Industrial Health 2010, **48**, 565–583 **Original Article**

Seat-to-head Transfer Function of Seated Men —Determination with Single and Three Axis Excitations at Different Magnitudes

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Received July 8, 2009 and accepted May 6, 2010

Abstract: Most research has investigated the seat-to-head transmissibility during single-axis excitations. Associations between head accelerations and discomfort or effects on vision were reported. Possible differences between the seat-to-head transmissibility determined during different vibration magnitudes with a variable number of excitation axes have not been systematically examined. An experimental study was performed with 8 male subjects sitting on a rigid seat with hands on a support. They were exposed to random whole-body vibration (E1=0.45 ms^{-2}, E2=0.90 ms^{-2}, and E3=1.80 ms^{-2}) to single- and three-axis vibration. All translational and rotational seat-to-head transmissibilities were calculated. The effects of the factors vibration magnitude and number of axes on the peak modulus and frequency of the seat-to-head transmissibilities were tested. In general the head motions follow constant pattern. These pattern of head motions comprise a combination of rotational and translational shares of transmissions, i.e. the curves show a dependence on the factors 'vibration magnitude' and 'number of vibration axes'. Mechanical properties of the soft tissue, relative motions of body parts, and muscle reactions were supposed to cause the nonlinearities of the head. Future research should consider effects of multi-axis vibration, if conclusions shall be drawn for the evaluation of possible health effects and model validations.

Key words: Seat-to-head transmissibilities, Whole-body vibration, Biodynamics

Introduction

Different methods exist to study the reasons for adverse effects of whole-body vibration on the human body. One of these methods involves consideration of how vibration is transmitted through the body. The transmissibilities through the human body reflect the biodynamic response of the body between the point at which the vibration enters the body, e.g. the seat interface, and the point at which the vibration is measured on the body, e.g. the head.

Previous studies were performed with input signals of different magnitudes, vibration directions, frequency content, and waveform (random, discrete sinusoidal, sine swept). The subjects had different seating conditions and/or postures (with and without backrest contact, from erect to slouched postures with resulting head postures) combined with different muscle tensions. The accelerations were measured at the head using several devices at different measurement positions at the head. The interindividual variability of the subjects has a large effect on the seat-to-head transmissibility.

The influences of the described factors were studied by numerous authors at the end of last century and were summarized in two review papers[1, 2]. Boileau and Rakheja[1] identified 10 data sets which satisfied the imposed selection rules to derive idealized values of the seat-to-head transmissibilities during exposure in Z-axis. These results were the basis for mean target values of modulus and phase of the seat-to-head transmissibilities in ISO 5982[3] (Table 3, Fig. 3) under the assumption of a linear vibration behaviour of the head. The maximum is given at 5 Hz with a mean modulus of 1.47 (range 1.28 to 1.87). Paddan and Griffin[2] included in their review data from 10 studies of the transmission of fore-and-aft seat vibration to fore-and-aft head motion (frequencies up to 16 Hz), from 14 studies of the transmission of lateral seat vibration to lateral head motion (frequencies up to 14 Hz), and from 46 studies of the transmission of vertical seat vibration to vertical head motion (up to 30 Hz). Medians, interquartiles and ranges were given. A maximum median of 1.26 (range 1.04 and 1.68) was found at 1 Hz for the fore-and-aft head motion during excitation in X-axis. With input accelerations in Y-axis a maximum median of 1.57 (range 1.07 to 2.17) was registered at 1 Hz, too. During excitation in Z-axis a maximum median of 1.25 (range 0.48 to 2.78) at 4 Hz was calculated based on the numerous publications.

The authors of some studies measured the head acceleration only in the excitation axis[2] (details in[2] Table 2), but the authors of few studies registered also rotational motions of the head during translational exposure to whole-body vibration[4–9]. During fore-and-aft seat motion six head transmissibilities in the excitation axis and cross axes were calculated. Important results were found in three dominant axes: x-, z-, and pitch[8].

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The maxima were registered around 2 Hz in x-axis and around 4 Hz for z- and pitch axes. During lateral seat motion the head motion occurred mostly in y-direction at frequencies around 1 Hz. Figure 8 of Paddan and Griffin[8)] shows clearly also head movements in roll- and pitch-axes. During vertical seat motion the transmissibilities obtained in six axes show three dominant axes: x-, z-, and pitch axes[9)].

Some authors have stated that a non-linearity of the transmission behaviour of the head occurs with different vibration magnitudes during exposures with vertical vibration[10, 11)]. Non-linear effects were also observed for the transmissibilities between vertical seat movements and pelvis rotation in nine postures tested[12, 13)]. Involuntary changes in muscle tension during whole-body vibration are supposed to be partly responsible for some of the nonlinear biodynamic behaviour during exposure observed during vertical seat movements[14, 15)]. Huang[16)] summarized the causes of the nonlinear behaviour of the whole human body, discussed by several authors, and mainly based on apparent mass data in three points: 1) the so called "geometric nonlinearity" of the body, i.e. bending and buckling of the spine, pitching of the pelvis, and rocking of the abdomen; 2) the voluntary and/or involuntary muscle activity to control unstable seated balance, and 3) the passive thixotropy of soft tissues, i.e. a softening characteristic in the passive soft tissue. Relations between the nonlinear vibration behaviour of the trunk and the vibration behaviour of the head were not discussed.

To the authors knowledge possible differences between seat-to-head transmissibilities determined during different vibration magnitudes and with a variable number of vibration axes have not been systematically investigated. The aim of the study is to examine the biodynamic behaviour of the head during single – and three-axis excitations at different magnitudes for one selected posture, i.e. to identify the resulting translational and rotational head motions in the main and cross axes without variability of the factor posture.

Table 1. Minimal, maximum, mean values and standard deviations (SD) for the root mean square values (rms) of the unweighted input accelerations a [ms^{-2}] measured in x-, y-, and z-direction during single axis (X, Y, Z), and three-axes (XYZ) excitations (N=16)

	Minimum	Maximum	Mean	SD
Exposure 1 (E1)				
rms ax X	0.46	0.58	0.50	0.04
rms ax XYZ	0.48	0.57	0.53	0.03
rms ay Y	0.48	0.63	0.54	0.04
rms ay XYZ	0.47	0.57	0.51	0.03
rms az Z	0.46	0.48	0.46	0.01
rms az XYZ	0.44	0.46	0.45	0.01
Exposure 2 (E2)				
rms ax X	0.91	1.07	0.99	0.05
rms ax XYZ	0.93	1.13	1.03	0.06
rms ay Y	0.93	1.18	1.02	0.08
rms ay XYZ	0.93	1.14	1.02	0.07
rms az Z	0.88	0.90	0.89	0.01
rms az XYZ	0.85	0.90	0.87	0.01
Exposure 3 (E3)				
rms ax X	1.82	2.12	1.96	0.09
rms ax XYZ	1.85	2.15	2.00	0.09
rms ay Y	1.89	2.32	2.06	0.12
rms ay XYZ	1.83	2.14	1.96	0.09
rms az Z	1.67	1.71	1.69	0.01
rms az XYZ	1.71	1.73	1.72	0.01

Subject and Methods

Exposure conditions and subjects

The exposures were generated by the control system of the hexapod simulator suited for human experiments. The requirements of ISO 13090-1[17)] were considered. The subjects were exposed at three vibration magnitudes to single-axis vibration in X-, Y-, and Z-axis and three-axes vibration in XYZ simultaneously. The excitation axes are marked by capitals, but the measuring directions by lower-case letters (e.g. ax X means seat acceleration measured in x-direction during the excitation in X-axis). The male subjects were exposed to random whole body vibration (nearly flat spectrum from 0.5 to 20 Hz for 60 s) with unweighted rms values according to Table 1. The variability in each frequency band of the PSD's of the input accelerations (standard deviation divided by mean value) was calculated. For the single axis excitation the medians of the variabilities of the PSDs were between 0.014 and 0.024 during E1 and between 0.008 and 0.015 during E3. The variability for the three axis vibration was found in the same range (0.021–0.025 during E1, 0.008–0.015 during E3). For each axis, one template of a random time series was generated and multiplied in the time domain in order to produce different magnitudes. Identical time series were used with single-axis and three axes vibration. Thus, effects of random variations of the time series structure on the transmissibility were avoided within one axis. The twofold presentation of the vibration magnitudes and directions was balanced across the subjects. The experiment was approved by the Central Ethic Commission of the Land Berlin. All subjects gave their informed consent.

An experimental study was performed with 8 male subjects with body masses between 64.0 and 105.9 kg (mean value 85.0 kg), and body heights between 173.5 and 197.0 cm (mean value 185.4 cm). A total of 26 anthropometric parameters in the standing and 12 parameters in the sitting posture were measured. The subjects sat on a rigid seat, with their ischial tuberosities approximately 20–30 cm from the front edge of the plate and with the hands on a support (Fig. 1).

The rigid seat had no resonance in any axis within the frequency range studied. The subjects were asked to adopt an upright posture with normal muscle tension for the duration of each test. The subjects were requested to hold the individual bite plate of the bite bar by their teeth in a manner that the contact between them remained nearly constant during each exposure section to secure sufficient and constant contact. They were instructed to minimize head posture variations and were provided with a visual marker to minimize changes of head orientation, which were adjusted that l_1, l_2, and l_3 of the bite bar (Fig. 1) were as near as possible in a horizontal plane. The feet were supported on a plate. The seat height was individually adapted by additional plates (aluminium sandwich construction "ALUCORE", mejo Metall Joslen GmbH & Co. KG) mounted on the feet plate to get a constant body

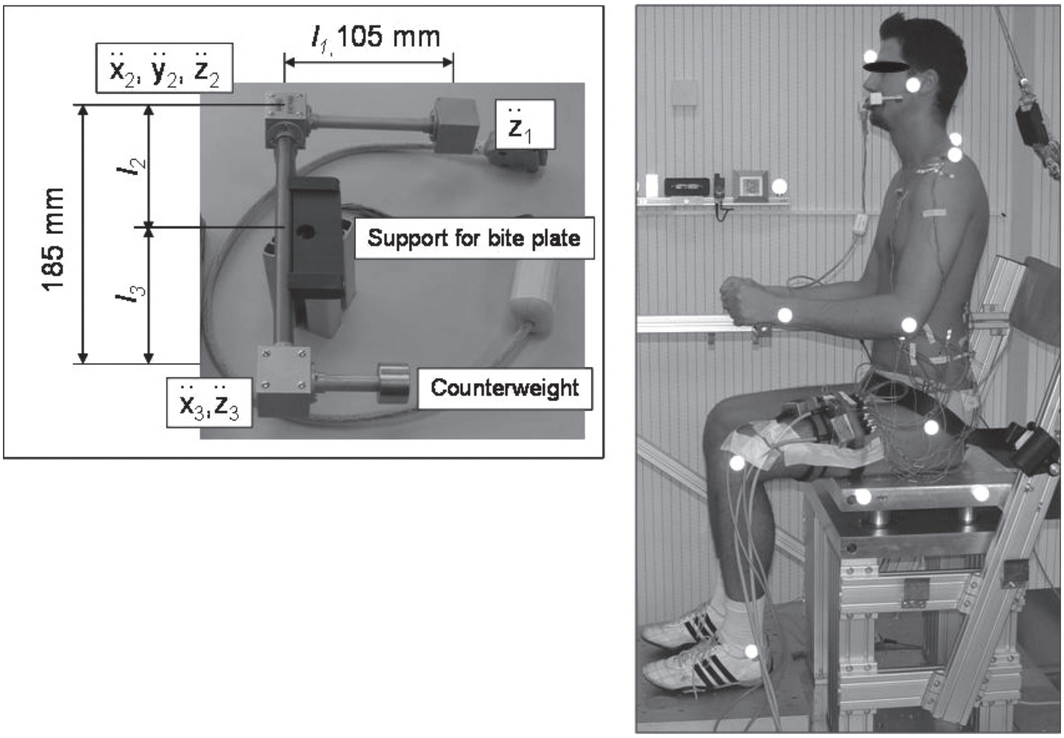


Fig. 1. The experimental situation is illustrated by the photography of a male subject sitting on a rigid seat and instrumented by a bite bar, markers of the movement analysis and additional accelerometers. The details of the bite bar including the distances are shown in the small picture on the left.

angle between thighs and lower legs of about 90 degrees. For safety reasons a loose hip belt was used and a safety bottom was available.

