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Power absorbed during whole-body vertical vibration: Effects of sitting posture, backrest, and footrest

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A B S T R A C T

Previous studies have quantified the power absorbed in the seated human body during exposure to vibration but have not investigated the effects of body posture or the power absorbed at the back and the feet. This study investigated the effects of support for the feet and back and the magnitude of vibration on the power absorbed during whole-body vertical vibration. Twelve subjects were exposed to four magnitudes (0.125, 0.25, 0.625, and 1.25 m s^{-2} rms) of random vertical vibration (0.25–20 Hz) while sitting on a rigid seat in four postures (feet hanging, maximum thigh contact, average thigh contact, and minimum thigh contact) both with and without a rigid vertical backrest. Force and acceleration were measured at the seat, the feet, and the backrest to calculate the power absorbed at these three locations. At all three interfaces (seat, feet, and back) the absorbed power increased in proportion to the square of the magnitude of vibration, with most power absorbed from vibration at the seat. Supporting the back with the backrest decreased the power absorbed at the seat at low frequencies but increased the power absorbed at high frequencies. Supporting the feet with the footrest reduced the total absorbed power at the seat, with greater reductions with higher footrests. It is concluded that contact between the thighs and the seat increases the power absorbed at the seat whereas a backrest can either increase or decrease the power absorbed at the seat.

1. Introduction

Biodynamic responses of the human body to whole-body vibration have been reported in terms of the driving point mechanical impedance and apparent mass (e.g., [1,2]), transmissibility (e.g. [3,4]), and the power absorbed by the body (e.g. [5,6]). The driving point apparent mass, which is calculated from the force and acceleration measured at the vibration input to the body, is required to understand the interaction between the body and compliant seating and has been influential in the development of many biodynamic models. The apparent mass is dominated by large masses, especially those close to the point of excitation. The transmissibility between the point of excitation and any location on the body can also be used to develop biodynamic models showing the motion of specific body parts. However, reliable measurements are only available for a few locations on the body, and current transmissibility models do not reflect the true multi-axis response of the body and have few applications. The power absorbed by the body is closely related to the apparent mass and is calculated from the same values: the force and acceleration measured at the vibration input to the body. It has been

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suggested that the power absorbed by the body might be used to predict subjective responses to vibration (e.g. [5,7,8]), although it has not been shown to have any general applicability for this purpose.

For a particular acceleration, the power entering the body depends on the inertia, damping, and elastic properties of the body while the power absorbed by the body depends only on the damping. One advantage claimed for absorbed power over other dynamic responses (e.g., apparent mass and transmissibility) is that it takes into account not only the magnitude, frequency, and direction of vibration but also the duration. Absorbed power also has the advantage of scalar summation: the overall power absorbed by the body can be found by adding the power absorbed in each direction of excitation (in a multi-axis environment) and at all interfaces between the body and vibrating surfaces (e.g., at the seat, back, and feet).

When sitting on a simple horizontal seat and exposed to vertical vibration with a flat constant bandwidth acceleration spectrum, the power absorbed in the body is greatest around 5 Hz [6,9,10]. The frequency of greatest absorbed power decreases with increasing magnitude of vibration due to the nonlinearity in the body, but the increase in total absorbed power (the area under the absorbed power spectrum) is approximately proportional to the square of the acceleration magnitude [6]. The power absorbed in the body has been reported to depend on both sitting posture and gender, leading to the suggestion that more restrictive risk assessment guidelines are required for females [9]. The power absorbed by the body depends on the direction of vibration excitation, with the absorbed power peaking at frequencies less than 2.5 Hz during horizontal vibration, compared to the 4–6 Hz frequency range during vertical excitation [10].

Although previous studies have focused on absorbed power measured at the supporting seat surface, the seated body is usually also in contact with vibration at the feet and the backrest and vibration at these location can contribute to discomfort. Lee and Pradko [5] reported absorbed power for the feet exposed to vibration without whole-body vibration. The power absorbed by the feet during whole-body vibration may differ from that absorbed during excitation of the feet alone because vibration of the body is expected to produce forces at the feet [11,12]. The power absorbed due to contact with a backrest has not previously been reported.

This paper reports the power absorbed by the human body due to vibration applied simultaneously and in-phase at the seat, backrest, and feet during whole-body vertical vibration. The main objective is to determine to what extent the power absorbed by the body during vertical excitation is affected by contact with a vibrating footrest and a vibrating backrest. The effect of vibration magnitude on the power absorbed at the seat, backrest, and feet was also studied. It was hypothesised that the power absorbed from vibration at the seat would vary with posture, due to changes in the percentage of the body

