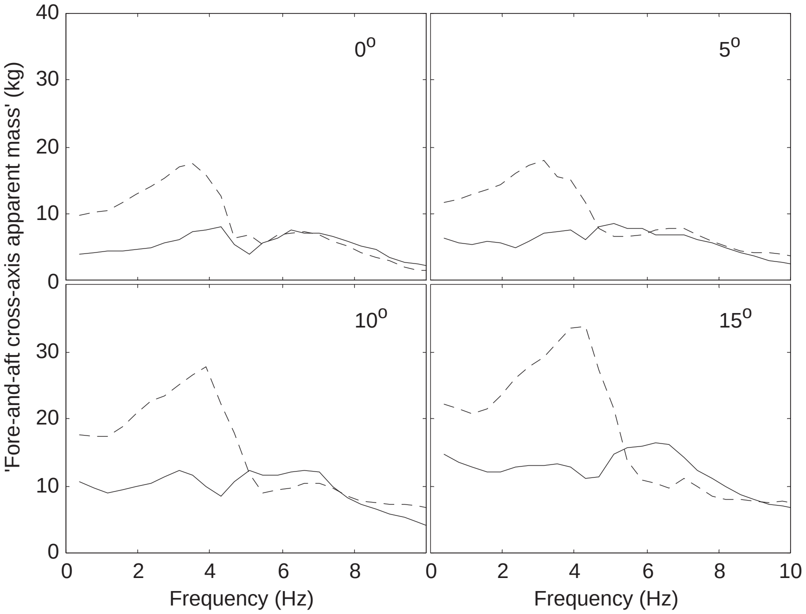

Fig. 13. Effect of backrest on median 'fore-and-aft cross-axis apparent masses' of 12 subjects measured at 1.25 m s^{-2} rms: ———, with backrest; – – – –, without backrest.

Matsumoto and Griffin [17] noticed a decrease in the nonlinearity when subjects sat with tensed buttocks tissue compared to a normal sitting posture, which implies that these tissues are partly responsible for the nonlinearity. Nawayseh and Griffin [11] reached the same conclusion when they noticed a decrease in the nonlinearity when the upper body was resting on the tissue of the buttocks in a minimum thigh contact posture compared to other postures with greater thigh contact. In the present study, it was expected that increasing the seat surface angle would increase the shear stiffness of the ischial tuberosities and this might affect the nonlinearity in the 'vertical' direction. However, the results showed no effect of seat surface angle on the nonlinearity, suggesting that shear movement of tissues at the ischial tuberosities was not a principal mechanism causing nonlinearity in the 'vertical' direction. This might imply that the decrease in the nonlinearity noticed by Matsumoto and Griffin [17] when subjects tensed their buttocks tissue was due to an increase in axial stiffness of the buttocks tissue rather than an increase in shear stiffness of the tissue.

Vibration magnitude had a greater effect on the 'vertical apparent mass' at resonance when the seat was at 0° (i.e. horizontal). However, unlike the effect of vibration magnitude on the resonance frequency, the effect of vibration magnitude on the modulus of the apparent mass at resonance is inconsistent in previous studies. For example, while Matsumoto [25] found no significant differences in the magnitude of the apparent mass at resonance measured with different vibration magnitudes, Mansfield and Griffin [24] found a slight, but statistically significant, increase in the normalised apparent mass magnitude at resonance with increasing vibration magnitude, using similar vibration magnitudes to those used by Matsumoto. The results obtained in this study at 0° show a statistically significant decrease in the apparent mass magnitude at resonance with increasing vibration magnitude. For example, the median vertical apparent mass at resonance decreases from about 103 to about 95 kg when the vibration magnitude increased from 0.125 to 1.25 m s^{-2} rms Understanding the factors that affect the changes in apparent mass at resonance may assist understanding of the nonlinearity.

The 'vertical apparent masses' had similar resonance frequencies and similar magnitudes at resonance, irrespective of seat angle. Wei and Griffin [13] measured the forces normal to the seat surface with cushion inclinations of 0°, 5°, 10°, 15°, and 20° and compared the apparent masses obtained from the vertical component of the measured force and the vertical acceleration. They found, generally, only small changes in the apparent mass below 5.5 Hz with the different seat angles. However, they found that with increasing seat inclination the seat transmissibility tended to decrease below 6 Hz and increase above 6 Hz. Wei and Griffin concluded that the small change in the apparent mass with different seat angles could not explain the change in the transmissibility of the seat. In this study, the absence of a considerable change in the 'vertical apparent mass' with a change in seat angle (up to 15°) over the whole frequency range may suggest that only a small, if any, postural change accompanied the change in seat angle. Alternatively, a change in posture with change in seat angle might have been offset by changes in the force normal to the seat surface (i.e. change in the cosine of the seat angle) so that the responses at the different seat angles remained similar: a change in the upper body posture might have accompanied the change in the seat angle so that the force measured normal to the seat surface was not greatly affected.

