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EFFECT OF MUSCLE TENSION ON NON-LINEARITIES IN THE APPARENT MASSES OF SEATED SUBJECTS EXPOSED TO VERTICAL WHOLE-BODY VIBRATION

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In subjects exposed to whole-body vibration, the cause of non-linear dynamic characteristics with changes in vibration magnitude is not understood. The effect of muscle tension on the non-linearity in apparent mass has been investigated in this study. Eight seated male subjects were exposed to random and sinusoidal vertical vibration at five magnitudes (0·35–1·4 m/s^2 r.m.s.). The random vibration was presented for 60 s over the frequency range 2·0–20 Hz; the sinusoidal vibration was presented for 10 s at five frequencies (3·15, 4·0, 5·0, 6·3 and 8·0 Hz). Three sitting conditions were adopted such that, in two conditions, muscle tension in the buttocks and the abdomen was controlled. It was assumed that, in these two conditions, involuntary changes in muscle tension would be minimized. The force and acceleration at the seat surface were used to obtain apparent masses of subjects. With both sinusoidal and random vibration, there was statistical support for the hypothesis that non-linear characteristics were less clear when muscle tension in the buttocks and the abdomen was controlled. With increases in the magnitude of random vibration from 0·35 to 1·4 m/s^2 r.m.s., the apparent mass resonance frequency decreased from 5·25 to 4·25 Hz with normal muscle tension, from 5·0 to 4·38 Hz with the buttocks muscles tensed, and from 5·13 to 4·5 Hz with the abdominal muscles tensed. Involuntary changes in muscle tension during whole-body vibration may be partly responsible for non-linear biodynamic responses.

1. INTRODUCTION

Non-linear responses of the human body exposed to vertical whole-body vibration at different magnitudes have been observed in various studies, including Hinz and Seidel [1], Fairley and Griffin [2], Mansfield and Griffin [3] and Matsumoto and Griffin [4, 5]. A consistent finding is a decrease in the principal resonance frequency of response functions (i.e., driving-point responses and transmissibilities) with increases in vibration magnitude.

With sinusoidal vibrations at two vibration magnitudes (1·5 and 3·0 m/s^2 r.m.s.), Hinz and Seidel [1] reported a non-linear characteristic in apparent mass and transmissibilities to the head, the shoulder and the upper trunk with four seated subjects. With successive increases in vibration magnitude (0·25, 0·5, 1·0 and 2·0 m/s^2 r.m.s.), Fairley and Griffin [2] found decreases in the lowest resonance frequency of the apparent mass for all of the eight seated subjects exposed to random vibration over the frequency range 0·25–20 Hz. It was reported that the mean resonance frequency decreased from 6 to 4 Hz with an increase in vibration magnitude from 0·25 to 2·0 m/s^2 r.m.s. A smaller change (from 5·4 Hz at 0·25 m/s^2 r.m.s. to 4·2 Hz at 2·5 m/s^2 r.m.s.) was found by Mansfield and Griffin [3] with 12 seated subjects exposed to random vibration over the frequency range 0·2–20 Hz. Fairley and Griffin [2] and Mansfield and Griffin [3] also observed that a second resonance in the apparent mass in the range 8–12 Hz also reduced in frequency with increased vibration magnitude. Mansfield and Griffin [3] and Matsumoto and Griffin [4] reported clear peaks in the transmission of vertical seat vibration to the head, the spine and the pelvis in the vertical, fore-and-aft and pitch axes with significant decreases in the frequency of the peaks with increases in vibration magnitude. Similar non-linear characteristics in apparent mass and transmissibility have been observed with standing subjects by Matsumoto and Griffin [5].

Although there have been consistent findings about the nature of the non-linearity, the cause is not understood. Possible causes include changes in posture, the geometry of the body, changes in muscle activity, and non-linear mechanical properties of the soft tissues.

Voluntary changes in posture have been reported to cause a change in the dynamic responses of the body, including shift in the resonance frequency [2]. Mansfield and Griffin [6] investigated whether the non-linearity in the apparent mass was affected by voluntary changes in posture and found that the resonance frequency decreased with increased vibration magnitude in all sitting postures investigated.

Mathematical models of the seated body developed by Kitazaki and Griffin [7] and Matsumoto and Griffin [8] suggest that during whole-body vertical motion the deformation of the tissues beneath the ischial tuberosities and the motion of the viscera contribute to the principal resonance of the apparent mass, with a minor contribution from bending or buckling of the vertebral column. According to these models, the geometry of the body will have a minor influence on the non-linearity observed at the principal resonance of the apparent mass.

The mathematical modelling studies [7, 8] suggest that a non-linear mechanism affecting the soft tissues (including the muscles) may cause the observed non-linearities. There are various possible non-linear mechanisms in the soft tissues and muscles, such as non-linear mechanical properties and voluntary muscle control. Involuntary muscle activity during vibration exposure could also be responsible for non-linearities in the biodynamic responses. Robertson and Griffin [9] reported, as part of a larger study, that tonic and phasic erectores spinae muscle activity in seated subjects changed over initial periods of vibration exposure. Pope *et al.* [10], originally Seroussi *et al.* [11], reported that the tonic activity of the erectores spinae muscle increased when a subject was exposed to vibration, compared to a static condition. The effect of muscle tension on apparent mass was investigated in this study.

2. METHOD AND ANALYSIS

An experiment has been conducted with eight male subjects (staff and students) in a laboratory of the Institute of Sound and Vibration Research at the University of Southampton. The characteristics of the subjects are summarized in Table 1. The experiment was approved by the Human Experimentation Safety and Ethics Committee in the Institute of Sound and Vibration Research.

