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EFFECTS RELATED TO RANDOM WHOLE-BODY VIBRATION AND POSTURE ON A SUSPENDED SEAT WITH AND WITHOUT BACKREST

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WBV-exposures are often linked with forced postures as prolonged sitting, bent forward sitting, or sitting without a backrest. No quantitative data are available to describe the exposure–effect relationships for different conditions of seating, posture, and the biological variability of workers. Experiments and subsequent predictions of forces acting within the spine during WBV can help to improve the assessment of the health risk. An experimental study was performed with 39 male subjects sitting on a suspension seat with or with no backrest contact. They were exposed to random whole-body vibration with a weighted r.m.s. value of $0{\cdot}6\,\mathrm{m/s^2}$ at a relaxed or a forward bending posture. A two-dimensional finite element model was used for the calculation of the internal spinal load. The model simulates the human response on a suspension driver seat. Individual exposure conditions were considered by including the transfer functions between the seat cushion and the seat base as well as between the backrest and the seat base for the calculation of the vibration input to the buttocks and to the back respectively. The average peak seat transmissibility was higher for the seat with the backrest, but the peak seat-to-head transmissibility was higher for the seat without the backrest for both postures. The peak transmissibilities between the accelerations at the seat base and the compressive forces at L5/S1 were highest for the seat without the backrest during the bending posture. Various biological effects can result from identical exposures combined with different backrest contact and postures. The backrest contact and posture conditions should not be neglected in the assessment of health risk caused by whole-body vibration.

1. INTRODUCTION

The human biodynamics with exposure to whole-body vibration has been examined since the 1950s. The results of the transmissibility from the seat to the head were implemented in 1987 in the standard ISO 7962 [1]. During the revision of this standard, the published results of 56 papers were summarized in review papers [2, 3] and critically compared with the results of our laboratory [4]. The majority of results of the 46 papers cited in the review by Paddan and Griffin [2] were obtained with rigid or semi-rigid seats. Only three studies used ejection seats, and one study was done with a racing car seat. The backrest was used in 15 studies, and five of those were performed with a soft backrest or cushion. The authors are not aware of any examination of the seat-to-head transmissibility in the z-axis that realized a comparative analysis of rigid and suspension seats with the same group of subjects. The published data were used for the calculation of a "grand average" [2] or "range of idealized values" [3]. Our own data on the transfer functions from seat to head obtained with a hard seat [4] were within the ranges of the median derived by Paddan and Griffin [2] for the relaxed posture. The maximum median amounted to 1·25 at 4 Hz (25% 1·06, 75% 1·42, lower range 0·48, upper range 2·78). In ISO/DIS 5982 [5], the maximum of the mean idealized seat-to-head transmissibility of the seated body under vertical vibration is at 5 Hz and equals 1·47 (range 1·28–1·82; *SD* 0·22). The range of these values is defined only for certain conditions—"for seated subjects on a rigid platform, with feet supported and vibrated and maintaining an erect posture without backrest support" [5]. It could be shown that the specified ranges do not well reflect the between-subject variability [4]. The "argument that several conditions associated with feet and back support, posture, excitation amplitude and subject mass could have a significant influence on measured biodynamic response" [5] led to the conclusion "that the definition of a range of idealized values would only be feasible if it were based on data sets known to have been determined under well-defined and restricted range of similar conditions" [5]. Field conditions such as, for example, on earth-moving machines, are significantly different from the conditions specified in ISO/DIS 5982 [5]. Workers are often exposed on suspended seats with an elastic seat surface, and they use their backrest depending on the task, sitting posture and design of the machine. The possible modifying effects of these conditions on biodynamics are, therefore, important, but have not been examined yet.

Another question is the estimation of the internal load acting on the lumbar spine under real working conditions. Direct measurements of the intraspinal forces are impossible for ethical reasons. A prediction of forces is feasible using appropriate models [6, 7]. These models simulate human biodynamics observed on a hard seat without a backrest and were successfully applied for a variety of conditions [8–10]. An advanced model was recently presented [11, 12] that considered the different input conditions at the feet, trunk and buttocks as well as an optional vibration input of the backrest.

The objectives of this study were to examine the effects of the use of a backrest with different postures on the seat-to-head transmissibility and to predict the forces acting on the lumbar disc L5/S1. Both aims should be realized under simulated working conditions with a suspended seat. A sufficiently large group of subjects was considered as a prerequisite for an adequate reflection of the between-subject variability.

2. METHODS

An experimental study was performed with 39 male subjects with body masses between 49 and 103 kg, and body heights between 163·3 and 191·0 cm. They sat with or with no backrest contact (factor backrest contact) on a suspension seat with supported feet. They were exposed for 65 s to random whole-body vibration with r.m.s. values measured at the seat base according to Table 1. The frequency content of the input to the seat base was located predominantly between 1 and 12 Hz (see Figure 1), i.e., it resembled the vibration of a crawler. The exposure was applied by means of a displacement controlled, electro-hydraulic vibrator ("Hydropuls" with a maximum stroke 400 mm, maximum force 10 kN) modified for human experiments according to ISO 13090-1 [13]. The vibration-isolating mechanical system of the passive suspension seat was housed in a flexible covering. The seats were adjusted for the individual body mass in the range from 48 to 131 kg according to the operating instructions.

Two sitting postures (factor posture) were examined—relaxed posture: steering wheel held with both hands, upper torso relaxed, loose, upright and subjectively comfortable

TABLE 1

Mean values and standard deviations for the root mean square values of the unweighted vertical input acceleration in the z-axis during the tested conditions

	wib bp		wib rp		nob bp		nob rp	
	MV	*SD*	*MV*	*SD*	*MV*	*SD*	*MV*	*SD*
r.m.s. *az* seat base	2·20	0·052	2·19	0·047	2·25†	0·084	2·25†	0·089

Note: wib—with backrest contact; nob—no backrest contact; bp—forward bending posture; rp—relaxed posture.
†$p < 0{\cdot}05$.

