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Comparison of the apparent masses and cross-axis apparent masses of seated humans exposed to single- and dual-axis whole-body vibration

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Abstract

Humans are exposed to whole-body vibration in many types of environment. In almost all cases, the vibration to which the human is exposed comprises multi-axis vibration, such that vibration occurs in all directions simultaneously. Despite the complex nature of vibration to which humans are exposed in the workplace, almost all laboratory studies investigating the biomechanical response of the person have been completed using single-axis simulators. This paper presents a study whereby 15 male subjects were exposed to single-axis whole-body vibration in the *x*-, *y*- and *z*-directions and dual-axis vibration in the *xy*-, *xz*-, and *yz*-directions using a 6 degree-of-freedom vibration simulator. All vibration magnitudes were $0.4\,\mathrm{ms}^{-2}$ rms in each axis. Acceleration and force was measured in the *x*-, *y*-, and *z*-direction during all trials. Subjects sat in two postures ('back-on' and 'back-off') on a flat rigid seat. Apparent masses measured using single-axis and dual-axis vibration stimuli showed comparable results; similarly, cross-axis apparent masses (i.e. the ratio of the force in one direction to the acceleration in another direction) were almost identical for the single- and dual-axis vibration stimuli. All results were in agreement with data previously published using single-axis vibration. In most cases, the peaks in the apparent mass and the cross-axis apparent mass occurred at a slightly lower frequency for the dual-axis vibration than for the single-axis vibration. It is hypothesised that this change is due to a nonlinear effect, analogous to that which occurs with increasing vibration magnitude for single-axis vibration.
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1. Introduction

One of the most commonly used interventions to reduce risks from exposure to whole-body vibration is to fit a vibration-isolating seat to a machine that vibrates. The effectiveness of the seat depends on the dynamics of the seat suspension mechanism, the vibration to which it is exposed and the biomechanical response of the seat occupant [1]. As a form of quality control for such seats, test codes exist that ensure that the seat provides appropriate isolation in the vertical direction when exposed to a pre-defined vibration spectrum. These test codes only apply vertical vibration to the seat, as the relevant seats are designed to isolate primarily in the

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vertical direction. However, in many machines where suspension seats are installed, there is substantial vibration in non-vertical directions. It is possible that the multi-axis vibration to which seats are exposed in the field is not well represented by the current series of seat test codes, due to cross-axis effects in the seat and cross-axis effects in the human occupier of the seat.

Almost all published data showing the biomechanical response of the seated human has been obtained from experiments in the laboratory that have used single-axis shakers (although some have investigated subjective ratings of multi-axis vibration [2–4]). Most experiments have measured either transmission of vibration through the body (transmissibility) or the apparent mass, which can be used to predict the forces in a seat if one has knowledge of the vibration to which the occupant is exposed [5]. Apparent mass is defined as the ratio of the force to the acceleration at any frequency

$$M(f) = \frac{F(f)}{a(f)}, \tag{1}$$

where $M(f)$ is the apparent mass, $F(f)$ is the force and $a(f)$ is the acceleration at frequency f. When exposed to vertical vibration, the seated body has a peak at about 4–6 Hz; the exact frequency depending on the individual, the posture and the magnitude of the vibration [6–20]. For fore-and-aft vibration, if a backrest is present, a peak occurs at approximately 4 Hz; if no backrest is present peaks occur at approximately 1 and at 2 Hz. For lateral vibration a peak is usually observed at about 2 Hz. Whilst a systematic single-axis approach has generated useful information, the application of the data into the field assumes a linear response such that data obtained from single-axis experiments can be applied to a multi-axis environment. To date there has been no validation of the validity of single-axis apparent mass data in multi-axis environments.

Some researchers have shown a cross-axis effect whereby forces can be measured in an axis orthogonal to that in which the vibration occurs, demonstrating the importance of considering the multi-axis response of the seat occupant [21–29]. The largest cross-axis effects correspond to a pitching mode of the upper body: vibration in the x-direction (fore-and-aft) induces forces in the z-direction (vertical), with a peak at 6–8 Hz when using a backrest; with no backrest contact the peak in the cross-axis apparent mass has been shown to depend on the thigh contact. For vibration in the z-direction, forces are induced in the x-direction with a peak at approximately 5 Hz, irrespective of backrest contact. This means that total forces on a seat in any direction are a combination of the forces from vibration in the direction being considered in addition to the forces that occur due to cross-axis effects. As there is a multi-axis component to biomechanical responses to single-axis vibration, one is justified in questioning the assumption that biomechanical responses to single-axis stimuli in the laboratory represent the responses to multi-axis stimuli in the workplace.

This paper reports a study investigating the biomechanical response of the seated human to single- and dual-axis vibration to indicate whether single-axis apparent mass data can be applied to complex multi-axis environments.

2. Methods

Fifteen male subjects participated in the experiment designed to establish whether biomechanical data obtained using single-axis vibration can be applied to environments with dual-axis vibration. Subjects were all male and had a mean age of 24.5 years (SD 4.0 years), a mean stature of 171 cm (SD 5.8 cm) and a mean mass of 64.3 kg (SD 8.9 kg).

Subjects sat on a horizontal flat seat with dimensions of 600×400 mm which was 540 mm above the footrest that moved with the seat (Fig. 1). The seat had a vertical braced backrest, which was 460 mm wide. Subjects sat in two postures: 'back-on' (where subjects sat in a relaxed upright posture with hands lightly resting on the thighs with the back in contact with the backrest) and 'back-off' (where subjects sat in a relaxed upright posture with hands lightly resting on the thighs). The posture was not physically constrained or manipulated by the experimenter, in accordance with previous studies, which this experiment was aiming to validate. Subjects were exposed to each stimulus for each posture. The order of presentation of stimuli was randomised.

Six different vibration stimuli were used in the experiment. Each stimulus comprised random vibration with equal energy at each frequency from 1 to 20 Hz. Three of the stimuli used single-axis vibration in the x-, y- and z-directions with a magnitude of 0.4 ms^{-2} rms (unweighted). The other three stimuli used dual-axis vibration

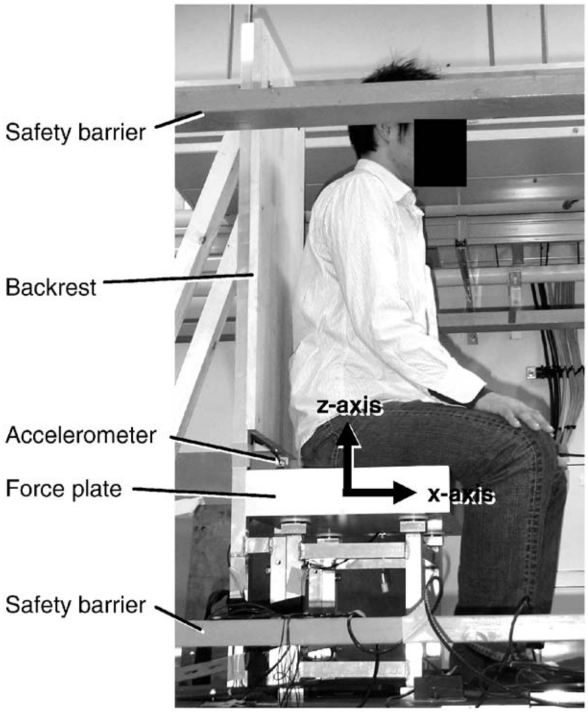

Fig. 1. Experimental set-up showing subject sitting in the 'back-off' posture.

for each pair of directions (x and y, x and z, y and z) with a magnitude of $0.4\,\mathrm{ms}^{-2}$ rms in each direction. The multi-axis stimuli were incoherent between directions. Each stimulus lasted 60 s.

