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Nonlinearity in apparent mass and transmissibility of the supine human body during vertical whole-body vibration

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Abstract

Resonance frequencies evident in the apparent mass and the transmissibility of the human body decrease with increasing vibration magnitude, but the mechanisms responsible for this nonlinearity have not been established. This experiment was designed to explore the effects of body location on the nonlinearity of the body in supine postures. In a group of 12 male subjects, the apparent mass and transmissibility to the sternum, upper abdomen, and lower abdomen were measured in three postures (relaxed semi-supine, flat supine and constrained semi-supine) with vertical random vibration (0.25–20 Hz) at seven vibration magnitudes (nominally 0.0313, 0.0625, 0.125, 0.25, 0.5, 0.75, and 1.0 $\mathrm{ms^{-2}}$ rms). In all three postures, the apparent mass resonance frequencies and the primary peak frequencies in the transmissibilities to the upper and lower abdomen decreased with increases in vibration magnitude from 0.25 to 1.0 $\mathrm{ms^{-2}}$ rms. Nonlinearity generally apparent in transmissibility to the abdomen was less evident in transmissibility to the sternum and less evident in transmissibilities to the abdomen at vibration magnitudes less than 0.125 $\mathrm{ms^{-2}}$ rms. The nonlinearity was more apparent in the flat supine posture than in the semi-supine postures. The findings are consistent with the nonlinearity being associated with the response of soft tissues, more likely a consequence of passive thixotropy than muscle activity.

1. Introduction

During vertical whole-body vibration, the resonance frequencies of the apparent mass and transmissibilities of the upright seated or standing human body decrease with increasing vibration magnitude (e.g. [1–3]). This nonlinearity has also been found in the apparent mass of the relaxed semi-supine human body exposed to vertical vibration [4] and longitudinal horizontal vibration [5]. With the response of the human body represented by a passive single degree-of-freedom mass–spring–damper model, the change in the resonance frequency can be represented by either a decrease in the stiffness or an increase in the sprung mass.

The transmissibilities to various locations on the body may be used to identify the modes contributing to resonances seen in the apparent mass. Improved understanding of the modes contributing to the resonances might improve understanding of the cause of the nonlinearity. Transmissibilities to the pelvis and the spinal

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column show that the resonance of the seated body is primarily caused by a whole-body rocking mode associated with bending and rotational modes of the spine, possibly caused by axial and shear deformation of the tissues beneath the pelvis (i.e. parts of the buttocks, e.g. [1,6]). Transmissibilities to the pelvis, thoracic and lumbar spine, and abdominal wall have been found to be nonlinear in upright seated subjects during vertical excitation (e.g. [2,3]). These studies with seated subjects suggest that the nonlinearity is caused by either a passive softening effect of the soft tissues beneath the ischial tuberosities (e.g. thixotropy) or some combination of voluntary and involuntary activity of the postural muscles.

With vertical intermittent vibration, the stiffness of the relaxed supine body has been reported to decrease during, and for about 3 s after, exposure to high magnitude vibration, and increase during and for about 3 s after exposure to low magnitude vibration—a response typical of thixotropy [4]. Thixotropy, in which stiffness reduces during excitation, might be the primary cause of the nonlinearity found with the seated, standing, and supine human body. Thixotropy has been found in various parts of the human body: wrist [7], finger extensor [8], finger flexor [8,9], and rib cage respiratory muscles [10]. It might be suspected that vibration transmission paths comprising more soft tissues (e.g. the abdomen of a supine subject) would be more thixotropic and therefore more nonlinear than paths dominated by boney structures (e.g. the spinal column and sternum of a supine subject). Transmissibilities measured to different locations (e.g. the abdomen and the sternum) with varying magnitudes of vibration will indicate whether some parts of the supine body are more nonlinear than other parts.

Whereas increased steady-state muscular contractions appear to cause small but systematic changes in the apparent mass nonlinearity of seated subjects [11], some voluntary periodic upper-body movements can cause relatively large reductions in the nonlinearity [12]. The upper-body movements were assumed to involve various postural muscles that are normally involved in supporting the body with 'tonic' activity (i.e. a state of continuous contraction). During vibration, in order to stabilise the body in the presence of the externally applied motion, muscle activity varies with a 'phasic' response (i.e. muscles try to compensate for the inertial forces of the oscillatory motion). Phasic responses may be voluntary or involuntary, although voluntary phasic contractions may only be effective at low frequencies (e.g. at frequencies less than about 1–2 Hz [13]). The present study was undertaken with supine postures so as to reduce the need for voluntary or involuntary phasic activity of the postural muscles to support the body.

It is not known whether the posture of the supine body affects the nonlinearity. Changing posture, contact conditions, and constraints of seated and standing subjects changes the resonance frequencies of the body, but the responses of the seated and standing body appear to remain nonlinear in all postures (e.g. [14,15]). Nawayseh and Griffin [16] reported a small reduction in the nonlinearity when seated subjects changed their posture from 'maximum thigh contact' to 'minimum thigh contact' by raising the feet. The 'maximum thigh contact' allowed more soft tissues of the thighs to couple with the seat, while the 'minimum thigh contact' reduced the soft tissues in contact with the seat. Mansfield and Griffin [14] found no significant change in the nonlinearity when an abdominal constraining belt was worn by upright seated subjects during vertical vibration. The present study employed three postures to vary the contact between the body and the excitation. In a 'flat supine' posture, the excitation involved the soft tissues of the lower back and part of the thighs, whereas in a 'semi-supine' posture with the lower legs raised there was less contact with these soft tissues (but greater contact with the skeletal structure of the entire back), and in a 'constrained semi-supine' posture the upper-body was constrained by a four-point harness so as to maximise the contact between the subjects and source of excitation. The 'semi-supine' posture was the same as that used by Huang and Griffin [4,5].

From previous studies it is not clear whether the human body is 'more nonlinear' at low magnitudes or high magnitudes of vibration. Voluntary periodic movement of the upper bodies of seated subjects changed the resonance frequency more at low vibration magnitudes (0.25 ms^{-2} rms) than at high magnitudes (2.0 ms^{-2} rms) [12]. The lowest vibration magnitudes investigated in previous studies with seated or standing subjects have been between 0.1 and 0.25 ms^{-2} rms. To investigate the nonlinearity at lower magnitudes, the present study measured apparent mass and transmissibility at vibration magnitudes as low as 0.03 ms^{-2} rms.

With vertical excitation at seven vibration magnitudes (from about 0.03 to 1.0 ms^{-2} rms), this study investigated the apparent mass and transmissibility of subjects in three supine postures. It was hypothesised that there would be nonlinearity in the apparent mass and also in transmissibilities to the sternum and the upper and lower abdomen: the resonance frequencies would decrease with increasing vibration magnitude.

Evidence of greater nonlinearity in transmissibility to the abdomen would suggest that soft tissues primarily cause the nonlinearity. The vibration transmission path in the semi-supine posture involved less soft tissues on the back than the flat supine posture. For this reason, it was hypothesised that the semi-supine posture would be less nonlinear than the flat supine posture. Constraining the body of a seated subject does not appear to affect the nonlinearity, so the constrained semi-supine posture was expected to have similar nonlinearity to the relaxed semi-supine posture.

2. Method

2.1. Apparatus

Subjects lay face up supported by a back support, leg rest, and headrest on the same apparatus used by Huang and Griffin [4] (Fig. 1). The back support was a horizontal flat rigid aluminium plate (660 mm × 660 mm × 10 mm) covered with a high stiffness 3 mm thick laterally treaded rubber layer. The back support was bolted to the upper surface of a force platform (Kistler 9281 B21 12-channel force platform) that monitored

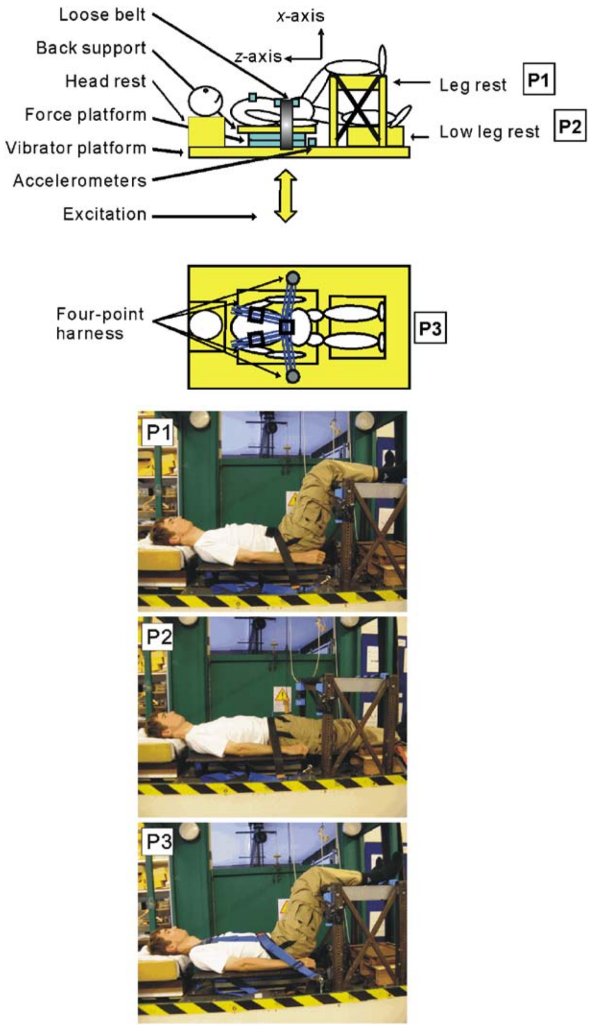

Fig. 1. Schematic (upper) and photographic (lower) representations of the supine support showing the supine postures (P1: semi-supine posture; P2: flat supine posture; P3: constrained semi-supine posture) and the axes of force (x-axis and z-axis) and acceleration (x-axis) transducers.

the vertical (x-axis of the supine subject) and longitudinal horizontal (z-axis of the supine subject) forces. The four vertical (x-axis) force signals, and the four longitudinal (z-axis) force signals, from the four corners of the platform were summed and conditioned using two Kistler 5001 charge amplifiers. Only the vertical forces are reported in this paper. The force platform was bolted to the vibrator platform. The horizontal gap between the back support and the leg rest was 50 mm (Fig. 1).

The headrest was a horizontal flat rigid wooden block with 75 mm thick uncompressed car-seat foam attached to the upper surface. The top surface of the uncompressed foam was approximately 50 mm higher than the back support. The horizontal distance between the back support and headrest was adjusted by moving the headrest so that a subject's head could rest comfortably.

Vertical vibration was produced by a 1 m stroke electro-hydraulic vertical vibrator capable of accelerations up to $\pm 10\,\mathrm{ms}^{-2}$ in the laboratory of the Human Factors Research Unit at the Institute of Sound and Vibration Research. Vertical (x-axis of the supine subjects) acceleration and longitudinal (z-axis) acceleration of the vibrator platform were measured using two identical Setra 141A $\pm 2g$ accelerometers (Fig. 2) on the vibrator platform.

Vertical (x-axis) acceleration at the middle of the sternum (4 cm above, i.e. superior to, the lower end of the sternum), at the upper abdomen (4 cm above the navel), and at the lower abdomen (4 cm below the navel) were measured using two Endevco 2265–10M2 $\pm 10g$ accelerometers and one Endevco 2265–20 $\pm 20g$ accelerometer, respectively (Fig. 2). The three accelerometers had the same size and weight. The base of each accelerometer was attached to rigid plywood ($27 \times 17 \times 2$ mm) by double-sided adhesive tape, and the other side of the plywood was attached to a plastic buckle connected to two ends of an elastic belt (Fig. 3a). The weight of the block, including the accelerometer, the plywood, and the buckle, was approximately $8g$. The contact area of the block to the skin was 12.8 mm (longitudinal) by 7.2 mm (lateral). The block was then fastened by tightening the elastic belt with a stiffness of approximately $75\,\mathrm{N\,m}^{-1}$ for all subjects. The locations of the accelerometers on the body surface are shown in Fig. 3(b).

The local tissue-accelerometer motion caused by the mounting of an accelerometer can be corrected with an impulse response function obtained from its free vibration [17]. Previous studies have measured transmissibilities to spinal vertebrae (e.g. [1,3,17]), and to the abdomen above and below the navel [2] in upright seated subjects during vertical excitation. Using the same correction method described by Kitazaki and Griffin [17], Mansfield and Griffin [2] reported that 'corrections for the measurements slightly changed the transmissibilities at frequencies greater than 10 Hz, although resonance frequencies were unaffected for any measurement location'. The present study was designed to compare the nonlinearity around resonances in the supine body where different transmission paths are likely. In the present study, pilot experimentation using the same method described by Kitazaki and Griffin [17] determined that the natural frequency of the local system was around 25–32 Hz at the lower and upper abdomen. Since only much lower frequencies are of current interest (transmissibilities are presented at frequencies less than 20 Hz in this paper), no correction for the local tissue-accelerometer system was applied.

