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The Effect of Seat Design on Vibration Comfort

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A field study was done to evaluate different seat designs in the aspect of minimizing vibration transmission and reducing the level of discomfort experienced by drivers subjected to transient vibration. Two seat designs (sliding or fixed in the horizontal direction) were compared in an experiment based on variation of sitting posture, speed, and type of obstacle. The comparison was done by assessing discomfort and perceived motion and by vibration measurement. Ten professional drivers were used as participants. Maximum Transient Vibration Value and Vibration Dose Value were used in the evaluation. The results showed that a sliding seat is superior in attenuating vibration containing transient vibration in the horizontal direction. It was also perceived as giving less overall and low back discomfort compared to a fixed seat.

seat design   transient vibration   vibration discomfort

1. INTRODUCTION

Field studies have shown that drivers are more likely to have low back problems than other workers who are not exposed to whole body vibration (Brenstrup & Biering-Sorensen, 1987; Hanley & Bednall, 1995). Drivers experienced not only periodic vibration but also occasional transient vibrations that could arise from external events such as driving over obstacles, potholes, or due to stop-end impact of suspensions resulting in momentary

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high vibration levels. It was postulated that exposure to vibrations with transient motion compared with periodic vibration is more hazardous to health, particularly that of the spine. The reason is that mechanical activity of back muscles to stabilize the spine is insufficient due to the high crest factor and short duration of transient vibrations.

To reduce vibration transmission to drivers, three modifications can be made. The first modification is a suspension system between the wheel and the chassis, the second one consists in floating the cabin, and the third one in modifying the seat design. In the case of a forklift, the necessity of stability makes it difficult to mount a suspension system that has a sufficient stroke distance. A floating cabin cannot be installed in existing forklifts. Thus modifying the seat design seems to be the most appropriate option as the improvement can be done for both new and existing forklifts.

One modified seat design aimed at reducing transient vibrations uses a sliding seat. A sliding seat is a seat equipped with a fore-and-aft isolator and which allows slide movement in the fore and aft directions. This sliding seat can presumably attenuate the occurrence of transient vibration.

The objective of this study was to evaluate the sliding seat design in the aspect of minimizing vibration transmission and reducing the level of discomfort experienced by drivers subjected to transient vibration.

2. METHODOLOGY

2.1. Experimental Design

The experiment was conducted as a factorial design with four factors to be tested (Box, Hunter, & Hunter, 1978). Each factor had two levels, which gave 16 tests for a test of interactions. The first factor was seat condition (fixed and sliding), the second was sitting posture (upright and posterior leaning posture), the third was speed (20 and 5 km/hr), and the last factor was the type of obstacle (single and double). The last three factors were chosen, as these were three conditions common while driving a forklift. Upright posture in this study was defined as the posture that the participant adopted following the command "Sit up straight." Measurements of pelvic angle and spine angle were not done. Posterior leaning posture was defined as the posture adopted when sitting against a 110° inclined backrest. The choice of the inclination angle was based on a previous study by Magnusson (1991), which recommended a 110° inclined backrest for operators who are subjected to prolonged sitting with or without whole body vibrations. The choice of speed and height of the obstacle was based on health risk considerations for the participants.

The study was done in an artificial test track. The reason for this choice was based on Burdoff and Swuste's (1993) recommendation that the effectiveness of seats in vibration reduction should ultimately be tested in the working environment. Using an artificial test track gave an advantage for this study, as it had similar conditions to the real work environment but at the same time the experimental variables could be controlled.

2.2. Apparatus

In this study a KALMAR-DCD70-6H (Kalmar Industries AB, Sweden) forklift was used. This industrial forklift was equipped with four pneumatic tyres on the front axle and two pneumatic tyres on the driving axle. During test runs the pressure of all tyres was 1,000 kPa. The cabin was isolated from the chassis with four rubber bushings (10-mm thick) located on each corner of the cabin.

To reduce the intervariability of seat properties during the test, a seat with double mechanism options (sliding and fixed) was used. The type of the seat was S85/LA130414 (manufactured by Grammer AG Industry, Germany). This seat had a cross-linkage mechanism and was equipped with a vertical pneumatic suspension and a horizontal isolator located under the seat pan.

Measurements on the floor were done with 3-axis piezo-electric accelerometers (B&K 4321; Bruel & Kjær, Denmark). Due to the limitation of the floor construction, the accelerometer was mounted on the base of the seat by using an aluminium beam. This mounting method did not have any major effects on vibration measurement results, as the resonance frequency of the aluminium beam was far above the frequency range of this study. The first natural frequency of the 5 × 50 × 40-mm aluminium beam was 1,580 Hz. The location of the mounting was in the middle of the left side of the seat base. The choice of location was based on the draft of European Standard No. prEN 13059:1999 (European Committee for Standardization [CEN], 1999), which indicates that when the transducer cannot be mounted under the seat pan, the alternative position is on the side of the seat. Measurements were done only for horizontal and vertical motions.

In order to measure acceleration in 5 degrees of freedom in the seat-driver interface, two 3-axis piezo-electric accelerometers (B&K 4321) were used. One accelerometer was imbedded in the centre of a hard-rubber disc (diameter: 250 mm) and placed below the participant's buttock, as shown in Figure 1a. Another one was located on the mid-scapular area of the participant's back by using a purpose-made back harness (as shown in Figure 1b).

