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THE SIGNIFICANCE OF VIBRATION DIRECTION FOR SUBJECTIVE EVALUATION OF DUAL-AXIS WHOLE-BODY VIBRATIONS

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ABSTRACT

Sixteen female and fifteen male subjects, 19-51 years of age participated in the present study. Its purpose was to determine various combinations of sinusoidal simultaneously presented (dual-axis) vertical and lateral whole-body vibrations that are sensed as equally strong as a preceding single-axis reference (a_w = 1.25 ms^{-2} r.m.s.) which was applied in either of both directions only and which had the same frequency, namely 1.6, 3.15, 6.3 or 12.5 Hz. The test motion consisted of a constant predefined and a variable component. The first was applied in the same direction and with either of 5 predefined percentages of the acceleration of the reference (10, 25, 50, 75, 90 %). The variable component was perpendicularly oriented to the first (resp. to the reference); its magnitude was varied by the subjects until the dual-axis test signal was judged as equally strong as the single-axis reference.

The curves of equally sensed combinations determined for the 4 frequencies were bended right-downwards as expected due to ISO/DIS 2631. But there were remarkable quantitative discrepancies for frequencies above 1.6 Hz with an underestimation of lateral vibrations; the factor k_y being 1.5 - 1.9 greater than in the standard. It is concluded that the weighting factors for lateral vibrations above 1.6 Hz need to be corrected for the proper evaluation of discomfort caused by multi-axis whole-body vibrations.

1 INTRODUCTION AND OBJECTIVES

Whole-body vibrations at the workplaces are usually complex, they consist of multifrequency translational and rotational motions, they occur simultaneously in different directions and they are interspersed with shocks of various strenghts [e.g. Hansson & Wikström, 1981].

ISO/DIS 2631 [1995] provides weighting factors to estimate equal discomfort for standing, sitting, and recumbent persons exposed to whole-body vibrations in the 3 orthogonal axes within the range of 0.5 to 80 Hz. This allows the calculation of comfort contours, which relate vibration magnitudes to frequencies where equal discomfort is expected at any point of the contours for vertical and horizontal motions.

The standard concerns as well multifrequency and multiaxis vibration stress. Regarding translatory vibrations, the entire stress is evaluated by the equation

$$a_v = (k_x^2\, a_{wx}^2 + k_y^2\, a_{wy}^2 + a_{wz}^2)^{½},$$

where a_v denotes the entire stress and a_{wx}, a_{wy} and a_{wz} the frequency-weighted effective acceleration in the sagittal (x), lateral (y) and vertical (z) direction, respectively. The factors k_x and k_y consider the relative sensitivity for frequency-weighted horizontal accelerations (x, y) as compared to vertical motions. For subjective assessment - as discussed here - they are set to $k_x = k_y = 1$.

The hypothesis proved here derived from preceding experiments, focused to the validity of intra-axial frequency weighting according to ISO/DIS 2631 under the aspect of inter-axial equivalence between single-axis vertical and single-axis horizontal vibrations transmitted through the seat (Griefahn & Bröde 1997). The respective results suggest, that ISO/DIS 2631 underestimates the effects of horizontal motions above 1.6 Hz, and led to the conclusion that the equation for the evaluation of dual-axis i.e. simultaneously acting vertical and horizontal motions as presented above cannot be valid, at least if $k_x = k_y = 1$. Therefore, the present study was designed to determine experimentally equally sensed combinations of vertical and lateral accelerations, separately for different sinusoidal frequencies and to compare the resulting dual-axis equivalence curves to the curves expected due to the standard.

2 MATERIAL, METHODS AND EXPERIMENTAL DESIGN

Technical equipment and environmental conditions: Vertical and lateral motions were transmitted to an aluminium platform on which a tractor seat was rigidly mounted with a strong metal tube (Ø 9.5 cm). The lateral and back rims of the slightly contoured metal seat were bent upwards, its height increased towards the back where it reached 22 cm thus performing a lumbar support rather than a backrest.