Vibration was generated using an IMV multi-axis shaker, driven by seven electrodynamic shakers [30]. Vibration was measured using a Bruel and Kjaer 4326A triaxial accelerometer amplified using a Nexus charge amplifier. The shaker had low cross-talk between axes (including cross-axis sensitivity of the measuring accelerometer, and errors due to accelerometer misalignment and background noise in the measurement system; Fig. 2). The force at the seat was measured using a Kistler 9281C force plate. The influence of the mass of the plate was removed using a mass cancellation technique in the frequency domain by subtracting the apparent mass of the unloaded force plate. Force and acceleration signals were acquired to a computer at 512 samples per second via anti-aliasing filters set at 170 Hz.

The experiment was approved by the Research Ethic Committee of the National Institute of Industrial Health.

Apparent masses and cross-axis apparent masses were calculated the cross-spectral density (CSD) method:

$$H(f) = \frac{G_{io}(f)}{G_{ii}(f)}, \tag{2}$$

where $G_{io}(f)$ is the CSD between the acceleration and the force, and $G_{ii}(f)$ is the power spectral density of the acceleration at frequency f. Coherence was calculated using

$$\mathrm{coherence}(f)^2 = \frac{|G_{io}(f)|^2}{G_{ii}(f) \times G_{oo}(f)}, \tag{3}$$

where G_{oo} is the power spectrum of the force. Transfer functions were calculated with a resolution of 0.25 Hz.

Results are reported with the following convention: for dual-axis apparent mass data, the first sequence of characters denotes the direction of vibration and the second character denotes the direction of the apparent mass calculation. For example, "xy, x" refers to the apparent mass in the x-direction whilst exposed to vibration in the x- and y-directions simultaneously. For cross-axis apparent masses, the first character(s)

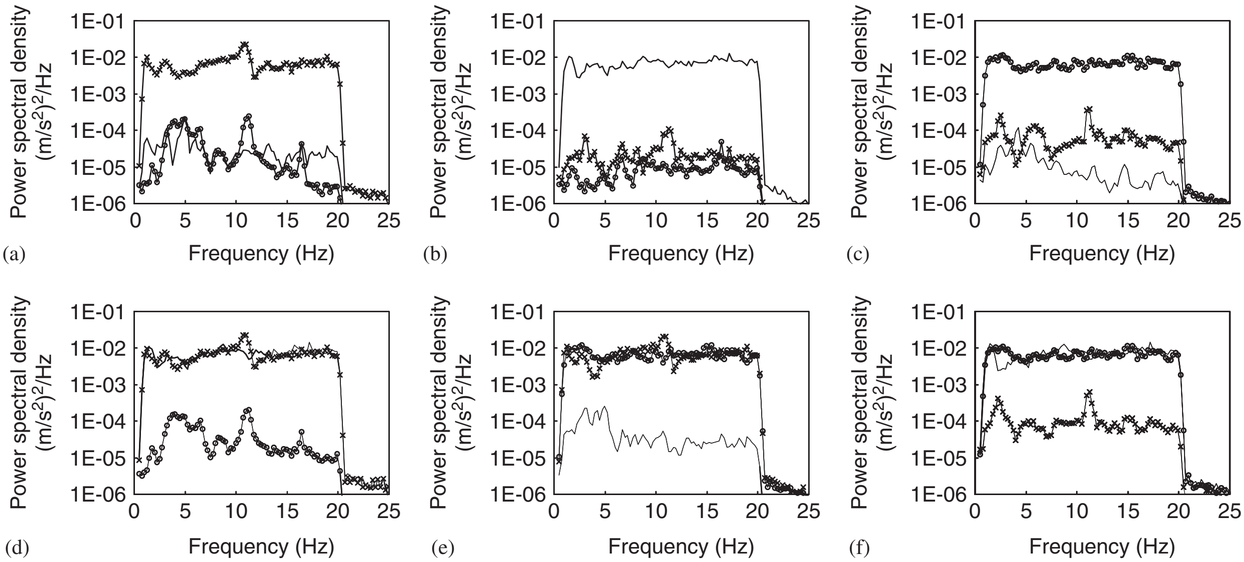

Fig. 2. Typical power spectral densities as measured on the surface of the seat for one subject showing the effect of cross-axis sensitivity of accelerometer, cross-talk of shaker system, accelerometer misalignment errors and noise in the measurement system. *x*-direction (— × —), *y*-direction (———) and *z*-direction (—o—). (a) *x*-vibration, (b) *y*-vibration, (c) *z*-vibration, (d) *xy*-vibration, (e) *xz*-vibration, (f) *yz*-vibration.

denote the direction of vibration and the second pair of characters denote the direction of calculation for the cross-axis apparent mass. For example, "*xz*, *x–y*" refers to the transfer function between the force in the *y*-direction to the vibration in the *x*-direction whilst exposed to vibration in the *x*- and *z*-directions simultaneously.

The purpose of the study was to compare data obtained using single-axis vibration with data obtained using dual-axis vibration and therefore paired statistical tests were appropriate. As normality was not assumed, non-parametric tests were chosen. SPSS v12.0 was used for statistical analysis. A *p*-value of 0.05 was selected as the critical value for significance.

3. Results

Apparent masses measured using single- and dual-axis whole-body vibration for the 15 subjects for the 'back-on' condition are presented in Fig. 3. These data show similar trends in the shape of the apparent mass between subjects, although the magnitude is proportional to the body mass (e.g. the maximum curve in the *z*-axis was for the heaviest subject, who had a sitting mass of 90 kg). Similar variability occurred for the 'back-off' condition.

Median data for the apparent masses measured using single- and dual-axis vibration for the 'back-on' and 'back-off' conditions are shown in Fig. 4. Median *x*-axis apparent masses for the 'back-off' condition decreased in magnitude as the frequency increased with evidence for a small peak at 2–3 Hz (the small 2–3 Hz peak was clearer in individual subject data). This is in agreement with previous data [9], which showed a peak in apparent mass at about 0.7 Hz and one between 1 and 3 Hz. The precise frequency of the first peak could not be established in this experiment due to the band-limiting of the vibration stimuli; data relating to the second peak are considered here. For other combinations of vibration stimuli and backrest condition investigated in this experiment, the first clear peak could be measured. For the *x*-axis 'back-on' condition the peak in the median apparent mass occurred at about 3.5 Hz. The median apparent mass in the *y*-axis had a peak at about 1.75 Hz and the median apparent mass in the *z*-axis had a peak at about 4–6 Hz. Only small differences were observed between the phase of the apparent mass when measured using single- or dual-axis vibration (e.g. Fig. 5).

