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ABSORPTION OF ENERGY DURING WHOLE-BODY VIBRATION EXPOSURE

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Absorbed power, P_{Abs}, during exposure to vertical and horizontal whole-body vibration in sitting posture was measured using 15 male and 15 female subjects. Different experimental conditions were applied, such as vibration level (0·25–1·4 m/s^2), frequency (1·13–80 Hz), body weight (54–93 kg), relaxed and erect upper body posture. Results show that P_{Abs} was strongly related to frequency of the vibration peaking, within the range of 4–6 Hz and below 2·5 Hz for vertical and horizontal directions respectively. P_{Abs} increased with acceleration level and body weight. If risk assessment is based on the assumption that the amount of P_{Abs}, independence of the frequency of the vibration, indicates a hazard, then the frequency weighting procedure in ISO-standard 2631 can be questioned. The ISO weighting for horizontal vibration seems to underestimate the risk for frequencies within the range of about 1·5–3 Hz and overestimate them above about 5 Hz. For the vertical direction the frequency weighting overestimates the risk for frequencies above about 6 Hz. The results also indicate a need for differential guidelines for females and males. Many types of vehicle produce whole-body vibration with frequencies in the range where the highest P_{Abs} was observed. Although not yet thoroughly evaluated, P_{Abs} may be a better quantity for risk assessment than acceleration as specified in ISO 2631, since it also takes into account the dynamic force applied to the human body.

1. INTRODUCTION

Many people are exposed to whole-body vibration (WBV) in their occupational lives, especially drivers of vehicles such as dumpers, excavators, scrapers, buses and trucks. The main categories of effects from WBV are perception, degraded comfort, interference with activities, impaired health and occurrence of motion sickness. For a review, see references [1–8]. Human response to WBV is a very complex phenomenon. Combinations of effects may occur simultaneously but also one effect may promote the onset of another. During exposure to WBV there are many physiological, psychophysical and physical factors which are relevant for the development of unwanted effects. These could be individual susceptibility, body constitution and posture together with the frequency, direction, magnitude and duration of the vibration.

The International Standard 2631 [9] presents guidelines for measurement and risk assessment of WBV. Accordingly, measurement of WBV should be conducted in three orthogonal directions ($x =$ fore-and-aft; $y =$ lateral; $z =$ vertical) on the surface transmitting vibration to the human body. A disadvantage with this measure is that it only describes the acceleration magnitude on the vibrating surface. Thus, it can be argued that it presents a poor description of the extent to which vibration is actually transmitted to the body. The amount of vibration energy, absorbed and/or exchanged between the source and body, may therefore be a better measure of the physical stress on the body since it

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takes into consideration the interaction between the vibrating structure and the body. This idea is further supported by earlier work conducted by American scientists [10–15].

The instantaneous power P_{Tr} transmitted to the body, consisting of the product of force $F(t)$ and velocity $v(t)$, is

$$P_{Tr} = F(t)v(t) \equiv P_{Abs}(t) + P_{El}(t). \quad (1)$$

$P_{Abs}(t)$ is the *absorbed* part of the power, accounting for the energy necessary for keeping pace with the energy dissipated through structural damping. The *elastic* power $P_{El}(t)$ is continuously delivered to and removed from the body during each period of excitation and averages to zero for each sinusoidal cycle of motion. Thus, the time-averaged absorbed power $\langle P_{Abs} \rangle$ equals the transmitted power $\langle P_{Tr} \rangle$: i.e.,

$$\langle P_{Abs} \rangle = \langle P_{Tr} \rangle = \langle F(t)v(t) \rangle. \quad (2)$$

The purpose of this study was to investigate WBV energy absorption during different experimental conditions. It focused on the relation between absorbed power and frequency, exposure level, direction, upper body posture, body weight and gender.

2. METHOD

Two study groups, each consisting of 15 females and 15 males, were involved in this study, one for the vertical direction (z) and one for the horizontal directions (x and y). Information about their age, work assignment, years at work, general state of health, previous or present exposure to WBV, etc., was provided by a questionnaire (see Table 1). Relevant anthropometric measures were taken by the experimenter. All subjects were healthy and had no signs or symptoms of disorders of the musculo-skeletal system, such as lower back pain or lumbago.

Sinusoidal vertical (2–80 Hz) and horizontal (1·13–80 Hz) whole-body vibration were generated with a signal generator (Brüel & Kjær 1049), an electrodynamic shaker (LDS 712 + ILS 712) and a power amplifier (LDS, MPA 1) (see Figure 1). A dual layered seat plate especially designed for measurement of absorbed power was used. The seat plate was equipped with five tri-axial piezo-electric transducers, four for force (Kistler 9251) and one for acceleration (Brüel & Kjær 4231). The measuring range for these transducers covered the frequency area of interest for this study.