Data acquisition

Accelerations in three translational directions (x, y, z) were measured at the seat plate using three capacitance accelerometers (ENDEVCO 7290A-10) mounted on a special block for them (ENDEVCO 7290A-10, capacitive sensors, uncertainty ± 5.0% in the range between 0 and 20 Hz). The block was fixed on the right side of the seat plate. Translational accelerometers mounted on a bite bar (material: titan, weight: 250 g including cable and counterweight) were used to measure head motions with full bridge piezo-resistive (strain gauge) type accelerometers (2 EGAXT3-M-10 and 1 EGAXT-10, Entran, capacitive sensors, uncertainty ± 5.0% in the range between 0 and 20 Hz). The bite bar was held by the teeth via an individually produced bite plate (Impression Compound, SPOFA-Dental, Praha). The accelerometers were located and orientated so as to enable the three translational and rotational axes of head accelerations to be monitored (Fig. 1). The data acquisition was performed by a WaveBook with WBK16 moduls (Iotech). Function integrity tests were performed before and after each test with a subject. The seat accelerometer-block and the complete bite bar were screwed on the seat plate and were exposed to E2 three-axis excitation. The transmissibilities were calculated between the seat and bite-bar accelerations (cf. section Data processing). The medians of the coefficient of variation of these transmissibilities varied between 0.002 and 0.004 in the range between 0.5 and 10 Hz and between 0.002 and 0.006 in the range between 10 and 20 Hz in the three axes.

A motion analysis system (Qualisys) was used to register the movements of body points (spinal process of C7, acromion process, elbow joint, wrist, pelvic, iliac crest, hip joint, knee joint, and ankle).

Data processing

The accelerations registered by means of the bite bar (cf. Fig. 1) were calculated using the six measured accelerations with the associated distances l_1, l_2, l_3 and the inverted transformation matrix (Equation (3)) considering the coordinates of the accelerometers[18, 19].

$$\begin{bmatrix} \ddot{z}_1 \\ \ddot{x}_2 \\ \ddot{y}_2 \\ \ddot{z}_2 \\ \ddot{x}_3 \\ \ddot{z}_3 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & -l_2 & l_1 & 0 \\ 1 & 0 & 0 & 0 & 0 & l_2 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & -l_2 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & -l_3 \\ 0 & 0 & 1 & l_3 & 0 & 0 \end{bmatrix} \begin{bmatrix} hx \\ hy \\ hz \\ rx \\ ry \\ rz \end{bmatrix} \tag{3}$$

The calculations using the inverted matrix delivered the translational (h) and rotational accelerations (r) in equations (4) to (6) which were designated as head accelerations:

$$hx = [l_3 \times \ddot{x}_2 + \ddot{x}_3 \times l_2]/(l_3 + l_2) \qquad rx = (\ddot{z}_3 - \ddot{z}_2)/(l_3 + l_2) \tag{4}$$

$$hy = \ddot{y}_2 \qquad ry = (\ddot{z}_1 - \ddot{z}_2)/l_1 \tag{5}$$

$$hz = [l_2 \times \ddot{z}_3 + \ddot{z}_2 \times l_3]/(l_3 + l_2) \qquad rz = (\ddot{x}_2 - \ddot{x}_3)/(l_3 + l_2) \tag{6}$$

In total 6 head accelerations (hx, hy, hz, rx, ry, rz) were caused by single (X, Y, Z) or three-axis (XYZ) seat vibration (ax, ay, az) and 12 (single-axis excitation) or 18 seat-to-head transmissibilities (three-axis excitation) resulted. In the following chapters only seat-to-head transmissibilities with important contributions to the head motions will be reported and discussed, i.e. magnitudes of translational transmissibilities higher than 0.5, magnitudes of rotational transmissibilities higher than 2 [rad/m] with coherencies above 0.5.

$$\begin{bmatrix} hx/ax & hy/ax & hz/ax \\ hx/ay & hy/ay & hz/ay \\ hx/az & hy/az & hz/az \end{bmatrix} \qquad \begin{bmatrix} rx/ax & ry/ax & rz/ax \\ rx/ay & ry/ay & rz/ay \\ rx/az & ry/az & rz/az \end{bmatrix} \qquad (7,\ 8)$$

All possible seat-to-head transfer functions in main and cross axis (7, 8) were calculated by dividing the cross spectral density functions (CPSD) between the seat acceleration (a) and the head acceleration (h, r) by the power spectral density (PSD) of the seat acceleration (9). The associated coherences were determined according to equation (10).

$$T(f)=\frac{CPSD(a,h)}{PSD(a)} \qquad T(f)=\frac{CPSD(a,r)}{PSD(a)} \qquad (9)$$

$$\gamma^2(f)=\frac{(CPSD\,(a,\,h))^2}{PSD\,a\times PSD\,h} \qquad \gamma^2(f)=\frac{(CPSD\,(a,\,r))^2}{PSD\,a\times PSD\,r} \qquad (10)$$

The cross spectral density method was chosen because it delivers the phase relations between two signals[20], although other methods may be considered better suited to investigate the human vibration behaviour. The mean curves of the moduli, phases and coherencies of the individual seat-to-head transfer functions were calculated by the linear averaging method to illustrate the findings.

For each individual seat-to-head transfer function the maximum modulus and its location, i.e. peak frequency, were determined for statistical analysis.

The influence of the factors vibration magnitude, repetition, and number of axes on the individual maxima of the moduli of the seat-to-head transfer functions and their individual peak frequencies were tested by the general linear model (GLM) Repeated Measures procedure (SPSS PC - analysis of variance, when the same measurement is made several times on the same subject.). The GLM Repeated Measures procedure provides both univariate and multivariate analysis including the Bonferroni post hoc test. The Bonferroni test, based on Student's statistic, adjusts the observed significance level to take account of the fact that multiple comparisons of mean values are made.

Results

Very small values without any further peaks were registered for the horizontal seat-to-head transmissibilities of the 8 subjects above 10 Hz. In all probability these values did not contribute essentially to the motion pattern of the head.

Seat-to-head transmissibilities during single-axis excitation

X-axis

During single X-axis excitation appreciable mean moduli were found in x-, z-, and pitch direction with peak frequencies around 1 Hz for hx/ax (Fig. 2A, a), between 2.1 and 2.9 Hz for hz/ax (Fig. 2A, b), and ry/ax (Fig. 3A, a). A fore-and-aft motion combined with a pitch and vertical head motion can be observed. A tendency to smaller rotational motions at lower frequencies was registered (Fig. 3A, a). In dependence on the increasing magnitudes, shifts of the mean curves of the moduli towards lower frequencies were registered (curves without markers, Fig. 2A, a, b, 3A, a). The mean curves of phases of hx/ax were positive at frequencies below 1 Hz (Fig. 2B, a). The phases were equal to zero at 1.5 Hz during E1 and 1.3 Hz during E3. The phases of hz/ax were positive only during E1 up to 1 Hz (Fig. 2B, b). With higher frequencies the phases decrease at all three vibration magnitudes, but the phases during E1 has the lowest absolute values. The mean phases of ry/ax during E1 and E2 were positive below 1 Hz and 0.75 Hz respectively (Fig. 3B, a). Above 1 Hz the phases decreased continuously up to about –450 degree at 10 Hz with the lowest absolute values during exposure E1.

The values of the coherence functions in the range of the maximum moduli were registered between 0.6 and 0.8. Above 6 Hz for hx/ax, ry/ax and above 4 Hz for hz/ax, the coherences were low (Fig. 2C, a, b; Fig. 3C, a).

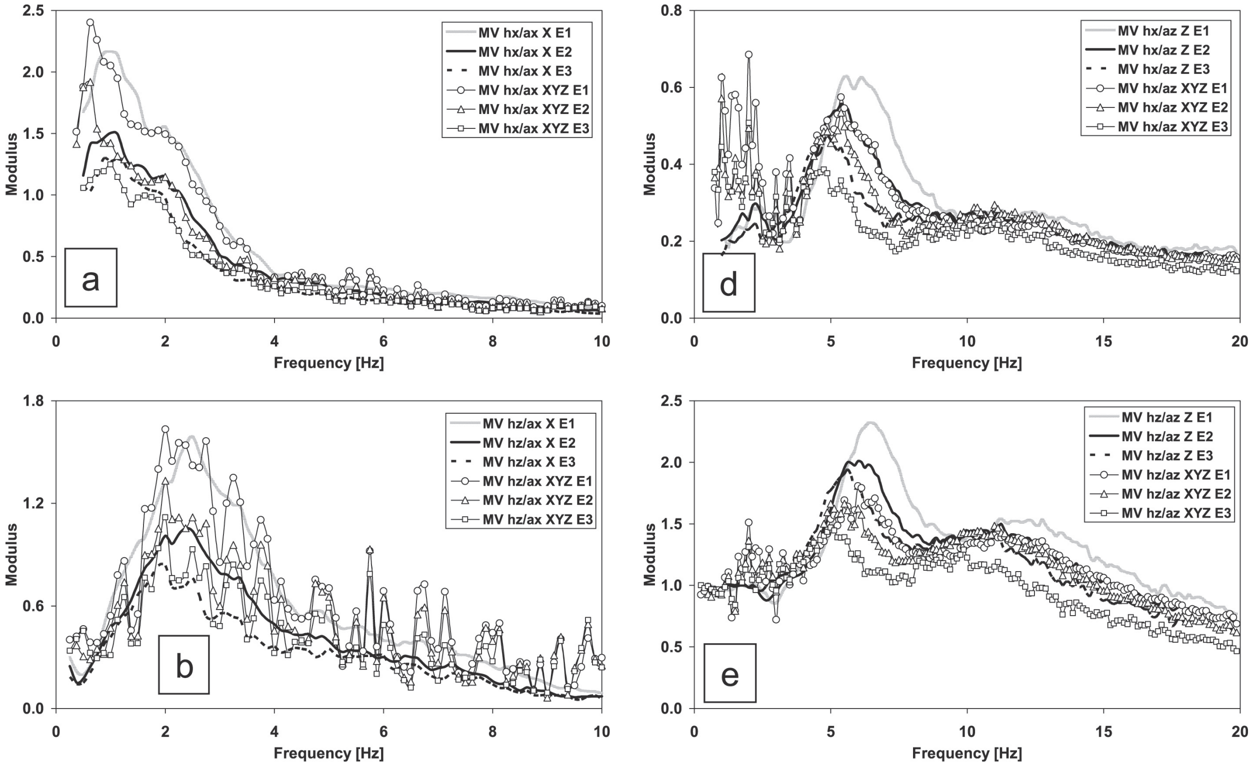
The mean peak moduli decreased with the increasing magnitude, for hx/ax from 2.4 to 1.4, for hz/ax from 1.6 to 0.9, and for ry/ax from 12.4 to 6.4 [rad/m] (Table 2B). The differences of mean moduli were significant (Table 2A). The peak frequencies remained nearly unchanged across the vibration magnitudes for hx/ax, whereas the peak frequencies decreased significantly for hz/ax from 2.6 to 2.1 Hz, and for ry/ax from 2.9 to 2.2, if the vibration magnitude increased from E1 to E3 (Table 2A, 2B).

The multivariate analyses (e3r2) showed a significant influence exerted by the vibration magnitude - whereas the repetition had no influence (Table 3). The univariate analysis showed a systematic dependence of the maximum moduli and the peak frequency (except hx/ax) of the seat-to-head transfer functions hz/ax and ry/ax on the vibration magnitude (Table 3).

Y-axis

During single Y-axis excitation important transmissions were registered in y-, roll and yaw direction with peak frequencies around 1 Hz for hy/ay (Fig. 2A, c) and rx/ay (Fig. 3A, b) and between 2.8 and 5.2 Hz for rz/ay (Fig. 3A, c). A lateral motion combined with roll and yaw motions of the head were found. The figures illustrate a dependence of hy/y and rx/ay on the vibration magnitude by a shift of the curves to the lower frequencies. (Fig. 2A, c, Fig. 3A, b). Two peaks around 2 and 4 Hz characterized the mean curves of rz/ay (Fig. 3A, c). With the highest vibration magnitude the peak around 4 Hz disappears.