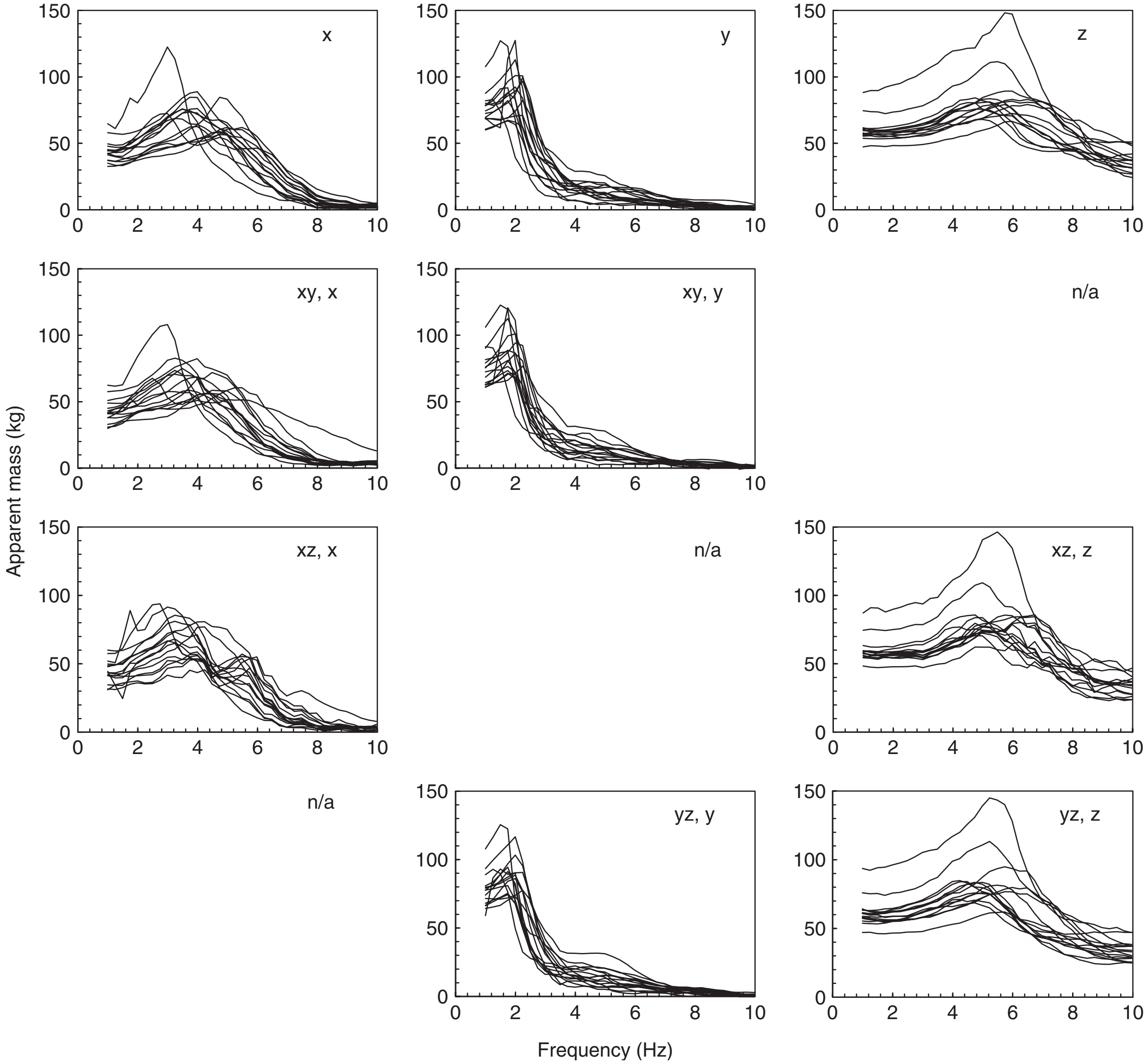

Fig. 3. Apparent mass amplitudes for 15 male subjects exposed to single axis and dual-axis whole-body vibration in the 'back-on' condition. '*x*', '*y*', '*z*' refer to apparent masses measured using single-axis vibration. Other labels refer to apparent masses measured using dual-axis vibration where first two letters refer to vibration directions and final letter refers to direction of apparent mass measurement (e.g. '*xy*, *x*' refers to the *x*-axis apparent mass whilst exposed to vibration in the *x*- and *y*-axis simultaneously). For clarity, results are presented in the 0–10 Hz frequency range.

The frequencies of the peak in apparent mass were clearly different between backrest conditions for *x*-axis vibration (Table 1). In the other directions, the change in frequency was small and/or statistically insignificant. Magnitudes of the peaks were significantly greater in the *y*-axis for the 'back-on' condition when compared to the 'back-off' condition (Tables 2 and 3). Frequencies of the peaks in apparent mass did not significantly change between single- and dual-axis whole-body vibration in the *x*-axis. In the *y*-axis, a small but significant difference in frequency was observed between *y* (median 2 Hz) and *xy* (median 1.75 Hz) vibration in the 'back-on' condition, but not between other combinations of data. In the *z*-axis, the frequency of the peak was significantly lower for the *yz*-vibration than for the *z* only vibration for both 'back-off' (medians 5.5 and 4.25 Hz) and for 'back-on' (medians 5.75 and 5.0 Hz) conditions; the differences between the resonance frequencies for the *xz* and *z* only vibration were not significant. The magnitudes of the peaks in the 'back-on'