The results showed no significant differences in the resonance frequency measured with and without a backrest at 0°,5°, and 10°. It seems that no study has previously compared the resonance frequency of the body with and without a backrest with seat angles other than 0°. At 0°, the insignificant effect of the backrest on the resonance frequency in this study is consistent with the results of Mansfield and Griffin [10], but inconsistent with the results of Nawayseh and Griffin [15], who reported significant differences in the resonance frequencies measured with and without a backrest. At 0°, one difference between this study and that of Nawayseh and Griffin [15] is the position of the lower legs: they were vertical in the previous study but not vertical in the present study. However, this explanation might be excluded because the lower legs were also vertical in the study by Mansfield and Griffin. This is also supported by Rakheja et al. [26], who found no effect on the resonance frequency when moving the feet from far away to close to a seat. The reason for the differences in the effect of the backrest on the resonance frequencies between studies may be the type of backrest employed. In this study, and in the Mansfield and Griffin study, the full length of the back of each subject (including the lumbar and pelvis areas) was in contact with the backrest, whereas in the study by Nawayseh and Griffin, the lumbar spine and the pelvis area were not in contact with the backrest.

The backrest was found to generally reduce the 'vertical apparent mass' at frequencies below resonance, while increasing the 'vertical apparent mass' at frequencies above resonance. This is consistent with the effect of a backrest in a previous study by Fairley and Griffin [2]. The present study found that the effect of the backrest on the 'vertical apparent mass' magnitude was greater with a decreased seat surface angle (see Table 3), although the effect of a backrest on the resonance frequency of the 'vertical apparent mass' was greater with increased seat angle. However, the effect of the backrest on the vertical apparent mass during vertical excitation is small compared to the effect of the backrest on fore-and-aft apparent mass during fore-and-aft excitation. During fore-and-aft excitation, a backrest considerably increases the fore-and-aft apparent mass at frequencies above about 1 Hz (e.g. Ref. [14]).

Among the different factors studied (vibration magnitude, seat angle and backrest), vibration magnitude had the greatest effect on the resonance frequency of the 'vertical apparent mass'.

4.2. *Fore-and-aft cross-axis apparent mass*

The 'fore-and-aft cross-axis apparent masses' (calculated from forces measured parallel to the seat surface and vertical applied acceleration) were large, but less than those in the 'vertical' direction at all seat angles and at all vibration magnitudes. The resonance frequencies of the 'fore-and-aft cross-axis apparent masses' were also lower than the 'vertical apparent masses'.

With the seat at 0° (i.e. horizontal), the high 'fore-and-aft cross-axis apparent masses' on the seat surface are likely to have been due to pitching modes of parts of the upper body, as suggested by Nawayseh and Griffin [11]. However, Nawayseh and Griffin found small fore-and-aft forces at low frequencies (below 1 Hz), in contrast to high forces at low frequencies measured in this study. In the four postures used by Nawayseh and Griffin, the lower legs were vertical and therefore did not contribute to fore-and-aft forces on the seat. In the present study, the lower legs were stretched forward and the feet rested on a footrest inclined at 45° (see Fig. 1). In this seating arrangement, forces at the feet may have contributed to fore-and-aft forces at the seat and may be responsible for the forces measured at low frequencies. The decrease in the fore-and-aft forces seen between 5 and 7 Hz (i.e. where the troughs occurred) may be due to forces coming from the feet through the legs to the seat, since measures of apparent mass at the feet show resonances at similar frequencies [11,27].

The increase in the 'fore-and-aft cross-axis apparent mass' at low frequencies as the seat angle increased (to 5°, 10° and 15°) seems to be caused mostly, if not totally, by the increase in the component of the mass in the 'fore-and-aft' direction (i.e. parallel to seat surface). When the seat was at 0°, the measured fore-and-aft force was perpendicular to the applied vertical acceleration and, hence, the measured fore-and-aft cross-axis apparent masses at low frequencies (around 1 Hz) may be assumed to come from forces applied at the feet, as explained above. Assuming the human body moves as a rigid body at very low frequencies, an increase in seat angle from θ_1 to θ_2 will increase the 'fore-and-aft cross-axis apparent mass' by the mass of the subject multiplied by $(\sin\theta_2 - \sin\theta_1)$. For example, subject 1 had a sitting mass of 74.0 kg (see apparent mass around 1 Hz in Fig. 4). When the seat angle increased between 5° and 15°, an increase of 12.7 kg $(74\,\text{kg} \times (\sin 15° - \sin 5°))$ would be expected in the 'fore-and-aft' component of the mass. From Fig. 10, at 1 Hz the difference between the 'fore-and-aft cross-axis apparent mass' measured at 15° and that measured at 5° is 12.6 kg (26.8 kg at 15° and 14.2 kg at 5°), consistent with the expected increase. These calculations assume that the forces coming from the feet do not change, or have a small change, with the variation in seat angle. Around the resonance frequency, these simple calculations will not apply because the resonance is associated with pitching modes of the body and there is a large nonlinearity.