A 17“ monitor in front of the seat was adjusted to the head level of the subjects and used to announce the various experimental phases. Air temperature was adjusted to 23 ± 0.1°C, velocity to 0.2 ± 0.05 m/s; humidity varied between 40 and 50 %. Specific noises produced by the operation of the equipment were masked by pink noise of 63 dBA.

Vibration measurements: Translational vibrations in the 3 orthogonal axes were measured between seat and ischial tuberosities according to ISO 2631 during the presentation of the reference motion and immediately after the subjects had signalled equality.

Unweighted triaxial background acceleration was < 0.1 ms^{-2} r.m.s. at the seat, its frequency weighted magnitude was < 0.02 ms^{-2} r.m.s.. Acceleration distortion varied between 7 and 11 % for vertical and between 9 and 18 % for lateral motions within the frequency range concerned (1.6 - 12.5 Hz). High-frequency background motions (> 100 Hz) which were percepted through the feet and suspected to influence the entire sensation were damped by suitable material which covered the platform (Armaflex™, 28 mm).

Experimental procedure: The determination of equal sensation was performed with the method of adjustment, where the subject altered the magnitude of a test signal until it was sensed as equally strong as a preceding reference signal (figs 1, 2).

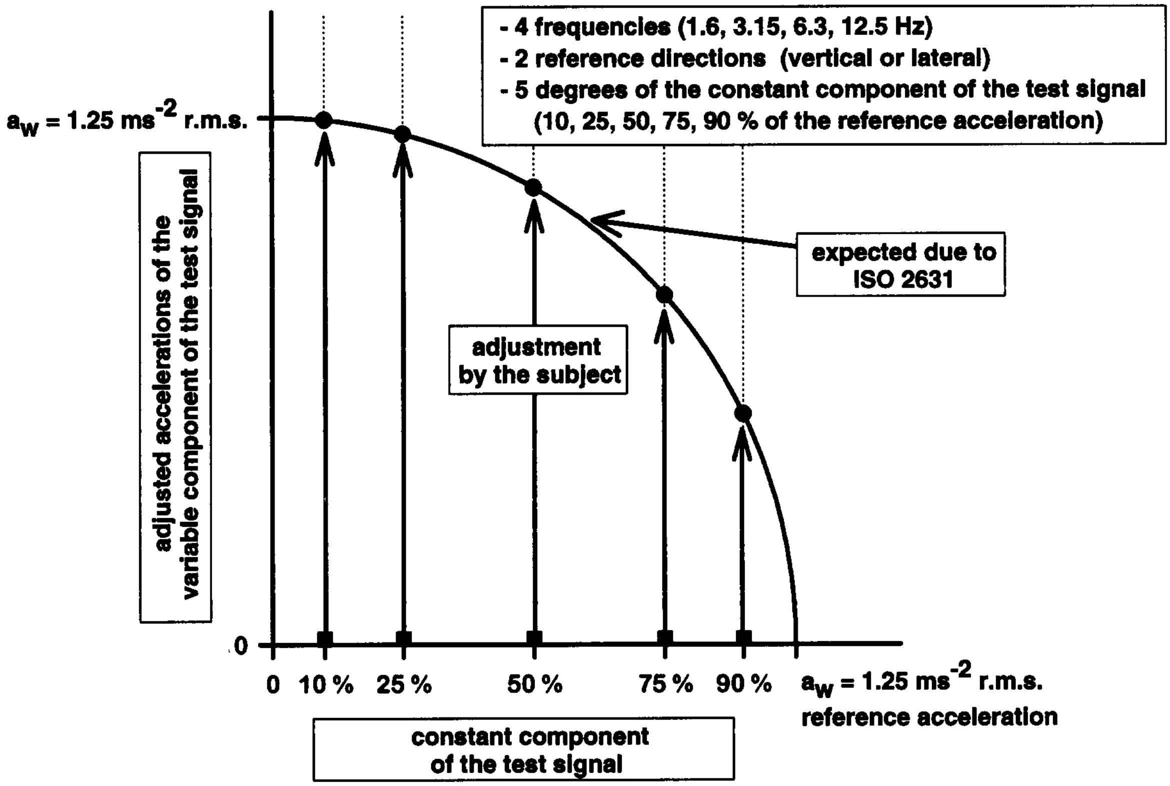

Figure 1: Experimental conditions and design.