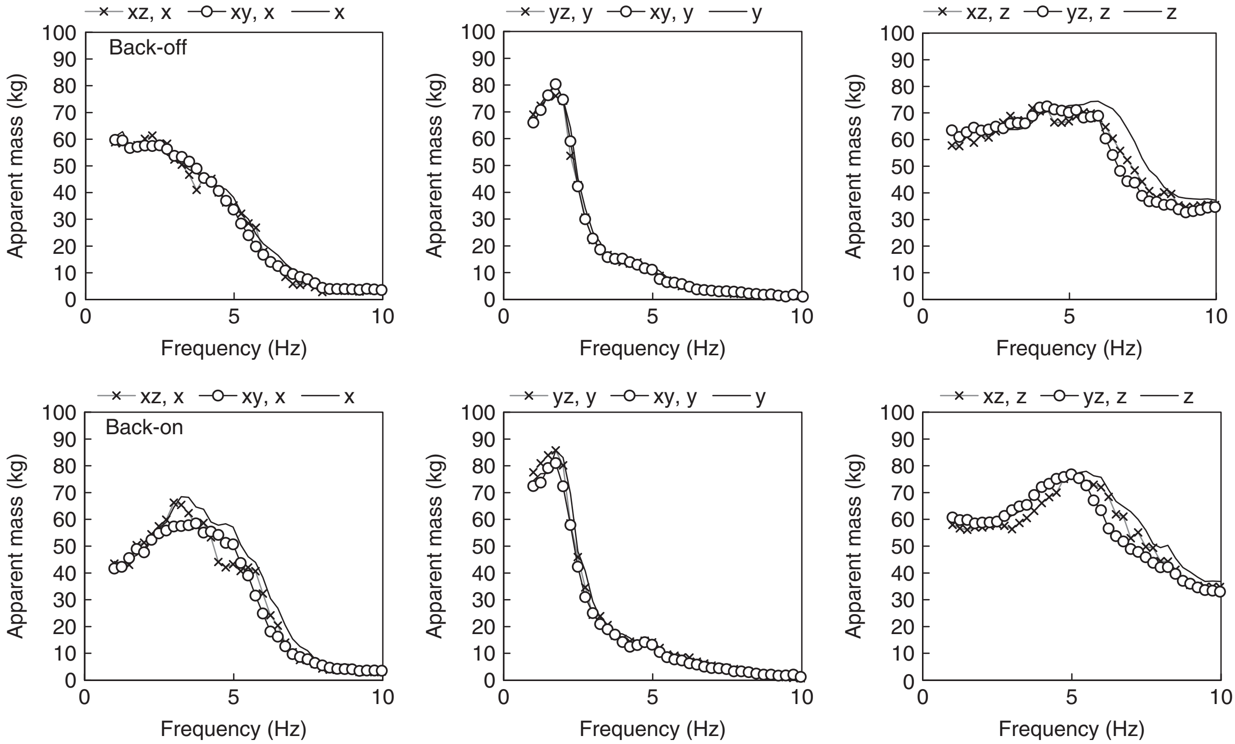

Fig. 4. Median apparent mass amplitudes for 15 male subjects exposed to single axis and dual-axis whole-body vibration in the 'back-off' (top row) and 'back-on' (bottom row) conditions. '*x*', '*y*', '*z*' refer to apparent masses measured using single-axis vibration. Other labels refer to median apparent masses measured using dual-axis vibration where first two letters refer to vibration directions and final letter refers to direction of apparent mass measurement (e.g. '*xy*, *x*' refers to the median *x*-axis apparent mass whilst exposed to vibration in the *x*- and *y*-axis simultaneously).

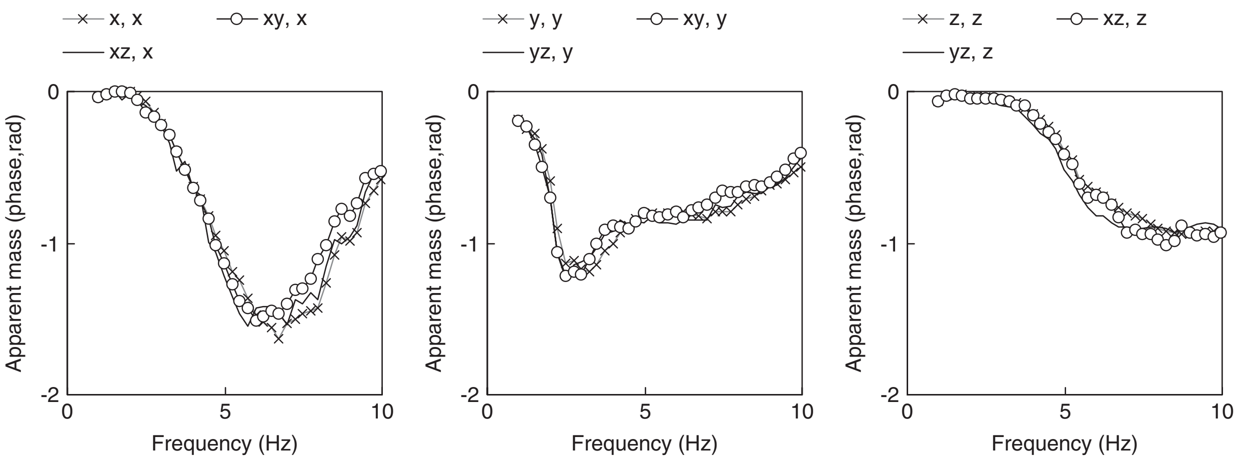

Fig. 5. Median apparent mass phase data for single and dual-axis vibration in the 'back-on' condition.

x-axis apparent mass were significantly smaller for the dual-axis vibration than for the *x*-vibration only condition (median 73.5 kg (*x*), 68.7 kg (*xy*), 68.1 kg (*xz*)). In the *y*-axis and *z*-axis, differences in the magnitudes of the peaks in apparent mass were insignificant except for the difference between the vertical apparent mass measured using *xz*- and *z*-only vibration, 'back-off' (medians 81.4 kg (*z*), 78.4 kg (*xz*)).

Table 1
Median and inter-quartile ranges of apparent mass resonance frequencies of 15 male subjects exposed to single- and dual-axis whole-body vibration in two different postures

Direction	Back-off									Back-on								
	x			*y*			*z*			*x*			*y*			*z*		
	25%	50%	75%	25%	50%	75%	25%	50%	75%	25%	50%	75%	25%	50%	75%	25%	50%	75%
Single axis	2.00	2.50	2.75	1.75	1.75	1.88	4.25	5.50	6.00	3.50	4.00	4.75	1.75	2.00	2.13	5.13	5.75	6.00
xy	1.75	2.00	2.50	1.50	1.75	1.75				3.25	3.75	4.50	1.75	1.75	2.00			
xz	2.00	2.25	2.50				3.88	5.25	5.75	3.25	3.25	4.88				4.88	5.00	6.00
yz				1.50	1.75	1.88	4.00	4.25	5.50				1.75	1.75	2.00	4.75	5.00	5.63

25%, 50% and 75% refer to 25th percentile, median and 75th percentile, respectively. Frequencies are expressed in Hz.

Table 2
Median and inter-quartile ranges of apparent mass resonance magnitudes of 15 male subjects exposed to single- and dual-axis whole-body vibration in two different postures

Direction	Back-off									Back-on								
	x			*y*			*z*			*x*			*y*			*z*		
	25%	50%	75%	25%	50%	75%	25%	50%	75%	25%	50%	75%	25%	50%	75%	25%	50%	75%
Single axis	56.9	64.1	67.2	77.7	86.0	92.5	74.4	81.4	88.4	62.4	73.5	80.4	82.1	91.8	100.2	77.5	81.1	83.9
xy	57.8	63.7	67.8	77.0	80.3	89.4				58.6	68.7	74.2	76.6	87.7	97.6			
	59.7	66.4	69.5				72.3	78.4	84.4	56.9	68.1	80.9				75.5	80.1	85.6
				76.0	79.6	86.4	71.6	77.5	88.1				79.3	90.7	93.7	75.9	81.4	84.5

25%, 50% and 75% refer to 25th percentile, median and 75th percentile, respectively. Magnitudes are expressed in kg.

