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APPARENT MASS AND ABSORBED POWER DURING EXPOSURE TO WHOLE-BODY VIBRATION AND REPEATED SHOCKS

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Exposure to mechanical shocks might pose a greater health risk than exposure to continuous vibration. Previous studies have investigated subjective responses, muscle activity or transmission of vibration to the spine or head during shock. If there is a difference between biomechanic responses of the seated body to shocks when compared to continuous vibration, then this may indicate a more, or less, hazardous vibration waveform. This paper presents measurements of apparent mass and absorbed power during exposure to random vibration, repeated shocks and combinations of shocks and random vibration. Eleven male and 13 female subjects were exposed to 15 vibration conditions generated using an electro-dynamic shaker. Subjects were exposed to five 20 s acceleration waveforms with nominally identical power spectra (random vibration, equally spaced shocks, unequally spaced shocks, random combined with equally spaced shocks, random combined with unequally spaced shocks) at each of 0·5, 1·0 and 1·5 m/s^2 r.m.s. The general shapes of the apparent mass or absorbed power curves were not affected by stimulus type, indicating that the biomechanical response of the body is fundamentally the same when exposed to shocks or random vibration. Two non-linear effects were observed: apparent mass resonance frequencies were slightly higher for exposure to shocks; apparent mass and absorbed power resonance frequencies decreased with increases in vibration magnitude for each stimulus type. It is concluded that the two non-linear mechanisms operate simultaneously: a stiffening effect during exposure to shocks and a softening effect as vibration magnitudes increase. Total absorbed powers were greatest for shock stimuli and least for random vibration.

1. INTRODUCTION

It is generally accepted that mechanical shocks are more hazardous to health than continuous vibration. In a review of literature and expert opinion on high acceleration events, Sandover [1] asked a group of researchers that included "all of the known major experts in the field", to respond to a questionnaire. In response to the question: "compared to ordinary vibration, do you consider that high acceleration events have a disproportionate effect on health?", 15 responded "yes", one was not sure and none responded "no". Despite the agreement amongst researchers that shocks are important when considering health, most studies of the biomechanic response of the body to whole-body vibration (WBV) have used continuous random or sinusoidal vibration. Although some studies have investigated transmission of acceleration to the spine and head

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[2–4], EMG activity [2, 5, 6] or subjective responses [7–9] there are no known studies of the apparent mass, driving point mechanical impedance or absorbed power during exposure to shocks.

Measurements of the biodynamic response of the body when exposed to WBV include using the driving point mechanical impedance, apparent mass or absorbed power. All three quantities can be calculated from measures of force and acceleration at a seat that is vibrating. The apparent mass, $M(f)$, and mechanical impedance, $Z(f)$, are defined as

$$M(f) = F(f)/a(f), \quad Z(f) = F(f)/v(f),$$

where $F(f)$ is the force, $a(f)$ is the acceleration and $v(f)$ is the velocity at the driving point expressed as a function of frequency, f. Apparent mass has the advantage of indicating subject weight at low frequencies. Converting between measurements of apparent mass and mechanical impedance is a simple process. Studies of the apparent mass of the seated body using random and sinusoidal vibration have consistently shown a vertical resonance at about 5 Hz and some evidence of a second peak at about 10 Hz [10–14]. These resonances were shown to reduce in frequency with increased vibration magnitude indicating that the body responds as a non-linear system. Although magnitude of vibration affects the shape of the apparent mass curve, it does not affect the overall magnitude of the curve. Similarly, as apparent mass does not include a time term, it does not increase with vibration duration. Consequently, apparent mass is not directly related to the vibration intensity or exposure time and is therefore an unsuitable quantity for assessment of vibration severity or vibration "dose".

An alternative analysis technique is to use the absorbed power, $P(f)$, which is defined as [15]

$$P(f) = F(f)v(f)\cos(\phi_{F,v}),$$

where $\phi_{F,v}$ is the phase between the force and the velocity. The absorbed power also shows peaks at about 5 Hz, which decrease in frequency with increases in vibration magnitude [16, 17]. One difference between absorbed power and apparent mass is that the absorbed power can be used to measure a vibration "dose", as it increases with vibration magnitude and duration. If absorbed power is proportional to injury risk then as it is accepted that the body is more sensitive to shocks than to continuous vibration, one might expect that the absorbed power would reflect these different sensitivities.

There are no known studies of the apparent mass or absorbed power during exposure to shocks. This paper reports an experimental study in which the biomechanic response of the body was measured for male and female subjects exposed to vibration stimuli comprising continuous random vibration, repeated shocks and combinations of random and shock stimuli.

