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The effect of posture and seat suspension design on discomfort and back muscle fatigue during simulated truck driving

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Several studies have shown a relationship between low-back problems and exposure to seated whole-body vibration. The amount of vibration transmitted to the operator is influenced by the posture of the subject in the vehicle. The aim of this study was to determine whether a truck seat with a gas spring in its suspension is superior to the standard spring seat in slowing the onset of muscle fatigue and reducing the level of discomfort experienced during road vibrations while maintaining typical driving postures. The experiment used a 2 × 3 (2 seats × 3 postures) repeated measures design. It was conducted on six males free from low-back pain. Subject comfort was rated before and directly after exposure to typical vibrations. Muscle fatigue using centre frequency was determined during vibration exposure, and the magnitude and phase of acceleration transfer were calculated from the base plate to the seat pan and from the seat pan to the bite bar. None of comfort, fatigue rate or fatigue average were affected by seat type or seat suspension design in the short term, 10 min vibration exposure. Fatigue and comfort measures could continue to be used to detect postural defects, but the more sensitive measures of seat/driver interactions remain mechanical ones using motion-measuring techniques such as accelerometry and correcting for the heavily damped nature of the system. Until more sophisticated manikins are available the characteristics of vibration-attenuating seats should be confirmed using live humans.

Keywords: Posture, seat suspension design, subjective comfort assessment, muscle fatigue, simulated truck driving, whole body vibration

Introduction

Several studies have shown a relationship between low-back problems and exposure to seated whole-body vibrations. Drivers of vehicles such as trucks, buses, tractors, taxis and locomotives, helicopter pilots, and drivers of heavy construction vehicles, have all been found to have developed pathological spinal changes. These relationships have been reviewed by Hulshof and van Zanten (1987) and Seidel and Heide (1986). In practice, few vehicles impart a pure sinusoidal input to the driver; instead, most vehicles transmit a complex vibration containing many impact shocks.

The amount of vibration transmitted to the driver is influenced by the posture of the subject in the vehicle (Coermann and Okada, 1964; Wilder *et al*, 1982, 1985). Coermann and Okada (1964) demonstrated that transmissibility was significantly reduced when subjects sat in an inclined back rest angle of greater than 105° from the horizontal. Wilder *et al* (1982) showed that there was an increase in transmissibility at 5 Hz when a person sat in a forward flexed position.

Morphological changes of the vertebral bodies have been associated with vibrations (Brinkmann *et al*, 1988). Vibratory exposure may accelerate and aggravate the development of degenerative changes in the spine (Schmidt, 1981). *In vivo* invasive studies have shown that the first resonant frequency of the human spine is around 5 Hz (Panjabi *et al*, 1986; Pope *et al*, 1987, 1989, 1990). *In vivo* experiments in the pig have shown that the axial load in the porcine spine is increased by a factor of 2 to 3 at the first resonant frequency of 5 Hz (Hansson *et al*, 1987). There was an increased metabolic cost when seated subjects were exposed to vibrations compared with non-vibration, even though the load on the spine was relatively small (Magnusson *et al*, 1987).

The biomechanical behaviour of the disc *in vivo* after vibration exposure has also been investigated by using changes in height as a measure of disc compression (Magnusson *et al*, 1992). Both Seidel *et al* (1980) and Seroussi *et al* (1989) consider that one reason why vibration leads to disc failure is that the muscles are not able to compensate for the cyclic load added to the spine, and so are not able to protect the spine from mechanical forces under many exposure cycles. Seidel *et al* (1980) found that at maximum acceleration levels, frequencies near the resonant frequency of the body (4–5 Hz) caused high forces. The result also showed that at certain frequencies the vibration caused the muscles to produce a compressive load on the spine at the minimum amplitude of the vibration cycle.

Hansson *et al* (1991) demonstrated that exposure to whole body vibration in the seated posture accelerated the occurrence of back muscle fatigue and caused more pronounced muscular fatigue. They suggested that the development of fatigue could be caused by constriction of the arterial supply to back muscles.

Thus the effects of back muscle activity under sinusoidal vibration have already been well tested (Seidel *et al*, 1980; Seroussi *et al*, 1989; Hansson *et al*, 1991). For this reason the present study aimed at measuring back muscle fatigue along with taking discomfort ratings and measures of mechanical motion transmissibility, in order to identify the influence of seat and posture during simulated truck driving.

The aims of the study were to determine whether a truck seat with a gas spring in its suspension is superior to a standard spring seat in slowing the onset of fatigue and reducing the level of discomfort experienced during road vibrations while maintaining typical driving postures.

Materials and methods

Six male subjects, all free from low-back pain, volunteered for the study. Their mean age was 28.5 years (22–47), mean height 178.8 cm (172.7–190.5) and mean weight 72.6 kg (64.4–79.5).

Vibrations were recorded from truck rides on special test tracks corresponding to different road conditions. The rides chosen for the experiment were those from the 'handling track', which is a standardized test surface, similar to a road with low traffic flow, with obstacles such as uneven surfaces and wrongly cambered curves. The truck was driven by a professional driver at a speed of 70 km h^{-1}.