TABLE 1

Mean (M), *standard deviation* ($\pm Sd$), *maximum* (max) *and minimum* (min) *values for the subject's age*, *body weight* (kg) *and height* (cm)

	Females (n = 15) M ($\pm Sd$, max, min)	Males (n = 15) M ($\pm Sd$, max, min)	All subjects (n = 30) M ($\pm Sd$, max, min)
Vertical direction			
Age	24 (2, 30, 23)	38 (12, 58, 22)	31 (11, 58, 22)
Weight	66 (10, 93, 54)	74 (9, 92, 57)	70 (11, 93, 54)
Height	168 (6, 180, 157)	177 (6, 190, 167)	173 (7, 190, 157)
Horizontal direction			
Age	35 (10, 51, 22)	38 (12, 59, 24)	37 (11, 59, 22)
Weight	63 (7, 76, 54)	75 (9, 93, 55)	69 (10, 93, 54)
Height	167 (4, 173, 160)	177 (6, 188, 167)	172 (27, 188, 160)

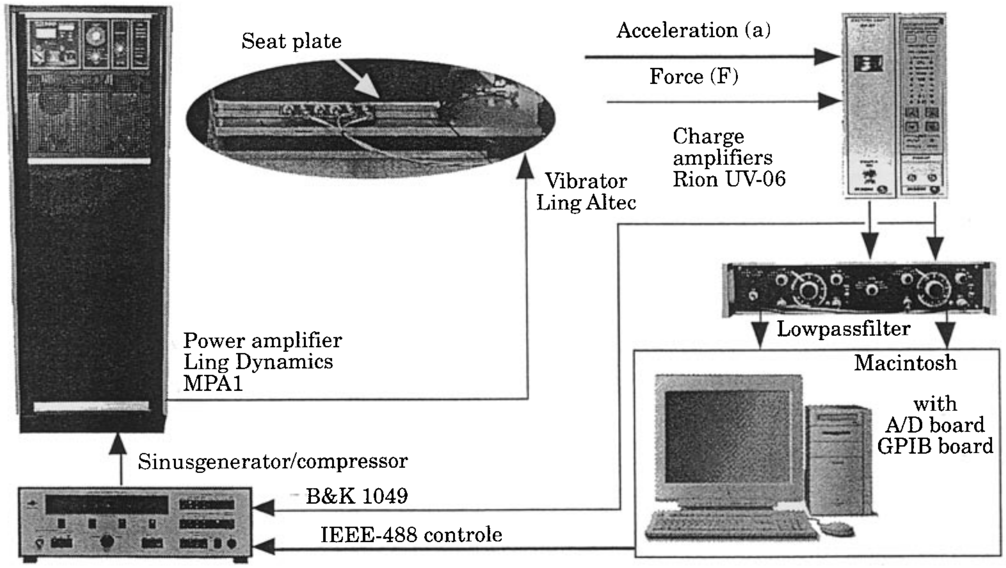

Figure 1. Experimental set-up (for more information see text).

The signals from the transducers were amplified and low-pass filtered by identical charge amplifiers (vertically: Brüel & Kjær 2635, horizontally: RION UV6) and Bessel filters (cut-off frequency: 300 Hz). By using the signal feedback function (i.e., compressor) in the signal generator, the vibration level could be kept constant independent of the frequency and load. After A/D conversion ($f_s = 1000$ Hz) of the force and acceleration signals, the values were continuously stored on disk for later analysis.

To calibrate the force channel dynamically at 5 Hz, the seat plate was loaded with solid concrete masses weighing 53 and 85 kg. An accelerometer calibrator (Brüel & Kjær 4291) was used for the vibration channel. Before the experiments the measuring system was tested without load in order to determine the signal-to-noise ratio and to check that P_{Abs} equalled zero. A non-zero result would, in this case, be erroneous. It could originate from unwanted offsets, phase shifts in the charge amplifiers or incorrect mass cancellation (see below).

The experimental procedure for all test runs followed a predetermined protocol. After being weighed in a standing position, the subject was asked to sit on the seat plate with their feet positioned on an adjustable, stationary footrest during vertical exposure or stationary on the floor during horizontal exposure. The lower legs were in a vertical position and the upper legs a horizontal position. The experimenter then instructed the subject to adopt an erect or relaxed posture. The erect posture is defined as sitting straight looking forward with the hands resting on the knees. The relaxed posture was derived from the erect by asking the subject first to sit erect and then just release the tension from their spinal musculature which allowed them to adopt a comfortable position. The static weight on the force plate ($m_{Sitting}$) and the footrest (m_{Leg}) were then determined simultaneously by two identical scales while sitting erect. On each occasion the subject was exposed to one acceleration level in random order, until all levels were completed, (vertically: 0·5, 0·7, 1·0 or 1·4 m/s^{-2} r.m.s., horizontally: 0·25, 0·35, 0·5, 0·7, 1·0 or 1·4 m/s^{-2} r.m.s.) in both erect (E) and relaxed (R) upper body postures. Each subject participated at only one occasion per day. The frequency was increased in steps of 1/6 octaves, except in the range 20–80 Hz where the steps were 1/3 octaves. The starting frequency was 2 Hz for the vertical direction but for the horizontal directions would be within the range of 1·13–2·5 Hz, varying with acceleration due to displacement restrictions for the shaker. The posture was visually controlled by the experimenter during each test run and, if necessary, corrected during measurement pauses. For vibration in the vertical direction the measurement period was 15 s for each frequency followed by a 5 s pause. Data was collected during 20 sinusoidal cycles for the horizontal directions. The total exposure time on each occasion was approximately 3 min for horizontal and 10 min for vertical vibration.