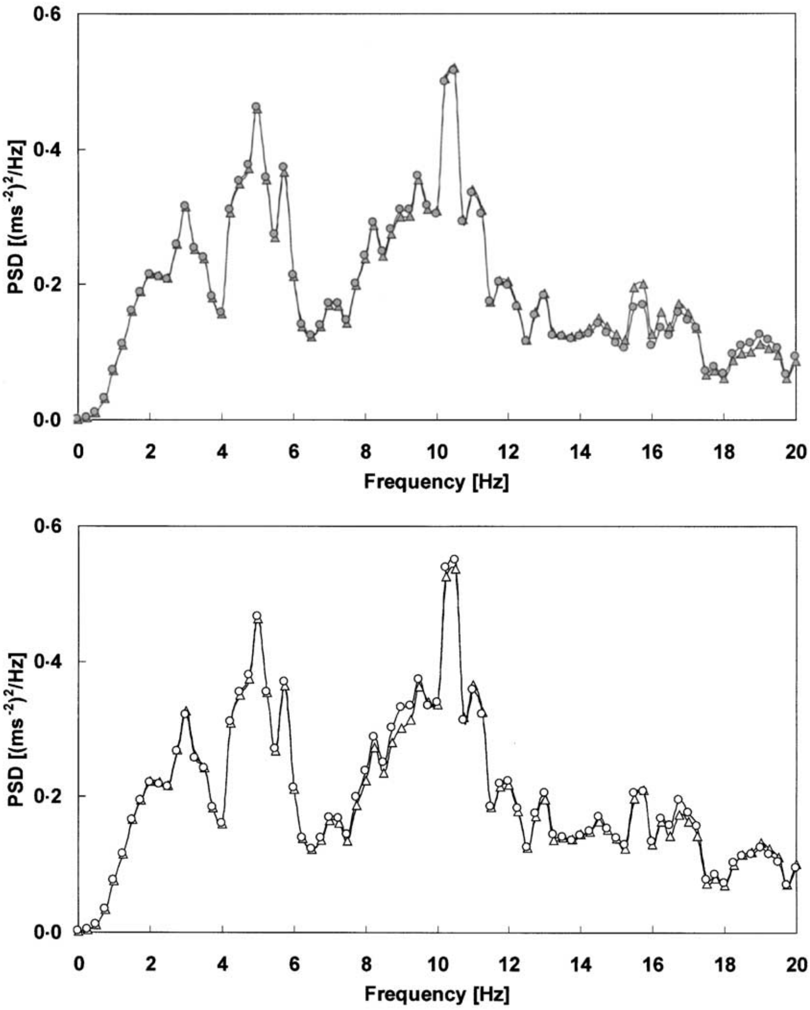

Figure 1. The medians ($N = 39$) of the power spectral densities (PSD) of the accelerations in the z direction measured at the seat base for seating with backrest contact during the forward bending (▲) and relaxed posture (●) (top) and for no backrest contact during the forward bending (△) and relaxed posture (○) (bottom).

posture; forward bending posture—upper torso bent forward, appropriate spherical control elements, side mounted below the plane of the seat, grasped with the hands. For the condition with backrest contact the subjects were instructed to preserve the backrest contact. That was effective as a pelvic support with bending posture.

The accelerations were measured at the seat base in the z direction (Type BWH 101, Metra), at the interfaces between the subject and the seat cushion as well as the backrest cushion for the condition with backrest contact in the z and in the x directions (tri-axial accelerometer 4322 mounted in a semi-rigid disc, B&K) and at the head (Type EGAX T3-M-10z, ENTRAN). The EGAX accelerometer was fastened to a high-grade steel bar, held via an individually produced bite plate with the subject's teeth. During the exposure the EGAX accelerometer was located near a vertical plane through the first molars. Rotation of the head was not measured. The transducers were connected to the measurement recording system SCADAS II (DIFA).

The seat effective amplitude transmissibility (SEAT) [14] was calculated as the ratio of the frequency-weighted and time–averaged vibration measured on the interface between the subject and the seat cushion in the z direction to the vibration in the same axis on the seat base conditioned by the same frequency weightings and time averaging. The seat transfer functions were calculated by dividing the cross-spectral density function between the input I (e.g., acceleration measured at the seat base) and the output O (e.g., the acceleration measured at the interface between the subject and the seat cushion) by the power spectral density of the input (e.g., acceleration measured at the seat base) with a MatLab routine (resolution of 0·25 Hz):

$$T(f) = \frac{S_{IO}(f)}{S_I(f)} \begin{array}{l} \rightarrow \text{cross-spectral density function,} \\ \rightarrow \text{power spectral density function.} \end{array} \tag{1}$$

The transfer functions were calculated between the accelerations in the z direction at the seat cushion and the seat base, at the backrest cushion in the z and the x directions and the seat base, the accelerations in the z direction at the head and seat cushion. The maxima of the moduli and the frequencies of their occurrence were ascertained. The associated coherence function was calculated as the ratio of the square of the absolute value of the cross-spectral density to the product of the spectral density functions of the input and output.

A two-dimensional finite element model with a detailed modelling of the spine between the first lumbar vertebra (L1) and the first spinous process in the Crista sacralis intermedia of the Os sacrum (S1) was used for the calculation of the internal spinal load [11, 12]. The model simulates the human response on a suspension driver seat and considers the different inputs at the feet and pelvis in the z direction as well as at the back in the z and the x directions. The accelerations in the x direction measured at the seat cushion were not considered in the model. These accelerations were in the same order as those in the z direction (see Table 2), but the share in the frequency range below 10 Hz was very low, as demonstrated by the difference between the unweighted r.m.s. value and the frequency-weighted r.m.s. value [15] of the acceleration in the x direction (see Table 2). The model and the subjects' interaction with the seat had been verified [11, 12] using data from experimental studies [16, 17]. Special modifications of the model were applied that enabled the modelling of the two posture's bending and relaxed posture, and the possibility of using the use of the backrest for each posture. The variability of the subjects was considered by adjusting the model to the individual body mass and body height. The consideration of the individual interaction of a subject with the seat was possible by using the modulus and phase of three transfer functions as input to the model—(1) from the acceleration at the seat

TABLE 2

Mean values and standard deviations ($N = 39$) *of r.m.s. values and frequency weighted r.m.s. values* (*ISO* 2631, 1997) *of accelerations measured at the seat and back cushion in the x and the z direction, at the head in the z direction, and the SEAT value for the conditions examined*

	wib bp		wib rp		nob bp		nob rp	
	MV	*SD*	*MV*	*SD*	*MV*	*SD*	*MV*	*SD*
r.m.s. *az* seat cushion	0·95	0·09	0·91	0·09	0·94	0·06	0·91	0·07
r.m.s. *ax* seat cushion	0·94	0·10	0·74	0·08	0·98	0·07	0·96†	0·07
r.m.s. *az* back cushion	1·24	0·16	1·13	0·10	—	—	—	—
r.m.s. *ax* back cushion	0·53	0·26	0·52	0·17	—	—	—	—
r.m.s. *awz* seat cushion	0·65	0·07	0·60	0·06	0·67	0·06	0·62†	0·05
r.m.s. *awx* seat cushion	0·15	0·03	0·14	0·04	0·16	0·03	0·15†	0·03
r.m.s. *awz* back cushion	0·74	0·08	0·69	0·06	—	—	—	—
r.m.s. *awx* back cushion	0·37	0·18	0·40	0·14	—	—	—	—
r.m.s. *az* head	1·12†	0·15	1·00†	0·12	1·02	0·13	0·95	0·13
SEAT value	0·35	0·04	0·33	0·31	0·35	0·03	0·32	0·03

Note: wib—with backrest contact; nob—no backrest contact; bp—forward bending posture; rp—relaxed posture.
†$p < 0{\cdot}05$.

base in the z direction to the acceleration at the seat cushion in the same direction, (2) to the acceleration at the backrest cushion in the z direction and (3) to the acceleration at the backrest cushion in the x direction. The transfer functions from the acceleration of the seat base to the resulting compressive or shear forces (output of the model) were calculated and used, together with the inverse Fourier transform, for the prediction of forces in the time domain. For the presentation of results the spinal forces acting on the disc L5/S1 were chosen. The maxima of the moduli and the frequency of their occurrence in the transfer function were determined in the ranges from 1 to 3 Hz and 3·25 to 7 Hz. The extreme peak values of the time series of the compressive and shear forces were determined.