Acceleration transducers were placed on the floor of the driving cabin, recording accelerations in the *x*, *y* and *z* directions. The input channels were calibrated before the vibration signal was recorded. The tape recorder was a TEAC Racal Recorder. The vertical component of the recorded vibration was used to drive the baseplate of the servohydraulic, vertical vibration simulator powered by a 30 hp (22 kW) hydraulic pump (Figure 1) (Wilder *et al*, 1985).

Two types of truck seat were used, one of which had a steel spring in its suspension and the other a gas spring. The main difference between these two seats is that the steel spring system absorbs less energy than the gas spring system. We did not evaluate the mechanical characteristics of either the steel or gas spring. With the gas spring suspension, the seat height is automatically adjusted to the weight applied; ie, it keeps a constant height independent of the weight of the driver. Both seats had a back rest with lumbar support, which could be adjusted by means of air pressure. A steering wheel was attached in front of the seat and a bar functioned as foot pedals. The seat and pedal positions could be adjusted for each subject. The seat was placed directly on the vibration simulator. The steering wheel and foot pedals did not move with the platform and seat belts were not used. Three driving postures were chosen and tested on each of the two seats:

1 two hands on the side of the wheel while leaning forwards and resting the forearms on the wheel;

2 two hands on the side of the wheel while seated upright; and

3 seated back against the back rest.

There were thus six different experimental conditions. In order to improve the simulation, a video tape of a ride in traffic was displayed for the subject during the test (Figure 2). All together, the test situation was very similar to a real ride in traffic, although performed in the laboratory. It should be noted, however, that the subjects did not use the steering wheels or pedals to 'follow' the road in the video. Each subject was exposed for 10 min to each of the test conditions, presented in a random order.

The experiment, then, was a 2 × 3 (2 seats × 3 postures) repeated-measures design and was conducted on six subjects exposed to vibration. Three uniaxial accelerometers were used to measure the transmission of acceleration. One accelerometer was placed on the baseplate, another at the seat pan/driver interface and a third one was fixed on a bitebar, that was moulded for each subject. The outcome measures used to evaluate the effects of the experimental conditions were:

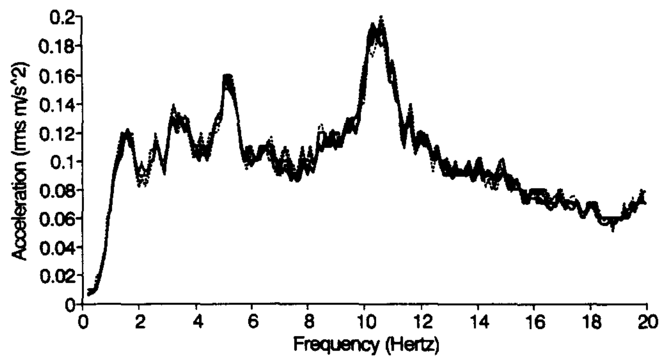

Figure 1 Frequency spectrum of the vertical vibration signal applied to the baseplate of the seat-shaker system. Each of six curves represents an average over the six subjects tested in a particular combination of seat type used and posture held. The six curves, each representing individual combinations of posture held and seat type used, are not revealed because of the tight overlap in the data