Reference signals were single-axis sinusoidal motions of 1.6, 3.15, 6.3 and 12.5 Hz presented with a weighted acceleration of 1.25 ms^{-2} r.m.s. in either the lateral or vertical direction for 8 seconds (plus 2 s rise-decay time).

The test signal started after a pause of 2 seconds; it consisted of a constant and a variable component, both with the same frequency as the reference signal. The acceleration of the constant component had the same direction as the reference and was presented with 5 predefined percentages of the accelerations of the reference, namely 10, 25, 50, 75 or 90 %. The variable component was presented in the perpendicular direction. Its magnitude was initially 0.1 ms^{-2} but was altered by the subjects until the dual-axis test signal was sensed as equally strong as the preceding single-axis reference (Fig. 1). Both these components were presented with phase shifts of either 0° or 180° which caused dual-axis linear motions (upper left to right down

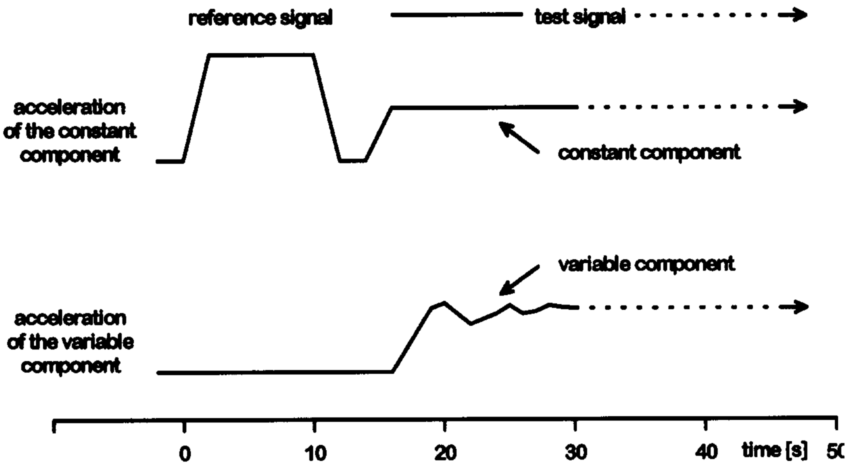

Figure 2: Adjustment of test signals

resp. upper right to left down). The time limit for the adjustment was 30 seconds.

The subjects adopted a slightly kyphotic, rather natural posture. They held a small keyboard in both hands. The latter was equipped with 3 keys which were inactive during the reference. The variable component of the test motions were amplified/attenuated by pressing the upper right or the upper left key respectively. Equality was signalled by the key located in the middle below the others. Thereafter, the accelerations were measured for 2 seconds then the signals were terminated and the following trial started after a pause of 15 seconds.

Experimental design: The subjects were randomly allocated to either of 2 subgroups determined by the direction of the dual-axis linear motion (upper left to lower right or upper right to lower left). The 4 frequencies were studied in separate sessions, so each subject participated in 4 experiments. The succession was balanced according to a latin-square design.

Ten different trials (2 directions of the reference resp. the constant component, 5 magnitudes of the constant component) were executed 3 times and randomly permuted. Two additional 'warm-up' trials (33 %, lateral and vertical reference) were executed at the beginning of each session. So, each session consisted of 32 trials and lasted about 30 minutes.

Subjects: 31 subjects (15 men, 16 women, 33.5 yrs, 69.7 kg, 173.9 cm) participated in the experiments which were approved by the local ethic committee. There were no medical contra-indications. As injuries were unlikely no criteria were defined for break-off, apart from subjects' decision. The safety aspects prescribed in ISO/DIS 13090-1 [1995] were taken into account. The experimenter and the subjects were in easy reach of an emergency button/ handle capable of stopping the vibrations.

Statistics: Weighted accelerations (r.m.s.) and distorsions were calculated using the discrete Fourier-transformation. Frequency weighting was done according to ISO/DIS 2631. The medians of ever 3 identical tests were used for statistical analyses.