TABLE 1

Characteristics of subjects

	Age	Height (m)	Weight (kg)
Median	31·5	1·79	73
Minimum	23	1·70	64
Maximum	44	1·85	87

An electro-dynamic shaker, Derritron VP180, was used to produce vibration. Subjects were exposed to random and sinusoidal vibration in the vertical axis at five magnitudes: 0·35, 0·5, 0·7, 1·0 and 1·4 m/s^2 r.m.s. Random vibration over the range 2·0–20 Hz was presented for 60 s; sinusoidal vibration was presented at 3·15, 4·0, 5·0, 6·3 and 8·0 Hz for periods of 10 s. For both the random vibration and the sinusoidal vibrations, the first and the last 0·5 s were tapered by multiplying the signals by a quarter cycle of a sinusoidal function so as to prevent exposing subjects to a sudden change of acceleration. The subjects sat on a force platform, Kistler 9281B, secured to the shaker so as to measure the force at the interface between the seat and subjects in the vertical and fore-and-aft axes. The seat acceleration was also measured in the vertical and fore-and-aft axes with accelerometers, Entran EGCSY-240*-10 and Entran EGA-125F*-10D. The basicentric axes of the human body in a seated position were used as defined in ISO 2631-1 [12]. Force and acceleration were digitized at 256 samples per second after low-pass filtering at 25 Hz.

Subjects were instructed to sit in three different ways: (1) comfortable, upright posture with normal muscle tension (Condition 1), (2) with the muscles of the buttocks tensed, or stiffened, as much as possible (Condition 2), and (3) with the volume of the abdomen minimized (Condition 3). Their feet were supported by a stationary footrest. Written instructions (see Appendix A) were supplemented by oral instructions prior to the commencement of the experiment. The experimenter observed no obvious postural change between the three sitting conditions.

It was assumed that, in the second and the third sitting condition, there would be a minimum of involuntary changes in muscle tension, if maximum voluntary muscle tension was maintained irrespective of the vibration: with maximum muscle tension maintained at different vibration magnitudes, it was assumed that the effect of involuntary changes in muscle tension would be reduced. The muscles in the two regions in the body were selected because these parts of the body appeared to be responsible for the principal resonance of the apparent mass in previous studies [7, 8]. In Condition 3, it was expected that the movement of the viscera would be restricted when the volume of the abdominal cavity was minimized. It was hypothesized that in the first condition, muscle tension would contribute to the apparent mass resonance, change involuntarily during exposure to vibration, and depend on vibration magnitude.

The order of the three sitting conditions within an experimental session was randomized among subjects. Within each sitting condition, the presentation of random and sinusoidal vibration was in a random order and differed between subjects.

The apparent mass was calculated by the cross-spectral density method for random vibration:

$$M(f) = S_{af}(f)/S_a(f), \tag{1}$$

where $M(f)$ is the apparent mass, $S_{af}(f)$ is the cross spectral density function between the vertical seat acceleration and the force at the seat surface (in either the vertical axis or the fore-and-aft axis), and $S_a(f)$ is the power-spectral density function of the vertical seat acceleration. In the calculation of the apparent mass, the square root of the ratio of the power-spectral densities gives the relation between two signals including any non-linear effect, including noise. The apparent masses calculated using the cross-spectral density method were almost identical to the apparent masses obtained by the power-spectral density method in the vertical direction, although the results are not presented in this paper. For the apparent mass obtained with force in the fore-and-aft axis (see below), the values obtained by the two methods differed by less than 10% at frequencies < 5 Hz for most subjects. The differences between the two methods were smaller at higher frequencies. The cross-spectral density method has the advantage of providing the phase relationship between the two signals. The apparent mass measured without a subject was subtracted from the apparent masses calculated by equation (1) so that the effect of the mass of the top plate on the force platform was eliminated.

For sinusoidal vibration, the apparent mass was calculated by the ratio of r.m.s. values of the vertical seat acceleration and of the force at the seat surface in the vertical axis (or in the fore-and-aft axis):

$$M_f = F_{f,r.m.s.}/A_{f,r.m.s.}, \tag{2}$$

where M_f is the apparent mass at f (Hz), $F_{f,r.m.s.}$ is the r.m.s. value of the force at the seat surface in the vertical axis (or in the fore-and-aft axis) at f (Hz), and $A_{f,r.m.s.}$ is the r.m.s. value of the vertical seat acceleration at f (Hz). The product of the mass of the top plate of the force platform and the seat acceleration in the vertical axis (or in the fore-and-aft axis) was subtracted from the force signal recorded so as to cancel the force due to the top plate of the force platform. The phase of the apparent mass was calculated from the maximum point in the cross-correlation function between the force at the seat surface and the vertical seat acceleration. The apparent mass and phase were calculated using the above method for each cycle of sinusoidal vibration in order to investigate the effect of time during exposure. When investigating changes in muscle activity over initial cycles of vibration, the apparent mass and phase have been previously calculated using the above method with sinusoidal vibration to investigate the effect of duration of exposure [9].

With both random and sinusoidal vibration, the median normalized apparent masses of the subjects were calculated from their individual normalized apparent masses obtained by dividing the apparent mass by the static weight of each subject.

3. RESULTS

3.1. APPARENT MASS WITH SINUSOIDAL VIBRATION

Figure 1 shows the median normalized apparent masses and phases with sinusoidal vibration for each of the three sitting conditions. The frequency of the peak of the apparent mass tended to decrease with increases in vibration magnitude when subjects sat in the comfortable upright posture with normal muscle tension (i.e., Condition 1). A significant change in the frequency of the peak of the apparent mass was only found for Condition 1: between 0·35 and 1·4 m/s^2 r.m.s., 0·5 and 1·4 m/s^2 and 0·7 and 1·4 m/s^2 r.m.s. ($p < 0{\cdot}05$, Wilcoxon matched-pairs signed ranks test, see Table 2). The effect of vibration magnitude on the apparent mass at the peak frequency was not statistically significant within any of the three experimental conditions used ($p > 0{\cdot}1$, Friedman two-way analysis of variance by ranks).