The accelerometers attached to the three locations on the body were adjusted to be perpendicular to the body surface before each vibration exposure. The static inclinations of the accelerometers were approximately $4°$–$6°$ at the sternum, and $0°$–$8°$ at the upper and lower abdomen. In addition to the static inclination, during vibration excitation the accelerometer at the sternum tilted by about $1°$–$2°$; during vibration the

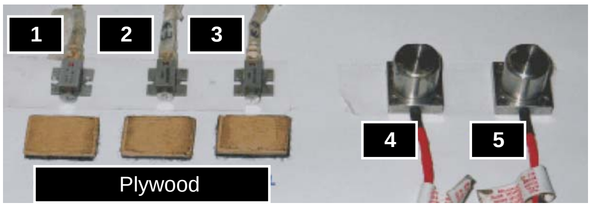

Fig. 2. Accelerometers used to measure accelerations at: 1: lower abdomen (Endevco 2265–20 $\pm 20g$); 2: upper abdomen (Endevco 2265–10M2 $\pm 10g$); 3: sternum (Endevco 2265–10M2 $\pm 10g$); 4: vibrator platform in the longitudinal (z-axis) direction (Setra 141A $\pm 2g$); 5: vibrator platform in the vertical (x-axis) direction (Setra 141A $\pm 2g$). Three pieces of identical $27 \times 17 \times 2$ mm rigid plywood are shown below the three accelerometers (1, 2, and 3) used to measure the transmissibilities.

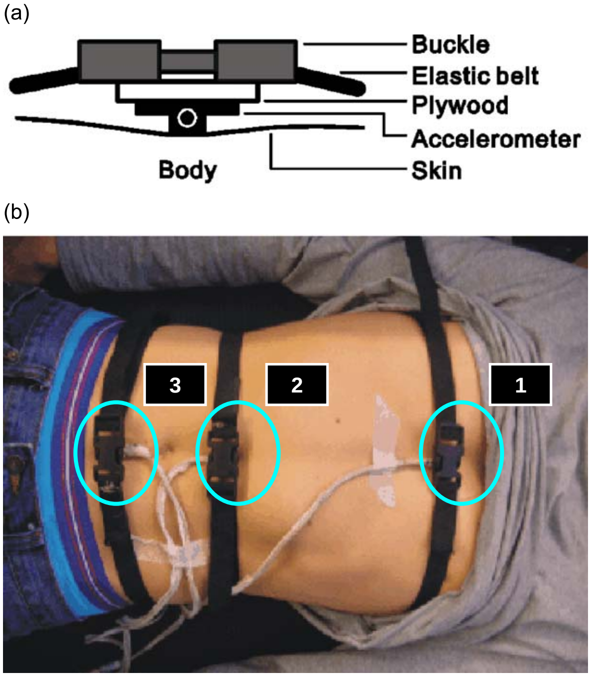

Fig. 3. Each accelerometer was in an upside-down position and in contact with the skin: (a) the three accelerometers and (b) were attached to each buckle via a 27 × 17 × 2 mm rigid plywood along the longitudinal axis of the body at the sternum (1), upper abdomen (2), and lower abdomen (3).

accelerometers at the upper and lower abdomen tilted by about 2°–4°. Matsumoto and Griffin [1] measured the inclination of the surface of the upright seated body at T1 (between 20° and 35°) and linearly compensated for the inclination by adding the sine of vertical transmissibility to the fore-and-aft transmissibility and subtracting the cosine of fore-and-aft transmissibility from the vertical transmissibility. The inclination of the accelerometers to the axis of excitation in the present experiment was less than 10 degrees and the cross-axis longitudinal motion of the supine subjects was less than for seated subjects. The inclination of the accelerometer was therefore not compensated.

The vibration stimuli were generated, and the four vertical accelerations and the vertical and horizontal forces were acquired, using an *HVLab* data acquisition and analysis system (version 3.81). The acceleration and force were acquired at 200 samples per second via 67 Hz analogue anti-aliasing filters.

2.2. Stimuli

The random vertical vibration had approximately flat constant-bandwidth acceleration power spectra over the frequency range 0.25–20 Hz. Seven unweighted accelerations, nominally at 0.0313, 0.0625, 0.125, 0.25, 0.5, 0.75, and 1.0 ms^{-2} rms, were generated using seven different random seeds. Each test motion had a duration of 90 s tapered at the start and end with 0.5 s cosine tapers. With vibrator powered but with no motion signal, the magnitude of the background vibration was about 0.017 ms^{-2} rms and mainly due to vibration at 50 Hz. Twelve subjects were randomly divided into six groups with two persons per group. With different groups, different random seeds were used to generate the random stimuli. The presentation order of the 21 test motions (seven magnitudes with three supine postures) was randomized independently for each subject.

2.3. Posture

Subjects lay in three different supine postures (Fig. 1). In the reference posture (‘semi-supine’), the lower legs rested on a raised horizontal leg rest so as to give maximum contact between the back and the back support (the same posture as the 'relaxed semi-supine' posture used by Huang and Griffin [4,5]). A loose safety belt passed around the abdomen and arms but did not constrain the body.

In the 'flat supine posture', the legs rested on a horizontally flat rigid wooden support at the same height as the back support allowing the subject to lie horizontally flat.

In the 'constrained semi-supine' posture, subjects maintained the 'semi-supine' posture with the upper body tightly constrained to the back support by a four-point harness. The harness was loosened before each test. Subjects tightened the harness to a 'comfortably tight' setting with the help of the experimenter. The harness was adjusted first at the waist and then the shoulder.

In all three postures, the support for the body, head and legs was exposed to the same vertical vibration. The subjects were instructed to relax with their eyes closed.

2.4. Subjects

Twelve male subjects, aged 19–33 years, with median (minimum and maximum) stature 1.79 m (1.72–1.89 m), total body mass 72.7 kg (58.9–96.7 kg), and waist circumference 0.80 m (0.73–0.96 m) participated in the study. The subjects wore loose and light shirts and trousers with no waist belt.

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.

2.5. Analysis

The vertical (x-axis) dynamic force and the vertical (x-axis) accelerations measured at the middle of the sternum, the upper abdomen, and the lower abdomen were expressed relative to the vertical (x-axis) acceleration of the vibrator platform. Four frequency response functions—apparent mass (where the force was in-line with the acceleration in the vertical direction), and three vertical transmissibilities (to the sternum, the upper abdomen, and the lower abdomen)—were calculated using the cross-spectral density method:

$$H(f) = S_{af}(f)/S_{aa}(f) \tag{1}$$

where $H(f)$ is the apparent mass, in kg (or the transmissibilities to the sternum, the upper abdomen, or the lower abdomen); $S_{af}(f)$ the cross spectral density between the dynamic forces at the back support (or the accelerations at the sternum, and upper and lower abdomen); and the vertical excitation acceleration; $S_{aa}(f)$ the power spectral density of the vertical excitation acceleration at the vibrator platform.

Before calculating the apparent mass, mass cancellation was carried out in the time domain to subtract the force caused by the masses above the force sensing elements (a total of 30.5 kg obtained dynamically in the frequency range 0.25–20 Hz).

The relation of the output motion to the input motion in the calculated frequency response functions was investigated using the coherency:

$$Y_{io}^2(f) = |S_{af}(f)|^2/(S_{aa}(f)S_{ff}(f)) \tag{2}$$

where $S_{ff}(f)$ is the power spectral density of the vertical force and $Y_{io}^2(f)$ the coherency of the system with a value between 0 and 1. The coherency has a maximum value of 1.0 in a linear single-input system with no noise—the output motion being entirely caused by, and linearly correlated with, the input motion.

The cross spectral densities and the power spectral densities were estimated via Welch's method at frequencies between 0.25 and 20 Hz. The frequency response functions for each 90 s signal were calculated with a frequency resolution of 0.78 Hz (Table 1). The coarse 0.78 Hz resolution was used to give a high confidence level (increased degrees of freedom) at each frequency, needed especially for the low magnitudes of vibration (0.0313, 0.0625, and 0.125 $\mathrm{ms^{-2}}$ rms).

The apparent masses at the seven magnitudes were normalised by dividing by the apparent mass modulus measured at frequencies between 0.25 and 2.5 Hz, where the body was considered virtually rigid. For excitation at 0.0313, 0.0625, 0.125, 0.25, and 0.5 $\mathrm{ms^{-2}}$ rms, the normalisation was carried out at 2.34 Hz; for excitation at 0.75 and 1.0 $\mathrm{ms^{-2}}$ rms the normalisation was carried out at 1.56 Hz. The median normalised apparent masses at the seven magnitudes were then calculated.

Table 1
Signal processing procedure used to calculate the apparent mass and the transmissibilities to the sternum, the upper abdomen, and the lower abdomen.

	Duration (s)	Samples per second	FFT length	Degrees of freedom	Windowing overlap	Frequency resolution (Hz)
0.78 Hz procedure	90	200	256	284	Hamming 100%	0.78

Differences in apparent mass and transmissibility (both modulus and phase) at different vibration magnitudes and postures were tested using the Friedman two-way analysis of variance and then, if there was a significant overall effect, the Wilcoxon matched-pairs signed ranks tests. These tests were carried out at eight discrete frequencies (3.91, 5.47, 7.03, 8.59, 10.16, 11.72, 13.28, and 14.84 Hz).

3. Results

3.1. Apparent mass

Fig. 4 shows inter-subject variability in apparent mass in the three postures at the seven magnitudes of vibration.

With the semi-supine posture, the coherency of the apparent mass of all subjects was greater than 0.90 at frequencies between 1 and 20 Hz at vibration magnitudes greater than 0.25 ms^{-2} rms. With the flat supine posture, the coherency was greater than 0.95 at magnitudes greater than 0.0625 ms^{-2} rms. With the constrained semi-supine posture, the coherency was greater than 0.90 at magnitudes greater than 0.5 ms^{-2} rms. An example of the coherency in the three postures for Subject 1 is shown in Fig. 5.

3.1.1. Effect of vibration magnitude

In all postures, subjects exhibited the typical nonlinearity at vibration magnitudes greater than 0.125 ms^{-2} rms. An example is shown in Fig. 6.

The effect of vibration magnitude on the modulus and phase of the apparent mass was investigated at the eight selected frequencies. First the Friedman two-way analysis of variance was performed at each frequency over the seven vibration magnitudes. Where this yielded a significant effect of vibration magnitude (i.e. $p<0.05$), the Wilcoxon matched-pairs signed ranks test was performed between all magnitudes. This statistical procedure was applied to the modulus and phase of the apparent mass. Examples of the procedure for the effect of vibration magnitude on the apparent mass modulus with the semi-supine posture are shown in Table 2. The same procedure was used to compare the phases of apparent mass between vibration magnitudes at the same frequencies within each posture. The number of significant differences between pairs (suggesting the degree of nonlinearity) for all postures and transfer functions is summarised in Table 4.

With the semi-supine posture, at frequencies lower than 8.59 Hz the apparent mass modulus was significantly greater with higher magnitudes of vibration ($p<0.05$, Wilcoxon), except between 0.0625 and 0.125 ms^{-2} rms. At frequencies greater than 10.16 Hz, the apparent mass modulus was significantly lower with greater magnitudes of vibration ($p<0.05$, Wilcoxon), except between 0.0313, 0.0625, and 0.125 ms^{-2} rms. A similar pattern was observed in the other two postures.

In all three postures, the changes in apparent mass were consistent with the resonance frequency decreasing with increasing vibration magnitude, although not consistently so at the lowest magnitudes. Changes in the phase of the apparent mass were consistent with changes in the modulus.

With the semi-supine posture, the median normalised apparent mass resonance frequency decreased from 9.38 to 7.03 Hz as the vibration magnitude increased from 0.0625 to 1.0 ms^{-2} rms, but the resonance frequencies did not differ significantly at magnitudes less than 0.125 ms^{-2} rms (Fig. 7P1).