The adjusted frequency-weighted accelerations (r.m.s.) were submitted to an analysis of variance for repeated measurements [Littel et al. 1996]. Independent grouping factors were gender and phase shifts (0°, 180°), covariables were age and weight, repetition factors were frequencies (1.6, 3.15, 6.3, 12.5 Hz), directions (lateral, vertical) and the percentage acceleration of the constant component (10, 25, 50, 75, 90 % of the reference). The interactions between the independent factors and the repetition factors were considered as well. Height was not considered, as it was highly correlated with weight ($r > 0.8$).

Statistical significance was assumed, if the probability of errors was less than 1 % ($p < 0.01$). Calculations were executed using SAS®, version 6.11.

3 RESULTS AND DISCUSSION

3.1 Curves of equal sensation

Five pairs of values indicating equal sensation were obtained for each reference defined by frequency and direction. Averaged adjusted accelerations of the variable component (y-axis) were plotted against the appropriate predefined magnitudes of the constant component (x-axis) in figure 3 and connected to curves of equal sensation. The overall 8 equivalence curves (4 frequencies, 2 directions of the reference) are shown in the figure. Despite a considerable inter-individual variability the individual curves are consistent with the average, as demonstrated in figure 4 for 1.6 and 3.15 Hz and lateral reference.

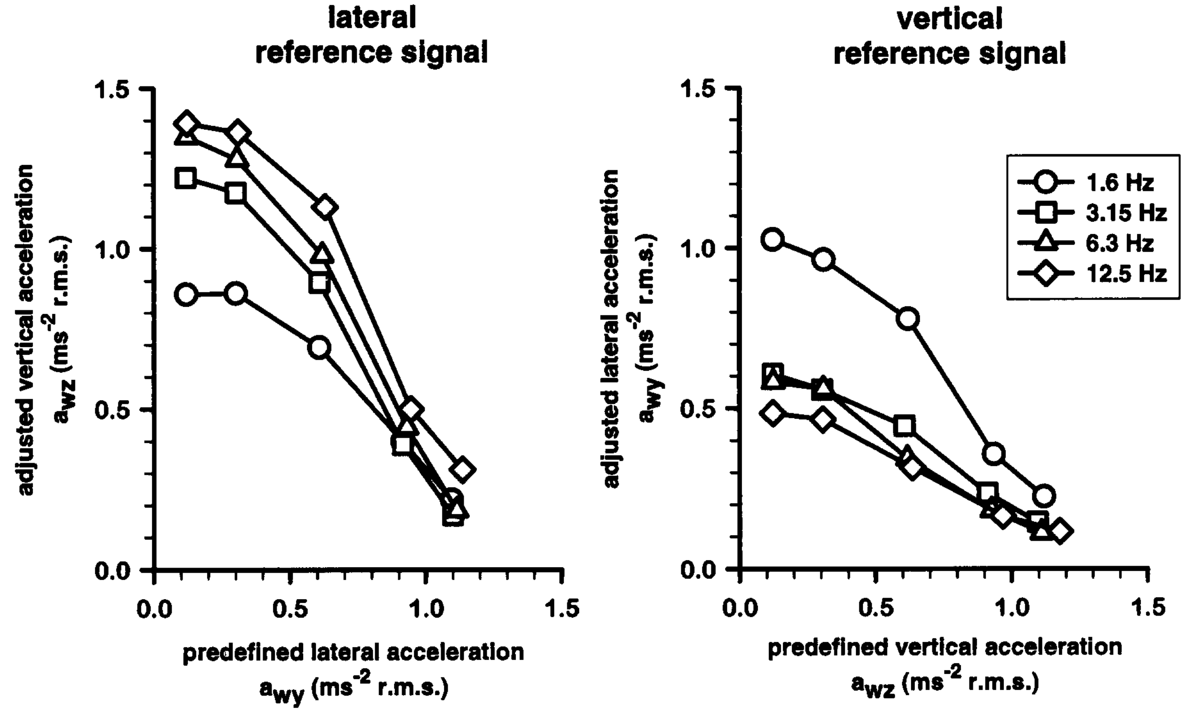

Figure 3: Curves of equivalence of the means of adjusted acceleration combinations for the 4 frequencies and 2 reference motions presented in lateral and vertical direction. Accelerations were frequency weighted according to ISO/DIS 2631.