An analysis of variance (SPSS PC) was used to test the effects of the factors backrest contact and posture. T-tests for paired samples (SPSS PC) were performed for the parameters maximum modulus and its frequency within one posture. The significance ($p < 0{\cdot}05$) of the differences between mean values with and no backrest contact is marked by † at the higher value in the tables. The effects of the factors posture and backrest contact were determined by variance analysis (SPSS PC) for all tested conditions.

3. RESULTS

3.1. ACCELERATIONS

Table 2 shows the effect of posture and backrest contact on the mean values and standard deviations of the root mean square (r.m.s.) values. The factors backrest contact and posture had no significant influence on the unweighted r.m.s. values of the accelerations at the seat cushion in the z direction.

The factor posture had a significant effect on the frequency-weighted r.m.s. values [15] of the accelerations at the seat cushion with the higher values during the bending forward posture. With the relaxed posture, the r.m.s. values for no backrest contact were significantly higher than for with backrest contact.

Both factors, backrest contact and posture, had a significant influence on the unweighted r.m.s. values of the accelerations at the seat cushion in the x direction. Additionally, for with backrest contact the values in the bending posture were significantly higher than for the relaxed posture. The factors backrest contact and posture had a significant influence on the frequency-weighted r.m.s. values [15] of the accelerations at the seat cushion in the x direction. The values for no backrest contact were higher than for with backrest contact in each posture, significantly only with the relaxed posture.

In the z direction the mean values of the unweighted and frequency-weighted [15] r.m.s. values of the accelerations at the backrest cushion were significantly higher for the bending than for the relaxed posture (see Table 2).

In the z direction the factors backrest and posture had a significant influence on the unweighted r.m.s. values of the accelerations at the head. These accelerations were higher during the bending than during the relaxed posture for with and no backrest contact (see Table 2). With both postures, accelerations during with backrest contact were significantly higher than during no backrest contact.

During the bending posture the SEAT values were significantly higher than during the relaxed posture. The backrest had no effect on the SEAT values.

3.2. TRANSFER FUNCTIONS BETWEEN ACCELERATIONS

The maxima of the moduli of the transfer functions from the accelerations at the seat base to accelerations at the seat cushion were located in the range from 1 to 2 Hz, the range for the typical resonance frequency of the suspension seats. In the range of maximum values, the absolute values of the seat transmission for with backrest contact were higher than for no backrest contact with both postures (Figure 2). For each backrest condition the median

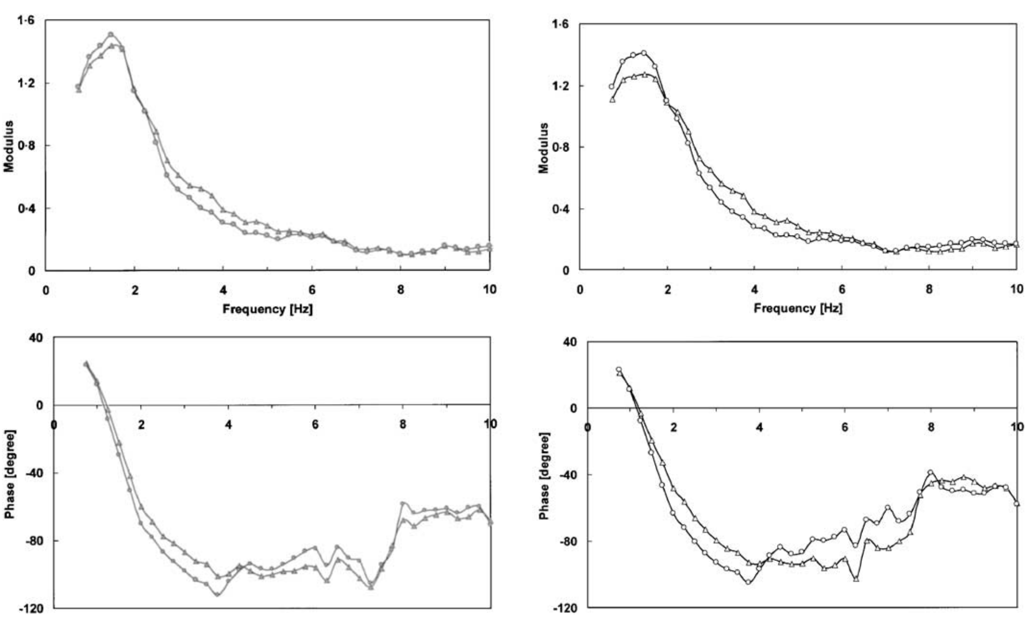

Figure 2. The medians ($N = 39$) of moduli (top) and phases (bottom) of the transfer function between the accelerations in the z direction at the seat base and at the seat cushion for seating with backrest contact during the forward bending (▲) and relaxed posture (●) (left) and for no backrest contact during the forward bending (△) and relaxed posture (○) (right).

TABLE 3

Maxima of the moduli of transfer functions between az at the seat base and accelerations at the seat cushion (TFSI), between az at the seat cushion and accelerations at the head (TFH), and their frequency (f(Hz)) of occurrence (N = 39)

	wib bp		wib rp		nob bp		nob rp	
	MV	*SD*	*MV*	*SD*	*MV*	*SD*	*MV*	*SD*
Seat base to cushion								
max. modul *TFSI*	1·50†	0·16	1·55†	0·19	1·32	0·15	1·46	0·16
f(max. modul *TFSI*)	1·48	0·27	1·44†	0·26	1·42	0·29	1·34	0·27
Seat cushion to head								
max. modul *TFH*	1·59	0·18	1·57	0·23	1·57	0·23	1·67	0·26
f(max. modul *TFH*)	2·89	1·19	4·10	1·32	3·59†	1·43	4·17	1·27

Note: wib—with backrest contact; nob—no backrest contact; bp—forward bending posture; rp—relaxed posture.
†$p < 0{\cdot}05$.

of the moduli for the relaxed posture had higher values than that for the forward bending posture (Figure 2).

The factors backrest and posture had a significant effect on the maxima of the moduli of the transfer functions from the accelerations at the seat base to accelerations at the seat cushion and the frequencies of their occurrence. The effect of the backrest contact was more pronounced with the relaxed posture (Table 3).

Figure 3 shows the medians of the moduli (top) and phases (bottom) of the transfer function between the accelerations in the z direction measured at the seat cushion and at the head for with (left) and no backrest contact (right). The medians of the moduli during the relaxed posture for with backrest contact appeared to shift towards higher frequencies (Figure 3 top left), and the absolute values of the phase values remain smaller for the relaxed posture over the whole frequency range tested (Figure 3 bottom left). For no backrest contact the median of the moduli during the relaxed posture reached higher values in the range from 2·5 to 5·5 Hz (Figure 3 top right). The differences between the phases up to 6 Hz were small, and above this frequency, the absolute phase values declined less for the relaxed posture (Figure 3 bottom right). The moduli have estimated maxima in the range from 3 to 4·5 Hz (Table 3). With both postures, the maxima for no backrest contact were located in the range of the resonance frequency of the human body (Figure 3 top right). The factors posture and backrest contact had a significant influence on the frequency of the maxima of the transfer function from the seat cushion to the head, especially pronounced with the bending posture (Table 3).

