EFFECT OF BACKREST INCLINATION ON APPARENT MASS AT THE SEAT AND THE BACKREST DURING VERTICAL WHOLE-BODY VIBRATION

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Abstract

Biodynamic models indicate that dynamic spinal forces depend on the biodynamic behaviour of the body, which varies with backrest inclination. With random vertical vibration (0.2 to 20 Hz at 1.0 ms^{-2} r.m.s.), this study measured the vertical in-line apparent mass and the fore-and-aft cross-axis apparent mass at the seat pan and the backrest with 12 subjects sitting with different rigid flat backrests (vertical, 10˚, 20˚, 30˚, and no backrest). With the vertical backrest, the effect of contact at a lumbar support (at L2) or a thoracic support (at T5) was investigated. Inclining the backrest tended to increase the resonance frequency and decrease the apparent mass at the resonance in the vertical in-line apparent mass measured at the seat pan. With an inclined backrest, the principal peak in the vertical in-line apparent mass at the seat pan was broader, and the resonance frequencies in the fore-and-aft cross-axis apparent mass and the vertical in-line apparent mass differed, suggesting changes in the motions of the thoracic and lumbar spine. With increasing inclination of the backrest, the overall dynamic forces exposed to the subjects in the vertical and fore-and-aft directions increased in the frequency range 6 to 15 Hz. It is concluded that varying the inclination of a backrest alters the motions of body parts and the fore-and-aft and vertical dynamic forces at the seat pan and the backrest.

1. Introduction

Drivers and passengers of many types of vehicle sit with their backs supported by a backrest. Backrest support can reduce the need for muscle activity to maintain posture in static conditions (Bennett *et al.*, 1989) and stabilise the body so as to reduce the need for muscle activity in dynamic conditions (Oliveira *et al.*, 2001).

A backrest can modify the vibration transmitted through the body (e.g., Paddan and Griffin, 1988) and so may affect the discomfort caused by vibration (e.g., Basri and Griffin, 2013). The inclination of a seat backrest also influences the vibration transmitted to the body (e.g., Pope *et al.*, 1998) and the discomfort caused by vibration (e.g., Basri and Griffin, 2013). Compared to sitting without a backrest, the use of backrest has been reported to reduce spinal loads during whole-body vertical vibration (0.3 to 30 Hz at 1.0 ms^{-2} r.m.s.) and inclining the backrest further reduces the forces measured in-vivo with vertebral body replacements (Rohlmann *et al*., 2010).

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The forces in the lumbar spine can be predicted from the sum of static spinal forces (caused by gravity) and dynamic spinal forces (induced by vertical vibration) using a simple biodynamic model (e.g., Yang *et al.*, 2013, 2014). Such models suggest the dynamic spinal forces depend on the vibration transmitted to the upper body. This led to the current experimental investigation of the effects of a backrest on biodynamic responses.

Compared to sitting without a backrest, a vertical backrest tends to increase the resonance frequency in the vertical apparent mass and decrease the apparent mass at resonance (Toward and Griffin, 2009; Qiu and Griffin, 2012). In part, this may be because a backrest changes the curvature of the spine and, therefore, the dynamic response of the body (Griffin, 1990). Increased backrest inclination tends to further increase the resonance frequency and further decrease the apparent mass at resonance (Toward and Griffin, 2009). The fore-and aft cross-axis apparent mass is also affected by contact with a vertical backrest and whether the feet are supported (Nawayseh and Griffin, 2004). When sitting supported by a vertical backrest, the resonance frequency in the fore-and-aft cross-axis apparent mass seems to be correlated with the resonance frequency in the vertical in-line apparent mass (e.g., Nawayseh and Griffin, 2004; Qiu and Griffin, 2012). The fore-and-aft cross-axis apparent mass at the seat has not been reported with inclined backrests.

During vertical whole-body vibration, there can be considerable forces at a vertical backrest in both the vertical and fore-and-aft directions, with both the vertical in-line apparent mass and the fore-and-aft cross-axis apparent mass at the backrest having resonances around 5 Hz (e.g., Nawayseh and Griffin, 2004). Dynamic forces in the vertical and fore-and-aft directions have not been reported with an inclined backrest.

The objective of this study was to investigate the vertical in-line apparent mass and fore-and-aft cross-axis apparent mass at the seat pan and the backrest and how backrest inclination affects the overall dynamic forces when seated. It was hypothesised that with increasing inclination of a backrest the fore-and-aft cross-axis apparent mass at the seat pan would increase, because there would be more excitation of the body in the fore-and-aft direction. The measured data were required for the development biodynamic models of the response of the seated human body to vertical whole-body vibration and predict spinal forces when sitting with different backrests.

2. Methods

2.1 Apparatus

Vertical vibration was generated by a 1-m vertical vibrator. A rigid seat with an adjustable rigid backrest was mounted on the platform of the vibrator (Figure 1). An aluminium alloy and plywood backrest was mounted on the rigid seat so that it could be adjusted to inclinations from 0 degrees (vertical) to 60 degrees. When vertical, the backrest extended from 100 mm to 700 mm above the seat pan surface. To produce backrest contact in either the lumbar region or the thoracic region when sitting with a vertical backrest, the subjects were asked to adjust the position of their pelvis on the seat to provide the required contact location.

