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EFFECT OF MAGNITUDE OF VERTICAL WHOLE-BODY VIBRATION ON ABSORBED POWER FOR THE SEATED HUMAN BODY

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The power absorbed by 12 male subjects during exposure to vertical whole-body vibration at six magnitudes of random vibration (0·25, 0·5, 1·0, 1·5, 2·0 and 2·5 ms^{-2} r.m.s.) has been measured in the laboratory. All subjects showed greatest absorbed power at about 5 Hz, but the frequency of this peak in the absorbed power reduced with increasing vibration magnitude. The total absorbed power increased approximately in proportion to the square of the acceleration magnitude: normalizing the absorbed power to the square of the r.m.s. vibration magnitude removed most of the differences, although the changes in resonance frequency were still evident. The frequency dependence of absorbed power at a constant magnitude of acceleration was approximated by a simple weighting having slopes of ± 6 dB/octave either side of 5 Hz. Comparing the characteristics of this absorbed power weighting to standard frequency weightings showed substantial differences, especially at high frequencies. It is concluded that the differences from currently accepted frequency weightings are so great that the absorbed power is unlikely to yield good general predictions of the discomfort or risks of injury from whole-body vertical vibration.

1. INTRODUCTION

The evaluation of human exposure to whole-body vibration so as to predict the risk of injury requires, at least, consideration of the effects of vibration magnitude, vibration frequency and exposure duration. In recent years it has been common to use a "frequency weighting", to allow for the differing injury potential of different frequencies, and a "time-dependency" to reflect any assumed increase in risk with increasing exposure duration. The severity of an exposure might then be given by some measure of the vibration magnitude which is corrected, or weighted, according to the vibration frequency and the exposure duration.

Various types of information from repeatable scientific study might be used to determine the weightings for frequency and duration, for example the observation of pathological changes after exposure to vibration, the monitoring of physiological responses occurring during or following exposure, or the gathering of opinions (e.g., discomfort and pain) reported by exposed subjects. Practical convenience and personal preference has also influenced the choice of evaluation methods. The frequency weightings in whole-body vibration standards (e.g., ISO 2631 [1, 2], BS 6841 [3]) use a combination of the above methods to arrive at uniform procedures for the quantification of vibration severity.

Some engineers may be concerned that the weightings for vibration frequency and exposure duration recommended for the design and assessment of machines and vehicles are derived from studies that are wholly, or partially, subjective. Perhaps some aspect of

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the mechanical structure or dynamic response of the body could be used to by-pass, or reduce, the psychological, physiological and pathological complexities of human responses to vibration.

One dynamic response of the human body that can be measured without requiring a subjective opinion or mounting a device on the body is the point apparent mass, $A(f)$, (or the point mechanical impedance, $Z(f)$),

$$A(f) = F(f)/a(f), \qquad Z(f) = F(f)/v(f) \tag{1, 2}$$

where $F(f)$ is the force at the driving point, $a(f)$ is the acceleration at the driving point and $v(f)$ is the velocity at the driving point, expressed as a function of the vibration frequency, f. The point apparent mass and the point mechanical impedance reflect the relationship between the force and acceleration (or velocity) at the driving point, and are therefore influenced by the mass, stiffness and damping within the body. They show, in a general way, the forces occurring at the seat caused by the internal movements of the body. The apparent mass of the seated body in the vertical direction generally has a vertical resonance in the region of about 5 Hz (see, e.g., references [4–6]) and falls at higher frequencies. So, consistent with discomfort data, the apparent mass would tend to suggest a greater potential for injury in the region of 5 Hz than at lower or higher frequencies. Although the apparent mass of a subject may give some general indication of the importance of vibration frequency, it gives no indication of the effects of either exposure duration or vibration magnitude: neither an increase in exposure duration nor an increase in vibration magnitude results in appreciable changes to the apparent mass [7].

The inclusion of the magnitude and the duration of exposure in a physical measure of the dynamic response of the body may be achieved by using the force and velocity, the same quantities used to determine apparent mass and impedance, so as to calculate the absorbed power: i.e.,

$$P(f) = F(f)v(f)\cos(\phi_{F,v}), \tag{3}$$

where $\phi_{F,v}$ is the phase between the force and velocity [8]. Several researchers have measured the power absorbed by the seated body (e.g., Lee and Pradko [9]; Lundström *et al*. [10]); the method has also been used to quantify vibration exposures of the hand (e.g., by Lidström [11] and Burström and Lundström [12]).

The early work of Pradko and his colleagues led to a proposed method of evaluating ride comfort using absorbed power: this involved the derivation of a frequency weighting (having a peak at about 5 Hz) from laboratory measures of absorbed power, and a time dependency which was "energy-based" (i.e., acceleration inversely proportional to the square root of the exposure duration) after a period of time allowed for the onset of fatigue. The derivation of the frequency weighting from their laboratory studies made it possible to estimate the absorbed power for a subject exposed to any spectrum (e.g., in a vehicle) by merely measuring the acceleration and not having to attempt to simultaneously measure the force.

Lundström *et al*. measured the absorbed power for 15 male and 15 female seated subjects during exposure to vertical whole-body vibration with a range of vibration magnitudes (0·5 to 1·4 ms^{-2} r.m.s.) over the frequency range 2 to 100 Hz while subjects sat with relaxed and erect upper body postures. They found that the absorbed power was a maximum at 5 Hz, that there was little difference between male and female subjects and that an erect sitting posture absorbed less energy than a relaxed posture.