3.3. COMPRESSIVE AND SHEAR FORCES

The maxima and the frequency of their occurrence were determined for the transfer functions between accelerations in the z direction at the seat base and the compressive (Figure 4) and shear forces (Figure 5) acting on the disc L5/S1. If there was no distinct maximum in the chosen range, then the highest value of the curve was determined. Table 4 shows the corresponding mean values and standard deviations for the conditions investigated.

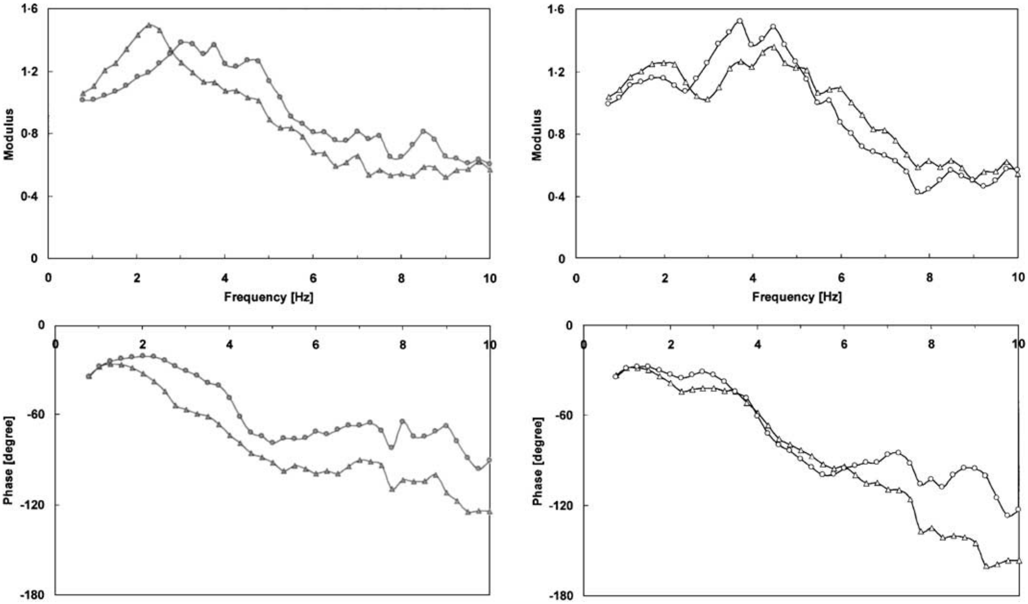

Figure 3. The medians ($N = 39$) of moduli (top) and phases (bottom) of the transfer function between the accelerations in the z direction at the seat cushion and at the head for seating with backrest contact during the forward bending (▲) and relaxed posture (●) (left) and for no backrest contact during the forward bending (△) and relaxed posture (○) (right).

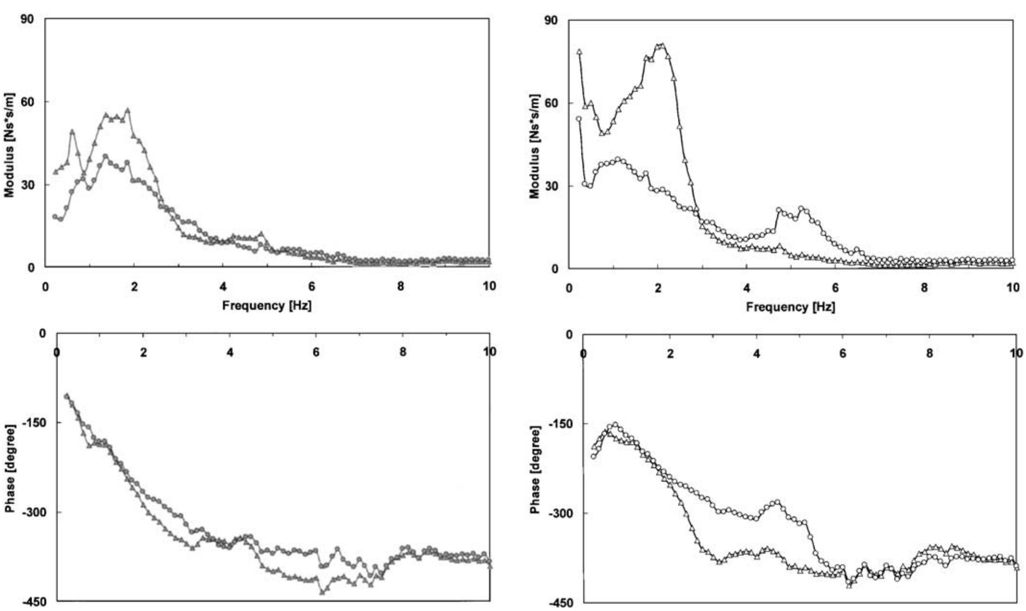

Figure 4. The medians ($N = 39$) of moduli (top) and phases (bottom) of the transfer function between the acceleration in the z direction at the seat base and the compressive force acting on the disc L5/S1 for seating with backrest contact during the forward bending (▲) and relaxed posture (●) (left) and for backrest contact during the forward bending (△) and relaxed posture (○) (right).

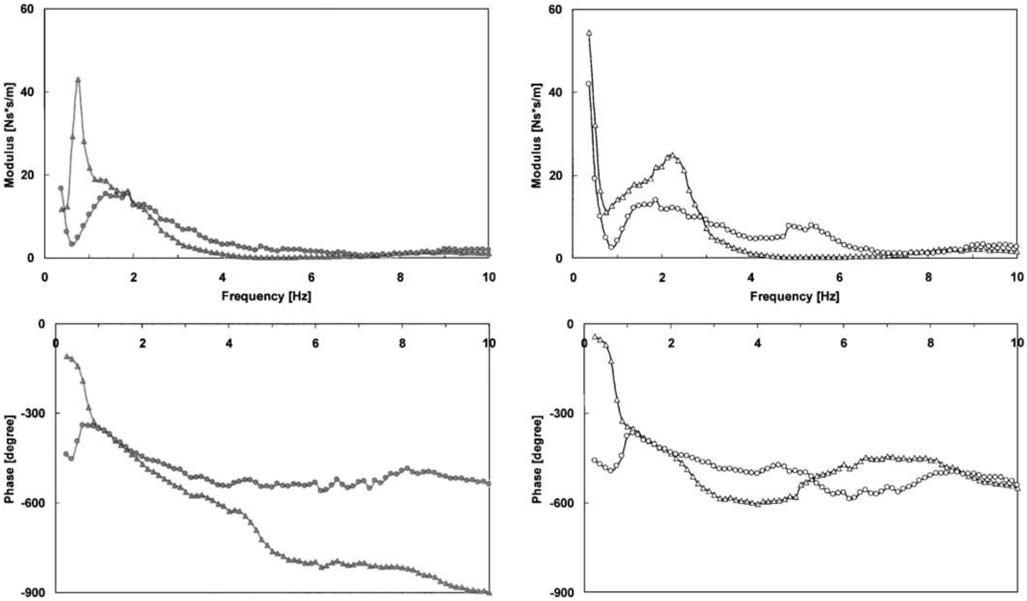

Figure 5. The medians ($N = 39$) of moduli (top) and phases (bottom) of the transfer function between the acceleration in the z direction at the seat base and the shear force acting on the disc L5/S1 for seating with backrest contact during the forward bending (▲) and relaxed posture (●) (left) and for no backrest contact during the forward bending posture (△) and relaxed posture (○) (right).