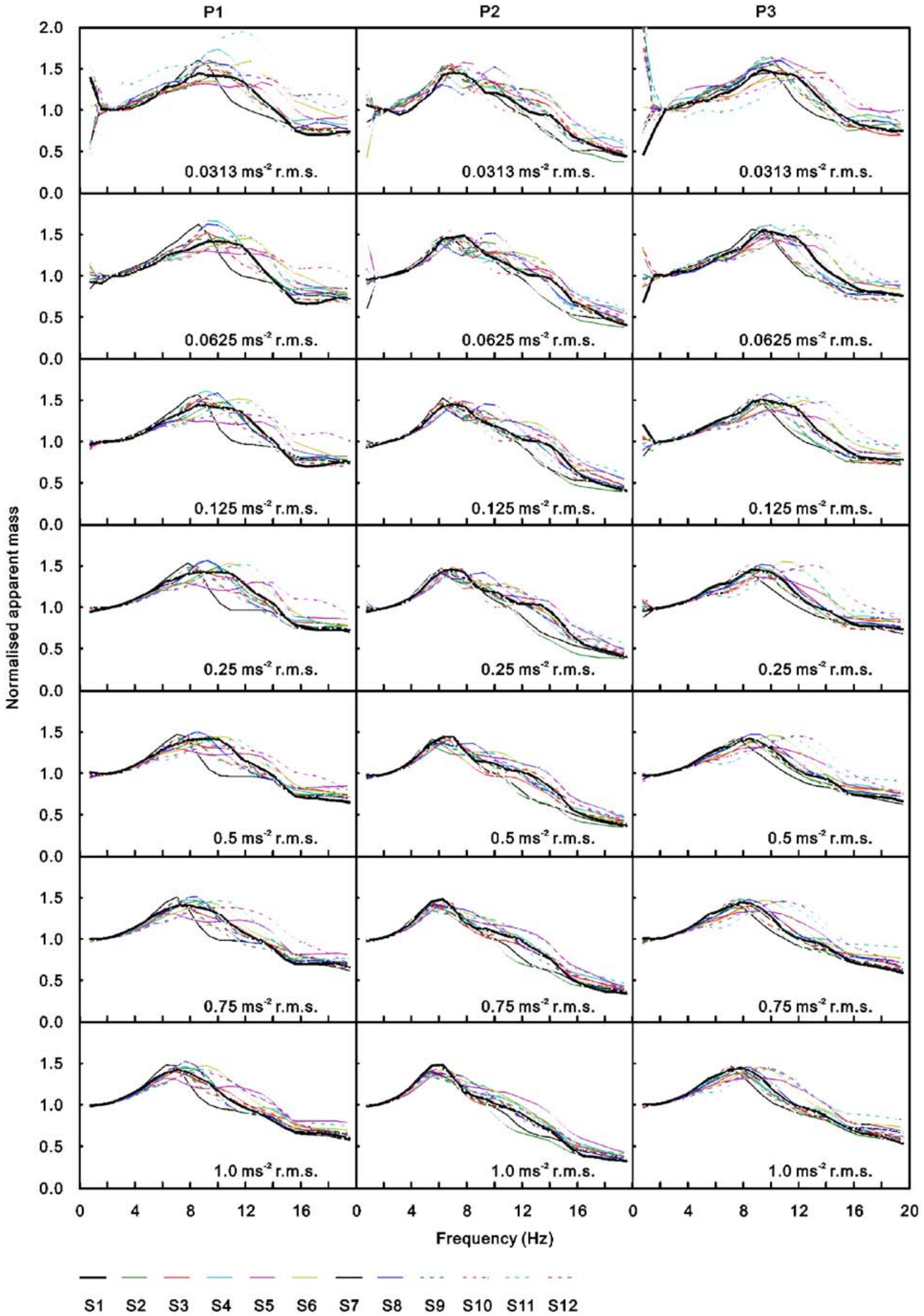

Fig. 4. Individual normalised apparent mass modulus with three supine postures (P1—semi-supine, P2—flat supine, P3—constrained semi-supine) at seven vibration magnitudes (MAG1—0.0313 ms^{-2} rms, MAG2—0.0625 ms^{-2} rms, MAG3—0.125 ms^{-2} rms, MAG4—0.25 ms^{-2} rms, MAG5—0.5 ms^{-2} rms, MAG6—0.75 ms^{-2} rms, MAG7—1.0 ms^{-2} rms) of all 12 subjects (S1–S12).

With the flat supine posture, the median normalised apparent mass resonance frequency decreased from 7.03 to 5.47 Hz as the vibration magnitude increased from 0.0625 to 1.0 ms^{-2} rms, but the resonance frequencies did not differ significantly at magnitudes less than 0.25 ms^{-2} rms (Fig. 7P2).

With the constrained semi-supine posture, the median normalised apparent mass resonance frequency decreased from 10.16 to 7.81 Hz as the vibration magnitude increased from 0.0625 to 1.0 ms^{-2} rms, but the resonance frequencies did not differ significantly at magnitudes less than 0.25 ms^{-2} rms (Fig. 7P3).

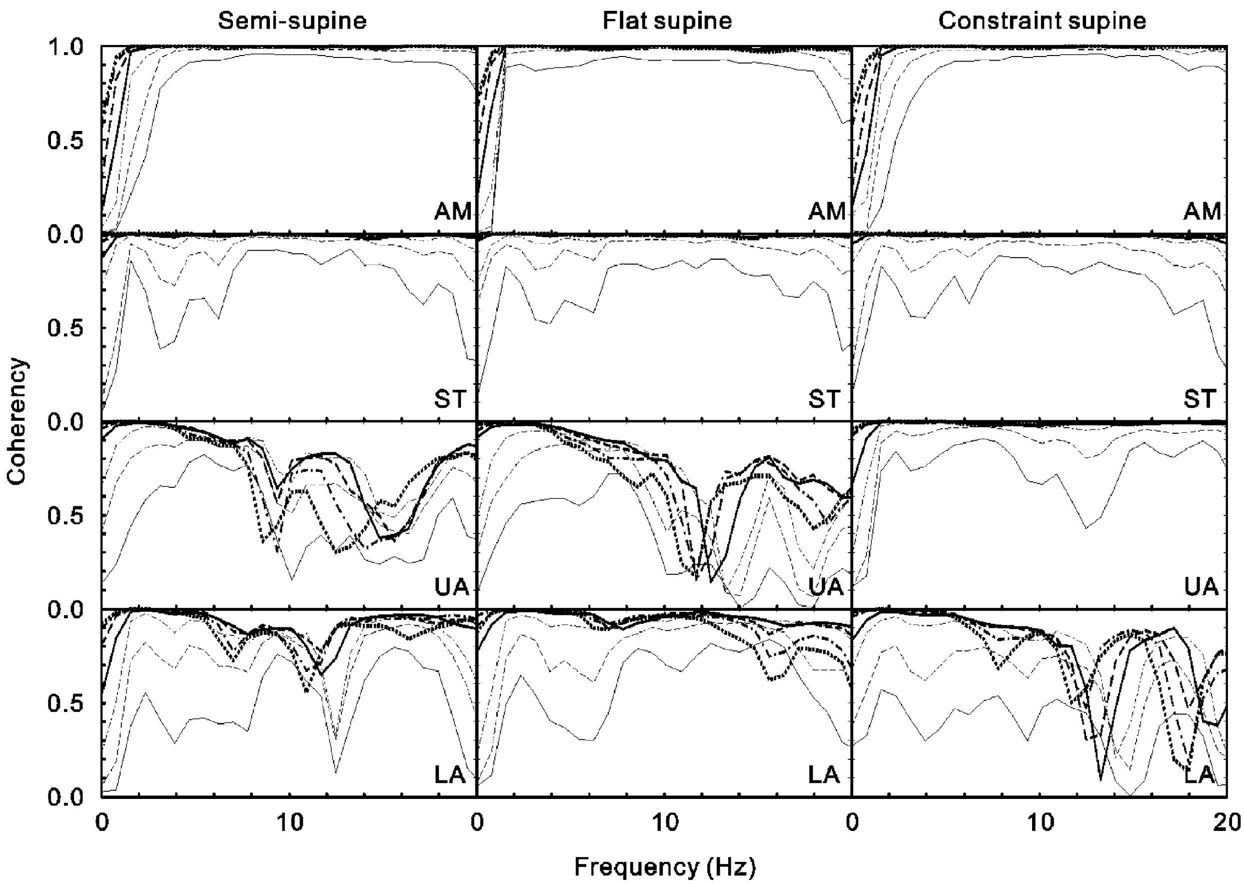

Fig. 5. Individual (Subject 1, i.e. S1) coherency of the apparent mass (AM) and the transmissibilities to the sternum (ST), upper abdomen (UA), and lower abdomen (LA) with three supine postures (semi-supine; flat supine; constrained semi-supine) at seven vibration magnitudes (——— 0.0313 ms^{-2} rms, — — — 0.0625 ms^{-2} rms, — · — · — 0.125 ms^{-2} rms, ——— 0.25 ms^{-2} rms, — — — 0.5 ms^{-2} rms, — · — · — 0.75 ms^{-2} rms, - - - - 1.0 ms^{-2} rms).

3.1.2. Effect of posture

The effect of posture on the modulus and phase of the apparent mass was investigated at the eight selected frequencies and the seven vibration magnitudes using the statistical procedure summarised at the beginning of Section 3.1.1. An example is shown in Table 3 and Fig. 8. At frequencies from 5.47 to 7.03 Hz, the modulus of the apparent mass in the flat supine posture was greater than that in either the semi-supine or the constrained semi-supine posture ($p<0.05$, Wilcoxon). Over the frequency range 10.16–14.84 Hz, the apparent mass in the flat supine posture was lower than that in either the semi-supine or the constrained semi-supine posture ($p<0.05$, Wilcoxon). The apparent masses of the semi-supine and the constrained semi-supine postures were not significantly different over the frequency range 5.47–10.16 Hz, where the resonance occurred ($p > 0.05$, Wilcoxon).

The changes in apparent mass were consistent with the resonance frequency being lower with the flat supine posture than either the semi-supine or the constrained semi-supine posture (Fig. 8). These changes also showed that changing from semi-supine to constrained semi-supine posture caused less change in the apparent mass than changing from semi-supine to flat supine (Table 5). Changes in the phase of the apparent mass were consistent with changes in the modulus.

3.2. Transmissibility to the sternum

The inter-subject variability in transmissibility to the sternum tended to be similar at different vibration magnitudes (Fig. 9).

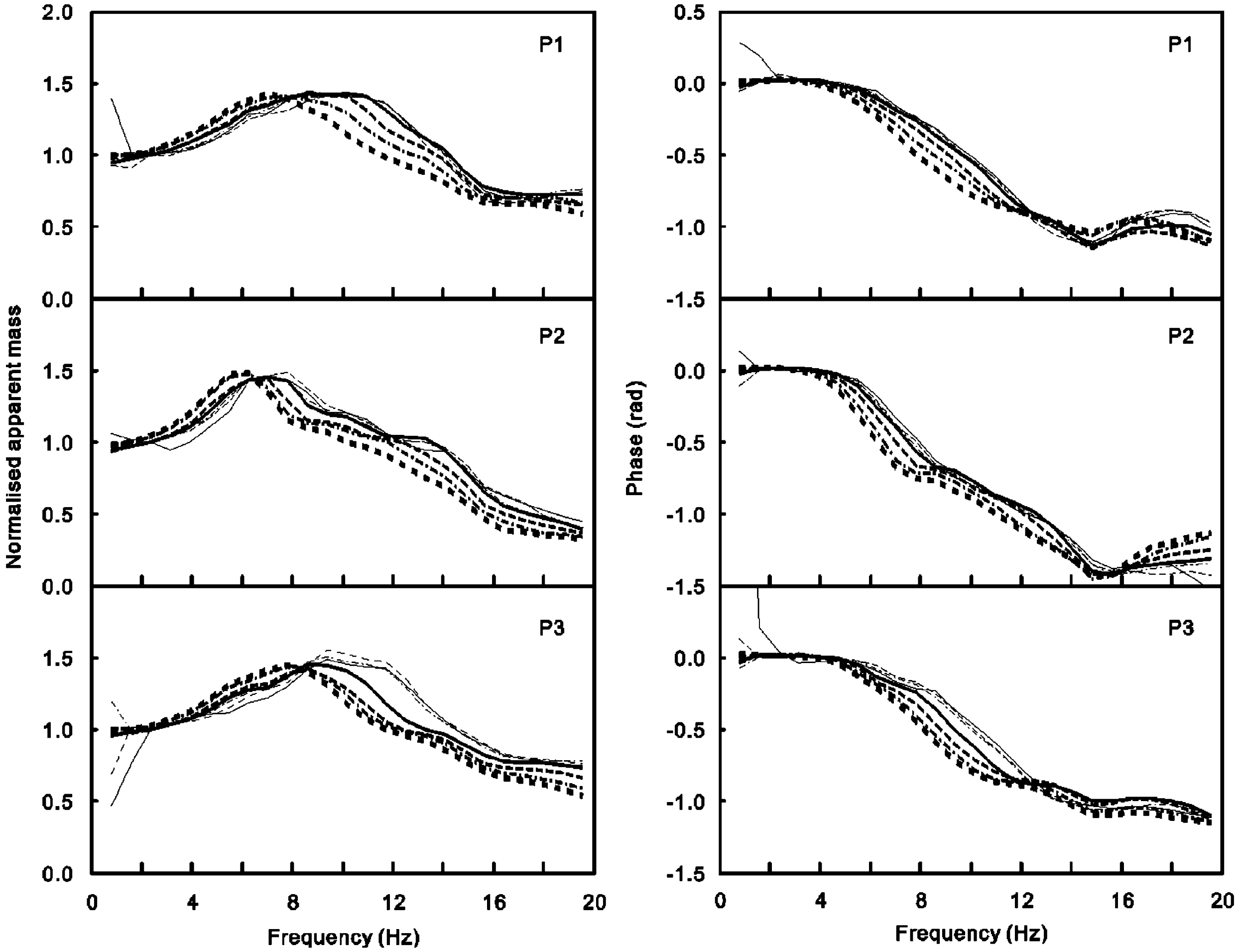

Fig. 6. Effect of vibration magnitude: normalised apparent mass modulus and phases of one subject (S1) with three supine postures (P1—semi-supine, P2—flat supine, P3—constrained semi-supine) at seven vibration magnitudes (——— 0.0313 ms^{-2} rms, — — — 0.0625 ms^{-2} rms, — · — · — 0.125 ms^{-2} rms, ——— 0.25 ms^{-2} rms, — — — 0.5 ms^{-2} rms, — · — · — 0.75 ms^{-2} rms, - - - - 1.0 ms^{-2} rms).