The apparent masses of seated subjects exposed to vertical vibration have been found to be non-linear with respect to vibration magnitude [5, 13]. In these studies, the frequency of greatest apparent mass shows a consistent reduction with increases in the magnitude of vibration; in one study, the apparent mass resonance frequency decreased from about 5.5 Hz to 4·5 Hz as the magnitude of a broad band random vibration increased from 0·25 to 2·5 ms^{-2} r.m.s. in each of 12 subjects studied [13]. Since the resonance frequency of the apparent mass depends upon vibration magnitude it must be expected that the frequency at which the absorbed power is greatest will also depend on vibration magnitude. In general, the frequency weighting appropriate to absorbed power must be expected to depend on the vibration magnitude, and so the absorbed power may not be easily calculated from a knowledge of the vibration magnitude.

The purpose of the present study was to investigate changes in absorbed power in seated subjects associated with changes in the magnitude of vertical vibration. It was hypothesized that the reduction in resonance frequency observed in the apparent mass with increases in magnitude would also be evident in the absorbed power. From the measurements, frequency weightings that would be needed to estimate absorbed power from acceleration spectra were required so that the effect of vibration magnitude on the weightings could be determined and so that the weightings could be compared with those currently used to evaluate exposures to whole-body vibration.

2. METHOD

The experiment was performed by using an electrohydraulic vibrator capable of producing a vertical displacement of 1 m with low distortion and certified safe for human experimentation. Motion of the vibrator was measured by using an Entran EGCSY-240D*-10 accelerometer mounted on the moving platform. A Kistler 9821B force platform, consisting of four matched force cells, was placed on a flat rigid seat secured to the vibrator. The signals from each vertical force transducer were summed prior to amplification and acquisition to provide a single signal. The seat and force platform were rigid in the frequency range of interest.

The accelerometer was calibrated to give an output corresponding to $+9{\cdot}8$ ms^{-2} when inclined at 0° to the vertical and $-9{\cdot}8$ ms^{-2} when inclined at 180° to the vertical, according to the procedure defined in ISO 5347 [15]. The force platform was calibrated statically and checked dynamically. Static calibration was carried out by placing and removing a rigid mass from the surface of the platform. The calibration was checked by measuring the apparent mass of the platform with different rigid loads. This procedure also served to find the mass of the top plate of the transducer (about 17 kg). It was not necessary to subtract the mass of the top plate from the force data (as required for impedance and apparent mass measurements), as a rigid mass does not absorb energy.

Subjects sat in a comfortable upright posture on the force platform and did not use a backrest. The posture was not physically controlled because previous studies have shown a larger variability between subjects than for small postural changes within subjects [16]. However, the experimenter was in constant visual contact with the subjects to ensure that there were no obvious postural changes. Each subject wore a loose safety belt around the lap and held an emergency stop button. The flat surface supporting the subjects was 600 mm wide, 400 mm deep and 470 mm above a foot support that moved with the seat.

A Gaussian random signal having a duration of 60 s and a nominally flat constant bandwidth spectrum over the frequency range 0·2 to 20 Hz was generated by using an HVLab data acquisition and analysis system. The signal was equalized to compensate for non-linearities in the response of the vibrator. The PC based *HVLab* system was comprised of a 16-channel 12-bit Advantech PCL-818 card and an Onsite Instruments Techfilter TF-16 antialiasing card giving −70 dB/octave at a software controlled cut-off frequency. Signals from the accelerometer and force platform were conditioned and acquired at 100

TABLE 1

Subject characteristics

Subject	Age (years)	Weight (kg)	Height (m)
1	23	60	1·84
2	26	72	1·80
3	23	75	1·89
4	30	65	1·73
5	25	70	1·85
6	21	85	1·87
7	34	66	1·65
8	23	60	1·73
9	29	68	1·74
10	37	72	1·80
11	23	66	1·84
12	21	60	1·75

samples per second, via antialiasing filters set at 33 Hz, into the *HVLab* system for analysis. Each subject was exposed to the same vibration waveform at six magnitudes (0·25, 0·5, 1·0, 1·5, 2·0 and 2·5 ms^{-2} r.m.s.) during one experimental session. The magnitude of the vibration to which subjects were exposed was checked after each run. All spectra were calculated by using a resolution of 0·39 Hz and 96 degrees of freedom. A balanced random order of presentation was used across subjects.

Twelve healthy male subjects participated in the experiment that was approved by the Human Experimentation Safety and Ethics Committee of the Institute of Sound and Vibration Research. Subjects had a mean height of 1·79 m (standard deviation, s.d. = 0·07 m) and a mean weight of 68·3 kg (s.d. = 7·3 kg). Subject characteristics are listed in Table 1.