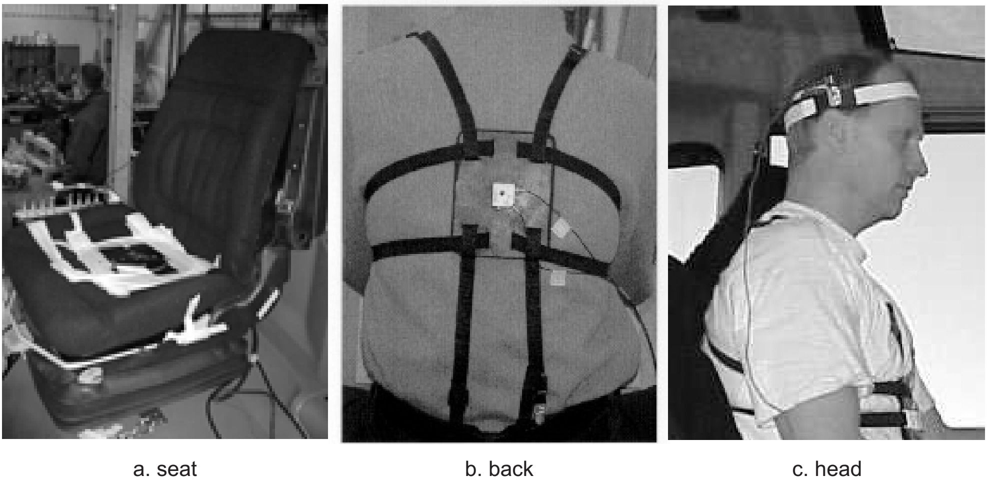

Figure 1. Location of accelerometer.

In order to measure vertical vibrations transmitted to the head, one single-axis piezo-electric accelerometer (B&K4339; Bruel & Kjær, Denmark) was located in a vertical line of the participant's ear by using a purpose-made head harness, as shown in Figure 1c. The choice of the location was based on an attempt to eliminate the pitching effect on the accelerometer by locating it as close as possible to the fulcrum of the head and neck system.

An 8-channel Sony (Japan) DAT recorder and an 8-channel charge amplifier (B&K 5974; Bruel & Kjær, Denmark) were used to record all vibration measurements. An 8-mm Sony video camera was installed inside the cabin to record the movement of the participants, and the results were used as an aid in the analysis procedure.

A questionnaire was used to collect information about the participants' background. For assessments of discomfort and perceived motion, a 7-point rating scale was developed. The rating scales consisted of two parts. The first part was made up of questions regarding how the participant perceived vibration discomfort and the second one was made up of questions on how the participant perceived vibration motion. The rating scale, which was used for this study, is shown in Figure 2.

In the first part of the rating scale, the neck-shoulder and the low back regions were chosen as the indicator of the driver's discomfort. This selection was based on the results from an earlier study of forklift drivers during normal work (Hansson & Kjellberg, 1981) and on epidemiological data (Seidel & Heide, 1986). Their results showed that discomfort was localized at the neck-shoulder and the low back regions.

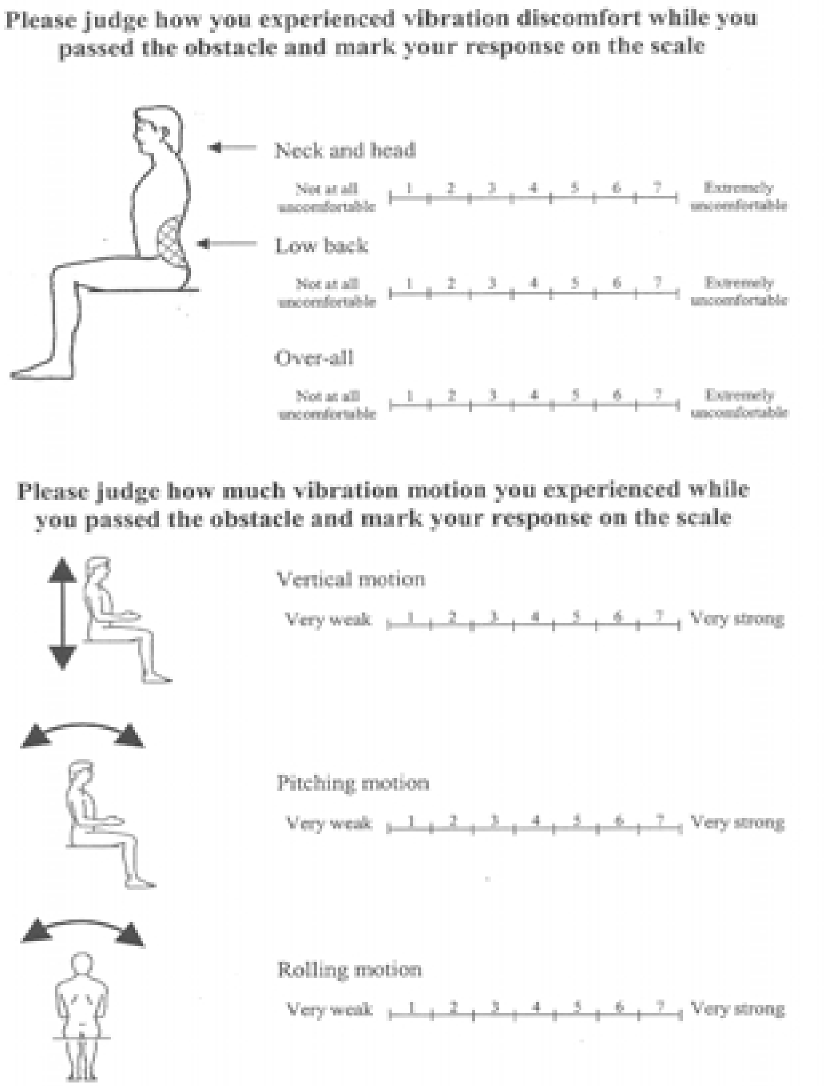

Figure 2. Rating scale for perceived vibration discomfort and motion.

2.3. Participants

Ten male professional drivers participated in this study: age 28–60 years (M = 43.4), height 172–187 cm (M = 179.1), weight 68–103 kg (M = 85.1).

