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COMPARISON OF SUBJECTIVE RESPONSES TO VIBRATION AND SHOCK WITH STANDARD ANALYSIS METHODS AND ABSORBED POWER

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Evaluation of human exposure whole-body vibration (WBV) and shock can be carried out in a variety of ways. The most commonly used standards for predicting discomfort from WBV are BS6841 (1987) and ISO2631-1 (1997) which offer different frequency weightings (W_b and W_k) and three methods of assessment: vibration dose value (VDV), estimated VDV (eVDV) and maximum transient vibration value (MTVV). Previous studies have also used DRI and absorbed power for assessments of shock and WBV. This paper reports a laboratory study in which 24 human subjects were exposed to 15 vertical vibration stimuli comprising of random vibration, repeated shocks and combinations of random vibration and shocks at 0·5, 1·0 and 1·5 m/s^2 r.m.s. Subjects rated the discomfort from the vibration on a numerical scale after each exposure. Acquired acceleration signals were analyzed using VDV, r.m.s. and MTVV for unweighted, W_b, W_k and DRI weighted signals. Acceleration and force were combined to give a measure of absorbed power. Subjective responses were correlated to vibration magnitude for the 13 analysis types. VDV was the best standard method of assessment; MTVV was the worst. W_b and W_k frequency weightings showed slightly greater correlations between vibration magnitude and discomfort than DRI weighted or unweighted signals. For VDV, there were no significant differences between the correlations obtained using any frequency weighting. For assessment of all stimuli types together, absorbed power gave higher correlations with subjective discomfort than acceleration-based methods. It is concluded that the methods described in ISO2631-1 should be clarified and simplified. Due to the difficulty in measuring absorbed power in the field, methods proposed in BS6841 are recommended as the most appropriate for assessment of discomfort from continuous vibration or repeated shocks.

1. INTRODUCTION

Occupational exposure to whole-body vibration (WBV) and mechanical shocks can cause discomfort and injury [1]. To assess whether any vibration environment

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constitutes a health risk, the motion must be measured. The acceleration is usually measured using accelerometers, weighted according to standard frequency response curves to allow for the different response of the body at different frequencies, analyzed using standard techniques and an assessement made according to the exposure duration. The choice of frequency weighting, analysis technique and time dependency is therefore critical for accurately determining how hazardous any exposure to shock and vibration might be [2].

For vertical vibration, British Standard BS6841 [3] specifies that acceleration should be weighted using frequency weighting W_b and assessed using methods based on root-mean-square (r.m.s.) or dose measures with an exponent of 4 (vibration dose values, VDV) depending on the crest factor (the ratio of the peak acceleration to the r.m.s.). International Standard ISO2631-1 [4] specifies that frequency weighting W_k be used for vertical vibration and that assessments be made using methods based on r.m.s., VDV or the maximum transient vibration value (MTVV). Griffin [5] has previously reported a complete comparison of these two standards and their limitations. There are no known studies comparing subjective responses of vibration and shock severity with assessments according to ISO 2631-1. Furthermore, it is not clear which frequency weighting or analysis method gives the best correlation with discomfort.

An alternative measure of vibration exposure, which does not rely on frequency weightings, is absorbed power [6–8]. Spectra of absorbed power indicate that vibration at frequencies above 5 Hz is less important than would be considered appropriate according to standard frequency weightings. Although the quantity has been measured in the laboratory and in vehicles, it also has not been correlated with subjective responses of discomfort.

Previous laboratory studies investigating subjective responses to shock have shown that either r.m.s. or fourth power methods correlate well to discomfort. Spång and Arnberg [9] showed no differences in correlations between the methods for exposures to single shocks and concluded that r.m.s. was a more appropriate method, as it was easier to measure. However, Howarth and Griffin [10] showed a better correlation for VDV than for dose values with an exponent of 2 for between 1 and 16 repeated shocks.

This paper reports a laboratory study comparing subjective judgements of vibration and shock severity with the absorbed power and with all combinations of standard frequency weightings and analysis methods.