For single-axis vibration in the 'back-on' condition, the magnitude of the cross-axis apparent masses was greatest for the *x*-axis vibration to *z*-axis force (*x*–*z*) and the *z*-axis force to *x*-axis vibration (*z*–*x*; Fig. 6). Similar results were obtained for the dual-axis vibration. Most subjects showed two peaks in the *x*–*z* cross-axis apparent mass; one at about 3–4 Hz and one between about 5 and 7 Hz. Subjects showed a peak in the *z*–*x* cross-axis apparent mass at about 5–6 Hz. Other combinations of directions of force and acceleration generally showed low values of cross-axis apparent mass for single and dual-axis vibration conditions. The overall shapes of the cross-axis apparent masses were similar for the 'back-on' and 'back-off' conditions apart from the *x*–*z* condition where, for the 'back-off' condition, there was a single peak at about 3 Hz for all subjects and the data increased at low frequency, possibly indicating an additional peak outside the frequency range measured in this experiment.

Median data shows that the peaks in the cross-axis apparent mass occurred at a slightly lower frequency for the dual-axis vibration compared to the single-axis vibration for the 'back-off' conditions and for the *z*–*x* 'back-on' condition (Fig. 7). There was no clear change in peak frequency for the *x*–*z* 'back-off' condition. This finding is coherent with median data from individual subjects' resonant peak frequencies and magnitudes (Table 4): the frequency of the peak reduced for the dual-axis vibration, except for the *x*–*z* 'back-off' data. The differences in the *z*–*x* cross-axis apparent mass resonance frequencies for the single-axis and multi-axis conditions were significant (Table 5); differences between *x*–*z* cross-axis apparent masses were not significant. The magnitudes of the peaks in the cross-axis apparent masses generally reduced for the dual-axis vibration when compared to the single-axis vibration, although differences were not significant ($p > 0.05$).

In agreement with all previously reported data, coherence was high for all apparent mass data. Cross-axis coherence was typically >0.8 between 2 and 10 Hz for combinations of *x*- and *z*-direction force and acceleration, but was low (<0.5) for all other combinations of directions.

Table 3
Summary of results of statistical analysis for apparent mass data

Peak frequency: single axis vs. dual axis

	Back-off			Back-on		
	x	*y*	*z*	*x*	*y*	*z*
xy	ns	ns	—	ns	*	—
xz	ns	—	ns	ns	—	ns
yz	—	ns	*	—	ns	**

Peak magnitude: single axis vs. dual axis

	Back-off			Back-on		
	x	*y*	*z*	*x*	*y*	*z*
xy	ns	ns	—	*	ns	—
xz	ns	—	*	*	—	ns
yz	—	ns	ns	—	ns	Ns

Peak frequency: back-on vs. back-off

		Apparent mass direction		
		x	*y*	*z*
Vibration direction	*x*	***	—	—
	y	—	*	—
	z	—	—	ns
	xy	***	ns	—
	xz	***	—	ns
	yz	—	***	ns

Peak magnitude: back-on vs. back-off

		Apparent mass direction		
		x	*y*	*z*
Vibration direction	*x*	ns	—	—
	y	—	*	—
	z	—	—	ns
	xy	ns	*	—
	xz	ns	—	ns
	yz	—	***	ns

Data show the effect of exposure to dual axis vibration in comparison to single axis vibration and the effect of backrest contact on apparent mass resonance frequency and magnitude at resonance. All tests are Wilcoxon (ns $p>0.05$, *$p<0.05$, **$p<0.01$, ***$p<0.005$).

4. Discussion

All apparent mass data are in agreement with those previously reported in the literature for measurements made using similar postures and magnitudes.

Of the experimental conditions used in this study, the most commonly investigated condition in the literature is 'back-off', vertical vibration. Studies that used relatively low magnitudes of vertical random vibration reported peaks between 5.00 and 6.00 Hz for vibration magnitudes of 0.2–0.625 ms^{-2} rms [8,31–34],

