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On the significance of body mass and vibration magnitude for acceleration transmission of vibration through seats with horizontal suspensions

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Abstract

Seats with horizontal suspensions can help to reduce detrimental effects of whole-body vibration (WBV) on health, comfort and performance. Two seats were used to examine the effect of body mass and WBV-magnitude on the transmission of WBV from the seat base to the cushion. Both seats have suspension in the x-direction while Seat 2 has suspension also in the y-direction. Twelve subjects with a body mass ranging from 59.0 to 97.3 kg volunteered for the study. A set of anthropometric characteristics was acquired. Three magnitudes of WBV were used with a truck-like signal (Seat 1, 0.3–0.59 $m\,s^{-2}$ w_d-weighted rms values at the seat base, x-direction) and a tractor-like signal (Seat 2, 0.55–1.09 $m\,s^{-2}$ w_d-weighted rms values at the seat base, x-direction, 0.52–1.07 $m\,s^{-2}$ w_d-weighted rms values, y-direction). The magnitude of WBV had a significant effect on the transmissibility characterized by SEAT-values. A significant influence of the body mass on SEAT-values was found for the y-direction only. Other anthropometric characteristics proved to be more important for the prediction of SEAT values by multiple regressions. There was no significant correlation of SEAT-values, x-direction, with the body mass. Other anthropometric characteristics enabled a satisfactory prediction of SEAT values also for x-direction in several cases. Tests with only two subjects of extreme body mass are not suited to obtain comparable and representative results required for a comparison of different seats with a suspension in the x-direction. The effect of the WBV-magnitude on the WBV-transmissibility should be considered with the design, testing and application of suspended seats.

1. Introduction

Whole-body vibration (WBV) in x- and y-axis, fore and aft and lateral, respectively, is supposed to contribute to the development of WBV-injuries of the lumbar spine [1,2]. The assumed strong effect could be related to the relatively low shear strength of the lumbar spinal segments [3]. The weighting-factor 1.4 for the evaluation of horizontal WBV with respect to health [1] reflects the assumed stronger effect compared to the factor 1 in the case of vertical WBV. Driver seats with horizontal suspensions are an important measure to protect the health of drivers.

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Current recommendations for testing suspension seats (e.g., Refs. [4,5]), just as a draft version for testing seats in horizontal directions elaborated within the European research project VIBSEAT [6], suggest two subjects as test persons with a low and high body mass. The question remains open, if the results obtained with two test subjects can be considered as representative for persons with body masses between the extremes tested. Hinz et al. [7] have shown that this assumption is doubtful, because the results of their experimental study with 37 subjects could not corroborate the significance of the total body mass as the specific parameter for the selection of test persons for testing seats in the z-direction. They recommended the consideration of more anthropometric parameters. Generally, the effect of the anthropometric characteristics of the test persons on the mechanical behaviour of the complex system seat/man has been hardly ever systematically examined. For this reason, other selected anthropometric parameters (cf. Ref. [7]) were additionally considered in this study.

Up to now, test codes (e.g. Ref. [5]) do not require the examination of different magnitudes for one specific input-spectral class derived for a group of machines. Because an effect of the vibration magnitude on the performance of suspended seats was reported [8], three different vibration magnitudes with identical PSDs and time series structures were investigated. Within the European Research Project VIBSEAT, this study aimed at examining the significance of body mass and WBV-magnitude on the transmission of WBV with suspension seats isolating in the x- and y-directions. An evaluation and comparison of different seats were not intended. The objectives of the European Research Project VIBSEAT are to develop a test method to evaluate the performance of suspension seats in axes other than the vertical, to improve the understanding of the dynamic behaviour of suspension seat in response to translational and rotational motions, and to develop theoretical and physical suspension systems capable of improved seat performance in these axes.

2. Method

2.1. Operator seats

Two different prototypes of seats were used with suspensions not fully optimized yet. A truck seat (Seat 1) was equipped with a suspension in the x-axis while Seat 2 with suspensions in both, the x- and y-axis was designed for a tractor. The suspensions of the seats in the z-axis were locked by an additional mechanical fixture. The angle between the seat cushion and the seat base was about 10°. The angle between the seat cushion and the backrest was 95° for Seat 1 and 100° for Seat 2. The angles of legs and feet [5] were realized with an adjustable footrest. The subjects sat in an upright relaxed posture using the backrest and the hands resting on an adjustable horizontal support (aluminium bar) during the exposure. By means of an anatomical goniometer, the angles of the elbow joint (125°) and between the upper arm and upper trunk (35°) were adjusted by varying the positions of the hand support. The subjects were instructed to keep the posture constant and to use the backrest during the vibration. Roll belts were used to guard the subject. Seat 1 had an integrated lap and diagonal seatbelt, a lap belt was used for Seat 2. The suspension of Seat 2 was locked for the non-excited direction.