In all postures, the coherency was in excess of 0.90 at frequencies greater than 1.0 Hz and at vibration magnitudes greater than 0.125 ms^{-2} rms, with no obvious difference between the three supine postures. An example of the coherency for Subject 1 is shown in Fig. 5 (ST). At the three lowest vibration magnitudes (i.e. 0.0313, 0.0625, 0.125 ms^{-2} rms), the coherency dropped in two regions: in the range 4–6 Hz, and around 18 Hz.

3.2.1. *Effect of vibration magnitude*

In all postures and in all individuals there was evidence of nonlinearity in transmissibility to the sternum, although it was less obvious than in the apparent mass. An example of the nonlinearity for Subject 1 is shown in Fig. 10 (ST).

The effect of vibration magnitude was examined using the same statistical procedure employed for the apparent mass (see Section 3.1.1 and Table 2).

With the semi-supine posture, at frequencies less than 8.59 Hz, the modulus of the transmissibility was greater at greater magnitudes of vibration over the range 0.25–1.0 ms^{-2} rms ($p<0.05$, Wilcoxon). At frequencies greater than 10.16 Hz, the modulus was greater with lower magnitudes of vibration over the range 0.25–1.0 ms^{-2} rms ($p<0.05$, Wilcoxon). A similar pattern was observed for the other two postures.

In all three postures, the nonlinearity in transmissibility to the sternum was consistent with the primary peak frequency decreasing with increasing vibration magnitude. Changes in the phase of the transmissibility were consistent with changes in the modulus.

Table 2
Significance of differences in apparent mass modulus between adjacent vibration magnitudes (1 to 7 for 0.0313 to 1.0 ms^{-2} rms) at eight frequencies (f_1 to f_8) with posture 1 (semi-supine).

Posture	f_1 3.91 Hz	f_2 5.47 Hz	f_3 7.03 Hz	f_4 8.59 Hz	f_5 10.16 Hz	f_6 11.72 Hz	f_7 13.28 Hz	f_8 14.84 Hz	Total significant differences
Semi- supine	1–2[a]	1–2[a]	1–2[a]	1–2[a]	1–2	1–2	1–2	1–2	31/48
	2–3	2–3	2–3	2–3[a]	2–3	2–3	2–3	2–3	
	3–4[a]	3–4[a]	3–4[a]	3–4[a]	3–4	3–4[a]	3–4[a]	3–4	
	4–5[a]	4–5[a]	4–5[a]	4–5	4–5	4–5[a]	4–5[a]	4–5[a]	
	5–6[a]	5–6[a]	5–6[a]	5–6	5–6[a]	5–6[a]	5–6[a]	5–6[a]	
	6–7[a]	6–7[a]	6–7[a]	6–7	6–7[a]	6–7[a]	6–7[a]	6–7[a]	

At 0.125 ms^{-2} rms (i.e. magnitude 3), and at greater magnitudes, there are significant differences in apparent mass for 26 of the 32 pairs (see comparisons 3–4, 4–5, 5–6, and 6–7 at all frequencies). At 0.125 ms^{-2} rms, and magnitudes lower than 0.125 ms^{-2} rms, there are significant differences in apparent mass for only 5 of the 16 pairs (see comparisons 1–2 and 2–3).
Vibration magnitudes: 1—0.0313 ms^{-2} rms; 2—0.0625 ms^{-2} rms; 3—0.125 ms^{-2} rms; 4—0.25 ms^{-2} rms; 5—0.5 ms^{-2} rms; 6—0.75 ms^{-2} rms; 7—1.0 ms^{-2} rms.
Underline—the apparent mass modulus at the lower magnitude was significantly greater than the apparent mass modulus at the higher magnitude ($p<0.05$, Wilcoxon).
[a]Significant difference $p<0.05$, Wilcoxon.

With the semi-supine posture, the primary peak frequency in the median transmissibility to the sternum reduced from 10.94 to 9.38 Hz as the vibration magnitude increased from 0.0625 to 1.0 ms^{-2} rms (Fig. 11 ST). Significant differences between resonance frequencies at adjacent vibration magnitudes were found in the range 0.25–1.0 ms^{-2} rms ($p<0.05$, Wilcoxon).

With the flat supine posture, the primary peak frequency in the median transmissibility reduced from 10.16 to 7.03 Hz as the vibration magnitude increased from 0.0625 to 1.0 ms^{-2} rms (Fig. 11 ST). Significant differences between resonance frequencies at adjacent vibration magnitudes were found in the range 0.25–1.0 ms^{-2} rms ($p<0.05$, Wilcoxon).

With the constrained semi-supine posture, the primary peak frequency in the median transmissibility reduced from 10.94 to 8.59 Hz as the vibration magnitude increased from 0.0625 to 1.0 ms^{-2} rms (Fig. 11 ST). Significant differences between resonance frequencies at adjacent vibration magnitudes were found in the range 0.25–1.0 ms^{-2} rms ($p<0.05$, Wilcoxon).

The individual transmissibilities (Fig. 10 ST) and median transmissibilities (Fig. 11 ST) to the sternum showed nonlinearity in all three postures. Statistical tests performed at the eight selected frequencies (see Table 4) suggested that the nonlinearity was more consistent in the flat supine posture (17 significant pairs) and the constrained semi-supine posture (22 significant pairs) than in the semi-supine posture (13 significant pairs).

3.2.2. Effect of posture

In all three postures, the individual transmissibilities (Fig. 9) and the median transmissibilities (Fig. 8 ST) to the sternum were similar at frequencies less than 15 Hz. The effect of posture on the transmissibility was examined using the same procedure employed for the effect of posture on the apparent mass (as described in Section 3.1.2 and shown in Table 3). Over the frequency range 3.91–14.84 Hz, the posture had less effect on transmissibility to the sternum than on apparent mass (Table 5).

3.3. Transmissibility to the upper abdomen

Inter-subject variability in transmissibility was greater to the upper abdomen than to the sternum (compare Fig. 12 with Fig. 9).

An example of coherency is shown for Subject 1 in Fig. 5 (UA). With the semi-supine posture, a coherency drop occurred over the frequency range 8–10 Hz and 12–16 Hz. The primary (and secondary) transmissibility peak frequency of this subject with the semi-supine posture was between 5.47 (10.16) and 7.03 (11.72) Hz as

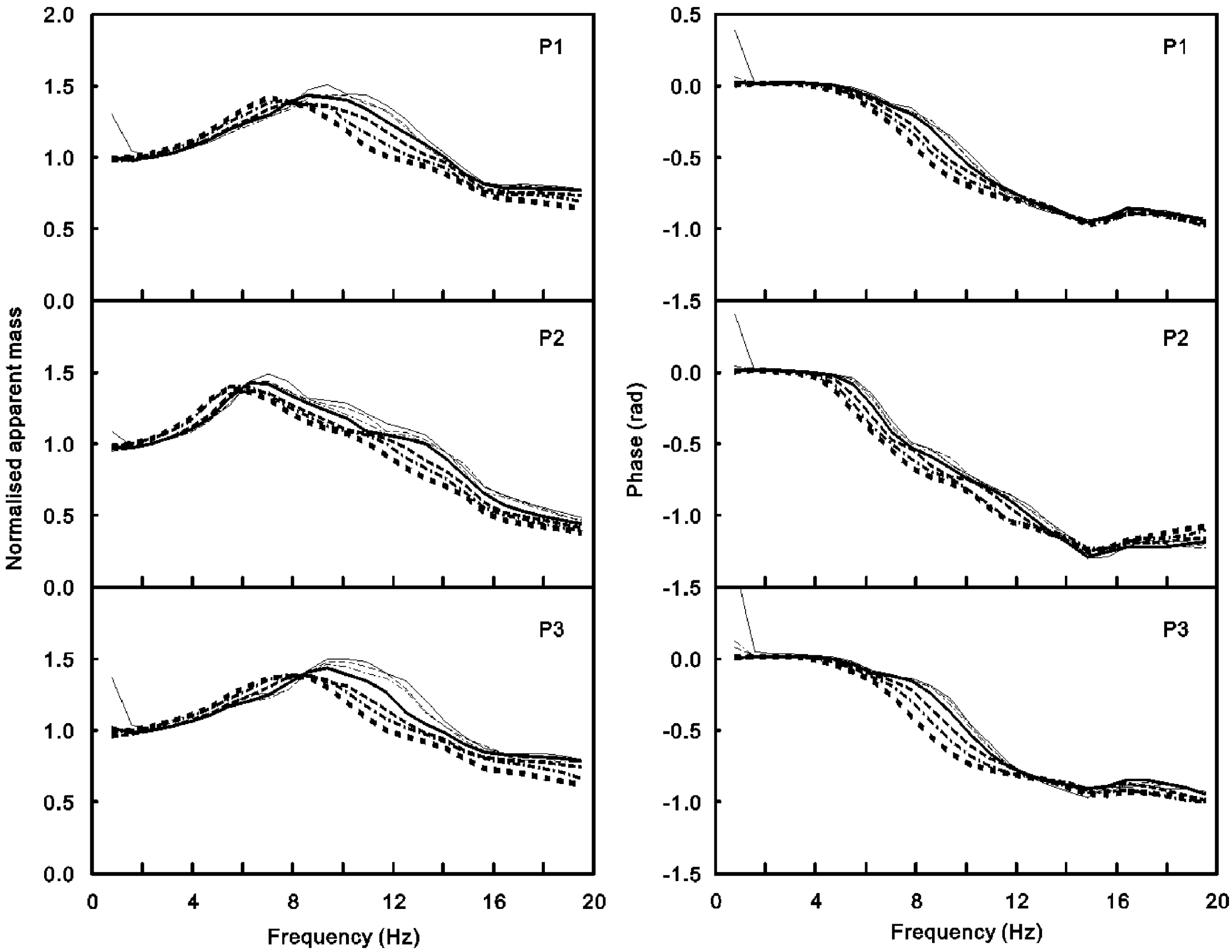

Fig. 7. Effect of vibration magnitude: median normalised apparent mass modulus and phases of the group of 12 subjects with three supine postures (P1—semi-supine, P2—flat supine, P3—constrained semi-supine) at seven vibration magnitudes (——— 0.0313 ms^{-2} rms, — — — 0.0625 ms^{-2} rms, — · — · — 0.125 ms^{-2} rms, ——— 0.25 ms^{-2} rms, — — — 0.5 ms^{-2} rms, — · — · — 0.75 ms^{-2} rms, - - - - 1.0 ms^{-2} rms).

vibration magnitude decreased from 1.0 to 0.0313 ms^{-2} rms. With the flat supine posture, the frequency range of the coherency drop was from 10 to 14 Hz and 18 to 20 Hz. The primary (and secondary) transmissibility peak frequency of the same subject with the flat supine posture was between 5.47 (9.38) and 7.03 (11.72) Hz as vibration magnitude decreased from 1.0 to 0.0313 ms^{-2} rms.

The frequency with the lowest coherency in the semi-supine posture and the constrained semi-supine posture tended to be lower with higher magnitudes of vibration (Fig. 5 (UA)). Although the frequency of the coherency drop varied between subjects, the changes with respect to vibration magnitude were consistent for all subjects.

