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Reducing whole-body vibration and musculoskeletal injury with a new car seat design

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A new car seat design, which allows the back part of the seat (BPS) to lower down while a protruded cushion supports the lumbar spine, was quantitatively tested to determine its effectiveness and potentials in reducing whole-body vibration (WBV) and musculoskeletal disorders in automobile drivers. Nine subjects were tested to drive with the seat in: 1) the conventional seating arrangement (Normal posture); and 2) the new seating design (without BPS (WO-BPS) posture). By reducing contact between the seat and the ischial tuberosities (ITs), the new seating design reduced both contact pressure and amplitude of vibrations transmitted through the body. Root-mean-squared values for acceleration along the z-axis at the lumbar spine and ITs significantly decreased 31.6% ($p < 0.01$) and 19.8% ($p < 0.05$), respectively, by using the WO-BPS posture. At the same time, vibration dose values significantly decreased along the z-axis of the lumbar spine and ITs by 43.0% ($p < 0.05$) and 34.5% ($p < 0.01$). This reduction in WBV allows more sustained driving than permitted by conventional seating devices, by several hours, before sustaining unacceptable WBV levels. Such seating devices, implemented in large trucks and other high-vibration vehicles, may reduce the risk of WBV-related musculoskeletal disorders among drivers.

Keywords: Whole-body vibration; Vehicle; Seat; Ergonomics

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1. Introduction

In 2001, back-related injuries accounted for almost 400 000 cases of work-related injuries in the United States (US Department of Labor 2003). Those whose occupations involve extended periods of driving, i.e. transit operators, truck, taxi and bus drivers, are at high risk for developing chronic musculoskeletal disorders, particularly those involving the lumbar spine (Griffin 1990, Porter and Gyi 2002, Massaccesi *et al.* 2003). These disorders may result from a combination of long-term exposure to whole-body vibration (WBV) and poor sitting posture (Johanning 1991, Boshuizen *et al.* 1992, Pope *et al.* 1998, Ebe and Griffin 2001, Porter and Gyi 2002, Massaccesi *et al.* 2003).

WBV exposure in vehicle drivers results from vibration that passes from the machinery through the buttocks and supporting areas of the back of seated individuals (Mabbott *et al.* 2002). Prolonged exposure to WBV may lead to adverse effects on health, activities and comfort, and may cause motion sickness (Mackie and Miller 1978, Lisper *et al.* 1986). An overview of the literature indicated that WBV exposure experienced by occupational drivers leads to muscle fatigue and weakening of the lumbar musculature, resulting in decreased spinal support and an increased risk of spinal injury (Pope *et al.* 1998). It has been suggested that over-exposure to WBV may result in lumbar disc disease (Seidel *et al.* 1986, Schwarze *et al.* 1998, Russo *et al.* 2001), and tissue failure or metabolic interference (Panjabi *et al.* 1986). Coupled with poor posture, extreme exposure to WBV may even result in lumbar disc failure (Wilder *et al.* 1996). Although an exact dose-response relationship has not yet been specifically identified between WBV and low back pain (LBP) (Griffin 1990, Thalheimer 1996), the most widely reported injury associated with WBV is LBP (Boshuizen *et al.* 1992, Bovenzi 1994, Pope *et al.* 1998, Varghese *et al.* 2001, Mabbott *et al.* 2002).

Tolerance limits for exposure to WBV vary with frequency and amplitude of the vibration and with vehicle type (Schwarze *et al.* 1998, Mansfield and Griffin 2002, Paddan and Griffin 2002). Although not as severely exposed to vibration as operating heavy machinery (Randall 1992, Maeda and Morioka 1998) and heavy transit vehicles (Swetman and McFarlane 2000), driving a regular passenger car also predisposes drivers to serious WBV (Chen *et al.* 2003, Funakoshi *et al.* 2004) and, therefore, to musculoskeletal disorders (Porter and Gyi 2002).