2. METHOD

2.1. EXPERIMENTAL CONDITIONS

Each subject was exposed to 15 vibration conditions during one experimental session of about 15 min. Five vertical acceleration waveforms were used, each presented at 0·5, 1·0 and 1·5 m/s^2 r.m.s., unweighted (Figure 1). Each stimulus lasted 20 s. The vibration magnitudes and duration were selected to represent typical exposures measured in vehicles, whilst minimizing the vibration dose of the subjects. Although longer exposures might increase discomfort, it was assumed that

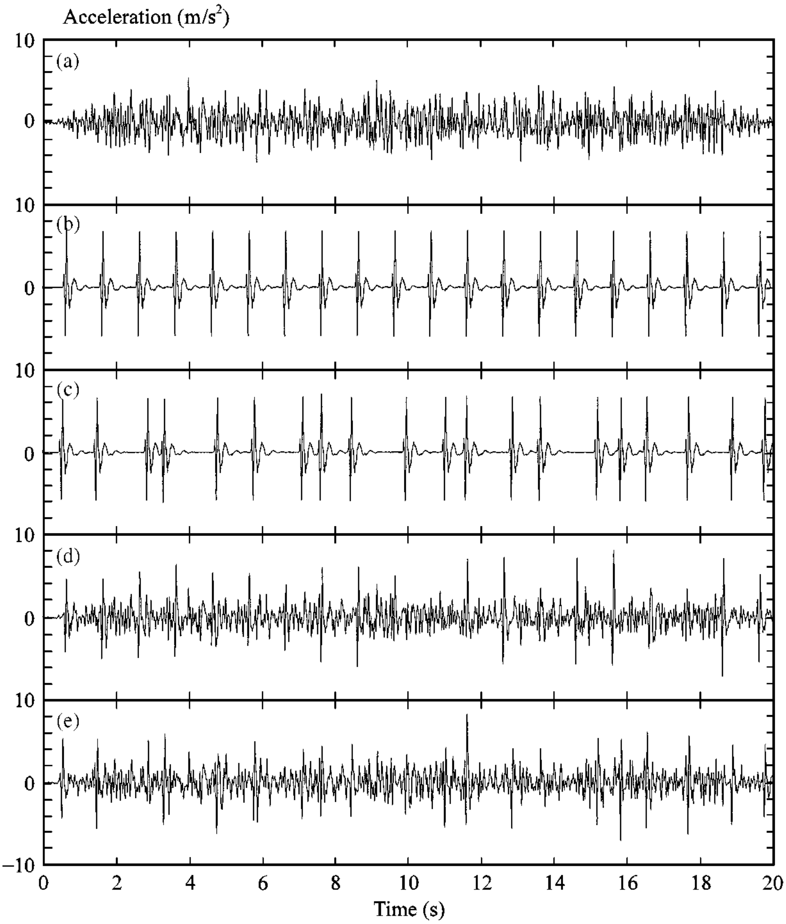

Figure 1. Five stimulus types used in the experiment: "a" random, "b" equally spaced shocks, "c" unequally spaced shocks, "d" random and equally spaced shocks combined, "e" random and unequally spaced shocks combined. Each stimulus was generated at 0·5, 1·0 and 1·5 m/s^2 r.m.s. (unweighted).

the relative discomfort levels between stimuli were not a function of vibration duration. Stimulus 1 consisted of random vibration in the frequency range of 2–20 Hz. Stimulus 2 consisted of 20 repeated mechanical shocks at equally spaced 1-s intervals (i.e., predictable). Stimulus 3 consisted of 20 repeated shocks that were not equally spaced (i.e., non-predictable). Stimuli 4 and 5 were combinations of stimuli 1 and 2 and of 1 and 3, respectively, with half the energy coming from the shocks, scaled to give the appropriate acceleration magnitude. The shocks were defined as sync pulses that were high- and low-pass filtered at 2 and 20 Hz using elliptic filters. The stimuli used to generate the vibration were equalized for the response of the amplifier and shaker to produce a flat spectrum at the seat. Consequently, each stimulus had nominally identical power spectra for each of the three vibration magnitudes. Although each subject was exposed to nominally identical vibration signals, the acquired acceleration at the seat was used for analysis to minimize the effects of variance in the stimuli. All measured values for unweighted vibration exposure were within 7% of those specified in the experimental design. A balanced random order of presentation of stimuli was used to minimize the influence of order effects or subject fatigue. After each 20-s exposure, subjects were asked to respond to the question:

"*How severe did you judge the vibration?*"

using a modified Borg CR-10 [11] scale from 0 ("not at all severe") to 10 ("very severe").