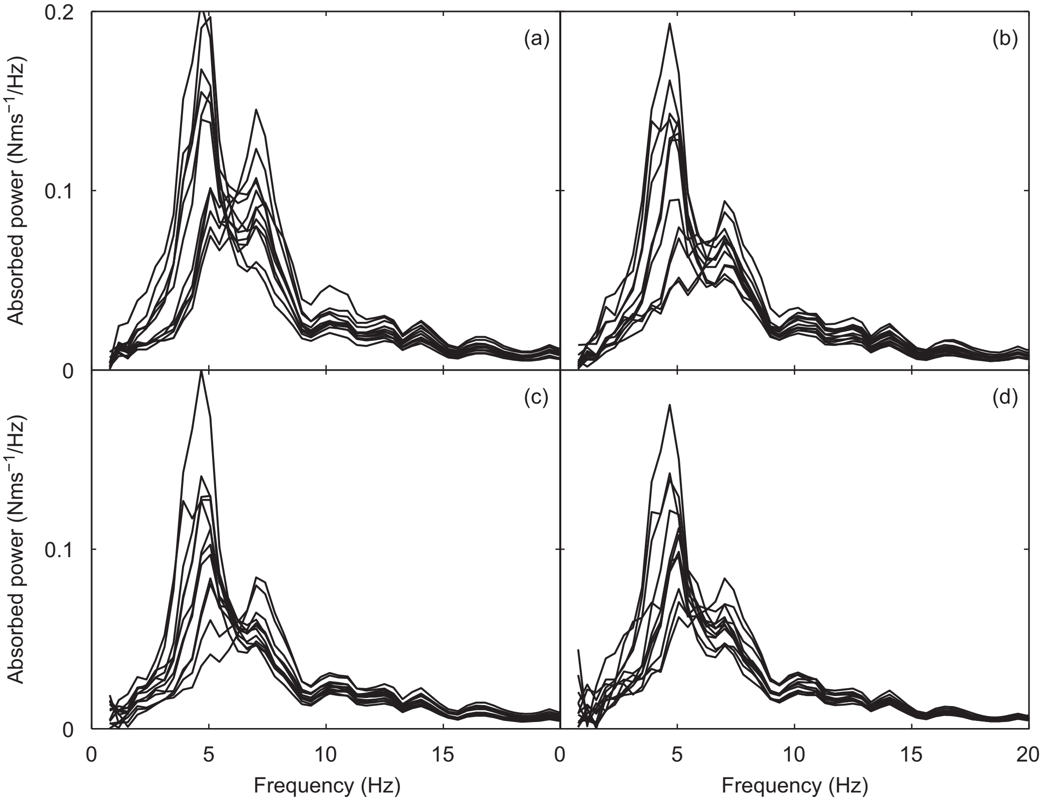

Fig. 1. Absorbed power measured at the seat at 1.25 m s^{-2} rms with four sitting postures: (a) feet hanging; (b) maximum thigh contact; (c) average thigh contact; and (d) minimum thigh contact (linear scales, individual data of 12 subjects).

supported by the seat, footrest, and backrest. It was also hypothesised that the total absorbed power (i.e. the power over a frequency range of interest) at each of the inputs would increase quadratically with an increase in vibration magnitude. The data used in this paper are those from a study of the apparent masses of the body [13,14] but reanalysed to calculate the absorbed power.

2. Apparatus, experimental design, and analysis

2.1. Apparatus

Subjects were exposed to random vertical vibration using an electro-hydraulic vibrator capable of producing a peak-to-peak displacement of 1 m. A rigid seat was rigidly mounted on the platform of the vibrator once without a backrest (data from Nawayseh and Griffin [13]) and once with a vertical rigid backrest (data from Nawayseh and Griffin [14]). Both studies used an adjustable footrest (to give different foot heights) that moved vertically in phase with the seat. Force signals from force plates (Kistler 9281 and Kistler Z 13053) were amplified by Kistler 5001 and Kistler 5007 charge amplifiers so as to measure the forces at the seat, the backrest, and the footrest. Vertical acceleration was measured at the centre of the force platforms using piezo-resistive accelerometers (Entran EGCSY-240D-10 and Entran EGCS-DO-10-/V10/L4M). The signals from the accelerometers and the force transducers were digitised at 200 samples per second via 67 Hz anti-aliasing filters.

2.2. Experimental design

The data from Nawayseh and Griffin [13] (i.e. without a backrest) were for 12 male subjects with average age 31.4 years (range 20–47 years), weight 74.6 kg (range 57–106 kg), and stature 1.78 m (range 1.68–1.86 m). The same subjects were used by Nawayseh and Griffin [14] (i.e. with backrest) except for one subject, which changed the subject characteristics to average age 29.9 years (range 20–46 years), weight 77.2 kg (range 62–106 kg), and stature 1.78 m (range 1.68–1.86 m). The subjects in both studies were exposed to random vertical vibration with an approximately flat constant bandwidth acceleration power spectrum over the frequency range 0.25–20 Hz. Using a frequency resolution of 0.39 Hz, the mean and

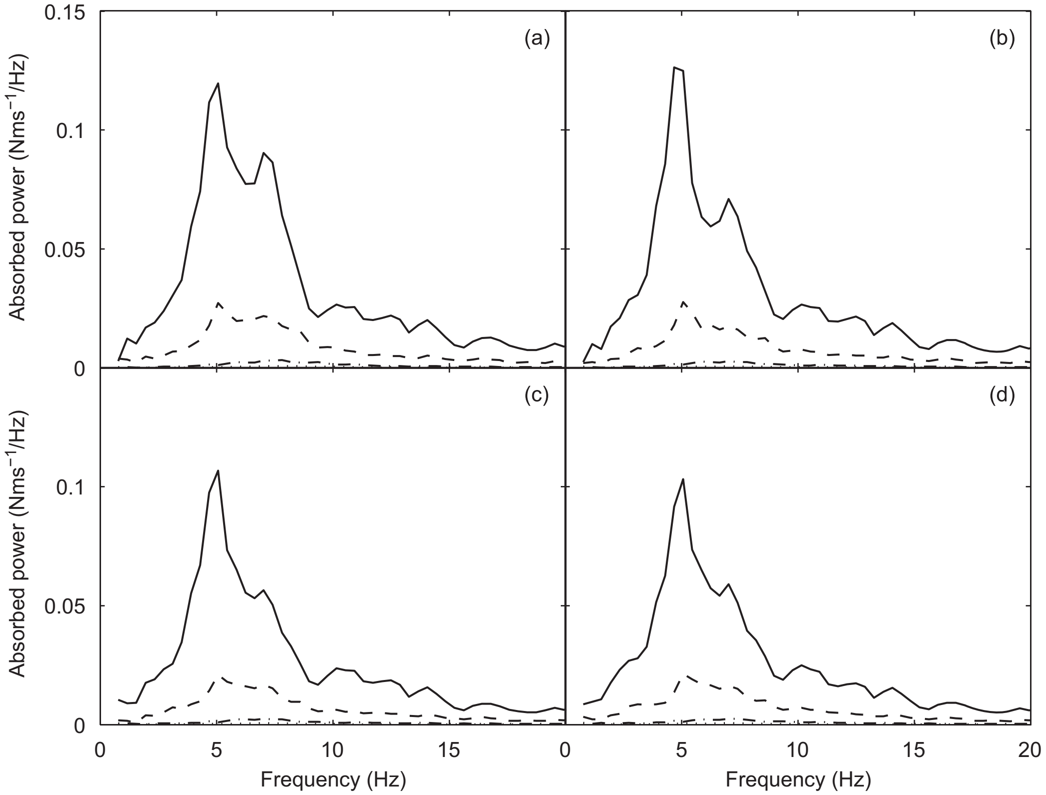

Fig. 2. Effect of vibration magnitude on absorbed power at the seat with four sitting postures: (a) feet hanging; (b) maximum thigh contact; (c) average thigh contact; and (d) minimum thigh contact. ……, 0.125; –·–·–·–, 0.25; – – – –, 0.625; ———, and 1.25 m s^{-2} rms (linear scales; medians of 12 subjects).

the standard deviation of the acceleration power spectral density (PSD) over the range 0.25–20 Hz were 0.000513 and 0.000089 $(\mathrm{m/s^2})^2/\mathrm{Hz}$, respectively, for the lowest vibration magnitude used in the study. For the highest vibration magnitude, the mean and the standard deviation of the PSD of the acceleration were 0.0514 and 0.0088 $(\mathrm{m/s^2})^2/\mathrm{Hz}$, respectively.

