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Relative Contribution of Translational and Rotational Vibration to Discomfort

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Abstract: Understanding how vibration affects discomfort is an important factor for improving work and travelling experience. Methods of evaluating health effects from whole-body vibration are closely linked to those for evaluating discomfort in ISO 2631-1. The standard includes a method to evaluate discomfort using twelve axes of vibration with a similar approach to that for evaluating health effects; thus using all twelve axes gives a possibility to evaluate both health and discomfort. The full 12-axis method has not been widely used in practice or validated in a multi-axis environment. The standard guidance is not explicit, thus different interpretations are possible especially when determining the method of comparing or combining vibration in different axes. Furthermore there are not enough studies conducted in multi-axis environments to suggest the optimal combination of axes. In this study ISO 2631-1 method was tested and optimised using a multi-axis test bench at Loughborough University, UK. Subjects were exposed to stimuli which represented vibration characteristics from field measurements. Each stimulus, lasting 15 s, was judged using a continuous judgement, cross-modal matching method. The seat translational and rotational and the backrest translational axes were used in the analyses. There was no vibration at the floor, in order to constrain the number of independent variables. Results showed that correlation for discomfort improved with more complex analysis procedures. However a good correlation was also achieved using just seat translational axes with optimised multiplying factors. The results showed that frequency weightings and r.m.s. averaging improved correlation between vibration and subjective ratings of discomfort. Multiplying factors specified in ISO 2631-1 degraded the correlation between objective and subjective measures of discomfort, therefore an improved set of factors were determined. The new factors showed improvement by placing more emphasis on seat fore-and-aft and lateral axes.

Key words: ISO 2631-1, Whole-body vibration, Health, Discomfort, Rotational, 12-axis, Cross-modal matching

Introduction

Human vibration exposure can occur at work, commuting between home and work, and in leisure activities. Any form of transportation will expose travellers to some degree of vibration. Exposure to vibration can cause health and comfort problems. Health problems are normally back and neck related, presenting as musculoskeletal pain. Back pain, to which vibration exposure is a significant contributor[1)], is one of the most common health problems in the world[2, 3)].

Even though health is the most critical issue in general, only a fraction of people are exposed to vibration that is severe enough to be identified as the sole cause of long-term health problems[4)]. Most exposed people experience vibration that may cause discomfort although it also constitutes a risk factor for low back pain. Discomfort can show as a general emotional or physical annoyance, lowered ability to concentrate, and increased fatigue, depending on the context and the emotional state of the human[5)]. For an example reading in a train is more difficult because of vibration[6)].

In the context of work, discomfort normally relates to fatigue, lowered concentration and work performance, and indirectly to work motivation and happiness[7)], which can increase workload and/or reduce performance[8)]. These factors are becoming more and more important in work environments. A worker-friendly workplace can also show benefits in productivity[9)]. Although there is not necessarily a link between discomfort and health, it is generally assumed that improved comfort is associated with reduced risk.

It is difficult to study whole-body vibration health effects directly in the laboratory, due to ethical considerations. It also has been proven difficult to find any pathological proof of back pain using MRI or other scanning techniques[10)], thus subjective opinion has been an important factor in cross-sectional studies of injury prevalence. Even though studies have shown increased prevalence of back pain when exposed to vibration, it has been difficult to isolate the effects from other confounding factors. Most of the techniques used to evaluate whole-body vibration health effects are based on perception and comfort studies[11)]. Since the publication of the methods in ISO 2631-1, there has been little attempt to validate their applicability.

Previous research has shown that humans are more perceptive to certain frequencies, directions and amplitudes[1, 11–16)], but these studies have not considered simultaneous multi-

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axis effects of vibration. Vertical vibration is perceived most easily around 5 Hz. Horizontal vibration, regardless of the direction, is perceived most easily at 1–2 Hz (or even lower), as are the rotational directions on the seat. Although most of the studies have evaluated only either one or two directions at the same time, the results show that there is a certain pattern of perception for each direction and location (although large variations between humans have been found)[17]. This conclusion has been used for developing frequency weighting curves of ISO 2631-1.

The standard guidance instructs measurement of vibration at the interface between the body and vibrating platform. For seated persons this means the seat, backrest and floor surfaces. The acquired acceleration signals are then frequency weighted to emphasise frequencies to which the body is most sensitive, and root mean square (r.m.s.) values are calculated for each measured axis. The r.m.s. values represent the weighted vibration energy of each axis. For evaluating health effects the standard guides to measure three translational axis from a seat surface. The standard does not directly guide how to use the acquired values to predict health effects, but gives information about vibration levels which are believed to be harmful in an informative annex.

For discomfort evaluation the standard suggests that, depending of the environment, vibration at the backrest, floor and rotation at the seat should be measured in addition to seat translational axes. The standard instructs the user to calculate point vibration total values and overall vibration total value from frequency weighted r.m.s. values.

ISO 2631-1 (1997) allows several possible ways for evaluating discomfort, because it does not explicitly define the use of certain combinations of axes and locations. The standard instructs to measure at least seat translational axes for conducting the evaluation, but it is also possible to use only one of the axes in the analysis, when other axes are less than 25% of the dominant axis. However, depending on circumstances, backrest and floor axes should also be included in the analyses. In addition there is a possible need to include rotational axes from the seat as well. Even though all twelve axes are proposed by the standard, there is no guidance on what circumstances to use them or what combination of axes correlate best with discomfort. The standard allows the replacement of backrest axes by using 1.4 multiplying factors for seat horizontal vibration. Thus there is a possibility for a confusion whether it is always necessary to use these multiplication factors when using only seat translational axes, or only in certain cases where there is no backrest contact.

If no better guidance is given, it is assumed that all of the twelve axes should be measured for best accuracy. The measurements from floor and backrest can be achieved using traditional 3-axis accelerometers that record translational accelerations. Measurements of rotation at the seat need a 6-axis seat pad sensor. Currently, commercially produced whole-body vibration seat pad sensors have only 3-axis sensors, which can record translation. Some special instruments that can be used to record all twelve axes have been developed by researchers, but they have not been actively marketed.

