Journal of Sound and Vibration (2002) **253**(1), 93–107
doi:10.1006/jsvi.2001.4251, available online at http://www.idealibrary.com on IDEAL®

EFFECTS OF POSTURE AND VIBRATION MAGNITUDE ON APPARENT MASS AND PELVIS ROTATION DURING EXPOSURE TO WHOLE-BODY VERTICAL VIBRATION

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(*Accepted* 19 *October* 2001)

The effect of variations in posture and vibration magnitude on apparent mass and seat-to-pelvis pitch transmissibility have been studied with vertical random vibration over the frequency range 1·0–20 Hz. Each of 12 subjects was exposed to 27 combinations of three vibration magnitudes (0·2, 1·0 and 2·0 m/s^2 r.m.s.) and nine sitting postures ("upright", "anterior lean", "posterior lean", "kyphotic", "back-on", "pelvis support", "inverted SIT-BAR" (increased pressure beneath ischial tuberosities), "bead cushion" (decreased pressure beneath ischial tuberosities) and "belt" (wearing an elasticated belt)).

Peaks in the apparent masses were observed at about 5 and 10 Hz, and in the seat-to-pelvis pitch transmissibilities at about 12 Hz. In all postures, the resonance frequencies in the apparent mass and transmissibility decreased with increased vibration magnitude, indicating a non-linear softening system. There were only small changes in apparent mass or transmissibility with posture, although peaks were lower for the apparent mass in the "kyphotic" posture and were lower for the transmissibility in the "belt" posture. The changes in apparent mass and transmissibility caused by changes in vibration magnitude were greater than the changes caused by variation in posture.

1. INTRODUCTION

Exposures to whole-body vibration involve a variety of postures and a range of vibration magnitudes. For example, car drivers usually sit with an inclined backrest and are exposed to moderate magnitudes of vibration; drivers of industrial trucks usually sit with an upright posture and are exposed to higher magnitudes of vibration. The complex combinations of postures and vibration magnitudes confound understanding of the extent to which whole-body vibration is responsible for injury: some sitting postures may result in back problems without vibration [1].

The effect of sitting posture on the apparent mass of a subject (i.e. the ratio of the force to the acceleration as a function of vibration frequency) has previously been reported [2–4]. Although Miwa [2] stated that "no clear difference was reckoned to exist" between sitting relaxed and erect, his data show a small effect that is consistent with results from both Fairley and Griffin [3] and Kitazaki and Griffin [4] suggesting that the resonance frequency of the human body is higher in a more erect sitting posture. Fairley and Griffin's

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0022-460X/02/$35.00

eight subjects sat in four postures ("normal", "erect", "backrest contact" and "tense") and generally exhibited higher resonance frequencies for the "erect" and "tense" postures compared to the "normal" posture. Kitazaki and Griffin showed an increase in the mean resonance frequency from 4·4 to 5·2 Hz when eight subjects sat in "slouched" and "erect" postures. The change can be described as a stiffening effect with erect postures.

The apparent mass of the seated human body is non-linear with respect to vibration magnitude in a "normal" upright posture [3, 5–7]. Using random vibration, Mansfield and Griffin [6] found a decrease in the primary resonance frequency of the apparent mass from 5·4 Hz, with a magnitude of 0·25 m/s^2 r.m.s., to 4·2 Hz with a magnitude of 2·5 m/s^2 r.m.s. There were corresponding changes in transmission to the lumbar spine and abdominal wall. Even small increases in the magnitude of the vibration showed a significant reduction in the resonance frequency. Matsumoto and Griffin [7] found non-linearity in both the driving point apparent mass and transmissibilities to the first, fifth, and tenth thoracic vertebrae, to the first, third, and fifth lumbar vertebrae and to the pelvis during exposure of seated subjects to vertical vibration. A similar softening effect has also been found for standing subjects [8] and for seated subjects exposed to horizontal vibration [9]. Although the non-linearity appears to be an underlying biomechanical phenomenon, one study has shown that increasing voluntary muscle tension in the abdominal muscles reduces the extent of the non-linearity in apparent mass [10]. So, in summary, previous studies of the non-linearity in the apparent masses of seated subjects have investigated upright postures and found a consistent non-linearity in apparent mass with vibration magnitude. The effect of posture on apparent mass has been studied (i.e. "normal" versus "erect") but the effect of sitting posture over the wide variety and types of postures encountered by drivers of work vehicles has not been explored.

The apparent mass of a person occupying a seat affects the dynamics of the seat (e.g., reference [11]). Non-linearities in the apparent mass of a person occupying a seat therefore change the dynamic response of the seat and can either increase or decrease the magnitudes of vibration on the seat surface. Large changes in apparent mass with changes in posture would require dynamic models of the response of the body used to determine seat transmissibility to take into account the posture as well as the vibration magnitude.

Studies of the effects of posture on body transmissibility have mostly been restricted to the effects of using a backrest and have not considered vibration magnitude as a variable (e.g., reference [12]). Pelvis rotation during whole-body vibration has not been reported, although some studies (e.g., reference [13]) have presented data at the front and rear of the pelvis from which rotation can be calculated. Some investigators have suggested pelvis rotation as a cause of peaks in apparent mass, without presenting measurements [14].

The characteristic dynamic responses of the seated person have not been fully explained and the causes of the non-linearities in apparent mass and transmissibility are currently unknown. Factors that have been suggested to influence the peaks in apparent mass include the dynamics of the tissue beneath the ischial tuberosities, pelvis rotation, visceral movement and whole-body bending. Changing the pressure beneath the ischial tuberosities, restricting pelvis movement, wearing a tight abdominal support or leaning (anteriorly or posteriorly) may, respectively, change the dynamic responses influenced by the previously suggested mechanisms. So, by monitoring the effect of posture on the character of the biomechanic response, the underlying mechanisms causing the response might be determined.

This study investigated the effects of both sitting posture and the magnitude of vertical vibration on apparent mass and pelvis rotation. It was hypothesized that the resonance frequencies of both the apparent mass and the transmissibility would decrease with increases in vibration magnitude, but that the extent of the decrease would vary with posture.

2. METHOD

The experiment was conducted on a 1-m stroke electro-hydraulic vertical shaker. Subjects sat on the flat rigid surface of a seat 470 mm above their feet, which were supported by the shaker table and moved with the seat. A loose lap strap was fastened around the subjects. The experiment was approved by the Human Experimentation, Safety and Ethics Committee of the Institute of Sound and Vibration Research at the University of Southampton.