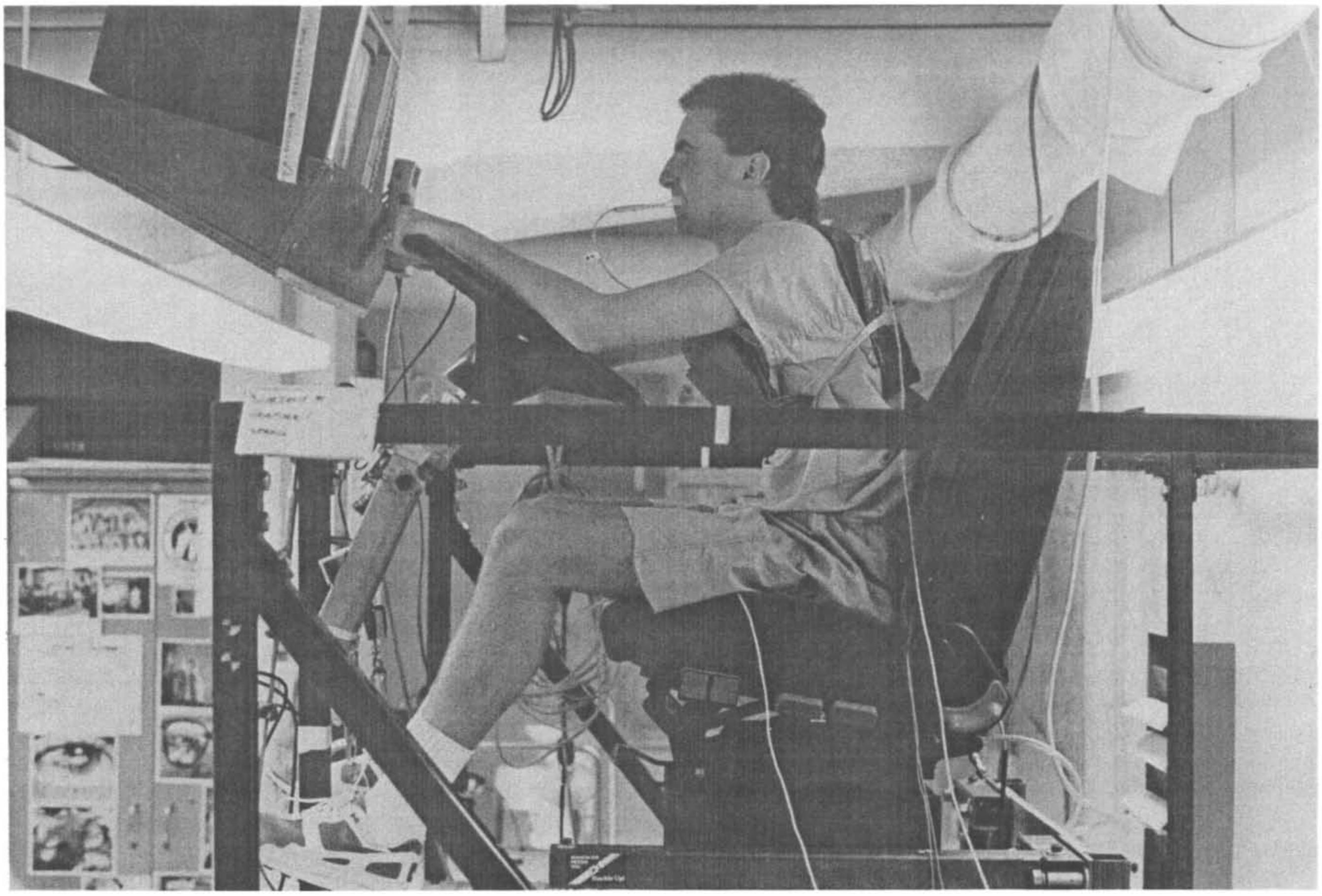

Figure 2 Side view of a subject on a seat on the shaker apparatus. He is holding the 'forward' seated posture while watching a videotape of driving and being vertically vibrated. A vertically oriented accelerometer is attached to the bitebar. The seatpan accelerometer is located between the seatpan and the subject's buttocks. Note the weight harness over his shoulder

1 ratings of subject comfort before and directly after the test, using a visual analogue scale;
2 muscle fatigue via median frequency of back muscle EMG determined during the vibration exposure; and
3 magnitude and phase of acceleration transfer functions both from the base plate to the seat pan and from the seat pan to the bite bar.

Discomfort assessment using a visual analogue scale (VAS)

The visual analogue scale provided a continuous scale for subjective magnitude estimation of any discomfort symptoms. It consisted of a straight line, the limits of which carried a verbal description of each comfort extreme. For the purposes of this experiment a line 10 cm long was used, ranging from 'very comfortable' to 'very uncomfortable'. Subjects were required to mark a point on the line that best described how they felt directly before and after the ride. Absolute and difference scores were calculated, the latter having been found useful in previous research (eg Reineke *et al*, 1993).

Muscle fatigue determination using electromyography

Muscle fatigue was monitored using changes in the spectral characteristics of the muscle electrical activity. As muscle fatigues, the amplitudes of its electromyographic spectral components shift so that the amplitudes of the lower frequencies increase and the upper decrease. This may also be due to a change of recruitment patterns (Örtengren *et al*, 1975). As a result, the median frequency shifts to a lower value.

For measurement of EMG, each subject had two pairs of surface electrodes attached (silver–silver chloride NDM 01-3810 ECG snap electrodes) to abraded, cleaned skin bilaterally over the erector spinae muscle groups at the L3 level (Figure 3). The inter-electrode distance was 4 cm. A ground electrode was placed in the mid-scapular region of the subject's back. Skin resistance between an electrode pair was generally about 25 kΩ.

The snap electrodes were connected to EMG amplifiers located at the electrode site. These amplifiers had a gain of about 3000, with a low frequency roll-off (−3 dB point) at 8 Hz, a flat response (±1 dB) to 10 kHz, and a common mode rejection ratio of about 100 dB. A foam rubber pad with cut-outs was used to protect the electrodes from contact with the seat back and, although it was not the intention that it be used as a lumbar support, some support was invariably provided in the 'full back' posture for both seats tested.

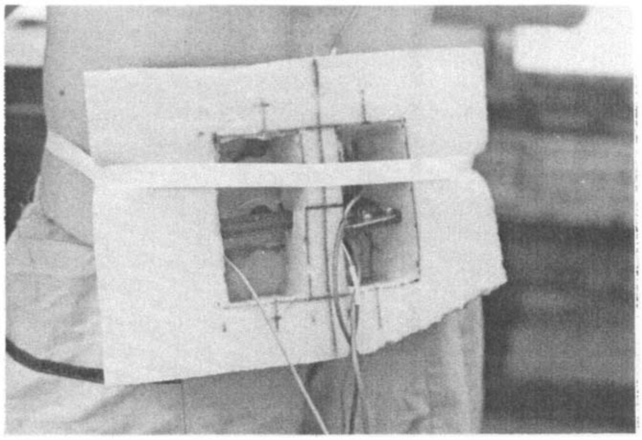

Figure 3 Electromyography preamplifiers and electrodes in place at the subject's L3 level. Note the foam rubber used to protect the EMG electrodes from contact with the seat. The foam rubber was kept in place under all test conditions and provided similar additional back support with each of the seats tested