In the absorbed power technique one assumes that the mechanical power, P, transmitted by the seat is equal to the product of the force, F, at the seat and velocity, v, at the seat,

$$\bar{P} = \bar{F} \times \bar{v}, \qquad (4)$$

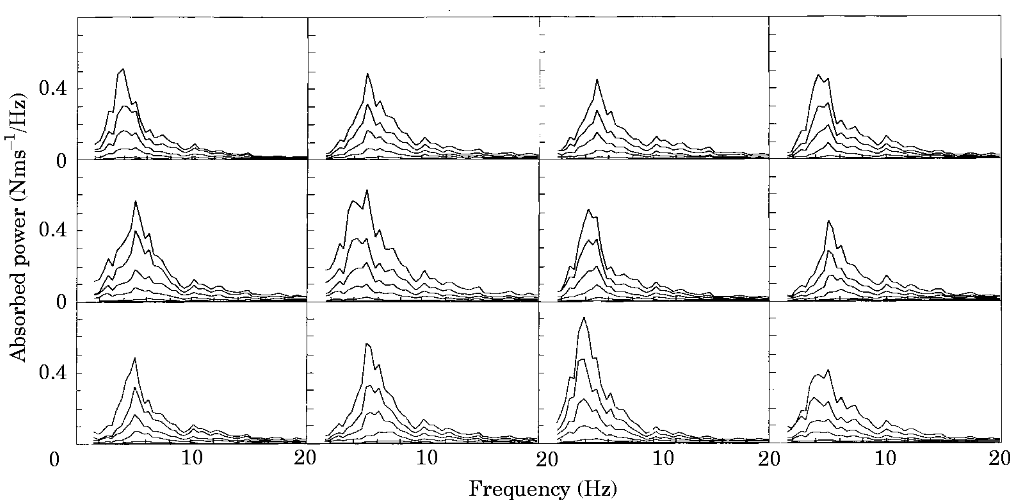

Figure 1. Absorbed power for 12 subjects at six magnitudes of motion. Absorbed power magnitude increases with increasing vibration magnitude.

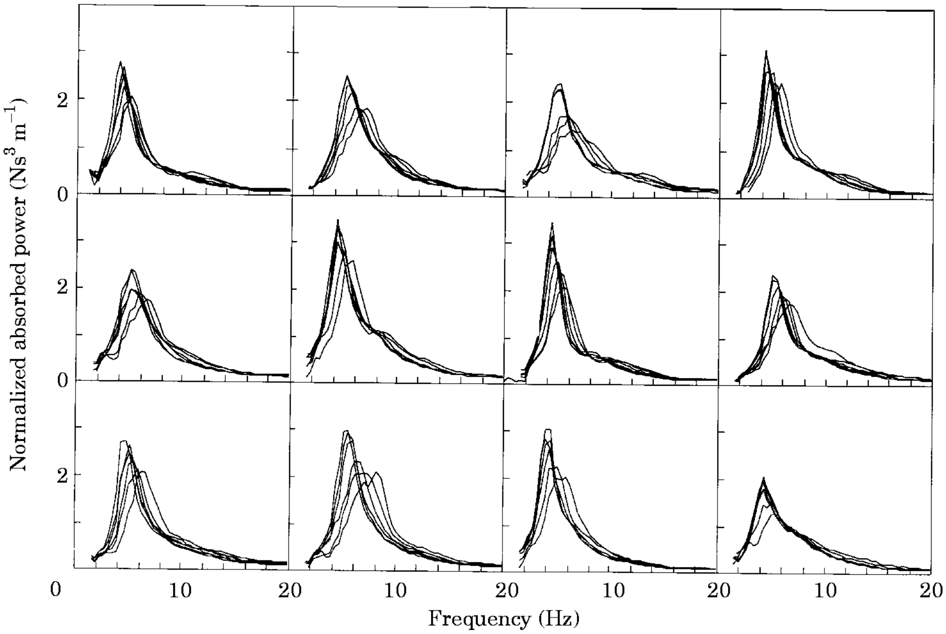

Figure 2. Normalized absorbed power of 12 subjects at six magnitudes of motion. Resonance frequency decreases with increasing vibration magnitude.

where all quantities are vectors, denoted by the bars. Separating the mechanical power into real and imaginary parts gives

$$P_{Re} = F \times v \times \cos(\theta), \qquad P_{Im} = F \times v \times \sin(\theta), \tag{5, 6}$$

where θ is the phase difference between the force and the velocity. When the force and velocity are 90° out of phase, all energy is in the imaginary part. When the force and velocity are in phase then all the energy is in the real part. The real part is the absorbed power. The absorbed power can be calculated by using

$$P_{Abs}(f) = |G_{io}(f)| \cos \phi(f), \tag{7}$$

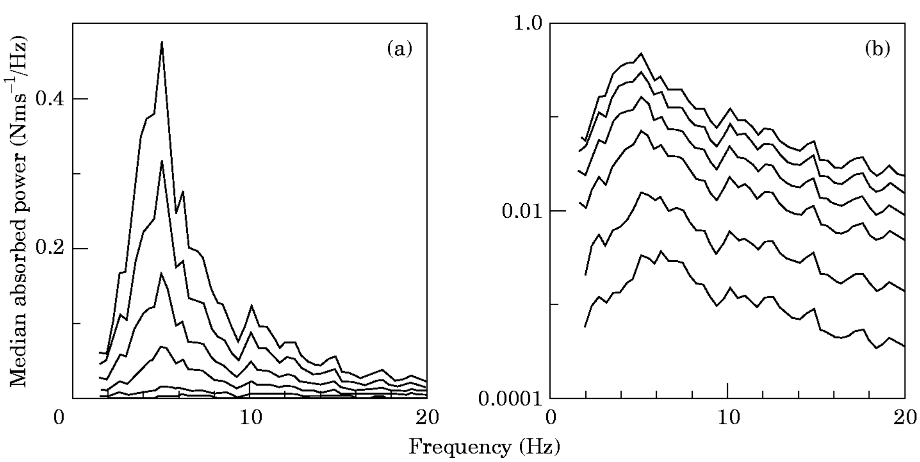

Figure 3. Median absorbed power of 12 subjects at six magnitudes of motion. Absorbed power magnitude increases with increasing vibration magnitude. (a) Linear ordinate; (b) log ordinate.