2.1. DATA AND STATISTICAL ANALYSIS

LabView™ was used for data acquisition and analysis. For each test frequency the acquired acceleration signal $a(t)$ was integrated to obtain velocity $v(t)$. The total force $F_{Means}(t)$ registered by the force transducers consisted of a contribution generated by the mass of the seat plate (m_{Plate}). This contribution was always in phase with the acceleration signal and was cancelled by vectorial subtraction. The force $F(t)$ transmitted to the sitting subject was determined as $F(t) = F_{Meas}(t) - m_{Plate}a(t)$. The individual, normalized by sitting weight, time-average absorbed power $\langle P_{NAbs} \rangle$ was thereafter determined according to

$$\langle P_{NAbs} \rangle = \langle F(t)v(t)/m_{Sitting} \rangle. \tag{3}$$

The statistical analyses consisted of determination of means and standard deviations plus analysis of variances (ANOVA) and Wilcoxon's non-parametric matched pair sign rank sum test. The calculations were carried out for each test frequency.

3. RESULTS

Figure 2 shows individual graphs for $\langle P_{NAbs} \rangle$ at different test frequencies and directions during vibration exposure at 0·5 m/s². As can be seen, individual graphs for the horizontal directions are relatively similar in shape but differ from the vertical direction. For all directions, absorbed power increases with frequency up to a peak, after which it decreases. $\langle P_{NAbs} \rangle$ peaks within the range of 4–6 Hz for the vertical direction and below about 3 Hz

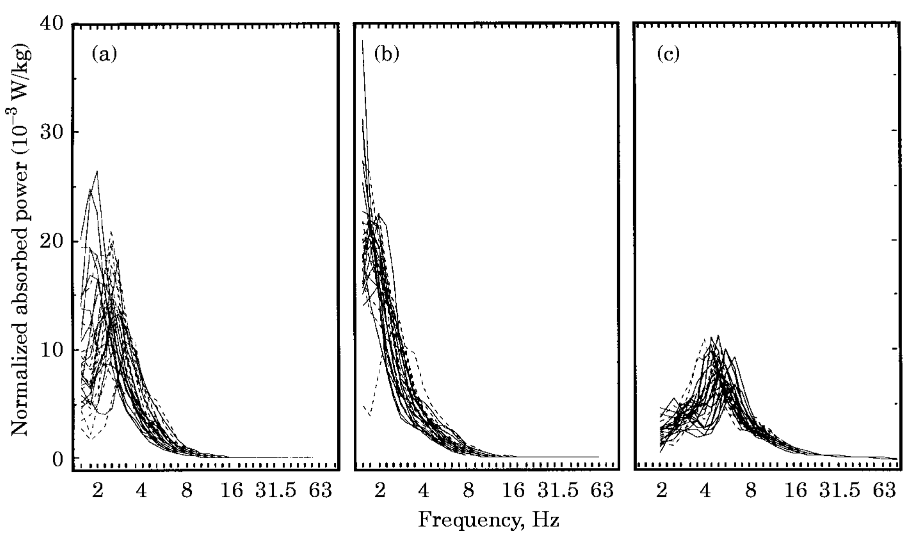

Figure 2. Individual graphs for absorbed power during exposure to an acceleration level of 0·5 m/s² in all three directions, at different frequencies for males ($n = 15$) and females ($n = 15$) sitting relaxed: (a) x direction, (b) y direction, (c) z direction. Key: ——, males; –––, females.