2.2. Exposure

WBV-exposures were produced by the six DOF electro-hydraulic hexapod with a control system (FCS Control Systems B.V., The Netherlands). The guidelines for human experiments with WBV [9] were observed. Simplified typical PSD-patterns of acceleration were created by using FCS-software with frequency contents and magnitudes similar to field measurements recorded at the cabin floor of the vehicles by partners within the EU Research Project VIBSEAT [6]. Based on these artificial PSDs, time series of acceleration with the frequency content of the created PSDs were used as desired signals with the lowest magnitude (M1). For Seat 1, a signal similar to that of a truck in x-direction was used and for Seat 2, the signals resembling those of a tractor in x- and y-directions were applied. To test the specific seats with different magnitudes the signals created with the magnitude 1 (M1) were increased by 3 and 6 dB for M2 and M3, respectively, by multiplying the desired accelerations in the time domain. This procedure was used in order to minimize a possible interaction effect of the magnitude and time series structure. Control files for the Hexapod-simulator to realize

Table 1
Non-weighted and frequency-weighted (w_d, in brackets) [1] rms-values of accelerations in ($m\,s^{-2}$) on the vibrator platform during the first 23 s beginning from the 2nd second after the start of the exposure, suspension of the excited direction activated

Magnitude	Seat 1 (truck-like signal)		Seat 2 (tractor-like signals)	
	x-direction	y-direction	x-direction	y-direction
M1	0.92(0.29)	—	1.06(0.60)	0.77(0.52)
M2	1.28(0.40)	—	1.47(0.84)	1.12(0.76)
M3	1.80(0.56)	—	2.03(1.19)	1.57(1.07)

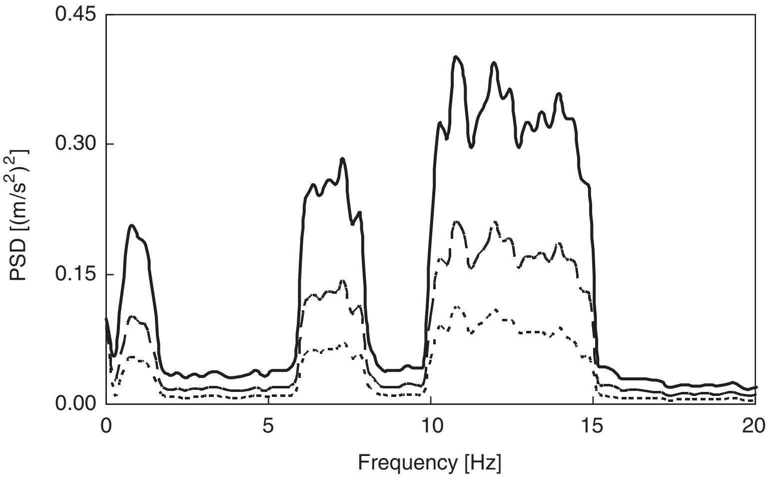

Fig. 1. Power spectral density distributions of the excitation signals measured at the platform in x-direction at three magnitudes with Seat 1, Subject 11. Key: (- - -) M1; (———) M2; (——), M3.

the desired signals in time domain were produced by an iteration procedure (FastTest Manager by FCS Control Systems B.V., The Netherlands) and using a mechanical dummy (73.7 kg) placed on both seats. A good reproduction of the desired signals, i.e. negligible differences between the simulated excitations and the desired signals in the time and frequency domain, was achieved. Table 1 shows the mean rms-values of the realized time series of the acceleration at the platform of the hexapod. The optimized drive signals were used for all subjects. The duration of each exposure was 166 s. All exposures were repeated twice. There were short breaks between repetitions without standing up. As examples, the power spectral density distributions of the platform accelerations of the simulator are presented in Figs. 1–3 for all conditions with Subject 11.

2.3. Subjects

Twelve male healthy subjects volunteered for the experiments and gave their informed consent. The body mass of the subjects varied between 59.0 and 97.3 kg (mean value 75.47 kg, SD $\pm$ 11.48 kg), and the body height ranged from 163.7 to 197.0 cm (mean value 181.2 cm, SD $\pm$ 8.8 cm). A set of 38 anthropometric parameters, 26 in the standing posture, 12 in the sitting posture (subset of the measurements described in Ref. [10]) was obtained for each subject.

2.4. Data acquisition and processing

Each exposure consisted of two segments. Up to the end of the 27th second of exposure, the subjects had to sit with their hands on a hand support. Tasks of cross-modality matching to derive subjective assessments by

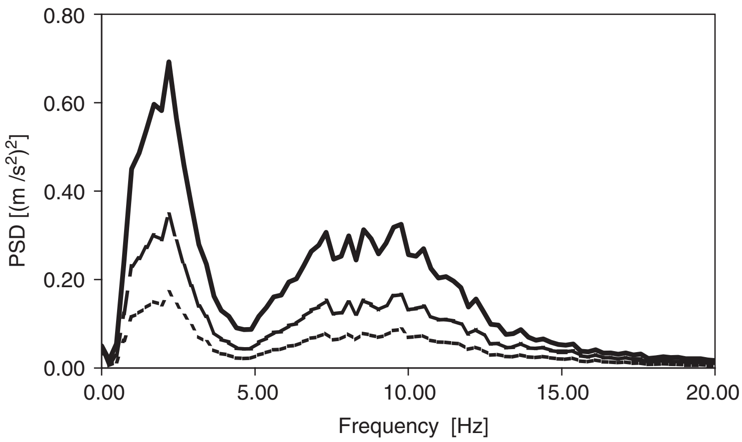

Fig. 2. Power spectral density distributions of the excitation signals measured at the platform in *x*-direction at three magnitudes with Seat 2, Subject 11. Key: (- - -) M1; (———) M2; and (——) M3.