Both studies employed the same exposure conditions: all 16 combinations of four vibration magnitudes (0.125, 0.25, 0.625, and 1.25 $\mathrm{ms^{-2}}$ rms) and four sitting postures. The four sitting postures were achieved by changing the height of an adjustable footrest while keeping the upper body in an upright posture. The postures were: (i) 'feet hanging' with no foot support, (ii) feet supported with 'maximum thigh contact' (i.e. heels just in touch with the footrest), (iii) 'average thigh contact' (i.e. upper legs horizontal, lower legs vertical and supported on the footrest), and (iv) 'minimum thigh contact' (i.e. the footrest 160 mm above the position with 'average thigh contact' in position (iii)). Each exposure to vibration lasted 60 s, and there was an interval of 2 to 3 min between exposures.

2.3. Analysis

The instantaneous power, P, transmitted to the human body during vibration can be calculated from the product of the force, F, and velocity, v, measured at the interface between the body and the vibrating surface. In this study, the velocity was obtained by integrating the measured acceleration time history. The power transmitted to the body can be calculated in the frequency domain from the cross-spectrum between the force and the velocity.

The real part of the transmitted power represents the power absorbed by the body

$$P_{\mathrm{abs}}(f) = \mathrm{Re}\{G_{vF}(f)\} = |G_{vF}(f)| \cos \phi(f)$$

where $P_{\mathrm{abs}}(f)$ is the absorbed power, $\mathrm{Re}\{G_{vF}(f)\}$ is the real part of the cross-spectrum between the velocity and the force, $|G_{vF}(f)|$ is the modulus of the cross-spectrum between the velocity and the force, ϕ is the phase of the cross-spectrum between the velocity and the force, and f is the frequency. The absorbed power, $P_{\mathrm{abs}}(f)$, has units of $\mathrm{N\,m\,s^{-1}\,Hz^{-1}}$. No mass cancellation was needed because the plates of the force platforms were rigid in the frequency range used in this study and a rigid body does not absorb power.

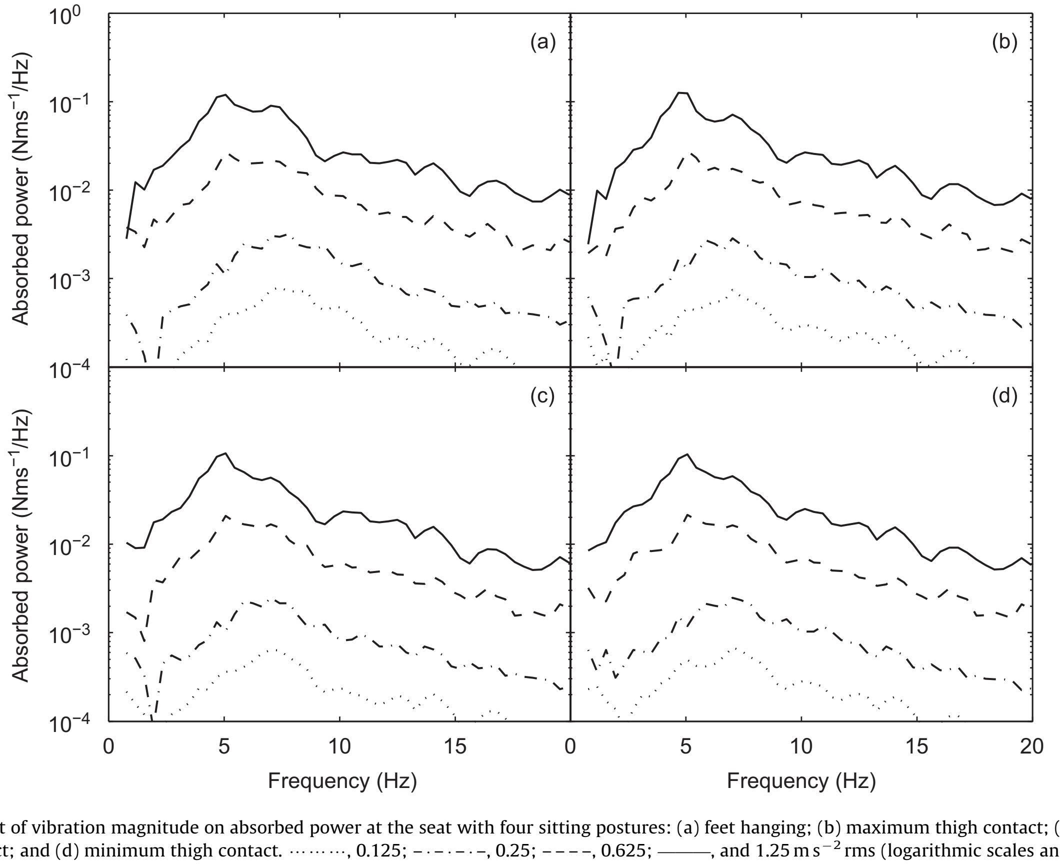

Fig. 3. Effect of vibration magnitude on absorbed power at the seat with four sitting postures: (a) feet hanging; (b) maximum thigh contact; (c) average thigh contact; and (d) minimum thigh contact. ·········, 0.125; –·–·–·–, 0.25; – – – –, 0.625; ———, and 1.25 $\mathrm{m\,s^{-2}}$ rms (logarithmic scales and medians of 12 subjects).

The imaginary part of the transmitted power represents the power that enters and leaves the body (i.e., there is an energy exchange between the body and the vibrating surface during each cycle of motion).

The total power absorbed at each input interface was obtained by integrating the absorbed power curves over the frequency range 2–20 Hz. The effects of using a footrest at different heights on the total absorbed power measured at the seat, at the feet, and at the backrest, as well as the effect of using a backrest on the total absorbed power at the seat were examined through statistical analysis using SPSS (version 15.0). The effects of placing the feet on a footrest and of using a backrest on the overall absorbed power (i.e. sum of total absorbed power at different interfaces) was also analysed statistically.