Motion of the seat was measured using an Entran EGCSY-240*-10 accelerometer on the shaker table directly beneath the seat. Motion of the pelvis was measured with small and lightweight (1 g) Entran EGA-125-10D accelerometers fixed to the skin above the iliac crest and posterior superior iliac spine. The seat contained a Kistler 9821B force platform directly beneath the seat surface. The vertical force signals were summed and conditioned using a Kistler 5001 charge amplifier.

Twelve male subjects participated in the experiment with mean (and standard deviation, SD) stature 1·81 m (SD 0·04 m) and mean weight 74·5 kg (SD 7·3 kg). Each subject was exposed to 27 different combinations of three vibration magnitudes (0·2, 1·0 and 2·0 m/s^2 r.m.s.) and nine sitting postures.

The 60 s vibration stimuli were Gaussian random vertical acceleration with a flat constant bandwidth spectrum over the range 1·0–20 Hz. The stimuli were equalized for the response of the shaker and generated and analyzed using an *HVLab* data acquisition and analysis system. Signals from the accelerometers and force platform were conditioned and acquired into the data acquisition system at 100 samples per second with anti-aliasing filters at 25 Hz.

The nine postures are described in Table 1 and illustrated in Figure 1. The inverted SIT-BAR [15] is a rigid indenter that is flat on one side and contoured on the other. Sitting on an inverted SIT-BAR increases the pressure at the ischial tuberosities relative to that on a flat rigid seat. The elasticated belt was manufactured by Chase Ergonomics (Albuquerque, NM, U.S.A.). The belt was flexible and fastened using a Velcro strip at the front of the abdomen. Postures were standardized by the experimenter who supervised all exposures. However, postures were not physically controlled, apart from those where the restriction

TABLE 1

Description of postures

Posture	Description
Upright	Comfortable upright posture, no backrest contact
Anterior lean	Leaning forward 10°, bending at the pelvis
Posterior lean	Leaning back 10°, bending at the pelvis
Kyphotic	As "upright" with slouched upper spine
Back-on	Back in contact with the backrest
Pelvis support	Rear of pelvis supported in rigid frame
Inverted SIT-BAR	Increased pressure at ischial tuberosities: sitting on inverted SIT-BAR
Bead cushion	Sitting on cushion of polystyrene beads (rigid up to 20 Hz)
Belt	Subjects wearing an elasticated belt

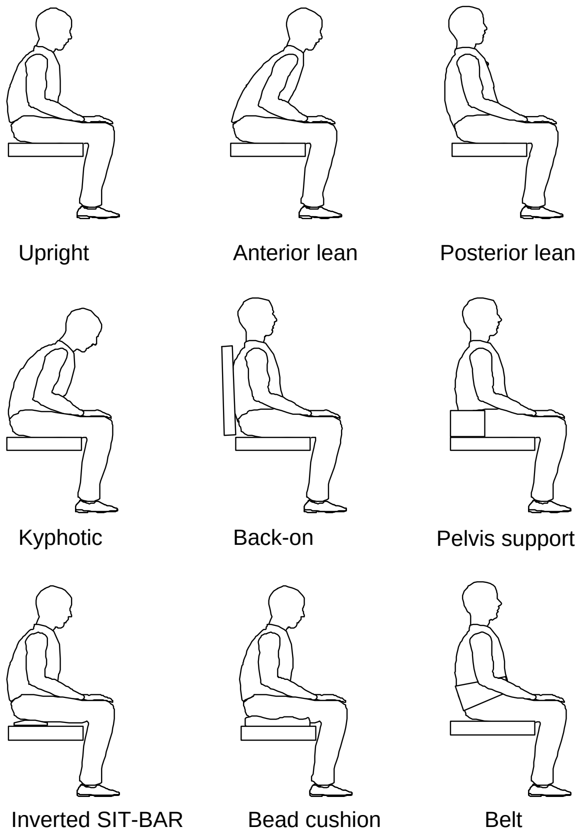

Figure 1. Diagrammatic representation of the nine postures used in the experiment.

was inherent to the condition. The angle of inclination for the anterior and posterior lean conditions was set using a mechanical goniometer.

Rotational acceleration of the pelvis was calculated from the vertical accelerations measured at the iliac crest and posterior superior iliac spine. Single axis accelerometers were fixed such that their sensitive direction was vertically aligned. The acceleration time histories were corrected to eliminate local skin-accelerometer motion (after reference [16]) and subtracted to find the difference in motion. Dividing by the accelerometer separation gave the rotational acceleration in radian per second square.

Transfer functions were calculated between the vertical seat acceleration and the rotational pelvis acceleration and between the vertical seat acceleration and the force at the seat (after subtraction of the mass of the force plate above the force transducers, i.e., mass cancellation). These measures gave the "seat vertical to pelvis rotation" transmissibility (termed "transmissibility" in the subsequent text) and the apparent mass, respectively. Transfer functions, $H_{io}(f)$, were calculated using the cross spectral density (CSD) method: the ratio of the CSD of acceleration at the seat and pelvis, $G_{io}(f)$, to the power spectral density (PSD) of the acceleration at the seat, $G_{ii}(f)$:

$$H_{io}(f) = \frac{G_{io}(f)}{G_{ii}(f)}.$$

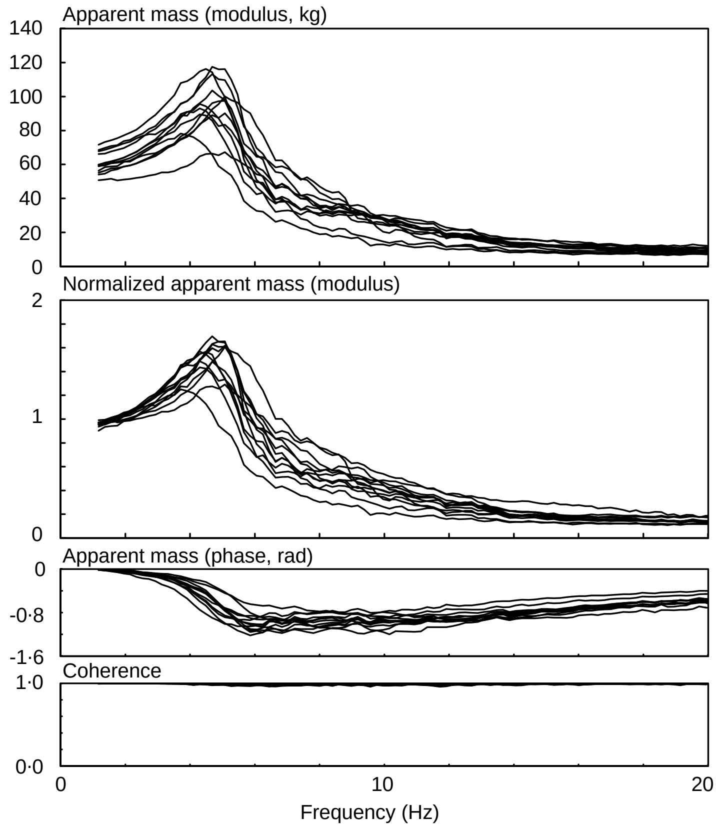

Figure 2. Apparent mass modulus, normalized apparent mass modulus, phase and coherence for 12 subjects exposed to vertical vibration at 1·0 m/s^2 r.m.s. in an "upright" posture.

Ordinary coherency, $\gamma_{io}^2(f)$ was calculated for all transfer functions using

$$\gamma_{io}^2(f) = \frac{|G_{io}(f)|^2}{G_{ii}(f)G_{oo}(f)},$$

where $G_{oo}(f)$ is the PSD of the acceleration at the pelvis. Transfer functions were calculated with a resolution of 0·195 Hz corresponding to 48 degrees of freedom.

To facilitate comparison of apparent masses for subjects of different weights, the modulus of each transfer function was divided by the sitting weight of the subject so as to generate the "normalized apparent mass".

3. RESULTS

3.1. APPARENT MASS

The apparent masses for all 12 subjects in an upright sitting posture at 1·0 m/s^2 r.m.s. are shown in Figure 2. All subjects showed similar general characteristics for the moduli and phases of the apparent mass and the coherence between the force and the acceleration signals. Some of the variation in the modulus could be attributed to the differences in the weights of the subjects and were reduced after normalization. A peak in the apparent mass

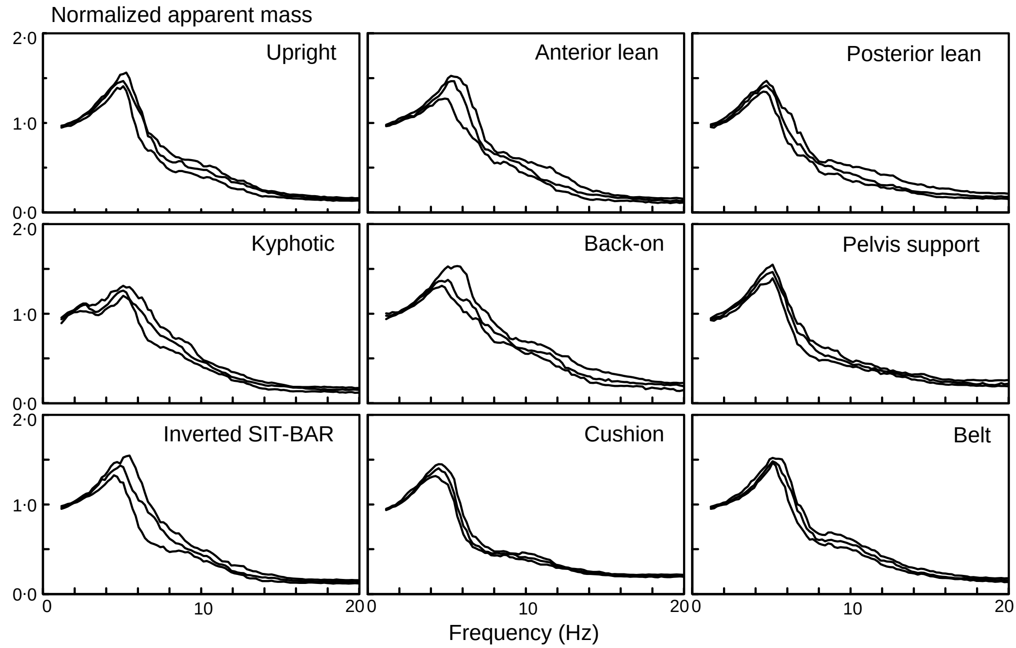

Figure 3. Inter-quartile ranges for normalized apparent masses for 12 subjects using nine postures at 1·0 m/s^2 r.m.s.

modulus at about 5 Hz corresponds to a region of increasing phase lag. Similar general forms for the apparent mass modulus, phase and coherence were obtained in all postures and at all magnitudes. Subjects also showed minor peaks in their apparent masses at about 10 Hz.

Median and inter-quartile ranges of the normalized apparent masses at 1·0 m/s^2 r.m.s. were calculated for all nine postures (Figure 3). There was most variability in apparent mass over the 4–15 Hz frequency range. Variability was quantified using the coefficient of variation (i.e., the ratio of the standard deviation to the mean, ε_r) at each frequency for each of the 27 posture/magnitude combinations. Considering ε_r averaged between 1 and 20 Hz for each condition, the most variability was observed at 0·2 m/s^2 r.m.s. for seven of the nine postures; all postures showed the least variability at 1·0 or 2·0 m/s^2 r.m.s. At all three magnitudes of vibration, the most variability was observed for the "anterior lean", "back-on" and "inverted SIT-BAR" postures; the least variability was observed for the "cushion" and "belt" postures.

The 10 Hz resonance observed in many of the individual data is not as clear in the average data. This may be due to the resonance occurring at a slightly different frequency for each subject and the effect being spread over a range of frequencies by the averaging process.