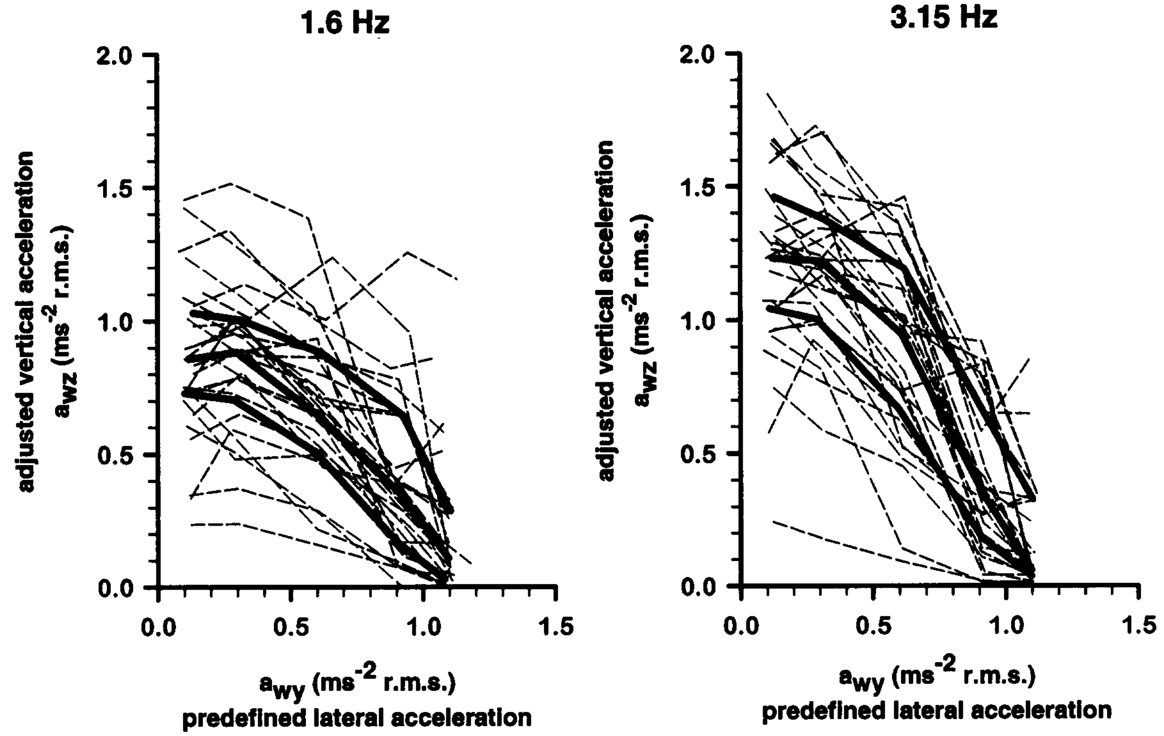

Figure 4: Individual courses of frequency-weighted accelerations (r.m.s.) of equally sensed dual-axis vibrations (examples for 1.6 and 3.15 Hz for lateral reference motions). Bold lines present the medians, 1st and 3rd quartile.

All the equivalence curves in figure 3 are bended right downwards. The curves for 1.6 Hz are nearly circular as expected due to ISO/DIS 2631, whereas those determined for 3.15, 6.3 and 12.5 Hz are significantly stretched (lateral reference) or compressed (vertical reference).

Table 1 presents means and standard deviations of the appropriate frequency-weighted accelerations of the paired values, separately for both reference directions and each frequency. Standard deviations of the predefined invariable components were - as expected - negligible, those of the adjusted accelerations varied between 0.2 and 0.6 ms^{-2} and were - apart from the data recorded for 1.6 Hz - greater for lateral than for vertical references.