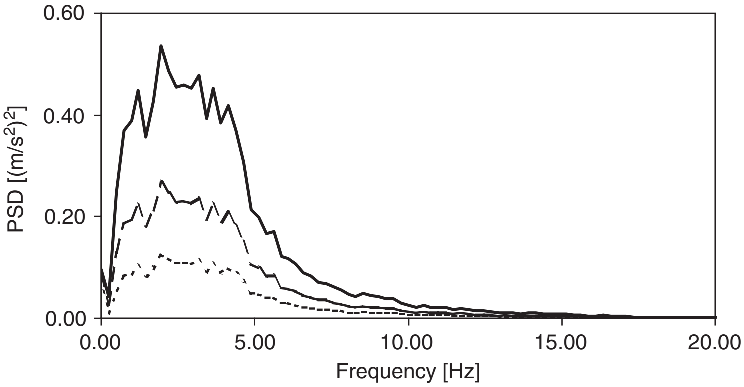

Fig. 3. Power spectral density distributions of the excitation signals measured at the platform in *y*-direction at three magnitudes with Seat 2, Subject 11. Key: (- - -) M1; (———) M2; (——) M3.

a mouse-controlled scale and measurements of reaction times by using pedals as performance tests were performed between the 28th and 166th seconds [11]. The move of the right hand and the right foot during these tasks could have an influence on the acceleration at the seat and backrest.

According to the recommendations of the draft test code [6], it was desirable to measure cross-axis accelerations at the present state.

The accelerations in *x*-, *y*-, and *z*-directions were measured at the platform, at the seat frame, on the seat cushion and the backrest. A metal block Endevco 7290 (Endevco, USA) with three accelerometers Endevco 7290A-10 was fixed on the platform under the midpoint of the seat. A block with three accelerometers of the same type was mounted on the seat frame located above the suspension. The accelerations on the seat cushion and the backrest were measured with accelerometers Endevco 65-100 in seat pads Endevco 2560.

A Wavebook (IOtech, USA) with a module WBK16 for sensors 7290A-10 and a module WBK 14 for the ICP-sensors Endevco 65-100 in the seat pads was used for conditioning and digitizing the acceleration signals. The sampling frequency was 1000 Hz. The hardware filters for antialiasing were set to 225 Hz for WBK 16 and 250 Hz for WBK 14. All data were stored on a notebook. Programmes written in Matlab were used for data processing and calculation of the SEAT-values [6,12]. The SEAT-values were calculated as ratio of the frequency weighted r.m.s. acceleration at the seat cushion divided by the frequency weighted rms acceleration at the seat base according to

$$\mathrm{SEAT}(x) = (P_{xs}(f)S^2(f)\,\mathrm{d}f)^{1/2}/(P_{xb}(f)S^2(f)\,\mathrm{d}f)^{1/2} \quad (1)$$

for the x-direction where $P_{xs}(f)$ is the power spectral density of the acceleration measured at the seat cushion and $P_{xb}(f)$ is the power spectral density of the acceleration measured at the platform in x-direction and

$$\mathrm{SEAT}(y) = (P_{ys}(f)S^2(f)\,\mathrm{d}f)^{1/2}/(P_{yb}(f)S^2(f)\,\mathrm{d}f)^{1/2} \tag{2}$$

for the y-direction where $P_{ys}(f)$ is the power spectral density of the acceleration measured at the seat cushion and $P_{yb}(f)$ is the power spectral density of the acceleration measured at the platform in y-direction. The weightings $S(f)$ specified in ISO 2631-1 [1] were used. Analogues SEAT values were calculated for the transmission from the seat base on the platform to the seat frame.

These parameters were calculated for two periods: (a) for 23 s beginning from the 2nd second after the start of the excitation designated as "short", i.e. during the period of motionless hands and feet and (b) for 162 s beginning from the 2nd second after the start of the excitation, i.e. for nearly the whole exposure duration, designated as "long".

SPSS (version 11.5.1) was used for statistics (General linear model repeated measures, univariate analysis of variance for testing the effects of factors magnitude and repetition, Bonferroni adjustment for the post hoc tests comparisons of mean values, significance level $p<0.05$, multiple linear regression analysis method with stepwise variable entry and removal for the prediction of SEAT-values.)