Median normalized apparent masses for all the three magnitudes of vibration in all nine postures are shown in Figure 4. The normalized apparent mass resonance frequency decreased for each increase in vibration magnitude, in all nine postures. This effect was also observed for all individual subjects. The median resonance frequencies and magnitudes at resonance for all conditions are listed in Table 2. All median resonance frequencies measured at 0·2 m/s^2 r.m.s. were above 5 Hz and all median resonance frequencies at 2·0 m/s^2 r.m.s. were below 5 Hz. There was no consistent change in the normalized apparent

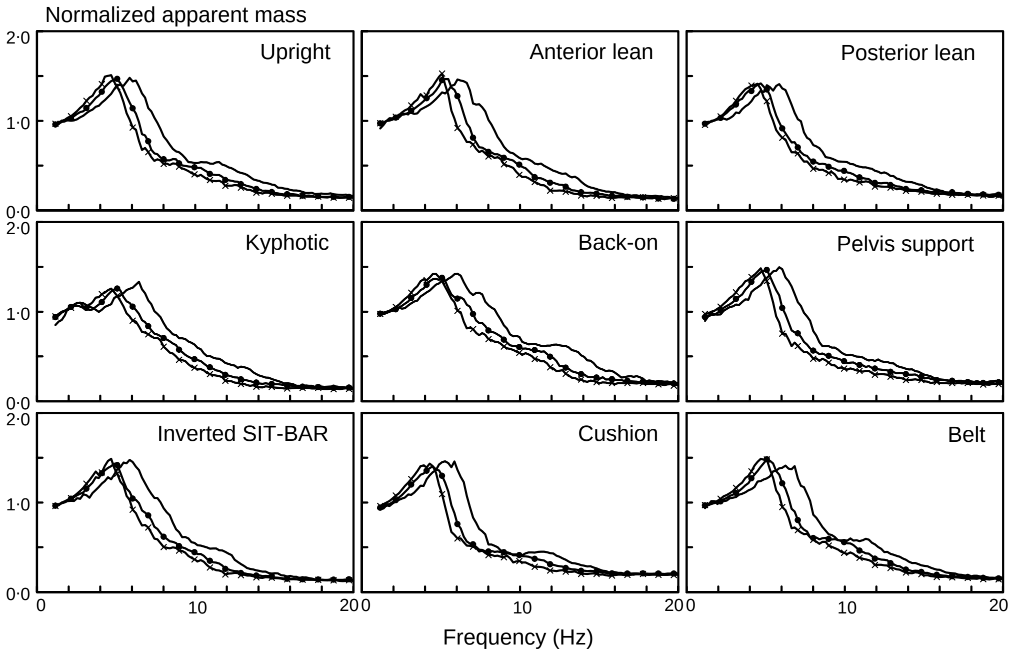

Figure 4. Median normalized apparent masses for 12 subjects using nine postures at 0·2, 1·0 and 2·0 m/s^2 r.m.s. ——, 0·2; —●—, 1·0; —×—, 2·0 m/s^2 r.m.s.

TABLE 2

Normalized apparent mass median resonance frequency and magnitude at resonance measured using nine postures at 0·2, 1·0 *and* 2·0 m/s^2 *r.m.s.*

Posture	Resonance frequency			Magnitude at resonance		
	0·2	1·0	2·0	0·2	1·0	2·0
Upright	5·27	5·08	4·69	1·50	1·48	1·57
Anterior lean	6·06	5·18	4·79	1·60	1·49	1·55
Posterior lean	5·47	4·59	4·39	1·47	1·42	1·43
Kyphotic	6·25	5·08	4·49	1·40	1·30	1·29
Back-on	5·47	5·08	4·69	1·54	1·46	1·51
Pelvis support	5·86	5·08	4·69	1·56	1·47	1·49
Inverted SIT-BAR	5·76	4·79	4·59	1·48	1·49	1·53
Cushion	5·37	4·49	4·10	1·51	1·41	1·45
Belt	6·45	5·08	4·88	1·47	1·51	1·53

mass at the resonance frequency with a change in vibration magnitude within postures. At all three vibration magnitudes, the lowest median normalized apparent mass at the resonance was observed with the “kyphotic” posture (Figure 5).

A clear second peak in the apparent mass was more common for some postures (e.g., “cushion”, 22 out of 36 possible occurrences) than for others (e.g., “kyphotic”, eight occurrences). The frequency of the second peak also reduced with increasing vibration magnitude for most postures (Table 3). The only exception occurred between 1·0 and 2·0 m/s^2 r.m.s. with the “kyphotic” condition, although it should be noted that just one subject showed a clear second peak at 2·0 m/s^2 r.m.s. in this posture.

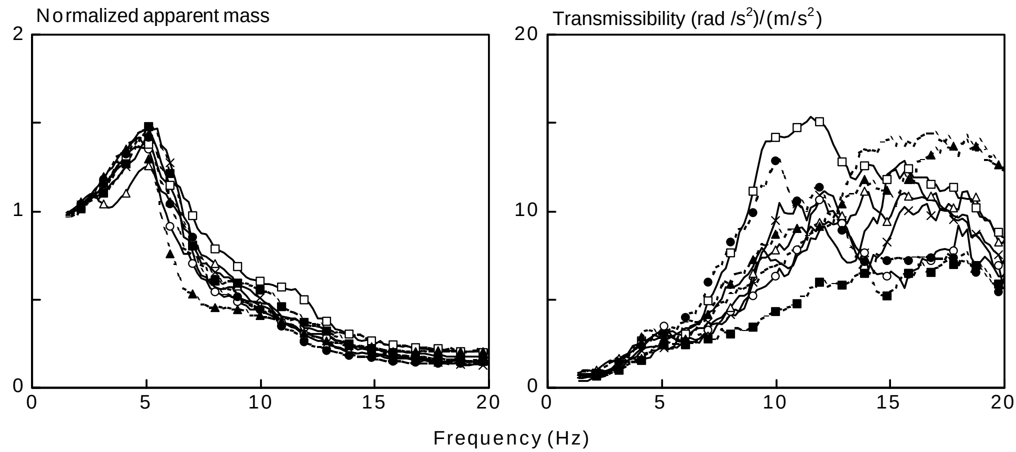

Figure 5. Median normalized apparent mass and seat vertical to pelvis rotation transmissibility for 12 subjects using nine postures at 1·0 m/s^2 r.m.s.: ——, upright; —×—, anterior lean, —○—, posterior lean; —△—, kyphotic; —□—, back-on; – – –, pelvis support; —●—, inverted SIT-BAR; —▲—, cushion; —■—, belt.