The mean phases of hy/ay and rx/ay were positive in the low frequency range were positive during all vibration magnitudes (Fig. 2B, c, Fig. 3B, b). The mean phases of rz/ax were registered around zero degree below about 2.5 Hz (Fig. 3B, c). At higher frequencies the phases of all three transmissibilities



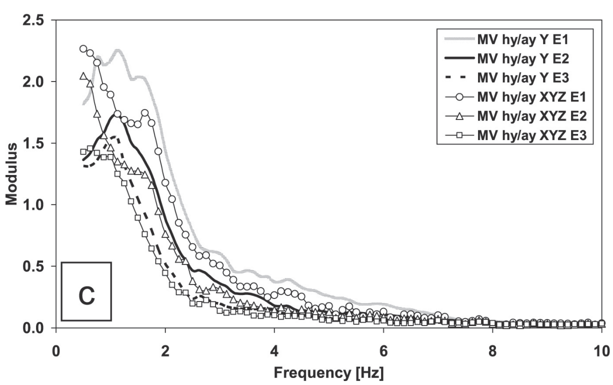


Fig. 2A. Mean curves of moduli of the dominant seat-to-head transmissibilities (translation) during single axis excitation (X, Y, Z) and three axis excitation (XYZ) at the vibration magnitudes E1, E2, and E3: a) hx/ax during excitation X and XYZ, b) hz/ax during excitation X and XYZ, c) hy/ay during excitation Y and XYZ, d) hx/az during excitation Z and XYZ, e) hz/az during excitation Z and XYZ.

decrease with the lowest absolute values during E1.

The mean coherence functions of hy/ay and rx/ay showed values in the range between 0.4 and 0.8 with the lower values at the higher frequencies (Fig. 2C, c; Fig. 3C, b). For rz/ay the coherencies were lower 0.6 at frequencies higher than 4 Hz

The mean peak moduli decreased with the increasing magnitude for hy/ay from 2.3 to 1.6, for rx/ay from 9.4 to 5.7 [rad/m], and for rz/ay with from 2.1 to 1.7 [rad/m] (Table 2B). The differences of mean values were significant (Table 2A). The mean peak frequencies were found for hy/ay and rx/ay in the range between 0.8 and 1.9 Hz and for rz/ay between 5.2 and 2.8 Hz with the lower values at the higher vibration magnitude, but without significantly different mean values (Table 2A, 2B).

The multivariate analyses showed a significant influence exerted by the vibration magnitude on the parameter of the three transmissibilities. The univariate analysis showed the same dependence of the maximum modulus on the factors vibration magnitude. But only the peak frequencies of rz/ay were influenced by the factor vibration magnitude (Table 3).

Z-axis

The head movements were characterized mainly by the transmissibilities hz/az, hx/az (Fig. 2A, d,e) and ry/az (Fig. 3A, d). A dependence of the mean curves on the vibration magnitude is obvious by lower peak amplitudes and shifts to the lower frequencies with the increasing vibration magnitude.

The mean phases of hz/az remain relatively constant around zero degree up to 5 Hz and decrease slowly up to about -150 degrees at 20 Hz (Fig. 2B, e). The phases of hx/az (Fig. 2B, d) and ry/az (Fig. 3B, d) were positive in the low frequency range. In the range between about 5.5 and 6 Hz the mean curves pass the zero line and decrease continuously (Fig. 2B, d, Fig. 3B, d). The mean phases were positive below about 5 Hz with the lowest values at the lowest vibration magnitude (Fig. 3B, d). The phases decrease to nearly –200 degrees at

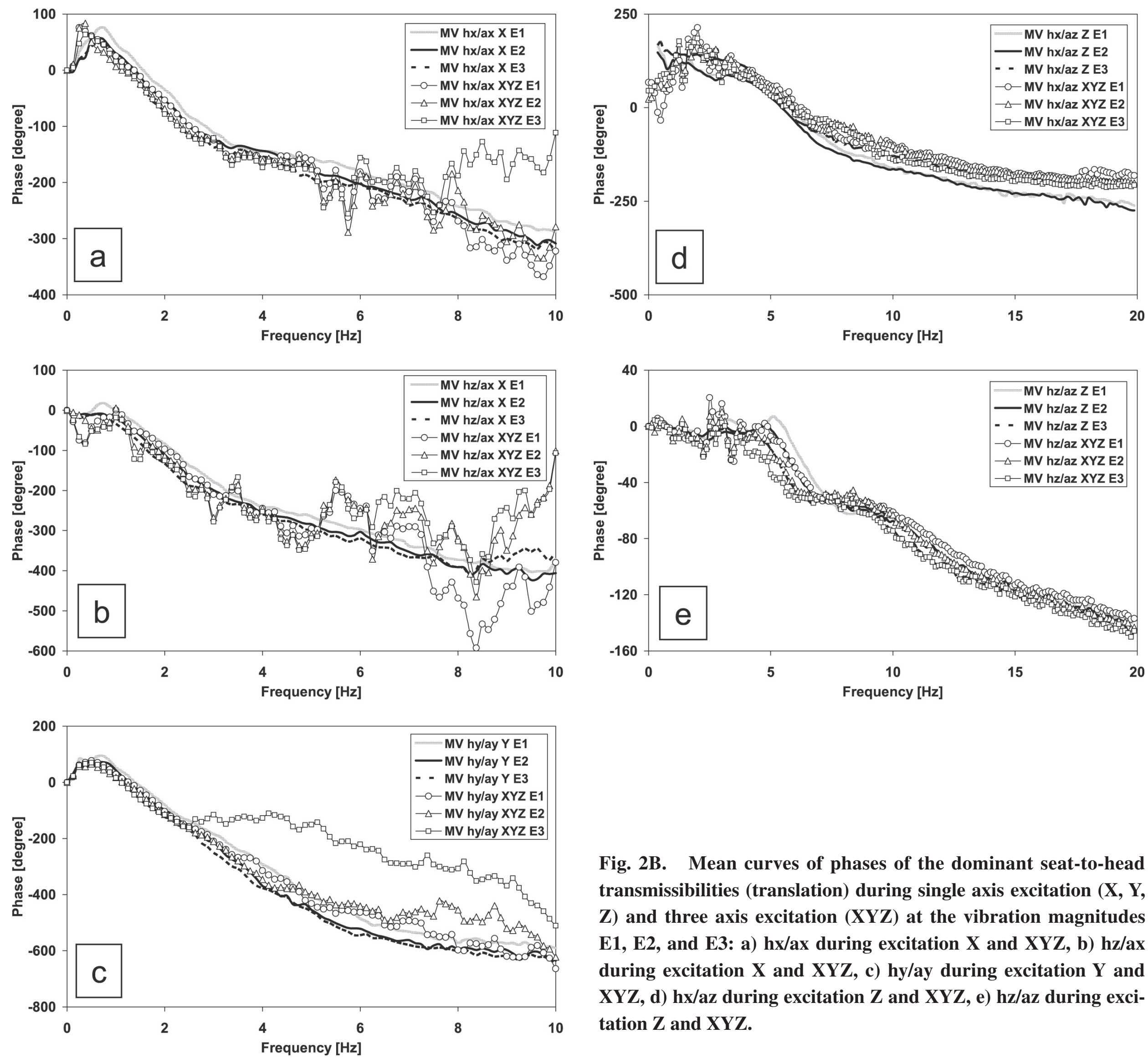


Fig. 2B. Mean curves of phases of the dominant seat-to-head transmissibilities (translation) during single axis excitation (X, Y, Z) and three axis excitation (XYZ) at the vibration magnitudes E1, E2, and E3: a) hx/ax during excitation X and XYZ, b) hz/ax during excitation X and XYZ, c) hy/ay during excitation Y and XYZ, d) hx/az during excitation Z and XYZ, e) hz/az during excitation Z and XYZ.

20 Hz.

Except the frequencies below 1 Hz, the values of the mean coherence functions of hz/az reach values between 0.9 and 1.0 in the frequency range tested (Fig. 2C, e). For the mean coherences of hx/az and ry/az values between about 0.7 and 0.9 were registered in dependence on the frequencies (Fig. 2C, d, Fig. 3C, d). For the moduli in z-direction 2 peaks were determined in the individual transmissibilities:

- First peak

The mean values of maximum magnitudes of the first peak between 6.5 and 5.3 Hz decreased for hz/az from 2.3 to 1.9, and for ry/ay from 12.8 to 8.0 [rad/m].

For hx/az the first peak occurred between 3.7 and 4.3 Hz and diminished from 0.7 to 0.5 with the increasing magnitude. The mean moduli were significantly different between E1 and E3 for the three transfer functions (Table 2A, 2B). The peak frequencies of three transmissibilities were significantly different between all magnitudes tested (Table 2B).

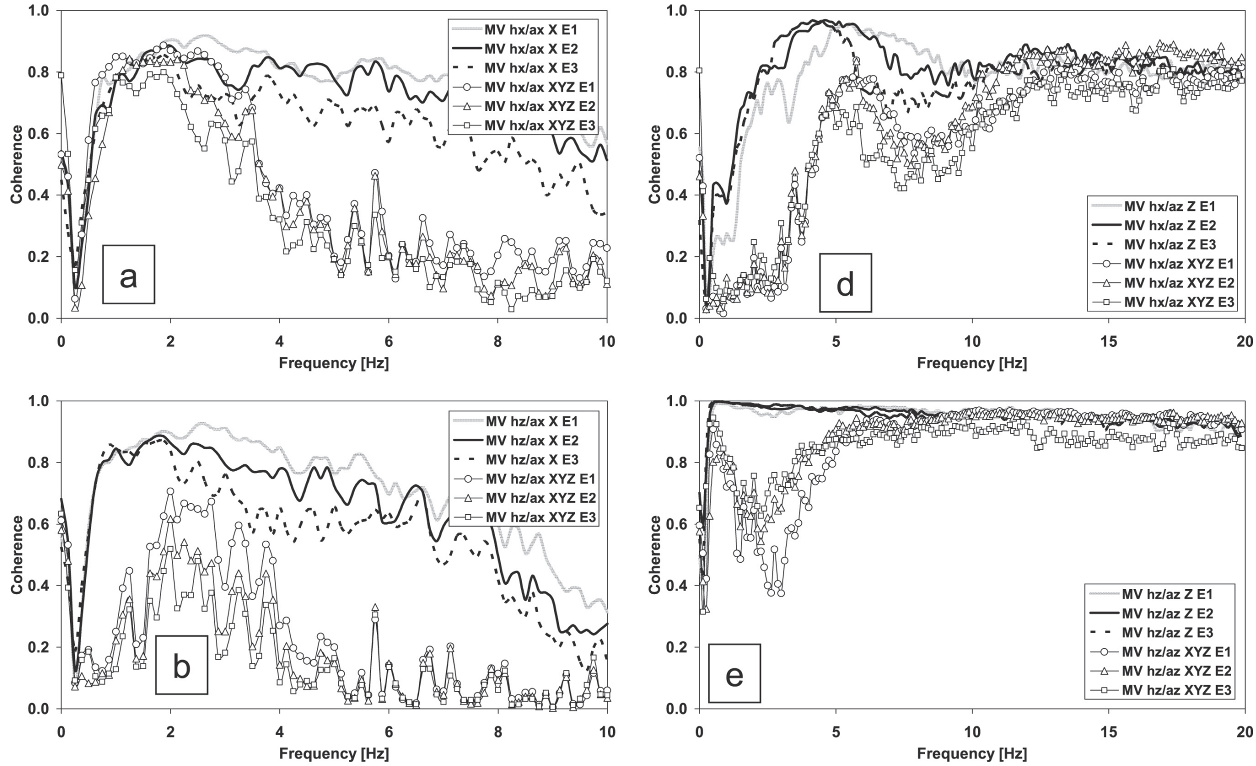
The multivariate analyses showed for the first peak of hx/az, hz/az, and ry/az a significant influence exerted by the vibration magnitude - whereas the repetition had no influence (Table 3). The univariate analysis showed a systematic dependence of the maximum moduli and the peak frequency (except hx/az) on the vibration magnitude (Table 3).

- Second peak

The mean values of maximum magnitudes of the second peak around 10 Hz have the same dependencies on the vibration magnitude, but the differences were smaller and non-significant - for hz/az between 1.9 and 1.6, for hx/az between 0.4 and 0.3, and for ry/az between 8.5 to 5.3 [rad/m] (Table 2B). The peak frequencies of hz/az and ry/az decreased non-significantly from 10.0 to 9.8 Hz with the increasing vibration magnitude (Table 2A, 2B). The multivariate and univariate analyses showed at the second peak no significant influences by the factors tested (Table 3).