2.4. Experimental Procedure

Before starting the test run, the specifications of the forklift, seat, and tyres were recorded. The pressure of tyres and the surrounding temperature were also recorded. The forklift was warmed up for about 10 min. The tyres were not warmed up due to the time constraint. The participant was provided with information and the procedure of the test study and asked to fill in the questionnaire. Then the measurement devices were installed on the participant. The inclination of the seat pan and the backrest were adjusted to 10º and 110º. The weight adjustment of the seat damping was set to the middle position. The participant was asked to adjust the seat position (vertically and longitudinally) according to his height, and the popliteal height and buttock-popliteal length were measured. The participant was asked to adjust the seat according to his preference, but only in the vertical and horizontal directions. The angle of knee flexion and the distance of the seat pan accelerometer and the back harness accelerometer were measured.

Each participant was asked to make a one-lap trial run according to his last test run order, and to give a subjective assessment after that. The results of the trial run were not used for evaluations. During the test run, the participant was asked to maintain his head in the vertical position and to put his hand on the steering wheel at the 10-past-10 position. For the posterior leaning posture, the participant was asked to lean on a 110º reclined seat. The upright posture was self-selected by the participant following the command "Sit up straight." In the upright posture participants could not be totally isolated from the backrest, their low back was still in contact with the lumbar support.

Each participant was required to accomplish 16 test runs. The experiment was restricted randomised in the meaning that the test runs were presented in different random order for each participant. The time to complete all test runs was 45 min for each participant. Four participants were tested on the first day and 6 participants on the second day. The forklift was driven on a 160-m long asphalt track with one pair of obstacles. The dimension of the obstacle was 53-mm height, 0.8-m width, and 2-m length with 3º inclination on both sides. The obstacle was made of a 20-mm thick steel plate, thus the deflection of the obstacle could be neglected. The layout of the track can be seen in Figure 3.

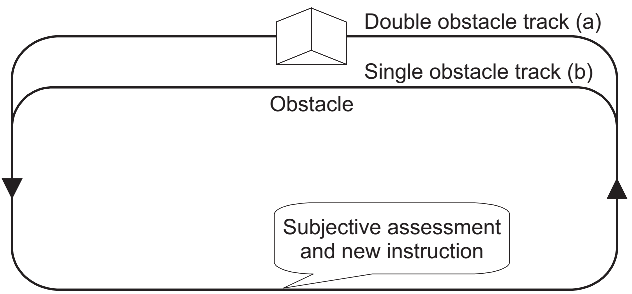

Figure 3. Layout of test track.

For a single obstacle test run, the driver had to drive on Track b, and for a double obstacles run test on Track a. The seat condition setting was done by adjusting the lock/unlock lever. Speed adjustment was done by automatic speed control. Recording time was written down before and after the test run. After accomplishing the test run the driver gave his subjective assessment and new instructions were given for the next test.

2.5. Data Analysis

For each test run, the duration of the measurement was cut into 20 s with the time of the transient peak as a mid-time. Time was cut to eliminate the time taken for accelerating and decelerating the forklift and to make the process of analysis easier. According to Standard No. ISO 2631-1:1997 (International Organization for Standardization [ISO], 1997), the basic evaluation method for vibration uses weighted root-mean-square acceleration (*rms*), defined as

$$a_w = \left[\frac{1}{T}\int_0^T a_w^2(t)dt\right]^{\frac{1}{2}}, \tag{1}$$

where T is the duration of measurement. In cases where the basic evaluation method may underestimate the effects of vibration (crest factor > 9, occasional shocks, transient vibration), one of two additional evaluation methods should also be determined. The two additional evaluation methods are Maximum Transient Vibration Value (*MTVV*) and Vibration Dose Value (*VDV*). *MTVV* is defined as the highest magnitude of $a_w(to)$:

$$MTVV = \max\,[a_w(to)], \tag{2}$$

where to is instantaneous time and $a_w(to)$ is the instantaneous frequency weighted acceleration obtained by using the running *rms* evaluation method with 1-s integration time (τ) for running averaging. Running *rms* is calculated with

$$a_w(to) = \left\{\frac{1}{\tau}\int_{to-\tau}^{to}[a_w(t)]^2\,dt\right\}^{\frac{1}{2}}. \tag{3}$$

Frequency weighted *VDV* is defined as

$$VDV = \left\{ \int_0^T [a_w(t)]^4 \, dt \right\}^{\frac{1}{4}}. \tag{4}$$

Analysis of Variance (ANOVA) was used for data analysis in order to find the main effect of each factor and the interaction among factors. The selected alpha significant level of the tests was $p < .05$.

3. RESULTS AND DISCUSSION

Mean values of selected acceleration measurements and subjective assessment for each test run are shown in Tables 1 and 2.

TABLE 1. Mean Values of Maximum Transient Vibration Value (*MTVV*) and Vibration Dose Value (*VDV*) for Each Test Run