TABLE 4

Maxima of the moduli (Ns^2/m) *of transfer functions between az at the seat base and the compressive* (TFC) *and shear forces* (TFS) *acting on the disc* $L5/S1$, *and their frequencies* ($f(Hz)$) *of occurrence in two frequency ranges* ($N = 39$)

	wib bp		wib rp		nob bp		nob rp	
	MV	*SD*	*MV*	*SD*	*MV*	*SD*	*MV*	*SD*
Range 1–3 *Hz*								
max. modul *TFC*	61·65	12·67	41·84†	8·62	84·92†	18·08	40·06	7·17
f(max. modul *TFC*)	1·69	0·25	1·54†	0·26	2·23†	0·27	1·31	0·20
max. modul *TFS*	22·56	3·08	17·08†	3·93	25·61†	5·66	14·28	2·93
f(max. modul *TFS*)	1·09	0·22	1·62	0·30	2·30†	0·23	1·89†	0·21
Range 3·125–7 *Hz*								
max. modul *TFC*	14·37	2·18	16·17	1·59	17·19†	5·92	32·94†	7·90
f(max. modul *TFC*)	4·08	0·68	3·26	0·28	3·22†	0·49	5·26†	0·41
max. modul *TFS*	3·26	0·72	6·82	0·81	5·68†	1·81	12·10†	2·71
f(max. modul *TFS*)	3·23	0·62	3·23	0·09	3·20	0·48	5·09†	0·69

Note: wib—with backrest contact; nob—no backrest contact; bp—forward bending posture; rp—relaxed posture.
†$p < 0{\cdot}05$.

3.3.1. *Compressive forces*

For each backrest condition the moduli for the bending posture were higher than for the relaxed posture in the range below about 3 Hz (Figure 4 top). The phases for with backrest contact show a bigger time lag between the input acceleration and force for the bending posture in the range from 2 to 3·5 and 4·5 to 7·5 Hz (Figure 4, bottom left). For no backrest contact these differences were more pronounced in the range between 2 and 6 Hz. The factors backrest contact and posture had a significant effect on the maxima of the transfer functions between accelerations in the z direction at the seat base and the compressive forces on disc L5/S1 and the frequency of their occurrence in the ranges 1–3 Hz and 3·125–7 Hz (see Table 4). In the range from 1 to 3 Hz, maxima of these transfer functions were higher for no backrest than for with backrest contact in the forward bending posture. Within one backrest condition, the values of these maxima were higher for the bending than for the relaxed posture. The maxima occurred in the forward bending posture for no backrest contact at significantly higher frequencies than for with backrest contact, and in the relaxed posture for no backrest contact at significantly lower frequencies than for with backrest contact (Table 4). In the range from 3·125 to 7 Hz the maxima of the transfer functions between accelerations in the z direction at the seat and the compressive forces on disc L5/S1 were significantly higher for no backrest than for with backrest contact. The maxima occurred in the forward bending posture for no backrest contact at significantly lower frequencies than for with backrest contact (Table 4).

3.3.2. *Shear forces*

The moduli of the medians of the transfer functions between the acceleration at the seat base and the shear force acting on the disc L5/S1 were higher with the bending than with the relaxed posture for with and no backrest contact below about 2 or 3 Hz, respectively (Figure 5, top). Above about 2 or 3 Hz the relations were reversed. The phases for with backrest contact show a bigger time lag between input acceleration and force for the forward bending posture in the range from 2 to 3·5 and 4·5 to 7·5 Hz (Figure 5, bottom left). The phase reached higher absolute values more quickly during the forward bending posture, whereas it remained relatively constant above 3·5 Hz during the relaxed posture (Figure 5, bottom). For no backrest contact a similar pattern was observed below 4 Hz (Figure 5, bottom right).

The factors backrest and posture had a significant effect on the maximum moduli of the transfer functions between accelerations in the z direction at the seat base and shear forces on disc L5/S1 and the frequencies of their occurrence in the ranges 1–3 Hz and 3·125–7 Hz with two exceptions: the factor backrest had no effect on the maximum moduli in the range 1–3 Hz, and the factor posture had no significant influence on the frequency of occurrence of the peak moduli in the same frequency range.

In the range from 1 to 3 Hz the maxima of these transfer functions were higher with no backrest contact compared to with backrest contact in the forward bending posture, but in the relaxed posture lower for no backrest than for with backrest contact. Within one backrest condition, the values for these maxima in the forward bending posture were significantly higher than in the relaxed posture. The maxima occurred with both postures for no backrest contact at significantly higher frequencies than for with backrest contact (Table 4).

In the range from 3·125 to 7 Hz, the maxima of the transfer functions between accelerations in the z direction at the seat base and the shear forces on disc L5/S1 were higher for no backrest than for with backrest contact at both postures. The maxima occurred in the forward bending posture for no backrest and for with backrest contact nearly at the same frequencies, and in the relaxed posture for with backrest contact at significantly lower frequencies than for no backrest contact (Table 4).

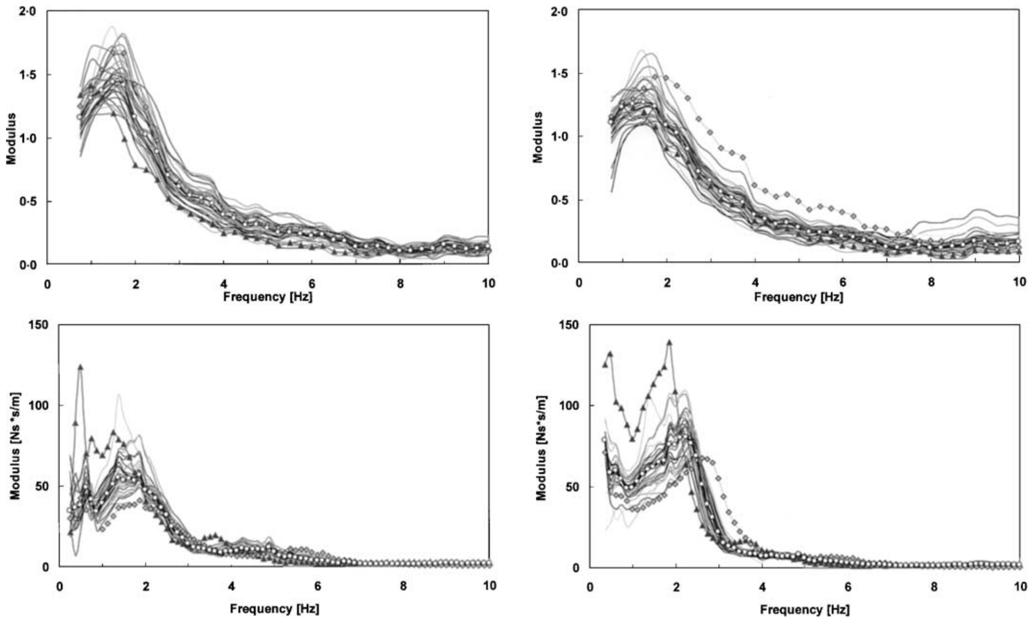

Figure 6. Individual values ($N = 39$) of moduli of the transfer function between the accelerations in the z direction at the seat base and at the seat cushion (top) and between the acceleration in the z direction at the seat base and the compressive force acting on the disc L5/S1 (bottom) for seating with backrest contact (left) and for no backrest contact (right) during the forward bending posture (▲, subject 2; ◆, subject 3; ○, median, details see text).