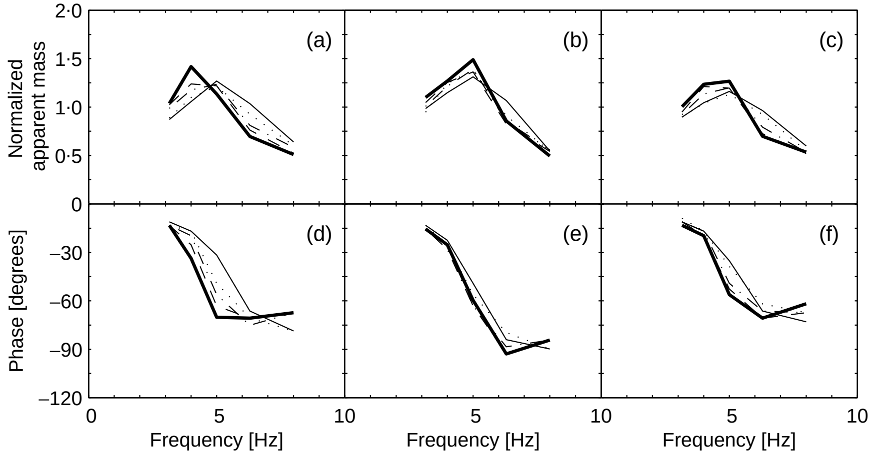

Figure 1. Median apparent masses and phases of eight subjects measured with sinusoidal vibration at five frequencies and five magnitudes with three postures. (a and d) Condition 1, (b and e) Condition 2, (c and f) Condition 3: ——, 0·35 m/s^2 r.m.s.; --------, 0·5 m/s^2 r.m.s.; – – –, 0·7 m/s^2 r.m.s.; — —, 1·0 m/s^2 r.m.s.; ——, 1·4 m/s^2 r.m.s.

TABLE 2

Statistical significance of differences between peak frequencies of apparent mass with sinusoidal vibration at various vibration magnitudes for each sitting condition. Wilcoxon matched-pairs signed ranks test

Vibration magnitude (m/s^2 r.m.s.)	0·35	0·5	0·7	1·0	1·4
(*a*) *Condition* 1 (*comfortable*, *upright*)					
0·35	—	0·317	0·317	0·102	0·020*
0·5		—	0·180	0·063	0·014*
0·7			—	0·180	0·034*
1·0				—	0·083
1·4					—
(*b*) *Condition* 2 (*buttocks muscles tensed*)					
0·35	—	0·180	0·102	0·102	0·180
0·5		—	0·317	0·317	1·000
0·7			—	1·000	0·317
1·0				—	0·317
1·4					—
(*c*) *Condition* 3 (*abdominal muscles tensed*)					
0·35	—	0·317	0·276	0·276	0·655
0·5		—	0·083	0·083	0·157
0·7			—	1·000	0·317
1·0				—	0·317
1·4					—

* $p < 0{\cdot}05$.

With the wide gap between the frequencies of the sinusoidal vibrations, the peak frequency of the apparent mass may not accurately represent the resonance. Therefore, at each of the five frequencies, the apparent masses at each magnitude were compared (see Table 3). If the non-linear characteristic observed here and in previous studies (e.g. reference [3])

Table 3

Statistically significant differences in apparent mass measured with sinusoidal vibration at different vibration magnitudes at each frequency for three sitting conditions

	3·15 Hz	4·0 Hz	5·0 Hz	6·3 Hz	8·0 Hz	Number of statistically significant differences
Condition 1	M1–M2 M1–M3 M1–M4 M1–M5 M2–M3 M2–M4 M2–M5	M1–M3 M1–M4 M1–M5 M2–M4 M2–M5	M3–M5*	M1–M2* M1–M3* M1–M4* M1–M5* M2–M3* M2–M4* M2–M5* M3–M4* M3–M5* M4–M5*	M1–M4* M1–M5* M2–M4* M2–M5* M3–M5*	28/50
Condition 2	M1–M4 M1–M5 M2–M4 M3–M4	M1–M3 M1–M4	None	M1–M4* M1–M5*	M1–M4* M1–M5* M2–M4* M2–M5* M4–M5*	13/50
Condition 3	M1–M5 M2–M5 M3–M5	M1–M3 M1–M4 M1–M5 M2–M4 M2–M5	None	M1–M3* M1–M4* M1–M5* M2–M4* M2–M5* M3–M5*	M1–M2* M1–M3* M1–M4* M1–M5* M2–M3* M2–M4* M2–M5*	21/50

Note: Wilcoxon matched-pairs signed ranks test at $p < 0{\cdot}05$. M1: 0·35 m/s^2 r.m.s.; M2: 0·5 m/s^2 r.m.s.; M3: 0·7 m/s^2 r.m.s.; M4: 1·0 m/s^2 r.m.s.; M5: 1·4 m/s^2 r.m.s.

*The apparent mass at the magnitude appearing first was greater than the apparent mass at the magnitude appearing second.

The right-hand column presents the number of pairs showing a statistically significant difference, with a maximum of 50 pairs.

is present, the apparent mass at a higher vibration magnitude tends to be greater than that at lower vibration magnitude at frequencies less than the peak frequency; at frequencies greater than the peak frequency, the apparent mass at a higher vibration magnitude tends to be less than that at a lower vibration magnitude. At frequencies between 3·15 and 6·3 Hz, this trend was most frequently statistically significant in Condition 1 and least frequently significant in Condition 2 (Table 3). At 8 Hz, this non-linear trend occurred equally in all three conditions.

Smaller changes in the phase of the apparent mass over the five vibration magnitudes were observed with the buttocks muscles tensed (Condition 2) than with the comfortable upright posture and a normal muscle tension (Condition 1) (Figures 1(d) and 1(e)). Statistically significant differences in the phases between various vibration magnitudes were most frequently found in Condition 1, less often in Conditions 2 and 3 (Table 4).