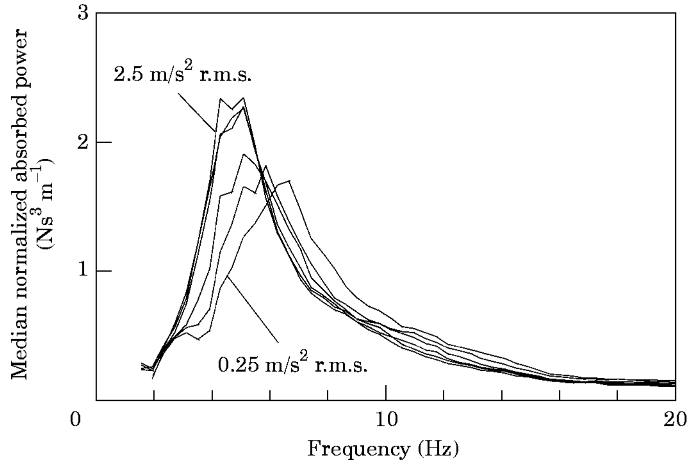

Figure 4. Median normalized absorbed power of 12 subjects at six magnitudes of motion.

where $|G_{io}(f)|$ is the modulus and $\phi(f)$ is the phase of the cross-spectrum between the force and velocity. A single value of the total absorbed power can be found from the area beneath the absorbed power spectrum so as to allow comparison of the total absorbed power between subjects or between conditions.

As the vibration magnitude increases, so the absorbed power increases, in proportion to approximately the square of the acceleration on the seat. Each measurement of absorbed power was normalized in the frequency domain by dividing the measured absorbed power by the acceleration power spectral density. This procedure corrected for minor deviations in the seat acceleration at the different vibration frequencies. A single value of the total normalised absorbed power can be calculated by integrating to find the area beneath the normalised absorbed power spectrum.

TABLE 2

Normalized absorbed power resonance frequencies measured for 12 *subjects at six magnitudes of motion* (Hz)

	Magnitude (ms^{-2} r.m.s.)					
Subject	0·25	0·50	1·00	1·50	2·00	2·50
1	5·08	4·69	4·30	4·30	4·30	3·91
2	5·86	5·86	5·47	5·08	5·08	5·08
3	5·86	5·86	5·86	5·08	5·08	5·08
4	5·86	5·08	5·08	4·69	4·30	4·30
5	5·86	5·86	5·47	5·08	5·08	5·08
6	5·86	5·08	4·30	4·30	4·30	4·30
7	5·47	5·08	5·08	4·30	4·30	4·30
8	5·86	5·86	5·86	5·47	5·08	5·08
9	5·86	5·86	5·47	5·08	5·08	4·69
10	5·86	5·86	5·86	5·86	5·47	5·47
11	5·86	5·08	4·30	4·30	3·91	4·30
12	5·47	5·08	4·30	4·30	4·30	4·30
Median	5·86	5·47	5·27	4·88	4·69	4·49

TABLE 3

Total absorbed power measured for 12 subjects at 6 magnitudes of motion (Nms^{-1})

Subject	Magnitude (ms^{-2} r.m.s.) 0·25	0·50	1·00	1·50	2·00	2·50
1	0·026	0·099	0·378	0·868	1·493	2·225
2	0·024	0·108	0·394	0·854	1·499	2·323
3	0·021	0·093	0·383	0·805	1·477	2·233
4	0·023	0·090	0·352	0·870	1·479	2·283
5	0·027	0·113	0·474	1·061	2·029	2·887
6	0·030	0·142	0·567	1·220	2·164	3·732
7	0·025	0·098	0·385	0·884	1·605	2·297
8	0·033	0·095	0·361	0·788	1·342	2·120
9	0·022	0·096	0·383	0·777	1·428	2·218
10	0·024	0·102	0·411	0·968	1·648	2·594
11	0·028	0·120	0·483	1·094	1·923	2·860
12	0·022	0·109	0·408	0·797	1·488	2·371
Median	0·024	0·100	0·390	0·869	1·496	2·310

The units of the absorbed power spectra are Nms^{-1}/Hz. Therefore, the area beneath the curve (defined as the total absorbed power) has units of Nms^{-1}. The normalised absorbed power was calculated by dividing an absorbed power spectrum by an acceleration power spectrum. As acceleration power spectra have units of $(ms^{-2})^2$/Hz, the units of the normalized absorbed power are $Ns^3\,m^{-1}$. Finally, the area beneath the normalized absorbed power curve (defined as the total normalized absorbed power) has units of $Ns^2\,m^{-1}$, due to the normalized absorbed power having units of $Ns^3\,m^{-1}$ and frequency having units of s^{-1} (usually written as Hz).