Table 3

Apparent mass median second resonance frequency and number of subjects showing a second peak using nine postures at 0·2, 1·0 *and* 2·0 m/s^2 *r.m.s.*

Posture	Resonance frequency			Number of subjects		
	0·2	1·0	2·0	0·2	1·0	2·0
Upright	11·13	10·16	8·79	7	5	5
Anterior lean	11·23	9·77	8·20	6	6	4
Posterior lean	11·42	10·06	8·79	4	4	3
Kyphotic	11·13	9·96	10·35	4	3	1
Back-on	11·91	10·35	8·79	6	5	4
Pelvis support	10·55	8·79	8·79	9	6	5
Inverted SIT-BAR	10·74	9·77	8·79	6	3	3
Cushion	11·33	9·38	9·18	9	8	5
Belt	10·84	9·96	8·79	8	7	5

3.2. TRANSMISSIBILITY

The transmissibilities for all 12 subjects in an upright posture at 1·0 m/s^2 r.m.s. are shown in Figure 6. Most subjects show greatest transmissibility in the frequency range 10–18 Hz and a steadily increasing phase lag with increasing frequency. Coherence was high for many subjects, although lower than for the apparent mass measurements. Most subjects showed a broad peak at 10–15 Hz and some also showed a small peak at about 5 Hz. Individual data showed greatest transmissibilities for the "back-on" and "bead cushion" conditions with transmissibilities reaching 40 (rad/s^2)/(m/s^2).

Figure 7 shows median and inter-quartile ranges for the transmissibilities measured at 1·0 m/s^2 r.m.s. in all nine postures. All conditions show more pelvis rotation in the frequency range from 10 to 18 Hz than at lower frequencies. There are clear resonances at about 10 Hz in the transmissibilities for the "upright", "back-on" and "inverted SIT-BAR" conditions. In

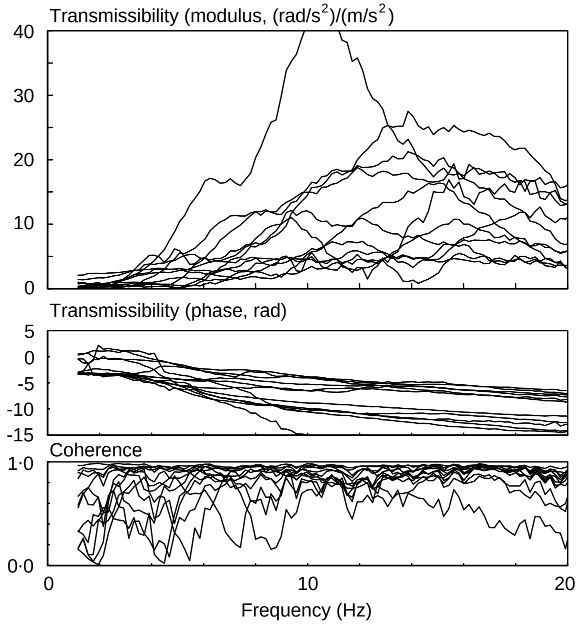

Figure 6. Seat vertical to pelvis rotation transmissibility modulus, phase and coherence for 12 subjects exposed to vertical vibration at 1·0 m/s^2 r.m.s. in an "upright" posture.

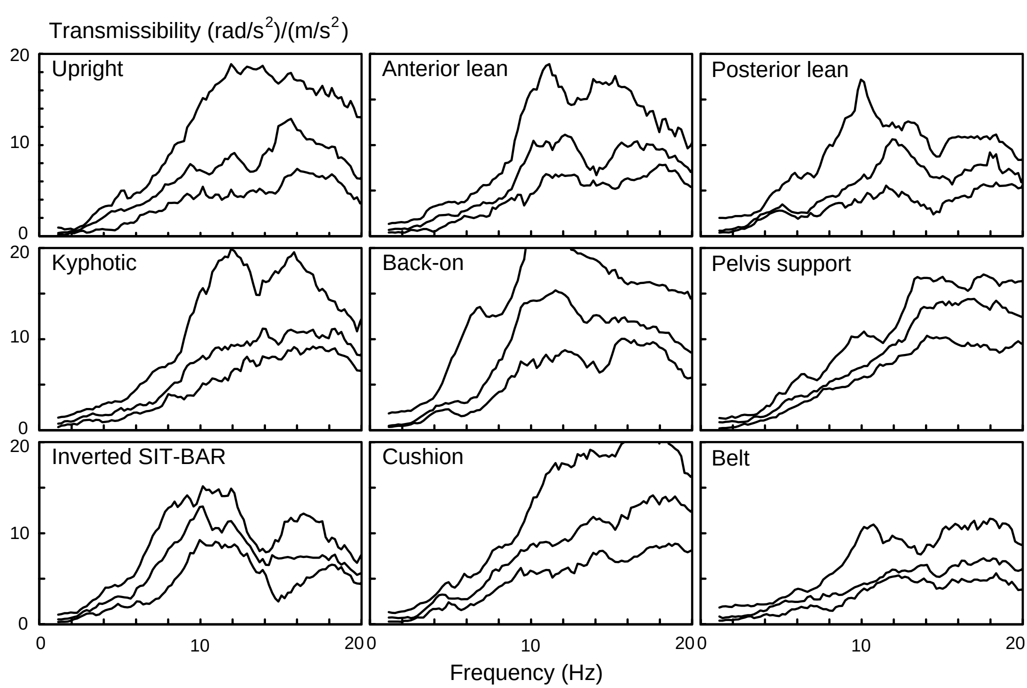

Figure 7. Inter-quartile ranges for seat vertical to pelvis rotation transmissibility for 12 subjects using nine postures at 1·0 m/s^2 r.m.s.