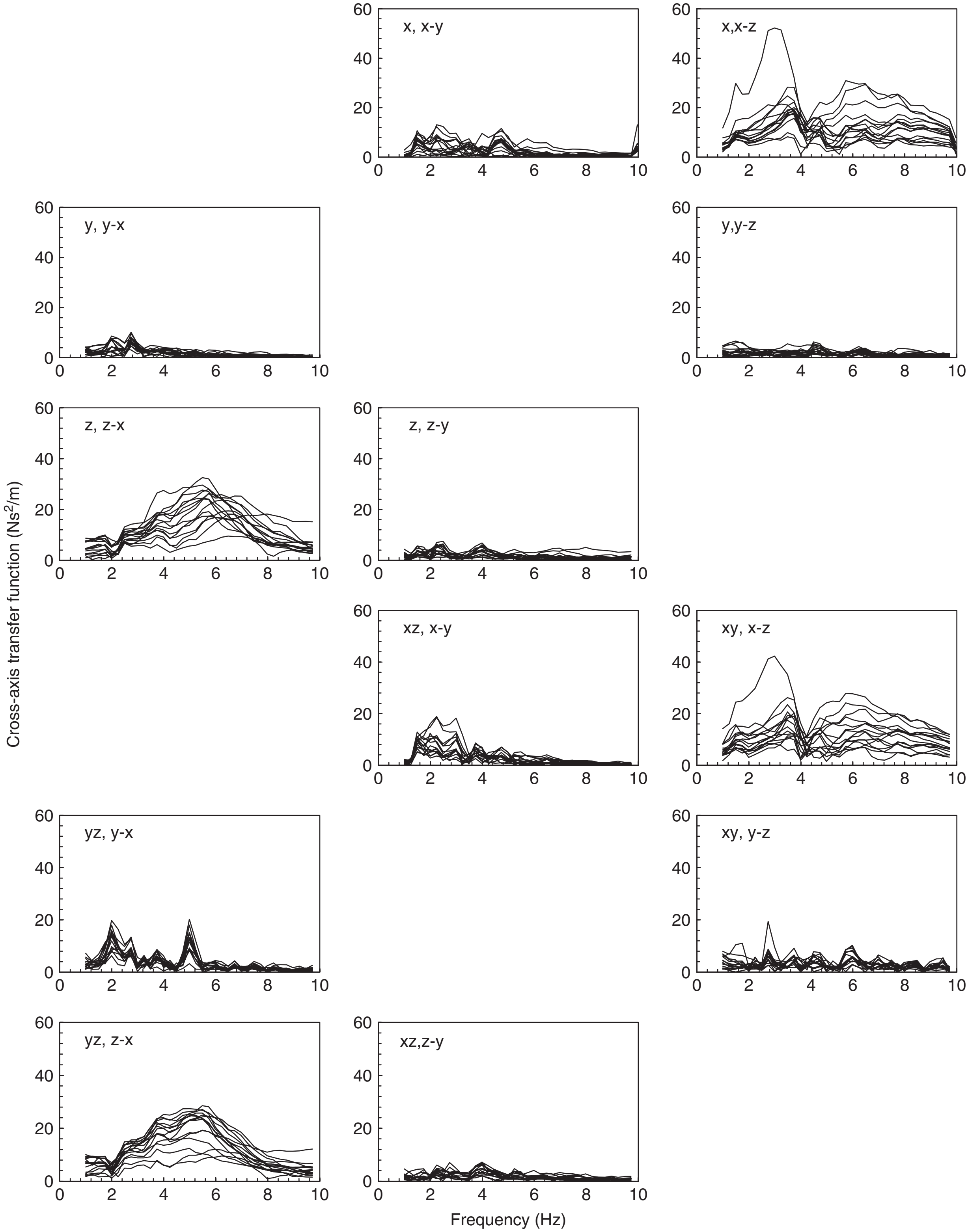

Fig. 6. Cross-axis apparent mass amplitudes for 15 male subjects exposed to single-axis and dual-axis whole-body vibration in the 'back-on' condition. Labels refer to the vibration direction and the nature of the cross-axis transfer function (e.g. '*yz*, *z*–*x*' refers to the cross-axis transfer function between *z* vibration and *x* force for the vibration condition with dual axis vibration in the *y*- and *z*-directions simultaneously).

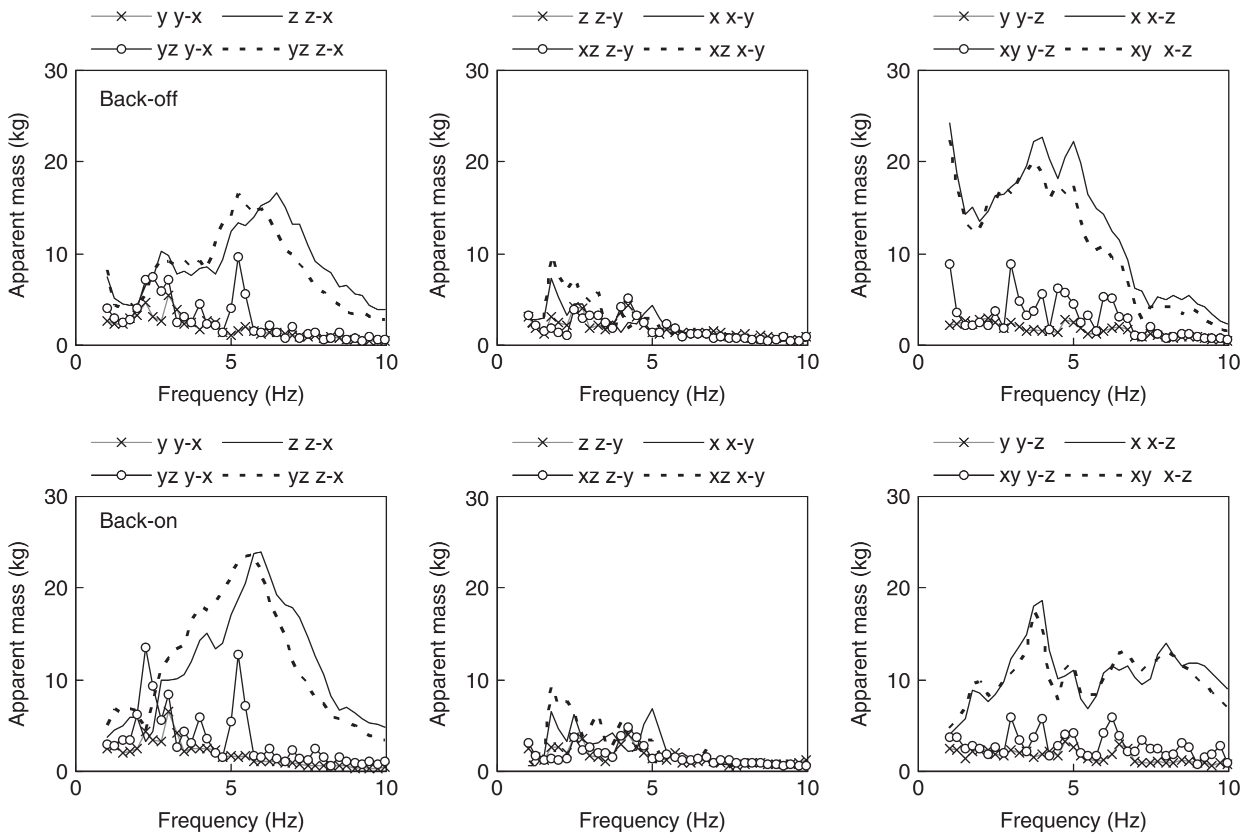

Fig. 7. Median cross-axis apparent mass amplitudes for subjects exposed to single axis and dual-axis whole-body vibration in the 'back-on' and 'back-off' conditions. Labels refer to the direction of vibration and the nature of the cross-axis transfer function (e.g. '*yz*, *z*–*x*' refers to the cross-axis transfer function between *z* vibration and *x* force for the vibration condition with dual axis vibration in the *y* and *z* directions simultaneously).

corresponding to the 5.5 Hz median frequency obtained here. Similarly, studies in the literature that compared vertical responses with and without a vertical backrest with relatively low magnitudes of vibration showed a slight increase in resonance frequency with back support, corresponding to the findings of this study [8,14,25,31].

For fore-aft vibration, without a backrest, a peak has been observed at low frequency (approximately 0.5–1 Hz) [9,20]. This peak was out with the range of vibration excitation in this study and so could not be determined clearly, but the low-frequency response of the subjects showed an increase in apparent mass with decreasing frequency in line with the literature. The higher-frequency peak previously observed between 2 and 3 Hz [9,12,20,21] corresponded to the peak at 2.5 Hz in this study. The three studies in the literature that have investigated the apparent mass in the fore-aft direction with backrest contact showed peaks at 4 and 6 Hz, depending on backrest angle [20], 3.5 Hz [14], and at about 4 Hz [22]. These correspond to the median peak frequency of 4.0 Hz obtained in this study.

In the lateral direction, peaks have been reported previously at between 1 and 2 Hz [9,20] and at 2 Hz [12] with only a small effect of backrest contact [9,20]. These results are in agreement with the findings of this study that showed median peak frequencies of 1.75 and 2.0 Hz for *y*-direction apparent mass in the 'back-off' and 'back-on' conditions respectively.