A force plate (Kistler 9281 B) consisting of four tri-axial quartz transducers at the four corners of a rectangular welded steel frame (600 mm x 400 mm) was secured on the supporting surface of the seat to measure the dynamic forces in vertical and fore-and-aft directions at the seat pan interface. Another force plate, consisting four tri-axial force transducers (Kistler 9602) at the four corners of a rectangular plywood frame (600 mm x 500 mm) was mounted on the backrest. The signals from the force transducers were amplified by Kistler 5073 charger amplifiers.

One single-axis piezo-resistive accelerometer (Entran EGCSY-240D-10) was mounted at the centre of the force plate on the seat pan to measure the vertical acceleration. Two more single-axis piezo-resistive accelerometers (Entran EGCSY-240D-10) were mounted at the middle of the backrest frame to measure the acceleration normal to the backrest surface and parallel to the backrest surface.

The signals measured at the four corners of the force plate at the seat pan were summed to give two signals corresponding to the vertical and fore-and-aft forces. The force signals from each corner of the backrest in directions normal and parallel to the backrest surface were acquired individually. All forces and acceleration signals were acquired with a 16-channel *HVLab* data acquisition system at a sampling rate of 256 samples per second via 100-Hz anti-aliasing filters.

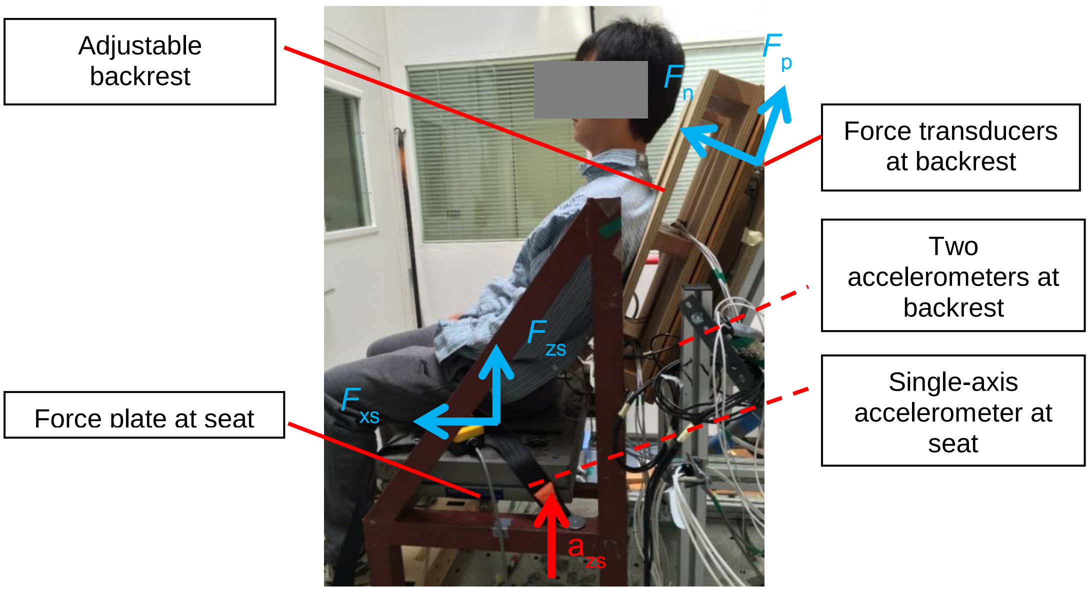

Figure 1 Seat on vibrator with a subject sitting against a 20º-inclined backrest

2.2 Experimental design

Twelve healthy male subjects with median age 29 years (range 22 to 34 years), median height 173.5 cm (range 160 to 184 cm) and median weight 69 kg (range 60 to 100 kg) participated in the experiment.

During the experiment subjects sat in the following conditions:

(i) upright without backrest contact (i.e., NB);

(ii) against the vertical backrest with contact at either L2 or T5 (i.e., B_{0L2} and B_{0T5});

(iii) against the backrest inclined by 10º, 20º or 30º with contact only at the thoracic region of the back (i.e., B_{10}, B_{20} and B_{30}).

In all six conditions, the feet were supported on an adjustable footrest to obtain average thigh contact. The hands rested on the lap.

In each condition, the subjects were exposed to 60-s periods of random vertical vibration with approximately flat constant-bandwidth acceleration spectra (0.2 to 20 Hz at 1.0 ms^{-2} r.m.s.). The experiment was approved by the Ethics Committee of the Faculty of Engineering and the Environment at the University of Southampton (approval number 14342).

2.3 Data analysis

2.3.1 Mass cancellation

For the calculation of the forces at the seat and the backrest, the effect of the mass of the force plates on the measured dynamic forces was eliminated by mass cancellation in the time-domain. The acceleration time-history was multiplied by the mass of the force platform 'above' the force sensors and the resulting force subtracted from the measured force. With inclined backrests, mass cancellation was performed on the dynamic forces in the directions normal and parallel to the backrest surface. In the normal and the parallel direction, the time history of the acceleration was multiplied by the mass of the plate and then subtracted from the measured force time history in the same direction.