2.2. INSTRUMENTATION

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

2.3. SUBJECTS

Eleven males and 13 females participated in the experiment (Table 1). Subjects sat in a comfortable upright posture with hands resting on the lap. Postures were not physically controlled but the experimenter was in constant visual contact with the subjects. The feet position was set using an adjustable footrest such that the subjects' thighs were horizontal. The footrest did not move with seat. No backrest was used in the experiment.

2.4. FREQUENCY WEIGHTINGS

Each acquired acceleration signal measured at the seat was weighted to give four weighting conditions (Figure 2). The first three conditions were for the raw data (i.e., no weighting), and signals weighted according to W_b and W_k. To allow for comparison with a frequency weighting with a more extreme shape and higher peak frequency, acceleration signals were also weighted using the dynamic response index (DRI) response curve [12, 13]. Some authors have historically advocated DRI for analysis of high-acceleration mechanical shocks, such as those experienced during aircraft ejection. The DRI "weighting" is defined as the response of a single-degree-of-freedom system with a resonance frequency of 8·4 Hz and a damping ratio of 0·224.

Table 1

Subject characteristics

	Male ($n = 11$)				Female ($n = 3$)				All ($n = 24$)			
	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max
Age	36	8	25	49	44	8	26	57	40	9	25	57
Weight	81	8	72	96	67	7	54	79	74	10	54	96
Height	182	5	173	188	166	4	154	171	173	9	154	188

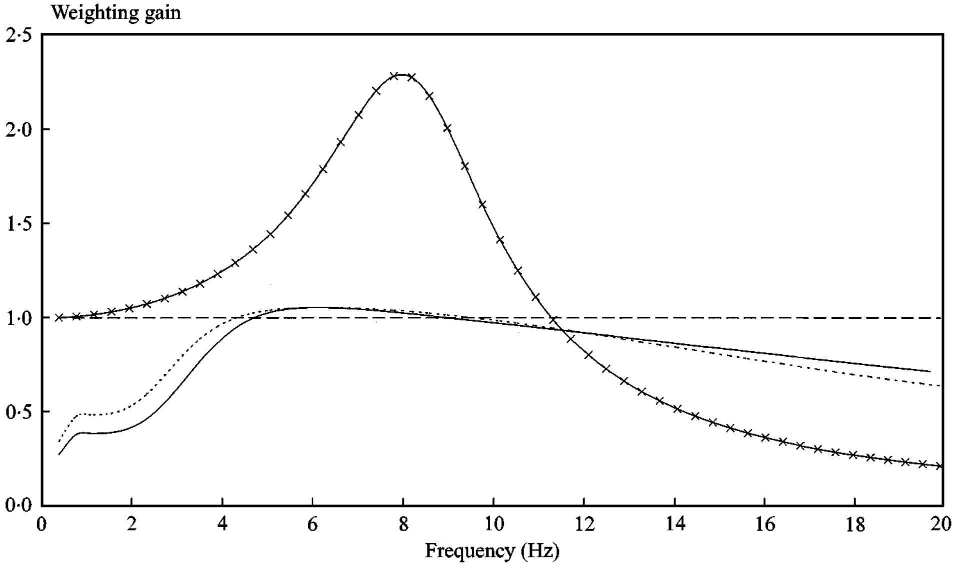

Figure 2. Four frequency weightings used for analysis of acceleration signals. Unweighted (– – – –), ISO 2631-1 (- - - - - - -), BS6841 (——), DRI (—×—).

2.5. ANALYSIS METHODS

For each of the frequency weighted signals, three analyses were carried out to enable comparisons of all combinations of frequency weighting and analysis methods defined in BS6841 and ISO2631-1. The r.m.s. of the acceleration was calculated using

$$\text{r.m.s.} = \left[\frac{1}{T}\int_{t=0}^{t=T} a_w^2(t)\,\mathrm{d}t\right]^{1/2},$$

where T is the measurement duration and $a_w(t)$ is the frequency weighted acceleration at time t. The VDV was calculated using

$$\text{VDV} = \left[\int_{t=0}^{t=T} a_w^4(t)\,\mathrm{d}t\right]^{1/4}.$$

The MTVV was calculated using

$$\mathrm{MTVV} = \max\left[\frac{1}{\tau}\int_{t_0-\tau}^{t_0} a_w^2(t)\,\mathrm{d}t\right]^{1/2},$$

where τ is the integration time and t_0 is the time of the measurement. An integration time of 1 s was used for the analysis, as recommended in ISO2631-1. The estimated vibration dose value (eVDV) is also used in BS6481 and ISO2631-1 and is defined as

$$\mathrm{eVDV} = 1{\cdot}4 \times \mathrm{r.m.s.} \times T^{1/4}.$$

Since each stimulus lasted 20 s, the eVDV was equivalent to 2·96 × the r.m.s. Correlations would therefore be identical to those obtained using the r.m.s. method alone and consequently the eVDVs are not reported in this paper.