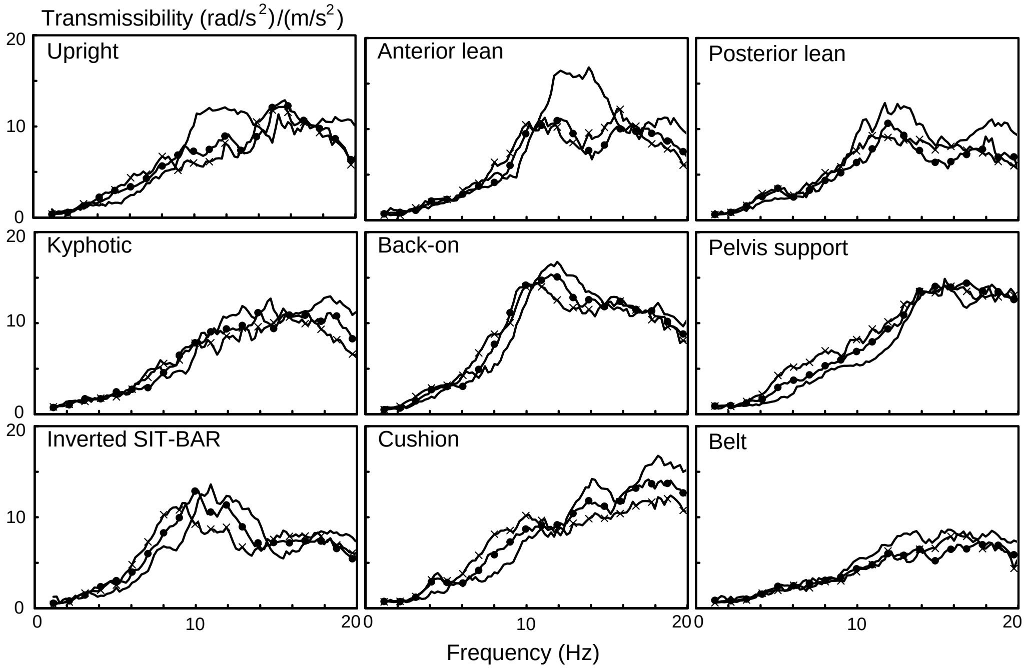

Figure 8. Median seat vertical to pelvis rotation transmissibility for 12 subjects using nine postures at 0·2, 1·0 and 2·0 m/s^2 r.m.s.: ——, 0.2; —○—, 1.0; —×— 2·0 m/s^2 r.m.s.

the "belt" and "pelvis support" conditions, the pitch motion of the pelvis was reduced. The transmissibility measured with the subjects wearing the belt was lower than that measured in the normal upright posture in the frequency range 6–20 Hz (Figure 5). Relative to the normal (i.e., upright) posture, the median transmissibility was lower for the "posterior lean" condition at around 16 Hz and for the "inverted SIT-BAR" condition at frequencies greater than 14 Hz. Coefficients of variation were calculated in a similar manner as for the apparent mass. There was no clear trend for more or less variability with vibration magnitude across the nine postures. At all three magnitudes of vibration, the most variability was observed for the "posterior lean", "belt" and "inverted SIT-BAR" postures. At 0·2 m/s^2 r.m.s., the least variability was observed for the "anterior lean" and "kyphotic" postures; at 1·0 and 2·0 m/s^2 r.m.s., the least variability was observed for the "pelvis support" and "cushion" postures.

Median transmissibilities for all three magnitudes of vibration in all nine postures are shown in Figure 8. Transmissibilities steadily increased up to 10 or 15 Hz for most postures; at higher frequencies the transmissibilities generally decreased. For most postures, peaks in the transmissibilities reduced in frequency with increasing vibration magnitude. This is also indicated by the rank ordering of the transmissibilities at frequencies below and above the peaks: at frequencies below resonance, the transmissibilities were lower for the lowest vibration magnitudes; at frequencies above resonance, the transmissibilities were highest for the lowest vibration magnitudes. The median resonance frequencies evident in the transmissibilities, and the transmissibilities at resonance, for all conditions are listed in Table 4. There was a decrease in the resonance frequency with each increase in vibration magnitude for all conditions, except between 0·2 and 1·0 m/s^2 r.m.s. for the "pelvis support" condition where the median frequency was unchanged. The greatest resonance frequencies occurred with the "pelvis support" condition at all three magnitudes of vibration. The lowest resonance frequencies occurred for the "inverted SIT-BAR" condition.

TABLE 4

Transmissibility median resonance frequency and magnitude measured using nine postures at 0·2, 1·0 and 2·0 m/s² r.m.s.

Posture	Resonance frequency			Magnitude at resonance		
	0·2	1·0	2·0	0·2	1·0	2·0
Upright	13·09	12·01	11·92	15·57	13·59	14·05
Anterior lean	13·09	11·72	11·43	21·33	13·13	12·58
Posterior lean	12·31	11·50	10·16	16·75	13·72	11·50
Kyphotic	13·38	11·92	10·94	15·97	13·95	11·61
Back-on	14·07	12·21	11·53	19·16	16·25	16·30
Pelvis support	14·85	14·85	14·55	15·00	13·65	12·37
Inverted SIT-BAR	12·31	10·55	10·16	16·70	15·76	13·22
Cushion	14·07	13·87	12·31	16·72	14·27	14·83
Belt	14·16	12·30	11·82	10·57	10·46	7·91

Transmissibilities at resonance generally decreased with increases in vibration magnitude; exceptions occurred between 1·0 and 2·0 m/s² r.m.s. with the “upright”, “back-on” and “cushion” conditions. The lowest magnitudes for the transmissibility peak occurred with the “belt” condition at all magnitudes of vibration.

4. DISCUSSION

The general forms of the apparent mass data are similar to those previously reported [3, 6]. The non-linearity indicated by the reduction in the resonance frequency with increased vibration magnitude is also similar to that previously observed in the upright posture. For 12 subjects measured using the same shaker, Mansfield and Griffin [6] reported median resonance frequencies at 0·25, 1·0 and 2·0 m/s² r.m.s. within 10% of those reported here for “upright” 0·2, 1·0 and 2·0 m/s² r.m.s. respectively. Normalized apparent masses at resonance were about 16% greater in the earlier study.

Table 5 compares normalized apparent mass resonance frequencies at different vibration magnitudes within postures. Differences in resonance frequencies at the three magnitudes of vibration were significant for most sets of data ($p < 0{\cdot}01$, Wilcoxon). The only exceptions were for the “back-on” and “belt” condition between 0·2 and 1·0 m/s² r.m.s. ($p < 0{\cdot}05$), “posterior lean”, “inverted SIT-BAR” and “cushion” conditions between 1·0 and 2·0 m/s² r.m.s. ($p < 0{\cdot}05$) and the “upright” condition between 1·0 and 2·0 m/s² r.m.s. ($p < 0{\cdot}1$). Therefore, the softening effect previously observed in upright sitting postures also occurred in the wide variety of postures investigated in this study.