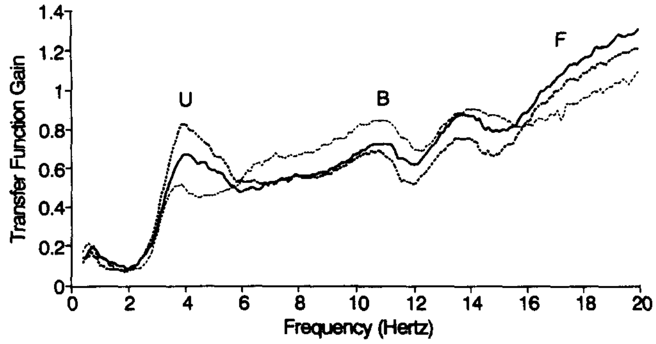

Figure 4 Transfer function gain of the regular seat suspension, from the baseplate to the seatpan. Note the effects of the different postures: sitting upright (U, heavy dotted line), sitting forwards (F, heavy solid line) and sitting back (B, light dotted line). Each curve is an average of the responses of the six subjects tested

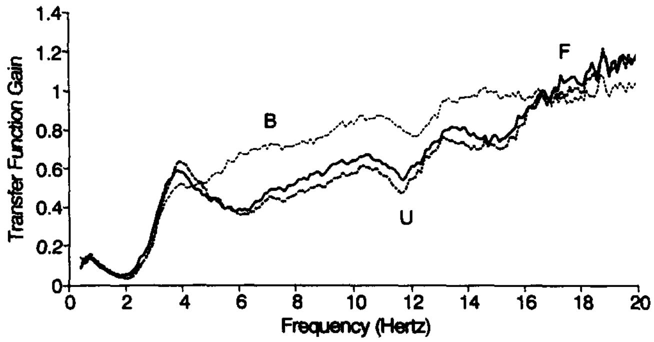

Figure 5 Transfer function gain of the gas seat suspension, from the baseplate to the seatpan. Note the effects of the different postures: sitting upright (U, heavy dotted line), sitting forwards (F, heavy solid line) and sitting back (B, light dotted line). Each curve is an average of the responses of the six subjects tested

Transmissibility

Acceleration transmission through an object is a common engineering method for assessing its response to vibration or impact (Pope *et al*, 1987). Both the seat suspensions and the seated human contain structures and materials that can heavily damp the vibration being transmitted. Motion damping that occurs between two points on a mechanism can be indicated by the difference in motion, acceleration being one such indicator. The difference between accelerations measured at two distinct points is called *relative acceleration*. In lightly damped conditions, relative acceleration can be expressed simply as a ratio of output divided by input. The heavy damping in both the seat and the subject necessitated taking the ratio of the difference between input and output compared with the input (Beliveau *et al*, 1986). The outcome measures used here were the transmission of acceleration from the baseplate to the seat pan (Figuress 4 and 5):

$$\frac{\text{Baseplate} - \text{Seat pan}}{\text{Baseplate}}$$

and from the seat pan to the bite bar (Figures 6 and 7):

$$\frac{\text{Seat pan} - \text{Bite bar}}{\text{Seat pan}}$$

These calculations were performed electronically over time. The electrical difference was obtained between the output and input acclerations and was considered as the response or output of the system and connected to the output channel of a Wavetek Rockland Model 582A cross-channel spectrum analyser for comparison with the input acceleration difference with respect to the input channel.

The transfer function magnitude and phase were then obtained from the acceleration difference with respect to the input. Acceleration transfer functions were obtained for the entire 10 min of each vibration exposure. Subject responses were then evaluated by analysis of variance to determine the combination of posture and seat suspension type that resulted in the lowest baseplate-to-seatpan and seatpan-to-bitebar resonant frequencies (where the transfer function phase relationship was −90°) and the lowest transfer function magnitude at the resonant frequency. In addition, the average transfer function magnitude was analysed in the following frequency ranges for the reasons given in parentheses:

- 1–20 Hz (the total range of clean data in the frequency domain);
- 4–8 Hz (this is the range where the sitting person is subjectively most sensitive to vertical vibration (ISO 2631, 1985));
- 4–6 Hz (the range in which the subject shows a mechanical natural frequency while sitting on a vibrating hard platform);
- 1–4 Hz (the region to which vehicle seat manufacturers try to shift the seat–driver natural frequency);
- 6–20 Hz (the range where average transmissibility is sensitive to posture).

A transfer function magnitude less than 1.0 and as close to zero as possible is the most desirable result. Any resonating structure or machine, especially where the transfer function exceeds 1.0, is more susceptible to

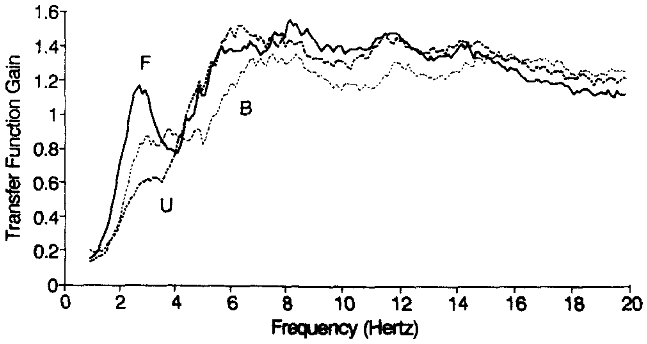

Figure 6 Transfer function gain of the regular seat suspension, from the seatpan to bitebar. Note the effects of the different postures: sitting upright (U, heavy dotted line), sitting forwards (F, heavy solid line) and sitting back (B, light dotted line). Each curve is an average of the responses of the six subjects tested