Unlike sitting in a chair traditionally, a driver cannot depend on his/her feet to assist with the support of the body because they are primarily devoted to the operation of pedals (Andreoni *et al.* 2002). Body balance and control, therefore, have to be assured by the seat and the backrest. Seats that do not accommodate the size and shape of an individual's body will force the occupant into a poor sitting posture. Thus, lack of effective adjustable seats correlates with LBP in long-term drivers (Porter and Gyi 2002). Also, a heightened awareness of high sitting interface pressure (Andreoni *et al.* 2002) and poor sitting posture (Gyi *et al.* 1998), caused by current vehicle seats (Grieco 1986), has raised attention for better ergonomic design (Massaccesi *et al.* 2003).

Various efforts have been made to decrease the risk of musculoskeletal injuries for long-term drivers. Most of the literature dealing with prevention of harmful WBV tends to favour habitual changes such as limiting WBV exposure periods (Johanning 1998, Funakoshi *et al.* 2004) or driving at lower speeds (Chen *et al.* 2003). These suggestions may be unrealistic or costly in a transportation industry where speed and time fuel profits. Other interventions call for elaborate suspension systems for the seat, cab and body of the vehicle (Patil *et al.* 1977, Donati 2002). Suspension systems have had some success but are often too expensive for implementation in a cost-effective manner. Nevertheless, others maintain that correcting awkward sitting postures is the key to

reducing musculoskeletal injury (Pope *et al.* 1998). However, Mansfield and Griffin (2002) showed that nine different sitting postures provided relatively the same transmissibility of vibration through the body. But none of these postures sought to drastically reduce pressure on the ischial tuberosities (ITs). In tests on wheelchairs, however, DiGiovine *et al.* (2000) demonstrated that by softening the seat at the ITs WBV is significantly reduced. The effect of near complete pressure relief of the ITs, as per this investigation, has not been addressed.

A new seating design was proposed (figure 1) that corrected posture in two ways. First, a padded protrusion was implemented to support the lumbar spine (L2 to L5 level). Second, the back part of the seat (BPS) was tilted down 20° so that the ITs were suspended with minimal seat contact. This posture, referred to as without BPS (WO-BPS), has been demonstrated on stationary office chairs to significantly reduce interface pressure on the subject's ischium, increase total and segmental lumbar lordosis, forwardly rotate the sacrum, increase lumbar intervertebral heights and decrease electromyogram (EMG) activity from most of the back muscles (Makhsous *et al.* 2003a). Furthermore, the pilot study (Makhsous *et al.* 2003b, 2004a,b) demonstrated that sitting alternately between Normal (with the BPS at the level and without lumbar support) and WO-BPS postures during prolonged sitting dynamically redistributed contact pressure and significantly reduced peak pressure over the ischium, promoted tissue viability and prevented skin temperature elevation.

The purpose of this study was to investigate the effectiveness of a new vehicle seat design featuring the WO-BPS posture in reducing WBV in vehicle drivers. The hypotheses were:

1. When the WO-BPS posture is applied, pressure on the ITs will be reduced and shifted to the thighs, providing a softer contact between the body and seat.
2. Reduction in WBV will be observed with an increased damping effect to vibration when the WO-BPS posture is applied.



Figure 1. The new seating design as implemented in the testing vehicle. BPS = back part of the seat.

2. Methods

2.1. Participants

The study was approved by the Institutional Review Board of Northwestern University. For the driving test, seven male and two female volunteers gave written informed consent to participate in the study. Their mean age, weight and height were 24.2 (SD $\pm$ 8.7) years, 73.8 (SD $\pm$ 14.6) kg and 179.6 (SD $\pm$ 5.8) cm, respectively. For the seat interface pressure measurement, in addition to the nine participants from the driving test, eight more volunteers consented to take part. The mean age, weight and height of these 17 volunteers (eight females and nine males) were 31.3 (SD $\pm$ 9.7) years, 76.2 (SD $\pm$ 26.8) kg and 169.3 (SD $\pm$ 10.0) cm, respectively. All participants in this study were healthy, licensed drivers, with no history of musculoskeletal disorders.