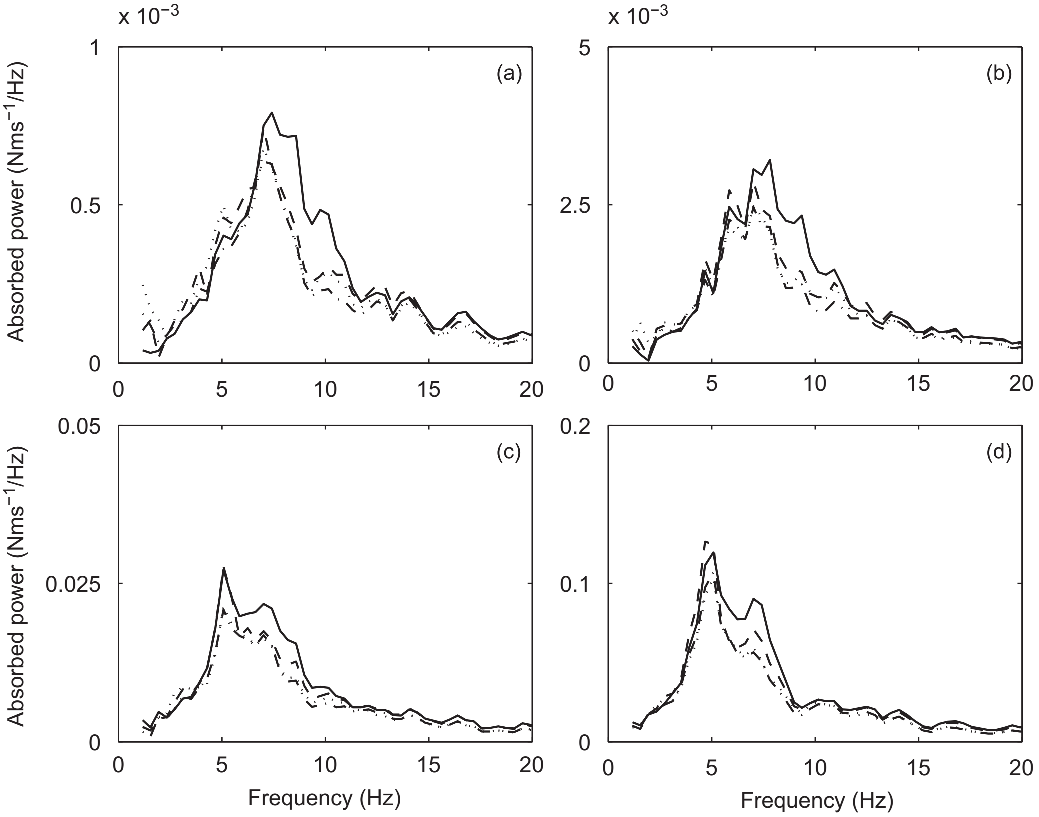

Fig. 4. Effect of posture on absorbed power at the seat at four vibration magnitudes: (a) 0.125 m s^{-2} rms; (b) 0.25 m s^{-2} rms; (c) 0.625 m s^{-2} rms; and (d) 1.25 m s^{-2} rms ———, feet hanging; – – – –, maximum thigh contact; – · – · – · –, average thigh contact; and ·········; minimum thigh contact (linear scales; medians of 12 subjects).

Table 1
Total absorbed power (W) at the seat, backrest, and footrest with each vibration exposure condition (medians of 12 subjects).

	Feet hanging				Maximum thigh contact			
	0.125 ms^{-2}	0.250 ms^{-2}	0.625 ms^{-2}	1.250 ms^{-2}	0.125 ms^{-2}	0.250 ms^{-2}	0.625 ms^{-2}	1.250 ms^{-2}
At the seat	0.0055	0.0221	0.1668	0.6665	0.0050	0.0193	0.1428	0.5550
At the backrest	0.0002	0.0008	0.0050	0.0184	0.0002	0.0007	0.0051	0.0187
At the footrest	–	–	–	–	0.0010	0.0039	0.0261	0.0941
	Average thigh contact				Minimum thigh contact			
	0.125 ms^{-2}	0.250 ms^{-2}	0.625 ms^{-2}	1.250 ms^{-2}	0.125 ms^{-2}	0.250 ms^{-2}	0.625 ms^{-2}	1.250 ms^{-2}
At the seat	0.0044	0.0170	0.1249	0.4951	0.0046	0.0176	0.1287	0.4980
At the backrest	0.0002	0.0008	0.0054	0.0197	0.0002	0.0008	0.0051	0.0184
At the footrest	0.0011	0.0044	0.0341	0.1356	0.0013	0.0051	0.0352	0.1401

3. Results

3.1. Effect of footrest on absorbed power measured at the seat without backrest

In all four sitting postures, the absorbed power measured at the seat was low at low frequencies but increased with increasing frequency to a peak around 5 Hz (Figs. 1 and 2). A second peak, with lower magnitude than the first peak, was evident around 8 Hz, especially in postures producing the greatest thigh contact with the seat (i.e., feet hanging and maximum thigh contact postures). As expected, the absorbed power increased with increasing magnitude of vibration. The power absorbed with 0.125 m s^{-2} rms was small and cannot be seen using a linear scale (Fig. 2) but is evident on a logarithmic scale (Fig. 3). The frequency at which most power was absorbed decreased with increasing magnitude of vibration.

There was no clear trend for an effect of the height of the foot support on the frequency at which power was absorbed among the three postures where the feet were supported (i.e. maximum thigh contact, average thigh contact, and minimum thigh contact postures) (Fig. 4). Without the foot support (i.e., feet hanging), there was increased absorbed power over a range of frequencies greater than the resonance frequency compared with the three postures where the feet were supported (e.g., 7–12 Hz with the lowest vibration magnitude, 5–9 Hz with the highest vibration magnitude). However, statistical analysis showed significant differences in the total absorbed power at the seat between all postures at all vibration magnitudes (Table 1; Friedman, $p < 0.0001$) with the feet hanging posture showing the greatest total absorbed power and the minimum thigh contact posture showing the least total absorbed power.

The power absorbed at the feet increased with increasing magnitude of vibration but depended on the contact with the footrest: with just the heels in contact with the footrest (i.e., maximum thigh contact posture), a single clear peak was evident in the absorbed power (around 7.5 Hz at 1.25 m s^{-2} rms) compared to multiple-peaks with the feet fully supported on the footrest (i.e., average thigh contact and minimum thigh contact postures) (Figs. 5 and 6).