With sinusoidal vibration at frequencies > 4 or 5 Hz, the phase lag of the apparent mass increased over the initial cycles of vibration. Figure 2 illustrates the increase in phase lag of the apparent mass over time for one subject exposed to 5·0 and 6·3 Hz vibration at five magnitudes. At 5 Hz, there was approximately 30° increased lag with vibration magnitudes of 1·0 and 1·4 m/s^2 r.m.s. (Figure 2(a)). At 6·3 Hz, the phase lag increased by more than 30° at

TABLE 4

Statistically significant differences in phase measured with sinusoidal vibration at different vibration magnitudes at each frequency for three sitting conditions

	3·15 Hz	4·0 Hz	5·0 Hz	6·3 Hz	8·0 Hz	Number of statistically significant differences
Condition 1	None	M1–M3 M1–M4 M1–M5 M2–M4 M2–M5 M3–M5	M1–M3 M1–M4 M1–M5 M2–M3 M2–M4 M2–M5 M3–M5 M4–M5	None	M1–M3* M1–M4* M1–M5* M2–M5* M3–M5*	20/50
Condition 2	None	M1–M4 M1–M5	M1–M3 M1–M4 M1–M5 M2–M3	M2–M4 M3–M4	None	8/50
Condition 3	M2–M5	M1–M4 M1–M5	M1–M4 M1–M5 M2–M3 M2–M4 M2–M5	M1–M5 M2–M5	None	10/50

Note: Wilcoxon matched-pairs signed ranks test at $p < 0{\cdot}05$. M1: 0·35 m/s^2 r.m.s.; M2: 0·5 m/s^2 r.m.s.; M3: 0·7 m/s^2 r.m.s.; M4: 1·0 m/s^2 r.m.s.; M5: 1·4 m/s^2 r.m.s.

*The phase lag at the magnitude appearing first was greater than the phase lag at the magnitude appearing second.

The right-hand column presents the number of pairs showing a statistically significant difference, with a maximum of 50 pairs.

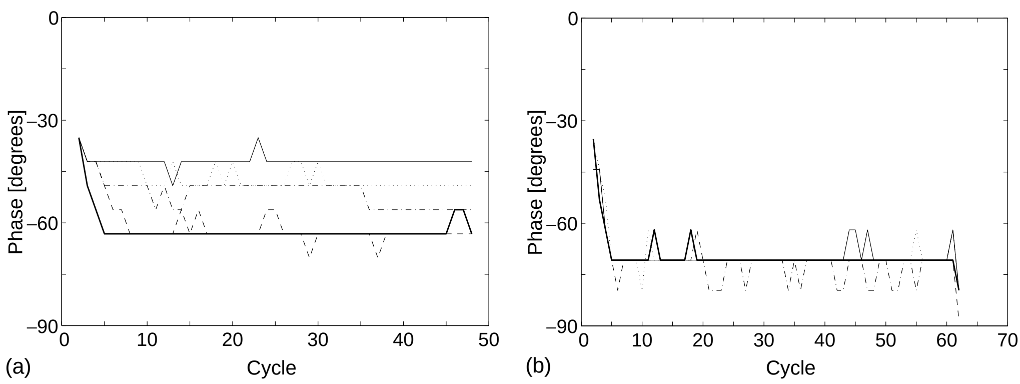

Figure 2. Phase of apparent mass of a subject calculated for each cycle of sinusoidal vibration (a) at 5 Hz and (b) at 6·3 Hz at five vibration magnitudes for Condition 1: ——, 0·35 m/s^2 r.m.s.; --------, 0·5 m/s^2 r.m.s.; – – –, 0·7 m/s^2 r.m.s.; — —, 1·0 m/s^2 r.m.s.; ——, 1·4 m/s^2 r.m.s.

all five vibration magnitudes (Figure 2(b)). This initial phase shift was observed in the results of all subjects irrespective of sitting condition, although the extent of the phase shift varied between subjects, sitting conditions and vibration magnitudes. An initial phase shift of more than 30° between the second cycle and the 10th cycle of sinusoidal vibration at 6·3 and at 8·0

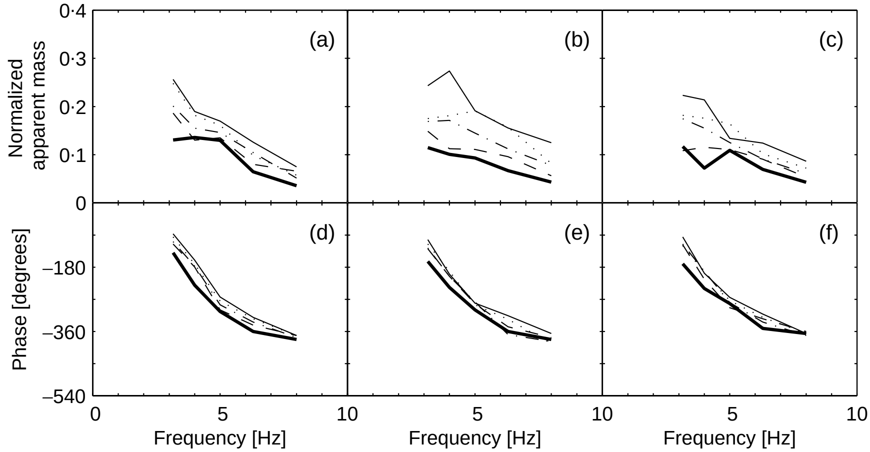

Figure 3. Median apparent masses and phases in the fore-and-aft axis of eight subjects measured with sinusoidal vibration at five frequencies and five magnitudes with three postures. (a and d) Condition 1, (b and e) Condition 2, (c and f) Condition 3: ——, 0·35 m/s^2 r.m.s.; --------, 0·5 m/s^2 r.m.s.; – – –, 0·7 m/s^2 r.m.s.; — —, 1·0 m/s^2 r.m.s.; ——, 1·4 m/s^2 r.m.s.

Hz was observed in 32 of 80 cases for Condition 1, in 49 of 80 cases for Condition 2, and in 20 of 80 cases for Condition 3 (80 cases = 8 (subjects) × 5 (vibration magnitudes) × 2 (frequencies)).