3. Results

3.1. Effects of repetition and duration of time series

The factor repetition had no significant effect on the SEAT values with one exception. The SEAT values (cushion) of the second repetition of the "short" time series of Seat 1 with the highest intensity M3 in x-direction were about 0.4 percent significantly smaller than those of the first repetition. Systematic differences between SEAT values (cushion and frame) calculated from "long" and "short" time series were not observed for both seats in the x-axis. In the y-axis, SEAT values determined from "long" time series with Seat 2 were uniformly larger than SEAT values determined from "short" time series. Under this condition, the mean rms-values of weighted accelerations at the platform were identical for the "short" and "long" time series, the maximum mean differences amounted to 0.0020, 0.0035 and 0.0036 m s^{-2} for M1, M2 and M3, respectively. The rms-values of weighted accelerations in the y-axis at the frame and cushion, however, were larger with "long" time series, thus explaining the higher SEAT values and indicating an effect of the human activities during cross-modality matching and performance tests. Therefore, the SEAT values derived from "short" time series were used mainly in order to exclude an influence of voluntary, performance test-related movements on the results.

3.2. Effect of the vibration magnitude

The factor magnitude had a significant effect on all but one SEAT-value calculated for the frame and cushion, "short" duration. The SEAT-values (frame) of Seat 2 in x-direction did not exhibit a significant influence of the vibration magnitude. Significant differences between the means of SEAT-values are given in the legends to Figs. 4 and 5.

Fig. 4 shows the mean values and standard deviations of the SEAT values obtained at three magnitudes for Seat 1, x-direction, "short" duration. The ranges of values were smaller for the frame (Fig. 4a) than for the cushion (Fig. 4b). For both measurement points, the mean SEAT values decreased significantly with an increasing vibration magnitude except the non-significant decrease from M1 to M2 at the cushion.

The SEAT values of Seat 2 were considerably higher than 1 for both, the seat frame (Fig. 5a) and the seat cushion (Fig. 5b). Larger ranges of values were observed for the cushion as with Seat 1. The weighted accelerations measured at the cushion were higher than those at the frame.

The ranges of SEAT values in the y-axis, Seat 2, were of the same order of magnitude for the frame (Fig. 6a) and cushion (Fig. 6b). The SEAT-values for the cushion were higher than the SEAT-values for the frame. The factor magnitude had a significant effect on the SEAT values for the frame and cushion. At both points, the SEAT values decreased with the increasing magnitude.

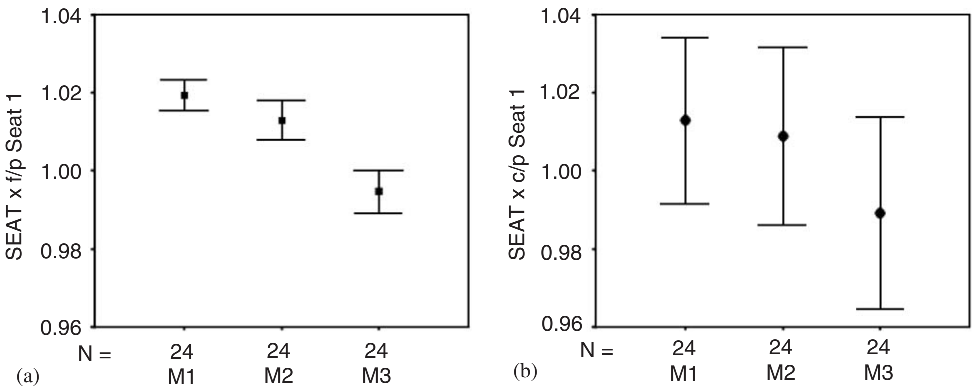

Fig. 4. Mean values ± 1 standard deviation of SEAT values (12 subjects, two runs) calculated for the frame/platform (f/p, a) and cushion/platform (c/p, b) of Seat 1, x-direction, "short" duration. Significant differences ($P = 0.05$): a—M1/M2, M1/M3, M2/M3; b—M1/M3, M2/M3.

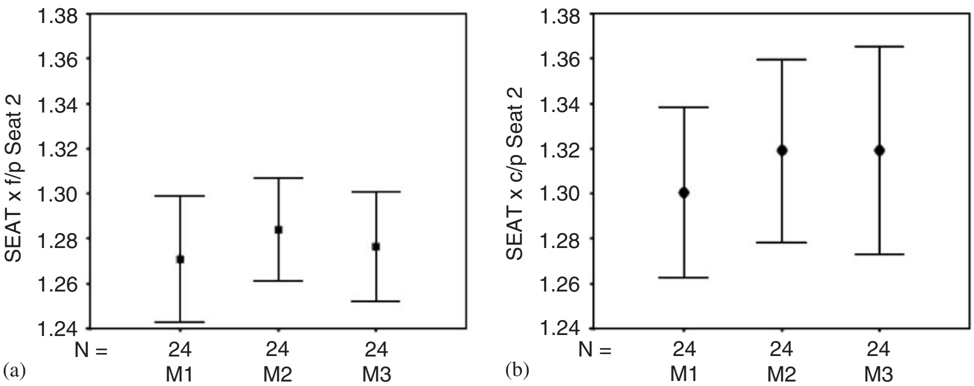

Fig. 5. Mean values ± 1 standard deviation of SEAT values (12 subjects, two runs) calculated for the frame/platform (f/p, a) and cushion/platform (c/p, b) of Seat 2, x-direction, "short" duration. Significant differences ($P = 0.05$): a—no; b—M1/M2, M1/M3.