The total absorbed power, P_{abs}(total), was also measured for each condition and is defined as [8]

$$P_{abs}(\mathrm{total}) = \int_{t=2}^{t=20} |G_{Fv}(f)| \cos\phi(f)\,\mathrm{d}f,$$

where $|G_{Fv}(f)|$ is the modulus and $\phi(f)$ is the phase of the cross-spectral density between the force, F, and the velocity, v, at frequency f.

In total, 13 analyses were carried out for each stimulus. These consisted of the absorbed power and the r.m.s., VDV and MTVV for each of the four frequency weighting conditions.

3. RESULTS

3.1. DISCOMFORT SCORES

As would be expected, all subjects gave greater discomfort scores for the stimuli with greater magnitudes. One male and three female subjects gave the maximum score of 10 for at least one of the stimuli. No subject gave response of less than 1. For all magnitudes, subjects generally judged shocks stimuli as most severe and the random stimuli as the least severe (Table 2). For females, mean responses for shocks at 1·0 m/s^2 r.m.s. were slightly greater than the responses for random vibration at 1·5 m/s^2 r.m.s.

Male subjects consistently scored the stimuli as less severe than female subjects did. However, the differences were only significant for 5 of the 15 conditions at the 10% level (Mann–Whitney). Males judged the unequally spaced shocks as more severe than the equally spaced shocks. Females judged the unequally spaced shocks as less severe than the equally spaced shocks.

3.2. EFFECT OF ANALYSIS METHOD

For each subject, discomfort scores were correlated to the vibration magnitudes of the 15 stimuli analyzed with the 13 techniques previously described. Spearman's

TABLE 2

Mean and standard deviation of subjective discomfort scores for 24 *subjects exposed to* 15 *vibration stimuli*

Stimulus type	Magnitude m/s^2 r.m.s. (unweighted)	Male		Female	
		Mean score	SD	Mean score	SD
Random		5·91	2·12	6·08	1·98
Shocks equal		6·18	2·23	8·00	1·83
Shocks unequal	1·5	6·36	2·11	7·77	1·88
Combined equal		6·00	2·05	7·15	1·82
Combined unequal		6·00	1·79	7·00	1·83
Random		4·64	1·69	5·00	1·91
Shocks equal		5·09	2·21	6·92	1·44
Shocks unequal	1·0	5·18	1·99	6·85	1·77
Combined equal		4·64	1·43	5·69	2·14
Combined unequal		4·18	1·94	5·46	2·15
Random		2·23	1·17	2·54	1·75
Shocks equal		3·14	1·79	5·31	1·93
Shocks unequal	0·5	3·18	1·94	4·92	1·89
Combined equal		3·09	1·51	3·23	2·49
Combined unequal		2·64	1·36	2·96	1·78

rank correlation method was used. Discomfort scores were positively correlated with all analysis methods for all subjects (Table 3). Correlations ranged between $r_s = 0{\cdot}37$ (subject 7, MTVV DRI weighted) and $r_s = 0{\cdot}95$ (subjected 14, VDV all weightings).

Median correlations between discomfort and vibration magnitude were greatest for the absorbed power and for VDV analysis methods. Similar trends were observed for individual subject data. The lowest median correlation was obtained for MTVV and DRI analysis, which was also reflected for individual subjects.

Considering only acceleration-based measurements, the VDV showed the highest correlations between subjective responses and magnitude. For each of the four frequency weighting conditions, the VDV gave greater correlations than MTVV or r.m.s. The median correlations for VDV using any frequency weighting were higher than the median correlation for any other acceleration-based method of analysis. Median correlations for the r.m.s. method were generally greater than median correlations for the MTVV, the only exception occurring for unweighted analysis.