2.2. Road

The testing route was a 5-mile closed segment of a local expressway. It was a typical road in the area, with four lanes in each direction and no traffic lights, which gave a safe driving zone to keep a constant cruise speed without being disturbed by traffic signals or other vehicles. The road condition was moderately bumpy, representative for the local area, with small road surface damages and repaired patches typically between 0.5 m and 1.5 m in length. The route contained very few curves, minimizing any weight shift secondary to centripetal force. Tests were conducted out of the rush hours to avoid traffic jams. The participating drivers were instructed to remain in the far right lane to avoid being distracted by other speeding vehicles. The high speed limit on this route was 40 mph and it was neither too slow to block the traffic, nor too high to increase the need to frequently pass other vehicles. Participants were instructed to remain in the far right lane for the length of each trial. All trials were performed between 4 and 15 August 2003. Weather on each testing day was seasonable (21–30°C) with no significant wind and no precipitation.

2.3. Experimental set-up for whole-body vibration assessment

2.3.1. Standards. Current international standard ISO 2631–1:1997 (International Organization for Standardization 1997) for WBV assessment was followed for the placement of the accelerometers, the vibration evaluation method and the frequency weighting for accelerations.

2.3.2. Car and experimental seat. The automobile used was a mid-sized passenger car (Nissan Maxima 1993 with 160 000 km mileage) maintained in good running condition with a 160-horse power V6 engine. Its curb weight was 1427 kg, and its wheelbase was 2.6 m. The driver-side seat was replaced with a new seating design incorporating WO-BPS posture (figure 1).

The experimental seat was mounted on the driver side of the testing vehicle. Since the tilting angle of the seat cushion from the native seat could not be adjusted, the experimental seat was mounted in the same seat tilting angle as demonstrated by the adjacent passenger seat (figure 1). The seat back angle of both experimental seat (driver side) and the native passenger seat was fixed at 20° backward inclination from the vertical direction, which formed approximately a 90~100° hip flexion angle for the driver, considering that the seat cushion was naturally tilted backward about 10°.

The experimental seat followed almost exactly the shape and the fabric seat cover of the native seat (figure 1).

2.3.3. Hardware. Nine tri-axial accelerometers, each custom-made from two miniaturized dual-axial accelerometers (ADXL210E, Analog Devices Inc., Norwood, MA, USA), were used to measure WBV of the driver. All accelerometers were calibrated before use with the method recommended by the manufacture (Analog Devices 2002). A calibration factor in the unit of $\text{m/s}^2/\text{V}$ was obtained for each axis of each accelerometer. In each experiment, signals from the accelerometers were conditioned with a 250 Hz low pass filter and then sampled in real-time at 500 Hz with two PCMCIA data acquisition cards (DAQCard 6036E, National Instruments, Texas, USA) plugged into two laptop computers. The two data acquisition cards were synchronized.

2.3.4. Placement of accelerometers. Vibration for seated operators was measured in three orthogonal directions in which the x-axis was in the direction of travel and the y-axis was transverse to it, pointing from the right side to the left. The z-axis was in the vertical direction passing through the body segment.

Nine tri-axial accelerometers were placed in the following positions (figure 2):

1. IT: on the ischial tuberosity of the pelvis on the right side.
2. Lumbar spine: 'lumbar spine' between L2 and L5.
3. Knee: the lateral epicondyle of the femur.
4. Ankle: the lateral malleolus of fibula.