Previous results from field measurements have given an indication of how the standard weights the axes and which of them are the most important in practice[1, 18, 19]. It can be concluded that rotational axes have marginal contribution to the overall vibration total value (< 6%)[19]. Other publications however have indicated that the standard's method itself might not be valid. There have been doubts expressed at least with frequency weighting[20], multiplying factors[21] and discomfort scaling[22]. There have been no studies to validate and optimise the standardised method in a multi-axis environment, and very little validation at all using stimuli that represent vibration from real work conditions.

The full 12-axis method requires complex equipment which is not available to most practitioners. It would be beneficial if as few axes as possible could be used for assessments, as this reduces complexity and cost, but currently there are no estimates of how much this reduced data set compromises the accuracy of whole-body vibration assessments. As there are no evidence-based guidelines or studies when to include the additional axes it is up to the measurer to select them appropriately. In many cases this has led to studies where only seat translational axes have been measured and rarely the discomfort has been evaluated. A further consideration is that many previous laboratory studies have been carried out using artificial single frequency sinusoidal stimuli which do not exist in real life, or combinations of vibration at different locations which are unrealistic. Therefore, techniques could have been optimised to a level of complexity and combinations of vibration in different directions which only exist in the laboratory.

There is a need to better understand which axes and locations contribute to the discomfort judgment and thus correlate with it. Also it could be possible to optimise the number of locations and axes needed to be measured to obtain practically accuracy. For efficiency and ecological validity it is important to validate the standardized method based on stimuli that is present in real environments, because that is where people are exposed to it.

The standard method can be improved by optimising 1) the frequency weightings, 2) the multiplying factors, 3) the calculation methods and/or 4) the measurement locations. Non-linear methods (e.g. those where the weighting changes dependent on magnitude) are beyond the scope of the standard method.

Frequency weightings have had considerable research and validation since late 1960's. The results show that the current frequency weightings for sitting persons (W_d and W_k) have been successful in predicting subjective response. The other frequency weighting curves (W_c and W_e) have not been subject to such thorough validation, but currently there are no conclusive results to support changing them. As current instrumentation supports the weighting filters and they have an evidence base, there is no reason to prioritise changing them at this point. Thus a practical optimised method should either use the current frequency weightings or no weightings at all.

The axis multiplying factors have had less research and validation than the frequency weighting curves. The purpose of the factors is to emphasise different axes and measurement locations. However there have been only few studies that have measured all twelve axes and validated their effects on discomfort[1, 18]. The origins of the current factors in ISO 2631-1 are not referenced. Because it is easy to apply a different set of multiplying factors without changing the instrumentation, the optimisation of the factors should be considered.

There have been only few studies that have investigated the effects of the 'additional' axes. These axes have been studied mostly in a single-axis environment. The studies indicate[18, 23] that the 3-axis measurements from the seat are not enough for evaluating discomfort from whole-body vibration. The relative importance of the axes is affected by the frequency weighting curves and the multiplying factors. The frequency weighting models of the response of the body in the frequency domain and the multiplying factors define the relative importance between different axes. The root-sum-of-squares method to combine the axes to the overall vibration total value emphasizes the dominant axis or axes and locations. Even though these methods have significant effects on the evaluation, they have not been validated in a practical multi-axis environment. It has been suggested that the current method does not provide accurate results which are comparable between environments[16].

This paper reports a a laboratory study designed to: 1) validate the standard method in a multi-axis environment, 2) evaluate different combinations of axes and locations and how they affect the correlation, 3) evaluate how frequency weighting, averaging method and multiplying factors affect the correlation and 4) to optimise the standard method for best correlation by calculating new multiplying factors and thus be usable without the need for new equipment.

Methods

Test environment and setup

A 6 degrees-of-freedom shaker at Loughborough University was used to simulate vibrations previously measured in the field (Fig. 1). The original twelve axis data was acquired using a developed equipment, which was validated in another study[24]. The vibration data from the seat translational and rotational axes were used for the shaker stimuli. A signal processing equalisation was conducted to the original measured vibration data, so that the stimuli represented characteristics of the original source. The acceleration data, which was band-pass filtered between 1 and 20 Hz, was converted to a displacement data using a digital integration algorithm. The converted signals were then manually adjusted using multiplying factors, for providing similar amplitudes than the original data. Each of the six axes were separately adjusted.

Accelerometers were installed based on the standard's guidance (Fig. 2). The backrest sensor was installed half way through the backrest (270 mm from SIP). The subject's feet rested on a footrest, which was adjusted based on the subject's height and did not move during the experiment, thus the foot vibration was not included in the analyses. It was reasonable to assume that feet did not make any significant contribution to the judgment, and this was confirmed in a pilot work[25]. Also it was previously concluded from the field measurements that floor axes showed marginal contribution to the overall vibration total value[19].

Subject judgement

Subjects evaluated discomfort of each stimulus using the continuous judgement method[26]. Subjects were presented a discomfort line (Fig. 3 left) that they could control in real-time using a rotary control (Fig. 3 right). There was no numerical scale indicating the length of the line. The test

Fig. 1. Six-axis hydraulic shaker at Loughborough University used in the study.

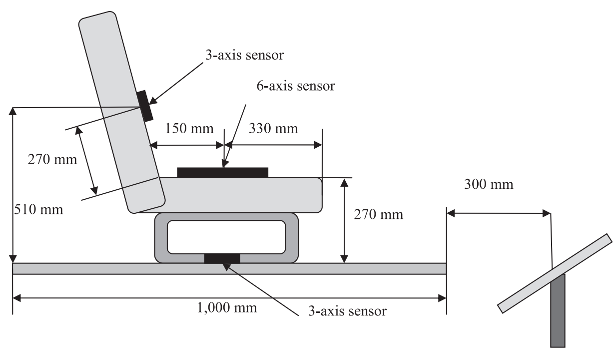

Fig. 2. Sensor locations and measures of six-axis hydraulic shaker and seat used in the study.

subjects were asked to adjust the line so that it corresponded to discomfort judgement between "no discomfort" and "high discomfort". The test subjects were guided to evaluate the discomfort of each stimulus separately. At the end of each stimulus the test subjects reset the judgement by turning the indicator to "no discomfort" position. From each stimulus the judgement of test subjects was evaluated by averaging the last 10 s of response.

For each trial, the value of discomfort judgement and vibration from the axes were recorded at sampling frequency of 1,000 Hz. The data was measured using a 12-axis Vibsolas Ltd sensor system, which included a 6-axis seat pad sensor and two 3-axis sensors for backrest and floor, and a National Instruments recording device. The recording and visualisation program was realized using a Labview 7.1 development environment.