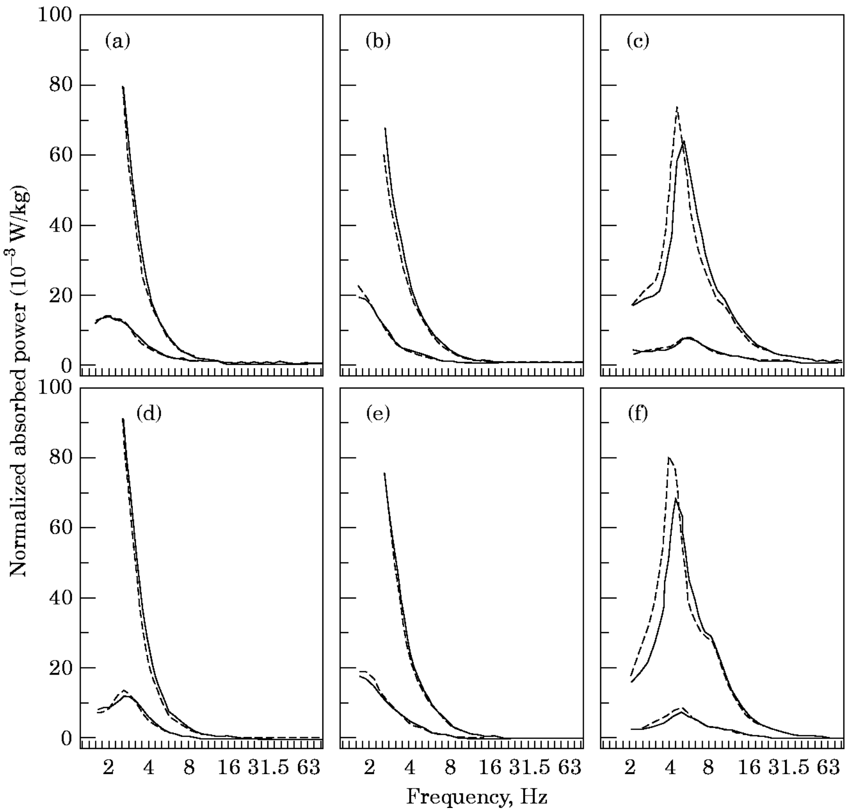

Figure 3. Averaged sitting weight normalized absorbed power at two acceleration levels (0·5 and 1·4 m/s^2) for x, y, and z directions for females ($n = 15$) and males ($n = 15$) split by sitting erect and relaxed: (a) male, x direction; (b) male, y direction; (c) male, z direction; (d) female, x direction; (e) female, y direction; (f) female, z direction. Key: ——, erect; ----, relaxed.

for the horizontal directions. The intra-individual variation in $\langle P_{NAbs} \rangle$ for both females and males, with respect to magnitude as well as the frequency at which maximum absorption occurs, is relatively large for all directions, particularly for frequencies below 10 Hz.

Figure 3 shows mean $\langle P_{NAbs} \rangle$ frequency spectra for females and males at two exposure levels, 0·5 and 1·4 m/s^2, split by posture. The graphs indicate that posture seems to have a small and non-significant effect on $\langle P_{NAbs} \rangle$ overall. However, the results from the Wilcoxson's matched pairs signed rank sum test clearly show that posture has a significant effect on $\langle P_{NAbs} \rangle$ for all directions (see Table 2). One exception however, was for males in the y direction at 1 m/s^2. Obtained p-levels were insignificant since they did not meet 0·05 and are therefore inconsistent with what one would expect. Corresponding graphs for erect and relaxed posture split by gender are shown in Figure 4. An ANOVA shows that there is a significant gender dependency in $\langle P_{NAbs} \rangle$ at many frequencies (see Table 3).

Pooled $\langle P_{NAbs} \rangle$ for all subjects and postures at different exposure levels are shown in Figure 5. The results show that overall $\langle P_{NAbs} \rangle$ is related to both frequency and magnitude of vibration exposure. $\langle P_{NAbs} \rangle$ peaks within the range of 4–6 Hz for the vertical direction and below about 3 Hz for the horizontal directions. Even though the peaks for the horizontal direction could not be visualized at all exposure levels due to the restrictions mentioned earlier, it seems likely that they occur at a somewhat lower frequency for the for-and-aft direction.

Structures with a fixed mass and internal damping absorption of power should, in theory, increase quadratically with exposure level; i.e., $\langle P_{Abs} \rangle \propto a^2$. Regression analyses based on this model support this idea for all directions ($r^2 > 0{\cdot}8$). Mansfield and Griffin [16] have presented data for the vertical direction which also shows that $\langle P_{Abs} \rangle$ is proportional to the square of the level of exposure.

4. DISCUSSION

This study showed that absorption of power significantly depends on all the experimental factors used in this study. However, frequency, direction and magnitude of vibration were the most significant. The outcome for the two horizontal directions was relatively similar but they differed significantly from the vertical direction. Generally, the amount of absorbed power increases with frequency up to a peak in the range of 4–6 Hz

TABLE 2

Results extracted from Wilcoxon's matched pairs signed rank test with respect to effects of posture, i.e., erect versus relaxed sitting posture, split by direction (x, y *and* z), *gender and acceleration level* (0·25, 0·35, 0·5, 0·7, 1·0 *and* 1·4 m/s²); *significant differences* ($p < 0{\cdot}05$) *are denoted*: a = *erect* > *relaxed*, b = *relaxed* > *erect*