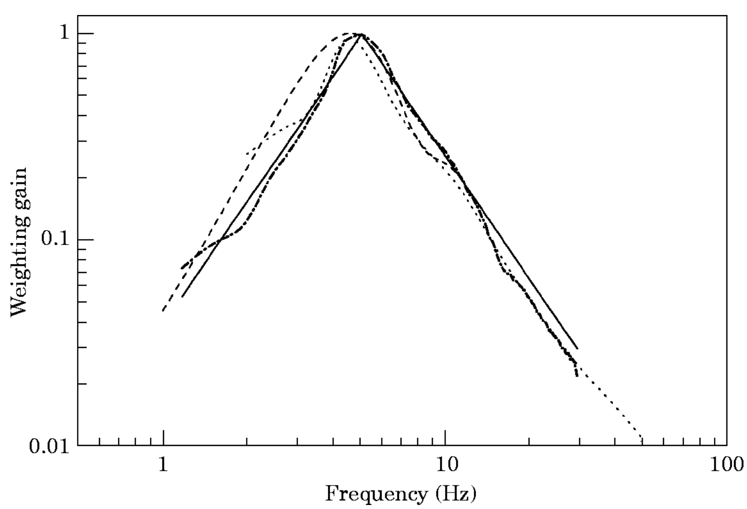

Figure 5. Comparison of absorbed power data from this study with that obtained by Lee and Pradko [9] and Lundström *et al*. [10]. (A ±12 dB/octave weighting based on 5 Hz also shown). Key: –·–·–, this study; ——, 12 dB/octave fit to this study; - - - -, Lee and Pradko [9]; · · · · , Lundström *et al*. [10].

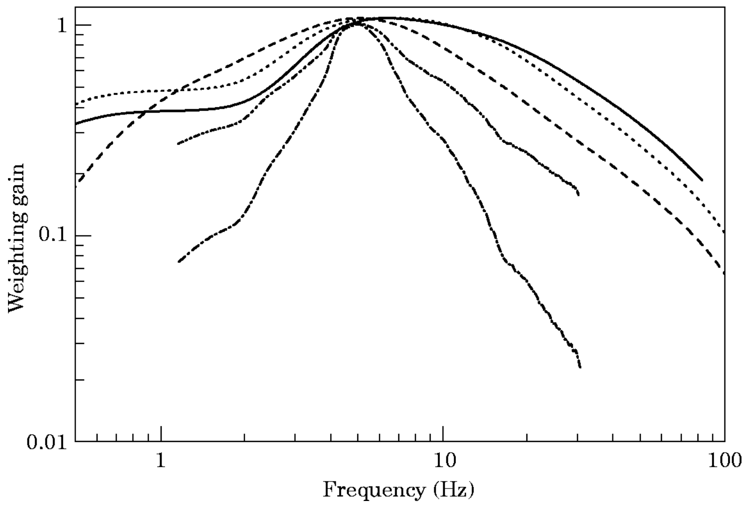

Figure 6. Comparison of frequency weightings for acceleration and acceleration power spectra with those suggested for vertical vibration of seated subjects in ISO 2631 [1, 2] and BS 6841 [3]. Key: ----, ISO 2631 (W_g) [1], ——, BS 6841 (W_b) [3]; · · · · ·, ISO 2631 (W_k) [2]; –·–·–, absorbed power (this study); – · · · – · · · –, , absorbed power (square root).

3. RESULTS

The absorbed power spectra obtained for all 12 subjects at the six magnitudes of vibration are shown in Figure 1. The figure shows that the absorbed power increased with increased magnitude of vibration. All subjects showed clear peaks in the absorbed power at about 5 Hz. The magnitude of the peak response differed slightly between subjects, ranging from 0·4 to 0·7 Nms^{-1}/Hz for the 2·5 ms^{-2} r.m.s. vibration.

Normalized absorbed power spectra for the 12 subjects are shown in Figure 2. These data show that the peak in the normalised absorbed power was dependent on the magnitude of the vibration. The peak was greater, and at a lower frequency, with greater magnitudes of vibration. There were larger changes in the resonance frequency between the three lower vibration magnitudes (0·25 to 1·0 ms^{-2} r.m.s.) than between the three higher vibration magnitudes (1·5 to 2·5 ms^{-2} r.m.s.).

Median absorbed power spectra are shown in Figure 3. The median resonance frequency reduced from 6·25 to 5·08 Hz as the magnitude increased from 0·25 to 2·5 ms^{-2} r.m.s. The median absorbed power at resonance increased by a factor of 130 (from 0·0037 to 0·48 Nms^{-1}/Hz) with the tenfold increase in vibration magnitude. The median normalized absorbed power spectra at the six magnitudes of vibration in Figure 4 show the non-linearity in both the resonance frequency and the magnitude of absorbed power at resonance. The frequency of the peak in the normalized absorbed power spectra reduced from 6·64 to 5·08 Hz, and the normalized absorbed power at resonance increased from 1·69 to 2·34 $Ns^3\,m^{-1}$, as the magnitude of the random vibration increased from 0·25 to 2·5 ms^{-2} r.m.s. There were more changes in the peak of the normalized absorbed power between 0·25 and 1·5 ms^{-2} r.m.s. than between 1·5 and 2·5 ms^{-2} r.m.s. This may have been due to the relative increases in magnitude between conditions being greater for the lower vibration magnitudes (i.e., changing vibration magnitude by 0·5 ms^{-2} r.m.s. from 0·5 to 1·0 ms^{-2} r.m.s. requires a 100% increase, whereas a similar absolute change from 2·0 to 2·5 ms^{-2} r.m.s. only requires a 25% increase).