Stimuli types

Stimuli used in the tests were based on field measurements from a previous field study[19]. The purpose was to create an environment that simulated frequencies and relative magnitudes of the axes that are present in the field, thus using an approach with high ecological validity. Stimuli were band-pass filtered between 1 and 20 Hz and each lasted 15 s.

Each of the five main stimuli was chosen so that different

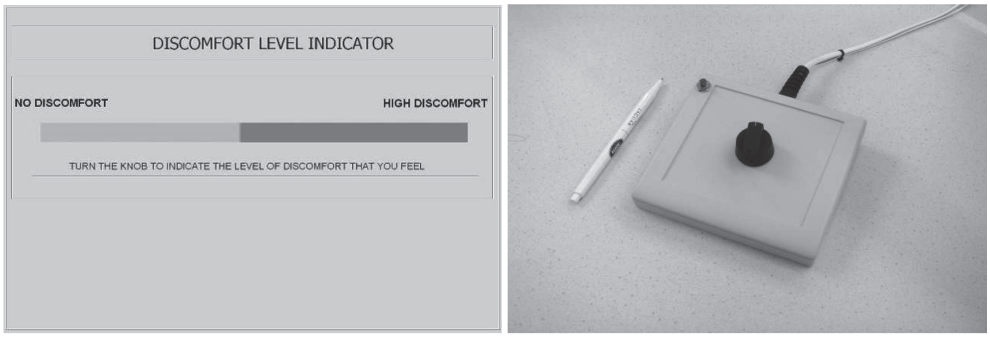

Fig. 3. Screen presented to participants to judge discomfort (left) and an indicator for evaluating discomfort (right).

Table 1. Six main stimulus used in the study based on 12-axis field measurements

Main stimulus	Simulated machine	Work phase	Terrain	Speed
A	Car	Moving	Cobble road – city	30 km/h
B	Truck	Moving	Asphalt – city	30–60 km/h
C	Forestry harvester	Moving	Forest	3 km/h
D	Train	Moving	Rail track	140 km/h
E	Excavator	Digging	Gravel road	0 km/h

typical frequency contents that are present in field were covered (Table 1). Based on the main stimuli six variations were created to represent changes in the dominant axis and the overall vibration total value in order to test the ISO 2631-1 method (Table 2). The variations of each main stimulus included different magnitudes and relative importance of the axes (including rotational), but similar frequency content. In total 30 different stimuli were created. At least one variation of each main stimulus had little or no rotational vibration present, but had a similar overall vibration total value than stimulus which had rotational vibration. Crest factors were below 10 for all stimuli. The frequency weighted r.m.s. values represented typical range of vibration levels in field environments (Table 3). Vibration was measured over all 9-axes even where there was no driving signal, to include any cross-axis response of the seat dynamics.

Subjects

The experiment used 22 subjects (12 males and 10 females). The average age of the subjects was 23 yr, and three subjects were above 30 yr. The average height was 181 cm for men and 164 cm for women. Average weight was 74.8 kg and 59.6 kg respectively. Each subject gave informed consent to participate in the trial. The trial was approved by Loughborough University Ethical Advisory Committee.

Study procedure

Test subjects were instructed to sit on the seat in a comfortable upright posture and leaning against the backrest. A test sequence of five stimuli from lowest vibration to the highest was used to familiarise subjects with the vibration before the trials began and to allow for training of subjects in controlling the judgement line on the screen. Each test subject was exposed to three randomised sequences of all 30 stimuli (90 tests in total). Between sequences there was a break where test subjects were asked to dismount from the seat and move around in the laboratory for five minutes, in order to minimise the effects of fatigue.

ISO 2631-1 analysis

Vibration was assessed with and without the appropriate frequency weightings and using r.m.s. and r.m.q. (VDV) averaging[27]. The point vibration total values (a_{pvtv}) were calculated:

$$a_{pvtv} = \sqrt{k_x^2 a_{wx}^2 + k_y^2 a_{wy}^2 + k_z^2 a_{wz}^2} \quad (1)$$

where k_x, k_y and k_z are the multiplying factors for the axes x, y and z (or roll, pitch and yaw) and a_{wx}, a_{wy} and a_{wz} are the frequency weighted r.m.s. values of x, y and z (or roll, pitch and yaw) axes. Table 4 shows the multiplying factors for each axis.

An overall vibration total value (a_v) was calculated by combining the necessary point vibration total values:

$$a_v = \sqrt{\sum_j a_j^2} \quad (2)$$

where a_j is a point vibration total value of location j and j is either seat, backrest or floor. For VDV analyses, exponents were raised to 4. Correlations between measurements of vibration on the surface of the seat and subjective responses were calculated using Spearman correlation.

Scenarios of combinatios of axes

ISO 2631-1 allows several possible combinations of axes to be used for discomfort analysis:

- An axis, which shows clear dominance (other axes less than 25%);
- A point vibration total value, which shows clear dominance (rest of the PVTV's are less than 25% of the dominant PVTV);
- A combination of point vibration total values of seat,

Table 2. Stimulus variations based on main stimuli. Factors were used to change amplitude levels of different axes
Overall vibration total value (OVTV) represents combined frequency weighted r.m.s. of backrest and seat axes.