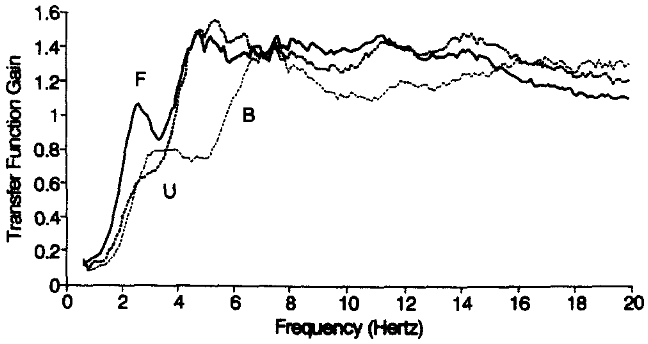

Figure 7 Transfer function gain of the gas seat suspension, from the seatpan to the bitebar. Note the effects of the different postures: sitting upright (U, heavy dotted line), sitting forwards (F, heavy solid line) and sitting back (B, light dotted line). Each curve is an average of the responses of the six subjects tested

mechanical failure. At resonance a structure acts as a mechanical amplifier, ie, increases its internal stresses and strains, and consequently is more prone to mechanical fatigue failure. A transfer function magnitude below 1.0 would indicate that the seat is attenuating vibration, hence reducing the cyclic loading in the seated subject's lumbar region. Therefore it is desirable that the transfer function magnitude be as low as possible.

Test procedure

EMG electrodes were applied to the left and right erector spinae muscles using the technique described above. Skin impedance was measured using a voltmeter to ensure that the values recorded were less than 40 kΩ. A piece of square rubber foam (30 cm × 20 cm) hollowed out in the centre was then placed over the L3 vertebra region of the back to protect the electrode amplifiers. Subjects were required to sit on either the gas spring or standard seat fixed on the vibration apparatus. Seat height and distance from control positions were adjusted so that knee flexion angle was always 100° (Figure 2).

A purpose-made harness, seen in Figure 2, with 22.2 N weights placed in each of the front and back pouches, was draped over the subject to increase the load on the upper body and hence to accelerate fatiguing effects. The subjects were then told to sit in one of the three postures described earlier on either the regular seat or gas spring seat. The visual analogue scale (VAS) was used to rate the comfort of the person before the test session. In addition to the accelerometer mounted on the baseplate, an accelerometer was placed on the seatpan and also on a bitebar placed in the person's mouth. Each subject was exposed to 10 min of vibration in one of the six driving conditions, selected in a random order. EMG activity of the erector spinae muscles as well as the amount of vibration occurring at the baseplate, seatpan and bitebar were recorded. Following vibration exposure, subjects assessed discomfort as before using the VAS.

Each subject was given a 20 min recovery period, during which time they were allowed to walk around but not sit down. This procedure was repeated for all subjects for all test conditions. On any one day only one of the two seats was used. This meant that each subject had to attend two experimental sessions on separate days.

Results

Comfort via visual analogue scale

The analysis of the VAS data used absolute and difference scores (pre/post exposure) for the six seat × posture conditions. These data are shown in Table 1.

Regardless of seat, the upright posture was the most uncomfortable one and produced significantly more discomfort than the fullback posture, as detected using the VAS.

The seat design did not significantly affect discomfort levels.

Table 1. Visual analogue scale (VAS), pre- and post-exposure and the difference between them

	Standard-spring seat			Gas-spring seat		
Posture	**Before**	**After**	**Difference**	**Before**	**After**	**Difference**
Forward	4.30	5.82	1.52	4.78	6.03	1.25
Upright	4.23	7.37	3.14	4.85	7.10	2.25
Full-back	3.10	5.10	2.00	3.97	5.05	1.08

0 indicates the least discomfort and 10 the most

Fatigue via centre frequency shift during vibration exposure

During the vibration exposure, measurements were made to determine the centre frequency of the muscle-firing behaviour, along with the (slope) rate of change of the centre frequency. This was done during vibration in the time periods 0–250 s and 250–600 s after the start of the experiment and then during the rest at the end of the experiment.

Muscle fatigue during vibration was detected by centre frequency determination every 10 s. The rate of change or slope of the centre frequency shift over the first 250 s was the dependent variable. This showed that there were no significant effects of either the seat used or the posture held on the rate of erector muscle fatigue (change in the muscle centre frequency with time) in the first 250 s of vibration exposure. Using the mean centre frequency for each of the three time segments (0–250 s, 250–600 s and 600–700 s) in the complete statistical model also showed that there was no effect due to the seat used. However, there were significant effects due to the following factors.

1 The side of the back measured: the mean centre frequency for the left erector spinae group exceeded that of the right ($p < 0.05$). Thus the left side was less fatigued than the right side.

2 The posture held: the centre frequency of the muscle activity for the upright posture was lower than the forward or full-back posture ($p < 0.05$). Thus there was more fatigue during upright sitting than during any other posture, as detected by the centre frequency difference.