					MTVV (ms^{-2})					*VDV* ($ms^{-1.75}$)				
Ts	A	B	C	D	*xs*	*ys*	*zs*	*xb*	*zh*	*xs*	*ys*	*zs*	*xb*	*zh*
1	–	–	–	–	0.38	1.37	1.70	0.71	0.84	2.29	7.01	11.50	4.70	5.92
2	+	–	–	–	0.34	1.23	1.83	0.90	0.88	2.16	6.51	11.54	5.37	6.00
3	–	+	–	–	0.33	1.19	1.63	0.87	0.88	2.02	6.24	11.17	5.68	6.00
4	+	+	–	–	0.41	1.22	1.64	0.83	0.86	2.46	6.40	11.04	5.32	5.95
5	–	–	+	–	0.96	2.75	3.04	1.90	1.66	5.22	13.82	16.94	10.35	9.77
6	+	–	+	–	1.09	2.82	3.09	2.16	1.73	5.70	13.92	17.20	11.54	10.22
7	–	+	+	–	1.03	2.76	3.16	2.43	1.77	5.48	13.71	17.56	13.16	10.18
8	+	+	+	–	1.11	2.78	3.16	2.99	1.77	5.86	13.81	17.56	15.49	10.18
9	–	–	–	+	0.47	0.80	2.56	1.04	1.33	3.06	4.68	15.09	6.20	7.98
10	+	–	–	+	0.51	0.71	2.33	1.19	1.30	3.36	4.19	13.56	7.02	7.47
11	–	+	–	+	0.43	0.73	2.38	1.36	1.28	2.80	4.13	14.10	7.79	7.64
12	+	+	–	+	0.53	0.78	2.35	1.66	1.43	3.40	4.48	13.94	9.16	8.11
13	–	–	+	+	1.58	1.22	3.59	3.20	2.35	8.13	6.98	19.17	16.71	12.77
14	+	–	+	+	1.86	1.35	3.82	4.16	2.87	9.11	7.50	20.35	21.29	15.70
15	–	+	+	+	1.47	1.21	3.72	3.46	2.33	7.39	6.74	19.92	17.34	12.78
16	+	+	+	+	1.82	1.26	3.71	5.29	3.14	8.78	7.16	19.86	26.57	17.87

Notes. Ts—test run; A—seat design: – —sliding, +—standard; B—posture: – —upright, +—leaning; C—speed: – —low, +—high; D—obstacle: – —single, +—double; *xs*—seat horizontal, *ys*—seat lateral, *zs*—seat vertical, *xb*—body horizontal, *zh*—head vertical.

TABLE 2. Mean Values of Root-Mean-Square (*rms*) and Assessment of Discomfort and Perceived Motion for Each Test Run

					rms (ms^{-2})					Assessment					
Ts	A	B	C	D	*xs*	*ys*	*zs*	*xb*	*zh*	HN	LB	OA	VM	PM	RM
1	–	–	–	–	0.18	0.49	1.09	0.42	0.55	1.90	2.10	1.90	1.80	1.60	2.50
2	+	–	–	–	0.18	0.46	1.08	0.44	0.56	2.00	2.10	2.20	1.90	1.90	2.50
3	–	+	–	–	0.17	0.45	1.08	0.50	0.56	2.20	2.30	2.40	1.95	2.10	2.90
4	+	+	–	–	0.19	0.47	1.06	0.47	0.55	2.10	2.20	2.30	2.00	2.00	2.70
5	–	–	+	–	0.41	0.84	1.34	0.84	0.82	3.00	3.10	2.90	3.05	3.15	3.50
6	+	–	+	–	0.44	0.83	1.39	0.91	0.86	3.15	3.65	3.60	3.20	3.40	4.30
7	–	+	+	–	0.41	0.82	1.38	1.05	0.85	3.10	3.40	3.50	3.20	3.40	4.40
8	+	+	+	–	0.45	0.85	1.38	1.19	0.85	3.30	3.40	3.20	2.90	3.40	3.90
9	–	–	–	+	0.23	0.37	1.28	0.50	0.66	2.00	1.90	1.90	2.10	1.90	1.90
10	+	–	–	+	0.24	0.34	1.17	0.54	0.65	2.05	2.10	2.30	1.90	2.20	1.90
11	–	+	–	+	0.21	0.34	1.21	0.62	0.65	1.60	1.65	1.60	1.80	1.50	1.60
12	+	+	–	+	0.24	0.36	1.19	0.69	0.69	1.90	2.40	2.30	2.40	2.40	1.50
13	–	–	+	+	0.54	0.57	1.42	1.17	0.95	2.80	2.80	2.80	2.90	3.10	2.00
14	+	–	+	+	0.66	0.60	1.49	1.43	1.10	3.10	3.50	3.30	3.30	3.60	2.10
15	–	+	+	+	0.49	0.56	1.48	1.21	0.95	2.70	2.80	2.60	2.90	3.05	2.20
16	+	+	+	+	0.59	0.59	1.45	1.74	1.19	3.70	3.80	3.80	3.50	4.30	2.80

Notes. Ts—test run; A—seat design: – —sliding, +—standard; B—posture: – —upright, +—leaning; C—speed: – —low, +—high; D—obstacle: – —single, +—double; *xs*—seat horizontal, *ys*—seat lateral, *zs*—seat vertical, *xb*—body horizontal, *zh*—head vertical; HN—head and neck comfort, LB—low back comfort, OA—overall comfort, VM—perceived vertical motion, PM—perceived pitching motion, RM—perceived rolling motion.

According to Standard No. ISO 2631-1:1997 (ISO, 1997) the use of additional evaluation methods will be important for the judgement of the effects of vibration on human beings when the following ratios are exceeded for evaluated comfort:

$$\frac{MTVV}{a_w} = 1.5\,, \tag{5}$$

$$\frac{VDV}{a_w T^{1/4}} = 1.75\,. \tag{6}$$

As the individual results showed that the ratios were exceeded for almost every case, hereafter the evaluations were based on *MTVV* and *VDV*.

The results of the factorial analysis are shown as a value of estimated main effects and interaction effects. ANOVA was performed to interpret the second order interaction effect. Interpretation of the interaction between speed and obstacle was excluded as it was not related to the purpose of this study. Selected results are shown in Table 3.