	x		y		z	
	Females	Males	Females	Males	Females	Males
	Exposure level (m/s²)					
Frequency (Hz)	0·25–1·4	0·25–1·4	0·25–1·4	0·25–1·4	0·5–1·4	0·5–1·4
1·13	–	–	–	–		
1·25	– –	– –	b –	– –		
1·4	– –	a –	– –	– –		
1·6	– – –	– – a	– b –	– b b		
1·8	– – a –	a – – –	b b b b	– – – –		
2	– – – – –	– – – – –	– b b b b	b – – – –	– – – –	a – – –
2·26	– b – – –	– – – – –	b – – – –	– – – – –		
2·5	– – – – – –	– – – – – –	– – – – – –	– – – a – a	– b – b	– b – –
2·83	– – – – – –	– – – – a a	– – – – a –	– – a – a a	b b b b	b b b b
3·15	– – – a – a	– – a a a a	– – – a a a	– – a – – a	b b b b	b b b b
3·56	– – a a – a	a a a a a a	– – a a a a	– – a – – a	b b b b	– b b b
4	a a a a – a	a a a a a a	– a a a a a	– – a – – a	b b b b	– b b b
4·5	a a a – – a	a a a – – –	a a a a a a	– – a a – a	– b b –	– – – b
5	a – – – – a	– – – a – –	a a a a a –	a – a a – a	– – – a	– – – –
5·7	– – – – – a	– – – a a a	a a a a a –	a – a a – a	– – a a	– – – a
6·3	– – – a – a	– a a a a a	a a a a a –	– – a a – a	– – a a	– – – a
7·1	a a – a a a	– – a a a a	a – – a a a	– – a a – a	– – – –	– – a a
8	a a a a a a	– a a a a a	a – a a – –	a a a a – a	– – – –	– a a a
9	a a a a a a	– a a a a a	– – – a – –	a a a a – a	– – – –	a a a a
10	– a a a a a	a a a a a a	a – – – a –	– a a a – a	– – – –	a a a a
11·3	– – a a a a	a a a a a a	– – – – – –	– – a – – a	a a a a	a a a a
12·5	– – a a a a	– a a a a a	a – – – – –	– – – a – a	a a a a	a a a a
14·3	– – a a a a	– – a a a a	a – a – – a	– – – – – a	a a a a	a a a a
16	– a – a a a	– a a a a a	a – – – – a	– – a a – a	a a a a	a a a a
18	– a a a a a	– – a a a a	– – – a a a	– – a a – a	a a a a	a a a a
20	– – – a a a	– – – a a a	a – – a a a	– – a a – a	a a a a	a a a a
25	– – – a a a	– – – a a a	– – a a a a	– – – a – a	– – a a	– – a –
31·5	– – – a a a	– – – – a a	– – a – a a	– – – a – a	– – – –	– – a –
40	– – – – a	– – – – –	– – – – a	– – – – a	– – – –	– – – –
50	– – – a	– – – a	– – – a	– – – –	– – – –	– – – –
63	– – a –	– – – –	– – – a	– – – –	– – – –	– – – –
80	– – –	– – –	– a a	– – –	– – – –	– – – –

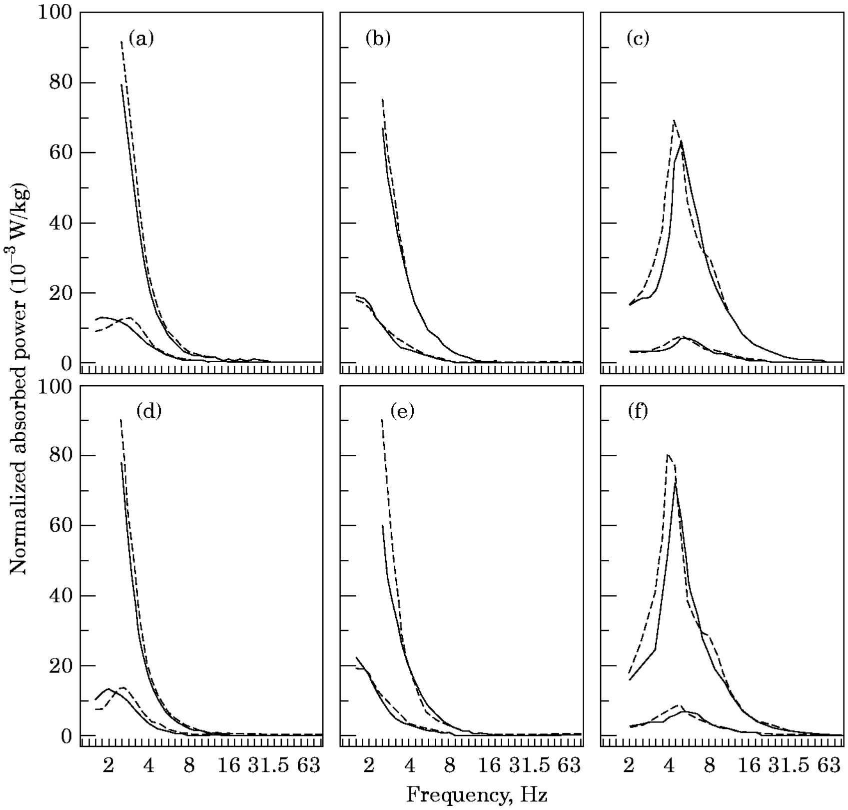

Figure 4. Averaged sitting weight normalized absorbed power at two acceleration levels (0·5 and 1·4 m/s^2) for x, y, and z direction for subjects sitting in an erect or relaxed posture split by females ($n = 15$) and males ($n = 15$): (a) erect, x direction; (b) erect, y direction; (c) erect, z direction; (d) relaxed, x direction; (e) relaxed, y direction; (f) relaxed z direction. Key: ——, males; – – –, females.

for vertical vibration and below around 3 Hz for horizontal vibration during exposure at constant acceleration level. Above this peak a gradual decrease in $\langle P_{Nabs} \rangle$ with increasing frequency occurred. Absorbed power at each frequency was also found to be proportional to the square of the acceleration.

An interesting finding was that females tend to absorb more power per kg of sitting weight. This may be due to gender differences in the bodily structure and biodynamics. A contributing factor could also be the higher m_{fat}/m_{muscle} ratio which is generally observed among females. Fat is viscous and inelastic, implying a high degree of damping and thus more power absorption. Another finding, especially for the vertical direction, was that maximum absorption tended to increase and occur at lower frequencies when the body position was changed from erect to relaxed. A possible explanation could be that relaxed sitting posture constitutes more relaxed muscles in the back and abdominal regions, which in turn reduces body stiffness and increases damping.