2. METHOD

2.1. EXPERIMENTAL CONDITIONS

Each subject was exposed to 15 vibration conditions during one experimental session of about 15 min. Five vertical acceleration waveforms were used, each presented at 0·5, 1·0 and 1·5 m/s^2 r.m.s., unweighted (all vibration magnitudes are expressed as unweighted r.m.s. in the following text). Each stimulus was restricted to 20 s in order to minimize subjects'

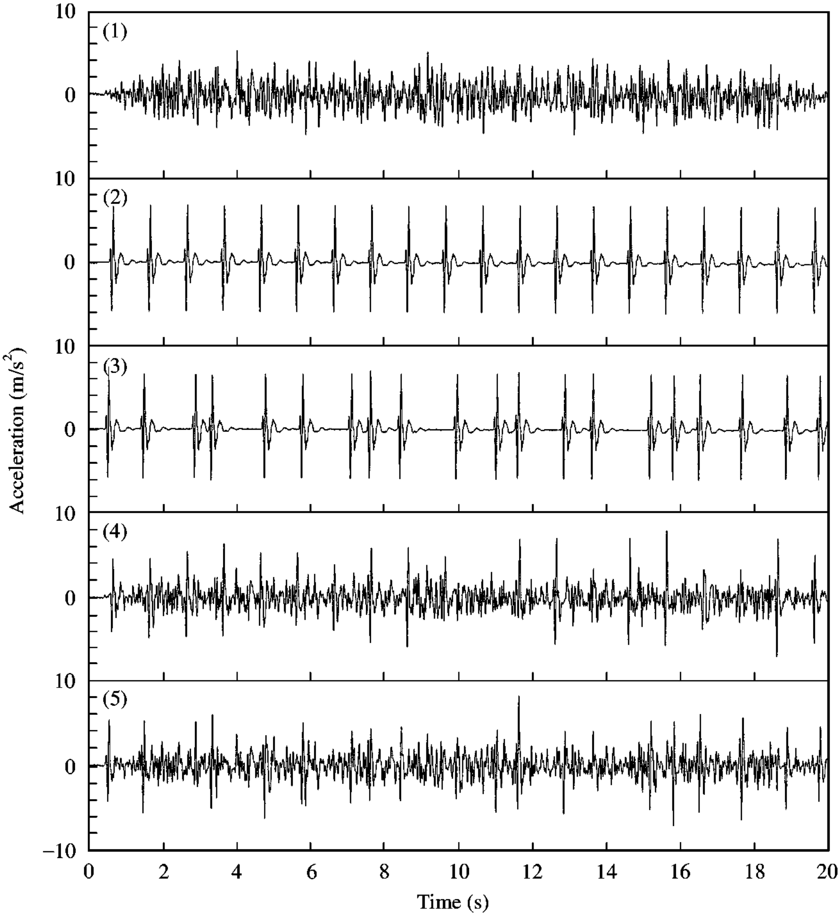

Figure 1. Five stimulus types used in the experiment: (1) random, (2) equally spaced shocks, (3) unequally spaced shocks, (4) random and equally spaced shocks combined, (5) random and unequally spaced shocks combined. Each stimulus was generated at 0·5, 1·0 and 1·5 m/s^2 r.m.s. (unweighted).

exposure, although pilot studies have shown that reliable apparent masses can be measured within 10 s using random vibration [18]. Stimulus 1 consisted of random vibration in the frequency range of 2–20 Hz (see Figure 1). Stimulus 2 consisted of 20 repeated mechanical shocks at equally spaced 1-s intervals (i.e., predictable). Stimulus 3 consisted of 20 repeated shocks that were not equally spaced (i.e., non-predictable). Stimuli 4 and 5 were combinations of stimuli 1 and 2 and of 1 and 3, respectively, with half of the energy coming from the shocks, scaled to give the appropriate unweighted acceleration magnitude. The shocks were defined as sinc pulses that were high- and low-pass filtered at 2 and 20 Hz using elliptic filters. The stimuli used to generate the vibration were equalized for the response of the amplifier and shaker to produce a flat spectrum at the seat. Consequently, for each of the three vibration magnitudes, each stimulus had nominally identical power spectra at frequencies above 3 Hz (see Figure 2). All measured values for unweighted vibration exposure were within 7% of those specified in the experimental design. At frequencies above 2 Hz there was a high coherence between force and acceleration signals (see Figure 2). A balanced random order of presentation of stimuli was used to minimize the influence of order effects or subject fatigue.

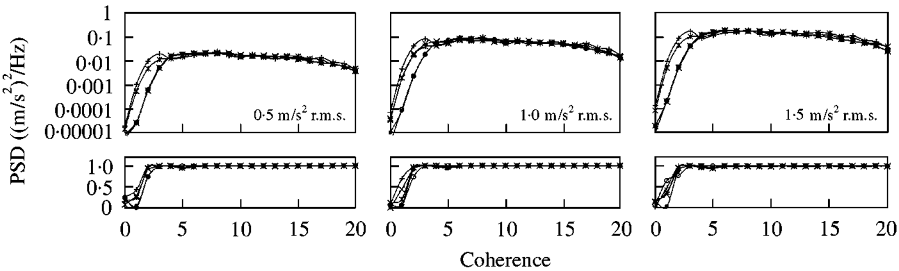

Figure 2. Typical power spectra of vibration stimuli and coherence between force and acceleration signals measured using the 15 stimuli (subject 1): random (+), equally spaced shocks (○), unequally spaced shocks (●), combined random and equally spaced shocks (×), combined random and unequally spaced shocks (✱).