TABLE 3. Estimated Effects for Maximum Transient Vibration Value (*MTVV*), Vibration Dose Value (*VDV*), and Assessment of Discomfort and Perceived Motion

	MTVV			***VDV***			**Assessment**		
Effect	***xs***	***xb***	***zh***	***xs***	***xb***	***zh***	**LB**	**OA**	**PM**
Average	0.90	2.13	1.65	4.83	11.48	9.66	2.70	2.66	2.69
Main effects									
A: Seat design	0.13*	0.53*	0.19*	0.56*	2.48*	1.06*	0.39*	0.42*	0.42*
B: Posture	–0.01	0.45*	0.06	–0.11	2.17*	0.36	0.09	0.10	0.16
C: Speed	0.94*	2.12*	1.10*	4.26*	10.15*	5.55*	1.21*	1.10*	1.48*
D: Obstacle	0.38*	1.07*	0.71*	1.85*	5.06*	3.26*	–0.16	–0.17	0.14
Interactions									
A × B	0.03	0.13	0.04	0.14	0.66	0.32	0.02	–0.05	0.09
A × C	0.08*	0.38*	0.16*	0.25	1.85*	1.06*	0.17	0.10	0.07
A × D	0.06*	0.28*	0.17*	0.26	1.52*	0.94*	0.27	0.27	0.31
B × C	–0.01	0.23*	0.04	–0.06	1.00	0.27	0.00	0.02	0.06
B × D	–0.03	0.09	0.02	–0.22	0.24	0.26	0.00	–0.02	–0.05
C × D	0.26*	0.58*	0.23*	0.93*	2.78*	1.43*	0.00	0.00	0.04

Notes. *—significant at the .05 level; *xs*—seat horizontal, *xb*—body horizontal, *zh*—head vertical; LB—low back comfort, OA—overall comfort, PM— perceived pitching motion.

Correlation of vibration measurement and comfort assessment is calculated by using Pearson product moment and given as a correlation of determination (r^2). Correlations were calculated for a single axis and for multi-axes (three translational axes and two rotational axes on the seat). Overall *MTVV*, determined from measured vibration in three translational axes (x, y, z) and two rotational axes (*pitch*, *roll*), is calculated as follows:

$$MTVV_{overall} = \max\left[\left(\begin{array}{l} k_x^2\, a_{wx}^2(to) + k_y^2\, a_{wy}^2(to) + \\ k_z^2\, a_{wz}^2(to) + k_r^2\, a_{wr}^2(to) + k_p^2\, a_{wp}^2(to) \end{array}\right)^{\frac{1}{2}}\right] \tag{7}$$

where, $a_{wx}(to)$, $a_{wy}(to)$, $a_{wz}(to)$, $a_{wr}(to)$, $a_{wp}(to)$ are instantaneous frequency weighted accelerations with respect to translational axes *x*, *y*, *z* and rotational axes r_x (*roll*), r_y (*pitch*) respectively and the multiplying factors k_x, k_y, k_z are 1, k_r is 0.63 m/rad, and k_p is 0.4 m/rad. And overall *VDV* is calculated as follows:

$$VDV_{overall} = \left[k_x^4\, vdv_x^4 + k_y^4\, vdv_y^4 + k_z^4\, vdv_z^4 + k_r^4\, vdv_r^4 + k_p^4\, vdv_p^4\right]^{\frac{1}{4}} \tag{8}$$

where, vdv_x, vdv_y, vdv_z, vdv_r, vdv_p are vibration dose values with respect to translational axes *x*, *y*, *z* and rotational axes r_x (*roll*), r_y (*pitch*) respectively. Calculations of overall *MTVV* and overall *VDV* were done for three axes and five axes. Selected results of correlation analysis are shown in Table 4.

TABLE 4. Correlation of Vibration Measurement and Vibration Discomfort (r^2)

Vibration Comfort	*MTVV*							*VDV*						
	r^2_{xs}	r^2_{ys}	r^2_{zs}	r^2_{pitch}	r^2_{roll}	$r^2_{3\,dof}$	$r^2_{5\,dof}$	r^2_{xs}	r^2_{ys}	r^2_{zs}	r^2_{pitch}	r^2_{roll}	$r^2_{3\,dof}$	$r^2_{5\,dof}$
Head and Neck	.76	.50	.59	.70	.45	.83	.81	.71	.56	.62	.70	.57	.75	.76
Low Back	.72	.53	.54	.65	.49	.80	.82	.68	.58	.57	.66	.59	.71	.76
Overall	.65	.48	.47	.58	.45	.71	.75	.61	.53	.49	.59	.54	.62	.67

Notes. MTVV—Maximum Transient Vibration Value, *VDV*—Vibration Dose Value; *xs*—seat horizontal, *ys*—seat lateral, *zs*—seat vertical, pitch, *roll*—rotational axes, 3 *dof*—a combination of 3 translational axes, 5 *dof*—a combination of 3 translational axes and 2 rotational axes.

3.1. Frequency Analysis

In general (as shown in Figure 4), both seat conditions reduced horizontal vibration above 4 Hz and increased horizontal vibration below 2.5 Hz. Amplification in the range below 2.5 Hz can be divided into three ranges, the first range is 0.5–1 Hz, the second is 1–2 Hz, and the third is 2–2.5 Hz. The first and the third ranges are most probably related to the resonance frequency of the body. This argument is supported by the results of Fairley and Griffin

(1990): By applying the apparent mass of a sitting human, they found that the human body had two “resonances” at low frequencies at about 0.7 and 2–2.5 Hz in the horizontal direction. The second range is probably related to the resonance frequency of the seat system. A study of horizontal transmissibility of six truck suspension seats by Corbrigde (1987) showed that frequencies above 2.5 Hz were attenuated and there was significant amplification between about 1 and 2 Hz. Thus it is reasonable that amplification in the range 1–2 Hz is related with resonance frequency of the seat in the horizontal direction.