There are several other experimental factors that may influence the characteristics of absorbed power, adding to the complexity in this context (see e.g., references [17–19]). Sinusoidal vibration induces, for instance, stretch reflexes in the paraspinal muscles synchronous with the mechanical vibration. Such evoked muscle activity will certainly change transmissibility as well as absorbed power. It can also be argued that the state of disc hydration is of importance since it will affect the biomechanical properties of the spine. Three subjects were tested for several times during a day on different occasions. Very small and unsystematical differences in absorbed power were observed which was taken to be an indication that neither diurnal changes nor fatigue due to short-term sitting were of significant importance in this context.

It is assumed that it is the absorbed portion of the total power which should be considered as most hazardous. It can, however, be argued that power, which is not absorbed, may also have a negative effect on the body. Other parts of the body, such as vessels, nerves, muscles, bone and joints, will be subjected to compression and extension during vibration exposure. If the physical strain on these structures does not exceed the elastic range then no power will be absorbed. This implies that organic damage occurs only after elastic limits are exceeded. This discussion presumes body structures behaving like ideal mass–spring systems without internal damping. Since most biological structures do have internal damping they will absorb power even when affecting dynamic forces are within the elastic range. Nons-absorbed power may still have an influence since vibration

TABLE 3

p-levels extracted from an analysis of variances ANOVA with respect to differences between females and males split by direction, posture and acceleration level (0·25, 0·35, 0·5, 0·7, 1·0 *and* 1·4 m/s²); *significant differences* ($p < 0{\cdot}05$) *are denoted*: *a = males > females*; *b = females > males*

Frequency (Hz)	x		y		z	
	Erect	Relaxed	Erect	Relaxed	Erect	Relaxed
	Exposure level (m/s²)					
	0·25–1·4	0·25–1·4	0·25–1·4	0·25–1·4	0·5–1·4	0·5–1·4
1·13	—	—	—	—		
1·25	— —	— —	— —	— —		
1·4	— —	— —	— —	— a		
1·6	— — —	— — —	a a —	— a —		
1·8	— — — —	— — a —	— a — —	— — — —		
2	— — — — —	— — a — —	— — — — —	a — — — —	a — — —	— — — —
2·26	— — — — —	— — — — —	— — — — —	— — — — b		
2·5	a — — b b —	— — — b b —	— — — — — —	— — b b b b	— — — —	— — — b
2·83	— — b b b —	— — b b b —	— — — — b —	— — b b b b	— — — —	— — — b
3·15	— — b b b —	b b b b b —	— — b b b —	— b b — b —	— — — b	— — b b
3·56	b b b b — —	b b b b b —	b b b b b —	b b b — — —	b b b b	b b b b
4	b b b — — —	b b b b b —	b b b — — —	b — b — — —	b b — b	— — — b
4·5	b b b — — —	b — b — — —	b b b — — —	b — b — — —	— — — —	— — — —
5	b — — — — —	b — — — — —	b b — — — —	b — b — — —	— — — —	— — a a
5·7	— — — — — —	— — — — — —	b — — — — —	— — — — — —	— a a a	a a a a
6·3	— — — — — —	— — — — — —	— — — — — —	— — — — — —	a a a a	a a a —
7·1	— — — — — —	— — — — — —	— — — — — —	— — — — — —	a — — —	a — — —
8	— — — — — —	— — — — — —	— — — — — —	— — — — — —	— — — —	— — b b
9	— — — — — —	— — — — — —	— — — — — —	— — — — — —	— — b —	— b b b
10	— — — — — —	— — — b b —	— — — — — —	— — — — — —	b b — —	b b b —
11·3	— — — — — —	— — — b b b	— — — — — —	— — — — — —	— — — —	b b — —
12·5	— — — — — —	— — b b b b	— — — — — —	— — — — — b	— — — —	— — — —
14·3	— — b — — —	b — b b b b	b — b — — —	— — b — — b	— — — —	— — — —
16	— — b b — b	— b b b b b	b — b — — —	b — b — — —	— — — —	— — — —
18	b — b b b b	b b b b b b	b — — — — —	b — b — — —	— — — —	— — — —
20	b b b b b b	— b b b b b	b — — — — —	b — b — — —	— — — —	— — — —
25	— b b b — —	— — b b b b	— — b — — —	— — — — — —	— — — —	— — — —
31·5	b — — b — —	b — b b — b	b — — — — —	b — — — — —	— — a —	— — — —
40	— — — — —	— — b — —	— — — — —	b — — — —	— — — —	— — — a
50	— — — —	— — — —	— — — —	— b — —	a — a —	a a a a
63	b — — —	b — — —	b — — —	b — — —	— — — —	— — — —
80	— — —	— — —	— — —	— — —	— — — —	— — — —