Seat-to-head transmissibilities during three-axis excitation

The head motions caused by the three axis excitation were



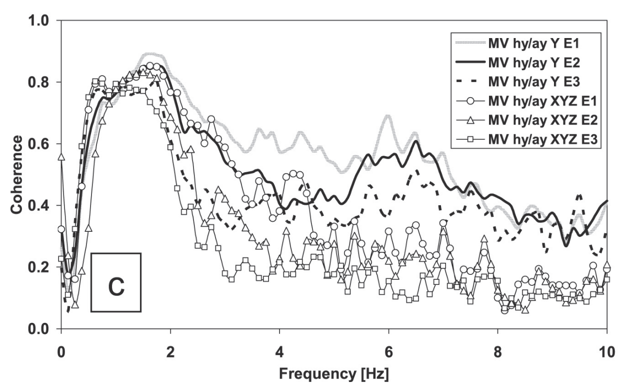


Fig. 2C. Mean curves of coherencies of the dominant seat-to-head transmissibilities (translation) during single axis excitation (X, Y, Z) and three axis excitation (XYZ) at the vibration magnitudes E1, E2, and E3: a) hx/ax during excitation X and XYZ, b) hz/ax during excitation X and XYZ, c) hy/ay during excitation Y and XYZ, d) hx/az during excitation Z and XYZ, e) hz/az during excitation Z and XYZ.

a very complex occurrence with sequence of head movement expressed in all nine seat-to-head transmissibilities. Seat accelerations in the three axes produce substantial head motions in the translational excitation axes. The seat-to-head transmissions related to the seat accelerations in X- and Z axis are accompanied by pitch motions and lower transmissions in the associated cross axis. Besides the lateral head motion were registered also roll motions in the same range as the pitch motions and lower yaw motions. All simultaneous motions influence each other. A detailed description of the results will be given for each excitation axes separately to ensure the clarity of the results.

X-axis

Head motions related to the X-axis seat vibration were found for hx/ax, hz/ax (curves with markers, Fig. 2A, a, b) and in pitch axis ry/ax (Fig. 3A, a). For the mean curves of hz/ax several sharp peaks occurred in the course of transfer functions between 2 and 5 Hz. These peaks may reflect an interaction with further head motions in z-direction caused by the simultaneously excited axes Y and Z.

The moduli of the mean transfer functions hx/ax, ry/ax, and hz/ax were lower with the increasing vibration magnitude, but a clear shift of the mean curves to lower frequencies can only be observed for hx/ax.

In the very low frequency range the mean phases of hx/ax and ry/ax were positive (Fig. 2B, a, Fig. 3B, a). In this frequency range the phases of hz/ax were negative (Fig. 2B, b). Above 1 Hz all phases decrease. At higher frequencies the interindividual differences in the phases of hz/ax and ry/ax reach a large spread associated with very low coherences.

The mean coherences in the range of the maximum moduli were registered around 0.8 to 0.9 for hx/ax, ry/ax and 0.6 for hz/ax (Fig. 2C, a, b Fig. 3C, a). Above this range the coherences decrease partially below 0.2 Hz.

The mean peak moduli decreased with the increasing magnitude, for hx/ax from 2.7 to 1.4, hz/ax from 1.7 to 1.1 and for ry/ax from 11.5 to 5.6 [rad/m] (Table 2B). The differenc-

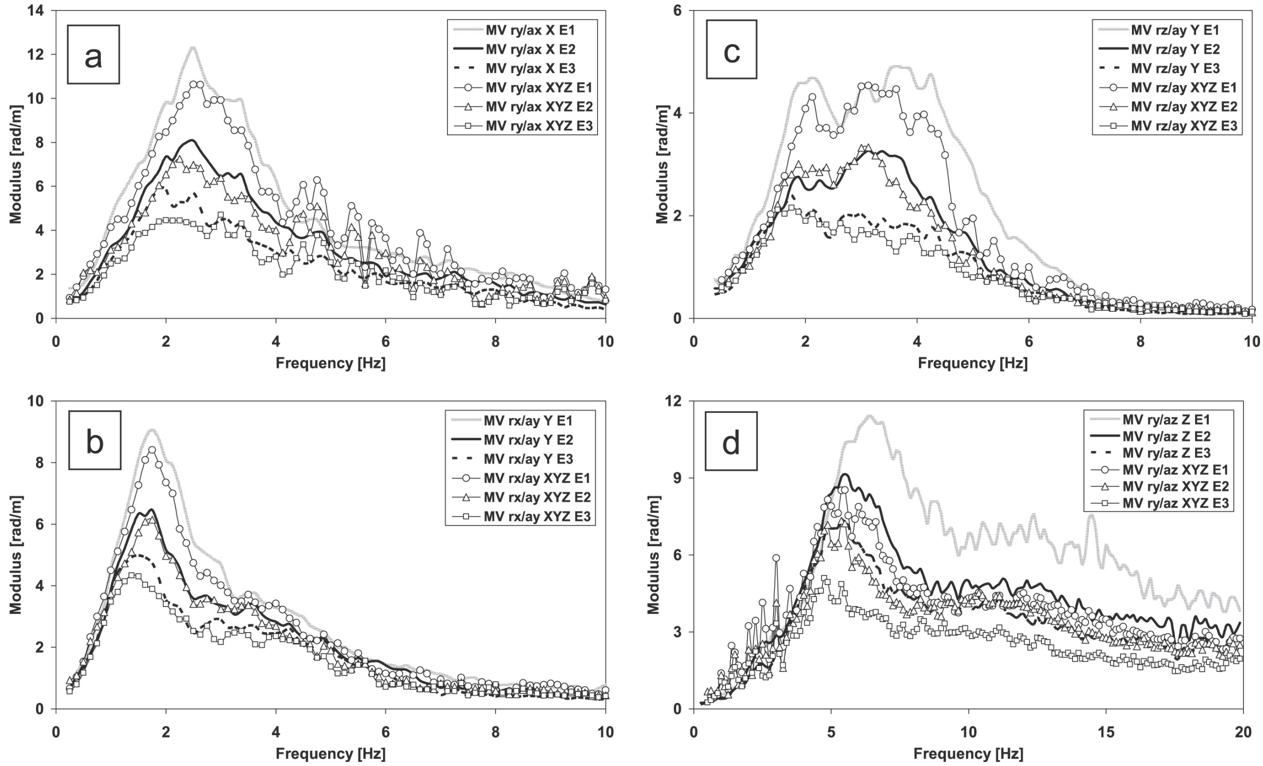


Fig. 3A. Mean curves of moduli of the dominant seat-to-head transmissibilities (rotation) during single axis excitation (X, Y, Z) and three axis excitation (XYZ) at the vibration magnitudes E1, E2, and E3: a) ry/ax during excitation X and XYZ, b) hx/ay during excitation Y and XYZ, c) rz/ay during excitation Y and XYZ, d) hy/az during excitation Z and XYZ.

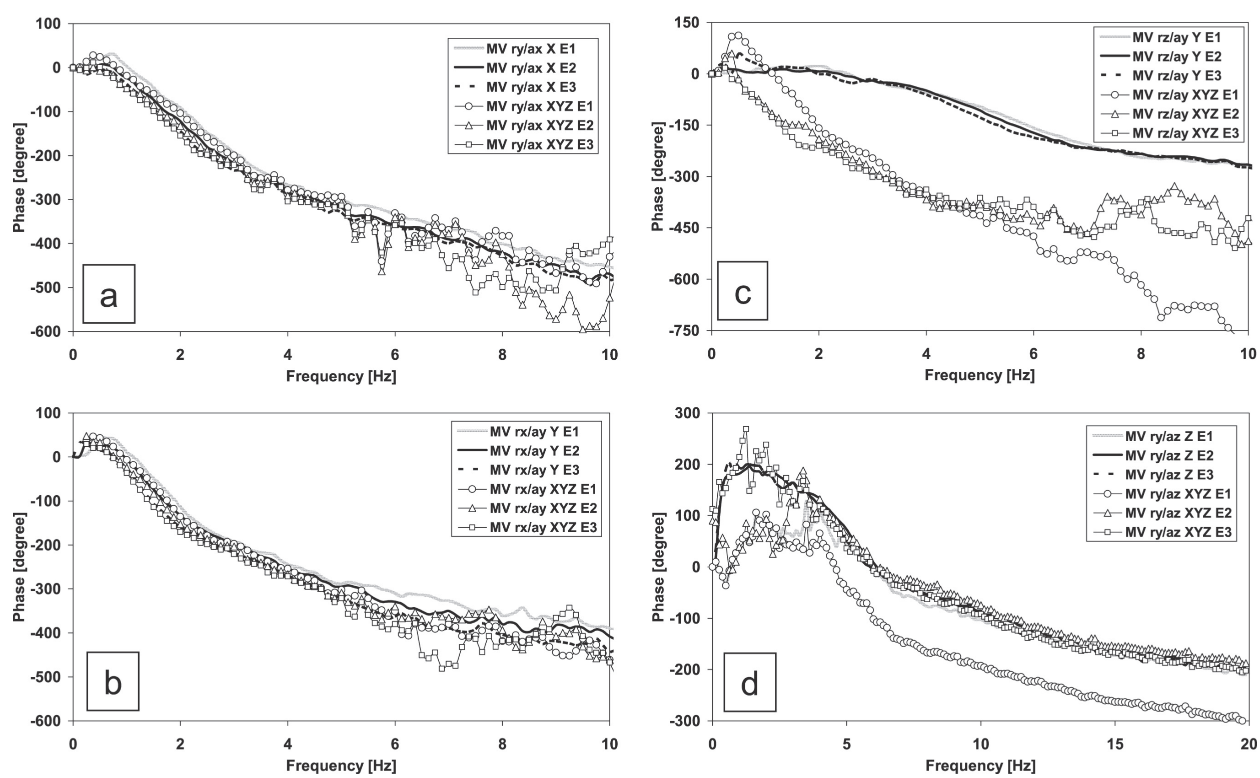


Fig. 3B. Mean curves of phases of the dominant seat-to-head transmissibilities (rotation) during single axis excitation (X, Y, Z) and three axis excitation (XYZ) at the vibration magnitudes E1, E2, and E3: a) ry/ax during excitation X and XYZ, b) hx/ay during excitation Y and XYZ, c) rz/ay during excitation Y and XYZ, d) hy/az during excitation Z and XYZ.

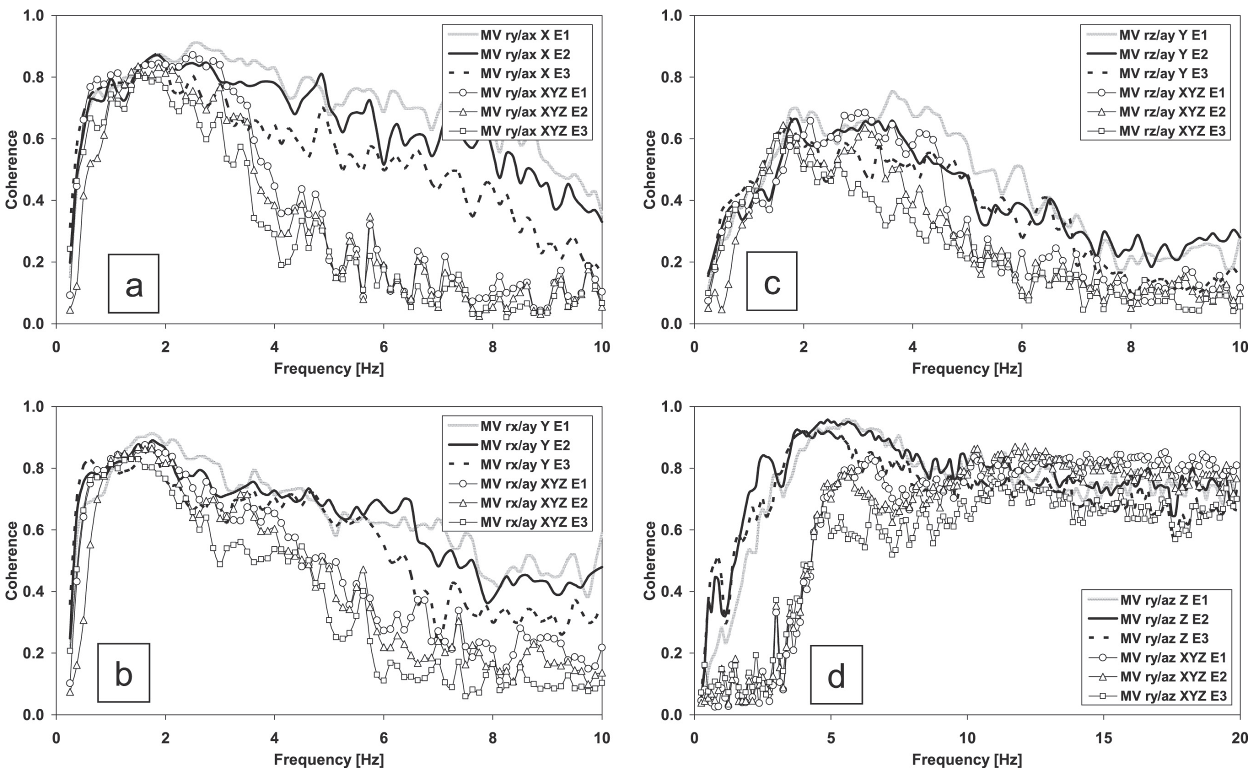


Fig. 3C. Mean curves of coherencies of the dominant seat-to-head transmissibilities (rotation) during single axis excitation (X, Y, Z) and three axis excitation (XYZ) at the vibration magnitudes E1, E2, and E3: a) ry/ax during excitation X and XYZ, b) hx/ay during excitation Y and XYZ, c) rz/ay during excitation Y and XYZ, d) hy/az during excitation Z and XYZ.

es of mean values were significant except between E1 and E2 of hx/ax (Table 2B). The peak frequencies of hx/ax increased with the vibration magnitude, those of hz/ax show a slight decrease with the vibration magnitudes, whereas the peak frequencies of ry/ax show no systematic changes across the moduli. The mean differences were not significant (Table 2A, 2B).