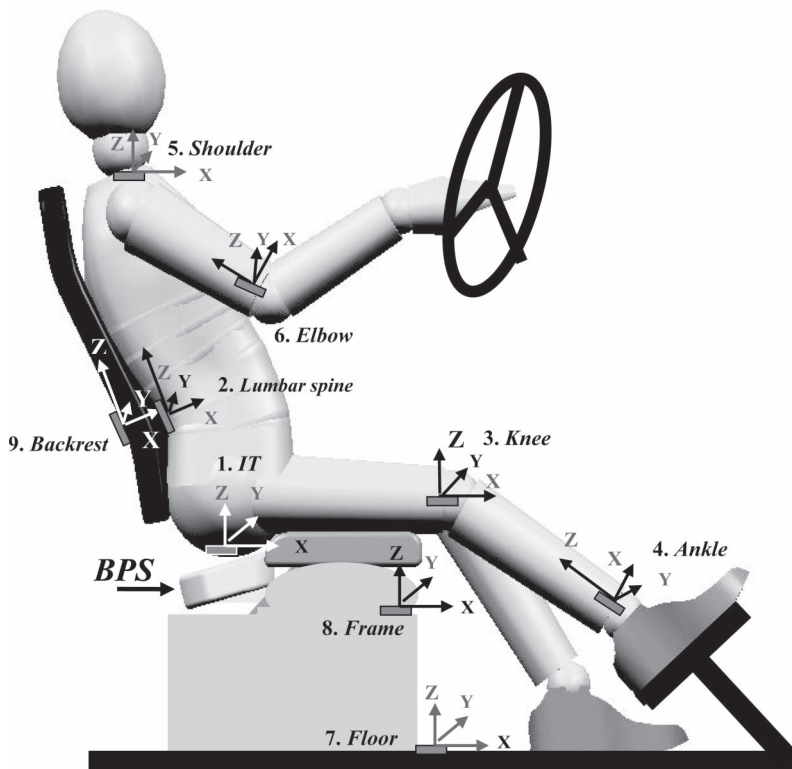


Figure 2. Locations and orientations of the nine tri-axial accelerometers on the subject and frame of the testing vehicle. IT = ischial tuberosities; BPS = back part of the seat.

5. Shoulder: the acromion at the acromio-clavicular joint.
6. Elbow: the medial epicondyle of the humerus, aligned with elbow axis.
7. Floor: On the steel frame of the floorboard under the seat.
8. Frame: On the steel frame of the seat near the BPS.
9. Back: On the seat frame near the lumbar region of the backrest.

Signals were recorded from the accelerometers in the x, y and z axes and then converted to acceleration (ms^{-2}) based on prior calibration factor.

2.4. Experimental set-up for interface pressure assessment

Contact pressure distribution on the seat–buttocks and back–backrest interfaces was recorded in the laboratory on this new driver seat for both the Normal and WO-BPS postures. XSensor[®] pressure mapping system (X36, XSENSOR Technology Corp., Alberta, Canada) was used.

2.5. Protocol

Driving tests were conducted in both driving directions on the testing route, i.e. driving towards north and coming back south. Each participant performed two trials in each driving direction, with one trial performed with the seat in the Normal (BPS remained level) posture and one in the WO-BPS posture. All trials started at the same marked road sign and lasted for 200 s. The cruise control was activated to ensure that the driver maintained a constant speed of 17.88 ms^{-1} (40 mph). A trial was prematurely terminated and not analysed if there were any lane changes or speed changes.

In a separate laboratory experiment, the seat interface pressure map was recorded in this experimental driver seat for each of the 17 participants in both Normal and WO-BPS configurations. During the recording, the experimental seat was set up in the same seat and back angles as when it was in the car. The participant was instructed to put his/her hands on the thighs. The participant had the right foot slightly pushed against a wood block on the floor in front of the seat simulating operating the gas pedal and the left foot rested on the floor. Both legs were moderately stretched forward with the knee flexed at 30° . One 5-min trial was performed for each posture and a 5-min break was allowed between the trials. The pressure map was recorded at 1 Hz.

2.6. Data processing

2.6.1. Whole-body vibration. Root-mean-square (RMS) values and vibration dose values were calculated for the three directions in all nine accelerometers according to the following equations (ISO 2631–1:1997):

$$RMS = \sqrt{\frac{1}{T} \int_0^t a_w^2(t) dt} \quad (1)$$

$$VDV = \sqrt[4]{\frac{1}{T} \int_0^t a_w^4(t) dt} \quad (2)$$

RMS values yield a good running estimate of the vibration absorbed by a body undergoing moderate vibrations with little shocks, i.e. an exposure measure of the vibration, while vibration dose values (VDVs), which is a measure of dose of the vibration, allow more preference to shocks and jolts (Griffin 1990). In the calculation of RMS and VDV, a_w was the frequency-weighted acceleration time history (Mabbott *et al.* 2002, Goglia *et al.* 2003). Weighting for acceleration values was performed according to ISO 2631–1:1997 using W_k .