The resonance frequencies from the two responses (i.e. 'vertical apparent mass' and 'fore-and-aft cross-axis apparent mass') were not correlated in any condition, implying a different mechanism produced the two resonances. Kitazaki and Griffin [28,29] reported two separate vibration modes at 3.4 and 4.9 Hz produced by two different mechanisms. The mode at 3.4 Hz was a bending mode of the entire spine, which caused fore-and-aft motion of the pelvis in phase with fore-and-aft motion of the head. The 4.9 Hz mode was the principal mode: an 'entire body mode in which the head, spinal column and the pelvis moved vertically due to axial and shear deformations of the buttocks tissue, in phase with a vertical visceral mode, and a bending mode of the upper thoracic and cervical spine'. Matsumoto and Griffin [20] also reported two vibration modes at 2.53 and 5.66 Hz when modelling the dynamic responses (apparent mass and transmissibility) of the human body to vibration using multi-degree-of-freedom models with rotational capability. The 2.53 Hz mode was produced by pitching motion of the pelvis in phase with a bending mode of the spine. The mode at 5.66 Hz was thought to be due to deformation of the buttocks tissues together with a vertical mode of the viscera and bending mode of the spine. The mode measured in the 'fore-and-aft' direction in the present study might be the same mode reported at 3.4 Hz (or 2.53 Hz) in the previous studies, while the mode measured in the vertical direction in the present study may be the 4.9 Hz (or the 5.66 Hz) mode measured in the previous studies.

Nonlinear behaviour similar to that with the 'vertical apparent mass' was found in the 'fore-and-aft cross-axis apparent mass': a decrease in the resonance frequency with an increase in vibration magnitude. The effect of vibration magnitude on the resonance frequency decreased with increasing seat angle. Since the mass in the 'fore-and-aft' direction increases with an increase in seat surface angle, the insignificant change in the resonance frequency found in the 'fore-and-aft cross-axis apparent mass' with the increase in seat surface angle suggests an increase in stiffness of the ischial tuberosities, where shear stiffness increases with the increase in seat surface angle. The increase in stiffness might have been the factor that reduced the softening effect of the vibration magnitude in the 'fore-and-aft' direction with the increase in seat angle, although this increase in stiffness had no effect on the nonlinearity in the 'vertical' direction.

The effect of the backrest on the 'fore-and-aft cross-axis apparent mass' was more pronounced than the effect on the 'vertical apparent mass'. The median fore-and-aft force at resonance decreased by, at least, 38% (at 10° with $0.125\,\mathrm{m\,s^{-2}}$ rms) and by, at most, 64% (at 0° and $0.625\,\mathrm{m\,s^{-2}}$ rms) when a backrest was used. At low frequencies, the high forces that were assumed to have transferred from the feet through the legs to the seat when no backrest was used also decreased when a backrest was used. The pitching of the upper body might have been damped or suppressed when using a backrest: although the great effect of the backrest on the fore-and-aft cross-axis apparent mass was not seen by Nawayseh and Griffin [15], the position of the feet in this study might have reduced forward pitching of the body when the backrest reduced backward pitching.

5. Conclusions

With four angles of a supporting seat surface (0°, 5°, 10°, and 15°), the resonance frequencies and the magnitudes at resonance were greater in the 'vertical apparent masses' (calculated from the forces measured normal to the seat surface and the applied vertical acceleration) than in the 'fore-and-aft cross-axis apparent masses' (calculated from forces measured parallel to the seat surface and the applied vertical acceleration). The resonance frequencies in the two directions were not correlated. At seat angles up to 15°, there were negligible changes in the 'vertical apparent mass' but considerable changes in the 'fore-and-aft cross-axis apparent mass', which increased with increasing seat angle. In both the 'vertical' and 'fore-and-aft' directions, the resonance frequencies decreased with increasing vibration magnitude, with least decrease of resonance frequency in the 'fore-and-aft cross-axis apparent mass' at the maximum inclination of 15°. The presence of a backrest decreased both the 'vertical apparent mass' and the 'fore-and-aft cross-axis apparent mass' at low frequencies, with the greatest reduction in the 'fore-and-aft cross-axis apparent mass'. The 'fore-and-aft cross-axis apparent mass' at resonance, but not the resonance frequency, was correlated with the masses and statures of the subjects. The high fore-and-aft forces during vertical excitation merit further consideration when designing or modelling non-vertical isolation devices for the body, especially suspension seating.

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