The multivariate and univariate analyses (e3r2) showed a significant influence exerted by the vibration magnitude on the maximum moduli (Table 3). Significant dependencies of the peak frequencies were not found.

To check the influence of the number of vibration axes the complete data set during the excitations with single and three axis vibration was tested (e3r2d2). In the multivariate analysis the factor axis has significant influence on hx/az, but not on hx/ax (Table 3). The univariate results show a significant influence of the vibration magnitude on the maximum moduli and on the peak frequencies of hx/ax and hz/ax and of the number of axis on both maximum moduli and the peak frequency of hz/ax (Table 3). The mean maximum moduli of hx/ax and hz/ax were significantly higher during three axis vibration than during single axis vibration (Table 2C). The peak frequencies of hx/ax and hz/ax were lower during three axes vibration than during single axis vibration, but only the mean frequencies of hz/ax were significantly different (Table 2C). The results of the analysis delivered no influence of the factor axis (Table 3) and no significant differences between the parameters of ry/ax during the single-and three axis vibration (Table 2C).

Y-axis

The mean curves of moduli of the seat-to-head transfer functions hy/ay, rx/ay, and rz/ay show a dependence on the vibration magnitude for the three axes vibration characterized by a shift of the curves to the lower frequencies with the higher vibration magnitudes (Fig. 2A, c, Fig. 3A, b, c). In the mean curves of rz/ay two peaks can be detected, whereas the second peak around 3 Hz disappears with the increasing vibration magnitude similar to those during the single axis excitation. The mean moduli of the transfer functions rx/ay and rz/ay were lower with the increasing vibration magnitude.

The mean phases of the three transmissibilities were positive in the low frequency range. They were negative in the range between about 1.0 and 1.5 Hz (Fig. 2B, c, Fig. 3B, b, c) and declined.

The coherence functions showed values in the range between 0.6 and 0.9 in the frequency range of the maximum moduli, but above 6 Hz the coherences were lower than 0.4 (Fig. 2C, c, Fig. 3C, b, c).

The mean peak moduli decreased significantly with the increasing magnitude, for hy/ay from 2.6 to 1.6, for rx/ay from 9.8 to 4.9 [rad/m], and for rz/ay from 5.5 to 2.6 [rad/m] (Table 2A, 2B) The peak frequencies of hy/ay did not show systematic changes across the vibration magnitudes and the mean differences were not significant (Table 2A, 2B). For the rotational transmissibilities the differences of mean values were significant (Table 2A, 2B) and the peak frequencies showed systematic changes across the magnitudes for rz/ay (2.0 to 1.7 Hz) (Table 2B).

Table 2A. Results (*p* values) of the Bonferroni post hoc test to test the significance level of differences between the mean values of maximum moduli and mean peak frequencies (f (maximum moduli)) of the dominant translational transmissibilities and rotational transmissibilities [rad/m] between the seat acceleration a and the translational (h) or rotational (r) head accelerations at three levels of the factor vibration magnitude (e3), two levels of repetition (r2), and two levels of excitation axes (d2) in brackets. For the head transmissibilities relation to vertical excitations two peaks (1 and 2) were determined

Transfer function	Significances					
	Maximum moduli			f (moduli)		
1 axis excitation	E1–E2	E1–E3	E2–E3	E1–E2	E1–E3	E2–E3
hx/ax X (e3r2)	0.014*	0.004*	0.027*	1.00	0.548	0.308
hz/ax X (e3r2)	0.001*	0.001*	0.009*	0.013*	0.004*	0.001*
ry/ax X (e3r2)	0.000*	0.000*	0.003*	0.858	0.001*	0.174
hy/ay Y (e3r2)	0.038*	0.032*	0.074	0.990	0.622	0.541
rx/ay Y (e3r2)	0.011*	0.004*	0.008*	1.00	1.00	0.619
rz/ay Y (e3r2)	0.013*	0.007*	0.174	0.328	0.084	0.701
hx/az 1 Z (e3r2)	1.00	0.005*	0.008*	0.595	1.00	1.00
hz/az 1 Z (e3r2)	0.069	0.005*	0.112	0.007*	0.000*	0.001*
ry/az 1 Z (e3r2)	0.022*	0.026*	0.056	0.003*	0.001*	0.110
hx/az 2 Z (e3r2)	1.00	0.304	0.283	1.00	0.204	0.390
hz/az 2 Z (e3r2)	0.369	0.334	0.432	1.00	1.00	1.00
ry/az 2 Z (e3r2)	0.489	0.383	0.262	1.00	1.00	1.00
	Maximum moduli			f (maximum moduli)		
3 axis excitation	E1–E2	E1–E3	E2–E3	E1–E2	E1–E3	E2–E3
hx/ax XYZ (e3r2)	0.887	0.002*	0.022*	1.00	0.063	0.097
hz/ax XYZ (e3r2)	0.001*	0.001*	0.014*	1.00	0.254	1.00
ry/ax XYZ (e3r2)	0.000*	0.000*	0.005*	1.00	0.993	0.635
hy/ay XYZ (e3r2)	0.008*	0.017*	0.037*	0.748	0.725	0.088
rx/ay XYZ (e3r2)	0.001*	0.001*	0.012*	0.833	1.00	1.00
rz/ay XYZ (e3r2)	0.030*	0.012*	0.028*	1.00	0.295	0.473
hx/az 1 XYZ (e3r2)	0.059	0.015*	0.099	0.956	0.419	0.987
hz/az 1 XYZ (e3r2)	0.008*	0.013*	0.082	0.882	0.557	1.00
ry/az 1 XYZ (e3r2)	0.001*	0.002*	0.021*	0.018*	0.179	1.00
hx/az 2 XYZ (e3r2)	1.00	0.356	0.333	0.408	0.698	1.00
hz/az 2 XYZ (e3r2)	1.00	0.040*	0.042*	0.156	0.145	0.727
ry/az 2 XYZ (e3r2)	1.00	0.096	0.006*	1.00	1.00	0.604
	Maximum moduli			f (maximum moduli)		
1 & 3 axis excitation	E1/E2	E1/E3	E2/E3	E1/E2	E1/E3	E2/E3
hx/ax (e3r2d2)	0.067	0.002*	0.015*	1.00	0.159	0.062
hz/ax (e3r2d2)	0.000*	0.000*	0.000*	0.061	0.004*	0.034*
ry/ax (e3r2d2)	0.000*	0.000*	0.003*	0.810	0.475	1.00
hy/ay (e3r2d2)	0.009*	0.012*	0.025*	0.470	1.00	0.192
rx/ay (e3r2d2)	0.003*	0.002*	0.007*	1.00	1.00	1.00
rz/ay (e3r2d2)	0.005*	0.001*	0.053	0.855	0.114	0.452
hx/az 1 (e3r2d2)	0.016*	0.006*	0.013*	0.169	0.659	1.00
hz/az 1 (e3r2d2)	0.004*	0.005*	0.078	0.263	0.000*	0.002*
ry/az 1 (e3r2d2)	0.002*	0.006*	0.030*	0.002*	0.000*	0.317
hx/az 2 (e3r2d2)	1.00	0.214	0.088	0.229	0.269	0.875
hz/az 2 (e3r2d2)	1.00	0.061	0.016*	0.205	0.326	1.00
ry/az 2 (e3r2d2)	0.688	0.244	0.057	1.00	1.00	1.00

*The difference is significant at the 0.05 level.

The multi- and univariate analyses (e3r2) showed a significant influence exerted by the vibration magnitude, whereas the repetition had no influence (Table 3). For the peak frequencies no significant dependencies were found. An influence of the repetition on the maximum moduli was registered for rx/ay and on the peak frequencies of rz/ay.

To check the influence of the number of vibration axes the complete data set during the excitations with single and three axis vibration was tested (e3r2d2). In the multivariate analysis the factor vibration magnitude has significant influence on

Table 2B. Mean maximum moduli and mean peak frequencies (f (maximum moduli)) of the dominant translational transmissibilities and rotational transmissibilities [rad/m] between the seat acceleration a and the translational (h) or rotational (r) head accelerations at three levels of the factor vibration magnitude (e3), two levels of repetition (r2), and two levels of excitation axes (d2) in brackets. For the head transmissibilities relation to vertical excitations two peaks (1 and 2) were determined

Transfer function	Mean values					
	Maximum moduli			f (maximum moduli)		
1 axis excitation	E1	E2	E3	E1	E2	E3
hx/ax X (e3r2)	2.42	1.75	1.37	0.97	0.96	1.25
hz/ax X (e3r2)	1.57	1.11	0.87	2.56	2.28	2.13
ry/ax X (e3r2)	12.38	8.78	6.44	2.88	2.69	2.18
hy/ay Y (e3r2)	2.33	1.89	1.64	0.99	0.86	0.82
rx/ay Y (e3r2)	9.41	7.22	5.70	1.75	1.96	1.66
rz/ay Y (e3r2)	2.08	1.93	1.71	5.15	3.46	2.76
hx/az 1 Z (e3r2)	0.72	0.69	0.54	4.30	3.22	3.66
hz/az 1 Z (e3r2)	2.32	2.21	1.95	6.46	6.05	5.45
ry/az 1 Z (e3r2)	12.81	10.65	7.95	6.25	5.72	5.31
hx/az 2 Z (e3r2)	0.40	0.38	0.33	9.88	10.14	10.89
hz/az 2 Z (e3r2)	1.85	1.73	1.63	10.03	9.89	9.77
ry/az 2 Z (e3r2)	8.46	6.62	5.25	10.11	10.06	9.82
	Maximum moduli			f (maximum moduli)		
3 axis excitation	E1	E2	E3	E1	E2	E3
hx/ax XYZ (e3r2)	2.74	2.55	1.41	0.64	0.76	1.13
hz/ax XYZ (e3r2)	1.73	1.38	1.13	2.26	2.19	2.14
ry/ax XYZ (e3r2)	11.50	8.28	5.56	2.61	2.58	2.87
hy/ay XYZ (e3r2)	2.62	2.29	1.64	0.69	0.56	0.77
rx/ay XYZ (e3r2)	9.76	7.04	4.88	1.89	1.67	1.99
rz/ay XYZ (e3r2)	5.53	3.71	2.61	2.03	2.04	1.69
hx/az 1 XYZ (e3r2)	0.65	0.57	0.48	5.42	5.02	4.84
hz/az 1 XYZ (e3r2)	1.97	1.83	1.63	5.81	5.39	5.33
ry/az 1 XYZ (e3r2)	9.36	8.05	5.86	5.79	5.37	5.31
hx/az 2 XYZ (e3r2)	0.37	0.35	0.31	9.77	10.64	10.54
hz/az 2 XYZ (e3r2)	1.55	1.57	1.38	10.70	9.91	9.50
ry/az 2 XYZ (e3r2)	5.45	5.45	4.17	9.63	10.16	9.61
	Maximum moduli			f (maximum moduli)		
1 & 3 axis excitation	E1	E2	E3	E1	E2	E3
hx/ax (e3r2d2)	2.57	2.15	1.39	0.81	0.86	1.19
hz/ax (e3r2d2)	1.65	1.25	1.00	2.41	2.23	2.14
ry/ax (e3r2d2)	11.94	8.53	6.00	2.74	2.63	2.52
hy/ay (e3r2d2)	2.47	2.09	1.64	0.84	0.71	0.79
rx/ay (e3r2d2)	9.58	7.13	5.29	1.82	1.82	1.83
rz/ay (e3r2d2)	4.99	3.59	2.68	2.06	1.98	1.70
hx/az 1 (e3r2d2)	0.69	0.63	0.51	4.86	4.12	4.25
hz/az 1 (e3r2d2)	2.14	2.02	1.79	6.13	5.72	4.98
ry/az 1 (e3r2d2)	11.09	9.35	6.91	6.02	5.54	5.31
hx/az 2 (e3r2d2)	0.38	0.36	0.32	9.82	10.39	10.72
hz/az 2 (e3r2d2)	1.70	1.65	1.51	10.36	9.90	9.64
ry/az 2 (e3r2d2)	6.96	6.03	4.71	9.87	10.11	9.72

the parameters of the three transmissibilities, but the factor axis only on the parameters of hy/ay (Table 3).