Magnitudes of vibration greater than 1·5 m/s^2 are common in some vehicles, and might be expected to give the clearest indications of non-linearities in the body. However, previous studies have shown the greatest non-linear effects between 0·5 and 1·5 m/s^2 [14]. The highest crest factor for any of the stimuli was 5·6. Therefore, the peak accelerations for the 1·5 m/s^2 r.m.s. stimulus were 8·4 m/s^2. If stimuli magnitudes were increased to encompass, for example, 2·0 m/s^2 then the peak accelerations would exceed 1 g, which could result in subjects leaving the surface of the seat and introducing an additional, uncontrolled source of non-linearity. For these and ethical reasons, the exposure magnitudes for the experiment were limited to 1 g peak which corresponded to a maximum stimulus of 1·5 m/s^2.

2.2. INSTRUMENTATION

Subjects sat on a rectangular flat rigid seat containing a Kistler 9251A force cell at each corner and a Brüel and Kjær 4231 accelerometer in the centre. The seat surface had dimensions of 230 × 300 mm and was horizontal. Outputs from the four force transducers were summed prior to amplification to give the total vertical force at the seat. Signals were amplified and filtered (0·2–100 Hz) using Brüel and Kjær 2635 charge amplifiers and acquired at 1024 samples per second using a computer-based data acquisition system. The accelerometer was calibrated using a Brüel and Kjær 4921 accelerometer calibrator. The force channel was calibrated dynamically by measuring the response of known masses exposed to random vibration. The seat was driven using an LDS MPA1 amplifier and LDS 712 electro-dynamic shaker.

2.3. SUBJECTS

Eleven males and 13 females participated in the experiment (see Table 1). Subjects sat in a comfortable upright posture with hands resting on the lap. The foot position was set using an adjustable footrest such that the subjects' thighs were horizontal and the knee angle was 90°. The footrest did not move with the seat. No backrest was used in the experiment.

Postures were not physically controlled as previous research has shown that vibration magnitude and inter-subject differences affect apparent mass more than small postural changes [18]. Therefore, it was assumed that small differences in posture between conditions were not significant. However, to minimize any possible effects, subjects were instructed to maintain the same posture throughout the experiment. No postural changes were observed by the experimenter, who was positioned such that the profile of the subjects

TABLE 1

Subject characteristics

	Male ($n = 11$)				Female ($n = 13$)				All ($n = 24$)			
	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max
Age	36	8	25	49	44	8	26	57	40	9	25	57
Weight	81	8	72	96	67	7	54	79	74	10	54	96
Height	182	5	173	188	166	4	154	171	173	9	154	188

could be continually monitored. Subjects were also video taped to enable post-experiment checking for postural changes.

2.4. ANALYSIS METHODS

Apparent masses, $M(f)$, were calculated by using

$$M(f) = F(f)/a(f),$$

where $F(f)$ is the force and $a(f)$ is the acceleration at the seat expressed as a function of frequency. Transfer functions were calculated using the cross-spectral density method [19]. As the force measurements were influenced by the mass of the surface of the seat supported on the force cells, a mass cancellation technique was applied to subtract the response of the seat surface in the frequency domain. To enable results to be compared for subjects of different weights, transfer functions were normalized by dividing the moduli of each subject's apparent mass by the subject's sitting weight. The subject's sitting weight was taken as the mean apparent mass for the 15 conditions at 2 Hz.

The absorbed power, $P_{abs}(f)$, was calculated by using [17]

$$P_{abs}(f) = |G_{Fv}(f)| \cos \phi(f),$$

where $|G_{Fv}(f)|$ is the modulus and $\phi(f)$ is the phase of the cross-spectral density between the force and the velocity at frequency f. As absorbed power is a quotient of force and velocity, it is sensitive to both subject weight and slight changes in acceleration magnitude at any frequency. To compare the responses for different subjects, or for different vibration magnitudes, transfer functions were divided by the power spectrum of the acceleration and the total subject weight to give the normalized absorbed power:

$$\text{normalized } P_{abs}(f) = P_{abs}(f)/mG_a(f),$$

where $G_a(f)$ is the power spectrum of the acceleration at the seat and m is the subject weight.

All analyses were carried out using LabVIEW 3.1.1 software at a frequency resolution of 0·25 Hz.

3. RESULTS

3.1. APPARENT MASS

Apparent masses of the 24 subjects showed similar features. All subjects showed a peak in apparent mass between 4 and 7 Hz which reduced in frequency with increased acceleration magnitude by about 0·6 Hz (see Table 2). The magnitude of the peak in apparent mass

TABLE 2

Apparent mass resonance frequencies measured for 11 *male and* 13 *female subjects exposed to* 15 *vibration stimuli* (*Hz*)