3 The duration that a posture was held: the overall significance level for interactions between time and posture was $p = 0.0205$. There was no difference in centre frequency over time within posture held. Within time segments, there were average centre frequency differences between postures at the significance level of $p < 0.05$:

0–250 s	upright < full-back < forward
250–600 s	upright < full-back = forward
600–700 s	upright < full-back = forward

Transmissibility results

The mean transmissibility values within stated frequency ranges between the baseplate and the seatpan are listed in Table 2. Baseplate vibrations were attenuated, ie transfer function values were below 1.0, in all the stated frequency ranges.

The baseplate to seatpan transmissibility was:

1 significantly ($p = 0.01$) affected by *posture* at the higher frequency levels (6–20 Hz). Sitting back caused significantly higher acceleration transmission to the seatpan than did sitting upright.

2 significantly ($p = 0.03$) affected by an interaction between the seat used and the posture held in the 4–6 Hz range. Only in the upright posture did the gas-spring seat transfer significantly less motion to the seatpan than did the regular seat. In the other two postures, the amount of motion transferred to the seatpan was similar for both seats.

3 significantly ($p = 0.01$) affected by an interaction between the seat used and the posture held in the 4–8 Hz range. Only in the upright posture did the gas-spring seat transfer less motion to the seatpan than did the regular seat. In the other two postures, the amount of motion transferred to the seatpan was similar with either seat used. When using the regular seat, the postures held had equal effects on vibration transmission from the baseplate to the seatpan. When using the gas-spring seat, the transmission was significantly higher when sitting back than when sitting upright or forwards. There was a marked difference in the mechanical behaviour of the gas-spring seat when the subject sat back.

Table 2 Average transfer function magnitudes between the baseplate and the seatpan, in the indicated frequency ranges

Frequency range (Hz)	Posture	Spring	Gas
1–4	Forward	0.274	0.243
	Upright	0.310	0.229
	Full-back	0.229	0.210
4–6	Forward	0.581	0.451
	Upright	0.676	0.472
	Full-back	0.479	0.564
4–8	Forward	0.554	0.456
	Upright	0.607	0.445
	Full-back	0.557	0.632
1–20	Forward	0.704	0.643
	Upright	0.674	0.611
	Full-back	0.690	0.739
6–20	Forward	0.814	0.757
	Upright	0.754	0.714
	Full-back	0.821	0.880

Data obtained from curves in Figures 4 and 5

The mean results for the transmissibility evaluation between the seatpan and the bitebar are shown in Table 3. Vibrations were attenuated in the low-frequency range (1–4 Hz), but were amplified in the frequency ranges 4–6 Hz, 4–8 Hz and 6–20 Hz.

The seatpan to bitebar vibration transmissibility was:

1 significantly affected by posture in all but the 6–20 Hz frequency level. Sitting back caused significantly lower vibration transmission from the seatpan to the bitebar than sitting forward (except in the 6–20 Hz range) and than sitting upright at 4–6 Hz, 4–8 Hz and 1–20 Hz. Forward sitting was always, except at 1–4 Hz, similar to upright sitting.

2 not affected by the seat used nor the interaction between the seat used and posture held at any frequency range.

The natural frequencies and the magnitude of transfer functions of the system between baseplate and seatpan are presented in Table 4. Neither posture nor seat had any significant effect on natural frequency nor transmissibility at that frequency.

The type of seat did not affect the natural frequency of the system between the seat and the bitebar. Nor did the seat suspensions affect the transmission magnitude. Posture was a significant factor for the natural frequency, being greater for the upright posture than for either of the two other postures. Posture did not, however, affect the transfer function magnitude at the natural frequency (Table 5).

Discussion

In an ideal world, vehicle seat suspension systems would attenuate all motion, preventing shock and vibration from reaching the driver. Because this is the real world, trade-offs exist for designs of mass-marketed mechanical systems of any kind. Development, production and marketing costs are balanced against design requirements. In the case of vehicular seating, design constraints are changing based on epidemiological and mechanical evidence that long-term exposure to vehicular shock and vibration leads to low-back pain (Kelsey and Hardy, 1975; Heliövaara, 1987; Kelsey and Golden, 1988; Bongers and Boshuizen 1990; Magnusson *et al*, 1993a). In a similar fashion to manufactured structures and mechanisms, the seated human exhibits a phenomenon called *mechanical resonance*. When the resonant frequency of a seated subject is excited by shock or vibration, the vibration transmissibility from the seatpan to the head exceeds 1.0 (Wilder *et al*, 1982, 1985; Pope *et al*, 1987). This means that the acceleration along the spine will exceed that of the seat and is mechanically significant in the production of low-back pain (Wilder, 1993).