2.3.2 Transfer functions

Various measures of apparent mass were calculated from transfer functions between dynamic force and acceleration using the cross spectral density method. For the 'vertical in-line apparent mass' at the seat pan, $M_{zzs}(f)$, the measured force and acceleration were in the same direction (i.e., vertical). For the 'fore-and-aft cross-axis apparent mass' at the seat pan, $M_{xzs}(f)$, the measured fore-and-aft force was perpendicular to the vertical acceleration at the seat pan. The two apparent masses at the seat pan, $M_{zzs}(f)$ and $M_{xzs}(f)$, and the associated coherencies, $C_{zzs}^2(f)$ and $C_{xzs}^2(f)$, were calculated as:

$$M_{zzs}(f) = \frac{G_{a_{zs}F_{zs}}(f)}{G_{a_{zs}}(f)}, \quad C_{zzs}^2(f) = \frac{\left|G_{a_{zs}F_{zs}}(f)\right|^2}{G_{a_{zs}}(f)G_{F_{zs}}(f)},$$

$$M_{xzs}(f) = \frac{G_{a_{zs}F_{xs}}(f)}{G_{a_{zs}}(f)}, \quad C_{xzs}^2(f) = \frac{\left|G_{a_{zs}F_{xs}}(f)\right|^2}{G_{a_{zs}}(f)G_{F_{xs}}(f)} \qquad (1)$$

where, $G_{a_{zs}}(f)$ is the auto-spectra of the vertical acceleration at the seat pan, $a_{zs}(t)$, $G_{F_{zs}}(f)$ and $G_{F_{xs}}(f)$ are the auto-spectra of vertical and fore-and-aft forces measured at the seat pan, $F_{zs}(t)$ and $F_{xs}(t)$, and $G_{a_{zs}F_{zs}}(f)$ and $G_{a_{zs}F_{xs}}(f)$ are the cross-spectra between $a_{zs}(t)$ and $F_{zs}(t)$ and between $a_{zs}(t)$ and $F_{xs}(t)$.

The force transducers at the backrest measured the dynamic forces in directions normal to the surface of the backrest, F_n, and parallel to the surface of the backrest, F_p. These forces were combined, after adjusting for the inclination of the backrest, so as to calculate the forces in the vertical and fore-and-aft directions (i.e., the same coordinates used for calculating the vertical in-line and fore-and-aft cross-axis apparent mass at the seat pan). For a backrest inclination angle *α*, the force time histories in the vertical and fore-and-aft directions were calculated as:

$$F_{zb}(t) = F_n(t)\sin\alpha + F_p(t)\cos\alpha \ , \qquad (2)$$
$$F_{xb}(t) = F_n(t)\cos\alpha - F_p(t)\sin\alpha$$

where $F_n(t)$ and $F_p(t)$ are the force time-histories measured by the force transducers in the local coordinate system, and $F_{zb}(t)$ and $F_{xb}(t)$ are the forces adjusted to the vertical and fore-and-aft directions, respectively.

The vertical in-line apparent mass at the back, $M_{zzb}(f)$, was given by the transfer function between $F_{zb}(t)$ and $a_{zs}(t)$. The fore-and-aft cross-axis apparent mass at the back, $M_{xzb}(f)$, was given by the transfer function between $F_{xb}(t)$ and $a_{zs}(t)$. The two apparent masses at the back, $M_{zzb}(f)$ and $M_{xzb}(f)$, and the associated coherencies, $C_{zzb}{}^2(f)$, $C_{xzb}{}^2(f)$, were calculated as:

$$M_{zzb}(f) = \frac{G_{a_{zs}F_{zb}}(f)}{G_{a_{zs}}(f)}, \ C_{zzb}{}^2(f) \ = \frac{\left|G_{a_{zs}F_{zb}}(f)\right|^2}{G_{a_{zs}}(f)G_{F_{zb}}(f)},$$

$$M_{xzb}(f) = \frac{G_{a_{zs}F_{xb}}(f)}{G_{a_{zs}}(f)}, \ C_{xzb}{}^2(f) \ = \frac{\left|G_{a_{zs}F_{xb}}(f)\right|^2}{G_{a_{zs}}(f)G_{F_{xb}}(f)} \qquad (3)$$

where $G_{F_{zb}}(f)$ and $G_{F_{xb}}(f)$ are the auto-spectra of the calculated vertical force $F_{zb}(t)$ and the calculated fore-and-aft force $F_{xb}(t)$ at the backrest; $G_{a_{zs}F_{zb}}(f)$ and $G_{a_{zs}F_{xb}}(f)$ are the cross-spectra between $a_{zs}(t)$ and $F_{zb}(t)$ and between $a_{zs}(t)$ and $F_{xb}(t)$.

2.3.3 Statistical analysis

Non-parametric statistical tests (Friedman two-way analysis of variance for *k*-related samples and Wilcoxon matched-pairs signed-ranks test for two-related samples) were used. The Spearman rank order correlation was employed in to investigate associations between variables.

3. Results

3.1 Apparent mass at the seat pan

3.1.1 Vertical in-line apparent mass

The median vertical apparent masses of the 12 subjects in each of the six sitting conditions (without backrest and with the vertical backrest at L2 or T5 or the backrest inclined by 10° 20°, and 30º) are shown in Figure 2.

The vertical apparent mass in the upright sitting posture shows a principal resonance at about 5 Hz. Some subjects also showed a secondary resonance around 8 to 10 Hz. These findings are consistent with previous studies (e.g., Fairley and Griffin, 1989).