Table 1: Means ± standard deviations of lateral (a_{wy}) and vertical (a_{wz}) frequency-weighted accelerations after adjustment.$a_{w,ref}$: percent of acceleration of the reference signal predefined for the constant component (= PCC), adjusted variable component (= AVC).

		lateral reference		vertical reference	
frequency	$a_{w,ref}$	PCC a_{wy} (ms^{-2} rms)	AVC a_{wz} (ms^{-2} rms)	PCC a_{wz} (ms^{-2} rms)	AVC a_{wy} (ms^{-2} rms)
1.6 Hz	10 %	0.12±0.02	0.86±0.28	0.12±0.01	1.03±0.28
	25 %	0.30±0.02	0.86±0.28	0.31±0.01	0.96±0.30
	50 %	0.61±0.02	0.69±0.28	0.62±0.01	0.78±0.31
	75 %	0.91±0.02	0.40±0.29	0.94±0.02	0.36±0.30
	90 %	1.10±0.02	0.22±0.27	1.12±0.01	0.22±0.29
3.15 Hz	10 %	0.12±0.02	1.22±0.34	0.12±0.01	0.61±0.21
	25 %	0.30±0.02	1.18±0.32	0.30±0.01	0.56±0.20
	50 %	0.61±0.01	0.89±0.35	0.61±0.01	0.44±0.19
	75 %	0.92±0.01	0.39±0.27	0.91±0.02	0.23±0.15
	90 %	1.10±0.01	0.17±0.21	1.10±0.02	0.15±0.17
6.3 Hz	10 %	0.12±0.01	1.35±0.44	0.12±0.01	0.58±0.17
	25 %	0.31±0.01	1.28±0.45	0.31±0.01	0.56±0.21
	50 %	0.62±0.01	0.98±0.46	0.62±0.01	0.34±0.20
	75 %	0.93±0.01	0.44±0.46	0.93±0.03	0.18±0.15
	90 %	1.11±0.01	0.18±0.28	1.11±0.03	0.11±0.14
12.5 Hz	10 %	0.12±0.01	1.39±0.54	0.12±0.05	0.48±0.17
	25 %	0.31±0.01	1.36±0.56	0.31±0.06	0.46±0.17
	50 %	0.63±0.01	1.13±0.51	0.64±0.05	0.31±0.18
	75 %	0.95±0.02	0.50±0.42	0.97±0.05	0.16±0.16
	90 %	1.14±0.02	0.31±0.34	1.18±0.06	0.12±0.15

Table 2: Analysis of variance of the adjusted frequency weighted accelerations

Effect	df1	df2	F	p-value
Gender	1	25	0.09	0.7723
Phase	1	25	1.80	0.1918
Gender*Phase	1	25	1.54	0.2265
Age	1	25	1.44	0.2411
Weight	1	25	1.33	0.2590
Frequency (FREQ)	3	1194	0.76	0.5143
Reference-direction (DIR)	1	1194	543.98	0.0001
FREQ*DIR	3	1194	103.45	0.0001
Percentage amount (PER)	1	1194	1696.45	0.0001
PER*FREQ	3	1194	1.28	0.2790
PER*DIR	1	1194	154.08	0.0001
PER*FREQ*DIR	3	1194	32.89	0.0001

Accordingly, the analysis of variance revealed that the adjustment of the variable component was significantly determined by the direction and the predefined acceleration of the constant component (table 2). There was no significant difference between the 4 frequencies studied which was expected as the frequency-weighted reference signal was ever 1.25 ms^{-2} r.m.s..

The phase shifts between both components of the test signal, namely the direction of the resulting linear motion (left down to right up or left up to right down) did not influence the result. This is in accordance with a study of Schoenberger (1987), who presented dual-axis sinusoidal reference motions (vertical and lateral) of 3.2, 5, and 8 Hz with accelerations of 1.5 and 2.5 ms^{-2} and phase shifts of 0°, 180°, and 90° resulting into dual-axis linear and dual-axis circular reference motions. The subjects then adjusted sagittal test motions of the same frequencies until equal sensation. There were no differences regarding the phase shifts. This is plausible, as the sensation of motions is mainly determined by the biodynamic behavior, which is not influenced by phase shifts between vertical and lateral shares of motions [Griffin & Whitham 1977]. Studies executed by Griefahn et al. [1997] revealed similar results.