The univariate results show a significant influence of the vibration magnitude on the maximum moduli of the three transmissibilities. The mean maximum moduli were higher during three axis vibration, but the mean differences were not significant for hy/ay (Table 2C). The mean peak frequencies were significantly lower during three axes than during the single axis excitation for hy/ay.

Z-axis

The mean curves of the moduli of the seat-to-head transfer functions show substantial moduli for hz/az, hx/az, ry/az which depend clearly on the vibration magnitude for the three

Table 2C. Column 2 and 3: Mean maximum moduli and mean peak frequencies (f (maximum moduli)) of the dominant translational transmissibilities and rotational transmissibilities [rad/m] between the seat acceleration a and the translational (h) or rotational (r) head accelerations for the two levels of the factor vibration axis (A1, A3). Column 4: Results (*p* values) of the Bonferroni post hoc test to test the significance level of differences between the mean values of maximum moduli and mean peak frequencies (f (maximum moduli)) of the dominant translational transmissibilities and rotational transmissibilities [rad/m] between the seat acceleration a and the translational (h) or rotational (r) head accelerations at two levels of excitation axes (A1, A3). For the head transmissibilities relation to vertical excitations two peaks (1 and 2) were determined

Transferfunction	Mean value		Mean value		Significance	
	Maximum moduli		f (maximum moduli)		Maximum moduli	f (maximum moduli)
	A1	A3	A1	A3	A1–A3	A1–A3
hx/ax	1.85	2.23	1.06	0.84	0.031*	0.064
hz/ax	1.18	1.41	2.32	2.20	0.001*	0.034*
ry/ax	9.20	8.45	2.58	2.69	0.125	0.287
hy/ay	1.95	2.18	0.89	0.67	0.085	0.001*
rx/ay	7.44	7.23	1.79	1.85	0.287	0.301
rz/ay	3.79	3.72	1.91	1.92	0.875	0.825
hx/az 1	0.65	0.57	3.74	5.10	0.010*	0.050*
hz/az 1	2.16	1.81	5.98	5.24	0.044*	0.006*
ry/az 1	10.47	7.76	5.76	5.49	0.036*	0.060
hx/az 2	0.37	0.34	10.30	10.32	0.075	0.957
hz/az 2	1.74	1.50	9.90	10.03	0.038*	0.700
ry/az 2	6.78	5.02	10.00	9.80	0.104	0.634

*The difference between the corresponding mean values in the same line is significant at the 0.05 level.

axis vibration in z-direction (Fig. 2A, d, e, Fig. 3A, d). All curves revealed rapid changes of the moduli in the very low frequency range which were associated with coherences lower than 0.5. An interaction between the effects of the excitations in X- and Z-axis may have contributed to the unexpected courses of hx/ax and hz/az in the frequency range, where the peaks of hx/ax and hz/ax occurred. The main resonance peak occurred in the range between about 5 and 7 Hz, a second smaller one between 10 and 12 Hz. The individual transfer functions indicate two peaks more clearly than the mean values.

The phases of hz/az (Fig. 2B, e) remain nearly constant around zero up to 4 Hz. In the ranges of the maximum moduli around 5 and 10 Hz the phases have also slight peaks, obviously with a slight dependence on the vibration magnitude.

The phases of hx/az and ry /az (Fig. 2B, d, Fig. 3B, d) have positive values in the low frequency range. The phases pass the zero line in this frequency range between 5 and 7 Hz. Above this frequency range the phases decrease up to 20 Hz.

The values of the coherence functions of hz/az (Fig. 2C, e) were in the range between 0.8 and 0.9 in the frequency range between about 6 and 20 Hz. Below 5 Hz the lowest value of the coherence was registered around 0.4. The mean coherences of hx/az (Fig. 2C, d) and ry/az (Fig. 3C, d) were lower than 0.2 for frequencies lower than 4 Hz indicating a missing reliability between the Z-axis excitation and head motion, as well as possible interaction with further excitation directions. The coherencies increase around 5 Hz and reach values between 0.5 and 0.8 up to 20 Hz. For the head motions in z-direction 2 peaks were determined:

- First peak

The mean values of peak frequencies of the first peak decreased for hz/az, hx/az and ry/az from about 6 to 5 Hz (Table 2B) with the increasing vibration magnitude just as the mean moduli of hz/az from 2.0 to 1.6, of hx/az from 0.7 to 0.5, and of ry/az from 9.4 to 5.9 [rad/m] (Table 2B). The differences of mean moduli were significant between E1 and E3 for the three transfer functions (Table 2A). The mean peak frequencies were significantly lower during E1 than during E3, but the differences between the peak frequencies were not significant (Table 2A, B).

The multi- and univariate analyses showed for the first peak a systematic dependence of the maximum moduli of hx/az, hz/az, and ry/az on the vibration magnitude and for the latter also on the peak frequency (Table 3, e3r2).

To check the influence of the number of vibration axes the complete data set during the excitation with single and three axes vibration was tested (Table 3, e3r2d2).

In the multivariate analysis concerning the first peak the factors vibration magnitude and axis had significant influence on the parameters of the seat-to-head transfer functions hz/az, hx/az, and ry/az (Table 3). The univariate results show a significant influence of the vibration magnitude and the number of axes on the maximum moduli of both transmissibilities and on the peak frequencies of hz/az. The maximum moduli and the peak frequencies of hz/az and ry/az were lower during three axis vibration whereas those of hx/az were higher. The mean values of maximum moduli were significantly different for all three transmissibilities (Table 2C), but the mean values of peak frequencies were significantly different only for the translational transmissibilities.

Table 3. Results (*p*-values) of the multi- and univariate analysis (GLM Repeated Measures) to test the effects of the factors vibration magnitude (Exp) repetition (Rep) and the number of axes (Axis) on the maximum moduli of the dominant seat-to-head transmissibilities and on their frequencies in x-, y- and z-direction during single axis (X, Y, Z) and three axis (XYZ) excitations (significance level $p<0.05$, the factor vibration magnitude was tested at 3 levels (e3), the factors repetition (r2) and axes (d2) were tested at 2 levels. For the head transmissibilities relation to vertical excitations two peaks (1 and 2) were determined

Transferfunction	Multivariate Analysis			Univariate Analysis					
				Maximum moduli			f (maximum moduli)		
1 axis excitation	Exp	Rep	Axis	Exp	Rep	Axis	Exp	Rep	Axis
hx/ax X (e3r2)	0.002*	0.518	-	0.000*	0.312	-	0.164	0.504	-
hz/ax X (e3r2)	0.000*	0.387	-	0.000*	0.297	-	0.000*	0.340	-
ry/ax X (e3r2)	0.000*	0.587	-	0.000*	0.385	-	0.004*	0.482	-
hy/ay Y (e3r2)	0.012*	0.035*	-	0.001*	0.008*	-	0.253	0.210	-
rx/ay Y (e3r2)	0.000*	0.235	-	0.000*	0.325	-	0.563	0.223	-
rz/ay Y (e3r2)	0.006*	0.212	-	0.000*	0.823	-	0.045*	0.068	-
hx/az 1 Z (e3r2)	0.005*	0.211	-	0.000*	0.159	-	0.380	0.250	-
hz/az 1 Z (e3r2)	0.002*	0.200	-	0.001*	0.066	-	0.000*	0.646	-
ry/az 1 Z (e3r2)	0.004*	0.432	-	0.001*	0.177	-	0.000*	0.397	-
hx/az 2 Z (e3r2)	0.197	0.475	-	0.134	0.758	-	0.087	0.207	-
hz/az 2 Z (e3r2)	0.209	0.676	-	0.074	0.397	-	0.812	0.823	-
ry/az 2 Z (e3r2)	0.274	0.318	-	0.087	0.127	-	0.859	0.536	-
				Maximum moduli			f (maximum moduli)		
3 axis excitation	Exp	Rep	Axis	Exp	Rep	Axis	Exp	Rep	Axis
hx/ax XYZ (e3r2)	0.009*	0.134	-	0.000*	0.158	-	0.028*	0.127	-
hz/ax XYZ (e3r2)	0.003*	0.098	-	0.000*	0.145	-	0.210	0.051	-
ry/ax XYZ (e3r2)	0.001*	0.893	-	0.000*	0.622	-	0.287	0.725	-
hy/ay XYZ (e3r2)	0.001*	0.461	-	0.000*	0.231	-	0.068	0.227	-
rx/ay XYZ (e3r2)	0.001*	0.094	-	0.000*	0.024*	-	0.435	0.838	-
rz/ay XYZ (e3r2)	0.004*	0.019	-	0.000*	0.060	-	0.098	0.100	-
hx/az 1 XYZ (e3r2)	0.018*	0.418	-	0.001*	0.778	-	0.197	0.231	-
hz/az 1 XYZ (e3r2)	0.011*	0.164	-	0.001*	0.069	-	0.290	0.926	-
ry/az 1 XYZ (e3r2)	0.001*	0.495	-	0.000*	0.803	-	0.031*	0.227	-
hx/az 2 XYZ (e3r2)	0.126	0.606	-	0.145	0.374	-	0.181	0.503	-
hz/az 2 XYZ (e3r2)	0.004*	0.356	-	0.004*	0.134	-	0.027*	0.392	-
ry/az 2 XYZ (e3r2)	0.041*	0.844	-	0.007*	0.559	-	0.597	0.553	-
				Maximum moduli			f (maximum moduli)		
1 & 3 axis excitation	Exp	Rep	Axis	Exp	Rep	Axis	Exp	Rep	Axis
hx/ax (e3r2d2)	0.001*	0.535	0.076	0.000*	0.499	0.031*	0.040*	0.284	0.064
hz/ax (e3r2d2)	0.001*	0.058	0.004*	0.000*	0.110	0.001*	0.000*	0.098	0.034*
ry/ax (e3r2d2)	0.000*	0.728	0.188	0.000*	0.603	0.125	0.196	0.532	0.287
hy/ay (e3r2d2)	0.001*	0.013	0.006*	0.000*	0.925	0.085	0.210	0.002*	0.001*
rx/ay (e3r2d2)	0.003*	0.120	0.543	0.000*	0.039*	0.287	0.996	0.456	0.301
rz/ay (e3r2d2)	0.002*	0.127	0.971	0.000*	0.617	0.875	0.045*	0.034*	0.825
hx/az 1 (e3r2d2)	0.001*	0.222	0.046*	0.000*	0.430	0.010*	0.157	0.128	0.051
hz/az 1 (e3r2d2)	0.000*	0.256	0.013*	0.000*	0.554	0.044*	0.000*	0.110	0.006*
ry/az 1 (e3r2d2)	0.001*	0.441	0.125	0.000*	0.242	0.036*	0.000*	0.402	0.060
hx/az 2 (e3r2d2)	0.081	0.334	0.089	0.037*	0.620	0.075	0.063	0.184	0.957
hz/az 2 (e3r2d2)	0.021*	0.394	0.132	0.006*	0.155	0.038*	0.090	0.393	0.700
ry/az 2 (e3r2d2)	0.162	0.270	0.103	0.042*	0.092	0.104	0.705	0.438	0.634

*The effect of the factor is significant at the 0.05 level.

- Second peak

The mean values of maximum moduli of the second peak have the same dependencies on the vibration magnitude as the first one, the mean moduli varied for hz/az between 1.6 and 1.4, for hx/az between 0.4 and 0.3 and for ry/az between 5.5 to 4.2 [rad/m] (Table 2B). The peak frequencies of hz/az and ry/az decreased from about 10 to 9 Hz with the increase of magnitudes. The peak frequencies of hx/az remain nearly constant in the same frequency range across the vibration magnitudes (Table 2B). The mean maximum moduli have significant different mean values of maximum moduli for hz/az between E1/E3 and E2/E3 (Table 2A, B). No further significant differences between the mean values of the maximum moduli and the peak frequencies were found.