With the addition of the vertical backrest at T5, the vertical in-line apparent mass reduced at the 5-Hz resonance (p=0.012). Similarly, with increasing inclination of the backrest (B_{0T5}, B_{10}, B_{20} and B_{30}), the vertical in-line apparent mass reduced at frequencies around the 5-Hz resonance (p<0.0001, Friedman) and at lower frequencies. Although over the four backrest inclinations (B_{0T5}, B_{10}, B_{20} and B_{30}) the resonance frequency appears to increase, the change was not statistically significant (p=0.122, Friedman). Even so, the resonance frequency in the vertical apparent mass was significantly greater with the 30º backrest inclination than with each of the other backrest conditions (p<0.05, Wilcoxon).

Changing the location of contact with a vertical backrest from L2 (B_{0L2}) to T5 (B_{0T5}) did not change the resonance frequency or the apparent mass at the resonance in the vertical in-line apparent mass at the seat pan (p>0.05, Wilcoxon). Differences in the resonance frequencies of the apparent mass and the apparent mass at resonance are summarised in Table 1.

Table 1 Statistical significance of the effects of backrest inclination on the resonance frequency in the vertical apparent mass at the seat pan and the modulus of the apparent mass at resonance. Wilcoxon matched-pairs signed ranks test.

Resonance frequency of vertical apparent mass at the seat pan						
	NB	B_{0L2}	B_{0T5}	B_{10}	B_{20}	B_{30}
NB	-	ns	ns	ns	ns	*
B_{0L2}		-	ns	ns	ns	*
B_{0T5}			-	ns	ns	*
B_{10}				-	ns	**
B_{20}					-	*
B_{30}						-

Vertical apparent mass at the seat pan at the resonance frequency						
	NB	B_{0L2}	B_{0T5}	B_{10}	B_{20}	B_{30}
NB	-	*	*	**	**	**
B_{0L2}		-	ns	*	**	**
B_{0T5}			-	**	**	**
B_{10}				-	**	**
B_{20}					-	**
B_{30}						-

ns: not significant; * p≤0.05; ** p≤0.01.

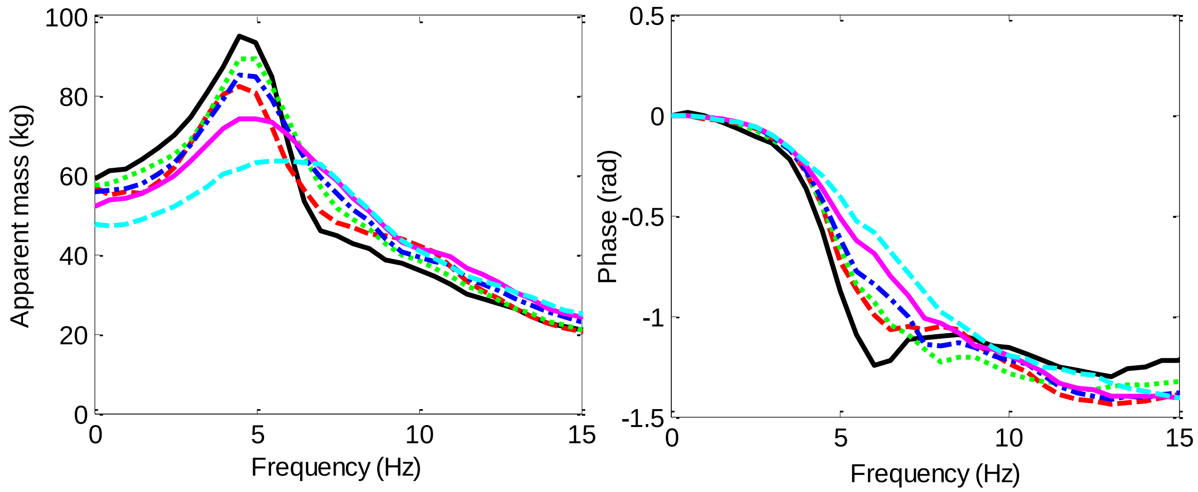

Figure 2 Vertical in-line apparent mass at the seat pan in different sitting conditions: normal upright sitting posture NB ('——'); vertical backrest contact at L2, B_{0L2} ('------'); vertical backrest contact at T5, B_{0T5} ('……'); contact with 10º inclined backrest, B_{10} ('–·–'); 20º inclined backrest, B_{20} ('——'); 30º inclined backrest, B_{30} ('------'). Left: modulus; right: phase. Median values from 12 subjects.

With the backrest inclined to 20 and 30 degrees, the vertical apparent mass at the resonance frequency broadened (Figure 2) and about 6 of the 12 subjects showed two peaks in the apparent mass in the range 5 to 7.5 Hz. With increasing inclination of the backrest, the magnitude of the peak at the higher frequency tended to be greater than the first peak, especially when the backrest was inclined to 30º.

3.1.2 Fore-and-aft cross-axis apparent mass

The fore-and-aft cross-axis apparent mass at the seat pan when sitting with no backrest showed a principal resonance around 5 Hz (Figure 3), similar to the resonance frequency in the vertical in-line apparent mass at the seat pan.

With the addition of the vertical backrest at either L2 or T5 there was no change in either the fore-and-aft cross axis apparent mass at resonance (p>0.05, Wilcoxon) or the resonance frequency (p>0.05, Wilcoxon). When the contact location with the vertical backrest changed from L2 to T5, there was no change in either the resonance frequency of the fore-and-aft cross-axis apparent mass at the seat pan or the apparent mass at this resonance (p>0.05, Wilcoxon).