Stimulus type	Random			Shocks equal			Shocks unequal			Combined equal			Combined unequal		
Vibration magnitude (m/s^2 r.m.s.)	0·5	1·0	1·5	0·5	1·0	1·5	0·5	1·0	1·5	0·5	1·0	1·5	0·5	1·0	1·5
Male 1	4·50	4·00	3·75	4·75	4·25	4·25	4·75	4·25	4·00	4·50	4·25	4·25	4·75	4·50	3·75
Male 2	5·50	4·50	4·25	5·50	5·00	4·75	5·50	4·50	4·75	5·50	4·75	4·50	5·50	4·75	4·50
Male 3	5·75	4·75	4·75	6·00	5·50	5·00	6·00	5·50	5·25	6·00	4·75	4·75	5·75	5·00	5·00
Male 4	4·75	4·25	4·00	4·75	4·50	4·25	5·00	4·50	4·25	4·75	4·50	4·25	4·75	4·50	4·25
Male 5	5·75	5·00	4·75	6·00	5·25	4·50	5·00	4·75	4·25	6·00	4·75	4·75	5·25	5·00	4·75
Male 6	5·00	4·75	4·50	5·50	5·25	4·75	5·50	5·00	5·00	5·25	4·75	4·50	5·25	5·00	4·75
Male 7	5·75	5·50	4·75	5·75	5·25	5·25	6·00	5·50	5·25	5·50	4·75	5·00	5·25	5·25	5·00
Male 8	5·75	5·75	5·25	6·25	5·50	5·25	6·00	5·25	5·25	6·25	5·00	5·00	5·75	5·25	5·00
Male 9	4·75	4·50	4·25	5·00	4·75	4·50	5·00	4·75	4·25	4·75	4·50	4·50	4·75	4·75	4·50
Male 10	4·50	4·00	4·00	4·75	4·50	4·25	5·00	4·25	4·00	4·75	4·50	4·25	4·75	4·25	3·75
Male 11	4·75	4·50	4·00	5·25	5·00	4·50	5·25	4·75	4·50	5·25	4·75	4·50	5·00	4·75	4·50
Female 1	5·50	4·75	4·75	5·50	5·00	4·75	5·50	5·00	5·00	5·25	4·75	4·75	5·25	5·00	4·75
Female 2	5·75	4·50	4·75	5·50	5·25	4·50	5·75	5·25	4·75	5·50	4·75	4·75	5·00	4·75	4·75
Female 3	4·00	3·75	3·75	4·75	4·50	4·50	4·75	4·75	4·50	4·50	4·50	4·50	4·75	4·75	4·75
Female 4	4·75	4·50	4·25	5·25	4·75	4·50	5·25	4·75	4·75	5·00	4·75	4·50	5·00	4·75	4·50
Female 5	6·50	5·75	5·75	6·50	6·00	5·75	6·25	6·00	5·75	6·50	6·25	5·75	6·75	5·50	5·25
Female 6	5·25	4·75	4·50	5·00	5·00	4·75	5·25	5·00	4·75	5·00	4·75	4·50	5·00	5·00	4·75
Female 7	5·50	4·75	4·50	5·50	5·00	5·00	5·50	5·00	4·75	5·50	4·75	4·75	5·25	4·75	4·75
Female 8	5·50	4·75	4·50	5·50	5·00	4·75	5·25	5·00	4·50	5·25	4·75	4·75	5·25	4·75	4·75
Female 9	4·75	4·75	4·00	5·00	5·00	4·75	5·00	4·75	4·75	5·00	4·75	4·50	5·00	4·75	4·75
Female 10	4·75	4·50	4·50	5·25	5·00	4·75	5·25	4·75	4·75	5·00	4·75	4·50	5·00	4·75	4·75
Female 11	5·50	4·50	4·50	5·50	5·00	5·00	5·25	5·00	5·00	5·25	4·75	4·75	5·00	4·75	4·75
Female 12	4·75	4·50	4·25	5·50	4·75	4·75	5·25	5·00	4·75	4·75	4·75	4·50	4·75	4·75	4·75
Female 13	5·25	5·25	4·75	5·25	5·25	5·00	5·50	5·25	5·00	5·75	4·75	4·75	5·50	5·00	5·00
Mean males	5·16	4·68	4·39	5·41	4·98	4·66	5·36	4·82	4·61	5·32	4·66	4·57	5·16	4·82	4·52
Mean females	5·21	4·69	4·52	5·38	5·04	4·83	5·37	5·04	4·85	5·25	4·85	4·71	5·19	4·87	4·79
Mean all	5·19	4·69	4·46	5·40	5·01	4·75	5·36	4·94	4·74	5·28	4·76	4·65	5·18	4·84	4·67

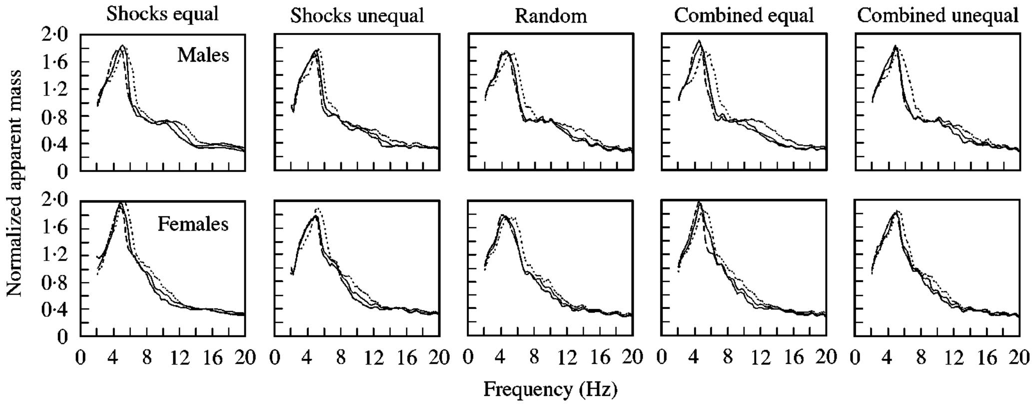

Figure 3. Median apparent masses measured for 11 male and 13 female subjects exposed to five vibration waveforms at 0·5 (----), 1·0 (——) and 1·5 m/s^2 r.m.s. (– – –).

showed no clear trends with vibration magnitude. For each vibration magnitude, mean resonance frequencies and normalized apparent mass magnitudes were generally highest for the equally spaced shocks and lowest for random stimuli, the difference being about 0·2–0·3 Hz. For most conditions, mean resonance frequencies and the magnitude of the normalized apparent masses were higher for female subjects than for male subjects, the only exceptions occurring for equally spaced shocks and combined random and equally spaced shocks at 0·5 m/s^2.