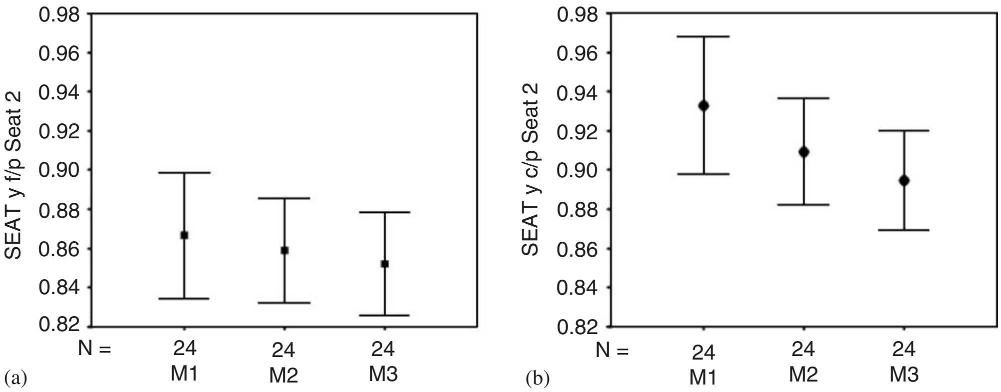

Fig. 6. Mean values ± 1 standard deviation of SEAT values (12 subjects, two runs) calculated for the frame/platform (f/p, a) and cushion/platform (c/p, b) of Seat 2, y-direction, "short" duration. Significant differences ($P = 0.05$): a—M1/M3, M2/M3; b—M1/M2, M1/M3, M2/M3.

3.3. Relationship between SEAT values, body mass and other anthropometric parameters

The relation between the SEAT values and body masses are demonstrated in Fig. 7 for all magnitudes of the excitation in x-direction, a for Seat 1 and b for Seat 2. As the results of the linear regressions with an insignificant share of the explained variance demonstrated, a systematic relationship between SEAT values and body mass has not been observed. The highest SEAT values were observed for the subjects with a medium body mass. Significant linear relationships between body masses and the SEAT values were found for the excitations in y-direction for Seat 2 (Fig. 8). The highest SEAT values were obtained for the lightest subjects.

Other anthropometric characteristics revealed relationships to SEAT values and enabled their prediction (Table 2), except from those of Seat 1 at the lowest and highest magnitudes. Height measures were important for the prediction of SEAT values of Seat 1 at the medium magnitude. A combination of anthropometric height, depth and breadth measures was included for the prediction of SEAT values, x-direction, Seat 2. Mainly breadth measures were selected by the regression analysis for the prediction of SEAT-values, y-direction, Seat 2.

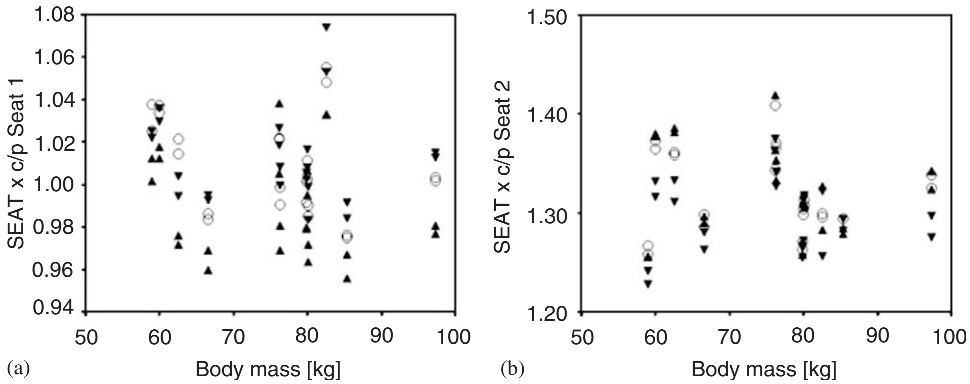

Fig. 7. Scatterplot of SEAT values, x-direction, ''short'' duration, calculated for the cushion/platform (c/p) and body mass of test persons (abscissa), Seat 1 (a) and Seat 2 (b). Coefficients of determination (linear regression) Seat 1, Magnitude (M) 1—0.0029, M2—0.1191, M3—0.0283; Seat 2, M1—0.0006, M2—0.0095, M3—0.0232. Key: (▼) Magnitude 1; (○) Magnitude 2; and (▲) Magnitude 3.