Table 3 Average transfer function magnitude between the seatpan and the bitebar in the indicated frequency ranges

Frequency range (Hz)	Posture	Spring	Gas
1–4	Forward	0.748	0.742
	Upright	0.464	0.520
	Full-back	0.599	0.498
4–6	Forward	1.126	1.375
	Upright	1.174	1.417
	Full-back	0.948	0.829
4–8	Forward	1.265	1.379
	Upright	1.311	1.408
	Full-back	1.115	1.059
1–20	Forward	1.217	1.226
	Upright	1.190	1.220
	Full-back	1.126	1.078
6–20	Forward	1.332	1.310
	Upright	1.351	1.344
	Full-back	1.266	1.241

Data obtained from curves in Figures 6 and 7

Table 4 Natural frequency and transmissibility of the system between baseplate and seatpan

	Natural frequency		Transmissibility	
	Spring	Gas	Spring	Gas
Forward	4.02	5.48	0.65	0.61
Upright	4.05	3.97	0.88	0.64
Full-back	4.97	5.42	0.59	0.64

Table 5 Natural frequency and transmissibility of the system between seatpan and bitebar

	Natural frequency		Transmissibility	
	Spring	Gas	Spring	Gas
Forward	2.72	2.92	1.13	1.20
Upright	4.60	4.13	1.26	1.31
Full-back	3.33	3.42	0.93	0.88

The work undertaken here attempted to quantify the relative benefit of an improved suspension system in a truck seat. Seat suspension design changes revolved around using a pneumatic cylinder to act as a spring with both stiffness and damping characteristics, and the ability to adjust easily to the body weights of different drivers. Seated subject responses were measured in each of three areas: subjective comfort, muscle fatigue and mechanical motion.

Subjective comfort assessment

One of the measures taken was that of subjective comfort using a visual analogue scale. Driver comfort is important because it will dictate how willingly a driver will use a seat and vehicle. Comfort is apparently easy to detect: for instance, a brief exposure to a 'comfortable' seat is used as a selling point in the vehicle showroom. In contrast in this study our sample was unable to discriminate between the two different seat designs in terms of comfort assessment. The marginally insignificant interaction of seat and time (ie before vibration exposure versus after) was primarily affected by the effects over time and not by the essentially indistinguishable effect of seat type. At the same time, the traditional seat with the metal spring suspension was marginally more comfortable in four of the six comparisons, but there was less degradation in comfort with the gas-suspension seat.

Back muscle fatigue

Back muscle fatigue is an indicator of the status of the primary postural controllers and points out how well the seat suspension accommodates by attenuating the vibration environment. Fatiguing effects as determined by median frequency of muscular activity did not significantly change with the two different seats. Perhaps if the tests were run for a longer time period or if heavier sacks were used (Magnusson *et al*, 1988) an increased response would occur. The muscles did, however, have different fatigue levels from dominant to non-dominant side. This is probably due to small habitual posture asymmetries, but this would benefit from further studies. Unsupported upright sitting produced more fatigue, lower mean centre frequencies, than did either supported forward or backward sitting. The posterior trunk muscles fatigued much sooner when exposed to an upright posture than during supported postures while leaning forwards with support or sitting back against a backrest. Thus the posture that caused greatest loading, ie, upright unsupported sitting, caused greatest muscle fatigue.

Mechanical motion

Measuring motion at three points on the seat–subject system yielded information that was most useful to discriminate differences between postures and seat designs. Where comfort and muscle fatigue were measures of the human response or indirect indicators of the environment, motion measurement proved the most direct measure of the environment and the body's mechanical response. Motion of the seatpan can be compared directly with suggested vibration exposure limits, such as the British vibration standard BS 6841 (1987) and the ISO FDP limits for task proficiency (ISO, 1985). Relative motion between the seatpan and bitebar can be used to predict vibration loading levels at the intervertebral disc (Seidel *et al*, 1980; Wilder *et al*, 1985; Seroussi *et al*, 1989; Wilder, 1993).

Mechanical motion at the natural frequency

A vibrating system can be characterized by parameters associated with its natural frequency. But these are only specific to one frequency and, in this case, using only system natural frequency characteristics would give misleading results. Neither seat suspension type nor posture had a significant effect on natural frequency or on transfer function magnitude at the natural frequency in the baseplate-to-seatpan system. Based solely on these data, there was no difference between the two seats in terms of effect on vibration transmission to the subject.

The type of seat suspension also had no effect on natural frequency or the transmissibility of the system between seatpan and bitebar, whereas posture was a significant factor. The natural frequency of the upright posture was greater than the equivalent natural frequencies of the forward and full-back postures. That the natural frequency of the upright posture was higher indicated that the driver is mechanically stiffer when sitting upright. This makes sense, as the upper body's spinal axis is aligned with the vertical acceleration vector when sitting upright and oriented away from the vertical when sitting forwards or full back. The centre of gravity of the upper body will be more in line over the base of support when sitting upright, and will be forward or behind that base when leaning forwards or backwards. While some friction damping may be occurring at the seat back/clothing interface, it is likely that the clothing/soft tissue/skeleton interface allows free sliding and very little damping. While an increasing seat-back angle can reduce the vertical reaction force at the seat base (Wilder *et al*, 1993), it is not clear whether there is any damping of the upper body motion.

Sitting forward differs from sitting against the backrest. When sitting forwards, the subject rested on the steering wheel, thereby isolating the upper body, hanging from the shoulders and removing the effect of the upper and lower arms. Sitting against the backrest allowed distributed support of the back from its base to the shoulder blades. The mass of the arms was included with the upper body in that case. When the spine is upright it behaves as a column in compression. When leaning forwards or backwards, the spine acts as a beam bending about a base. The spine's compressive stiffness is higher than its flexion or extension stiffness (Schultz *et al*, 1979; Tencer *et al*, 1982). Therefore, the natural frequency of the upright posture would be expected to be higher. These are the differences between sitting upright and sitting forwards or backwards.