The multivariate and univariate analyses showed at second peak a significant influence of the vibration magnitude on the moduli of hz/az and ry/az (Table 3, line e3r2) and the peak frequency of hz/az.

To check the influence of the number of vibration axes the complete data set at the second peak during the excitation with single and three axes vibration was tested (Table3, e3r2d2). In the multivariate analysis the factor vibration magnitude has a significant influence only on the parameters of the seat-to-head transfer functions hz/az (Table 3). The univariate results show a significant influence of the vibration magnitude on the maximum moduli of both transfer functions and of the number of axes on the maximum moduli of hz/az. The mean maximum moduli of hz/az were significantly lower during three axes vibration than during single axis vibration (Table 2C). For the transfer function ry/az the maximum moduli and peak frequencies were lower during three axes vibration than during single axis excitation (Table 2C), but the differences of mean values were not significant.

Discussion

Critique of the methodology

The results of several studies show large effects of different postures and/or seating conditions[2, 11, 21]. The chosen experimental conditions and instructions aimed at minimizing these effects. Tests with different weights of the bite bar up to 375 g lead to variations generally not greater than those of repeated measurements[9]. In the current study invisible changes of the postures by different muscle tension and/or voluntary and involuntary contractions can effect the head movements as well as different forces exerted on the hands support which were not registered in this study. However, the latter were considered to be small due to the position of the hands (cf. Fig. 1). Effects of head acceleration caused by natural movements on jaw movements[22], co-ordinated mandibular and head movements[23], and also co-activations of the sternocleidomastoid muscle and craniocervical musculature[24] were discussed in the literature and might have had some effect on the result of the bite bar measurements. However, they seem to be negligible in comparison with the activation of neck muscles to maintain posture and voluntary forces to ensure a close contact between teeth and bite bare.

Low weight material of the bite bar and the use of miniature accelerometers minimized possible additional moments acting on the head. Individual bite plates at the identical bite bar were prepared for each subject. Possible anatomical differences of the crown and different relations between width and depth of the dentitions can lead to a certain variability of distances of the accelerometers to the mass centre of the head, thus contributing to interindividual differences.

The accelerometers mounted inside the bite bar measured the translational accelerations, as expected, in the sensitive axes. But, an inclination of α degree of a horizontal orientated accelerometer in the gravitational field (g) can lead to an additional apparent increase of the translational head acceleration by the factor ($g*\sin\alpha$). A remarkable gravitational influence can be expected during high pitch or roll movements of the head at low frequencies[9]. The results (cf. Fig. 3A) show small rotational transmissibilities at the low frequencies and high frequencies of the frequency range tested. The gravitational influence on the data of this study can be considered as low.

The location of the translational accelerometers influence the measured amplitudes of head movements, because the head movements can be considered as a combination of translational and rotational movements related to the centre of gravity. The anatomical location is not consistently defined. The ISO 8727[25] defined the origin of the anatomical coordinate system of the head as midpoint of a line connecting the superior margins of the right and left external auditory meatus of the skull (cf. Fig. A.5 a) in[25]). Experimental anatomical invitro studies report, that the centre of gravity is located almost exactly in the mid-sagittal plane (± 0.3 cm), 2.2 to 4.3 cm above the Frankfurt plane, and 0.2 to 1.3 cm in front of an axis connecting the external auditory meati[26]. The inertial ellipsoid is degenerated to a rotational ellipsoid with the axis pointing to the forehead under an angle of 45 to 69 degree to the Frankfurt plane[27]. The results of the anatomical study support the findings of Paddan and Griffin[2] concerning the variation of the measured acceleration in dependence on the location. The own measurements were performed at three locations: two points symmetrical to the mid-sagittal plane near a vertical plane through the first molars, the third point at the right was located nearby the ear. Due to these dependencies of the results on the location of measurements, greater differences in transmissibilities can be expected in comparison with data which were acquired with transducers at other anatomical points. The maximum magnitudes can differ by a factor 3 for vertical and by a factor 5 for fore-and-aft direction (Fig. 7 in[2]).

Comparison with seat-to-head transmissibility curves of other authors during single axis excitations

To compare the own results with those of other authors summarized in review studies[1–3], the medians together with the 25th and 75th quartiles of the moduli were calculated for the seat-to-head transmissibilities (Fig. 4).

Paddan and Griffin[2] listed 13 variable experimental conditions and different locations of measurements in the studies summarized. Due to these reason care is required when comparing the own data with the results of the review data.

The data of the transmissibilities during exposure in X-axis were clearly higher in the review data than in the own results (Fig. 4, a). A high percentage of studies tested postures with backrest contact. The peak around 8 Hz characterised the use of the backrest[8]. The relative high values during the exposures in Y-axis were caused by one study in which a racing car type seat was used (Fig. 4, b). The seat provided lateral support at the shoulders together with a 4-point harness including shoulder straps. Except this special result the median curves of the own results agree approximately with the results of these studies for the exposure to horizontal vibration in spite of different postures, vibration magnitudes and measurement methods. During the exposures in Z-axis the transmissibilities of the own study were higher than those of the reviews (Fig. 4, c). The frequency at which the maxima moduli occur vary relatively strongly with the magnitude of

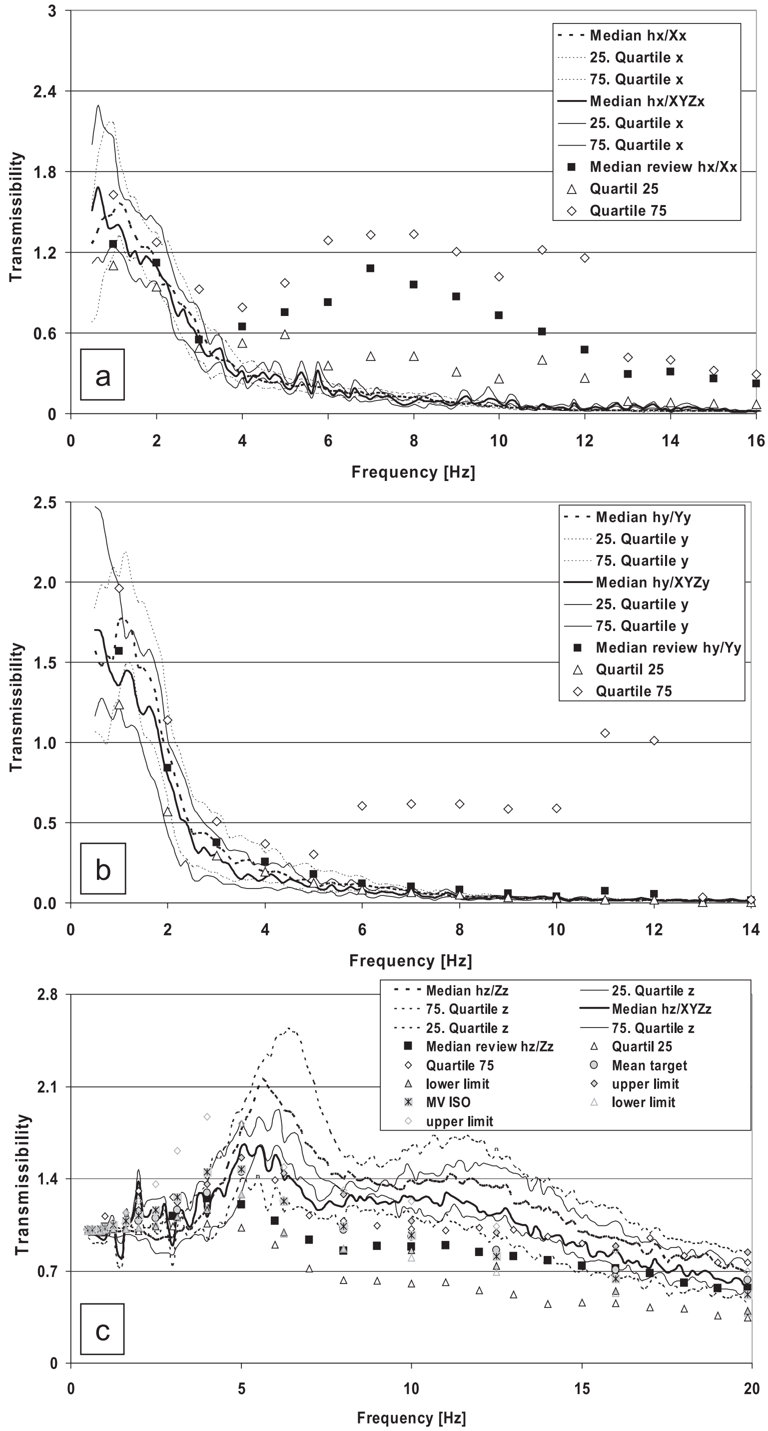


Fig. 4. Comparisons of the medians of the 25th and 75th quartile of the seat-to-head transmissibility of this study (Median hz Zz, single axis excitation) with results of the review study of Paddan and Griffin[2] (Median review hz /Zz), and the mean target values of ISO 5982[3].

the seat vibration, postures, seating conditions of the tested subjects, and the location of the measurement at the head. Further the number of studies with exposure in z-direction which were included in the review was 3 times higher than those during the horizontal excitations. Some authors[12, 28] noticed a loss of information when summarizing transfer functions. This loss of information is described as 'smeared out' by averaging when calculating a mean or median response, because not all modes are at the same frequencies in all subjects. Due to this reason the peaks of the review results

(Fig. 4, c) were probably lower than the results of this study, e.g. around 5 Hz, or disappear nearly completely, e.g. around 10 Hz. Under the consideration of this effect a certain agreement of the results can be stated.

Only Paddan and Griffin[8, 9] published results of the seat-to-head transmissibility during single-axis excitation in X-, Y-, and Z-axis with a description of the measuring results of the head movements in 6 axes for each excitation. The data were also measured with a bite bar, but some differences to the present study were obvious: seat was inclined backwards at an angle of 3 degree, the posture was comfortable upright for the condition without backrest contact, the hand posture and feet support were not specified by the authors. Further one magnitude of 1.75 ms^{-2} rms was used, which was slightly smaller than E3 in the study presented. Generally the authors found identical dominant axes of the head movements in agreement with the own results during the single axis excitation. In both studies[8, 9] the frequencies at which the maximum magnitudes occurred were during the single-axis excitation in X-, and Y-axis nearly in the range between 1 and 2 Hz. The exceptional 2.76 Hz for rz/ay in this study was possibly caused by the complex of the stronger upright posture and hand support. Two peaks were found during the exposure in Z-axis around 5 and 11 Hz, i.e. similar to this study. The peaks of rotational head movements were slightly lower than in the study presented, possibly caused by the different seat inclinations and postures. The phase between seat motion and head motion was illustrated by results of one subject in the dominant axes during exposure in Z-axis[9]. This individual phase coincides with the mean curves in this study for the head movement in x- and z-direction (Fig. 2B, d, e). The individual phase in pitch axis increases from zero degree in the study of Paddan and Griffin[9], whereas the phases in the present study follow the scatter of the phases in x-direction, i.e. they were positive up to 5 Hz and have the zero-crossing around 5 Hz. Different seating and posture conditions may have been responsible for these differences.

Overall, all data obtained in this study using single-axis vibration are in general agreement with the literature, thereby validating the multi-axis system used in this study.

Relations between the vibration behaviour of the trunk and head

Anatomical coupling of the head

The head is the body part with the smallest mass and the highest distance to the seat interface where the path of vibration through the body starts.

The reaction of the head to whole body vibration is probably influenced to a higher extent than other body parts by its anatomical connection. The neck and shoulder region consists of several complex muscle arrangements and multi-segmental cervical joints that move and stabilize the head and neck[27]. Grip[27] mentioned also that neuronal pathways run through the neck and are involved in daily functions. For example, cervical nerve afferents project to the superior colliculus, which is a reflex centre for coordination between head and neck movement and is also involved in reflex responses for gaze stability when moving the head, i.e. a very important function during vibration exposure.