Since the effect on WBV from using the new driver seat concept was unknown and it might be very small, it was necessary to develop a well-defined data processing method to prevent the possible seat effect being masked by the variations in the total car vibration from trial to trial and from subject to subject. After the RMS accelerations were obtained from the raw signal, all values were normalized by the acceleration value on the car floor. For this normalization, the RMS value in each direction for each body location was first divided by the RMS value in the same direction on the floor from that same trial. The value was, essentially, the fraction of vibration from the frame of the car, which passed to this body part. Next, to quantitatively compare acceleration values for different body locations across all subjects, the above ratio was multiplied by the average RMS value over all subjects in this direction on the car floor. This yielded values that approximated acceleration through the body as if all trials of all subjects were performed with the exact same vibration passing from the road to the floor of the car. For example, for the RMS value at location i in axis j for subject k , the normalization would be:

$$\text{Normalized } RMS_{ijk} = (raw RMS_{ijk} / RMS_{floorjk}) \times \overline{RMS_{floorj}} \quad (3)$$

The VDVs were normalized using the same method.

2.6.2. Seat interface pressure. Raw data from the pressure mapping pads were used to calculate the pressure distribution on seat and backrest, i.e. total contact area (TCA), peak contact pressure (PP) and average contact pressure (AP). Those parameters on the seat pan were further interpreted in three evenly divided regions, i.e. anterior, middle and posterior, to characterize the distribution of the pressure on the seat cushion.

2.7. Transmissibility test

An experiment was run involving two of the participants and two trials to see how the new seat transmitted vibrations compared to the native passenger seat. Two volunteers of approximately equal weights and stature sat in the front two seats of the car and drove down a straight road for 200 s while accelerometers measured vibrations from the floor, the back and the frame of the seat on each side of the car. During the first trial, the driver sat in the Normal posture, and in the second trial, the driver sat in the WO-BPS posture. For both trials, the passenger sat in the Normal posture. Seat Effective Amplitude Transmissibility (S.E.A.T.) values (Griffin 1978) were then calculated according to the equation: $S.E.A.T._{RMS}\% = RMS_{seat} / RMS_{floor} \times 100\%$.

2.8. Statistical analysis

For WBV data, normalized RMS accelerations and VDVs for the same posture were averaged between the two trials corresponding to both driving directions for each participant. They were then compared between sitting with the Normal and WO-BPS

postures for each recording body location along each axis using t-test to detect the statistical differences in the average normalized RMS values and VDV_s induced by posture change from Normal to WO-BPS. For data from each posture, ANOVA was performed to test effect of recording location and axis on RMS and VDV.

For seat pressure map data, the TCA, PP and AP were averaged over the middle 3 min of the 5-min trial for each participant. The average TCA, PP and AP were compared between the Normal and WO-BPS postures using t-test to detect possible posture effect.

The SAS statistical software package (SAS Institute, Cary, NC, USA) was used and the significance level was set at 0.05.

3. Results

3.1. Root mean square vibrations (figure 3)

In Normal sitting posture, the mean RMS accelerations at different body locations were 0.71 ($SE \pm 0.05$) ms^{-2} , 0.84 ($SE \pm 0.08$) ms^{-2} , 0.67 ($SE \pm 0.04$) ms^{-2} , 0.78 ($SE \pm 0.09$) ms^{-2} , 0.70 ($SE \pm 0.04$) ms^{-2} and 0.86 ($SE \pm 0.13$) ms^{-2} for ITs, lumbar spine, elbow, shoulder, ankle and knee, respectively. When the participants were driving in WO-BPS posture, the mean RMS accelerations at different body locations were 0.57 ($SE \pm 0.04$) ms^{-2} , 0.58 ($SE \pm 0.04$) ms^{-2} , 0.54 ($SE \pm 0.04$) ms^{-2} , 0.62 ($SE \pm 0.06$) ms^{-2} , 0.51 ($SE \pm 0.03$) ms^{-2} , and 0.65 ($SE \pm 0.07$) ms^{-2} for ITs, lumbar spine, elbow, shoulder, ankle and knee, respectively.