Comparing between postures, the power absorbed at the feet was greatest for the maximum thigh contact posture, with the peak around 10 Hz with the lowest vibration magnitude and around 7.5 Hz with the highest vibration magnitude (Fig. 7). At higher frequencies, less power was absorbed with maximum thigh contact than with average thigh contact and minimum thigh contact (Fig. 7). Statistical analysis showed significant differences in the total absorbed power at the feet

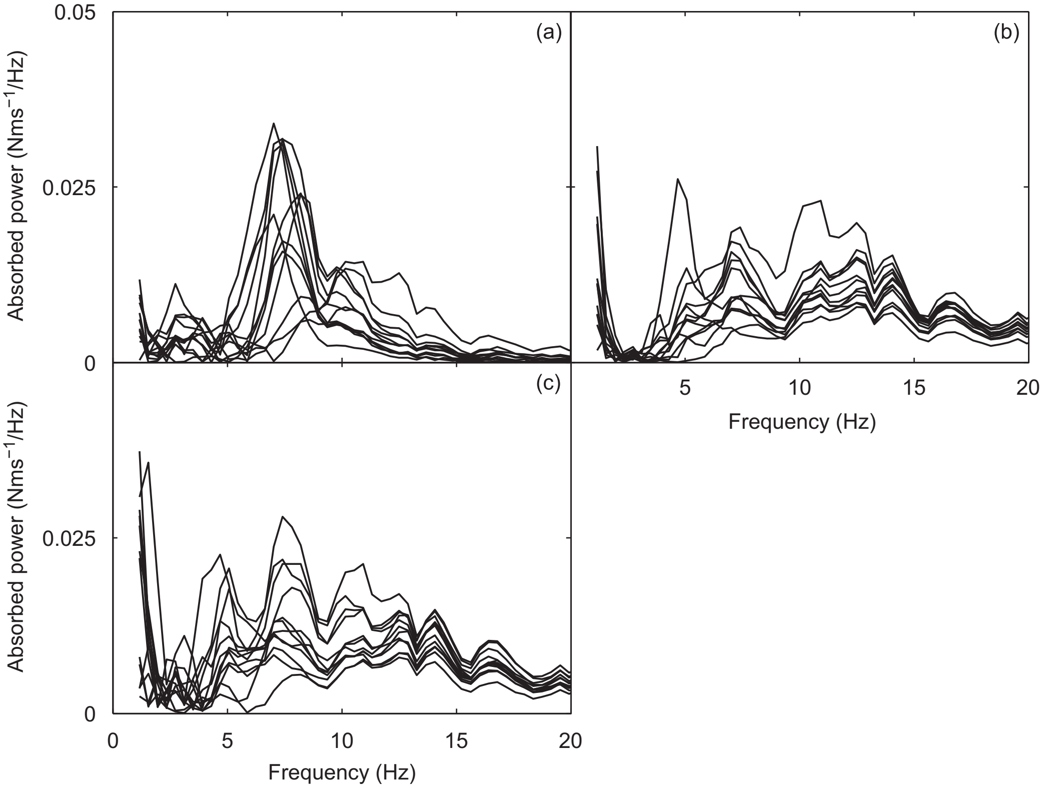

Fig. 5. Absorbed power measured at the feet at 1.25 m s^{-2} rms with three sitting postures: (a) maximum thigh contact; (b) average thigh contact; and (c) minimum thigh contact (linear scales and individual data of 12 subjects).

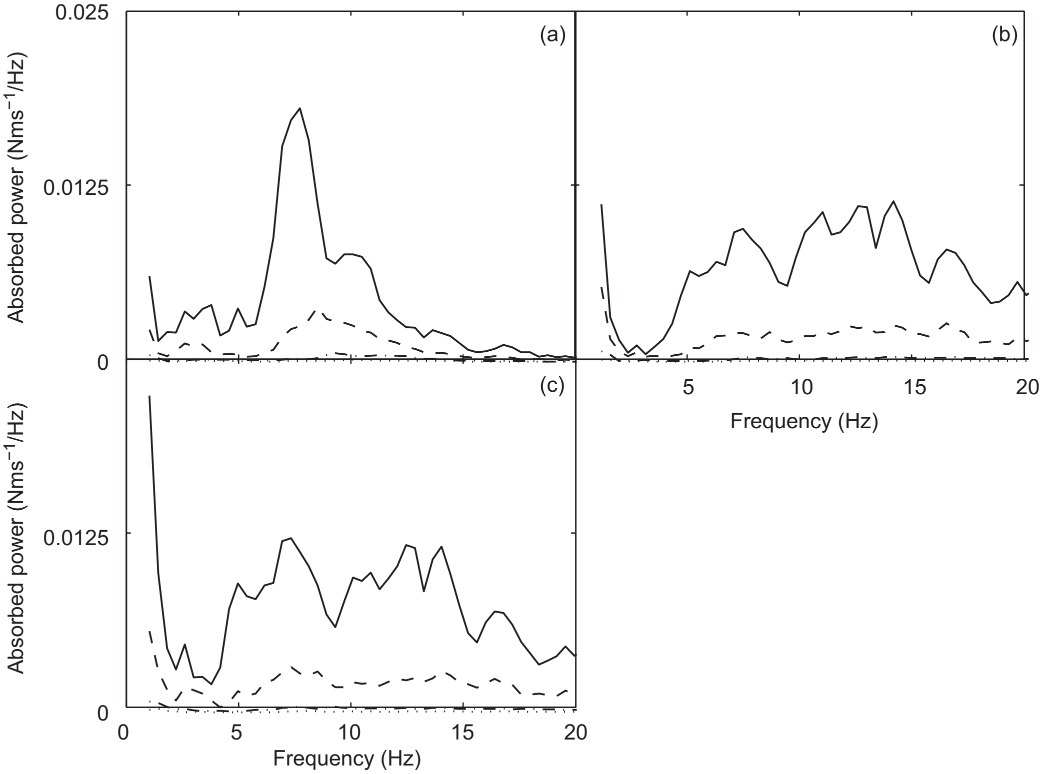

Fig. 6. Effect of vibration magnitude on absorbed power at the feet with three sitting postures: (a) maximum thigh contact; (b) average thigh contact; and (c) minimum thigh contact. ·········, 0.125; – · – · – · –, 0.25; – – – –, 0.625; and ———, 1.25 m s^{-2} rms (linear scales and medians of 12 subjects).

between the three postures with all vibration magnitudes ($p < 0.0001$; Friedman; Table 1) with minimum thigh contact showing greatest total absorbed power and maximum thigh contact with the least total absorbed power.

With all vibration magnitudes, statistically significant differences ($p < 0.05$) were found between the total power absorbed at the seat with the feet hanging without the backrest (i.e. the overall absorbed power for this posture) and the sum of the total powers absorbed at the seat and at the backrest when a backrest was used. The sum of the total powers absorbed at the seat and at the backrest was always higher than the total absorbed power measured on the seat without backrest. The percentage increase differed greatly between subjects, showing an average increase of 10% (standard deviation, S.D., 13%) with 0.125 m s^{-2} rms, 9% (S.D.=6%) with 0.25 m s^{-2} rms, 7% (S.D.=6%) with 0.625 m s^{-2} rms and 6% (S.D.=3%) with 1.25 m s^{-2} rms.