3.3.1. Effect of vibration magnitude

In all postures, individuals exhibited the typical nonlinearity at magnitudes greater than 0.125 ms^{-2} rms. In the constrained semi-supine posture, the resonance peak was eliminated as a result of the constraining harness. In the semi-supine posture and the flat supine posture, individuals showed a primary resonance peak at around 6–8 Hz. An example individual response is shown for S1 in Fig. 10 (UA).

The effect of vibration magnitude was examined using the same statistical procedure described in Section 3.1.1 and shown in Table 2.

Table 3
Significant differences in apparent mass modulus between postures at eight frequencies and seven vibration magnitudes.

Magnitude number	f_1 3.91 Hz	f_2 5.47 Hz	f_3 7.03 Hz	f_4 8.59 Hz	f_5 10.16 Hz	f_6 11.72 Hz	f_7 13.28 Hz	f_8 14.84 Hz	Total significant differences
1	**R–F**	R–F	R–F	R–F	**R–F**	R–F[a]	R–F[a]	R–F[a]	48/56
2	R–F	R–F	R–F	**R–F**	R–F[a]	R–F[a]	R–F[a]	R–F[a]	
3	R–F	R–F	R–F	**R–F**	R–F[a]	R–F[a]	R–F[a]	R–F[a]	
4	R–F	R–F	R–F	**R–F**	R–F[a]	R–F[a]	R–F[a]	R–F[a]	
5	R–F	R–F	R–F	**R–F**	R–F[a]	R–F[a]	R–F[a]	R–F[a]	
6	R–F	R–F	R–F	R–F[a]	R–F[a]	R–F[a]	R–F[a]	R–F[a]	
7	R–F	R–F	**R–F**	R–F[a]	R–F[a]	**R–F**	R–F[a]	R–F[a]	
1	R–C	**R–C**	**R–C**	**R–C**	**R–C**	R–C	R–C	R–C	21/56
2	R–C	**R–C**	**R–C**	**R–C**	**R–C**	R–C	R–C	R–C	
3	R–C	R–C	**R–C**	**R–C**	**R–C**	R–C	R–C	R–C	
4	R–C	**R–C**	**R–C**	**R–C**	**R–C**	**R–C**	**R–C**	**R–C**	
5	R–C	**R–C**	**R–C**	**R–C**	**R–C**	**R–C**	**R–C**	**R–C**	
6	R–C	**R–C**	**R–C**	**R–C**	R–C	R–C	**R–C**	**R–C**	
7	R–C	**R–C**	**R–C**	**R–C**	R–C	R–C	**R–C**	**R–C**	
1	**F–C**	F–C[a]	F–C[a]	F–C[a]	**F–C**	F–C	F–C	F–C	45/56
2	**F–C**	F–C[a]	F–C[a]	**F–C**	F–C	F–C	F–C	F–C	
3	**F–C**	F–C[a]	F–C[a]	**F–C**	F–C	F–C	F–C	F–C	
4	**F–C**	F–C[a]	F–C[a]	**F–C**	F–C	F–C	F–C	F–C	
5	**F–C**	F–C[a]	F–C[a]	**F–C**	F–C	F–C	F–C	F–C	
6	F–C[a]	F–C[a]	F–C[a]	F–C	F–C	F–C	F–C	F–C	
7	F–C[a]	F–C[a]	**F–C**	F–C	F–C	F–C	F–C	F–C	

Postures: R—Semi-supine (as a reference condition); F—Flat supine; C—Constrained semi-supine.
Vibration magnitudes: 1–0.0313 ms^{-2} rms; 2–0.0625 ms^{-2} rms; 3–0.125 ms^{-2} rms; 4–0.25 ms^{-2} rms; 5–0.5 ms^{-2} rms; 6–0.75 ms^{-2} rms; 7–1.0 ms^{-2} rms.
Bold pairs—insignificant pairs. For example, F–C at a specific frequency 1–3 indicates the apparent mass at 0.0313 ms^{-2} rms is not significantly different to the apparent mass at 0.0625 ms^{-2} rms Normal black pairs—significant pairs.
[a]The apparent mass modulus appearing first was significantly greater than the apparent mass modulus appearing second ($p<0.05$, Wilcoxon).

With the semi-supine posture, at frequencies lower than 7.03 Hz the transmissibility was greater with greater magnitudes of vibration over the range 0.25 to 1.0 ms^{-2} rms ($p<0.05$, Wilcoxon). At 8.59 Hz and frequencies greater than 8.59 Hz and vibration magnitudes over the range 0.25 to 0.75 ms^{-2} rms, the transmissibility was lower with greater magnitudes of vibration ($p<0.05$, Wilcoxon). The nonlinearity was more consistent in transmissibility to the upper abdomen than in transmissibility to the sternum, but less consistent than in the apparent mass (Table 4). A similar pattern was also observed in the flat supine posture. However, with the constrained semi-supine posture, the transmissibility to the upper abdomen exhibited a less consistent nonlinearity than the transmissibility to the sternum (Table 4).

In all postures, the changes in the transmissibility to the upper abdomen were consistent with the primary peak frequency decreasing with increasing vibration magnitude. Changes in the phase of the transmissibility were consistent with changes in the modulus.

With the semi-supine posture, the primary peak frequency of the median transmissibility to the upper abdomen decreased from 7.03 to 6.25 Hz as the vibration magnitude increased from 0.0625 to 1.0 ms^{-2} rms, but the peak frequencies did not differ significantly at magnitudes less than 0.25 ms^{-2} rms (Fig. 11 UA).

With the flat supine posture, the primary peak frequency of the median transmissibility to the upper abdomen decreased from 7.81 to 6.25 Hz while the vibration magnitude increased from 0.0625 to 1.0 ms^{-2} rms, but the peak frequencies did not differ significantly at magnitudes less than 0.125 ms^{-2} rms (Fig. 11 UA).

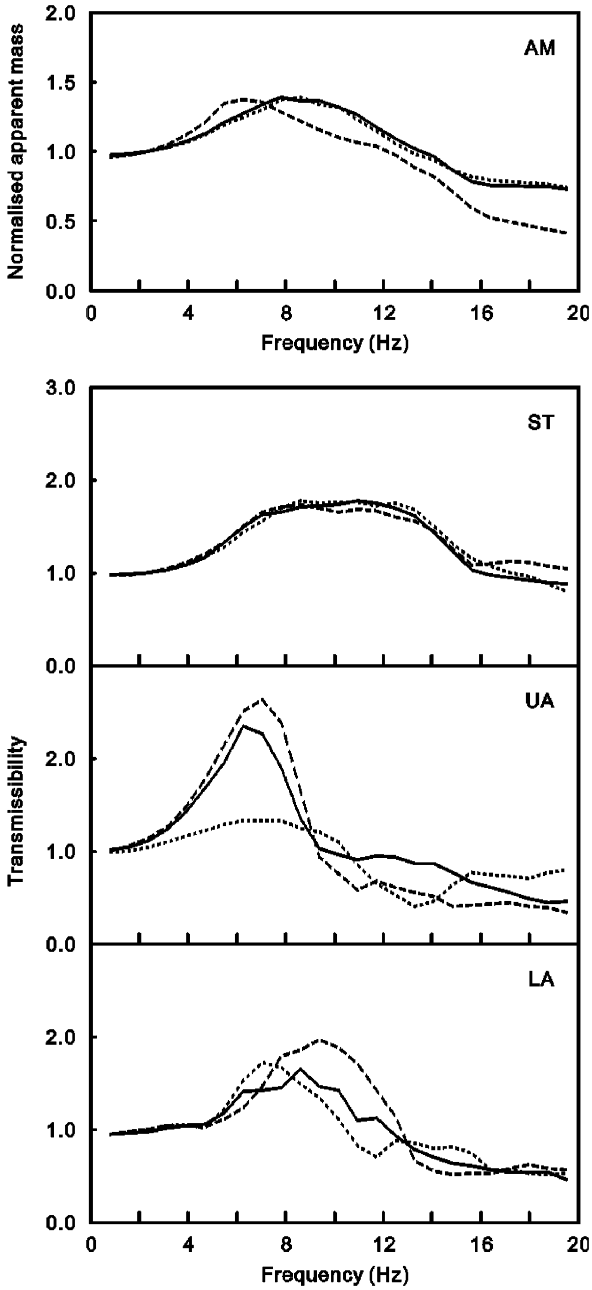

Fig. 8. Effect of supine posture: median normalised apparent mass (AM) and transmissibilities to the sternum (ST), the upper abdomen (UA), and the lower abdomen (LA) with the three supine postures (——— semi-supine; - - - - flat supine; …… constrained semi-supine) at the vibration magnitude of 0.5 ms^{-2} rms.

With the constrained semi-supine posture, the primary peak frequency of the median transmissibility to the upper abdomen decreased from 7.81 to 5.47 Hz as the vibration magnitude increased from 0.0625 to 1.0 ms^{-2} rms, but the peak frequencies did not differ significantly at magnitudes less than 0.25 ms^{-2} rms (Fig. 11 UA).

The individual (Fig. 10 UA) and median (Fig. 11 UA) transmissibility to the upper abdomen exhibited the characteristic nonlinearity in all postures, although not consistently so at the lowest vibration magnitudes. The statistical tests performed at the eight selected frequencies showed that in flat supine posture, where nonlinearity was found in the range 0.125–1.0 ms^{-2} rms, there was a more consistent nonlinearity than in the

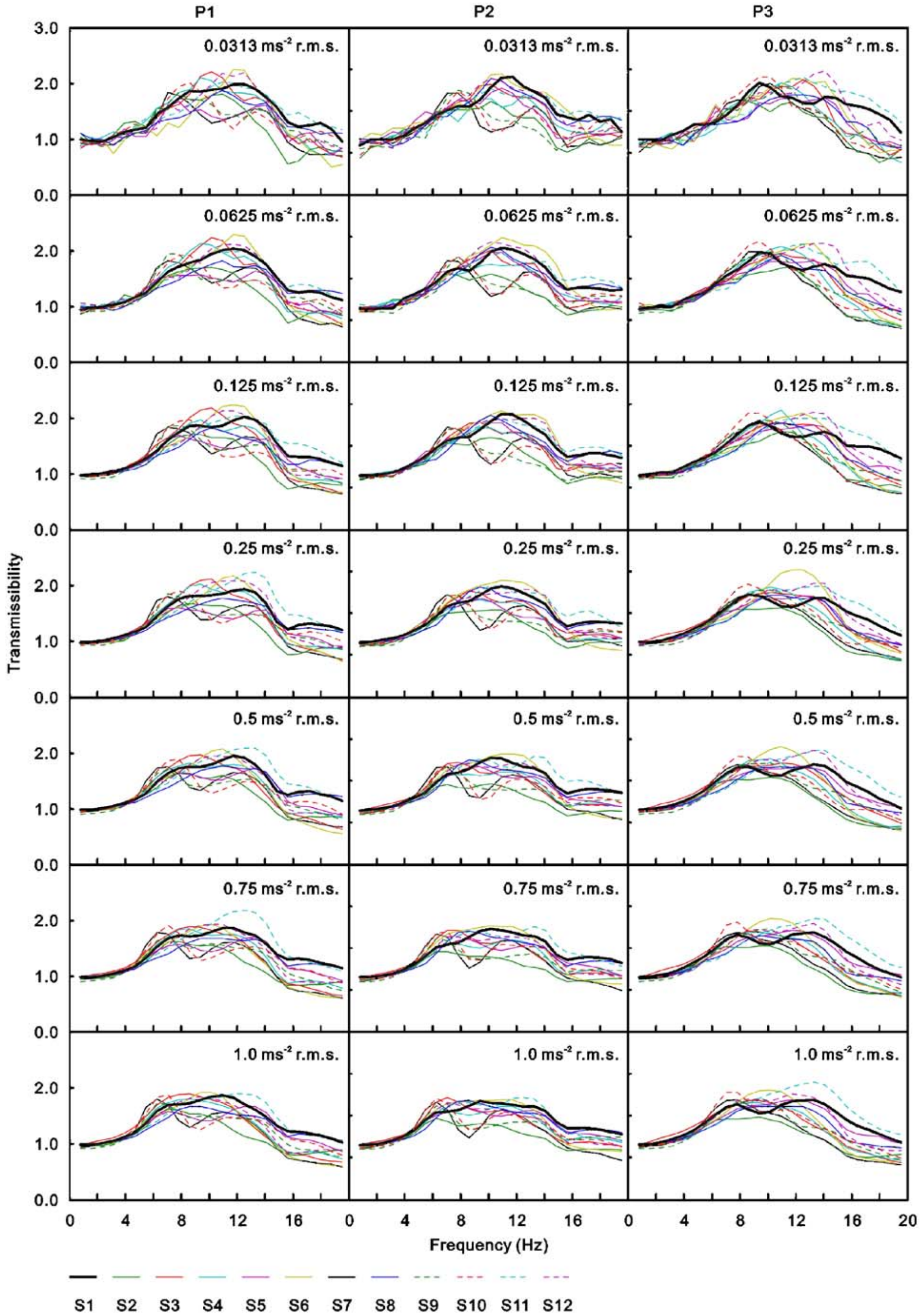

Fig. 9. Individual sternum transmissibility modulus with three supine postures (P1—semi-supine, P2—flat supine, P3—constrained semi-supine) at seven vibration magnitudes (MAG1—0.0313 ms^{-2} rms, MAG2—0.0625 ms^{-2} rms, MAG3—0.125 ms^{-2} rms, MAG4—0.25 ms^{-2} rms, MAG5—0. 5 ms^{-2} rms, MAG6—0.75 ms^{-2} rms, MAG7—1.0 ms^{-2} rms) of all 12 subjects (S1–S12).

semi-supine posture, where the nonlinearity was found from 0.25 to 1.0 ms^{-2} rms (Table 4). The nonlinearity was less consistent in the constrained semi-supine posture than in the semi-supine posture (Table 4).