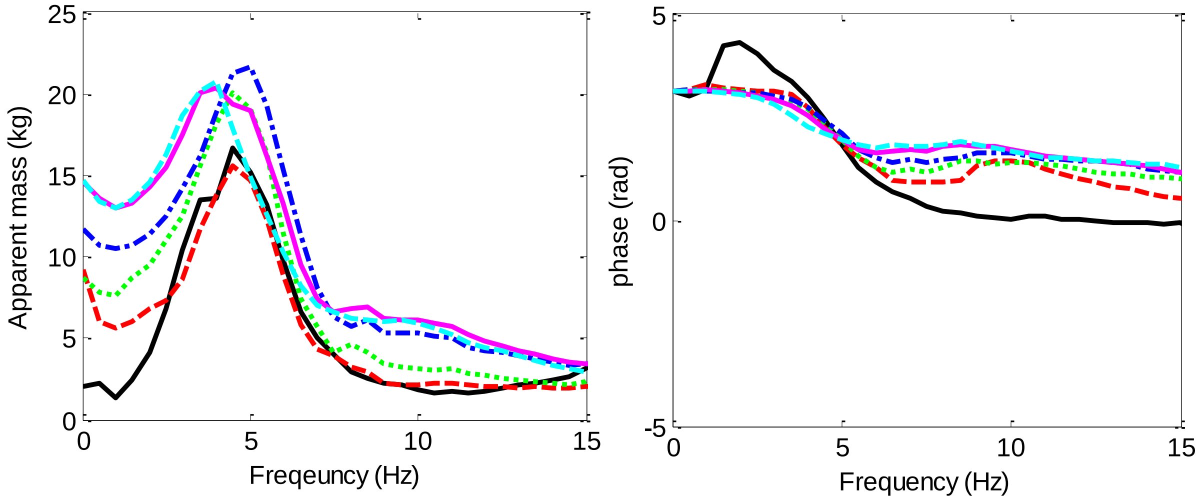

Figure 3 Fore-and-aft cross-axis apparent mass at the seat pan in different sitting conditions: normal upright sitting posture NB ('——'); vertical backrest contact at L2, B_{0L2} ('------'); vertical backrest contact at T5, B_{0T5} ('……'); contact with 10º inclined backrest, B_{10} ('–·–'); 20º inclined backrest, B_{20} ('——'); 30º inclined backrest, B_{30} ('------'). Left: modulus; right: phase. Median values from 12 subjects.

Table 2 Statistical significance of the effects of backrest inclination on the resonance frequency in the fore-and-aft cross-axis apparent mass at the seat pan and the modulus of the cross-axis apparent mass at resonance. Wilcoxon matched-pairs signed ranks test.

Resonance frequency of fore-and-aft apparent mass at the seat pan						
	NB	B_{0L2}	B_{0T5}	B_{10}	B_{20}	B_{30}
NB	-	ns	ns	ns	ns	*
B_{0L2}		-	ns	ns	*	**
B_{0T5}			-	ns	*	**
B_{10}				-	*	**
B_{20}					-	**
B_{30}						-

Fore-and-aft apparent mass at the seat pan at the resonance frequency						
	NB	B_{0L2}	B_{0T5}	B_{10}	B_{20}	B_{30}
NB	-	ns	ns	*	ns	ns
B_{0L2}		-	ns	**	ns	ns
B_{0T5}			-	*	ns	ns
B_{10}				-	ns	ns
B_{20}					-	ns
B_{30}						-

ns: not significant; * p≤0.05; ** p≤0.01.

Comparing the fore-and-aft cross-axis apparent mass measured at the seat pan with the vertical backrest at T5 and the three inclinations of the backrest (i.e., B_{10}, B_{20} and B_{30}), there was a change in the frequency of the principal resonance (p<0.0001, Friedman), with a difference between inclinations of 10º and 20º (p=0.013, Wilcoxon; Table 2, Figure 3). However, the fore-and-aft cross-axis apparent mass at resonance did not differ over the vertical backrest at T5 and the three inclinations of the backrest (p=0.1335, Friedman).

More detail on the differences in the resonance frequency of the fore-and-aft apparent mass and the fore-and-aft apparent mass at resonance are shown in Table 2.

The fore-and-aft cross-axis apparent mass at the seat pan increased at frequencies less than the resonance frequency when there was backrest contact at T5 (p=0.002, Wilcoxon; analysed at 2.5 Hz), and increased further with increasing inclination of the backrest (p=0.001, Friedman; analysed at 2.5 Hz; Figure 3).

3.2 Apparent mass at the backrest

3.2.1 Vertical in-line apparent mass

The vertical in-line apparent mass at the backrest showed a resonance in the frequency range 4 to 5.5 Hz (Figure 4).

The resonance frequencies in the vertical in-line apparent mass at the backrest were similar with contact at L2 and T5 (p>0.05, Wilcoxon), although the apparent mass at resonance was greater with contact at T5 than contact at L2 (p=0.009, Wilcoxon).