Main stimulus	Variation	Note	Factors						r.m.s. values
			x	y	z	Roll	Pitch	Yaw	OVTV
A	1	Car – original	1	1	1	1	1	1	1.129
A	2	Car - enhanced vertical	0.5	0.5	1	0.5	0.5	0.5	1.023
A	3	Car - w/o rotation	0.5	0.5	1	0	0	0	0.997
A	4	Car - enhanced rotation	1.5	1.5	1	1.5	1.5	1	1.270
A	5	Car - enhanced pitch	1.5	0.75	0.5	0.75	1.5	0.5	0.760
A	6	Car - enhanced fore-aft	1.5	0.75	0.5	0	0	0	0.459
B	1	Truck – baseline	0.9	1	0.6	1	0.8	1	1.179
B	2	Truck - enhanced lateral	0.45	1	0.3	0.5	0.5	0.5	0.934
B	3	Truck - enhanced lateral w/o rotation	0.45	1	0.3	0	0	0	0.824
B	4	Truck - enhanced vertical	0.9	0.5	1.2	1	0.8	1	1.327
B	5	Truck - enhanced vertical	0.45	0.25	1.2	0.5	0.4	0.5	1.044
B	6	Truck: w/o rotation	0.45	0.25	1.2	0	0	0	1.001
C	1	Harvester – original	1	1	1	1	1	1	2.100
C	2	Harvester - enhanced vertical	0.5	0.5	1	0.5	0.5	0.5	1.608
C	3	Harvester - enhanced vertical	0.5	0.5	1	0	0	0	1.489
C	4	Harvester - reduced all	0.5	0.5	0.5	0.5	0.5	0.5	0.903
C	5	Harvester - enhanced vertical	0.25	0.25	0.5	0.25	0.25	0.25	0.652
C	6	Harvester - w/o rotation	0.25	0.25	0.5	0	0	0	0.588
D	1	Train - enhanced rotation	0.5	0.5	0.5	1	1	1	1.025
D	2	Train - w/o rotation	0.5	0.5	0.5	0	0	0	0.659
D	3	Train - enhanced vertical w/o rotation	0.25	0.25	0.5	0	0	0	0.424
D	4	Train - enhanced pitch	0.6	0.25	0.25	0.5	1	1	0.836
D	5	Train - enhanced fore-aft	0.75	0.25	0.25	0	0	0	0.711
D	6	Train - enhanced fore-aft	0.75	0.125	0.125	0	0	0	0.669
E	1	Excavator – original	1	1	1	1	1	1	2.505
E	2	Excavator - enhanced vertical	0.5	0.5	1	0.5	0.5	0.5	1.991
E	3	Excavator - enhanced vertical	0.2	0.2	1	0.2	0.2	0.2	1.828
E	4	Excavator - enhanced fore-aft	1	0.2	0.2	0.2	0.2	0.2	0.671
E	5	Excavator - enhanced rotation	1	0.1	0.1	0.2	1.5	0.2	1.050
E	6	Excavator - enhanced pitch	1	0.1	0.1	1.5	0.2	0.2	1.026

backrest and floor (where PVTV's are larger than 25% of the dominant PVTV);

- All twelve axes.

Because of the number of combinations of the axes which are possible by the standard, a set of practically realisable scenarios were created to analyse the correlation between discomfort and vibration (Table 5). The scenarios were chosen to include most possible interpretations of the standard.

Evaluating frequency weighting and averaging methods

The effects of averaging method were compared by analysing correlation of overall vibration total values based on r.m.s. and r.m.q. methods. The effect of frequency weighting was analysed by using frequency weighted and unweighted r.m.s. values for calculating the overall vibration total values of the scenarios, and comparing the correlation.

Optimising standard method

The Brute Force search method was used to find optimal multiplying factors. Brute force algorithm is simple to implement and will always find the answer if it exists. If the combinations (i.e. calculation time) can be limited to a practical level, then the method is the most robust as it does not require a priori knowledge and assumptions (such as Nelder-Meade algorithms).

Table 6 shows the range and steps of multiplying factors tried for each axis. The seat vertical was considered the axis to which rest of the axes were compared to, thus the results show relative emphasis to the vertical axis. As seat translational axes were identified as the most important axes, the resolution of the step was 0.1 for them. For the rest the step size was 0.2. So the final number of combinations used was 1.70×10^9 for the initial Brute Force optimisation.

Multiple linear regression was also used to model relationship between all nine axes (i.e. independent variables) and judgement value (dependent variable).

Results

Judgement of vibration

Figure 4 shows an example of continuous judgement of a stimulus. The measured acceleration signal is the dominant axis (seat vertical) with frequency weighting. The judgement process includes three stages: 1) delay before responding to vibration, 2) adjustment period (based on first few seconds of vibration) and 3) fine tuning period (where final judgement is calculated). The last 10 s of judgement were used for analysis.

Table 3. The frequency weighted r.m.s. values (m/s^2) of each stimulus with respective multiplying factors
The floor translational axes are reported, but were not included in the analyses, as subjects used a non-moving footrest.

Main stimulus	Variation	Seat trans. axes			Seat rot. axes			Backrest trans. axes			Floor trans. axes		
		x	y	z	Roll	Pitch	Yaw	x	y	z	x	y	z
A	1	0.308	0.284	0.702	0.224	0.136	0.029	0.580	0.168	0.251	0.080	0.086	0.259
A	2	0.192	0.162	0.701	0.117	0.077	0.026	0.419	0.095	0.246	0.063	0.063	0.257
A	3	0.154	0.107	0.704	0.062	0.059	0.026	0.387	0.059	0.242	0.062	0.059	0.258
A	4	0.429	0.401	0.706	0.318	0.197	0.030	0.756	0.242	0.255	0.100	0.108	0.260
A	5	0.404	0.215	0.297	0.165	0.185	0.018	0.686	0.135	0.135	0.074	0.057	0.106
A	6	0.149	0.108	0.273	0.054	0.037	0.012	0.220	0.056	0.116	0.059	0.047	0.100
B	1	0.250	0.803	0.349	0.452	0.128	0.052	0.511	0.434	0.078	0.088	0.237	0.146
B	2	0.163	0.705	0.158	0.381	0.084	0.041	0.355	0.354	0.043	0.053	0.205	0.065
B	3	0.082	0.659	0.133	0.308	0.043	0.023	0.199	0.316	0.034	0.047	0.190	0.060
B	4	0.270	0.554	0.765	0.374	0.139	0.047	0.564	0.338	0.149	0.123	0.171	0.347
B	5	0.153	0.272	0.718	0.185	0.080	0.026	0.390	0.167	0.137	0.081	0.086	0.328
B	6	0.103	0.199	0.728	0.091	0.055	0.017	0.365	0.103	0.136	0.082	0.083	0.329
C	1	0.741	0.803	1.197	0.528	0.381	0.073	1.303	0.472	0.251	0.248	0.149	0.380
C	2	0.400	0.417	1.126	0.287	0.197	0.043	0.874	0.244	0.232	0.148	0.094	0.364
C	3	0.302	0.238	1.135	0.126	0.122	0.031	0.792	0.116	0.223	0.150	0.078	0.358
C	4	0.335	0.389	0.458	0.262	0.157	0.030	0.625	0.227	0.102	0.093	0.068	0.142
C	5	0.171	0.208	0.432	0.138	0.076	0.018	0.382	0.123	0.093	0.056	0.050	0.133
C	6	0.123	0.130	0.437	0.064	0.038	0.011	0.308	0.064	0.090	0.060	0.045	0.132
D	1	0.472	0.435	0.331	0.361	0.233	0.058	0.883	0.284	0.092	0.236	0.106	0.100
D	2	0.225	0.323	0.297	0.161	0.084	0.012	0.375	0.158	0.083	0.198	0.089	0.091
D	3	0.111	0.171	0.257	0.081	0.043	0.008	0.225	0.085	0.068	0.090	0.052	0.078
D	4	0.473	0.246	0.240	0.194	0.224	0.052	0.845	0.164	0.077	0.256	0.068	0.056
D	5	0.351	0.163	0.287	0.083	0.124	0.011	0.479	0.078	0.084	0.319	0.049	0.067
D	6	0.341	0.087	0.277	0.050	0.118	0.010	0.460	0.040	0.077	0.310	0.032	0.059
E	1	0.620	0.915	1.461	0.498	0.286	0.070	1.009	0.565	0.239	0.477	0.523	0.668
E	2	0.349	0.461	1.371	0.255	0.146	0.039	0.647	0.274	0.201	0.300	0.281	0.638
E	3	0.211	0.210	1.389	0.117	0.093	0.028	0.599	0.119	0.181	0.188	0.144	0.634
E	4	0.296	0.147	0.317	0.082	0.094	0.014	0.336	0.086	0.081	0.229	0.056	0.103
E	5	0.660	0.216	0.243	0.098	0.353	0.022	1.205	0.123	0.098	0.221	0.103	0.077
E	6	0.352	0.550	0.286	0.406	0.105	0.030	0.473	0.403	0.082	0.241	0.094	0.075