Statistical analysis was performed to test for differences between the total power absorbed at the seat with the feet hanging posture without backrest and the overall absorbed power obtained by summing the total powers absorbed at the feet and the seat with the three postures where the feet were supported. There were significant differences between the total absorbed power at the seat with the feet hanging posture and the overall absorbed power at the seat and the footrest in the other three postures as follows: with the maximum thigh contact posture at 0.125, 0.25 and 0.625 m s^{-2} rms ($p < 0.05$), with the average thigh contact posture at 1.25 m s^{-2} rms ($p < 0.05$), and with the minimum thigh contact posture at both 0.125 and 0.25 m s^{-2} rms ($p < 0.05$). With both the maximum thigh contact posture and the minimum thigh contact posture, the overall absorbed power (i.e. sum of the absorbed power at the seat and the footrest) was greater than the absorbed power at the seat with the feet hanging posture. The greatest percentage increase occurred with the maximum thigh contact posture with a mean increase of 9% (S.D.=5%). With the average thigh contact posture, the overall absorbed power was 4% less (S.D.=3%) than the total absorbed power measured at the seat with the feet hanging posture.

It was not possible to find the overall absorbed power when sitting with contact at all three interfaces (the seat, backrest, and feet) because force measurements at the feet and the backrest were not obtained simultaneously: the total absorbed power at the feet in the session with no backrest may have differed if there had been a backrest.

3.2. *Effect of backrest on power absorbed at the seat*

Contact with the rigid flat vertical backrest tended to decrease the absorbed power measured at the seat at low frequencies (frequencies less than the frequency of the principal resonance) but increase the absorbed power measured at the seat at high frequencies (Fig. 8). However, the total absorbed power measured at the seat was not affected by the

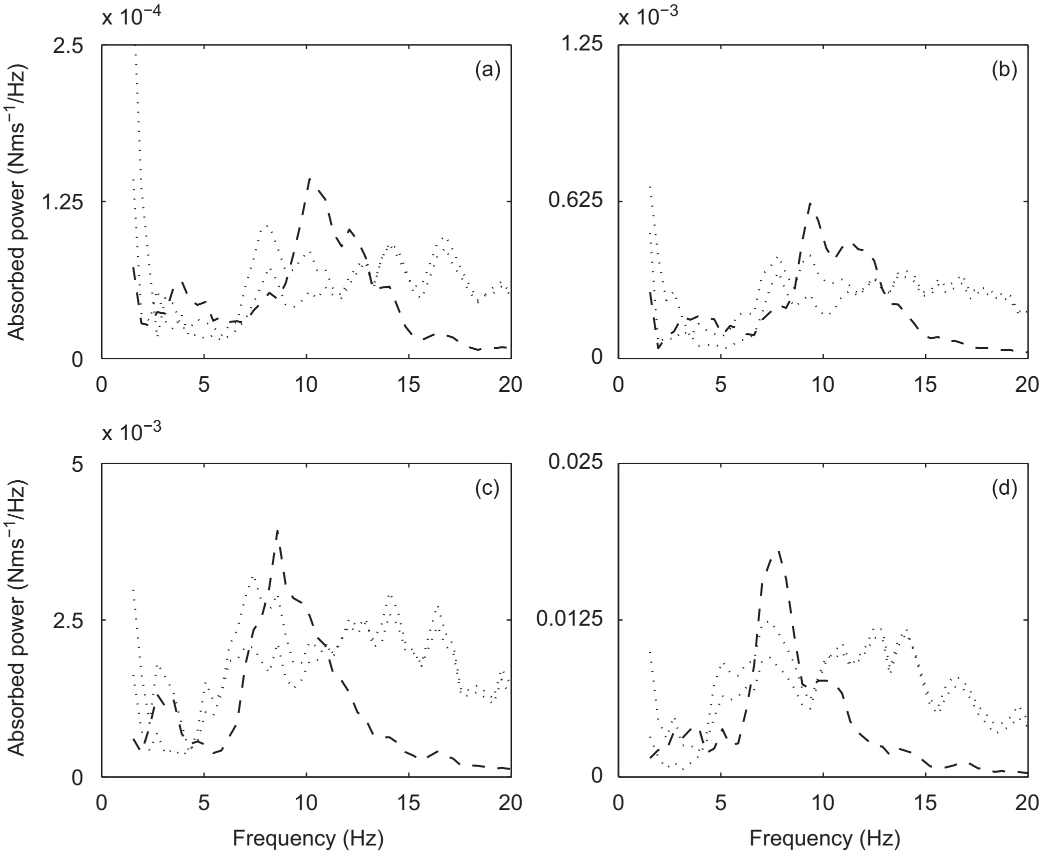

Fig. 7. Effect of posture on absorbed power at the feet at four vibration magnitudes: (a) 0.125 m s^{-2} rms; (b) 0.25 m s^{-2} rms; (c) 0.625 m s^{-2} rms; and (d) 1.25 m s^{-2} rms – – – –, maximum thigh contact; – · – · – · –, average thigh contact; and ·········, minimum thigh contact (linear scales and medians of 12 subjects).

backrest in any of the four sitting postures: there was no statistically significant difference in the total absorbed power measured at the seat with and without the backrest (Wilcoxon, $p > 0.05$), except with the minimum thigh contact posture at 0.625 and 1.25 m s^{-2} rms ($p = 0.041$).

The absorbed power measured at the backrest was much less than that measured at the seat and the footrest (compare Fig. 9 with Figs. 2 and 6). The power absorbed at the backrest was less at high frequencies than at low frequencies and, as expected, an increase in the magnitude of vibration increased the absorbed power. No statistically significant difference was found in the total absorbed power at the backrest between postures at any magnitude of vibration (Table 1, Friedman, $p > 0.3$).

4. Discussion

The human body is assumed to behave as a rigid system when exposed to low frequency vertical vibration: the apparent mass of the body is the same as the static mass of the body at low frequencies (e.g., [15]). The measurements reported here show low absorbed power at the seat at low frequencies, consistent with the human body responding to vibration as an almost rigid system at low frequencies.