Figure 3 shows, for each sitting condition, the median normalized apparent masses and phases calculated from the force at the seat surface in the fore-and-aft axis and the acceleration at the seat in the vertical axis. The fore-and-aft cross-axis apparent mass during vertical vibration generally decreased with increasing frequency, although a peak at 4·0 or 5·0 Hz was observed for two subjects. The fore-and-aft cross-axis apparent mass during vertical vibration tended to decrease with increases in vibration magnitude at all frequencies studied. Statistical tests showed that this non-linear effect occurred equally in all three sitting conditions, although the effect of vibration magnitude appeared less significant at 4·0 Hz with the normal sitting condition (Condition 1) (Table 5).

3.2. APPARENT MASS WITH RANDOM VIBRATION

An example of the apparent mass and phase for a single subject measured with random vibration at five vibration magnitudes is presented in Figure 4. It can be seen that in Condition 1 (i.e., comfortable, upright posture with normal muscle tension), the resonance frequency decreased with increases in vibration magnitude, consistent with previous findings (Figure 4(a)). This frequency shift is less clear in the apparent mass in Condition 2 (i.e., buttocks muscles tensed), although an indication of a shift in the resonance frequency may be observed in the phase data (Figures 4(b) and 4(e)). The effect of vibration magnitude on the apparent mass was less clear in Condition 3 than in Condition 1 but, for this subject, more clear in Condition 3 than in Condition 2.

The median normalized apparent mass of all eight subjects measured with random vibration at five vibration magnitudes is shown for each sitting condition in Figure 5. In the median data, the dependency of the apparent mass on the vibration magnitude appeared to be less clear than that described for one subject. The mean resonance frequencies for all

TABLE 5

Statistically significant differences in apparent mass in the fore-and-aft axis measured with sinusoidal vibration at different vibration magnitudes at each frequency for three sitting conditions

	3·15 Hz	4·0 Hz	5·0 Hz	6·3 Hz	8·0 Hz	Number of statistically significant differences
Condition 1	M1–M3 M1–M4 M1–M5 M2–M3 M2–M4 M2–M5 M3–M5 M4–M5	M1–M5 M2–M3	M1–M3 M1–M4 M1–M5 M2–M4 M2–M5 M3–M5	M1–M4 M1–M5 M2–M4 M2–M5 M3–M4 M3–M5 M4–M5	M1–M2 M1–M3 M1–M5 M2–M3 M2–M5 M3–M5 M4–M5	30/50
Condition 2	M1–M2 M1–M3 M1–M4 M1–M5 M2–M5 M4–M5	M1–M3 M1–M4 M1–M5 M2–M4 M2–M5 M3–M4 M3–M5	M1–M3 M1–M4 M1–M5 M2–M4 M2–M5 M3–M5 M4–M5	M1–M3 M1–M4 M1–M5 M2–M3 M2–M4 M2–M5 M3–M5 M4–M5	M1–M3 M1–M4 M1–M5 M2–M4 M2–M5 M3–M5 M4–M5	35/50
Condition 3	M1–M2 M1–M3 M1–M4 M1–M5 M2–M5 M3–M5	M1–M2 M1–M3 M1–M4 M1–M5 M2–M5 M3–M4 M3–M5 M4–M5	M1–M3 M1–M4 M1–M5 M2–M5 M3–M5	M1–M2 M1–M4 M1–M5 M2–M5 M3–M5 M4–M5	M1–M3 M1–M4 M1–M5 M2–M5 M2–M5 M3–M5 M4–M5	32/50

Note: Wilcoxon matched-pairs signed ranks test at $p < 0{\cdot}05$. M1: 0·35 m/s^2 r.m.s.; M2: 0·5 m/s^2 r.m.s.; M3: 0·7 m/s^2 r.m.s.; M4: 1·0 m/s^2 r.m.s.; M5: 1·4 m/s^2 r.m.s.

The right-hand column presents the number of pairs showing a statistically significant difference, with a maximum of 50 pairs.

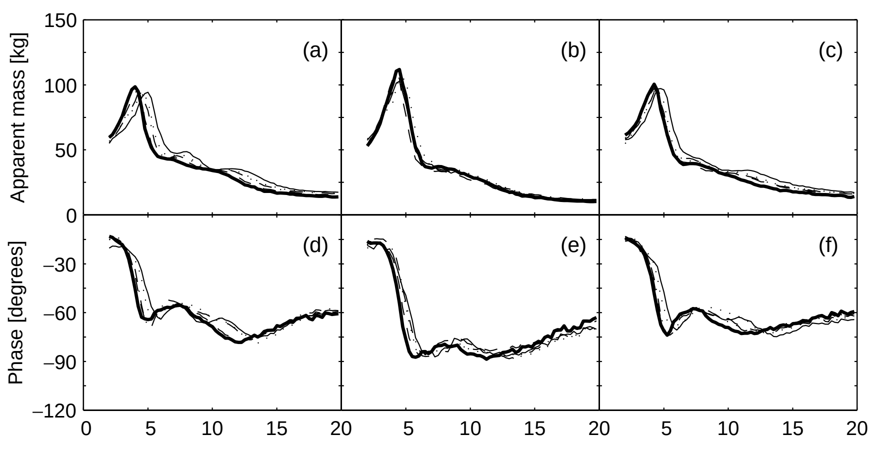

Figure 4. Apparent masses and phases of a subject measured with random vibration at five vibration magnitudes with three postures. (a and d) Condition 1, (b and e) Condition 2, (c and f) Condition 3: ——, 0·35 m/s^2 r.m.s.; --------, 0·5 m/s^2 r.m.s.; – – –, 0·7 m/s^2 r.m.s.; — —, 1·0 m/s^2 r.m.s.; ——, 1·4 m/s^2 r.m.s.