Resonance frequencies of the normalized absorbed power spectra for the 12 subjects at the six magnitudes of vibration are listed in Table 2. The median resonance frequency

TABLE 4

Median normalized absorbed power spectra (values may be used to calculate the absorbed power from acceleration power spectra)

Frequency (Hz)	Acceleration magnitude (ms^{-2} r.m.s.)					
	0·25	0·50	1·00	1·50	2·00	2·50
1·56	0·08	0·18	0·27	0·28	0·24	0·23
1·95	0·18	0·16	0·22	0·24	0·26	0·22
2·34	0·36	0·38	0·39	0·39	0·43	0·40
2·73	0·47	0·48	0·49	0·52	0·56	0·59
3·13	0·52	0·56	0·58	0·73	0·78	0·83
3·52	0·47	0·58	0·77	1·13	1·21	1·21
3·91	0·53	0·70	1·01	1·54	1·64	1·69
4·30	0·86	1·14	1·58	2·05	2·03	2·34
4·69	1·02	1·35	1·60	2·10	2·18	2·25
5·08	1·26	1·65	1·90	2·27	2·25	2·34
5·47	1·36	1·60	1·82	1·93	1·93	1·96
5·86	1·50	1·81	1·69	1·68	1·62	1·56
6·25	1·66	1·58	1·51	1·35	1·30	1·29
6·64	1·69	1·38	1·32	1·17	1·11	1·10
7·03	1·46	1·20	1·16	1·02	0·96	0·92
7·42	1·24	1·04	0·94	0·86	0·84	0·82
7·81	1·13	0·91	0·85	0·80	0·79	0·75
8·20	1·01	0·78	0·76	0·73	0·72	0·69
8·59	0·88	0·74	0·70	0·67	0·69	0·66
8·98	0·79	0·68	0·63	0·60	0·62	0·60
9·38	0·72	0·62	0·60	0·56	0·58	0·54
9·77	0·69	0·59	0·59	0·52	0·56	0·50
10·16	0·63	0·55	0·54	0·48	0·49	0·45
10·55	0·57	0·53	0·51	0·46	0·43	0·40
10·94	0·55	0·52	0·48	0·42	0·39	0·37
11·33	0·52	0·47	0·44	0·38	0·35	0·33
11·72	0·49	0·44	0·41	0·36	0·33	0·31
12·11	0·43	0·40	0·36	0·31	0·30	0·28
12·50	0·41	0·37	0·33	0·29	0·28	0·26
12·89	0·39	0·35	0·30	0·27	0·26	0·25
13·28	0·36	0·31	0·27	0·25	0·24	0·22
13·67	0·34	0·29	0·25	0·23	0·23	0·21
14·06	0·32	0·27	0·23	0·22	0·21	0·20
14·45	0·28	0·24	0·20	0·20	0·19	0·18
14·84	0·25	0·22	0·19	0·19	0·18	0·17
15·23	0·22	0·20	0·17	0·17	0·16	0·15
15·63	0·19	0·18	0·15	0·15	0·14	0·14
16·02	0·18	0·17	0·15	0·14	0·14	0·13
16·41	0·18	0·16	0·14	0·14	0·13	0·12
16·80	0·17	0·15	0·14	0·13	0·13	0·12
17·19	0·16	0·16	0·14	0·13	0·13	0·12
17·58	0·16	0·15	0·13	0·12	0·12	0·11
17·97	0·16	0·15	0·14	0·12	0·12	0·11
18·36	0·15	0·15	0·13	0·12	0·11	0·11
18·75	0·15	0·14	0·13	0·11	0·11	0·11
19·14	0·15	0·14	0·13	0·11	0·11	0·11
19·53	0·14	0·13	0·12	0·11	0·10	0·09
19·92	0·14	0·13	0·12	0·11	0·10	0·09

reduced from 5·86 Hz at 0·25 ms^{-2} r.m.s. to 4·49 Hz at 2·5 ms^{-2} r.m.s. Wilcoxon matched-pairs signed ranks tests showed that there were significant differences between the resonance frequencies at most magnitudes ($p < 0{\cdot}05$). The only exception was between the two highest magnitudes (2·0 and 2·5 ms^{-2} r.m.s.), although for these magnitudes the lower resonance frequency was still obtained with the greater vibration magnitude.

The median total power absorbed by the subjects increased from 0·024 Nms^{-1} at 0·25 ms^{-2} r.m.s. to 2·31 Nms^{-1} at 2·5 ms^{-2} r.m.s. (see Table 3). Wilcoxon matched-pairs signed ranks tests between the total absorbed powers at the six magnitudes of vibration showed significant differences between each magnitude ($p < 0{\cdot}005$).