Median apparent masses for male and female subjects for each condition are shown in Figure 3. The general shape of the apparent masses was similar between measurements made using different stimulus types, although the magnitude of the peak at about 5 Hz was slightly lower for the random signals. Most subjects showed a second, highly damped, resonance at about 10 Hz. For the median apparent masses, the averaging process caused the second peak to become less clear, but it could be observed at about 10 Hz, particularly for the males. For each stimulus type, the peak shifted down in frequency with increased vibration magnitude. Consequently, at frequencies above resonance, the highest apparent mass modulus was obtained for measurements made at 0·5 m/s^2 and the lowest at 1·5 m/s^2. At frequencies below resonance, this trend was reversed. Where a second peak could be clearly observed, it too showed a reduction in frequency with vibration magnitude. At frequencies below 6 Hz, the normalized apparent masses for males and females were similar. Between 6 and 10 Hz, male subjects had a lower median apparent mass modulus than females; between 10 and 15 Hz, the apparent mass modulus was slightly greater for males. Above 15 Hz, there were no clear differences in the normalized apparent masses between males and females. Females had a broader peak in the apparent mass than males.

3.2. ABSORBED POWER

All absorbed power spectra showed a peak occurring between 4 and 7 Hz. As for the apparent masses, the frequency of the peak reduced with successive increases in vibration magnitude for all subjects and stimuli types (see Table 3 and Figure 4). The median magnitude of the peak in normalized absorbed power increased with vibration magnitude. At 0·5 m/s^2 the mean resonance frequency was greatest for the combined equally spaced shocks condition. At 1·0 and 1·5 m/s^2, equally spaced shocks stimuli showed the highest

TABLE 3

Absorbed power resonance frequencies measured for 11 *male and* 13 *female subjects exposed to* 15 *vibration stimuli* (*Hz*)

Stimulus type	Random			Shocks equal			Shocks unequal			Combined equal			Combined unequal		
Vibration magnitude (m/s^2 r.m.s.)	0·5	1·0	1·5	0·5	1·0	1·5	0·5	1·0	1·5	0·5	1·0	1·5	0·5	1·0	1·5
Male 1	4·75	4·50	4·25	5·00	4·50	4·50	5·00	4·50	4·50	4·75	4·50	4·50	4·75	4·75	4·50
Male 2	5·50	4·75	4·75	5·75	5·25	5·00	5·75	5·25	5·00	5·50	5·00	4·75	5·50	5·00	4·75
Male 3	6·50	5·25	5·50	6·25	5·75	5·25	6·00	5·50	5·50	6·50	5·25	5·25	6·25	5·25	5·25
Male 4	5·25	4·50	4·50	5·00	4·75	4·50	5·00	4·75	4·75	5·25	4·75	4·50	5·00	4·75	4·75
Male 5	6·25	5·50	5·25	6·50	5·50	4·75	5·25	4·75	4·75	6·25	5·00	5·25	5·75	5·25	5·00
Male 6	5·50	5·50	4·75	5·50	5·25	5·00	5·75	5·25	5·25	5·50	5·25	5·00	5·50	5·25	5·00
Male 7	6·25	5·50	5·25	6·25	5·50	5·50	6·25	6·00	5·50	6·25	5·25	5·50	6·00	5·50	5·25
Male 8	6·50	6·00	5·50	6·50	5·75	5·50	6·00	5·50	5·50	6·50	5·50	5·50	6·00	5·50	5·25
Male 9	5·25	4·75	4·75	5·25	5·00	4·75	5·25	5·00	4·75	5·00	4·75	4·50	5·00	4·75	4·75
Male 10	4·75	4·50	4·50	5·00	4·75	4·50	5·00	4·75	4·50	5·00	4·50	4·50	5·00	4·50	4·50
Male 11	5·50	4·75	4·50	5·25	5·25	4·75	5·50	5·00	4·75	5·50	4·75	4·50	5·25	4·75	4·75
Female 1	5·50	5·50	5·25	5·75	5·25	5·25	5·75	5·50	5·25	5·50	5·25	5·00	6·00	5·50	5·00
Female 2	6·25	4·50	5·25	5·50	5·50	4·75	6·00	5·75	5·00	6·25	5·50	5·25	5·25	5·25	5·25
Female 3	4·00	4·75	4·50	5·00	4·75	4·75	5·00	5·00	4·75	4·75	4·75	4·50	5·00	4·75	4·75
Female 4	5·50	4·75	4·75	5·25	5·00	4·75	5·50	5·00	4·75	5·50	5·00	4·75	5·25	5·00	4·75
Female 5	6·50	6·25	6·25	6·75	6·25	6·00	6·75	6·25	6·00	7·00	6·50	6·25	6·75	6·25	6·00
Female 6	5·50	5·25	4·75	5·25	5·25	5·00	5·50	5·00	5·00	5·50	5·25	4·75	5·50	5·25	5·25
Female 7	5·50	5·50	4·75	5·75	5·25	5·00	5·75	5·25	5·00	5·50	5·25	5·00	5·50	5·00	5·00
Female 8	5·50	5·50	4·75	5·75	5·25	5·00	5·50	5·00	4·75	5·50	5·00	4·75	5·50	5·00	4·75
Female 9	5·50	5·00	4·75	5·25	5·25	4·75	5·25	5·00	5·00	5·25	5·00	4·75	5·25	5·00	4·75
Female 10	5·50	4·75	4·75	5·50	5·25	5·00	5·50	5·00	5·00	5·50	5·00	4·75	5·25	5·00	4·75
Female 11	5·50	5·50	5·25	5·75	5·25	5·25	5·75	5·25	5·25	5·50	5·25	5·00	5·50	5·25	4·75
Female 12	5·25	5·25	4·75	5·75	5·25	5·00	5·75	5·00	5·00	5·25	5·00	4·75	5·00	5·00	4·75
Female 13	5·50	5·50	5·25	5·50	5·50	5·25	6·00	5·50	5·00	6·25	5·50	5·25	5·75	5·25	5·25
Mean males	5·64	5·05	4·86	5·66	5·20	4·91	5·52	5·11	4·98	5·64	4·95	4·89	5·45	5·02	4·89
Mean females	5·50	5·23	5·00	5·60	5·31	5·06	5·69	5·27	5·06	5·63	5·25	4·98	5·50	5·19	5·00
Mean all	5·56	5·15	4·94	5·63	5·26	4·99	5·61	5·20	5·02	5·64	5·11	4·94	5·48	5·11	4·95