The fact, that gender, age, and weight did not determine the adjustment is in accordance with the results of other studies as well [e.g. Donati et al. 1983; Griffin et al. 1982; Griefahn & Bröde 1997].

3.2 Comparison between experimentally determined and expected curves

The experimentally determined equivalence curves shown in figures 3 and 4 are bent right downwards as expected due to ISO/DIS 2631 [1995]. For comparison they were approximated by non-linear functions of the form $(k_y^{-n} a_{wy}^n + a_{wz}^n)^{1/n}$.

The bend of the function increases with increasing values for n (Fairley & Griffin 1988). The approximations were calculated for n = 1, 2, 3, 4 (Mistrot et al. 1990), where n = 2 corresponds to the case described in the draft standard ISO/DIS 2631.

Table 3: Coefficient of sensitivity (k_y) and determination (r^2) of the approximation to $(k_y^{-n} a_{wy}^n + a_{wz}^n)^{1/n}$ calculated for n = 1, 2, 3, 4 based on the averages of frequency-weighted lateral and vertical accelerations (Tab. 1).

Frequency	Reference	n=1		n=2		n=3		n=4	
		k_y	r^2	k_y	r^2	k_y	r^2	k_y	r^2
1.6 Hz	lateral	0.68	0.94	0.75	0.96	0.70	0.85	0.68	0.75
	vertical	1.18	0.96	1.20	0.91	1.30	0.76	1.35	0.66
3.15 Hz	lateral	1.13	0.96	1.02	0.91	0.93	0.76	0.89	0.67
	vertical	2.04	0.98	2.01	0.92	2.16	0.78	2.25	0.68
6.3 Hz	lateral	1.22	0.97	1.11	0.92	1.01	0.77	0.97	0.68
	vertical	1.95	0.98	2.19	0.84	2.40	0.67	2.50	0.57
12.5 Hz	lateral	1.15	0.94	1.16	0.91	1.07	0.77	1.03	0.67
	vertical	2.64	0.98	2.78	0.85	3.00	0.68	3.12	0.58

The results shown in table 3 indicate that the linear model with n = 1 provides a good approximation as well as the approximation with n = 2 which corresponds to the standard ($r^2 > 0.9$), whereas the approximations with n = 3 or n = 4 are less good.

The optimal exponent (n) which describes the bends of the curves for simultaneously acting of lateral and vertical motions most accurately was between 1 and 2. This confirms the results of Fairley and Griffin (1988), who studied dual-axis motions in the vertical and in the sagittal direction. Fairley (1995) executed additionally a field study on tractor drivers and came to similar results: the predictability of self-estimated subjective impairment due to whole-body vibrations was almost the same for n = 1 and n = 2

This leads to the conclusion that the procedure suggested in ISO/DIS 2631 for the evaluation of multiaxis motions is qualitatively valid, though it must be considered, that sinusoidal dual-axis linear motions are probably the most simple case for evaluation.

The coefficient k_y indicates the relative sensitivity for lateral versus vertical motions additionally to the already different frequency weighting. It descibes the discrepancy between the weighting of the direction and the frequencies. Contrary to the standard its exponent is negative in the present example, as the extents of the adjusted accelerations are inversely related to the sensitivity to the respective motions.

Apart from 1.6 Hz where k_y does not exceed 1.35 (table 3) k_y is about 1 for lateral reference but varies in trials with vertical references between 2 and 3. This confirms the conclusion drawn above that the evaluation is stronger for lateral motions.

The discrepancies between the weighting of direction and frequencies are supported by a previous study on inter-axis equivalence where single-axis motions of the same frequencies but of different directions were compared to each other (Griefahn & Bröde 1997).

The results are also supported by field studies (Fairley 1995; Mistrot et al. 1990), where subjective evaluation was fairly well predicted by the procedure suggested in ISO 2631, better than by other procedures but with a stronger weighting of lateral (y) and sagittal (x) accelerations than suggested in the present draft of ISO 2631 ($k_x = k_y = 1.4$).

This study again points out the need for the revision of the weighting factors provided in ISO 2631 as well as for the investigation of multi-axis and multi-frequency whole-body vibrations.

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