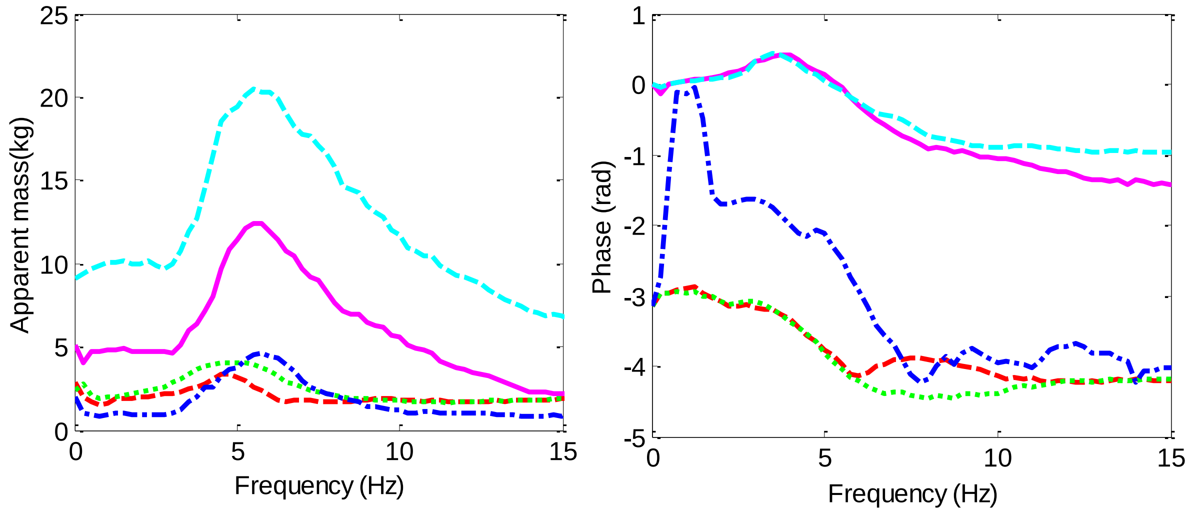

Figure 4 Vertical in-line apparent mass at the backrest in different sitting conditions: vertical backrest contact at L2, B_{0L2} ('------'); vertical backrest contact at T5, B_{0T5} ('……'); contact with 10º inclined backrest, B_{10} ('–·–'); 20º inclined backrest, B_{20} ('——'); 30º inclined backrest, B_{30} ('------'). Left: modulus; right: phase. Median values from 12 subjects.

Comparing the vertical in-line apparent mass measured at the backrest with the vertical backrest at T5 and with the three inclinations of the backrest (i.e., B_{10}, B_{20} and B_{30}), there was a change in both the resonance frequency (p=0.006, Friedman) and the apparent mass at resonance (p<0.0001, Friedman). The resonance frequency in the apparent mass increased between the vertical backrest at T5 and each of the three inclined backrest conditions (p<0.05, Wilcoxon). However, the resonance frequencies in the vertical in-line apparent mass did not differ with 10º, 20º and 30º inclination of the backrest (p=0.146, Friedman).

The vertical in-line apparent mass at the backrest increased at frequencies less than the resonance frequency as the inclination of the backrest increased (Figure 4).

3.2.2 Fore-and-aft cross-axis apparent mass

In all backrest conditions, the median fore-and-aft cross-axis apparent mass at the back showed a peak around 5 Hz (Figure 5).

When contact with the vertical backrest changed from L2 to T5, the fore-and-aft cross-axis apparent mass at the back at resonance increased (p=0.035, Wilcoxon) although the resonance frequency did not change (p=0.098, Wilcoxon).

Comparing the fore-and-aft cross-axis apparent mass measured with the vertical backrest at T5 and with the three inclinations of the backrest (i.e., B_{10}, B_{20} and B_{30}), there was a change in the resonance frequency (p=0.009, Friedman) and the apparent mass increased at all frequencies as the backrest inclination increased.