3.3. EFFECT OF FREQUENCY WEIGHTING

For the VDV, similar median correlation coefficients were obtained irrespective of the frequency weighting chosen. Many individual subjects showed identical

TABLE 3

Spearman correlation coefficients (r_s) between subjective discomfort scores and vibration magnitude analyzed using 13 *techniques for* 24 *subjects exposed to* 15 *vibration stimuli. Acceleration signals were analyzed using r.m.s., VDV and MTVV methods for unweighted, W_b, W_k and DRI weighted acceleration*

	Spearman correlation coefficient												
		r.m.s.				VDV				MTVV			
Subject	Absorbed power	Unweighted	W_b	W_k	DRI	Unweighted	W_b	W_k	DRI	Unweighted	W_b	W_k	DRI
1	0·88	0·89	0·91	0·90	0·87	0·83	0·83	0·83	0·82	0·92	0·93	0·93	0·88
2	0·85	0·61	0·80	0·78	0·83	0·88	0·88	0·88	0·88	0·62	0·68	0·68	0·59
3	0·80	0·63	0·74	0·74	0·72	0·82	0·82	0·82	0·82	0·71	0·76	0·76	0·67
4	0·61	0·69	0·65	0·65	0·60	0·55	0·55	0·55	0·58	0·77	0·76	0·76	0·76
5	0·84	0·83	0·78	0·79	0·79	0·76	0·77	0·77	0·77	0·77	0·75	0·76	0·81
6	0·61	0·52	0·65	0·65	0·66	0·68	0·68	0·68	0·68	0·48	0·51	0·51	0·38
7	0·65	0·47	0·71	0·69	0·69	0·68	0·68	0·68	0·68	0·42	0·42	0·42	0·37
8	0·70	0·78	0·73	0·73	0·76	0·75	0·75	0·75	0·75	0·75	0·68	0·70	0·78
9	0·79	0·63	0·74	0·73	0·80	0·84	0·84	0·84	0·84	0·62	0·74	0·74	0·63
10	0·82	0·77	0·78	0·78	0·78	0·84	0·84	0·84	0·83	0·73	0·75	0·75	0·76
11	0·89	0·80	0·82	0·83	0·87	0·88	0·88	0·88	0·88	0·74	0·75	0·75	0·80
12	0·78	0·44	0·68	0·68	0·72	0·80	0·80	0·80	0·80	0·53	0·54	0·54	0·44
13	0·92	0·90	0·93	0·93	0·93	0·93	0·93	0·93	0·93	0·90	0·89	0·90	0·91
14	0·91	0·84	0·90	0·89	0·94	0·95	0·95	0·95	0·95	0·86	0·90	0·90	0·82
15	0·84	0·71	0·79	0·79	0·82	0·89	0·89	0·89	0·89	0·73	0·78	0·76	0·67
16	0·72	0·46	0·62	0·62	0·66	0·72	0·72	0·72	0·72	0·57	0·56	0·56	0·53
17	0·95	0·81	0·93	0·90	0·91	0·95	0·95	0·95	0·95	0·82	0·84	0·84	0·74
18	0·83	0·54	0·77	0·77	0·77	0·81	0·81	0·81	0·81	0·63	0·64	0·64	0·51
19	0·92	0·76	0·91	0·91	0·92	0·91	0·91	0·91	0·91	0·70	0·71	0·71	0·66
20	0·71	0·61	0·73	0·73	0·68	0·71	0·71	0·71	0·73	0·66	0·75	0·75	0·55
21	0·87	0·58	0·81	0·79	0·81	0·85	0·85	0·85	0·85	0·68	0·70	0·70	0·64
22	0·91	0·79	0·85	0·85	0·88	0·90	0·90	0·91	0·90	0·84	0·86	0·86	0·77
23	0·85	0·66	0·82	0·82	0·84	0·83	0·83	0·83	0·83	0·65	0·70	0·70	0·64
24	0·88	0·64	0·81	0·82	0·84	0·87	0·87	0·87	0·87	0·68	0·70	0·70	0·59
Median	0·84	0·68	0·78	0·78	0·81	0·83	0·83	0·83	0·83	0·70	0·74	0·74	0·66

correlations between discomfort score and VDV for all frequency weightings. For r.m.s. analyses, the median correlations were the lowest and highest for the unweighted and DRI weighted acceleration, respectively. For MTVV, W_b and W_k gave better correlations between acceleration and subjective responses than unweighted or DRI weighted acceleration.

3.4. EFFECT OF STIMULUS TYPE

To facilitate pooling of data from different subjects, responses for each subject were normalized. The normalization procedure was carried out by subtracting each subject's mean score from each condition score and dividing by the standard deviation. Thus, for each subject, the normalized responses had a mean score of zero and a standard deviation of unity.