The static and dynamic control of the head and neck is managed by a complex arrangement of about 20 muscles that enclose the cervical spine (Fig. 2.4 and Table 2.3 in[27]). Due the importance of an intact functionality of the head and its movements, the human body tries to protect these functions during the natural movements[29]. Also in cases of effects of whole-body vibration the muscle complex seems to stabilize the head. Tests with high shock vibration have shown that head/neck movements in x- and z-direction can be reduced by headrests. But a fixation of the whole torso including shoulders during exposures with a dominant Y-axis can cause increased risks of neck injuries during heavy head movements in y-direction. In contrast a free upper torso and a hip support can reduce these head movements, because the lumbar spine absorbs the impact by bending[30, 31]. The results of the transmissibilities in the current study show, that the fore-and-aft head motions were reduced during single and three axes excitation, the pitch motion additionally only during the three axis excitation. The decreasing maximum moduli at higher peak frequencies may be understood as a stiffening effect of the numerous cervical muscles. An increase of the number of axes seems to cause a certain reduction of the moduli in the pitch, roll and yaw head motion as well as of the moduli of the fore-and-aft motion (hx/az) together with an increase of the peak frequency (Table 2C). These changes might reflect also an increase in stiffness due to muscle reactions to avoid unpleasant head motions.

Relation between the dependencies of the apparent mass and the seat-to-head transmissbilities on the vibration magnitude and the number of axes

A comparison between the *peak frequencies* and the *peak magnitudes* of the apparent masses[28] and those of the seat-to-head transmissibilities could help to identify the relations between trunk and head motion and to understand the influence of the vibration magnitude and the number of axes.

A consistent finding for the apparent mass in z-direction was the decrease of peak frequencies with higher *vibration magnitudes* which was often interpreted as a nonlinear softening effect and/or involuntary changes in muscle tension[32, 33]. This effect was also registered in the horizontal directions[28].

The ranges of mean peak frequencies of both transmission measures – the seat-to-head transmissibility and the apparent mass - will be discussed in ascending order. Mean peaks of the horizontal translational head transmissibilities (hx/ax, hy/ay) occurred between 0.6 to 1.1 Hz during fore-and-aft seat accelerations (cf. Table 2B). In the same range the first peaks of the apparent masses in horizontal directions were registered, mainly in the individual curves. These peaks between 0.6 to 1.1 Hz remain nearly unchanged with the increase of magnitudes for the apparent masses[34] as the peak frequencies of the head transmissibilities.

The rotational head transmissibilities excited by lateral seat accelerations (rx/ay and rz/ay) have mean peaks in the range between 1.7 and 2.0 Hz, in which also the main peaks of the apparent masses in y-direction were found. During the single Y-axis excitation, especially during low magnitudes, a second peak of rz/ay in the range between 5.1 and 2.8 Hz had higher values than the peak mentioned before. The second peak was smaller with the increase of magnitude and axes, and disappeared during the conditions XYZ E2/E3. Also for the apparent mass a similar aspect was registered. With the highest magnitude the two peaks seem to merge to form a plateau[28]. These phenomena may have been caused by the pelvic motions and the counter motions of the head. Mean peaks of two further head transmissibilities (hz/ax and ry/ax) excited by seat accelerations in x-direction were found in the range between 2.1 and 2.9 Hz which coincided with the frequency range of the main peak of the apparent mass in x-direction. During vertical excitation mean peaks of the three head transmissibilities (hx/az, hz/az, ry/az) were observed in the frequency range between 4 and 6 Hz just as the main peak of the apparent masses. A strong nonlinear behavior of both transmission measures was observed during vertical excitations.

If the *number of axes* increases from one to three, the maximum moduli of the apparent masses decrease slightly in z-direction, but remain nearly unchanged in the y-direction, and increase in the x-direction, whereas the peak frequencies decrease. The maximum moduli and the peak frequencies of the translational transmissibilities show a similar dependence on the number of axes. The findings demonstrate the relations between head- and whole body motions. The head motions seem to be coupled to the trunk motions especially during vertical excitations. Because the apparent mass is defined as a resulting force at the seat interface, motions of body parts can only be supposed as possible cause, but not quantified.

Relations between the dependencies of transmissibilities to different body parts and the seat-to-head transmissibilities on the vibration magnitude and the number of axes

Transmissibilities between the excitation and several body parts were investigated to clarify possible interactions of body parts as one reason for a nonlinearity of the head. Seat-to-pelvis pitch transmissibilities reach maximum values at about 10–15 Hz in an upright posture during single Z-axis excitation[13]. In the vertical seat-to-head transmissibilities hz/az of the present study the second peak occurs around 10 Hz (cf. Fig. 2Ae). The significant decrease of this maximum modulus with the increasing magnitudes from E1 to E3 during three-axis vibration (cf. Table 2A, B) and with the increase of the number of axes (cf. Table 2C) indicate a nonlinear behaviour in this frequency range for the head, too.

During random vertical vibration in the frequency range from 0.2–20 Hz at 5 magnitudes between 0.125 and 2.0 ms^{-2} the movements of the upper body and the head were quantified by transmissibilities[14]. The results indicate that the upper thoracic spine, (T1 to T10) tended to rock about a point on the lower thoracic spine in the sagittal plane with some slight bending. The registered vibration modes of body parts and their relative movements and couplings were supposed to contribute to the principal resonance and the reason for the heavy damping of the human body. A mode at 5.6 Hz was found to consist of a bending mode of the lumbar spine, lower thoracic spine and a pitching mode of the head[14]. In the present study the peaks of the seat-to-head transmissibility in pitch axis were also registered in the range between about 5 to 6 Hz during vibration in Z-axis. The motions of the trunk and within the trunk can be supposed as one reason for the nonlinearity of the head transmission during vertical excitation. The majority of the seat-to-head transmissibilities in the current study show lower peak moduli at lower peak frequencies with increasing vibration magnitudes (Table 2B), and this nonlinearity is likely to be a consequence of the nonlinearity of the trunk.

Based on the observed degree of nonlinearity in the relative transmissibility between T1 and the head as well as relative to L5, Matsumoto and Griffin[14] supposed that a softening characteristic in the soft tissue of the body contributes to the decrease of the resonance frequency with increases in the vibration magnitudes.

Simultaneous measurements within this study show, that the horizontal transmission in the excitation axis from the seat to the sacrum (S1x/ax, X and XYZ excitation) exhibited also a substantial nonlinearity during X-axis excitation due to a decrease of the maximum modulus located about between 2.0 and 2.5 Hz and its frequency with increasing magnitude[35]. In y-direction, a distinct nonlinearity was found between 2.5 and 5 Hz as a decrease the peak modulus of the transmissibility (S1y/ay) in this frequency range with rising magnitude, whereas the maximum peak around 1.4 Hz exhibited minor changes in dependence on the magnitude during single and three axis excitation. In z-direction a shift of the transmissibilities (S1z/az) towards the lower frequencies together with a slight increase (single-axis excitation Z) or constant values (three-axis excitation XYZ) of the maximum modulus during single axis excitation was obvious with the higher vibration magnitudes, and the maximum modulus was smaller with additional simultaneous horizontal excitation. These findings are partially opposite to those observed at the head. They illustrate the significance of the buttocks tissue and pelvic motion for understanding the nonlinear transmission to the head. The latter can be considered as result of the mechanical behaviour of structures below the head. This assumption is backed up by three exemplary findings of this experimental study, but not reported in detail - (1) clear signs of nonlinearity with the vibration transmission from the sacrum to the head in all three axes examined; (2) opposite differences of the vibration transmission between seat and sacrum depending on the number of axes, i.e. smaller maximum moduli in z-direction with three-axes vibration, and between sacrum and head, i.e. larger maximum moduli in z-direction with three-axes vibration; (3) clear signs of roll motion of the pelvis during excitations in Y-axis at the seat.

The present results indicate that the reduction of the transmissibility and softening of the system are non-linear phenomena which are not associated with each other. Therefore, different mechanisms may be assumed behind them. The reduction of the transmissibilities with rising magnitudes was a more generalised phenomenon (cf. Table 2B). Except from the second peak of hz/az observed between 9 and 11 Hz, all moduli decreased more or less pronounced. The authors assume an increasing voluntary effort to stabilise the head as the dominating mechanism behind this result probably associated with motions of body parts. The significant reduction of the peak frequencies was restricted to several transmissibilities (hz/az, ry/az, hz/ax, ry/ax) single axis input (Table 2A). All of them are associated with length-changes of structures that occur in line with gravity. Similar effects with three-axis vibration have been hidden by the additional influence of the increasing number of axes. Gravity causes a significant preload on parts relevant for vibration transmission like buttocks and vertebral discs. Numerous experiments have shown clear non-linear mechanical properties of biomaterials[36]. Rützel[37] reported nonlinear dynamic behaviour of buttocks tissue. Hofmann *et al*.[38] reviewed the mechanical characteristic of the skin and subcutaneous tissue also characterized by non-linear properties. Huber *et al*.[39] reported force-displacement curves for lumbar vertebral segments that exhibited clear hysteresis under compression. The linearization of such curves suggests a decreasing stiffness with increasing load amplitude, if the compression and decompression alternate around a compressive offset-load like that one caused by gravity (Fig.4.8, p.95 in[39]). Correspondingly, they found a softening of lumbar segments with increasing dynamic load amplitude and constant offset load in z-direction. Such mechanisms seem to be suited to explain the different results concerning a "softening" with rising magnitude in this study. They were predominantly observed with transmissibilities that are characterized by an involvement of anatomic structures with coinciding directions of the preload by gravity and dynamic load due to vibration.

It can be summarized, that the motion pattern of the head remains nearly unchanged with the number of vibration axes, i.e. transmissibilities were determined in the same dominant axes during single and three axis excitation. Non-linear characteristics of head transmissibilities were observed in dependence on vibration magnitude and number of vibration axis.

The reduction of moduli with rising *magnitudes* seems to be a more generalized phenomenon. Body motion associated with voluntary and involuntary muscle activities can be assumed to stabilize the posture of the trunk and the head. The reduction of peak frequencies was predominantly obtained when transmissibilities were characterized by an involvement of anatomic structures with coinciding directions of preload by gravity and dynamic load due to vibration, which might reflect a softening characteristic in the soft tissue.

Both reasons seem to be also responsible for lower moduli and peak frequencies of several transmissibilities during three-*axis* excitation (e.g. hz/az, ry/az). Rising moduli and lower peak frequencies are probably caused by a larger proportion of soft tissue in the body with three-axis vibration (e.g. hx/ax, hy/ay). Reduced transmission and higher peak frequencies might reflect a slight stiffening of cervical and neck muscles to avoid unpleasant head motions (e.g. ry/ax, rx/ay, rz/ay).

Consequences for health effects and modelling

Several epidemiological studies show that professional drivers of various heavy machines have increased risks for musculoskeletal symptoms and disorders in the lower back. Various terrain vehicles generate exposure conditions characterized by high levels of vibrations in several directions containing high peak values[40]. Some of these acceleration peaks could be unpredictable for the driver due to special terrain conditions, e.g. for drivers of forestry machines. A stabilization of the trunk and especially the head is required. These activities during a whole working day can cause additional muscular stress in the shoulder system. Rehn[41] found for all terrain drivers an increased risk of musculoskeletal symptoms in the neck, shoulder and thoracic region, clinically diagnosed as asymmetrical and focal neuropathies. The motion pattern during three axis exposures and the supposed mechanism to avoid heavy head motions were supposed to cause the diagnostic findings[41]. Further results are needed to support our findings also for further postures and in order to quantify the possible exposure-effect relationships.

The qualitatively new results could open the possibility to modify the common target values in ISO 5982[3] for modelling. Modulus and phase of mean (target) values and range of idealized seat-to-head accelerations are given in this ISO for the seated human body under vertical vibration (sine or broad-band random) in the range between 0.5 and 50 Hz and vibration magnitudes between 1 and 5 ms^{-2}. To the authors' knowledge models of the head-neck complex exist for separate excitation axes[42, 43]. The results of the present study suggest an extension of this International Standard to the horizontal direction under the consideration of excitation with more than one axis. But more data during tests under consideration of other postures are needed, possibly with a direct relation to usual postures of occupational drivers of heavy and all terrain machines including the use of the backrest.

The limited data basis in the current Standards may even lead to a wrong assumption on the linearity/non-linearity and of the frequency range of the maximum seat-to-head transmissibilities. Based on the experimental results and results of epidemiological studies, more attention should be drawn to the exposure-effect relationship between horizontal shock-containing vibration and health problems in head-neck-shoulder complex.

Conclusion

The results of the experimental study yield a first database to describe complex head motions for the consideration in model development and normative regulations, taking into account the vibration magnitude, the vibration direction, and the number of vibration axes acting simultaneously. They are limited to exposure conditions and the range of the subjects' anthropometric data. Further studies are needed to confirm the results and to investigate the influence of further factors as posture, backrest contact and soft seat conditions.

Acknowledgements

The authors wish to thank Jana Thiel and Lutz Gericke for their support.

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