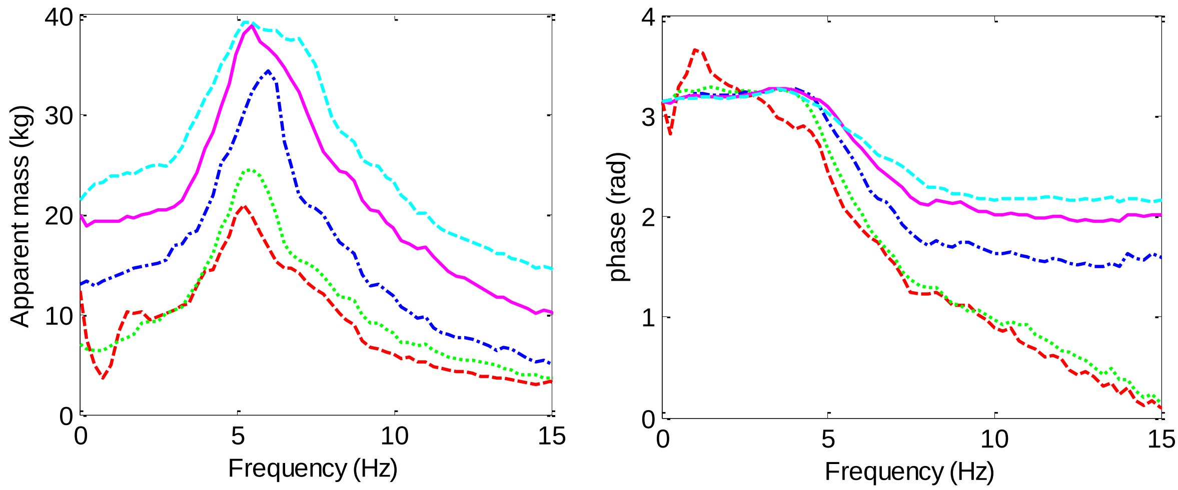

Figure 5 Fore-and-aft cross-axis apparent mass at the backrest in different sitting conditions: vertical backrest contact at L2, B_{0L2} ('------'); vertical backrest contact at T5, B_{0T5} ('……'); contact with 10º inclined backrest, B_{10} ('–·–'); 20º inclined backrest, B_{20} ('——'); 30º inclined backrest, B_{30} ('------'). Left: modulus; right: phase. Median values from 12 subjects.

4. Discussion

4.1 Effect of vertical and inclined backrests on the vertical in-line apparent mass at the seat pan

An increase in the resonance frequency of the vertical in-line apparent mass at the seat pan has been reported when the back is supported by a vertical backrest (Nawayseh and Griffin, 2004) with the resonance frequency increasing further if the backrest is inclined (Toward and Griffin, 2009). In the present study, there was a similar increasing trend in the resonance frequency of the vertical in-line apparent mass at seat pan, although a statistically significant difference was only found with a 30º inclined backrest.

As the backrest inclination increased, the vertical apparent mass measured at the seat pan decreased around the 5-Hz resonance and at lower frequencies, presumably because more of the weight of the body was supported by the backrest.

With increasing backrest inclination, the peak in the vertical apparent mass around the resonance broadened. With the backrest inclined to 20º or 30º, some subjects exhibited two peaks at frequencies around the resonance (in the range 4 to 8 Hz). According to a modal analysis of the human body in an upright sitting posture without backrest (e.g., Kitazaki and Griffin, 1997; Matsumoto and Griffin, 2001), the resonance frequency (around 5 Hz) arises from several body modes that are merged by the heavy damping of the body. The modes include pitch motion of the pelvis with bending of the spine combined with shear and axial deformation of buttocks tissues. The two peaks observed in the present study indicate that two or more body modes were excited in the range of 4 to 8 Hz and that increasing the inclination of the backrest separated the two modes.

4.2 Effect of vertical and inclined backrests on fore-and-aft cross-axis apparent mass at the seat pan

When sitting without a backrest, the principal resonance in the fore-and-aft cross-axis apparent mass at the seat pan was correlated with the resonance frequency in the vertical in-line apparent mass (p=<0.001, Spearman). This correlation is consistent with the findings of some previous studies (Nawayseh and Griffin, 2004; Qiu and Griffin, 2012), and suggests that when sitting without a backrest the resonances evident in the vertical in-line apparent mass and the fore-and-aft cross-axis apparent mass have a common cause.

When sitting with a vertical backrest and supported at L2 or T5 (B_{0L2} and B_{0T5}), the resonance frequencies in the vertical in-line apparent mass and the fore-and-aft cross-axis apparent mass were also correlated (B_{0L2}, p=0.012; B_{0T5}, p=0.003; Spearman). However, with the backrest inclined (B_{10}, B_{20} and B_{30}), the correlation was no longer statistically significant (p>0.05, Spearman). The resonance tended to be at a lower frequency in the fore-and-aft cross-axis apparent mass than in the vertical in-line apparent mass, especially when the backrest was inclined by 20º and 30º (at 20º – 4 Hz in the fore-and-aft cross-axis and 5 Hz in the vertical in-line apparent mass; at 30º – 4 Hz in the fore-and-aft cross-axis and 5.5 Hz in the vertical in-line apparent mass; Figures 2 and 3). The absence of correlations when the backrest was inclined indicate that different body motions then contribute to the resonances in the fore-and-aft cross-axis apparent mass and the vertical in-line apparent mass.

4.3 Vertical in-line apparent mass and fore-and-aft cross-axis apparent mass at the back

When contact with the vertical backrest changed from L2 (B_{0L2}) to T5 (B_{0T5}), both the vertical in-line apparent mass and the fore-and-aft cross-axis apparent mass at the backrest increased at the resonance frequency. The resonance in the fore-and-aft cross-axis apparent mass at the back may be influenced by the motions of head-neck system and fore-and-aft motion of the spine (Nawayseh and Griffin, 2004). The increased fore-and-aft cross-axis apparent mass at the backrest at resonance suggests more motion of the spine with the back support in the thoracic region (i.e., B_{0T2}), although the differences are not large.

With increasing inclination of the backrest, the vertical in-line apparent mass and the fore-and-aft cross-axis apparent masses at the back increased. The increase in both apparent masses at low frequencies indicates that more mass was supported on the backrest as the backrest inclination increased. The fore-and-aft cross-axis apparent mass at the back tended to be greater than the vertical in-line apparent mass at the back. At the resonance, with increasing inclination of the backrest (from B_{0T5} to B_{30}) the median fore-and-aft cross-axis apparent mass at the backrest increased from 22 to 40 kg whereas the median vertical in-line apparent mass at the backrest increased from 4 to 12 kg (Figures 4 and 5).