Cross-axis apparent masses are in general agreement with those reported by Nawayseh and Griffin [21–23,25,34]. Nawayseh and Griffin used 'thigh contact' as an independent variable; the posture used in this study is most similar to their 'maximum' and 'average' thigh contact conditions. For both backrest conditions, the *z*–*x* cross-axis apparent masses measured in this study at 0.4 ms^{-2} rms had a median peak of 6.0 Hz which is in agreement with Nawayseh and Griffin's results (who showed a peak at 5–6 Hz at 0.25 and 0.625 ms^{-2} rms

Table 4
Median and inter-quartile ranges of cross-axis apparent mass resonance frequencies and magnitudes of 15 male subjects exposed to single- and dual-axis whole-body vibration in two different postures

Measurement	Frequency of peak (Hz)									Magnitude of peak (Ns^2/m)								
	Back-off			Back-on (peak 1)			Back-on (peak 2)			Back-off			Back-on (peak 1)			Back-on (peak 2)		
	25%	50%	75%	25%	50%	75%	25%	50%	75%	25%	50%	75%	25%	50%	75%	25%	50%	75%
x, x–z	2.75	3.75	5.00	3.75	4.00	4.00	5.00	6.75	8.00	18.5	26.0	27.7	17.4	19.2	21.9	13.7	15.3	17.2
z, z–x	5.63	6.00	6.50	5.75	6.00	6.63	n/a	n/a	n/a	15.4	18.6	19.8	18.7	24.2	27.0	n/a	n/a	n/a
xy, x–z	3.50	3.75	3.88	3.75	3.75	4.00	5.25	6.00	6.75	18.7	20.7	26.2	12.7	17.4	20.4	11.8	14.1	17.5
yz, z–x	5.00	5.25	5.75	5.25	5.75	5.75	n/a	n/a	n/a	13.1	16.4	18.8	18.6	24.6	25.5	n/a	n/a	n/a

Measurement refers to vibration direction and cross-axis measurement (e.g. *xy*, *x–z* refers to the *x* acceleration to *z* force transfer function for vibration in the *x*- and *y*-axis simultaneously). 25%, 50% and 75% refer to 25th percentile, median and 75th percentile, respectively.

Table 5
Summary of results of statistical analysis for cross-axis apparent mass data

Single axis vs. dual axis

	Back-off		Back-on	
	x–z	*z–x*	*x–z*	*z–x*
Frequency	ns	**	Ns	**
Magnitude	ns	ns	Ns	ns

Back-on vs. back-off

	Single axis		Dual axis	
	x–z	*z–x*	*x–z*	*z–x*
Frequency	ns	ns	Ns	ns
Magnitude	ns	***	Ns	***

Data show the effect of exposure to dual-axis vibration in comparison to single-axis vibration and the effect of backrest contact on cross-axis apparent mass resonance frequency and magnitude at resonance. All tests are Wilcoxon (ns $p>0.05$, *$p<0.05$, **$p<0.01$, ***$p<0.005$).

for the maximum and average thigh contact conditions for 'back-off' and the 'back-on' conditions). The magnitude of the *z–x* cross-axis apparent mass median peak in this study was slightly greater than Nawayseh and Griffin's for the 'back-on' condition (24 vs. 20 kg), despite the mean mass of their subjects being greater than the mean mass of subjects in this study.

x–z cross-axis apparent masses for the 'back-on' condition showed two peaks. These were not shown in Nawayseh and Griffin's median data, who showed a single peak corresponding to the higher-frequency peak in this study but with a greater magnitude. However, their individual subject data showed both peaks for many individuals, partly supporting the data reported here, although further studies will be necessary to confirm the nature of this cross-axis transfer function. The *z–x* cross-axis apparent masses for the 'back-off' condition corresponded to those of Nawayseh and Griffin in their 'maximum thigh contact' condition.

Overall, all data obtained in this study using single-axis vibration are in general agreement with the literature, thereby validating the multi-axis system used in this study.

Results from this experiment indicate that apparent masses and cross-axis apparent masses have similar shapes for data obtained using single-axis vibration and dual-axis vibration stimuli. There is no reason to suspect that there would be any additional changes in apparent mass if vibration occurred in three axes simultaneously, although this will require confirmation experimentally. This finding suggests that models derived from previous experiments, that have always used single-axis stimuli, could be applied in more complex multi-axis environments.

Although the general shape of the apparent mass curves remained similar between single- and dual-axis environments, the resonance frequencies tended to be lower for the dual-axis conditions. This finding parallels the nonlinearity that has often been reported in the literature where the peak in the apparent mass reduces in frequency as the vibration magnitude increases, when subjects sit in a relaxed posture. Vibration magnitudes in more than one direction are often combined using the root-sum-of-squares method; if this method is applied to the stimuli used in this experiment the single-axis data would have a magnitude of $0.4\,\mathrm{ms}^{-2}$ rms and the dual-axis data would have a magnitude of $0.57\,\mathrm{ms}^{-2}$ rms This experiment showed a median reduction of 14% between vertical apparent mass resonance frequencies for the single- and dual-axis conditions. This suggests that the magnitude of vibration in an orthogonal axis contributes to the nonlinearity.

The most consistent, and significant, difference between single- and dual-axis vibration occurred between the *z*-axis apparent mass measured using single-axis vibration and *yz*-vibration, for both backrest conditions. This suggests an alternative mechanism of biomechanical cross-talk to that shown using the cross-axis apparent masses, as there was little evidence of any cross-axis effects in the lateral direction. Further work is required to confirm this observation, to establish the extent of the cross-axis effect and to explain the effect.

Despite this study indicating only small differences between single and multi-axis environments, it has shown that it is important to consider vibration in all directions when calculating forces acting on the suspension mechanism of a suspension seat. Three components of force combine to produce a force on the suspension. First, there is the inertial force of the moving parts of the seat; assuming this part of the seat is nominally rigid in the frequency of interest, this is equal to the product of the moving mass and the acceleration at any frequency. The second component of the force acting on the suspension is due to the human loading the seat in the direction of the vibration, and equal to the product of the apparent mass and acceleration at any frequency. The third component of the force is the force due to the cross-axis components, equal to the product of the cross-axis apparent mass and acceleration in the relevant orthogonal direction. In practice, the cross-axis components are only important between the *x*- and *z*-directions. Although this approach can enhance the prediction of forces on a suspension, it remains a simple model and other factors, such as seat/cab inclination are also important [23]. Other nonlinear effects might occur due to multi-axis vibration (e.g. changes in suspension friction forces), but these are beyond the scope of this paper.

5. Conclusions

Apparent masses and cross-axis apparent masses measured using dual-axis vibration are almost identical to those obtained using single-axis vibration. There is some evidence of a decrease in apparent mass resonance frequency with increased r.s.s. vibration magnitude, analogous to the nonlinearity that occurs with increases in vibration magnitude for single-axis vibration. Vertical apparent masses measured using combined *yz*-vibration have primary peaks at a significantly lower frequency than those measured using *z*-axis vibration, despite there being negligible magnitude in the cross-axis apparent mass between the *y*-axis and the *z*-axis. Further work is required to establish whether the similarities between biomechanical responses to single and dual-axis vibration also hold for tri-axial vibration. Further work is also required to confirm that these similarities are also apparent at other magnitudes of vibration.

References

[1] N.J. Mansfield, *Human Response to Vibration*, CRC Press, Boca Raton, FL, USA, 2005.