Table 4. Multiplying factors of ISO 2631-1 for each axis used for evaluating discomfort from whole-body vibration of seat persons

Translational									Rotational		
Seat			Backrest			Floor			Seat		
x	y	z	x	y	z	x	y	z	r_x	r_y	r_z
1	1	1	0.8	0.5	0.4	0.25	0.25	0.4	0.63	0.4	0.2
1.4*	1.4*	1*									

*These factors are used when only translational axes from seat are used in the analysis.

Differences between men and women

There were no clear differences between judgement scores from males and females (Fig. 5). Although males tended to score slightly higher on average, the difference was not significant (Mann-Whitney U, p=0.31). Thus all further analyses were made without separating male and females.

Correlation for combinations of axes

Mean judgement values of vibration generally increased with overall vibration total values of each stimulus in a nominally linear fashion (Fig. 6). Correlation tended to improve when more axes were included in the analysis, the best occurring for the full 9-axis analysis (scenario 7, 0.850). However, it was also evident that the correlation (r^2) was almost identical for scenarios 2 (0.823), 4 (0.836), 6 (0.844) and 7 (0.850). Scenario 1 had the worst correlation (r^2) of 0.623. The correlation (r^2) of scenario 3 (0.799) and scenario 5 (0.743) were better than for scenario 1, but were worse than the best scenario.

Effect of weighting curves and r.m.s./r.m.q. methods to correlation

Application of frequency weightings improved the correlation for all scenarios, except for scenario 1 (Table 7). The scenario of the best correlation changed to number 4 without the frequency weighting, but the best overall correlation remained scenario 7 with the frequency weighting. R.m.q. (VDV) analysis generated slightly poorer correlations than r.m.s. for each scenario.

Table 5. Chosen combination of axes based on ISO 2631-1 standard for the study

Scenario number	Explanation
1	Point vibration total value of seat translational axes (*without* 1.4 multiplying factors for horizontal axes)
2	Point vibration total value of seat translational axes (*with* 1.4 multiplying factors for horizontal axes)
3	Overall vibration total value based on point vibration total values of seat translational axes (*without* 1.4 multiplying factors) and backrest fore-aft axis (*with* 0.8 multiplying factor)
4	Overall vibration total value based on point vibration total values of seat translational axes (*without* 1.4 multiplying factors) and backrest translational axes (*with* multiplying factors)
5	Overall vibration total value based on point vibration total values of seat translational and rotational axes (*without* 1.4 multiplying factor for seat horizontal axes, but *with* multiplying factors for rotational axes)
6	Overall vibration total value based on point vibration total values of seat translational and rotational axes (*with* all multiplying factors – 1.4 multiplying factors for seat horizontal axes)
7	Overall vibration total value based on point vibration total values of seat translational and rotational axes and backrest translational axes (*with* all multiplying factors – 1.0 multiplying factors for seat horizontal axes)

Table 6. The range and steps of multiplying factors used for Brute force calculation

Axis	Range	Step
Seat fore-aft	[0.0–3.0]	0.1
Seat lateral	[0.0–3.0]	0.1
Seat vertical	[1.0]	-
Seat roll	[0.0–2.0]	0.2
Seat pitch	[0.0–2.0]	0.2
Seat yaw	[0.0–2.0]	0.2
Backrest fore-aft	[0.0–2.0]	0.2
Backrest lateral	[0.0–2.0]	0.2
Backrest vertical	[0.0–2.0]	0.2

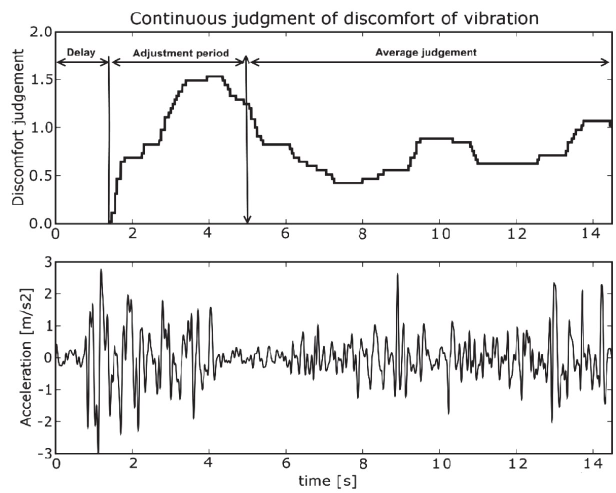

Fig. 4. An example of continuous judgement of vibration (lower figure shows acceleration of seat vertical axis, upper figure shows discomfort judgement).