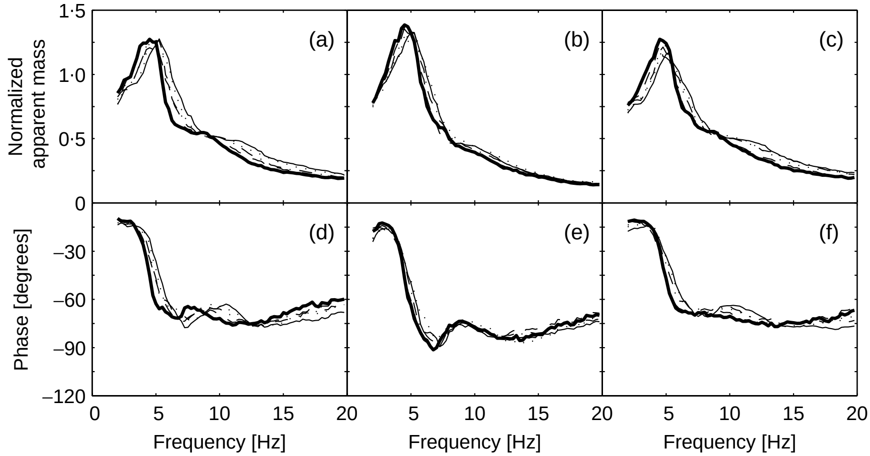

Figure 5. Median normalized apparent masses and phases of eight subjects measured with random vibration at five vibration magnitudes with three postures. (a and d) Condition 1, (b and e) Condition 2, (c and f) Condition 3. ——, 0·35 m/s^2 r.m.s.; --------, 0·5 m/s^2 r.m.s.; – – –, 0·7 m/s^2 r.m.s.; — —, 1·0 m/s^2 r.m.s.; ——, 1·4 m/s^2 r.m.s.

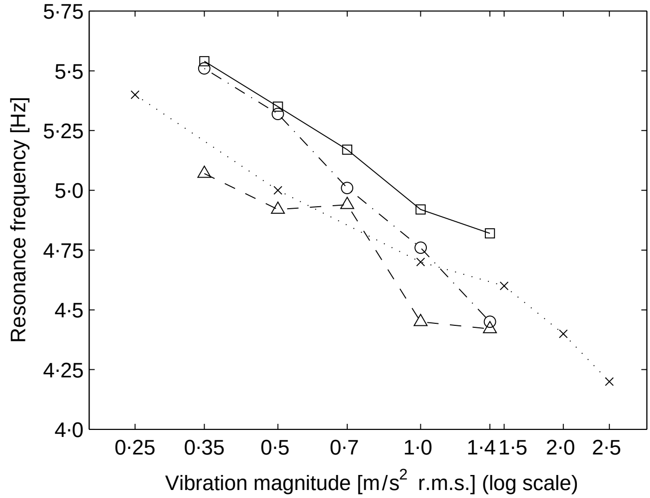

Figure 6. Mean resonance frequencies of the apparent mass with random vibration for all conditions. Median resonance frequencies obtained by Mansfield and Griffin [3] are also presented. · –○· –, Condition 1; –△–, Condition 2; –□–, Condition 3; · · ×· ·, [3].

conditions are presented in Figure 6, together with the median resonance frequencies obtained by Mansfield and Griffin [3]. For all sitting conditions, a statistically significant change in the resonance frequency was found when the vibration magnitude was doubled or more, except between 0·7 and 1·4 m/s^2 r.m.s. for sitting Condition 3 ($p < 0{\cdot}05$, Wilcoxon, Table 6). Additionally, for Condition 1, the resonance frequencies changed significantly between 0·5 and 0·7 m/s^2 r.m.s. and 1·0 and 1·4 m/s^2 r.m.s.; for Condition 2 there were changes between 0·7 and 1·0 m/s^2 r.m.s. ($p < 0{\cdot}05$, Wilcoxon). The sizes of the differences in the principal resonance frequency when the vibration magnitude was doubled or more, which were found statistically significant, were compared between sitting conditions. It was

TABLE 6

Statistical significance of differences between peak frequencies of apparent mass with random vibration at various vibration magnitudes for each sitting condition. Wilcoxon matched-pairs signed ranks test

Vibration magnitude (m/s^2 r.m.s.)	0·35	0·5	0·7	1·0	1·4
(*a*) *Condition* 1 (*comfortable*, *upright*)					
0·35	—	0·084	0·017*	0·016*	0·011*
0·5		—	0·016*	0·020*	0·011*
0·7			—	0·167	0·010*
1·0				—	0·047*
1·4					—
(*b*) *Condition* 2 (*buttocks muscles tensed*)					
0·35	—	0·197	0·046*	0·011*	0·008*
0·5		—	0·914	0·027*	0·016*
0·7			—	0·016*	0·016*
1·0				—	0·564
1·4					—
(*c*) *Condition* 3 (*abdominal muscles tensed*)					
0·35	—	0·172	0·017*	0·017*	0·020*
0·5		—	0·285	0·023*	0·009*
0·7			—	0·139	0·085
1·0				—	0·916
1·4					—

* $p < 0·05$.

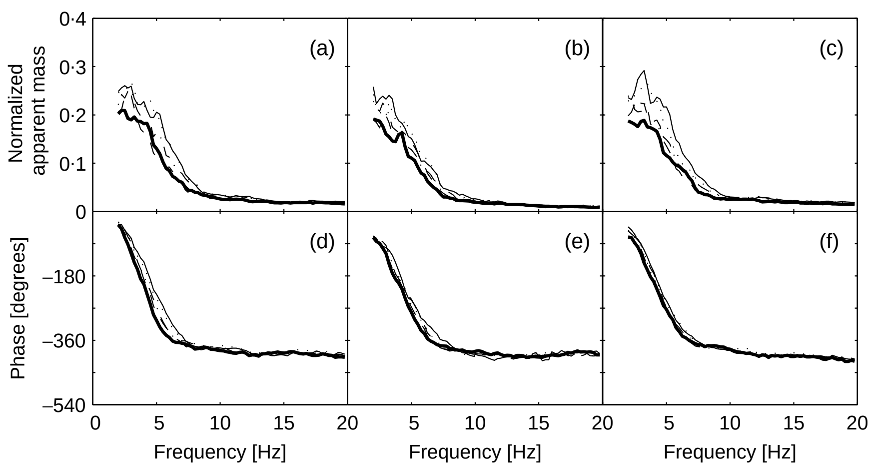

Figure 7. Median apparent masses and phases in the fore-and-aft axis of eight subjects measured with random vibration at five vibration magnitudes with three postures. (a and d) Condition 1, (b and e) Condition 2, (c and f) Condition 3: ——, 0·35 m/s^2 r.m.s.; --------, 0·5 m/s^2 r.m.s.; – – –, 0·7 m/s^2 r.m.s.; — —, 1·0 m/s^2 r.m.s.; ——, 1·4 m/s^2 r.m.s.

found that the size of the difference in resonance frequency with Condition 2 was significantly smaller than the size of difference with Condition 1 for the change in vibration magnitude between 0·5 and 1·4 m/s^2 and 0·35 and 1·4 m/s^2 r.m.s. ($p < 0·05$, Wilcoxon).