In WO-BPS posture, RMS acceleration showed significant ($p < 0.05$) decrease from the values in Normal sitting posture at four body locations (ITs, $t = 3.35$, $p < 0.05$, lumbar spine, $t = 4.00$, $p < 0.005$, elbow, $t = 3.23$, $p < 0.05$; and ankle, $t = 4.85$, $p < 0.01$) in z-axis. Among them, RMS values were found to decrease substantially in the crucial area, at the lumbar spine, by 31.6% when WO-BPS posture was used. The change of RMS acceleration in z-axis was not significant at shoulder and knee ($p > 0.05$, $t_{shoulder} = 2.30$, $t_{knee} = 1.92$). RMS vibration in x- and y-axis did not show any significant change between Normal and WO-BPS postures ($p > 0.05$, $t < 2.30$), except at elbow, where RMS acceleration along x-axis decreased from a mean of 0.89 ($SE \pm 0.11$) ms^{-2} to 0.68 ($SE \pm 0.09$) ms^{-2} with a statistical significance ($t = 2.56$, $p < 0.05$).

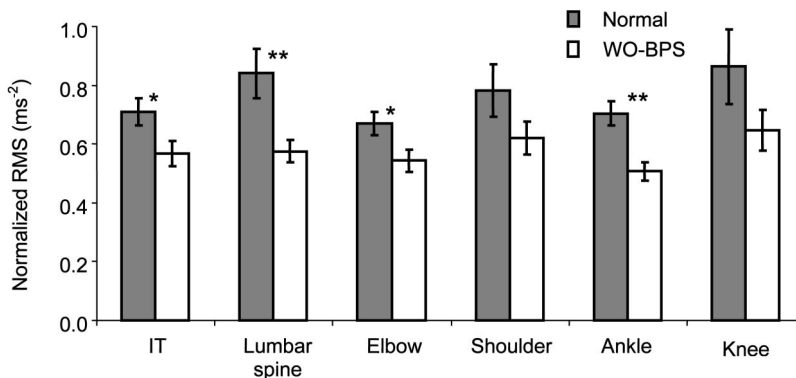


Figure 3. Average normalized root mean square (RMS) values in the z-axis by body location. * $p < 0.05$ or ** $p < 0.01$ indicates a significant difference between the Normal and without back part of the seat (WO-BPS) postures for that location.

While recording location was found to have no effect on RMS acceleration in either the Normal ($p > 0.05$, $F = 1.33$) or the WO-BPS postures ($p > 0.05$, $F = 0.52$), RMS was found to be significantly different among values recorded along different axes in Normal posture ($p < 0.001$, $F = 7.5$).