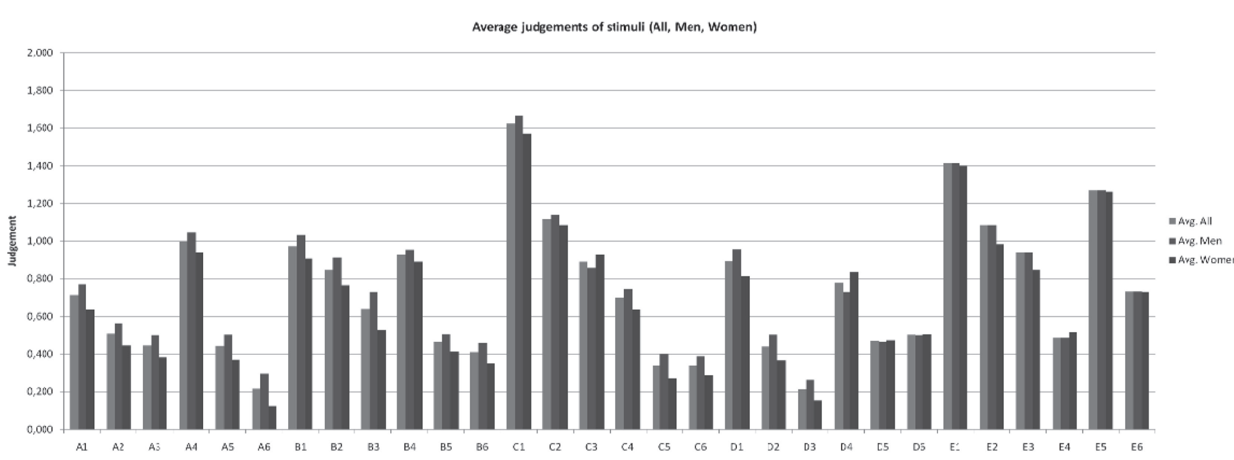

Fig. 5. Average judgement values of all subjects, men and women for each stimulus.

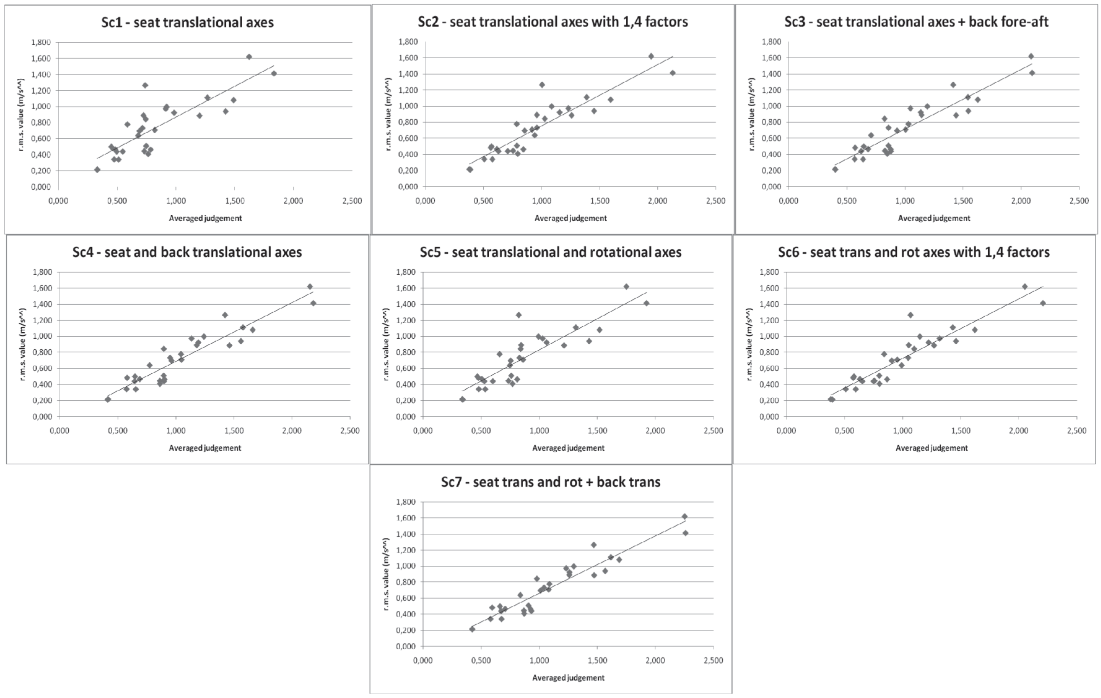

Fig. 6. Correlation between mean judgements of all subjects and chosen scenarios.

Table 7. Comparison of correlations (Spearman r^2) for using the r.m.s. and r.m.q. averaging methods for the frequency weighting with the multiplying factors (w multp), the frequency weighting without the multiplying factors (w/o multp) and without the frequency weighting and the multiplying factors (W/o all).

		OVTV Scenarios						
		1 Seat trans	2 Seat trans+1.4 factors	3 Seat trans+back x	4 Seat+back trans	5 Seat trans+rot	6 Seat trans+rot+1.4 factors	7 Seat trans+rot, back trans
r.m.s. values	Weighting w multp	0.417	0.551	0.530	0.557	0.500	0.564	0.569
	Weighting. w/o multp	0.417	0.417	0.538	0.578	0.573	0.586	0.591
	W/o all	0.460	0.460	0.509	0.524	0.443	0.446	0.466
r.m.q. values	Weighting w multp	0.376	0.516	0.523	0.530	0.442	0.534	0.551
	Weighting. w/o multp	0.376	0.376	0.527	0.545	0.541	0.566	0.569
	W/o all	0.426	0.426	0.480	0.474	0.436	0.430	0.435

Optimising multiplying factors

The Brute Force optimisation of the multiplication factors showed that it was possible to improve the correlation between the weighted vibration and the subjective responses. The results show that the best correlation found was better than using any standard scenarios (Table 8). The best correlation was found using only seat translational axes with emphasising fore-aft and lateral axis compared to vertical. All top ten best correlations were produced without backrest or rotational axes (the factors were zero).