TABLE 7

Statistically significant differences in apparent masses in the fore-and-aft axis measured with random vibration at different vibration magnitudes at 5 and 8 Hz for three sitting conditions

	5·0 Hz	8·0 Hz	Number of statistically significant differences
Condition 1	M1–M4 M1–M5 M2–M3 M2–M4 M2–M5 M3–M5	M1–M3 M1–M4 M1–M5 M2–M3 M2–M4 M2–M5 M3–M4 M3–M5	14/20
Condition 2	M1–M5 M2–M5	M1–M4 M1–M5 M2–M3 M2–M4 M2–M5 M3–M5	8/20
Condition 3	M1–M3 M1–M4 M1–M5 M2–M4 M2–M5	M1–M4 M1–M5 M2–M4 M2–M5 M3–M4 M3–M5	11/20

Note: Wilcoxon matched-pairs signed ranks test at $p < 0{\cdot}05$. M1: 0·35 m/s^2 r.m.s.; M2: 0·5 m/s^2 r.m.s.; M3: 0·7 m/s^2 r.m.s.; M4: 1·0 m/s^2 r.m.s.; M5: 1·4 m/s^2 r.m.s.

The right-hand column presents the number of pairs showing a statistically significant difference, with a maximum of 20 pairs.

The median apparent mass and phase obtained from the force at the seat surface in the fore-and-aft direction and the vertical seat acceleration at five magnitudes are presented for each sitting condition in Figure 7. The fore-and-aft cross-axis apparent mass generally decreased with increasing frequency between 2 and 10 Hz, although a peak at about 4 Hz was found for some subjects. At frequencies > 10 Hz, the fore-and-aft cross-axis apparent mass was low, only a few percent of the static mass of a subject. At frequencies below 10 Hz, the apparent mass tended to decrease with increases in vibration magnitude, as seen with sinusoidal vibration. At 5·0 and 8·0 Hz, the fore-and-aft cross-axis apparent mass obtained with different magnitudes of random vibration was compared (Table 7). The effect of vibration magnitude on the apparent mass was less often significantly dependent on magnitude at 5·0 Hz for Condition 2. At 8·0 Hz, the apparent mass decreased significantly when the vibration magnitude was doubled, irrespective of sitting conditions, except between 0·35 and 0·7 m/s^2 r.m.s. for Conditions 2 and 3.

4. DISCUSSION

4.1. COMPARISON WITH PREVIOUS STUDIES

A non-linear characteristic consistently found in this and previous studies is a decrease in the principal resonance frequency of the apparent mass with an increase in vibration magnitude. Hinz and Seidel [1] found this phenomenon in the apparent mass measured with sinusoidal vibration and Fairley and Griffin [2] and Mansfield and Griffin [3] reported this phenomenon in the apparent mass with random vibration. In these previous studies, the postures of subjects used can be categorized as a "normal" sitting posture and may roughly correspond to Condition 1 in this study. For the apparent mass with sinusoidal vibration, Hinz and Seidel [1] used four subjects and no statistical investigation of the finding was made. The statistical significance of the shift in the peak frequency of the apparent mass in Condition 1 of this study, therefore, supports the finding by Hinz and Seidel [1]. For the apparent mass with random vibration in Condition 1, decreases in the peak frequency of the apparent mass with an increase in vibration magnitude were found with smaller increases in vibration magnitude than used in previous studies: a factor of $\sqrt{2}$ increase in magnitude was used in this study compared with a factor of 2 in previous studies.

The effect of posture on the non-linear characteristics of the apparent mass has been investigated by Mansfield and Griffin [6] using random vibration over the frequency range 1–20 Hz. It was concluded that the resonance frequency of the apparent mass decreased for each increase in vibration magnitude (0·2, 1·0 and 2·0 m/s^2 r.m.s.) in all nine postures investigated. In this study, the effect of muscle tension on the non-linear characteristics in the apparent mass was investigated with random vibration over a similar frequency range to that used by Mansfield and Griffin but with a narrower range of vibration magnitudes (0·35–1·4 m/s^2 r.m.s.). There was a significant decrease in the resonance frequency for all three sitting conditions when the vibration magnitude was doubled, except between 0·7 and 1·4 m/s^2 r.m.s. for Condition 3 (Table 6). The two-fold change in vibration magnitude is the same as the change from 1·0 to 2·0 m/s^2 r.m.s. used by Mansfield and Griffin [6]. Therefore, neglecting the smaller change in vibration magnitude needed to influence apparent mass in this study, the resonance frequency of the apparent mass decreased with increases in vibration magnitude for both studies. There was a significantly smaller change in resonance frequency in Condition 2 than in Condition 1 and, with the smaller change in vibration magnitude (a factor of $\sqrt{2}$), the effect of vibration magnitude on the apparent mass resonance frequency was less significant in Conditions 2 and 3 than in Condition 1 (see Figures 4 and 5 and Table 6).