The authors understand that there is a complex mechanical system, consisting of many parts, located between the seatpan and the bitebar. Several groups have done valuable work defining the motions that occur, either in standing or sitting vibration environments (Christ and Dupuis, 1966; Hagena *et al*, 1986a, 1986b; Panjabi *et al*, 1986; Pope *et al*, 1986; Sandover and Dupuis, 1987; Kaigle *et al*, 1992; Magnusson *et al*, 1993b). The objective of this present work was to measure the effect of positions maintained in different seats on the net acceleration transfer from the seatpan to the bitebar. We acknowledge that there are many motions occurring within the system between those points that would affect local flexion and extension during each oscillation and the phase-shift behaviour within the spine.

Mechanical motion at other frequencies

The type of seat suspension used made no significant difference in transmission of vibration through the back of the seated operator, from the seatpan to the bitebar. There were significant differences due to posture. Sitting backwards engendered a significantly smaller vibration transmissibility to the bitebar than did sitting forwards or sitting upright.

Between the baseplate and the seatpan the gas-suspension seat was generally found to be better under controlled, upright seated conditions than the traditional seat. However, the gas suspension significantly increased the motion to the seat pan when the subject sat forwards or leaned back.

A seat suspension located below the seatpan can, under certain conditions, decrease the absolute vibration levels to the seatpan and the vibration transmission through the body. In this respect the best results occurred when the subject sat back in the seat and the natural frequency decreased and the acceleration was attenuated. This provides a useful, if not unexpected, recommendation that can be made to drivers. Unsupported postures, which also cause higher muscle contractions, should be avoided.

Seat design and testing considerations

It is possible to design a seat suspension that will attenuate vibration to the driver and through the driver. The seat designer must be cautioned, however, on how the seat is tested. The use of rigid masses to assess the attenuation will produce results that differ from those for an actual person. Although none of the tests described in this work was performed with rigid masses such as a test dummy, the most rigid posture, sitting upright, showed that there was a large difference between suspension types. Therefore, in order to show that a vehicle seat reduces vibration to the driver, confirmatory testing should be done with people, until accurate mechanical test dummies are available. These suggestions have also been made by Smith (1988, 1992) based on work with primates.

Seat purchasing and acceptance considerations

Epidemiologic data (Kelsey and Hardy, 1975; Heliövaara, 1987; Golden, 1988; Bongers and Boshuizen 1990) confirm that prolonged exposure to vibration environments leads to low-back pain. In order to minimize the significant attendant human suffering and financial costs, those considering the purchase of vehicle seating should make sure that the seat suspension provides sufficient vibration attenuation. Because vibration-induced low-back pain is certainly a dose-related phenomenon (Riddell *et al*, 1966; Hertzberg and Manson, 1980; Weisman *et al*, 1980; Fung, 1981), it is important that the seating purchaser knows the mechanical characteristics of the environment involved. With that information, the purchaser can then make it incumbent upon the vehicle or seat vendor to ensure that the vibration environment reaching the driver will not exceed the ISO, vertical, 16 h, fatigue, decreased-proficiency limit (ISO, 1985). This is based on observations that the ISO, vertical, 8-hour FDP limit is not conservative enough to prevent low-back pain (Bongers and Boshuizen, 1990) or mechanical changes in the lumbar spine motion segment (Wilder *et al*, 1989).

Although the seated human is especially sensitive to vertical vibration in the 4.5–5.5 Hz range, vibration and shock should be attenuated as much as is practical not only at these frequencies, but also at lower and higher frequencies. Work by Hagena *et al* (1986) and Wilder and Pope (1993) has shown the vibration-amplifying capacity of the lumbar region outside the narrow range of the seated operator's natural frequency. Sitting is an extreme posture for the intervertebral disc in the lumbar spine and affects it by increasing its posterior height (Galante, 1967; Farfan, 1973; Panjabi and White, 1978; Krag *et al*, 1987), increasing its intradiscal pressure (Nachemson and Morris, 1964; Okushima, 1970; Andersson, 1974) and destabilizing the spine by the slight disengagement of its articular facets (Panjabi *et al*, 1977; Schultz *et al*, 1979; Tencer *et al*, 1982). With vibration, a combined flexion–compression repetitive loading typical in sitting would be superimposed on the mechanically less robust posterior aspect of the disc (Galante, 1967). This condition represents a significant repetitive loading environment, accelerated by higher loads and higher frequencies, leading to fatigue of the material comprising the intervertebral disc.

Conclusions

These experiments have demonstrated a method for evaluating truck seats, in the laboratory, that mechanically simulates real driving conditions and is capable of distinguishing betweeen seat types and the postures adopted on them. Seat suspensions can modify vehicular vibration environments if designed and tested with appropriate considerations for the driver who is subject to vibration-induced low-back pain. Neither subjective comfort assessment, fatigue rate (rate of median frequency change) nor fatigue average (average median frequency) could detect differences in seat type or seat suspension design in short-term, 10 min, vibration exposure. Fatigue and comfort measures could continue to be used to detect postural effects, but the more sensitive measures of seat–driver interactions remain mechanical, using motion-measuring techniques such as accelerometry, and correcting for the heavily damped nature of the system. Until more sophisticated manikins are available, the characteristics of vibration-attenuating seats should be confirmed using human subjects.

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