The variability of the results for the moduli of the seat transmissibility and the transmission from the acceleration at the seat base to the compressive force acting on the disc L5/S1 were illustrated by Figure 6 for the bending posture and Figure 7 for the relaxed posture. Two subjects, subject 3 with a body mass of 49 kg and body height of 163·3 cm and subject 2 with a body mass of 103 kg and a body height of 191 cm, are marked by special symbols. For the seat transmissibility subject 3 reached higher peak values at a higher frequency than subject 2 for all conditions examined. But the relations are reserved for the transmission from the acceleration at the seat base to the compressive force acting on the disc L5/S1. These differences are especially distinct with both postures for no backrest contact (Figures 6 and 7, bottom right).

4. DISCUSSION

The SEAT values of the suspended seat used in this study varied between 0·32 and 0·35 for the conditions examined. The spectrum of the vibration input at the seat base was similar to the input spectral class EM6 [18]. The required SEAT value for this class equals 0·6. Therefore, an appropriate good vibration isolation of the seat under the test conditions could be assumed.

The similarity of our data on the seat-to-head transmissibility obtained on a hard seat [19] with the median of the modulus derived from 46 studies [2] has been shown. The maximum of the modulus and its frequency were also similar; they amounted to 4·25 at 4 Hz [2] compared with 1·42 at 3·5 Hz [4].

The median of the modulus of the transfer function from seat acceleration to head acceleration exhibited a distinctly narrower peak with the hard seat [4] than with the

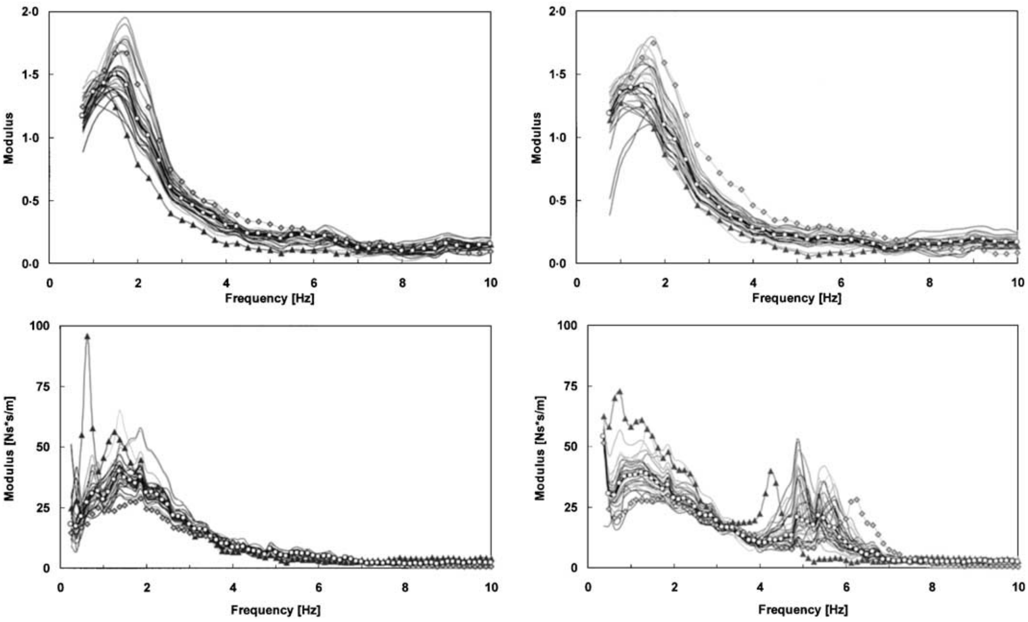

Figure 7. Individual values ($N = 39$) of moduli of the transfer function between the accelerations in the z direction at the seat base and at the seat cushion (top) and between the acceleration in the z direction at the seat base and the compressive force acting on the disc L5/S1 (bottom) for seating with backrest contact (left) and no backrest contact (right) during the relaxed posture (▲, subject 2; ◆, subject 3; ○, median; details see text).

suspended seat (Figure 8). In both studies, the same 39 subjects participated and adopted nearly the same postures. The magnitude of the low-frequency random vibration was slightly higher (0·7 m/s^2 r.m.s. of the weighted acceleration) in the study with the hard seat than in this study (0·60 m/s^2 r.m.s. at no and 0·62 m/s^2 r.m.s. at with backrest contact). With the suspended seat, the shape of the modulus near the resonance is broader and shows two or three local peaks, and the phase lag is not as large up to about 5 Hz (Figure 8). The modulus is somewhat smaller between about 4·5–6 Hz and below about 3 Hz. These differences could be caused by several reasons, for example, different conditions of the vibration input at the interface between the seat and body, or various transfer functions inside the human body. The latter are less probable for the large group of subjects who participated in both studies, but cannot be excluded, since differences of a similar order could be observed within one backrest condition for different postures (Figure 3). This comparison of data obtained with a hard seat with those acquired with a suspended seat (Figure 8) suggests the necessity of a critical application and transfer of results obtained with a hard seat to other conditions.

Results on the seat-to-head transfer functions obtained with the use of a backrest could be found in Paddan and Griffin [20] only. They used a rigid seat with 3 mm special rubber. In this study, 12 male subjects adopted a comfortable upright posture or were leaning against a backrest. The position of the arms was not described. Despite some differences, a conditional comparison seems to be possible with our results on the effect of a backrest with the relaxed posture. According to Paddan and Griffin [20], the backrest increased the r.m.s. values of head vibration and was supposed to provide a stiffening and so tend to increase some resonance frequency. The former result coincided with our data, whereas an opposite tendency was observed with the resonance frequency. As a reanalysis of the data in