The results showed significant clustering of the seat horizontal multiplying factors (Fig. 7). Correlation is optimal (higher elevation in the Figure) when the seat fore-aft multiplying factor is between 2.0 and 3.1 and seat lateral factor between 1.3 and 2.1. The figure shows clear clustering of the best combinations and that the Standard's multiplying factors (1.4) for seat horizontal axes improve correlation compared to no multiplication factors, but not as much as higher factors.

Based on these results an optimised model can be created, providing the best set of multiplying factors for the vibration stimuli used in the experiment:

$$a_v = \left(2.7^2 a_{wx}^2 + 1.8^2 a_{wy}^2 + 1.0^2 a_{wz}^2\right)^{\frac{1}{2}} \quad (3)$$

where a_v is discomfort value, a_{wx} is frequency weighted r.m.s. value for seat fore-aft axis, a_{wy} is frequency weighted r.m.s. value for seat lateral axis, a_{wz} is frequency weighted r.m.s.

Table 8. The top ten combinations of multiplying factors using Brute force method

Spearman		Seat						Back		
r^2	p	x	y	z	Roll	Pitch	Yaw	x	y	z
0.9499	<0.001	2.7	1.8	1.0	0.0	0.0	0.0	0.0	0.0	0.0
0.9465	<0.001	2.7	1.7	1.0	0.0	0.0	0.0	0.0	0.0	0.0
0.9447	<0.001	2.6	1.6	1.0	0.0	0.0	0.0	0.0	0.0	0.0
0.9447	<0.001	2.6	1.9	1.0	0.0	0.0	0.0	0.0	0.0	0.0
0.9447	<0.001	2.7	1.9	1.0	0.0	0.0	0.0	0.0	0.0	0.0
0.9430	<0.001	2.5	1.7	1.0	0.0	0.0	0.0	0.0	0.0	0.0
0.9430	<0.001	2.6	1.7	1.0	0.0	0.0	0.0	0.0	0.0	0.0
0.9430	<0.001	2.6	1.8	1.0	0.0	0.0	0.0	0.0	0.0	0.0
0.9430	<0.001	2.8	1.7	1.0	0.0	0.0	0.0	0.0	0.0	0.0
0.9421	<0.001	2.4	1.6	1.0	0.0	0.0	0.0	0.0	0.0	0.0

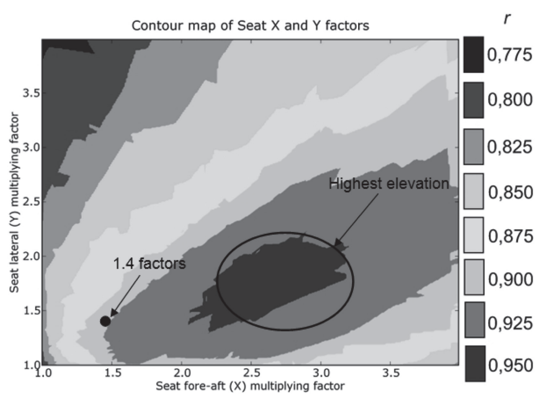

Fig. 7. Contour map of seat translational axes' multiplying factors where vertical axis is considered 1.0. Higher elevation means higher correlation (i.e. warmer colour).

value for seat vertical axis. Similar results (2.78 x, 1.68 y, 1.00 z, zero other axes) were obtained using using Linear Regression of the 9-axes of vibration.

Correlation using optimised multiplying factors

The best new multiplying factors (seat fore-aft 2.7, lateral 1.8 and vertical 1.0) were used to create an additional test scenario (scenario 8) and new correlation values were calculated for all test subjects and their average judgements (Table 9). The new factors became the best scenario for 19 out of 22 subjects. It also improved the average correlation of all subjects to vibration, and the correlations of the "worst" and the "best" subject. There was a clear improvement from scenario 1, despite both scenarios being based on just seat translational axes (Fig. 8).

Table 9. Comparison between best scenario using the standard and best new multiplying factors (seat fore-aft 2.7, lateral 1.8 and vertical 1.0)

	Standard scenarios		New factors	
Test subject	r^2	Scenario	r^2	Scenario
1	0.420	sc6	0.471	sc8
2	0.611	sc6	0.611	sc6
3	0.612	sc6	0.615	sc8
4	0.635	sc7	0.650	sc8
5	0.694	sc6	0.752	sc8
6	0.585	sc6	0.585	sc6
7	0.468	sc7	0.484	sc8
8	0.710	sc6	0.803	sc8
9	0.396	sc6	0.409	sc8
10	0.518	sc3	0.531	sc8
11	0.552	sc7	0.584	sc8
12	0.586	sc7	0.710	sc8
13	0.645	sc6	0.714	sc8
14	0.731	sc7	0.751	sc8
15	0.642	sc7	0.674	sc8
16	0.635	sc6	0.680	sc8
17	0.653	sc6	0.716	sc8
18	0.597	sc7	0.597	sc7
19	0.664	sc6	0.707	sc8
20	0.496	sc7	0.548	sc8
21	0.614	sc7	0.621	sc8
22	0.485	sc7	0.493	sc8

Discussion

Problems with standard guidance

Evaluation of discomfort from vibration can be achieved using several different combinations of axes according to interpretation of the detail of ISO 2631-1. Only seat translational axes are required for use every time, but inclusion of all other axes is optional. Thus many different combinations of axes are possible to be used in analyses.

The standard gives a possibility to use the translational axes measured from the seat to estimate the effects of seat-back using a multiplier. There is no reference to any study that can confirm the validity of the multiplier. This also concerns the other multipliers and frequency weighting curves used for all axes in the standard[21].