The frequency of the first peak in the absorbed power at the seat was around 5 Hz, as previously reported (e.g., [6,10]). The body increases the force around 5 Hz due to a resonance at this frequency (e.g., [13,14]). A second peak in the absorbed power was evident between 8 and 10 Hz and is similar to a peak often seen in the apparent mass (e.g., [16,17]). This second peak between 8 and 10 Hz seems to be clearer in postures where there was increased thigh contact with the seat (i.e., feet hanging and maximum thigh contact). Smith [18] has suggested that the thighs resonate in this frequency range. In the other two postures (i.e., average thigh contact and minimum thigh contact), forces at frequencies between 8 and 10 Hz may have been reduced by stiffening of the body system from the feet on the footrest. The reduced absorbed power with reduced thigh contact could also be due to reduced mass on the seat: statistical analysis showed significant positive correlations between subject mass and the total power absorbed at the seat at all vibration magnitudes ($p < 0.01$, Spearman). This is consistent with increased absorbed power with increased body weight reported previously [9].

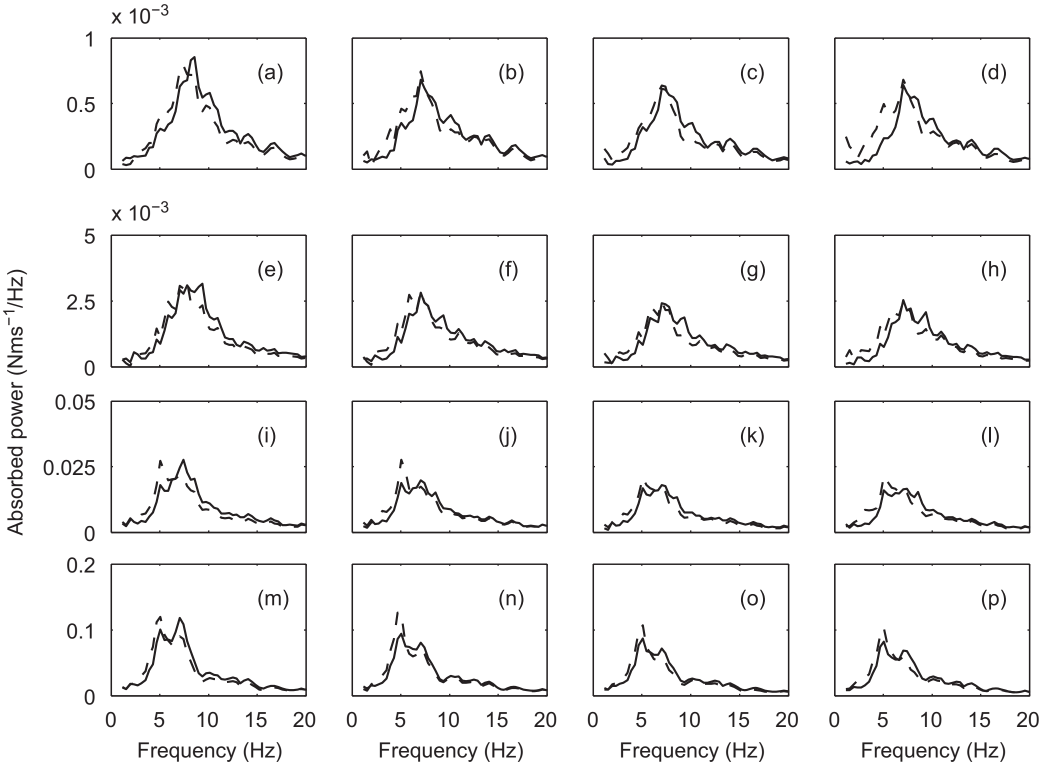

Fig. 8. Effect of backrest on absorbed power at the seat. ———, with backrest; – · – · – · –, without backrest. (a), (b), (c), (d), 0.125 ms^{-2} rms; (e), (f), (g), (h), 0.25 ms^{-2} rms; (i), (j), (k), (l), 0.625 ms^{-2} rms; (a), (b), (c), (d), 1.25 ms^{-2} rms (a), (e), (i), (m), feet hanging; (b), (f), (j), (n), maximum thigh contact; (c), (g), (k), (o), average thigh contact; (d), (h), (l), (p), minimum thigh contact; (linear scales and medians of 11 subjects).

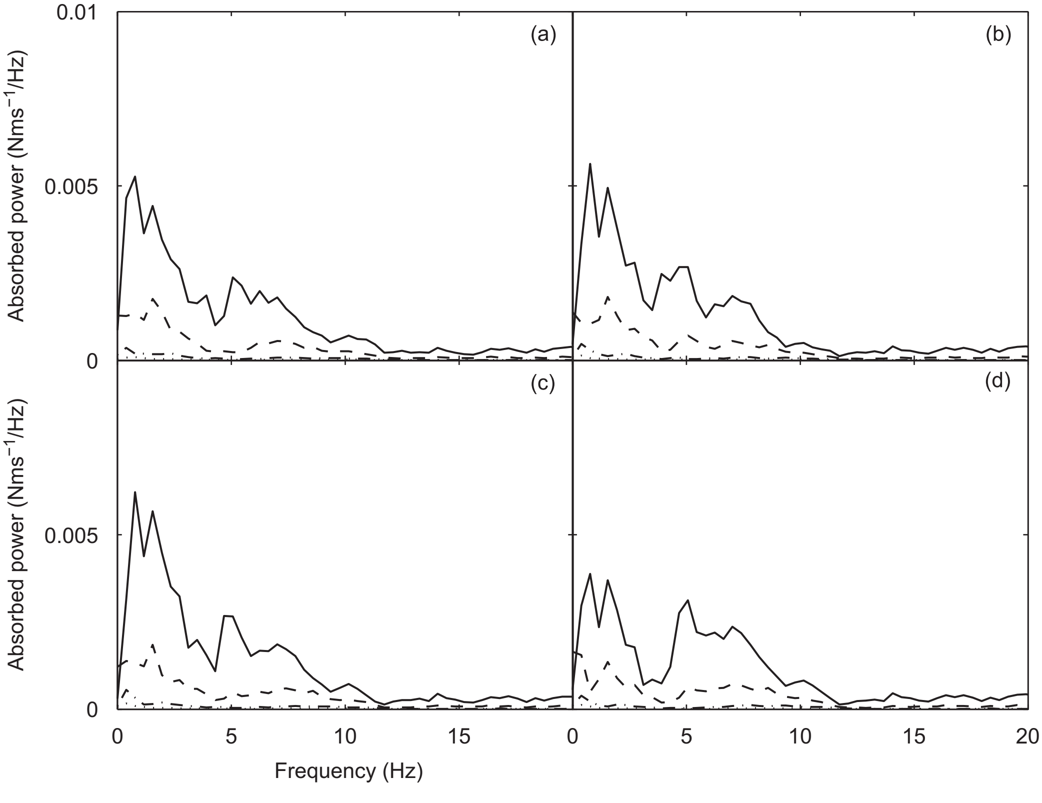

Fig. 9. Effect of vibration magnitude on absorbed power at the backrest with four sitting postures: (a) feet hanging; (b) maximum thigh contact; (c) average thigh contact; (d) minimum thigh contact. ⋯⋯⋯, 0.125; – · – · – · –, 0.25; – – – –, 0.625; and ———, 1.25 ms^{-2} rms (linear scales and medians of 12 subjects).