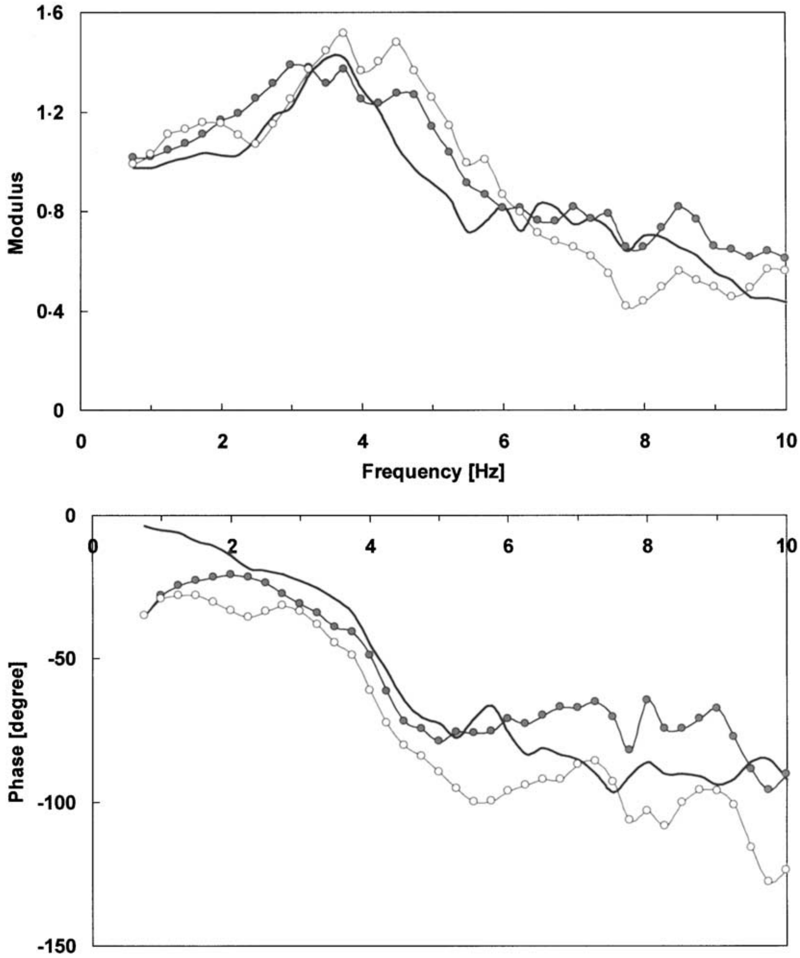

Figure 8. Comparison of the seat-to-head transmissibility with a suspension seat with and no backrest contact and a hard seat during the relaxed posture. The medians ($N = 39$) of moduli (top) and phases (bottom) of the transfer function between the accelerations in the z direction at the seat and at the head for the hard seat (▬) as well as of the transfer function between the accelerations in the z direction at the seat cushion and at the head for the suspension seat with backrest (●) and without backrest (○), are also shown. $N = 39$.

reference [20] by Wu [21, p. 38] has shown, the mean values of the modulus of the seat-to-head transmissibility exhibited higher values for with than for no backrest contact above 5 Hz. In this study, a similar result was observed above 6 Hz (Figure 8). Paddan and Griffin [20] observed a smaller dispersion of the moduli of the seat-to-head transfer function that could not be confirmed by our data (see Table 3).

The analysis of variance showed that the backrest condition had a significant effect on the transmission of vibration to the head. The main tendencies were similar to those reported by Paddan and Griffin [20], although the conditions were not identical. Paddan and Griffin [20] found that the subjects showed a distinct peak and less variation in the vertical head motions with the "back-on" condition than with a "back-off" posture. A similar finding could not be observed in this study, possibly due to the mechanical characteristics of the seat. With the relaxed posture, the peak near the resonance is rather less distinct for with than for no backrest contact (see Figure 3).

The advanced model for the calculation of forces acting on the lumbar spine [11, 12] represents a considerable progress towards a better understanding of the health risk due to realistic exposures. The interpretation of the model calculations should, however, consider some limitations. The individual posture is reflected by an average posture, the pressure distributions on the seat cushion and backrest are neglected as well as the friction between the backrest and body. More experimental data are required for an improvement of the model. The intraspinal forces caused by vibration seem to be small compared with forces predicted for manual material handling. Recent measurements of the intradiscal pressure with different static sitting postures [22, 23] suggest static forces that are by a factor between 2 and 3 higher than those calculated by the model [9]. Reasons for this discrepancy could be, e.g., the inhomogeneous stress distribution within the disc, the underestimation of muscle forces and/or of forces produced by ligaments. Although the predicted dynamic forces might be also considerably underestimated due to the same reasons, the relations between these forces at different conditions seem to be reliable. If one assumes fatigue failure to be an important pathogenetic mechanism [24] and considers the static and dynamic strength of vertebrae [8], the predicted forces can reach critical peak values especially with a bent forward posture.

One might assume that the strain experienced by an operator of a vibrating machine depends on the quality of the seat as assessed by the SEAT value determined in a standardized procedure with two test persons—one light-weight and one heavy person. In order to test this assumption, the relationships of the normalized moduli of the transfer function from the acceleration of the seat base to the seat cushion (see Figures 6 and 7) were compared with those of the normalized moduli of the transfer function from the seat base to the compressive force acting on disc L5/S1 for subjects 3 and 2. The normalization was performed with the median of the corresponding modulus set to 1. Figure 9 indicates that

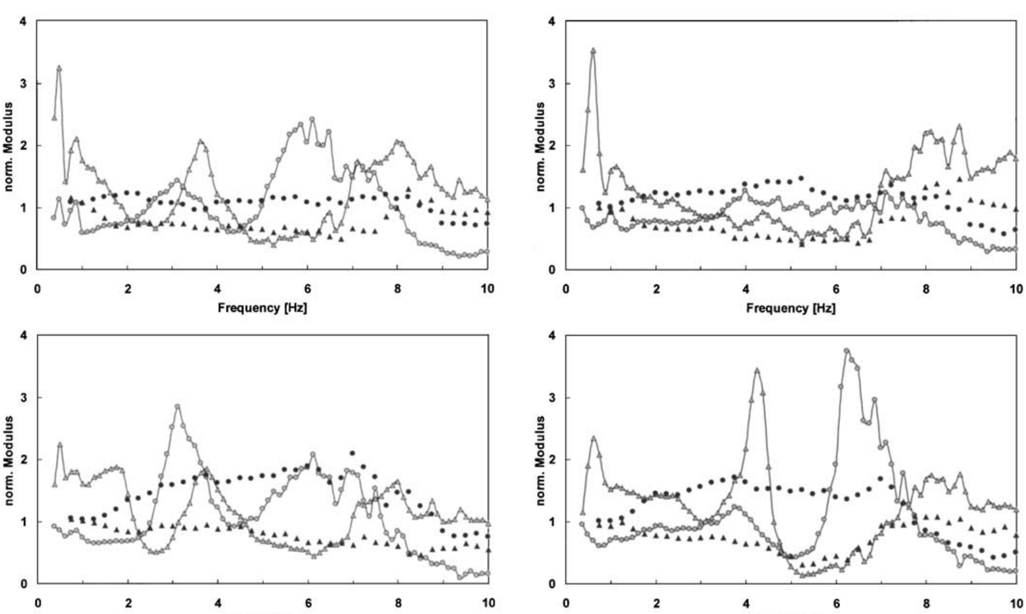

Figure 9. The normalized medians of the transfer function between the accelerations in the *z* direction at the seat base and at the seat cushion (▲, subject 2; ●, subject 3) in comparison to the normalized medians of the transfer function between the acceleration in the *z* direction at the seat base and the compressive force acting on the disc L5/S1 (-▲-, subject 2; -●-, subject 3) in the forward bending posture (left) and in the relaxed posture (right) for seating with backrest contact (top) and no backrest contact (bottom).