4.2. EFFECT OF MUSCLE TENSION CONTROL ON RESONANCE FREQUENCY

With random vibration, the apparent mass of some subjects showed less decrease in the principal resonance frequency in Condition 2 than in Condition 1, although the shift was not eliminated (e.g., Figure 4). Some other subjects showed less shift in the resonance frequency in Condition 3 than in Condition 1 (data not presented). Some subjects showed no effect of sitting condition on the shift of the resonance frequency: the shift was observed irrespective of the sitting condition (data not presented). Overall, there was no clear effect of the sitting condition on the non-linearity in the apparent mass with random vibration, although some subjects showed the expected decrease in the non-linear trend in Conditions 2 and 3 (Table 6). Possible causes of the difference between individuals in the effect of muscle tension on the apparent mass mentioned above may include individual differences in the ability to control particular muscles at a particular tension. Some subjects reported that it was difficult to maintain the maximum muscle tension while exposed to vibration for 60 s. Some training in the retention of constant muscle tension may be required for any future study. It may also be appropriate to monitor the muscle activity of interest during vibration exposure.

4.3. INITIAL PHASE SHIFT

With sinusoidal vibration, there was no significant shift in the principal peak frequency of the apparent mass with a change in vibration magnitude in Conditions 2 and 3 (Figure 2 and Table 2). The effect of vibration magnitude on apparent mass over the frequency range 3·15–6·3 Hz was less often significant in Conditions 2 and 3 than in Condition 1 (Table 3). These findings imply that the muscle tension in the buttocks and abdomen influenced the apparent mass at frequencies around the principal resonance frequency. If involuntary changes in muscle tension were minimized by maximum voluntary tension, involuntary changes in muscle tension may have contributed to a decrease in the resonance frequency with increasing vibration magnitude in Condition 1 of this study, and in previous studies.

With sinusoidal vibration there was increasing phase lag between force and acceleration over the initial cycles of motion. This initial phase shift was mostly complete within the first 1·5 s of vibration at frequencies above the peak frequency of the apparent mass. In this experiment, the sinusoidal vibrations were tapered over the first and last 0·5 s so as to prevent exposing subjects to a sudden change of acceleration. This variation in vibration magnitude might be partly responsible for the initial phase shift. However, the difference in the phase due to variations in vibration magnitude at 6·3 and 8·0 Hz may not be sufficient to explain the initial 30° shift of phase that was observed (see Figure 1). It therefore seems likely that some cause other than a change in vibration magnitude was responsible for the initial phase shift.

Robertson and Griffin [9] reported that there was a gradual increase in the amplitude of electromyographic activity from the erectores spinae muscles over the first cycles of sinusoidal oscillation. The decrease in the phase of the apparent mass observed in this study also occurred over the initial periods of exposure. However, the initial increase in the back muscle activity observed by Robertson and Griffin [9] was found with sinusoidal vibration at 2 and 4 Hz, while the initial phase shift observed in this study was found mostly with sinusoidal vibration at 6·3 and 8·0 Hz, and seldom at 3·15 and 4 Hz. Therefore, although both non-linear phenomena were observed during the initial periods of exposure, it is not clear whether the change in back muscle activity and the change in the apparent mass phase over the initial periods are related.

The initial phase shift was observed in all sitting conditions, but most often in Condition 2 and least often in Condition 3. This non-linear characteristic may, therefore, be most significant in Condition 2 in which the buttocks muscle tension was controlled. The effect of vibration magnitude on the apparent mass in the region of the principal resonance frequency was more significant in Condition 1 than in Conditions 2 and 3 (Tables 2 and 3). These two non-linear characteristics appear to be most significant in different sitting conditions: the initial phase shift may not be responsible for the change in apparent mass with change in vibration magnitude around the principal resonance frequency, although the frequency at which the phase shift occurred (at frequencies greater than the resonance frequency) was apparently related to the resonance frequency of the apparent mass.

4.4. FORE-AND-AFT CROSS-AXIS APPARENT MASS

In this experiment, the ratio between the force at the seat surface in the fore-and-aft axis and the seat acceleration in the vertical direction was measured for the first time (i.e., fore-and-aft cross-axis apparent mass). The fore-and-aft cross-axis apparent mass varied up to 40% of the static weight of subjects over the frequency range investigated and is consistent with the two-dimensional motion of the body during vertical vibration as found in previous studies (e.g., Matsumoto and Griffin [13]). There was no obvious effect of sitting condition on the non-linearity observed in the cross-axis apparent mass: the cross-axis apparent mass decreased with increased vibration magnitude in all conditions (Figures 3 and 6 and Tables 4 and 6). The cross-axis apparent mass also decreased with increased frequency with obvious local peaks for some subjects. This implies that the cross-axis apparent mass may be attributed to one or more vibration modes at frequencies below 2 Hz, which mainly consisted of rocking and bending motion of the spine, as found by Kitazaki and Griffin [7] and Matsumoto and Griffin [8]. These vibration modes may contribute to the non-linear phenomenon observed in the cross-axis apparent mass but it appears that they are not significantly affected by muscle tension in the buttocks or abdomen.

5. CONCLUSIONS

Non-linear characteristics in the apparent masses of seated subjects were less clear when muscle tension in the abdomen and, particularly, in the buttocks was controlled. Involuntary changes in muscle tension during whole-body vibration may be partly responsible for some of the non-linear biodynamic responses observed during exposure to vertical vibration.

The apparent mass obtained from force at the seat surface in the fore-and-aft axis and vertical seat acceleration decreased with increases in vibration magnitude over the frequency range 2–10 Hz. This non-linear characteristic was not significantly affected by the muscle tension in the abdomen or buttocks.

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APPENDIX A: INSTRUCTIONS TO SUBJECTS

The purpose of this experiment is to find out how the muscle tension affects the mechanical response of the seated body to vertical vibration.

Three sitting conditions required in the experiment are as follows:

(1) Comfortable, upright posture with normal muscle tension
(2) Sitting with your buttocks muscles tensed as much as possible
(3) Sitting with your abdominal muscles tensed as much as possible (minimize the volume of your abdomen).

It is very important to keep each sitting condition during exposures. The experimenter will indicate the order in which these conditions should be adopted. In each condition, you will be exposed to 30 different vibrations, five random vibrations and 25 sinusoidal vibrations.

You may stop the vibration at any time by pressing the red STOP button.

Thank you for your help.