There were significant correlations between the subject weights and the total normalised absorbed powers ($p < 0{\cdot}005$, 2-tailed Spearman) at each magnitude of vibration. The total normalized absorbed power measured at 0·25 and 0·5 ms^{-2} r.m.s. were also correlated with subject heights ($p < 0{\cdot}05$), but the effect was due to a correlation between height and weight and disappeared after partialling out the effect of weight. There were no correlations between subject age and total normalised absorbed powers.

A median total normalized absorbed power of about 11 $Ns^2\,m^{-1}$ was obtained for all magnitudes of motion, but this value will differ with different vibration spectra. The median total normalized absorbed power increased slightly at the higher vibration magnitudes: there were significant differences at most magnitudes of vibration ($p < 0{\cdot}05$), the only exceptions were between 0·25 and 0·5 ms^{-2} r.m.s., between 0·25 and 1·0 ms^{-2} r.m.s., and between 1·5 and 2·0 ms^{-2} r.m.s.

4. DISCUSSION

The absorbed power spectra in Figure 1 show similar minor peaks at all magnitudes of vibration. This was caused by minor fluctuations in the acceleration spectra on the seat. Dividing the absorbed power spectra by the acceleration power spectra densities removed this characteristic from the data (see Figure 2).

Absorbed power data obtained by Lee and Pradko [9] and Lundström *et al*. [10] are compared with the data from the present experiment in Figure 5. All sets of data have been normalised to give a peak magnitude of 1·0 such that the differences in response due to vibration magnitude are removed. The manner in which the absorbed power depended on vibration frequency in this study is remarkably similar to that reported by Lee and Pradko and by Lundström *et al*. It may be seen that all three sets of data have a similar shape, although the absorbed power for the current study tends to be slightly lower than for the other two studies at frequencies below resonance. In all studies the resonance frequency was at about 5 Hz. At frequencies below and above resonance the data have gradients of about ± 12 dB/octave.

The absorbed power curves shown in Figure 3 could be used to weight acceleration spectra measured on the seat of a machine or vehicle so as to estimate the absorbed power spectra and calculate the total absorbed power for the environment. The absorbed power increases in proportion to the square of the acceleration, so these weightings cannot be used in the same manner as the frequency weightings commonly used to determine the severity of whole-body vibration exposures from the acceleration measured on a seat. In the case of a single frequency of vibration, the absorbed power could be determined from the square of the acceleration magnitude multiplied by the absorbed power for that frequency at unit magnitude of acceleration. The normalized absorbed power spectra shown in Figure 4 provide a useful basis for calculating the absorbed power from acceleration power spectra: the absorbed power spectrum for an environment can be obtained by multiplying the acceleration power spectrum for the environment by the normalized absorbed power spectrum.

Three frequency weightings are in current use for the evaluation of the severity of vertical whole body vibration. The old International Standard 2631 [1] specified a frequency weighting having a unity gain between 4 and 8 Hz, with reduced sensitivity at lower and higher frequencies (this weighting is referred to as weighting W_g in BS 6841 [3]). British Standard 6841 [3] recommends a weighting called W_b for evaluating vertical whole-body vibration with respect to health and comfort: this weighting has a maximum response around 5 Hz, with a decrease in gain at lower frequencies and a slower decrease at higher frequencies. A new version of ISO 2631 [2], advocates the use of a weighting W_k for evaluating vibration with respect to health but allows either W_k or W_b for evaluations with respect to comfort. Frequency weighting W_k is very similar to weighting W_b except that it decreases in response at frequencies below about 4 Hz (not below 5 Hz as for W_b) and has a slightly lower response than W_b at higher frequencies. In Figure 6 these three frequency weightings are shown in realizable form (the realizable weighting for W_g has been taken from ISO 8041 [14]).

Figure 6 also shows the gain of the normalized absorbed power weighting, which is appropriate to acceleration power spectra. Also shown is the square root of this weighting, which is appropriate for acceleration measures: the acceleration at any frequency is multiplied by the value of this weighting at the appropriate frequency; the square of the resulting value is the absorbed power at that frequency. These curves were obtained from the average of the median normalized absorbed power curves shown in Figure 4. At frequencies between 2 and 5 Hz the frequency weighting for acceleration is highly consistent with the W_b weighting for acceleration. However, at frequencies above 5 Hz the gain of this absorbed power weighting falls such that it suggests a lower sensitivity to high frequency vibration than any of the three standards. The change in the weighting from W_g to W_b, or from W_g to W_k, reflected a need to increase the sensitivity of weightings to these higher frequencies: opposite to the direction implied by the use of absorbed power at these frequencies.

From the present results, a frequency weighting to estimate the absorbed power from measures of acceleration can be approximated by a combination of slopes of ± 6 dB/octave centred on 5 Hz (see Figure 6). Table 4 shows the numerical values of the normalised absorbed power spectra shown in Figure 4. These values can be used to calculate the absorbed power (after modification to allow for a different frequency resolution, if necessary) from acceleration spectra.

If it is assumed that standard weighting curves (e.g., W_b and W_k) give reasonable approximations of vibration severity, the absorbed power curve must be rejected as a useful tool for evaluating whole-body vibration over a wide range of frequencies with respect to the risk of injury. This also implies that the absorbed power does not fully explain the relevant injury mechanisms, presumably power can be absorbed without causing injury and injury can occur with little absorption of power.