Comparisons of resonance frequencies between the “upright” and the other eight postures at each of the vibration magnitudes are listed in Table 6. At 0·2 m/s² r.m.s., there were significant differences between the apparent mass resonance frequencies measured in the “upright” and “anterior lean” postures, between “upright” and “kyphotic” postures and between the “upright” and “belt” postures. At 1·0 m/s² r.m.s., there were significant differences between the “upright” and “cushion” postures. At 2·0 m/s² r.m.s., significant differences occurred between the “upright” and “pelvis support” postures, between “upright” and “cushion” postures and between the “upright” and “belt” postures. These results differ from those for one subject presented by Sandover [17]: he found no effect of

TABLE 5

Wilcoxon matched-pairs signed-ranks for normalized apparent mass and transmissibility resonance frequencies measured using nine postures. Effect of vibration magnitude $*p < 0{\cdot}1$, $**p < 0{\cdot}05$, $***p < 0{\cdot}01$

Posture	Magnitude (m/s² r.m.s)	Apparent mass 1·0	Apparent mass 2·0	Transmissibility 1·0	Transmissibility 2·0
Upright	0·2	***	***	**	**
	1·0	—	*	—	ns
Anterior lean	0·2	***	***	ns	**
	1·0	—	***	—	**
Posterior lean	0·2	***	***	**	***
	1·0	—	**	—	***
Kyphotic	0·2	***	***	***	**
	1·0	—	***	—	ns
Back-on	0·2	**	***	***	***
	1·0	—	***	—	***
Pelvis support	0·2	***	***	**	**
	1·0	—	***	—	ns
Inverted SIT-BAR	0·2	***	***	***	***
	1·0	—	**	—	**
Cushion	0·2	***	***	**	**
	1·0	—	**	—	**
Belt	0·2	**	***	**	***
	1·0	—	***	—	***

TABLE 6

Wilcoxon matched-pairs signed-ranks for normalized apparent mass and transmissibility resonance frequencies measured using nine postures at 0·2, 1·0 *and* 2·0 m/s² *r.m.s. Effect of posture: comparison with "upright" posture.* $*p < 0{\cdot}1$, $**p < 0{\cdot}05$, $***p < 0{\cdot}01$

Posture	Apparent mass 0·2	Apparent mass 1·0	Apparent mass 2·0	Transmissibility 0·2	Transmissibility 1·0	Transmissibility 2·0
Anterior lean	**	ns	ns	ns	ns	ns
Posterior lean	ns	ns	ns	ns	ns	ns
Kyphotic	**	ns	ns	ns	ns	ns
Back-on	ns	ns	ns	ns	ns	ns
Pelvis support	ns	ns	**	*	**	*
Inverted SIT-BAR	ns	ns	ns	ns	*	ns
Cushion	ns	**	***	ns	ns	ns
Belt	*	ns	*	ns	ns	ns

visceral support (similar to the "belt" condition here) but an increase in resonance frequency from 4 to 6 Hz when sitting with increased pressure beneath the ischial tuberosities (similar to the "inverted SIT-BAR" condition here).

The magnitude of the modulus of the normalized apparent mass at resonance may reflect the degree of damping in the system. Figures 4 and 5 suggest that the most highly damped posture was "kyphotic". Normalized apparent mass at resonance was significantly lower for the "kyphotic" posture than for the "upright" posture at all vibration magnitudes. This implies that the “kyphotic” posture increased the damping in the biodynamic system. There were significant differences between the normalized apparent mass at resonance in the “upright” posture and the normalized apparent mass in most other postures. Exceptions were evident for the comparison of apparent mass in the “upright” and “inverted SIT-BAR” postures and the “upright” and “belt” postures, where no differences in the normalized apparent mass at resonance were observed at any vibration magnitude.

The changes observed with variations in vibration magnitude were greater than the changes observed with variations in posture. The changes of resonance frequency with magnitude were significant for all measures of apparent mass and most measures of transmissibility. Conversely, changes of resonance frequency with posture were generally not significant. It might therefore be concluded that inclusion of vibration magnitude in the prediction of this type of biodynamic response is more critical than the inclusion of small postural changes.

The most extreme measurements of apparent mass in this study (“cushion” at 2·0 m/s^2 r.m.s. and “belt” at 0·2 m/s^2 r.m.s.) showed a 57% difference in median apparent mass resonance frequency (from 4·10 to 6·45 Hz). This change may be sufficient to be taken into account when assessing the dynamic performance of seats.

Reductions in the transmissibility resonance frequency with increases in vibration magnitude were statistically significant for most combinations of posture and vibration magnitude (Table 5). Reductions were not statistically significant between 1·0 and 2·0 m/s^2 r.m.s. for the “upright”, “kyphotic” and “pelvis support” conditions or between 0·2 and 1·0 m/s^2 r.m.s. for the “anterior lean” condition. Comparison of resonance frequencies in the transmissibility between “upright” and other postures showed few significant differences (Table 6). Differences were significant at 0·2 m/s^2 r.m.s. between “pelvis support” and “upright” ($p < 0{\cdot}1$), at 1·0 m/s^2 r.m.s. between “pelvis support” and “upright” ($p < 0{\cdot}05$) and between “inverted SIT-BAR” and “upright” ($p < 0{\cdot}1$) and at 2·0 m/s^2 r.m.s. between “pelvis support” and “upright” ($p < 0{\cdot}1$). Therefore, utilizing a pelvis support significantly increased the resonance frequency in the pelvis transmissibility.

Many individual subjects showed a second peak in their apparent mass at about 10 Hz. Since the peak occurred at a similar frequency to the pelvis rotation, a similar cause might be suspected. However, data from individual subjects showed that the peaks in transmissibility generally occurred at a higher frequency than those for the apparent mass. For all postures, over the frequency range 10–15 Hz, the frequencies of the peaks in pelvis transmissibilities were significantly greater than the peaks in apparent mass (“kyphotic”, $p < 0{\cdot}1$; “upright”, $p < 0{\cdot}05$; $p < 0{\cdot}01$ all other postures). Nine subjects showed a second peak in apparent mass for four or more conditions. For these, the differences between the frequency of peaks in transmissibility and the second peak in apparent mass were significantly different (Wilcoxon). For only one of the 27 posture/magnitude combinations were resonance frequencies in transmissibility and the second peak in apparent mass significantly correlated ($p < 0{\cdot}1$, Spearman). The findings did not, therefore, confirm that the peaks at 10–15 Hz in apparent mass are due to the same mode as the peaks in pelvis rotation at a similar frequency. However, both features showed a similar non-linearity and may therefore have been influenced by the same mechanisms causing the softening effect with increasing vibration magnitude.