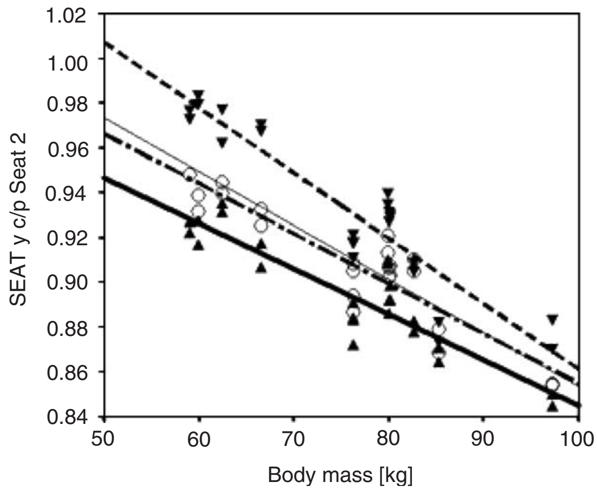

Fig. 8. Scatterplot of SEAT values and regression lines, y-direction, ''short'' duration, calculated for the cushion/platform (c/p) and body mass of test persons (abscissa), Seat 2. Key: (▼) and (– – –), Magnitude 1; (○) and (–·–·–) Magnitude 2; (▲) and (——) Magnitude 3. Coefficients of determination (linear regression) Magnitude M1—0.8629, M2—0.8460, and M3—0.8189.

Table 2
Results of the multiple linear regression analysis for the prediction of the SEAT-values calculated for the cushion, "short" duration (c/p short), by anthropometric measurements [10] of 12 subjects

Direction, magnitude	Seat	Predictors	Adjusted R^2
x, M1	1	—	
x, M2	1	L4 height (+), shoulder height (−), seated height (+), chest breadth (+), bi-deltoidal shoulder width (−), body height (−), shoulder breadth (−)	0.964
x, M3	1	Greatest sagittal diameter of the abdomen sit (−)	0.149
x, M1	2	Elbow breadth (+), greatest sagittal diameter of the abdomen sit (−), chest depth (+), buttocks–knee-length (−)	0.799
x, M2	2	Greatest sagittal diameter of the abdomen sit (−), elbow breadth (+), inferior height of the scapula sit (−), wrist width (+), height of the ankle (−)	0.857
x, M3	2	Greatest sagittal diameter of the abdomen sit (−), elbow breadth (+), inferior height of the scapula sit (−), spinal breadth (+)	0.803
y, M1	2	Body mass (−), knee breadth (−), chest breadth (+), wrist width (−), bi-deltoidal shoulder width (+), ankle breadth (+)	0.981
y, M2	2	Body mass (−), wrist width (−)	0.900
y, M3	2	Hip breadth (−), shoulder breadth (−), buttocks–knee-length (+), elbow breadth (−), circumferenc of the shank (+), chest circumference (−)	0.960

Predictors are listed according to their order in the stepwise procedure of linear multiple regressions with the sign of the regression coefficient given in brackets. All lengths, breadths, depths, and circumferences in cm, body mass in kg. x–x-direction, y–y-direction, M—magnitude.

4. Discussion

Since the systematic effect of the repetition was either missing or extremely small, the combination of both repetitions is justified. Considering the identical tendencies of SEAT values calculated from "long" and "short" time series, the results of the "short" time series can be considered as representative. The results obtained with short signals enabled the detection of seemingly small effects and were not, therefore, considered as a shortcoming of the study.

Moderate changes of the posture and small voluntary movements joined with the performance tests had probably a certain, but not an essential effect. One may assume that the alternation of the left and right foot pedals for brake and acceleration (cf. Ref. [11]) had a greater effect on the "long" time series of the cushion acceleration in y-axis than in x-axis. Hence, the minor variation of these factors cannot explain the differences of results when different laboratories test the same seat with subjects of a nearly identical body mass.

SEAT values depend also on the frequency content of excitation [8]. Since the factors "frequency of excitation" and "seat" were inseparably mixed in our study, the different effects of the magnitude on the SEAT-values of both seats in the x-direction cannot be referred to one of these factors without additional information. The inspection of the transfer and coherence functions of the acceleration in the x-direction from the seat base to the seat cushion calculated by the cross-spectral density method using MATLAB-routines showed clear differences between seats exemplified with Fig. 9. The transfer functions of Seat 1 (Fig. 9a) demonstrate a marked effect of the magnitude in a sense of a distinct improvement of the attenuation of vibration across the whole frequency range. Those of Seat 2 reveal a moderate effect of the magnitude with a deterioration of the isolation between about 6 and 15 Hz (Fig. 9c). There are several factors that can help to explain these findings. Above about 4 Hz, the moduli of the transfer functions between the seat base and the seat cushion with the x-suspensions locked (Fig. 10) suggest a somewhat greater mechanical stability of Seat 1 than of Seat 2 when the magnitude increases.

With the locked suspension, the peak magnitudes of the transfer functions of both seats show a minor shift towards lower frequencies that may be caused by the nonlinearity of the apparent mass function [13] via an interaction between the subject and the seat.

The obvious missing isolating effect of the x-suspension of Seat 1 with the low magnitude could have been produced by the Coulomb friction that stops the suspension working when the input vibration is at a low level [8].