For random and combined stimuli, the highest correlations between vibration magnitude and normalized responses were obtained using the absorbed power technique (Table 4). For the shocks stimuli, highest correlations were obtained using the r.m.s. method for all frequency weightings. The DRI frequency weighting gave the highest correlations for acceleration-based analyses of the random stimuli. Unweighted acceleration gave the highest correlations for combined stimuli. Correlations for the shocks stimuli were slightly greater for the W_b and W_k frequency weightings.

4. DISCUSSION

This experiment has shown that, at least between 2 and 20 Hz, correlations with discomfort were more dependent on the analysis method than the frequency weighting. This general conclusion is in agreement with Wikström *et al.* [14] in a field study using industrial trucks. Although different weighting curves can lead to different absolute values of vibration magnitude for measurements of vibration in vehicles depending on the spectral content of the vibration [2], this study suggests that the relative discomfort correlations from the signals is unchanged. One might therefore conclude that efforts to improve standard techniques of vibration exposure assessment with respect to discomfort should be concentrated on the optimization of the analysis method rather than any changes to the frequency weightings.

For the VDV analysis method, correlations between the vibration magnitude and subjective responses were not significantly different for any frequency weighting. Similarly, comparison of the correlations obtained using W_b and W_k weightings showed no significant difference for any analysis method. However, this study used stimuli with negligible vibration content below 2 Hz or above 20 Hz, where the largest difference between these weighting curves occur. All the three frequency weightings (i.e., W_b, W_k and DRI) gave a significant improvement over the unweighted acceleration for correlations with discomfort when using r.m.s. analysis ($p < 0{\cdot}001$). Although, for r.m.s. data, the median correlation for DRI was greater than that observed for W_b or W_k, differences were not significant. For the

TABLE 4

Spearman correlation coefficient (r_s) between normalized subjective discomfort scores and vibration magnitude analyzed using 13 techniques for 24 subjects exposed to random, shocks and combined stimuli. Acceleration signals were analyzed using r.m.s., VDV and MTVV methods for unweighted, W_b, W_k and DRI weighted acceleration

Stimulus type	Absorbed power	Spearman correlation coefficient											
		r.m.s.				VDV				MTVV			
		Unweighted	W_b	W_k	DRI	Unweighted	W_b	W_k	DRI	Unweighted	W_b	W_k	DRI
Random	0·81	0·73	0·73	0·74	0·79	0·73	0·73	0·74	0·79	0·76	0·75	0·75	0·79
Shocks	0·66	0·74	0·75	0·75	0·75	0·72	0·73	0·73	0·73	0·72	0·73	0·73	0·72
Combined	0·84	0·79	0·78	0·78	0·77	0·83	0·82	0·82	0·80	0·77	0·76	0·76	0·75

MTVV analysis, W_b and W_k performed significantly better than unweighted or DRI weighted acceleration ($p < 0{\cdot}001$). Considering all analysis options, there were no methods where a significantly better correlation was obtained using weightings other than W_b or W_k.

For analysis methods based on acceleration, VDV gave the highest correlations between vibration magnitude and discomfort. This is in agreement with previous studies [10]. The VDV method was significantly better than the other methods for all frequency weightings at predicting subjective discomfort ($p < 0{\cdot}01$, Wilcoxon). The higher correlations obtained using the r.m.s. method compared to the MTVV method were significant for all except for the unweighted data ($p < 0{\cdot}005$). Therefore, for these data, VDV gave the best correlation to discomfort and to MTVV the worst. In a similar laboratory study using reproductions of shocks measured in off-road vehicles, Spång and Arnberg [9] also showed higher correlations for fourth power dose methods than for r.m.s. or for methods based on peak accelerations, when data were analyzed using non-parametric methods.