The statistics indicate that the nonlinearity was less consistent in the transmissibility to the upper abdomen than in the apparent mass, and less consistent in the transmissibility to the sternum than in the transmissibility to the upper abdomen (Table 4).

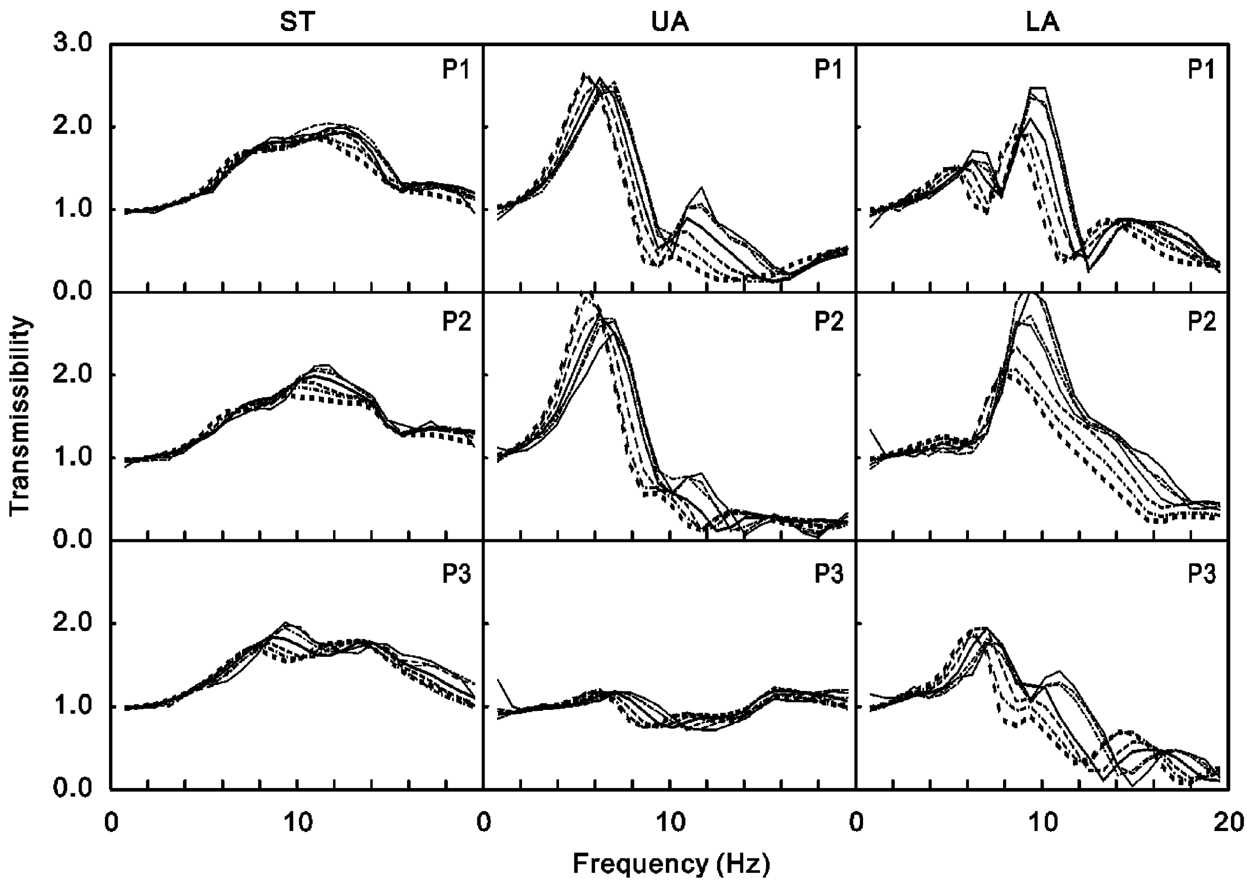

Fig. 10. Effect of vibration magnitude: transmissibilities to the sternum (ST), the upper abdomen (UA) and the lower abdomen (LA) of one subject (S1) with three supine postures (P1—semi-supine, P2—flat supine, P3—constrained semi-supine) at seven vibration magnitudes (——— $0.0313\,\mathrm{ms}^{-2}$ rms, — — — $0.0625\,\mathrm{ms}^{-2}$ rms, — · — · — $0.125\,\mathrm{ms}^{-2}$ rms, ——— $0.25\,\mathrm{ms}^{-2}$ rms, — — — $0.5\,\mathrm{ms}^{-2}$ rms, — · — · — $0.75\,\mathrm{ms}^{-2}$ rms, - - - - $1.0\,\mathrm{ms}^{-2}$ rms).

3.3.2. *Effect of posture*

The individual (Fig. 12) and median (Fig. 8 UA) transmissibility to the upper abdomen showed that the semi-supine posture and the flat supine posture had a similar primary peak frequency around 6–8 Hz, with the flat supine having a slightly higher primary peak and a less apparent secondary peak. The constrained semi-supine posture exhibited a highly damped resonance peak at a slightly higher frequency than the other two postures. The effect of posture was examined using the same posture statistical procedure used for the modulus and phase of the apparent mass, as demonstrated in Table 3. The statistics indicate that the effect of posture on transmissibility to the upper abdomen was greater than the effect of posture on transmissibility to the sternum (Table 5). Changing from semi-supine to flat supine had less effect on the transmissibility to the upper abdomen than on the apparent mass, whereas changing from semi-supine to constrained semi-supine had a greater effect on transmissibility to the upper abdomen than on the apparent mass.

3.4. *Transmissibility to the lower abdomen*

Similar to transmissibility to the upper abdomen, transmissibility to the lower abdomen showed greater inter-subject variability than transmissibility to the sternum (Fig. 13).

In all three postures, there were drops in coherency that depended on vibration magnitude similarly to the upper abdomen (Fig. 5 LA). The coherency drop occurred from 4 to 8 Hz and 10 to 13 Hz in the semi-supine

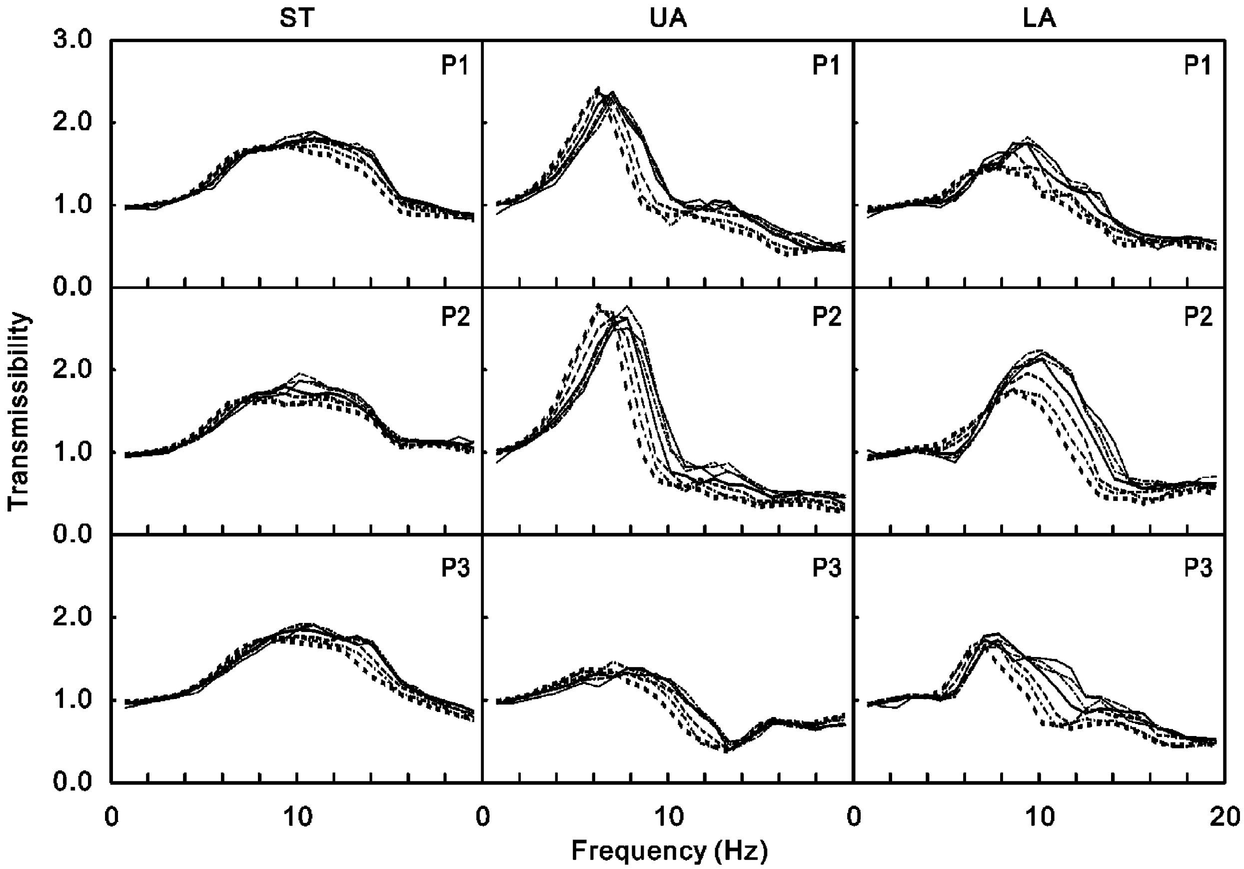

Fig. 11. Effect of vibration magnitude: median transmissibilities to the sternum (ST), the upper abdomen (UA) and the lower abdomen (LA) of the group of 12 subjects with three supine postures (P1—semi-supine, P2—flat supine, P3—constrained semi-supine) at seven vibration magnitudes (——— $0.0313\,\mathrm{ms^{-2}}$ rms, — — — $0.0625\,\mathrm{ms^{-2}}$ rms, — · — · — $0.125\,\mathrm{ms^{-2}}$ rms, ——— $0.25\,\mathrm{ms^{-2}}$ rms, — — — $0.5\,\mathrm{ms^{-2}}$ rms, — · — · — $0.75\,\mathrm{ms^{-2}}$ rms, - - - - $1.0\,\mathrm{ms^{-2}}$ rms).

Table 4
Number of significant differences in the modulus of the apparent mass (AM) and transmissibilities to the body (ST: sternum; UA: upper-abdomen; LA: lower abdomen) due to vibration magnitude in three supine postures—the total number of significant differences between pairs of adjacent magnitudes over eight frequencies (48 combinations, i.e. 6 adjacent magnitude pairs by 8 frequencies).

	Semi-supine (R)	Flat supine (F)	Constrained semi-supine (C)
AM	31/48	33/48	30/48
ST	13/48	17/48	22/48
UA	17/48	23/48	12/48
LA	15/48	26/48	17/48

posture, from 14 to 20 Hz in the flat supine posture, and from 12 to 16 and 18 to 20 Hz in the constrained semi-supine posture.

3.4.1. *Effect of vibration magnitude*

In all postures, individuals exhibited the typical nonlinearity at vibration magnitudes greater than $0.125\,\mathrm{ms^{-2}}$ rms. In the semi-supine and the flat supine postures, individuals showed a primary resonance peak at around 8–10 Hz. A typical individual response is shown for S1 in Fig. 10 LA.