In the Normal posture, significant interaction ($p < 0.05$, $F = 2.10$) was found between recording location and axis effects; therefore, the axis effect was tested further at each body location. At the lumbar spine and knee, RMS acceleration was found to be the largest along the z-axis with significance vs. RMS acceleration in y-axis (lumbar spine: $\text{RMS}_z = 0.84$ ($\text{SE} \pm 0.08$) ms^{-2} vs. $\text{RMS}_y = 0.58$ ($\text{SE} \pm 0.08$) ms^{-2} , $p < 0.05$, knee: $\text{RMS}_z = 0.86$ ($\text{SE} \pm 0.13$) ms^{-2} vs. $\text{RMS}_y = 0.51$ ($\text{SE} \pm 0.13$) ms^{-2} , $p < 0.01$), but no significance vs. that along x-axis ($p > 0.05$). At both ankle and elbow, RMS acceleration along x-axis was found to be the largest with significance vs. that along y and/or z axes (ankle: $\text{RMS}_x = 0.96$ ($\text{SE} \pm 0.09$) ms^{-2} vs. $\text{RMS}_y = 0.61$ ($\text{SE} \pm 0.06$) ms^{-2} , $p < 0.01$; $\text{RMS}_x = 0.96$ ($\text{SE} \pm 0.09$) ms^{-2} vs. $\text{RMS}_z = 0.70$ ($\text{SE} \pm 0.04$) ms^{-2} , $p < 0.05$; elbow: $\text{RMS}_x = 0.89$ ($\text{SE} \pm 0.11$) ms^{-2} vs. $\text{RMS}_y = 0.63$ ($\text{SE} \pm 0.05$) ms^{-2} , $p < 0.05$). No significant axis effect was found on RMS acceleration at IT and shoulder.

In the WO-BPS posture, neither recording location nor recording axis was found to have a statistically significant effect on RMS acceleration ($p > 0.05$).

3.2. Vibration dose values (figure 4)

In Normal sitting posture, the mean VDV_z at different body locations were 1.52 ($\text{SE} \pm 0.14$) $\text{ms}^{-1.75}$, 1.76 ($\text{SE} \pm 0.28$) $\text{ms}^{-1.75}$, 1.63 ($\text{SE} \pm 0.23$) $\text{ms}^{-1.75}$, 1.56 ($\text{SE} \pm 0.21$) $\text{ms}^{-1.75}$, 1.54 ($\text{SE} \pm 0.18$) $\text{ms}^{-1.75}$ and 1.83 ($\text{SE} \pm 0.34$) $\text{ms}^{-1.75}$ for IT, lumbar spine, elbow, shoulder, ankle, and knee, respectively. When the participants were using WO-BPS posture, the mean VDV_z at different body locations were 0.99 ($\text{SE} \pm 0.10$) $\text{ms}^{-1.75}$, 1.01 ($\text{SE} \pm 0.09$) $\text{ms}^{-1.75}$, 0.97 ($\text{SE} \pm 0.06$) $\text{ms}^{-1.75}$, 1.21 ($\text{SE} \pm 0.13$) $\text{ms}^{-1.75}$, 0.88 ($\text{SE} \pm 0.07$) $\text{ms}^{-1.75}$ and 1.12 ($\text{SE} \pm 0.15$) $\text{ms}^{-1.75}$ for IT, lumbar spine, elbow, shoulder, ankle, and knee, respectively.

VDV_z were also significantly ($p < 0.050$) reduced along the z-axis in the WO-BPS posture for the same four body locations, i.e. IT, lumbar spine, elbow and ankle, as seen

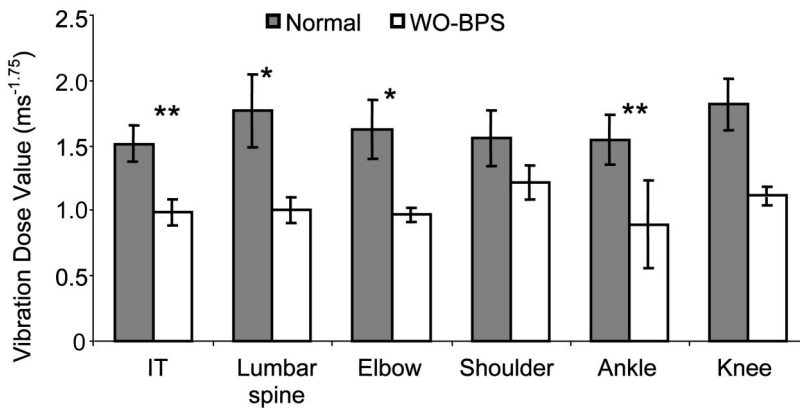


Figure 4. Average normalized vibration dose values in the z-axis by body location. * $p < 0.05$ or ** $p < 0.01$ indicates a significant difference between the Normal and without back part of the seat (WO-BPS) postures for that location.