BS6841 and ISO2631-1 use W_b and W_k frequency weightings, respectively, which have been shown to correlate equally well to discomfort. For stimuli with a “low” crest factor, both standards recommend using the eVDV method of analysis; for stimuli with a “high” crest factor, BS6841 recommends using VDV and ISO2631-1 recommends using VDV or MTVV for analysis. The threshold that separates “low” from “high” crest factors is 6 for BS6841 and 9 for ISO2631-1. As each stimulus in the experiment lasted 20 s, eVDV was a linear function of r.m.s. For random and shocks signals, r.m.s. analysis gave slightly higher correlations between normalized responses and vibration magnitude than VDV. In contrast, combined signals showed slightly higher correlations for the VDV method than for the r.m.s. Crest factors for the random and shocks stimuli were 3·5 and 4·7 respectively. The combined signals had higher crest factors of 4·8 and 5·6 for the unequally spaced and equally spaced shocks respectively. Consequently, for these data, the threshold where VDV gave an improvement over eVDV was 4·8. The recommended crest factor specified in BS6841 therefore seems more reasonable than that specified in ISO2631-1. It is interesting to note that previous versions of ISO2631 recommended lower crest factors of 3 [15] and 6 [16]. ISO2631-1 [4] states that under some circumstances, signals with a crest factor of less than 9 should be analyzed using MTVV or VDV. Although VDV has been shown here to give better correlations to discomfort than r.m.s. methods for signals with high crest factors. MTVV does not necessarily improve the prediction. For the signals with the highest crest factor (i.e., combined random and shocks), MTVV gave inferior predictions of discomfort than r.m.s. For the signals with the lowest crest factor (i.e., random), MTVV gave better predictions of discomfort than r.m.s. These are the trends opposite to what would be expected if ISO2631-1 is applicable. From these data, the method specified in BS6841 would give better predictions of discomfort than those specified in ISO2631-1 for stimuli with high crest factors.

If the acceleration-based analysis methods are considered in the time domain, it is also possible to see the advantage of eVDV or VDV when compared to MTVV (Figure 3). For these 20 s stimuli, the value of the r.m.s. acceleration is erratic during

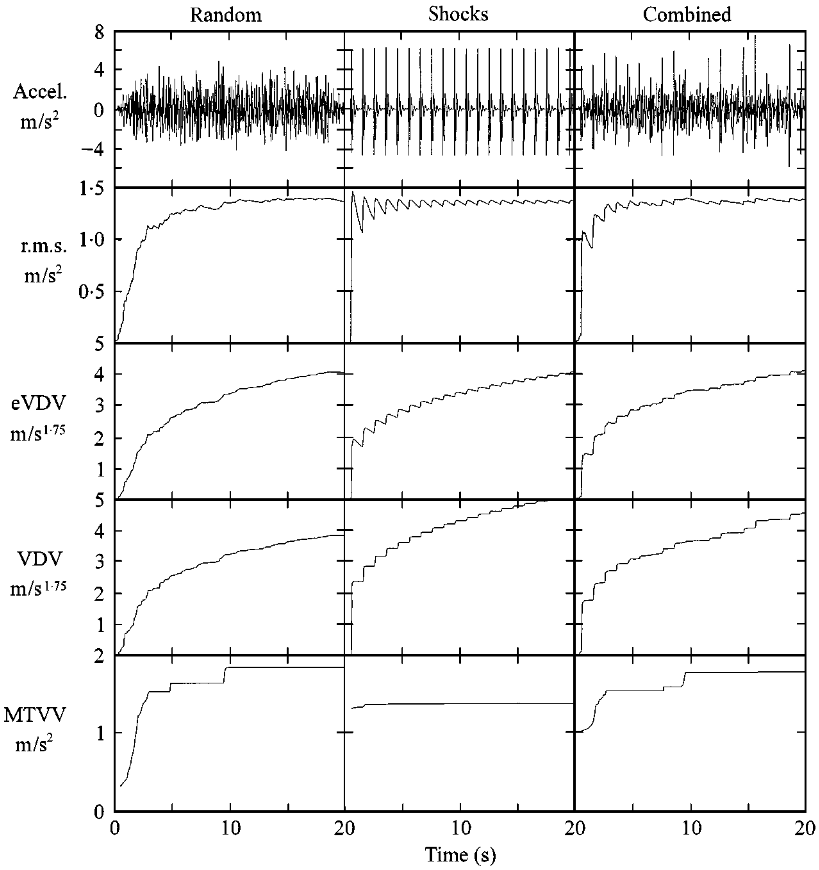

Figure 3. Effect of exposure time on analysis of random, equally spaced shocks and equally spaced shocks combined with random acceleration signals at 1·5 m/s^2 r.m.s. Data are measured acceleration signals from Subject 1 and are W_b weighted.

the first few seconds of analysis but stabilizes as the number of time averages increases. There was very little change in the r.m.s. for the last 10 s of the signal. As eVDV is a function of the vibration duration and the r.m.s., for stationary signals it steadily increases as vibration exposure increases. Similarly, VDV increases with vibration exposure time. Comparison of eVDVs and VDVs in the time domain indicates that although the shapes of the two functions were generally similar, there were some differences. In particular, for the equally spaced shocks signal the eVDV decreases between each shock. This is caused by the reduction in the r.m.s. due to increased averaging time. Therefore, if eVDV is used to analyze signals containing shocks, it is possible to record a lower "dose" for a longer vibration exposure duration than what would be recorded immediately after the shock. By definition, VDV cannot decrease as exposure duration increases.