Table 5
Number of significant differences in the modulus of the apparent mass (AM) and transmissibilities to the body (ST: sternum; UA: upper-abdomen; LA: lower abdomen) due to supine posture at seven vibration magnitudes—the total number of significant differences between the three postures at all seven vibration magnitudes over eight frequencies (56 combinations, i.e. 7 magnitudes by 8 frequencies).

	R–F	R–C	F–C
AM	48/56	21/56	45/56
ST	9/56	8/56	12/56
UA	20/56	31/56	30/56
LA	14/56	1/56	21/56

The effect of vibration magnitude was examined using the same statistical procedures described in Section 3.1.1 and shown in Table 2.

With the semi-supine posture, at frequencies lower than 7.03 Hz, the transmissibility modulus was greater with greater magnitudes of vibration, but only at magnitudes greater than 0.25 ms^{-2} rms ($p<0.05$, Wilcoxon). At frequencies greater than 8.59 Hz and vibration magnitudes greater than 0.125 ms^{-2} rms, the modulus was lower with greater magnitudes of vibration ($p<0.05$, Wilcoxon). Similar to the upper abdomen transmissibility, the nonlinearity in the transmissibility to the lower abdomen was more consistent than that to the sternum, but less consistent than in the apparent mass (Table 4).

In all postures, the changes in the transmissibility to the lower abdomen were consistent with the primary peak frequency decreasing with increasing vibration magnitude. Changes in the phase of the transmissibility were consistent with changes in the modulus.

With the semi-supine posture, the primary peak frequency in the median transmissibility decreased from 9.38 to 7.81 Hz as the vibration magnitude increased from 0.0625 to 1.0 ms^{-2} rms, but the peak frequencies did not differ significantly at magnitudes less than 0.25 ms^{-2} rms (Fig. 11 LA).

With the flat supine posture, the primary peak frequency in the median transmissibility decreased from 10.16 to 8.59 Hz as the vibration magnitude increased from 0.0625 to 1.0 ms^{-2} rms, but the peak frequencies did not differ significantly at magnitudes less than 0.125 ms^{-2} rms (Fig. 11 LA).

With the constrained semi-supine posture, the primary peak frequency in the median transmissibility changed from 7.81 to 7.03 Hz as the vibration magnitude increased from 0.0625 to 1.0 ms^{-2} rms, but the peak frequencies did not differ significantly at magnitudes less than 0.125 ms^{-2} rms (Fig. 11 LA).

The statistical tests at the eight selected frequencies also showed that the nonlinearity in the flat supine posture and the constrained semi-supine posture (where the nonlinearity was found from 0.125 to 1.0 ms^{-2} rms) was more consistent than in the semi-supine posture (where the nonlinearity was found from 0.25 to 1.0 ms^{-2} rms, Table 4).

3.4.2. *Effect of posture*

The individual (Fig. 13) and median (Fig. 8 LA) transmissibility to the lower abdomen showed that the semi-supine and the flat supine postures had a similar primary peak frequency around 8–10 Hz; the flat supine posture had a slightly higher primary peak and a less apparent secondary peak. The constrained semi-supine posture exhibited a lower resonance peak at a slightly lower frequency (around 6–8 Hz) than the other two postures. The effect of posture on the modulus and phase of the transmissibility was investigated using the same statistical procedure described in Table 3. The difference in the transmissibility to the upper abdomen between the flat supine posture and the semi-supine posture was greater than the difference in the transmissibility to the lower abdomen between the two postures (Table 5). Similar to the transmissibility to the upper abdomen, the nonlinearity in transmissibility to the lower abdomen was less consistent than in the apparent mass, but more consistent than that in the transmissibility to the sternum. Unlike its effect on transmissibility to the upper abdomen, the constrained semi-supine posture had little effect on transmissibility to the lower abdomen.

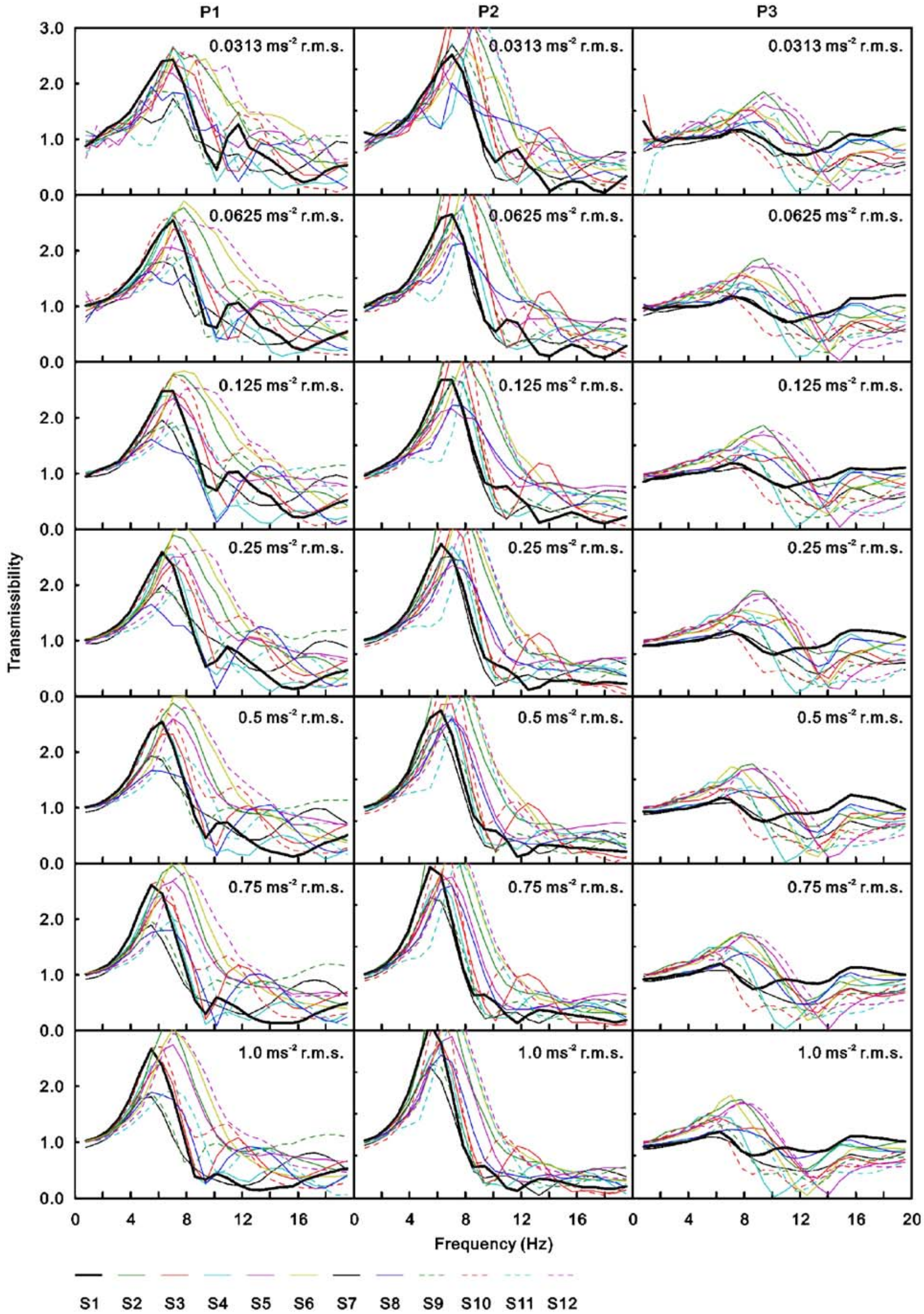

Fig. 12. Individual upper abdomen transmissibility modulus with three supine postures (P1—semi-supine, P2—flat supine, P3—constrained semi-supine) at seven vibration magnitudes (MAG1—0.0313 ms^{-2} rms, MAG2—0.0625 ms^{-2} rms, MAG3—0.125 ms^{-2} rms, MAG4—0.25 ms^{-2} rms, MAG5—0.5 ms^{-2} rms, MAG6—0.75 ms^{-2} rms, MAG7—1.0 ms^{-2} rms) of all 12 subjects (S1–S12).

4. Discussion

4.1. Coherency

The coherency associated with the transmissibilities to the upper and lower abdomen varied systematically with frequency, with a clear drop in coherency at a frequency that decreased with increasing vibration

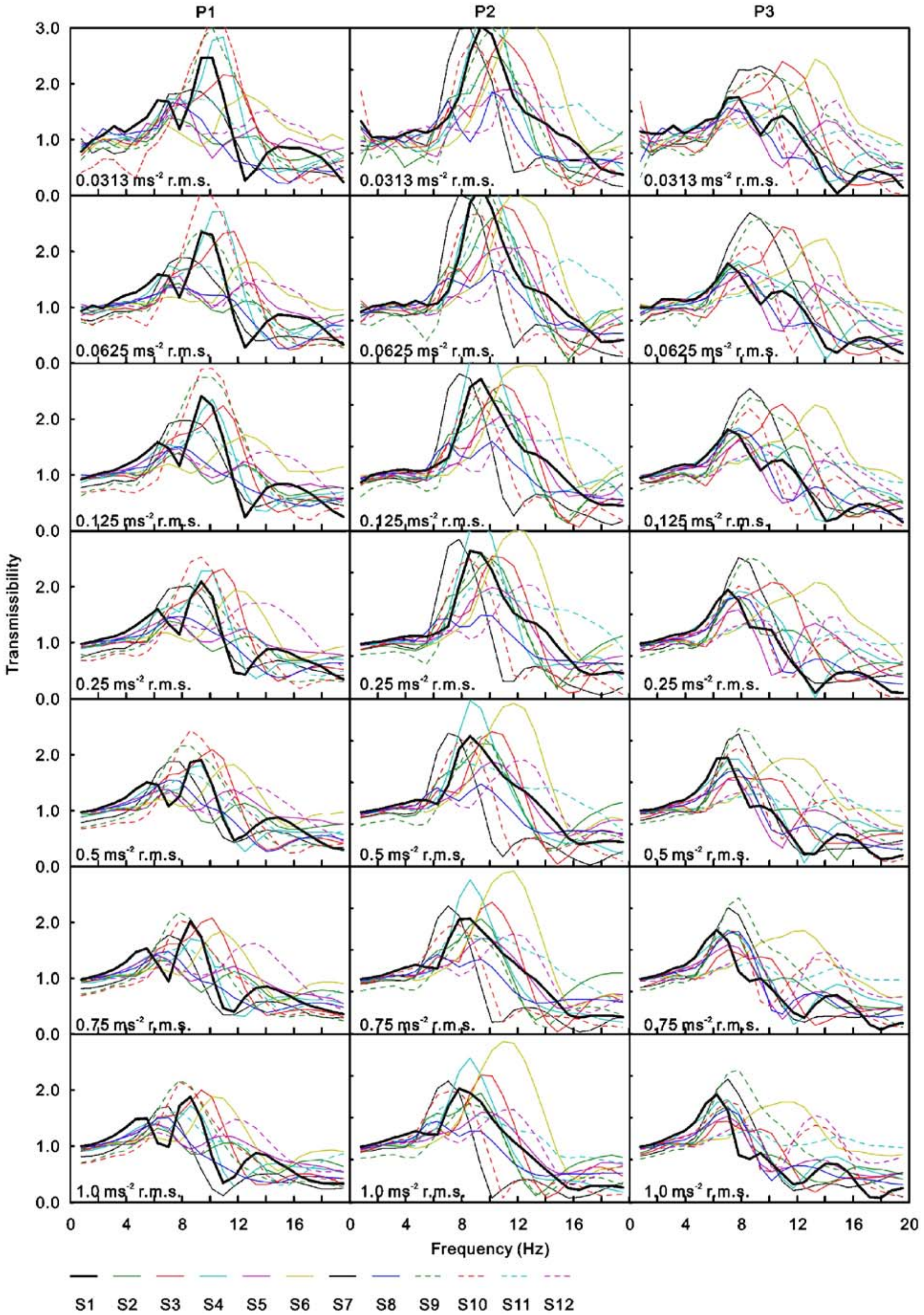

Fig. 13. Individual lower abdomen transmissibility modulus with three supine postures (P1—semi-supine, P2—flat supine, P3—constrained semi-supine) at seven vibration magnitudes (MAG1—0.0313 ms^{-2} rms, MAG2—0.0625 ms^{-2} rms, MAG3—0.125 ms^{-2} rms, MAG4—0.25 ms^{-2} rms, MAG5—0.5 ms^{-2} rms, MAG6—0.75 ms^{-2} rms, MAG7—1.0 ms^{-2} rms) of all 12 subjects (S1–S12).

magnitude (Fig. 5). Similar drops in coherency have been seen in the longitudinal (i.e. horizontal, foot-to-head) apparent masses of subjects in the same relaxed semi-supine posture over the frequency range 6–20 Hz [5]. The authors attributed the drop in coherency to low forces at the back at the frequencies of the coherency drop. Decreases in the coherencies of the transmissibilities to the abdomen in the present study are consistent with either noise or the nonlinearity of soft tissues reducing coherency at frequencies where there is low transmissibility to the abdomen, as seen in the coherencies in Fig. 5 UA and LA and the transmissibilities in Fig. 10 UA and LA.