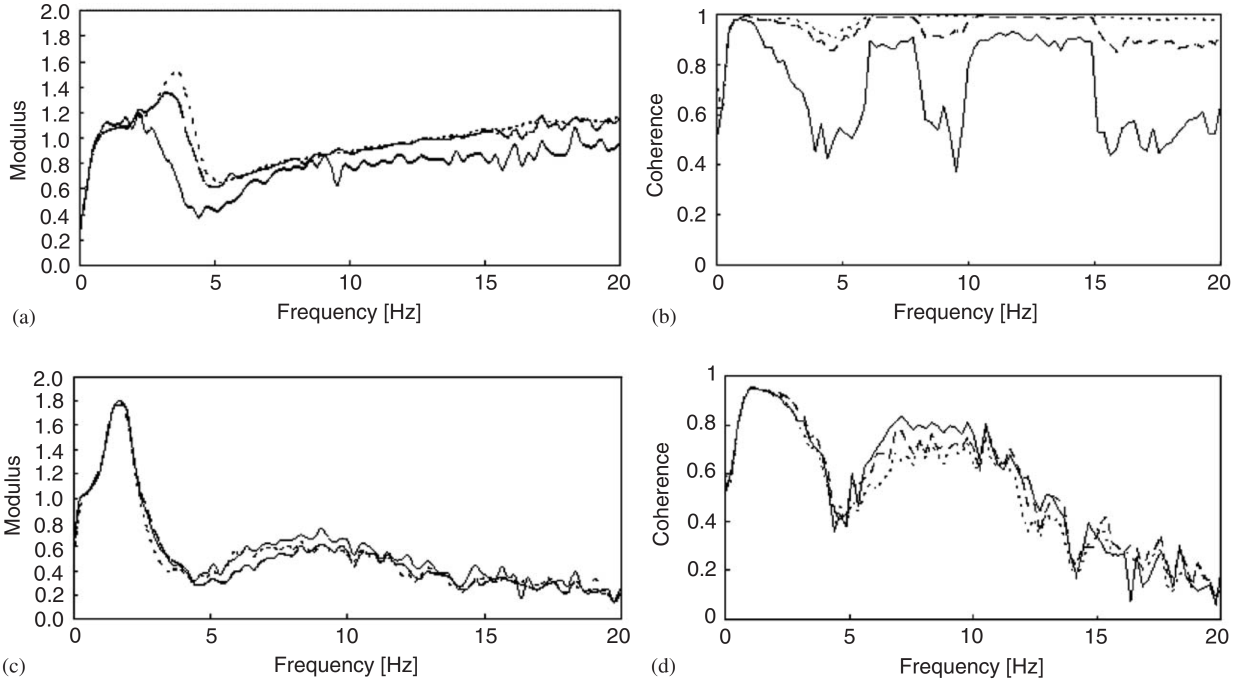

Fig. 9. Moduli of the transfer functions (a, c) and coherence functions (b, d) between the accelerations at the seat base and the accelerations at the cushion in x-direction, Subject 1, exposures with magnitudes M1, M2 and M3 (cf. Table 1), Seat 1 (a, b) and Seat 2 (c, d), x-suspensions activated. Key: (- - -) M1; (———) M2; and (——) M3.

The x-suspension of both seats leads at the high input level to shifts of the peak magnitudes of the transfer functions towards lower frequencies, accompanied by either a diminution or amplification of the vibration input to Seats 1 or 2, respectively. Due to the frequency weighting [1], the more effective diminution of higher frequencies by Seat 2 cannot compensate the unfavourable effect at lower frequencies. As the transfer functions illustrate (Figs. 9 and 10), the complex 'seat-human' is not a simple mechanical system.

Although the differences between mean values of SEAT values obtained under different conditions for the same seat may seem to be small, the interpretation with respect to the practical significance of the results should consider: (i) the larger between-subject differences which gain importance, if only two subjects would be tested as recommended in current test codes; (ii) the significance of apparently small differences for the selection of the best suited seat for a certain type of machinery by the ultimate buyer; and (iii) the statistical significance of differences.

One striking similarity of both seats is obvious with the x-direction—the missing systematic effect of body mass on the SEAT-values. The absent correlation contradicts usual expectations and assumptions [4–6,8,14]. The missing effect of the body mass with the low magnitude and Seat 1 is intelligible because of the missing effect of the suspension (Figs. 9 and 10a). The large difference between the explained variances at the two higher magnitudes (Table 2, Seat 1, M2 and M3) cannot be explained with the existing data. One might speculate that the transition from a pronounced correlation of anthropometric characteristics with the vibration transmission to a nearly missing correlation was caused by an increased involuntary effort to counteract the vibration, e.g., by a higher muscle tension. The frequent inclusion of the greatest sagittal diameter of the abdomen measured in the sitting posture could be interpreted as a hint to the importance of mass distribution within the human body for the SEAT-value instead of the total body mass.