[2] M.J. Griffin, E.M. Whitham, Assessing the discomfort of dual-axis whole-body vibration, *Journal of Sound and Vibration* 54 (1) (1977) 107–116.

[3] R.W. Shoenberger, Intensity judgments of vibrations in the *Y*-axis, *Z*-axis, and *Y*-plus-*Z* axes, *Aviation Space and Environmental Medicine* 58 (8) (1987) 783–787.

[4] R.W. Shoenberger, Intensity judgments of vibrations in the *X*-axis, *Z*-axis, and *X*-plus-*Z* axes, *Aviation Space and Environmental Medicine* 59 (8) (1988) 749–753.

[5] N.J. Mansfield, Impedance methods (apparent mass, driving point mechanical impedance and absorbed power) for assessment of the biomechanical response of the seated person to whole-body vibration, *Industrial Health* 43 (3) (2005) 378–389.

[6] International Organization for Standardization, Mechanical Vibration and Shock—Range of Idealised Values to Characterize Seated-body Biodynamic Response under Vertical Vibration. ISO 5982, Geneva, 2001.
[7] N.J. Mansfield, S. Maeda, Comparison of the apparent mass of the seated human measured using random and sinusoidal vibration, *Industrial Health* 43 (1) (2005) 233–240.
[8] T.E. Fairley, M.J. Griffin, The apparent mass of the seated human body: vertical vibration, *Journal of Biomechanics* 22 (2) (1989) 81–94.
[9] T.E. Fairley, M.J. Griffin, The apparent mass of the seated human body in the fore-and-aft and lateral directions, *Journal of Sound and Vibration* 139 (2) (1990) 299–306.
[10] P. Holmlund, R. Lundström, L. Lindberg, Mechanical impedance of the human body in the vertical direction, *Applied Ergonomics* 31 (2000) 415–422.
[11] P. Holmlund, R. Lundström, Mechanical impedance of the human body in the horizontal direction, *Journal of Sound and Vibration* 215 (4) (1998).
[12] N.J. Mansfield, R. Lundström, The apparent mass of the human body exposed to non-orthogonal horizontal vibration, *Journal of Biomechanics* 32 (12) (1999) 1269–1278.
[13] Y. Matsumoto, M.J. Griffin, Effect of muscle tension on non-linearities in the apparent masses of seated subjects exposed to vertical whole-body vibration, *Journal of Sound and Vibration* 253 (1) (2002) 77–92.
[14] W. Wang, S. Rakheja, P.E. Boileau, Effects of sitting postures on biodynamic response of seated occupants under vertical vibration, *International Journal of Industrial Ergonomics* 34 (4) (2004) 289–306.
[15] S. Rakheja, I. Haru, P.E. Boileau, Seated occupant apparent mass characteristics under automotive postures and vertical vibration, *Journal of Sound and Vibration* 253 (1) (2002) 57–75.
[16] S.D. Smith, L.E. Kazarian, The effects of acceleration on the mechanical impedance response of a primate model exposed to sinusoidal vibration, *Annals of Biomedical Engineering* 22 (1994) 78–87.
[17] J. Giacomin, Apparent mass of small children: experimental measurements, *Ergonomics* 47 (13) (2004) 1454–1474.
[18] S. Maeda, N.J. Mansfield, Comparison of the apparent mass during exposure to whole-body vertical vibration between Japanese subjects and ISO 5982 standard, *Industrial Health* 43 (3) (2005) 436–440.
[19] N.J. Mansfield, S. Maeda, Effect of backrest and torso twist on the apparent mass of the seated body exposed to vertical vibration, *Industrial Health* 43 (3) (2005) 413–420.
[20] S.C. Mandapuram, S. Rakheja, M.A. Shiping, R.G. Demont, P.E. Boileau, Influence of back support conditions on the apparent mass of seated occupants under horizontal vibration, *Industrial Health* 43 (3) (2005) 421–435.
[21] N. Nawayseh, M.J. Griffin, Non-linear dual-axis biodynamic response to fore-and-aft whole-body vibration, *Journal of Sound and Vibration* 282 (3–5) (2005) 831–862.
[22] N. Nawayseh, M.J. Griffin, Tri-axial forces at the seat and backrest during whole-body fore-and-aft vibration, *Journal of Sound and Vibration* 281 (3–5) (2005) 921–942.
[23] N. Nawayseh, M.J. Griffin, Effect of seat surface angle on forces at the seat surface during whole-body vertical vibration, *Journal of Sound and Vibration* 284 (3–5) (2005) 613–634.
[24] N.J. Mansfield, R. Lundström, Orthogonal force response of the seated person when exposed to horizontal whole-body vibration, in: *Paper Presented at the 34th United Kingdom Group Meeting on Human Response to Vibration*, Held at Ford Motor Company, Dunton, Essex, England, 22–24 September 1999, 1999.
[25] N. Nawayseh, M.J. Griffin, Tri-axial forces at the seat and backrest during whole-body vertical vibration, *Journal of Sound and Vibration* 277 (1–2) (2004) 309–326.
[26] G.S. Paddan, M.J. Griffin, A review of the transmission of translational seat vibration to the head, *Journal of Sound and Vibration* 215 (4) (1998).
[27] G.S. Paddan, M.J. Griffin, The transmission of translational seat vibration to the head—II: horizontal seat vibration, *Journal of Biomechanics* 21 (3) (1988) 199–206.
[28] G.S. Paddan, M.J. Griffin, The transmission of translational seat vibration to the head—I: vertical seat vibration, *Journal of Biomechanics* 21 (3) (1988) 191–198.
[29] N.J. Mansfield, P. Holmlund, R. Lundström, P. Lenzuni, P. Nataletti, Effect of vibration magnitude, vibration spectrum and muscle tension on apparent mass and cross axis transfer functions during whole-body vibration exposure, *Journal of Biomechanics* (2006) (in press), doi:10.1016/j.jbiomech.2005.09.024.
[30] S. Maeda, Six degree of freedom electro vibrator for human response to vibration experiment, in: *Paper Presented at the 38th United Kingdom Conference on Human Response to Vibration*, Held at Institute of Naval Medicine, Alverstoke, Gosport, PO12 2DL, England, 17–19 September 2003.
[31] N.J. Mansfield, M.J. Griffin, Effects of posture and vibration magnitude on apparent mass and pelvis rotation during exposure to whole-body vertical vibration, *Journal of Sound and Vibration* 253 (1) (2002) 93–107.
[32] N.J. Mansfield, M.J. Griffin, Non-linearities in apparent mass and transmissibility during exposure to whole-body vertical vibration, *Journal of Biomechanics* 33 (8) (2000) 933–941.
[33] N.J. Mansfield, P. Holmlund, R. Lundström, Apparent mass and absorbed power during exposure to whole-body vibration and repeated shocks, *Journal of Sound and Vibration* 248 (3) (2001) 427–440.
[34] N. Nawayseh, M.J. Griffin, Non-linear dual-axis biodynamic response to vertical whole-body vibration, *Journal of Sound and Vibration* 268 (3) (2003) 503–523.