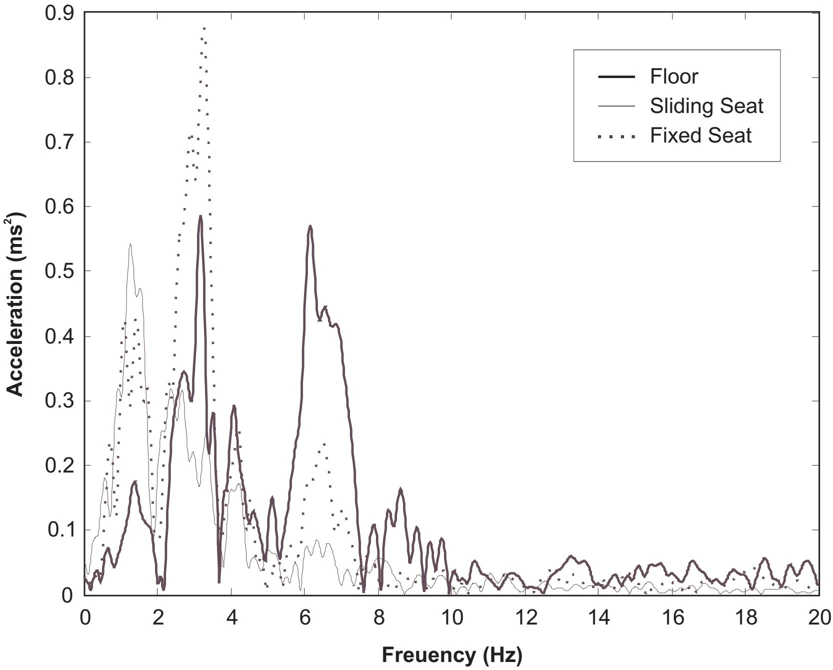

Figure 4. Spectrum of horizontal vibration of seat (*xs*) in high speed and upright posture.

Figure 4 also shows a frequency shift in the low frequencies, where the sliding seat gave a lower frequency. The reasons for this behavior may be that the seat system became mechanically softer due to the free slide movement. The sliding movement also altered a variation of the knee angle and pelvic orientation, which changed the stiffness of the body due to the variation of the lumbar curve and also changed the contact area of human-seat interface. All of these reasons could modify the vibration spectrum on the seat pan.

3.2. *MTVV* and *VDV*

The statistical analysis of *MTVV* shows that horizontal vibrations in the seat were affected by the interaction of seat design and speed and the interaction of seat design and the obstacle as shown in Figure 5.

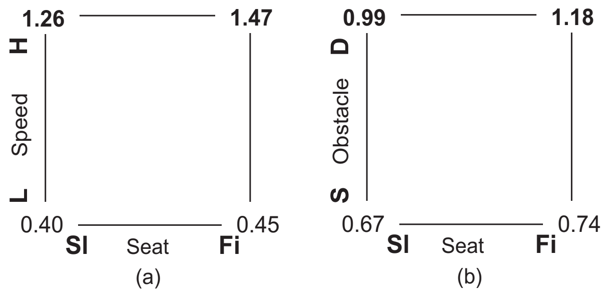

Figure 5. Two-way table for Maximum Transient Vibration Value (*MTVV*) of horizontal vibration in seat: (a) seat-speed interaction, (b) seat-obstacle interaction. *Notes.* H—high speed, L—low speed, S—single obstacle, D—double obstacle, Sl—sliding seat, Fi—fixed seat.

At high speed, changing the sliding seat to the fixed seat increased *MTVV* from 1.26 to 1.47 ms^{-2}. At double obstacle, changing the sliding seat to the fixed seat increased *MTVV* from 0.99 to 1.18 ms^{-2}. This indicates that in the case of high speed and a double obstacle, the sliding seat performed better in attenuating horizontal motion than the fixed seat.

The statistical analysis of *VDV* shows that seat design had an effect on horizontal vibration on the seat (see Table 3). The sliding seat gave a lower vibration dose value in all conditions, with the estimated effect of 0.56 $ms^{-1.75}$. The reason for the different results of *MTVV* and *VDV* is that *MTVV* considers one single transient peak, whereas *VDV* considers the whole signal. Thus, in other words, *MTVV* results show that the sliding seat effectively attenuated transient vibration in the case of high speed and a double obstacle, and *VDV* results show that the sliding seat effectively attenuated vibration containing transient vibration in all cases.

The end-stop impacts that can happen when the seat reaches the end of its travel in the horizontal direction did not take place. An analysis of the signals shows that after the first transient, no other transients were observed.

In the measured horizontal motion of the body, an interaction of seat design and speed, and seat design and obstacle are shown for *MTVV* and

VDV analysis (see Figures 6 and 7). For high speed and for a double obstacle, the sliding seat gave lower vibration values, which were also found for the horizontal motion of the seat. As the motion of the seat affects the motions of the upper body, similar results on the body are expected.

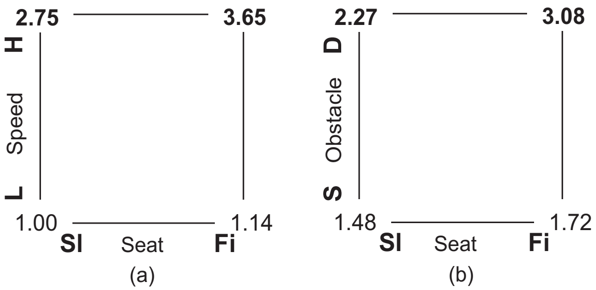

Figure 6. Two-way table for Maximum Transient Vibration Value (*MTVV*) of horizontal vibration of body: (a) seat-speed interaction, (b) seat-obstacle interaction. *Notes.* H—high speed, L—low speed, S—single obstacle, D—double obstacle, Sl—sliding seat, Fi—fixed seat.