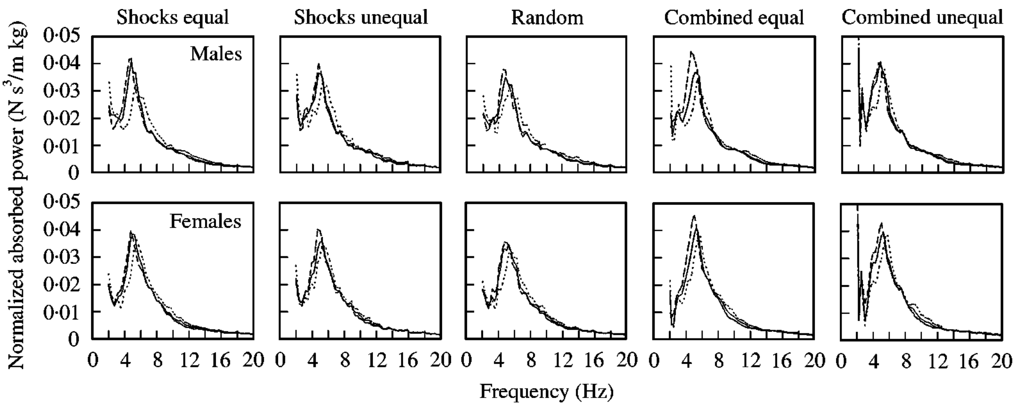

Figure 4. Median absorbed powers measured for 11 male and 13 female subjects exposed to five vibration waveforms at 0·5 (- - - -), 1·0 (——) and 1·5 m/s^2 r.m.s. (– – –).

resonance frequencies. The peak normalized absorbed power at resonance was greatest and lowest for equally spaced shocks and random stimuli, respectively, for all vibration magnitudes. Mean resonance frequencies for the normalized absorbed power were generally higher for females than for males. The magnitude of the peak normalized absorbed power at resonance was generally lower for females than for males. At frequencies below 3 Hz there was no consistent value for normalized absorbed power.

4. DISCUSSION

Apparent masses measured using all stimulus types had a similar shape to those observed in previous studies, which used random or sinusoidal vibration. Fairley and Griffin [10] showed almost identical mean normalized apparent masses for 24 men and 24 women, whereas this study agreed with that of Holmlund *et al.* [11, 12], who showed differences in impedance with gender at frequencies above resonance. However, for random stimuli, gender differences were only significant at 9 Hz 0·5 m/s^2 ($p < 0{\cdot}1$, Mann–Whitney), at 7 and 8 Hz for 1·0 m/s^2 ($p < 0{\cdot}1$, $p < 0{\cdot}05$, respectively), and at 7 Hz for 1·5 m/s^2 ($p < 0{\cdot}05$). There were no significant differences between male and female subjects for apparent mass resonance frequencies or normalized magnitudes at resonance.

Absorbed power spectra were also similar to those previously reported, if the various methods for normalization are taken into account [16, 17, 20]. For random stimuli, average resonance frequencies for male subjects at the three vibration magnitudes were within 5% of those reported by Mansfield and Griffin [17], who used the same vibration magnitudes but different subjects and a different laboratory. The peaks in the absorbed power generally occurred at a slightly higher frequency and lower magnitude for females than for males. This is in contrast to the results of Lundström and Holmlund [16], who showed opposite trends. However, differences in the normalized absorbed power resonance frequency or magnitude between males and females were not significant.