4.4 Dynamic forces experienced by the seated body in the vertical and fore-and-aft directions

The measurements allow the calculation of how the sum of the vertical in-line and fore-and-aft cross-axis forces at the seat and the backrest vary according to the nature of the backrest. The transfer functions between the vertical seat acceleration and the sums of the forces at the seat pan and the backrest in the vertical and fore-and-aft directions were calculated in the frequency domain for each subject to give the ‘overall vertical in-line apparent mass’ and the ‘overall fore-and-aft cross-axis apparent mass’ (Figure 6).

No difference has been reported in the apparent mass at 0.78 Hz calculated from the seat acceleration and the sum of vertical forces (at the seat pan and backrest) when sitting with and without a backrest (Nawayseh and Griffin, 2004). In the present study, irrespective of the backrest condition, the overall vertical apparent mass at very low frequencies (e.g., 0.5 Hz) was close to the static mass when sitting with no backrest (Figure 6). The slight differences could be due to variations in the support from the footrest when the backrest varied. With increasing inclination of the backrest the overall vertical in-line dynamic forces showed no significant change at frequencies up to 5 Hz but increased at higher frequencies in the range 6 to 15 Hz ($p<0.001$, Friedman). With increasing inclination of the backrest, the overall fore-and-aft cross-axis dynamic forces increased in the frequency range 5 to 15 Hz ($p<0.001$, Friedman).

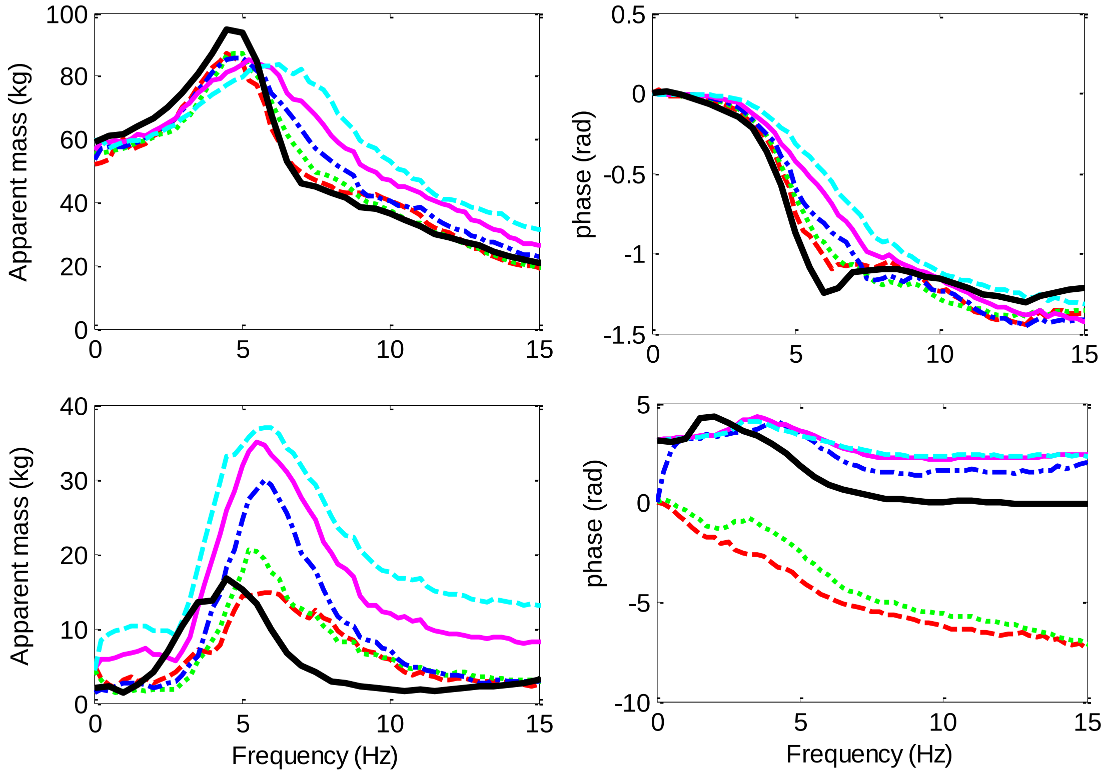

Figure 6 Overall vertical in-line apparent mass (top row) and overall fore-and-aft cross-axis apparent mass (bottom row) in different sitting conditions: normal upright sitting posture NB ('——'); vertical backrest contact at L2, B_{0L2} ('------'); vertical backrest contact at T5, B_{0T5} ('……'); contact with 10º inclined backrest, B_{10} ('–·–'); 20º inclined backrest, B_{20} ('——'); 30º inclined backrest, B_{30} ('------'). Left: modulus; right: phase. Median values from 12 subjects.

5. Conclusion

Contact with an inclined backrest reduces the mass of the body supported on the seat pan but increases the fore-and-aft dynamic shearing force between body and the seat pan. The presence of an inclined backrest alters the body motions and resonance frequencies in the vertical in-line and fore-and-aft cross-axis apparent mass measured at the seat pan.

When there is no backrest or a vertical backrest, the resonance frequency in the fore-and-aft cross-axis apparent mass at the seat pan is correlated with the resonance frequency in the vertical in-line apparent mass at the seat pan. However, the two resonances became less correlated with increasing inclination of the backrest, suggesting different body modes may contribute to the vertical in-line and fore-and-aft cross-axis apparent mass when the backrest is inclined.

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