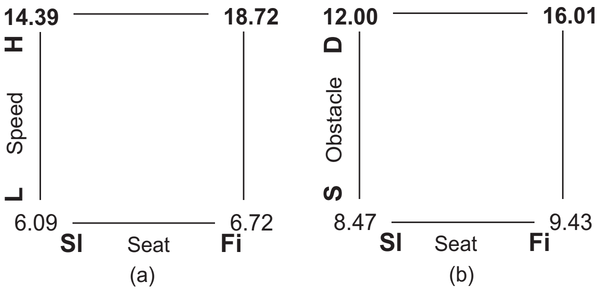

Figure 7. Two-way table for Vibration Dose Value (*VDV*) of horizontal vibration of body: (a) seat-speed interaction, (b) seat-obstacle interaction. *Notes.* H—high speed, L—low speed, S—single obstacle, D—double obstacle, Sl—sliding seat, Fi—fixed seat.

The results of *VDV* show that posture has a significant effect on the horizontal motion of the body. Sitting up straight gave a lower vibration value than sitting against a backrest. While sitting against a backrest, some of the vertical motions of the backrest were transmitted as an additional input of the horizontal motion to the upper body due to the contact of the body with the backrest. In *MTVV* the differences were large enough to be significant only in the case of high speed.

Measured vibration in the vertical direction of the head shows an interaction between seat design and speed, and seat design and an obstacle for both analyses (see Figures 8 and 9).

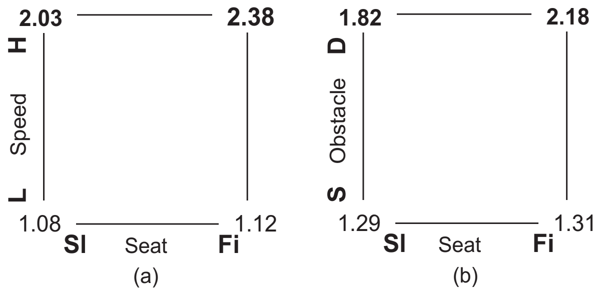

Figure 8. Two-way table for Maximum Transient Vibration Value (*MTVV*) of vertical vibration of head: (a) seat-speed interaction, (b) seat-obstacle interaction. *Notes.* H—high speed, L—low speed, S—single obstacle, D—double obstacle, Sl—sliding seat, Fi—fixed seat.

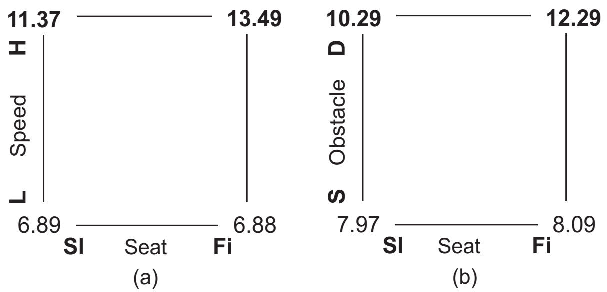

Figure 9. Two-way table for Vibration Dose Value (*VDV*) of vertical vibration of head: (a) seat-speed interaction, (b) seat-obstacle interaction. *Notes.* H—high speed, L—low speed, S—single obstacle, D—double obstacle, Sl—sliding seat, Fi—fixed seat.

In the case of high speed and a double obstacle, the sliding seat gave a lower vibration value on the head. The explanation is that the horizontal movement of the seat affects the vertical vibration transmitted to the head. In their research on the transmission of translational seat vibration to the head using a bite-bar, Paddan and Griffin (1988) found that horizontal seat motion mainly resulted in head motion within the mid-sagittal plane (i.e., horizontal and vertical axes). However, it should be noted that the location of the accelerometer in this present study was in a vertical line above the right ear. The horizontal and lateral motion of the head could be interpreted as vertical motion due to the distance of the accelerometer to the center of the head co-ordinate system.

3.3. Perceived Vibration Comfort and Motion

The results of the assessment of vibration comfort shows that seat design has a significant effect on overall discomfort and low back discomfort. In their study of the subjective equivalence of the sitting position, Donati, Grosjean, Mistrot, and Roure (1983) suggested that seated persons' maximum sensitivity to horizontal motion was found at frequencies between 3 and 4 Hz rather than at frequency below 2 Hz. The attenuation of horizontal motions in the range 2.5–3.5 Hz by the sliding seat is the reason why the participants considered the sliding seat more comfortable than the fixed seat. This is also supported by the results of a study on translational vibration of the back by Parsons and Griffin (1982), which showed that seated persons were considerably more sensitive to back vibration in the horizontal direction than in either of the other directions. Meanwhile the results of the horizontal motion of the body showed that the sliding seat reduced the vibration value for high speed and for a double obstacle.

Seat design has a significant effect on perceived pitching motion. The sliding seat was perceived to give lower pitching motion of the body compared to the fixed seat. This result was confirmed by the results of the analysis of the damping behaviour of the seat after the shock by using *rms* 4 second, which shows that seat design has a significant effect on pitching motion. The sliding seat gave lower pitching motion than the fixed seat. The explanation is that when the human body is considered as a rigid body, the pitching motion of the body occurs when the upper body rotates in the sagittal plane with the lumbo-sacral joint as a centre of rotation. So, the sliding seat attenuated the horizontal motion of the seat and the body. Concurrently, it also reduced the pitching motion of the body.

3.4. Correlation of Vibration Measurement and Comfort Assessment

Table 4 shows that measured horizontal vibration in the seat and pitch provide better correlation with discomfort assessment than other measurement axes. The correlation values were improved when evaluation was based on a combination of three axes or five axes, and the reason is that there is no dominant axis in this study as the vibrations are pure multi-axes excitations. It also shows that similar correlation values were found for *MTVV* and *VDV*. These results are understandable as in this study participants were exposed to vibrations containing a single shock, thus the differences between *MTVV* and *VDV* methods were not pronounced.