The increased values for absorbed power at frequencies below 3 Hz was an effect of the normalization process. At low frequencies, small involuntary postural changes or any response of the 2 Hz horizontal mode of the body affect the force measurements at the seat. When this coincides with a low value of acceleration power spectra, as indicated in Figure 2 for some stimuli, the normalized absorbed power shows a large value that is not observed

TABLE 4

Wilcoxon matched-pairs signed-ranks test results for comparison of apparent mass and absorbed power resonance frequencies measured using five vibration waveforms at three acceleration magnitudes (*apparent mass data*: $*p < 0{\cdot}01$; $**p < 0{\cdot}005$; $***p < 0{\cdot}001$; *absorbed power data*: $^{+}p < 0{\cdot}01$; $^{++}p < 0{\cdot}005$; $^{+++}p < 0{\cdot}001$)

Vibration magnitude m/s^2 r.m.s.	Stimulus type	Random	Shocks equal	Shocks unequal	Combined equal	Combined unequal
	Random	—				
	Shocks equal	**	—			
0·5	Shocks unequal			—		
	Combined equal				—	
	Combined unequal		**	**		—
	Random	—				
	Shocks equal	***	—		++	++
1·0	Shocks unequal	**		—		
	Combined equal		***	*	—	
	Combined unequal		**			—
	Random	—				
	Shocks equal	***	—			
1·5	Shocks unequal	**		—		
	Combined equal	**	*		—	
	Combined unequal	**				—

in non-normalized data. As apparent mass is defined as a ratio of the force to acceleration, such effects do not occur.

Reductions in the resonance frequency of apparent mass and absorbed power with vibration magnitude were significant for all stimuli ($p < 0{\cdot}01$, Wilcoxon). Comparisons of the magnitude of the peak apparent masses with vibration magnitudes showed significant differences for only two of the conditions: unequally spaced shocks 1·0 and 1·5 m/s^2 (significant decrease, $p < 0{\cdot}05$); combined random and equally spaced shocks 0·5 and 1·0 m/s^2 (significant increase, $p < 0{\cdot}005$). For the absorbed power, increased vibration magnitude from 0·5 to 1·0 m/s^2 caused significant increases in the magnitude of the peak for all stimuli types ($p < 0{\cdot}001$). Between 1·0 and 1·5 m/s^2, the increases were significant for combined ($p < 0{\cdot}05$, equally spaced; $p < 0{\cdot}001$, unequally spaced), random ($p < 0{\cdot}1$) and equally spaced shock stimuli ($p < 0{\cdot}1$).

Apparent mass resonance frequencies were not significantly different between equal and unequally spaced shocks or between the two combined stimuli for any vibration magnitude (see Table 4). The magnitudes at resonance were generally significantly greater for equally spaced shocks than for unequally spaced shocks. The frequency and magnitude of peaks in apparent mass are often related to the stiffness and damping of a system respectively. As there was no difference in frequency, but a difference in magnitude, these data indicate that the spacing (and hence the predictability) of the shocks do not affect the stiffness but do affect the damping of the biodynamic system. A similar conclusion can be reached from the absorbed power data.

Despite the trends in the ranking of apparent mass resonance frequencies with stimulus type, statistical analyses of the resonance frequencies at the three vibration magnitudes were not consistent. At 0·5 m/s^2, apparent mass resonance frequencies were significantly greater for shock stimuli than for combined unequally spaced shocks ($p < 0{\cdot}005$, Wilcoxon, Table 1). Similarly, equally spaced shocks generated significantly greater apparent mass resonance frequencies than random vibration ($p < 0{\cdot}005$). At $1{\cdot}0\ m/s^2$, apparent mass resonance frequencies were significantly greater for shocks stimuli than other stimuli types for five of the six combinations ($p < 0.01$). At $1{\cdot}5\ m/s^2$, resonance frequencies for random stimuli were significantly lower than those obtained using other stimuli ($p < 0{\cdot}005$).

There were generally no significant differences between absorbed power resonance frequencies measured using different stimuli at each vibration magnitude. Significant differences were only obtained between two sets of conditions: equally spaced shocks with combined stimuli at $1{\cdot}0\ m/s^2$.

Although these data show that there were small differences between resonance frequencies, apparent mass and absorbed power spectra were generally similar between vibration conditions across the frequency range measured. One might therefore conclude that the mechanisms responsible for causing the biomechanical response of the body during exposure to steady state vibration are the same as those operating during exposure to shock. A similar conclusion has previously been reported for measurements of transmission of vibration to the head when measured using shocks and sinusoidal vibration at discrete frequencies [4].