The total body mass was the dominating predictor for the SEAT-value in the y-direction at magnitudes M1 and M2. With the highest magnitude M3, the hip breadth became the most important predictor, although the body mass correlated with the SEAT-value, too (cf. Fig. 8). The significance of the length of lever arms for stabilizing the body in the frontal plane is a conceivable explanation for the importance of the hip breadth.

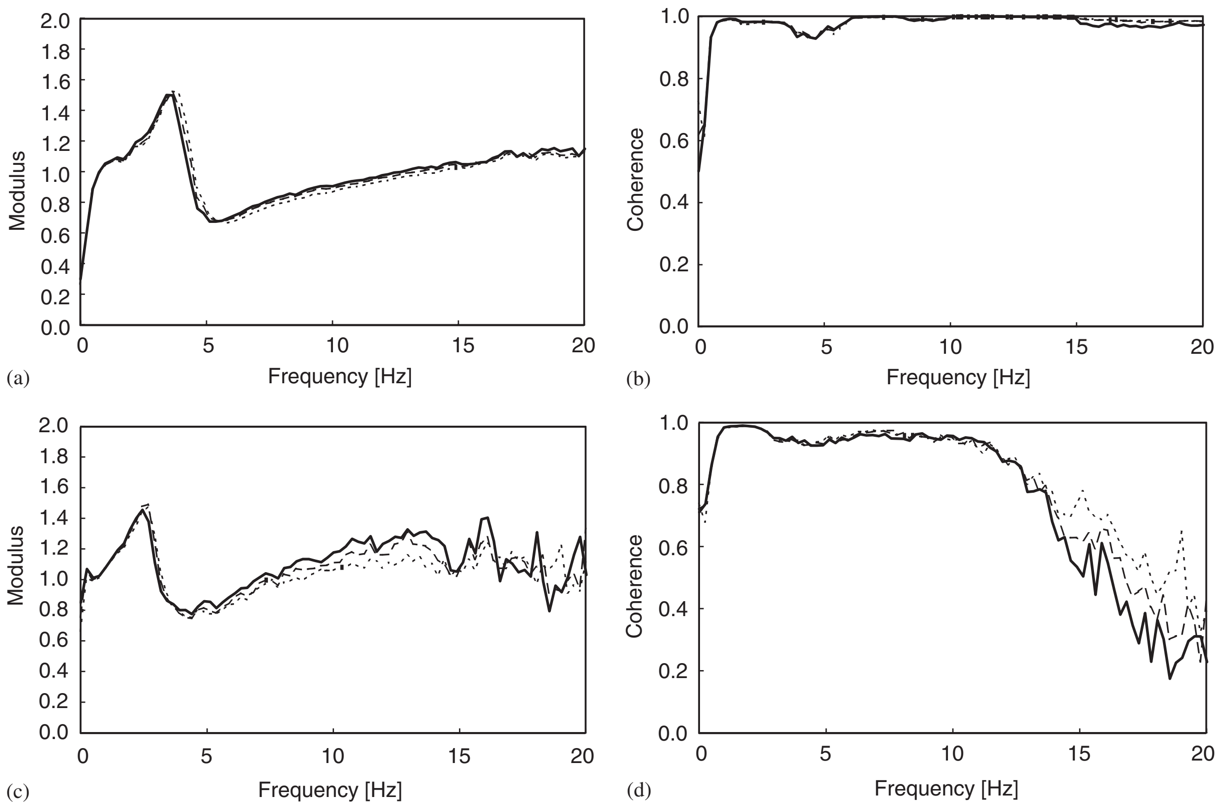

Fig. 10. Moduli of the transfer functions (a, c) and coherence functions (b, d) between the accelerations at the seat base and the accelerations at the cushion in x-direction, Subject 1, exposures with magnitudes M1, M2 and M3 (cf. Table 1), Seat 1 (a, c) and Seat 2 (b, d), x-suspensions locked. Key: (- - -) M1; (———) M2; (——) M3.

The decreasing range of SEAT-values (cushion) with a rising magnitude (cf. Fig. 6b) might be linked with the transition to a simpler biodynamic behaviour of the human body. Based on experimental data obtained with a rigid seat, Holmlund and Lundström [15] assumed the body to act as a two-mass system during low vibration magnitudes and as a one mass system at higher ones [15]. Recent findings [13] confirmed this hypothesis.

5. Conclusions

Although the following conclusions were derived from experiments with only two driver seats, they rely on a sufficient number of subjects and can be considered as a good starting point for further research and development. Possible direction-dependent relationships between the body mass and the WBV-transmission by suspended seats should be taken into account with the development of future standardized test procedures. Tests with only two subjects of extreme body weight may be not suited to obtain comparable and representative results that enable a comparison of different seats with a suspension for the x-direction. Other anthropometric characteristics can correlate closer with the transmission of vibration by seats with horizontal suspensions. These characteristics could be considered as criteria for the choice of test subjects in future test codes. They may also be of importance for the development of mathematical models that can be used during the design process. The effects of the vibration magnitude on the vibration transmission suggest the consideration of the former when the range of application of such seats is known and shall be taken into account.

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