Theoretically the absorbed power would be expected to increase quadratically with increases in vibration magnitude (e.g. [9]). Fig. 10 shows that the increase in the total power was quadratic at the seat, at the feet, and at the back, although not clear at the back due to the low magnitudes of the power absorbed at the back on the vertical scale of the figure.

In the maximum thigh contact posture, the peak in the absorbed power at the feet is at the same frequency as the peak in the apparent mass at the feet in this posture [13]. This peak (near 7.5 Hz with the highest vibration magnitude and near 10 Hz with the lowest vibration magnitude) also occurs around the frequency of the second peak in the absorbed power at the seat and may involve a resonance at the thighs. With vertical excitation around 7.5 Hz, Mansfield and Griffin [19] found peaks in the vertical transmissibility to the spine and pelvis and Matsumoto and Griffin [20] found bending of the spine. Irrespective of the cause of the peak, it seems that the response at the seat affects the response at the feet.

The multiple peaks in absorbed power at the feet when the feet were more supported (i.e. average thigh contact and minimum thigh contact) are similar to the apparent mass at the feet as reported in the previous research [11,13]. The similarity in the curves shapes between the absorbed power obtained at the feet in this study (Fig. 5) and the apparent mass at the feet measured by Nawayseh and Griffin [13] is clearer when comparing the absorbed power and apparent mass for individuals, as peaks smear out in the computation of medians.

The greater absorbed power at the feet with the minimum thigh contact than the average thigh contact may be associated with increased mass supported on the footrest with the minimum thigh contact posture. Additionally, pitch motion of the upper-body is greater in the minimum thigh contact posture [13] and may have increased the forces at the feet in this posture.

The backrest reduced both the absorbed power and the apparent mass at low frequencies but increased absorbed power and apparent mass at high frequencies (e.g. [14]). The reduction in the absorbed power at low frequencies may be due to stiffening of the body when in contact with a backrest. The reduction in absorbed power at the seat at low frequencies when using a backrest may also be partly explained by power absorbed at the backrest (see Fig. 9).

The acceleration spectrum used in this study was approximately flat in the frequency range of interest. Moreover, the vibration was vertical at all inputs (i.e. at the seat, back and feet) with no phase differences between inputs. In real situations, people are exposed to vibration with varying spectra, with multi-directional inputs, and with phase differences between these inputs. The spectra of absorbed power presented in this paper only apply to the conditions investigated, but

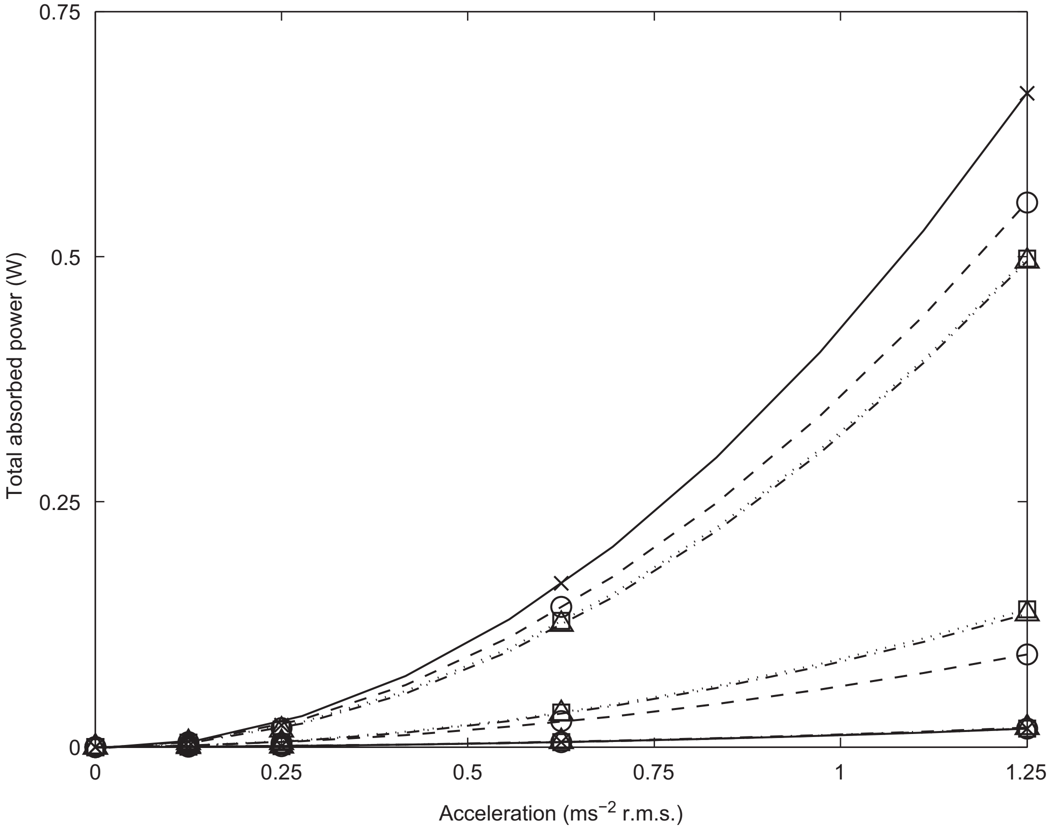

Fig. 10. Total absorbed power as a function of the magnitude of the acceleration. ———, feet hanging; – – – –, maximum thigh contact; – · – · – · –, average thigh contact; and ·········, minimum thigh contact. ×, ○, △, and □ are the measured absorbed power. (The upper curves are at the seat, the middle curves are at the feet, and the lower curves are at the back). (Linear scale and medians of 12 subjects).

they may be used to infer how the power absorbed in the human body is likely to depend on the frequency and magnitude of vibration and contact with footrests and backrests in real vibration environments.

5. Conclusions

During whole-body vertical vibration, the use of a footrest to support the feet reduces the total absorbed power at the seat, with greater reductions with higher footrests. The use of a backrest reduces the absorbed power at the seat at low frequencies but increases the absorbed power at the seat at high frequencies. The total absorbed power at the seat, the feet, and the backrest increase approximately quadratically with increasing vibration magnitude.

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