MTVV is, by definition, the r.m.s. of the most severe 1 s of vibration. For a stationary signal, the MTVV can reach a maximum within a few seconds and is then unaffected by the vibration duration. For repeated shocks, the MTVV reaches a maximum after the first shock, and is unaffected by the number of shocks. For all stimuli used in the experiment, the MTVV after 10 s had already reached a maximum and did not increase with subsequent exposure (Figure 3). A further problem might be encountered using the MTVV for shocks spaced at intervals of less than the integration time. In this case, two shocks could occur within one averaging period and would be analyzed together, thereby increasing the MTVV. Reducing the integration time to eliminate such effects is allowable within ISO 2631-1 but would increase all other measurements of MTVV [2].

For analysis of signals containing shocks, both eVDV and MTVV can be misleading. For signals that do not contain shocks, eVDV and VDV behave similarly. Due to the problem of selection of the crest factor where eVDV becomes unreliable, it therefore seems appropriate to report VDV for all vibration analyses.

The higher correlation for dose methods compared to peak methods is logical, as one would expect that exposure to two shocks would cause more discomfort than exposure to a single shock. It is more difficult to speculate why fourth power dose methods are more appropriate than other indices, although it is hypothesized that it is likely to be a combination of physiological, biodynamic and psychological factors.

Although absorbed power gave the highest median correlation between subjective responses and vibration magnitude, the differences in the correlations obtained using VDV method were not significant. Absorbed power was significantly better than r.m.s. or MTVV methods at predicting discomfort, irrespective of the frequency weighting chosen ($p < 0{\cdot}05$, Wilcoxon). Although absorbed power shows promising results here under controlled laboratory conditions, it is currently unclear whether time-varying force signals can be reliably measured on soft seats where most workers are exposed to whole-body vibration. Some preliminary studies have reported absorbed power in vehicles [17, 18] which appear to give reasonable values when compared to laboratory studies, but further work is still required to verify these findings.

Some previous investigators have proposed that r.m.s methods are used in preference to VDV as most laboratories have access to instrumentation for r.m.s. analyses (e.g., reference [9]). Since these proposals were made, the ability to digitize signals has become a standard facility for most vibration measuring equipment and so VDV methods can be implemented without the need for new specialized hardware. Therefore, those evaluating whole-body vibration should be able to use VDV for all analyses. In contrast, measuring absorbed power in working environments requires force cells suitable for mounting on a seat, which are costly and not generally available. For the time being, absorbed power should be used as a research tool, rather than for standard evaluation of discomfort from vibration.

Many occupational exposures to WBV consist of substantial components of vibration in the horizontal axes [19]. It would therefore be of interest to compare analysis methods for fore-and-aft, lateral and intermediate directions of vibration. BS6841 and ISO2631-1 use similar frequency weightings for assessment of horizontal vibration, but different multiplication factors and techniques for summing multi-axis exposure, depending on the reader's interpretation of ISO2631-1.

From this study it is possible to recommend a revision of ISO2631-1 [4] for application to discomfort:

- MTVV should not be recommended in the standard and,
- the crest factor where VDV methods are specified in preference to r.m.s. methods should be reduced or,
- VDV should be recommended for all analyses.

5. CONCLUSIONS

For prediction of discomfort from exposure to whole-body vibration and repeated shocks:

- Correlations between discomfort and acceleration magnitude are more dependent on analysis method than frequency weighting.
- W_b and W_k weighted acceleration give slightly better predictions of discomfort than DRI or unweighted acceleration.
- VDV gives higher correlations to discomfort than r.m.s. or MTVV across all stimuli types.
- Absorbed power correlates well to subjective discomfort.
- ISO2631-1 requires clarification and amendment.
- BS6841 is the most reasonable standard to apply to assess measurements of vibration and mechanical shocks.

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