The frequency weightings in the current standards were based on various considerations, with little real information on the nature or causes of injuries in the body. It might be suggested that the weightings are incorrect and that the absorbed power curve shown in Figure 6 is more appropriate. However, this seems unlikely because the absorbed power weighting will allow very high magnitudes at high frequencies, where it is known that vibration can be most unpleasant. Although severe discomfort, and even pain, may not necessarily signal a risk of injury it seems reasonable in the absence of information to the contrary not to depart from the assumption that a vibration which causes greater discomfort is also more likely to create a greater risk of injury.

The comparisons in Figure 6 also suggests that absorbed power will not, in general, provide a good indication of the effects of vibration on comfort. The frequency weighting W_b is more closely based on comfort data than the other weightings and is similar to the absorbed power weighting for acceleration between 2 and 5 Hz. For some vehicles the dominant vibration may occur in this range and then both weightings may yield similar conclusions. However, where vibration occurs over a wider range of frequencies the conclusions may be very different. It is therefore difficult to see any justification for using an absorbed power weighting to predict vibration discomfort in preference to a frequency weighting derived from discomfort studies. If the degree of discomfort is accepted as an approximate indicator of risk of injury it follows that absorbed power cannot be advocated for evaluating the risk of exposures to vibration with respect to injury.

5. CONCLUSIONS

Similar to measures of apparent mass, the absorbed power of seated subjects exposed to vertical whole-body vibration showed a downwards shift in the resonance as the vibration magnitude increased. Apart from this change, the total absorbed power increased in proportion to approximately the square of the vibration magnitude. A frequency weighting derived from the square root of the normalised absorbed power data had slopes of ± 6 dB/octave centred on 5 Hz. Comparison of the measured absorbed power with the frequency weighting curves in current standards showed large differences, especially at frequencies above resonance. It is not recommended that a weighting based on absorbed power is used in preference to weightings derived from other human responses to whole-body vibration.

REFERENCES

1. INTERNATIONAL ORGANIZATION FOR STANDARDIZATION 1985 *ISO* 2631/1. Evaluation of human exposure to whole-body vibration—Part 1: general requirements.
2. INTERNATIONAL ORGANIZATION FOR STANDARDIZATION 1997 *ISO* 2631/1. Evaluation of human exposure to whole-body vibration—Part 1: general requirements.
3. BRITISH STANDARDS INSTITUTION 1987 *BS* 6841. Measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock.
4. INTERNATIONAL ORGANIZATION FOR STANDARDIZATION 1981 *ISO* 5982. Vibration and shock—Mechanical driving point impedance of the human body.
5. T. E. FAIRLEY and M. J. GRIFFIN 1989 *Journal of Biomechanics* **22**, 81–94. The apparent mass of the seated human body: vertical vibration.
6. N. J. MANSFIELD 1994 *Paper presented at the United Kingdom Informal Group Meeting on Human Response to Vibration held at the Institute of Naval Medicine*, *Alverstoke*, *Gosport*, *Hants*., *PO*12 2*DL*, 19–21 *September*. The apparent mass of the human body in the vertical direction—the effect of vibration magnitude.
7. N. J. MANSFIELD 1996 *Paper presented at the United Kingdom Informal Group Meeting on Human Response to Vibration held at MIRA*, *Watling Street*, *Nuneaton*, *Warwickshire*, 18–20 *September*. A study of the effect of vibration duration on the apparent mass of the seated human body.
8. M. J. GRIFFIN 1990 *Handbook of human vibration*. London: Academic Press; ISBN: 0-12-303040-4.
9. R. A. LEE and F. PRADKO 1968 *Automotive Engineering Congress*, *Detroit*, *Michigan*, 8–12 *January*. Society of Automotive Engineers, Paper 680091. Analytical analysis of human vibration.
10. R. LUNDSTRÖM, P. HOLMLUND and L. LINDBERG 1995 *Paper presented at the United Kingdom Informal Group Meeting on Human Response to Vibration held at the Silsoe Research Institute*, *Wrest Park*, *Silsoe*, *Bedford MK*45 4*HS*, 18–20 *September*. Absorbtion of energy during exposure to whole-body vibration.

11. I.-M. Lidström 1977 *Proceedings of the International Occupational Hand–Arm Vibration Conference*, *National Institute of Occupational Safety and Health*, *Cincinnati*, 1975. *NIOSH* 77-170. Vibration injury in rock drillers, chisellers, and grinders. Some views on the relationship between the quantity of energy absorbed and the risk of occurrence of vibration injury.
12. L. Burström and R. Lundström 1988 *International Archives of Occupational and Environmental Health* **61**, 213–216. Mechanical energy absorption in human hand-arm exposed to sinusoidal vibration.
13. N. J. Mansfield and M. J. Griffin 1997 *Awaiting publication*. Non-linearities in biodynamic responses to whole-body vertical vibration.
14. International Organization for Standardization 1990 *ISO* 8041. Human response to vibration—measuring instrumentation.
15. International Organization for Standardization 1993 *ISO* 5347. Calibration of vibration and shock pick-ups. Part 5: method of calibration by Earth's gravitation.
16. T. E. Fairley 1986 *Ph.D. thesis*, *University of Southampton*. Predicting the dynamic performance of seats.