Considering apparent mass data, resonance frequencies were generally lowest for random vibration and highest for the shock stimuli. Due to the different stimuli waveforms, vibration dose values (VDVs; [21]) were also lowest for random vibration and highest for shock stimuli. For example, at $1{\cdot}5\ m/s^2$, VDVs were about 3·8, 4·5 and $5{\cdot}3\ m/s^{1{\cdot}75}$ (W_k weighted) for random, combined and shock stimuli where mean resonance frequencies were 4·46, about 4·65 and about 4·75 respectively. Hence, at each of the three vibration magnitudes studied, resonance frequencies increased with VDV. This trend was the opposite of that observed when considering the effect of vibration magnitude alone (i.e., resonance frequencies decreased with increases in vibration magnitude). It is possible that the stiffening response occurred after the first impact, when subjects were aware of the stimulus type to which they were being exposed. As this study used stimuli with 20 repeated shocks, it is unclear whether the stiffening characteristic would be observed for single discrete shocks.

The apparent conflicting results showing either stiffening with increased VDV (due to waveform changes) or softening with increased VDV (due to magnitude changes) indicate that simple mathematical models cannot fully represent the apparent mass of the body to a variety of vibration magnitude and waveforms. In attempts to reproduce the softening response of the body with increased vibration magnitude, previous studies have reported lumped parameter models with quasi-static non-linear components where values for the model parameters were defined for a range of discrete vibration magnitudes [22–25]. A problem with such approaches is that the vibration characteristics must be known prior to the modelling to fit the parameters. An alternative is to use models with non-linear elements. A system with a mass non-linearity can also reproduce a softening effect. In practice, this can be realized by an inverted pendulum or by feedback of the absolute acceleration to an active element in the system [24]. Combinations of linear and cubic components in the stiffness term of a single-degree-of-freedom system can also represent a softening system. Finally, it is possible to represent a softening system using continuous models with buckling elements. One problem with all of these non-linear models is that although they can represent the changes in apparent mass with vibration magnitude, they are unable to show the stiffening effect during the shock conditions. Defining and verifying an appropriate non-linear model which reproduces the observed waveform and vibration magnitude effects would be complex and not trivial.

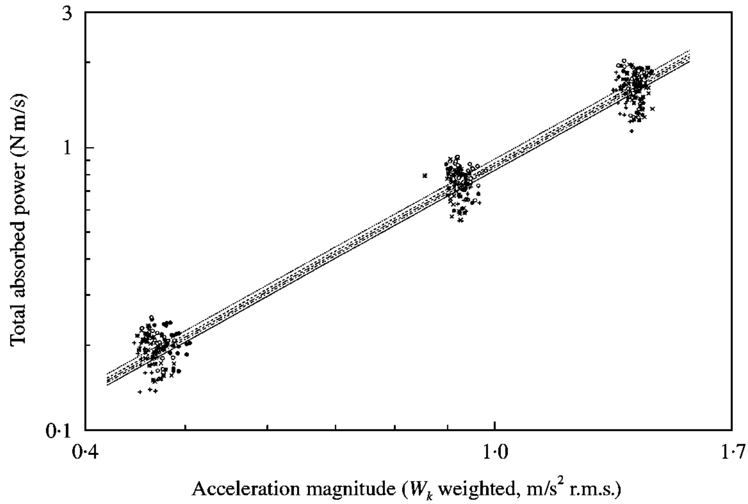

Figure 5. Total absorbed powers and fitted curves plotted against W_k weighted acceleration for 24 subjects exposed to five vibration waveforms: random (+), equally spaced shocks (○), unequally spaced shocks (●), combined random and equally spaced shocks (×), combined random and unequally spaced shocks (∗). Fitted curve to random (——), equally spaced shocks (- - - -), unequally spaced shocks (– – –), combined random and equally spaced shocks (– – – – –), combined random and unequally spaced shocks (— - — - —).

An additional method of analysis is to use the "total absorbed power" ($P_{abs}total$), obtained by integrating the absorbed power spectra across the frequency range of interest; in this case between 3 and 20 Hz [17]:

$$P_{abs}total = \int_{f=3}^{f=20} P_{abs}\,\mathrm{d}f,$$

3 Hz was chosen as a lower limit as slight discrepancies between vibration spectra for different stimuli types occurred at lower frequencies. For a linear system, total absorbed power increases proportionally with mass and to the square of the acceleration.

For these data, total absorbed power had a large variability, primarily due to the differences in subject weight (see Figure 5). However, individual subject data generally showed that the total absorbed powers were greatest for shock stimuli and least for random stimuli. This general finding is in agreement with measurements of absorbed power in the hand–arm system during exposure to impulsive and non-impulsive vibration [26]. Differences between total absorbed powers at the three magnitudes of vibration were significant ($p < 0{\cdot}0001$, Wilcoxon) between all stimuli types except for the comparison of combined equally and unequally spaced shocks. If it is assumed that the total absorbed power is an indicator of injury risk, one can therefore conclude that exposure to shocks is more severe than would be indicated by assessments based on weighted r.m.s. acceleration alone.

5. CONCLUSIONS

Apparent mass and absorbed power spectra have been shown to be similar during shock exposure to spectra measured using random vibration or to previous studies which used sinusoidal vibration for vibration stimuli amplitudes up to 1·5. Resonance frequencies consistently decreased with successive increases in vibration magnitude, characteristic of a softening system with respect to vibration magnitude. Apparent mass data showed slightly higher resonance frequencies for shock stimuli than those obtained during random vibration, indicating a stiffer system during exposure to shocks. The predictability of the shock signals showed no consistent changes in the apparent mass or absorbed power. Total absorbed powers were greatest for shock stimuli and least for random vibration.

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