4.2. Effect of posture

4.2.1. Effect of changes in posture on apparent mass

Changing from the semi-supine posture to the flat supine posture decreased the primary resonance frequency of the apparent mass (Fig. 8). Although nonlinearity was found in both postures (Fig. 7), the 'semi-supine' posture with raised lower legs and less soft tissue contact between the body and the vibrating support exhibited slightly less nonlinearity than the 'flat supine' posture (Table 4). This is consistent with reduced nonlinearity in seated subjects with reduced thigh contact with a seat when varying footrest-height [16].

In the semi-supine subjects, any effect of the constraining harness on the apparent mass was small (Fig. 8). In seated subjects, an 'elastic belt' to constrain the abdomen had little effect on the apparent mass resonance frequency with a vibration magnitude of 1.0 ms^{-2} rms and only small effects with 0.2 and 2.0 ms^{-2} rms [14]. Similar to the present study, the constraining belt did not change the nonlinearity in the apparent mass resonance frequency, possibly because in seated subjects the soft tissues between the body and the vibration source (i.e. buttocks) are unchanged by a belt, and in semi-supine subjects the soft tissues in the back and in the body (i.e. viscera and abdomen) were unchanged by the harness.

4.2.2. Effect of changes in posture on transmissibilities

Changes to the supine posture had less effect on transmissibility to the sternum than on transmissibility to the abdomen and the apparent mass (Fig. 11 and Table 5). It seems that changing leg posture and constraints altered the response of soft tissues or the response of joints between the thighs, pelvis, and lower spine, with little change in the transmission to the sternum.

In Fig. 8, the transmissibility to the upper abdomen shows a large difference between the semi-supine posture and the constrained semi-supine posture. Since the apparent mass was similar in the semi-supine posture and the constrained semi-supine, this change in transmissibility was probably caused by the constraining harness compressing tissues near the accelerometer on the upper abdomen.

In the semi-supine posture, the constraint provided by the harness appeared to increase nonlinearity in the transmissibility of vibration to the sternum (13 significant differences in 48 comparisons for the unconstrained posture, compared to 22 significant differences in 48 comparisons for the constrained semi-supine posture, Table 4 and Fig. 10). In contrast, the harness appeared to reduce nonlinearity in the transmissibility to the upper abdomen (17 significant differences in 48 comparisons for the unconstrained posture compared with 12 significant differences in 48 comparisons for the constrained posture). These statistics depend on the precision with which the resonance frequencies could be determined, and this varied between conditions, but this does not seem to be a sufficient explanation of the changes in nonlinearity associated with the harness. In the constrained semi-supine posture, the greater nonlinearity to the sternum may have been caused by the harness increasing the influence of local movement of soft tissues on the motion of the sternum (i.e. the harness increased the coupling between the soft tissues and the sternum). The reduction in the nonlinearity to the upper abdomen may have been caused by the harness reducing the local movement of the soft tissues of the upper abdomen (as apparent in the transmissibilities shown in Figs. 8 and 10). Such an involvement of soft tissues in the nonlinearity of the apparent mass and the transmissibility of the body appears to be consistent with that reported for seated subjects (e.g. [3]).

4.3. Effect of vibration magnitude

4.3.1. Effect of vibration magnitude on the nonlinearity

Nonlinearities in the apparent mass and transmissibilities were generally statistically significant at vibration magnitudes greater than 0.125 ms^{-2} rms, but not consistently significant at the lower magnitudes (i.e. 0.0313, 0.0625, 0.125 ms^{-2} rms, see Table 2, Figs. 6 and 10). Less nonlinearity at the low magnitudes (less than 0.125 ms^{-2} rms in the present study) may seem inconsistent with greater variation in the apparent mass resonance frequency at low magnitudes (i.e. 0.25 ms^{-2} rms) when seated subjects make voluntary upper-body movements [12]. If the nonlinearity is caused by either thixotropy or muscle activity, one or other of these mechanisms should be capable of explaining these findings.

For passive thixotropy to cause the nonlinearity, there must be lower limit to the range of magnitudes over which the structure of body tissues is 'broken down' or 'softened' by movement. In the relaxed semi-supine body it appears the limit is around 0.125 ms^{-2} rms for the bandwidth of vertical vibration studied here. In an upright sitting posture, more soft tissues (e.g. in the thighs and buttocks) may be involved than when the body is in a semi-supine posture. Furthermore, the seated body appears to amplify low frequency movements more than the supine body (compare Fig. 7 in this paper with Fig. 4A in Ref. [12]). The voluntary periodic bending of the upper-bodies of seated subjects may have increased the movement within their body sufficiently for vibration at magnitudes less than 0.25 ms^{-2} rms to reduce the equivalent stiffness of body.

For either voluntary or involuntary muscle activity to cause the observed nonlinearity there must be sufficient variation in muscle activity to influence the effective stiffness of the body over the range of vibration magnitudes where the nonlinearity occurred. In a semi-supine posture, there is no requirement for either voluntary or involuntary muscle activity to maintain posture during vibration and it may be assumed that both are, at least, reduced relative to an upright sitting posture. For any involuntary phasic muscle activity induced by vibration, there will be vibration magnitude below which the muscles are not activated and, perhaps, a variation in the form and extent of the muscle activity as the vibration magnitude increases [18,19]. Such changes in muscle activity may seem plausible explanations of the nonlinearity observed in an upright seated posture where a variety of muscles are activated and could influence body motion (e.g. the spinae erector, multifidus, and abdominal muscles). However, in the supine postures studied here, it seems unlikely that there was either sufficient muscle activity, or sufficient variations in muscle activity, to explain the nonlinearity observed.

4.3.2. Contribution of soft tissues to the nonlinearity

With seated and standing subjects, nonlinearity has been found in transmissibilities to the pelvis and locations along the spine (e.g. [1–3]) as well as in the apparent mass. The primary resonance of seated subjects is associated with rocking of the upper-body on the buttocks with bending and rotational motions of the spine in the mid-sagittal plane (e.g. [1,6]).

With supine subjects, there is also nonlinearity in transmissibility and apparent mass, but the nonlinearity in transmissibility to the sternum is less than the nonlinearity in transmissibility to the upper and lower abdomen and also less than the nonlinearity in the apparent mass. The resonance of supine subjects may involve broadly similar mechanisms to those in seated subjects: the entire skeletal structure and internal organs supported on superficial tissues of the back move in the direction of excitation. Transmission of vibration to the spine and pelvis of a seated subject, and to the abdomen of a supine subject, involves more soft tissue (e.g. the buttocks when seated and the viscera and abdomen when supine) than transmission to the sternum of a supine subject. The main transmission path to the sternum of a supine subject is via tissues beneath the recumbent spine, although there may be interaction with soft tissues within the rib cage and the abdomen. Less nonlinearity at the sternum than at the abdomen would be consistent with soft tissues causing the nonlinearity.

4.3.3. Thixotropy hypothesis

The nonlinear softening apparently associated with the soft tissues could be caused by thixotropy. Changes in the resonance frequency of the apparent mass of the relaxed supine body immediately after exposure to high magnitude and low magnitude vibration are small but apparently characteristic of thixotropy [4]. The dynamic properties of the body may be assumed to be influenced by the movement of soft tissues that account for most of the body mass and not only by the movement of joints. The movement of joints can be affected by muscular activity, but the movement of soft tissues (including relaxed muscles) is unlikely to be affected by muscle activity in the relaxed supine postures investigated here. Soft tissues will have little influence on the primary transmission path to the sternum but the coupling of the sternum to the soft tissues of the body will allow their nonlinear response to have a small influence on transmission of vibration to the sternum. The varying degrees of nonlinearity found in the apparent mass of the supine body and transmissibilities to the sternum and abdomen seem consistent with the thixotropy of soft tissues being the primary cause of the nonlinear softening of the body apparent with increasing magnitudes of vibration.

4.3.4. Muscle activity hypothesis

The supine postures in the present study were designed to minimise the need for voluntary muscular activity. However, it may seem plausible for involuntary muscle activity to have influenced the transmission of vibration, with a greater influence on transmissibility to the abdomen than to the sternum. This might occur if there was phasic muscular activity having a different influence at low and high magnitudes of vibration—the timing of phasic muscular activity may vary with vibration magnitude such that the peak force occurs at different times during high and low magnitudes of vibration, as contemplated by Huang and Griffin [12]. The responses shown in Figs. 10 and 11, and the associated statistical analyses reported in Table 4, do not eliminate the possibility that muscle activity may influence in some unknown way the apparent masses and transmissibilities and their nonlinearities.

4.3.5. The evidence favours the thixotropy hypothesis

Although involuntary reflex activity of muscles may contribute to nonlinearity, the evidence with seated, standing, and supine subjects is more easily explained by passive thixotropy. The principal resonances in the apparent masses of seated, standing, and supine subjects seem to be associated with movement in the soft tissues at the subject-excitation interface. A nonlinear response of the soft tissues at the interfaces would be sufficient to cause a nonlinearity that is most apparent at resonance. The nonlinearity has been found in both the vertical and fore-and-aft responses of subjects in various sitting postures during both vertical and fore-and-aft excitation (e.g. [11,16,20]), in the vertical and fore-and-aft responses of subjects standing in various postures during vertical excitation (e.g. [15,21]), and in the vertical and longitudinal responses of subject lying in relaxed semi-supine postures during vertical and longitudinal excitation [4,5]. In seated subjects, voluntary or involuntary muscular activity along the spine could affect the response of the body and cause a nonlinearity. With various standing conditions, such as with the knees straight and locked, bent, standing on one leg, with an anterior lean or a lordotic posture, the nonlinearity has been consistently found in the apparent mass and transmissibilities to the spinal column, pelvis, and knee [15,21,22]. The results of these studies with standing subjects would be consistent with some nonlinearity in response at the soles of the feet. The soles of the feet are unlikely to have muscular activity sufficient to greatly alter responses to vertical vibration [21]. Similarly, in the present study, tissues at the backs of the supine subjects were unlikely to influence the dynamic forces and motions transmitted to the sternum by muscular activity.

A thixotropic characteristic has been reported in a wide range of human tissues, protoplasm, and mucus (e.g. [23]) and so it seems likely that thixotropy will be present and cause nonlinearity to some degree. The nature of thixotropy is such that it allows perturbations to break down structures but after a period of stillness the structures reform [24]. After Lakie [8] reported a softening effect of the relaxed human finger with increasing vibratory excitations, thixotropy has been used to describe this dynamic property of human tissues. Thixotropy will cause a softening effect with increasing vibration magnitude and a lowering of resonance frequencies, as observed with a wide range of vibratory excitations of the body. For muscle activity to cause the nonlinearity there must be muscles capable of controlling a significant portion of body mass and body movement, the forces contributed by the muscles must change in an appropriate way with increasing vibration magnitude. For tonic muscle activity to cause the observed nonlinearity, the forces caused by tonic muscular contraction must decrease with increasing vibration magnitude, but this is not evident in those studies that have measured muscle activity during vibration (e.g. [18,19]). For phasic muscle activity to cause the observed nonlinearity, the contractions must change in magnitude or phase such that they always reduce the overall stiffness of the body with increasing vibration magnitude. Since different muscles would be involved in the different postures and directions of excitation, and phasic muscle activity will depend on the excitation, it seems unlikely that muscle activity would always reduce stiffness and not sometimes increase stiffness with increasing vibration magnitude. Since many more assumptions are required to explain the nonlinearity by muscle activity than by thixotropy, it seems more likely that the principal nonlinearity seen in many biodynamic measurements is primarily caused by thixotropy.

5. Conclusions

With a semi-supine posture, a flat supine posture, and a constrained semi-supine posture, the apparent mass resonance frequency and the primary peak frequencies in transmissibilities to the upper and lower abdomen decrease with increasing magnitude of vertical vibration from 0.25 to 1.0 ms^{-2} rms. The nonlinearity is less evident at vibration magnitudes less than 0.125 ms^{-2} rms.

The nonlinearity was more apparent in a flat supine posture than a semi-supine posture, suggesting that supporting soft tissues contributed to the nonlinearity.

Although involuntary reflex muscular activity may contribute to nonlinearity in the biodynamic responses of the body, the thixotropy of soft tissues is more likely to be the primary cause of nonlinearity.

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