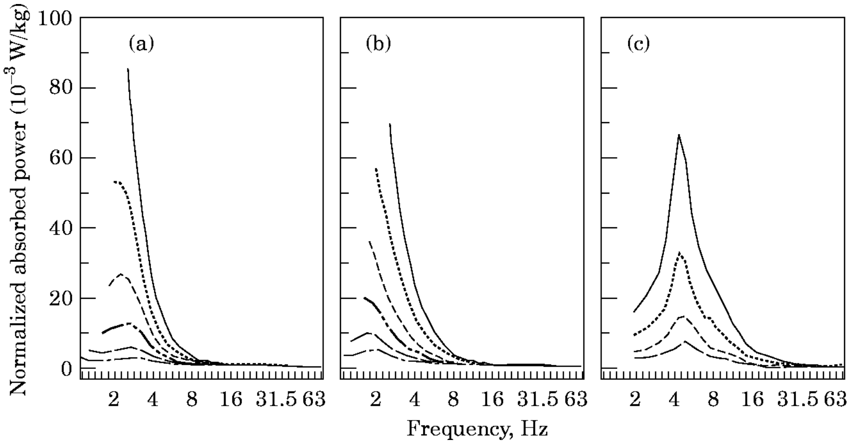

Figure 5. Averaged sitting weight normalized absorbed power for x, y, and z directions at six acceleration levels (0·25, 0·35, 0·5, 0·7, 1·0 and 1·4 m/s^2). Pooled data for females and males sitting in erect and relaxed postures ($n = 60$). (a) x direction; (b) y direction; (c) z direction. Key: acceleration levels (m/s^2): ——, 1·4; ····, 1·0; – – –, 0·7; –···–··–, 0·5; ———, 0·35; –·–·–, 0·25.

activates different types of receptors, such as mechanoreceptors, proprioceptors, thermoceptors and nociceptors. This, and the mechanical strain itself may have an influence on biochemical processes and interfere with blood circulation and nutrition. It is thus possible that some types of complaints or disorders are solely related to either absorbed or non-absorbed power while others are related to both. An example of an absorbed power related effect could be musculo-skeletal disorders, while effects on comfort and perception would be related to non-absorbed power. This is of course purely speculative since no support exists in scientific literature. Another possibility is that detrimental effects are purely related to the total amount of power affecting the body.

As shown in Figure 2 the inter-individual variation in absorbed power is relatively large, both in the magnitude and frequency planes. Differences in body weight and bodily structure are to be the most important factors. In order to reduce the influence of differences in body weight we chose to normalize individual results with respect to the sitting weight. This procedure has certain advantages. It not only makes the data easier to compile and interpret, but also increases the usefulness of the results. An estimation of the amount of absorbed power can then be calculated by multiplying normalised data and sitting weight. The average sitting to standing weight ratio for subjects participating in this study was 0·77 ($Sd \pm 0{\cdot}033$) and 0·76 ($Sd \pm 0{\cdot}030$) for females and males respectively. A normalization with respect to other measures for bodily structure, for instance an upper body mass index, is desirable but requires a more extensive data set before a more complete model for normalisation can be outlined.

An interesting aspect of the results was how absorbed power relates to the guidelines presented in ISO 2631 [9]. The frequency weighting procedure implies that human response to WBV is not only related to magnitude and duration but also to the frequency of the vibration. The purpose of the frequency weighting procedure is thus to compensate, or in other words, to normalise differences in human susceptibility at different frequencies. As stated earlier, vibration quantified in terms of acceleration does not necessarily mirror the physical strain on the body. It merely reflects the vibration level on the contact surface between the body and the vibration source. A better way to quantify the immission, i.e., the actual vibration dose, may therefore be "power", either absorbed, non-absorbed or both, since this measure also takes into account the dynamic force affecting the body

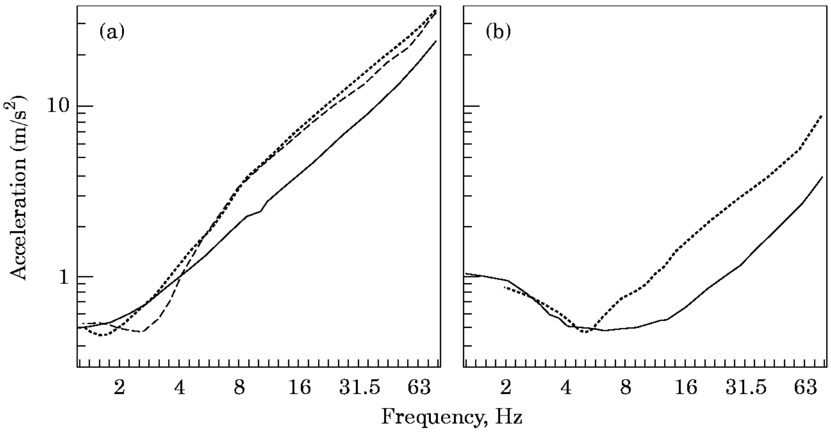

Figure 6. Comparisons of two concepts for risk assessments of whole-body vibration exposure: i.e., constant frequency weighted acceleration of 0·5 m/s^2 in accordance with ISO 2631 versus constant absorbed power. Graphs for the latter concept are based on pooled data for females and males sitting erect and relaxed but converted to frequency weighted acceleration levels. For more information see text. (a) ——, ISO 2631, W_d; ----, P_{Abs} x; ····, P_{Abs} y; (b) ———, ISO 2631 W_k; ····, P_{Abs} z.