To analyse the consistency of agreement of discomfort assessment among the participants, correlation of determination of individual assessment and the median of the group were calculated. Results show that participant No. 7 gave a lower correlation value (.34) than the rest of the group (.60–.93). The reason is that participant No. 7 gave an assessment in the narrow range (2 out of 7 available scales). The usage of this narrow scale did not correspond to the measured vibration that varies in a wide range. When participant No. 7 was excluded from the calculation of the correlation of vibration measurement and vibration comfort assessment, the correlation values improved, as shown in Table 5.

TABLE 5. Correlation Values Without Participant Number 7 (r^2)

Vibration Comfort	*MTVV*							*VDV*						
	r^2_{xs}	r^2_{ys}	r^2_{zs}	r^2_{pitch}	r^2_{roll}	$r^2_{3\,dof}$	$r^2_{5\,dof}$	r^2_{xs}	r^2_{ys}	r^2_{zs}	r^2_{pitch}	r^2_{roll}	$r^2_{3\,dof}$	$r^2_{5\,dof}$
Head and Neck	.85	.63	.79	.83	.63	.90	.87	.84	.68	.80	.84	.70	.86	.86
Low Back	.81	.67	.75	.79	.67	.88	.88	.80	.71	.76	.80	.73	.83	.87
Overall	.76	.65	.70	.73	.66	.83	.84	.76	.70	.70	.75	.72	.77	.84

Notes. MTVV—Maximum Transient Vibration Value, *VDV*—Vibration Dose Value; *xs*—seat horizontal, *ys*—seat lateral, *zs*—seat vertical, pitch, *roll*—rotational axes, 3 *dof*—a combination of 3 translational axes, 5 *dof*—a combination of 3 translational axes and 2 rotational axes.

Further analysis was done by grouping the data into two groups according to speed (high and low speed). Results show that within the group correlation values were lower. Two significant results were found in the high-speed group, the correlation of $MTVV_{overall}$ of 3 axes (3 *dof*) and overall discomfort ($r^2 = .50$), and the correlation of $MTVV_{overall}$ of 3 axes and low back discomfort ($r^2 = .59$). These results indicate that within the group of speed, variability was low, which made it difficult for participants to assess discomfort. This also indicates that for those particular conditions (pure multi-axes excitations) a good model of discomfort requires at least measurements of 3 degrees of freedom.

4. CONCLUSION AND FURTHER STUDY

The results show that a sliding seat is better in attenuating vibrations containing single transient vibration in the horizontal direction than a fixed seat. In attenuating transient vibration in the horizontal direction a sliding seat is superior only in the case of high speed or a double obstacle. The sliding seat was perceived as giving less overall discomfort, less low back discomfort, and less pitch motion.

Further study should be done to discover its effects on task performance, as the slide movement presumably could detriment the performance of drivers in precision tasks while traveling, such as operating the brake and the accelerator and in idling operation, such as loading and unloading. A study of its performance in vibrations containing multiple shocks would also be interesting.

REFERENCES

Box, G.E.P., Hunter, W.G., & Hunter, J.S. (1978). *Statistics for experimenters: An introduction to design, data analysis, and model building*. New York, NY, USA: Wiley.

Brenstrup, T., & Biering-Sorensen, F. (1987). Effects of fork-lift truck driving on low-back trouble. *Scandinavian Journal of Work, Environment and Health, 13,* 445–452.

Burdoff, A., & Swuste, P. (1993). The effects of seat suspension on exposure to whole-body vibration of professional drivers. *Annual Occupational Hygiene, 37*(1), 45–55.

Corbridge, C. (1987). *Vibration in vehicles: Its effect on comfort*. Unpublished doctoral dissertation, University of Southampton, Southampton, UK.

Donati, P., Grosjean, A., Mistrot, P., & Roure, L. (1983). The subjective equivalence of sinusoidal and random whole-body vibration in the sitting position (an experimental study using the “floating reference vibration” method). *Ergonomics*, *26*, 251–273.

European Committee for Standardization. (CEN). (1999). *Safety of industrial trucks—Test methods for measuring vibration* (Standard No. prEN 13059:1999). Brussels, Belgium: Author.

Fairley, T.E., & Griffin, M.J. (1990). The apparent mass of the seated human body in fore-and-aft and lateral directions. *Journal of Sound and Vibration*, *139*(2), 299–306.

Hanley, P., & Bednall, A.W. (1995). *Lift truck—Vibration and related ergonomic hazards* (Health and Safety Executive [HSE] Specialist Inspector Report No. 49). Sudbury, UK: Health and Safety Executive.

Hansson J.E., & Kjellberg, A. (1981). *Vibration exposure and discomfort during truck driving on goods stations* (Research Report No. 1981:1). Stockholm, Sweden: Swedish National Board of Occupational Safety and Health.

International Organization for Standardization. (ISO). (1997). *Mechanical vibration and shock—Evaluation of human exposure to whole body vibration—Part 1: General requirements* (Standard No. ISO 2631-1:1997). Geneva, Switzerland: Author.

Magnusson, M.L. (1991). *Effects of seated whole body vibrations on the spine: An experimental study in man.* Unpublished doctoral dissertation, University of Gothenburg, Gothenburg, Sweden.

Paddan, G.S., & Griffin, M.J. (1988). The transmission of translational seat vibration to the head. II. Horizontal seat vibration. *Journal of Biomechanics*, *21*, 199–206.

Parsons, K.C., & Griffin, M.J. (1982). Vibration and comfort. III. Translational vibration of the feet and back. *Ergonomics*, *8*, 705–719.

Seidel, H., & Heide, R. (1986). Long term effects of whole body vibration: A critical survey of the literature. *International Archives of Occupational and Environmental Health*, *58*, 1–26.