Some of the postures used in this study were chosen in response to previously suggested mechanisms that might influence the primary peak in the apparent mass. The significant differences in the transmissibility resonance frequencies indicate that the pelvis support condition altered the rotation of the pelvis when compared to the upright posture (Table 6). However, this was not accompanied by a significant change in the apparent mass resonance frequency, except at 2·0 m/s^2 r.m.s. Visceral movement was restricted by the elasticated belt; for the "belt" condition, the resonance frequencies were significantly higher at 0·2 and 2·0 m/s^2 r.m.s., but not at 1·0 m/s^2 r.m.s. The anterior and posterior lean conditions were designed to influence whole body bending. The only significant difference in apparent mass resonance frequency in these postures compared to the upright posture was observed for "anterior lean" at 0·2 m/s^2 r.m.s. The influence of the dynamics of the tissue beneath the ischial tuberosities was tested using the "inverted SIT-BAR" and "cushion" conditions. Increasing the loading area (i.e., the "cushion" condition) showed a significant decrease in the apparent mass resonance frequencies at 1·0 and 2·0 m/s^2 r.m.s. when compared to the upright posture. The results of this study therefore gave no consistent corroboration of the previously suggested mechanisms that might influence the frequency of the primary peak in the apparent mass.

The changes in apparent mass and transmissibility reported here do not directly indicate hazardous vibration magnitudes or hazardous postures. For example, the 2·0 m/s^2 r.m.s. vibration can be considered to be 10 times the severity of the 0·2 m/s^2 r.m.s. vibration, irrespective of relatively small changes in apparent mass and transmissibility. Similarly, although minimal differences in the biomechanic responses of the body have been found with the variety of postures, some are likely to be more hazardous than others. Increased spinal load during anterior lean compared to sitting upright whilst stationary might indicate a poor working posture despite this study indicating no differences in apparent mass or transmissibility between the "upright" and "anterior lean" or "kyphotic" postures at 1·0 or 2·0 m/s^2 r.m.s. [18, 19].

5. CONCLUSIONS

In nine different sitting postures, resonance frequencies in the whole-body vertical apparent mass reduced in frequency with increases in vibration magnitude, indicating a non-linear softening effect. A similarly non-linear softening effect was observed for transmissibilities between vertical seat vibration and pelvis rotation in all nine postures. Changes in vibration magnitude (from 0·2 to 2·0 m/s^2 r.m.s.) resulted in greater changes in apparent mass and seat-to-pelvis transmissibility than changes in posture. Resonance frequencies in the apparent mass and transmissibility at about 10–15 Hz were not clearly related and may involve different modes. The development of biodynamic models should include consideration of the non-linearity in apparent mass.

REFERENCES

1. M. L. MAGNUSSON and M. H. POPE 1998 *Journal of Sound and Vibration* **215**, 965–976. A review of the biomechanics and epidemiology of working postures (it isn't always vibration which is to blame!).
2. T. MIWA 1973 *Industrial Health* **13**, 1–22. Mechanical impedance of the human body in various postures.
3. T. E. FAIRLEY and M. J. GRIFFIN 1989 *Journal of Biomechanics* **22**, 81–94. The apparent mass of the seated human body: vertical vibration.
4. S. KITAZAKI and M. J. GRIFFIN 1998 *Journal of Biomechanics* **31**, 143–149. Resonance behaviour of the seated human body and effects of posture.
5. S. D. SMITH 1994 *Shock and Vibration* **1**, 439–450. Nonlinear resonance behaviour in the human exposed to whole-body vibration.
6. N. J. MANSFIELD and M. J. GRIFFIN 2000 *Journal of Biomechanics* **33**, 933–941. Non-linearities in apparent mass and transmissibility during exposure to whole-body vertical vibration.
7. Y. MATSUMOTO and M. J. GRIFFIN 2002 *American Society of Mechanical Engineers, ASME* (*awaiting publication*). Non-linear characteristics in the dynamic responses of seated subjects exposed to vertical whole-body vibration.

8. Y. MATSUMOTO and M. J. GRIFFIN 1998 *Journal of Sound and Vibration* **212**, 85–107. Dynamic response of the standing human body exposed to vertical vibration: influence of posture and vibration magnitude.
9. N. J. MANSFIELD and R. LUNDSTRÖM 1999 *Journal of Biomechanics* **32**, 1269–1278. The apparent mass of the human body exposed to non-orthogonal horizontal vibration.
10. Y. MATSUMOTO and M. J. GRIFFIN 2002 *Journal of Sound and Vibration* **253**, 77–92. Effect of muscle tension on non-linearities in the apparent masses of seated subjects exposed to vertical whole-body vibration.
11. L. WEI and M. J. GRIFFIN 1998 *Journal of Sound and Vibration* **214**, 121–137. The prediction of seat transmissibility from measures of seat impedance.
12. G. S. PADDAN and M. J. GRIFFIN 1996 *ISVR Technical report* 260. *August* 1996, *Institute of Sound and Vibration Research*, *University of Southampton*. Transmission of mechanical vibration through the human body to the head.
13. S. KITAZAKI 1994 *Ph.D. Thesis*, *University of Southampton*, *Southampton*, *U.K.* Modelling Mechanical Responses to Human Whole-Body Vibration.
14. J. SANDOVER and H. DUPUIS 1987 *Ergonomics* **30**, 975–985. A reanalysis of spinal motion during vibration.
15. E. M. WHITHAM and M. J. GRIFFIN 1977 *Society of Automotive Engineers paper* 770253. Measuring vibration on soft seats.
16. S. KITAZAKI and M. J. GRIFFIN 1995 *Journal of Biomechanics* **28**, 885–890. A data correction method for surface measurement of vibration on the human body.
17. J. SANDOVER 1978 *Aviation*, *Space and Environmental Medicine*, January 1978, 335–339. Modelling human response to vibration.
18. K. SATO, S. KIKUCHI and T. YONEZAWA 1999 *Spine* **24**, 2468–2474. In vivo intradiscal pressure measurement in healthy individuals and in patients with ongoing back problems.
19. H. J. WILKE, P. NEEF, M. CAIMI, T. HOOGLAND and L. E. CLAES 1999 *Spine* **24**, 755–762. New in vivo measurements of pressures in the intervertebral disc in daily life.