Best combination of axes of ISO 2631-1

The results showed that the best overall correlation was achieved using scenario 7, which included the translational and rotational axes from the seat surface and the backrest axes. Thus the correlation was best when all available axes were used with their respective multiplying factors. However, scenarios 2 and 6 showed that the 1.4 multiplying factors to replace the backrest axes gave almost identical correlations

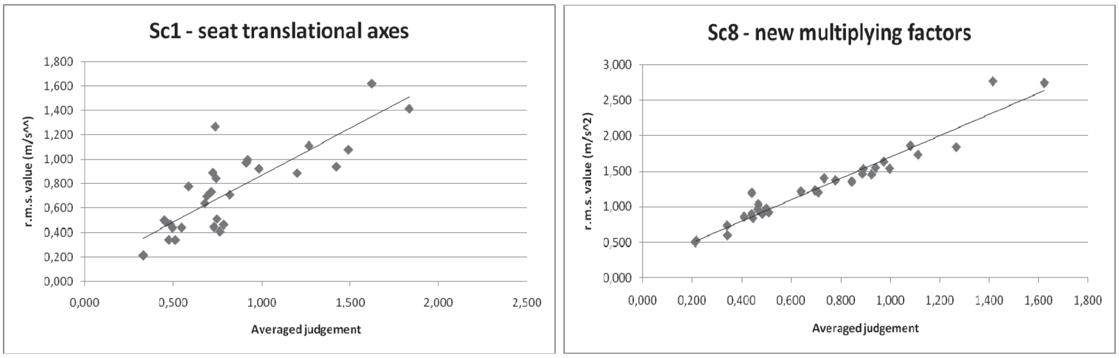

Fig. 8. Correlation of mean judgements of all subjects for each stimulus for scenario 1 (left) and scenario 8 (right) with new multiplying factors (right).

Scenario 1 is overall vibration total value with seat translational axes without multiplying factors and scenario 8 is seat translational axes with 2.8 multiplying factor for fore-aft, 1.8 for lateral and 1.0 for vertical axis.

with subjective comfort. There was a marginal difference between scenarios 2 and 6, which used the 1.4 multiplying factors to replace the backrest axes, and scenario 7 which included the backrest axes. This suggests that multiplying factors can be used to estimate the effect of backrest vibration on discomfort and could be used instead of backrest axes at least in cases where the backrest is rigidly mounted to the seat surface.

Scenario 1 (seat translational axes without 1.4 multiplying factors) showed the worst correlation of all scenarios. The standard guides using factors 1.0 to seat translational axes in the main text. However, there is a note in smaller text, which suggests using the 1.4 multiplying factors for seat horizontal axes, if backrest axes cannot be measured. This has proved confusing and had led to a lack of consensus of handling data for discomfort assessment from seat translational only, resulting in a commonly-used method being the worst possible interpretation of the standard.

Variability of correlation of subjects

The correlation calculated from the mean judgements of all test subjects was better than the mean correlation of the test subjects. This was an expected result, as averaging reduces the influence of outliers. A high correlation between discomfort and vibration was found (r^2= 0.850; scenario 7). This suggests that 85% of the change in discomfort judgements were able to be explained by change in the vibration values.

The best correlation (r^2) of individual test subjects varied between 0.396 and 0.731. Thus there was a large variability between subjects. However, for each subject the trend was similar: additional axes improved correlation. Correlation between vibration and discomfort was positive and linear. Although the amplitude range in stimuli was limited, they covered most of the practical exposures humans are exposed in every day work life.

Effect of weighting curves and averaging methods to correlation

Previous field measurements have shown that for most environment the rotational axes have only a small contribution to the overall vibration total value[19]. This is because of small multiplying factors and the effect of the frequency weighting curves. The results in this study indicated that although seat rotational axes did improve correlation, the effect was again relatively small (scenario 4 compared to scenario 7).

The r.m.q. method showed a systematically poorer correlation than r.m.s. for all stimuli, thus there was no evidence that the use of vibration dose value (VDV) would improve correlation for the types of stimuli used in the trial.

Optimised multiplying factors

The results showed that by increasing the multiplying factors of seat fore-aft and lateral axes, the correlation improved systematically. Even though including the rotational and backrest axes improved correlation, the effect was marginal (about 1.4%). This was due to the high collinearity between seat and backrest axes. This suggests that in many cases the seat translational axes will capture most vibration that affects the discomfort.

Both brute force and linear regression models showed similar results where fore-aft axis should be emphasised at 2.7 times and lateral axis 1.8 times compared to the vertical axis. The brute force results showed clear clustering of the factors, which was evident from the contour map. This also explained why the same correlation was possible with different combinations of factors.

ISO 2631-1 discomfort evaluation in practice

The whole purpose to evaluate discomfort from whole-body vibration is to understand what characteristics in the vibration cause discomfort and how to minimise them. If the method does not predict discomfort reliably it will not be used. Other methods such as r.m.q. and VDV, which have been suggested as superior to the r.m.s. method when evaluating health effects, have not been shown to work better for discomfort for the range of stimuli used in this study. It might be that different circumstances and environments will lead to different emphasis of the axes, thus no generalised model can be realised. In this case the model should allow changeable parameters for each environment. However, this study design used commonly experienced vibration stimuli from road and off-road vehicles designed to capture the widest population of those exposed.

Limitations of the study design

It should be noted that the vibration amplitudes from the backrest depend on the location of the sensor, thus the correlation might be different if it was placed on another location. This strengthens the argument of using the 1.4 multiplying factors to replace the backrest axes even if it is possible to measure them. For this study a conventional seat was used, as is common in almost all work vehicles. For this type of seat, vibration at the seat cushion and backrest has been transmitted through the seat mounting points and therefore would be expected to correlate. Although some machines have different mounting points for the backrest and seat cushion where vibration could have less correlation, they are still fixed to the same chassis and therefore signals will almost always have similarities at low frequencies.

The shaker used in the trials could produce movement between 0 and 25 Hz. In this case, because of the band-pass filtering, the frequency range was in practice between 1 and 20 Hz. However as most of the energy in mobile work machines are within this frequency range, the shaker could be used to simulate vibration present in the field. Even though the study design and shaker caused limitations to the usability of the data, they were not considered critical considering the goals.

The study was limited to using subjects in a sitting posture and leaning against the backrest using a European small-car seat, which had previously been run-in. The results might not accurately predict responses in a work machine seat, which has a different design and results in occupants adopting a different posture with different backrest contact. However stimuli from mobile work machines were used in the study, along with those from other road and off-road vehicles.

Conclusion

The standard method for predicting discomfort from whole-body vibration was validated using a multi-axis test bench. It was concluded that the correlation improved when axes additional to seat translation were included. The frequency weighting curves improved correlation and the r.m.s. method was better the than r.m.q. method. However it was evident that the standard's multiplying factors were not optimal, thus an improved set of multiplying factors for all measured axes were calculated. Currently the standard instructs using 1.4 multiplying factors for seat horizontal axes if only seat axes are used in the evaluation. Modelling suggested improved prediction of discomfort would be achieved using higher factors for fore-aft and lateral axis vibration.

Acknowledgements

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