TABLE 5

Extreme peak values of dynamic part of the time series of the compressive (CF) and shear forces (SF) acting on disc L5/S1 during a computer simulated input acceleration according to ISO 7096, EM2 when considerating the individual transfer functions at the seat interfaces ($N = 39$; details see text)

	wib bp				wib rp			
L5/S1	*MV*	*SD*	maxS_S	minS_S	*MV*	*SD*	maxS_S	minS_S
max. CF	206·6	35·3	307·2	150·2	151·4†	32·8	243·7	86·1
min. CF	−213·7	39·6	−332·7	−142·1	−152·5	29·9	−225·7	−97·5
max. SF	62·8	11·3	99·1	42·3	63·1†	13·0	95·1	39·6
min. SF	−62·6	10·8	−86·9	−44·4	−62·8†	13·4	−103·8	−35·1
	nob bp				nob rp			
L5/S1	*MV*	*SD*	maxS_S	minS_S	*MV*	*SD*	maxS_S	minS_S
max. CF	299·9†	65·3	456·9	114·5	150·4	27·7	220·1	99·7
min. CF	−301·8†	55·6	−411·6	−113·9	−155·6†	30·3	−263·7	−102·9
max. SF	90·0†	17·2	126·7	32·0	62·1	12·1	100·7	37·8
min. SF	−90·2†	20·1	−142·9	−37·9	−60·3	11·3	−87·1	−41·9

Notes: wib—with backrest contact; nob—no backrest contact; bp—forward bending posture; rp—relaxed posture.
† $p < 0{\cdot}05$.

the transmission of acceleration from the seat base to the seat cushion was less variable and complex than the relationship between the vibration input to the seat base and the predicted force output in the spine. The figure illustrates that peaks in one transfer function do not coincide with peaks in the other one. The large differences between these two subjects exemplify strikingly the extent of the between-subject variability of the biological effect as compared with the variability of a technical measure.

In order to test exclusively the effect of the individual characteristics of the subjects, exactly the same input acceleration would be required. For that purpose, the individual models and individually measured transfer functions (from the seat base to the seat cushion and to the backrest) were combined with a synthetic vibration input to the seat base according the exposure defined for EM2 in ISO 7096 [18]. Table 5 presents the mean values, standard deviations and ranges of the dynamic peak compression and shear calculated for disc L5/S1 under these conditions, thus illustrating the predicted variability of the internal loads with an identical external exposure. If the model output is related to the peak acceleration at the seat cushion, some clear tendencies become obvious (Figure 10). The use of the backrest causes smaller absolute peak values; that is, also smaller ranges between compression and decompression. The bent forward posture causes larger peak loads than the relaxed posture. It is not surprising that there is no strong correlation between the unweighted peak accelerations of the seat cushion and the predicted peak forces acting on disc L5/S1. An estimation of the corresponding health risk [8] should duly consider the additional static loads (mean with the relaxed posture: −787·52 N, with the bending posture: −450·99 N) and the possible underestimation of the predicted forces, when they are compared with strength data given in MPa [8].

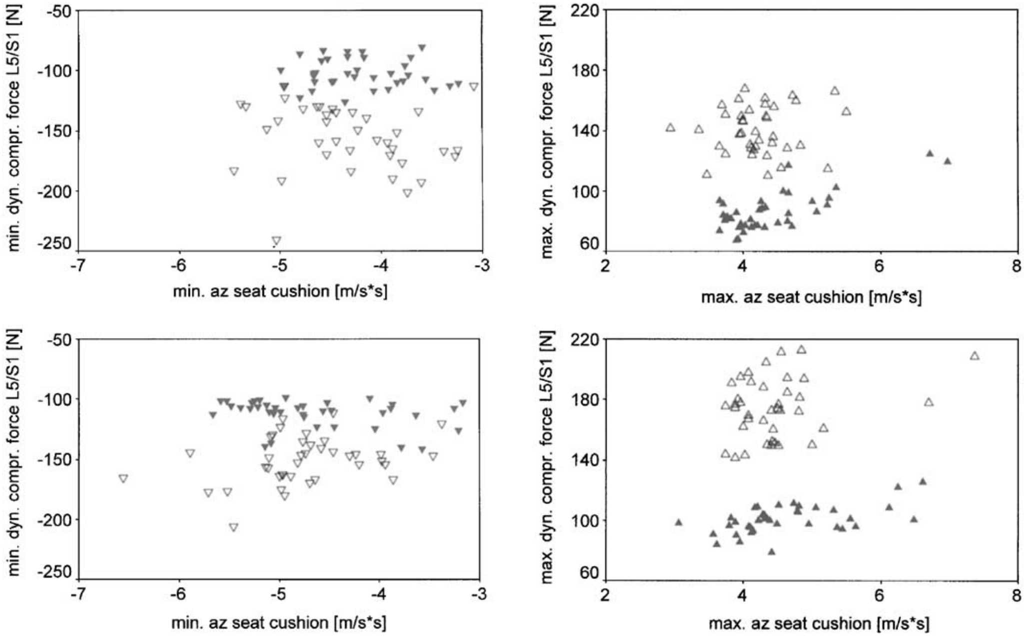

Figure 10. Scatter plots of the extreme values of the time series of the dynamic compressive forces acting on disc L5/S1 for seating with backrest contact (▲, right maxima; ▼, left minima) and for no backrest contact (△, right maxima; ▽, left minima) (ordinate) and the corresponding extreme values of the acceleration in the z direction at the seat base (abscissa) during the relaxed posture (top) and the forward bending posture (bottom).

5. CONCLUSIONS

Emission values as a result of standardized test procedures [18] can provide only an orientation for the exposure values to be expected under real conditions with various subjects, different postures and a variable use of the backrest. The quality of the seat surface, the posture and the use of the backrest should be considered as factors that effect the vibration transmission to the head. A bent forward posture without the use of a pelvic support seems to be a particularly unfavourable condition with respect to a possible injury of the spine. The between-subject variability of the forces acting on the spine could be larger than the between-subject variability of exposure data measured on the seat cushion. The characterization of whole-body vibration exposures by exclusive measurements on the seat cushion may not be sufficient for a reliable evaluation of the exposure with respect to the human criterion preservation of health.

More research work is needed in order to improve the approximation of the model to the individual data of the subject and the exposure condition in the real working life.

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APPENDIX A: NOMENCLATURE

a	vibration acceleration (m/s^2)
aw	frequency-weighted acceleration according to ISO 2631 [15]

bp	forward bending posture
CF	time series of the compressive force acting on L5/S1 (N)
EM2	spectral class of input vibration according ISO 7096 [18]
f	frequency (Hz)
L1	the first lumbar vertebra
L5	the fifth lumbar vertebra
max.	maximum
min.	minimum
MV	mean value
nob	no backrest contact
r.m.s. value	the root mean square value
rp	relaxed posture
S1	the first spinous process in the Crista sacralis intermedia of the Os sacrum
SD	standard deviation
SEAT	seat effective amplitude transmissibility
SF	time series of the shear force acting on L5/S1 (N)
S_S	within the group of 39 subjects
TFC	transfer function between *az* at the seat base and the compressive force in the spine acting on the disc L5/S1
TFH	transfer function between the accelerations at the seat base and at the head in the *z* direction
TFS	transfer function between *az* at the seat base and the shear force in the spine
TFSI	transfer function between the accelerations at the seat base and at the seat cushion in the *z* direction
wib	with backrest contact
x direction	the direction according to the body axis ventral–dorsal, the negative *x* direction defines the ventral-directed accelerations
z direction	the direction according to the body axis caudal–cranial, the negative *z* direction defined the cranial-directed accelerations