during exposure to vibration. The concept of "power" for risk assessment thus implies that the driver must be mechanically coupled to the seat before any immission can occur. This is not the case for risk assessment according to the current ISO-standard since an acceleration level can be measured irrespective of whether the driver is actually sitting on the seat or not. Whether a frequency weighting procedure is also required for "power" can not yet be determined. One assumption could be that a certain amount of absorbed power is equally harmful or annoying regardless of frequency. A frequency weighting would then not be necessary. Figure 6 shows calculated acceleration levels at different frequencies corresponding to constant absorbed power. The frequency weighting curves, W_d and W_k, in accordance with ISO 2631 [9], correspond to an acceleration level of 0·5 m/s^2. The amount of absorbed power at 1·25 and 4·5 Hz, at which the W_d and W_k correction factors are about 1, were all calculated to be 11, 15 and 6·5 to 10^{-3} W for the x, y and z directions, respectively. Corresponding acceleration levels at other frequencies were predicted. For horizontal vibration it seems likely that the frequency weighting procedure underestimates the risk for unwanted effects within the range of 1·5–3 Hz and overestimates the risk for frequencies above about 5 Hz. For the vertical direction the weighting network overestimates the effect of vibration with frequencies higher than about 6 Hz.

The concept of absorbed power as a measure for evaluation of WBV exposure opens a new area for research. A useful way to compare this concept with other measures of vibration exposure in relation to health effects would be to conduct epidemiological studies on different categories of professional drivers. Corresponding comparison, but with respect to the effects of WBV on comfort and perception, could be done during controlled WBV excitation in a laboratory environment or while driving a vehicle on a test track.

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REFERENCES

1. E. Christ, H. Brusl, P. Donati, M. Griffin, B. Hohmann, R. Lundström, J. Meyer and H. Straatsma 1989 *International Section "Research", Institut National de Recherche et de Securité (INRS), Paris*. Vibration at work.
2. H. Dupuis and G. Zerlett 1986 *The effects of whole-body vibration*. Berlin: Springer-Verlag.
3. M. J. Griffin 1990 *Handbook of human vibration*. London: Academic Press.
4. C. Hulshof and v. B. V. Zanten 1987 *International Archives of Occupational and Environmental Health* **59**, 205–220. Whole-body vibration and low-back pain—a review of epidemiological studies.
5. A. Kjellberg, B. O. Wikström and U. Landström 1994 *Arbete och Hälsa*. **41**, 1–63. Injuries and other adverse effects of occupational exposure to whole-body vibration.
6. M. L. Magnusson 1991 *Doctoral dissertation from the Division of Occupational Orthopaedics, Department of Orthopaedics, University of Göteborg and Sahlgrenska Hospital, Sweden*. Effects of seated whole body vibrations on the spine.
7. M. H. Pope, M. I. V. Jayson, A. D. Blann, A. M. Kaigle, J. N. Weinstein and D. G. Wilder 1994 *European Spine Journal* **3**, 143–145. The effect of vibration on back discomfort and serum levels of von Willebrand factor antigen: a preliminary communication.
8. J. Sandover 1988 *Clinical Biomechanics* **3**, 249–256. Behaviour of the spine under shock and vibration: a review.
9. International Organization for Standardization 1997 *ISO* 2631-1. Mechanical vibration and shock—evaluation of human exposure to whole-body vibration. Part I: general requirements.
10. F. Pradko, T. R. Orr and R. A. Lee 1965 *SAE*, 331–339. Human vibration analysis.
11. F. Pradko, R. A. Lee and J. D. Greene 1965 In *Proceedings of The Winter Annual Meeting, Chicago, November* 7–11, *the American Society of Mechanical Engineers*. Human vibration–response theory; pp. 11.
12. F. Pradko and R. A. Lee 1966 *SAE Paper No*. 660139. Vibration comfort criteria.
13. R. A. Lee and F. Pradko 1968 *ASME, Paper No*. 680091. Analytical analysis of human vibration.
14. F. Pradko and R. Lee 1968 *SAE Paper No*. 680091. Analysis of human vibration.
15. R. N. Janeway 1975 *SAE Paper No*. 750166. Human vibration tolerance criteria and application to ride evaluation.
16. N. J. Mansfield and M. J. Griffin 1998 *Journal of Sound and Vibration* (awaiting publication). Effect of magnitude of vertical whole-body vibration on absorbed power for the seated human body.
17. J. Sandover 1981 *DHS Report No*. 402. *Department of Human Sciences, University of Loughborough*. Vibration, posture and low-back pain disorders of professional drivers.
18. H. Seidel 1988 *European Journal of Applied Physiology* **57**, 558–562. Myoelectric reactions to ultra-low frequency and low-frequency whole body vibration.
19. R. E. Seroussi, D. G. Wilder and M. H. Pope 1989 *Journal of Biomechanics* **22**, 219–229. Trunk muscle electromyography and whole-body vibration.