in RMS changes. Shown in figure 4, at these four body locations, VDV along the z-axis were significantly lower in the WO-BPS trial than those in the Normal posture, i.e. IT ($p < 0.01$, $t = 3.82$), lumbar spine ($p < 0.05$, $t = 2.69$), elbow ($p < 0.05$, $t = 2.73$) and ankle ($p < 0.01$, $t = 3.58$). Among them, the VDV on the IT and lumbar spine experienced substantial decreases along the z-axis as 43.0% and 34.5%, respectively. The change of VDV in z-axis was not significant at shoulder ($p > 0.05$, $t = 1.93$) and knee ($p > 0.05$, $t = 1.32$). Similar to that shown for RMS accelerations, no change of the VDV between sitting at Normal and WO-BPS posture was found significant for any body location in x and y axes ($p > 0.050$) except at elbow, where VDV along x-axis decreased from a mean of 1.93 ($SE \pm 0.28$) $ms^{-1.75}$ to 1.29 ($SE \pm 0.20$) $ms^{-1.75}$ with a statistical significance ($t = 2.48$, $p = 0.038$).

Similar to that of RMS, body location was found to have no effect on VDV at both the Normal ($p > 0.05$, $F = 0.73$) and WO-BPS postures ($p > 0.05$, $F = 0.58$), while the recording axis significantly affected the VDV with $p < 0.01$ for Normal posture.

Since no interaction (Normal: $p > 0.05$, $F = 1.04$; WO-BPS: $p > 0.05$, $F = 1.23$) was found between body location and axis effects, therefore, the influence of recording axis on VDV values was reported for all body locations. In the Normal posture, the VDV along the y-axis was found to be significantly smaller than that in x and z-axis, both with $p < 0.01$. No difference was detected between VDV along x and z axes ($p > 0.05$).

In the WO-BPS posture, no difference was detected among three axes ($p > 0.05$).

The RMS data of the lumbar spine in the z-axis from this study for the Normal and WO-BPS postures were given together with the exposure guidelines provided by ISO 2631-1:1997 in figure 5. Dashed and dotted lines are indicated in the graph for Normal and WO-BPS posture, respectively.

Typical recording of XSensor[®] pressure images of the buttocks and lumbar spine are shown in figure 6. In the Normal posture (left column), contact pressure is centralized to the ITs with little to no pressure distributed elsewhere. However, the WO-BPS posture (right column) resulted in a more even load distribution along the thighs and lower back.

Table 1 shows the average changes of pressure parameters, from the Normal to WO-BPS postures, across 17 subjects. Data reported are the TCA, AP and PP. Those on the seat pan were also grouped in three regions of the seat-body interfaces, i.e. anterior, middle and posterior regions, to evaluate the pressure distribution changes. Data from 17 subjects showed that, while sitting in the WO-BPS posture, the TCA, AP and PP in the posterior region of the seat substantially decreased significantly by 53.4% ($SE \pm 4.6$) ($p < 0.001$, $t = 9.74$), 39.5% ($SE \pm 3.3$) ($p < 0.001$, $t = 9.63$) and 50% ($SE \pm 4.0$) ($p < 0.001$, $t = 12.35$), respectively. This decrease in the posterior regions also corresponded to the significant increases in the TCA, AP and PP in the anterior region of the seat (table 1). At the same time, the TCA and AP were seen moderately, however, with statistical significance, increased in the middle region of the seat cushion. The PP in the middle cushion was slightly decreased 5.2% with significance ($p < 0.05$, $t = 1.79$).

In the transmissibility test, the driver-side seat (new seating design) yielded S.E.A.T. values of 84% in the Normal seating posture and 96% in the WO-BPS posture. The native passenger seat had a mean value of 93% ($SD \pm 13$) for both trials.

4. Discussion

This study is a quantitative analysis of the effect of a new seating concept for vehicle drivers on the reduction of WBV and improvement of sitting pressure load. It was designed to determine if the new design has the potential to reduce lumbar spine load and

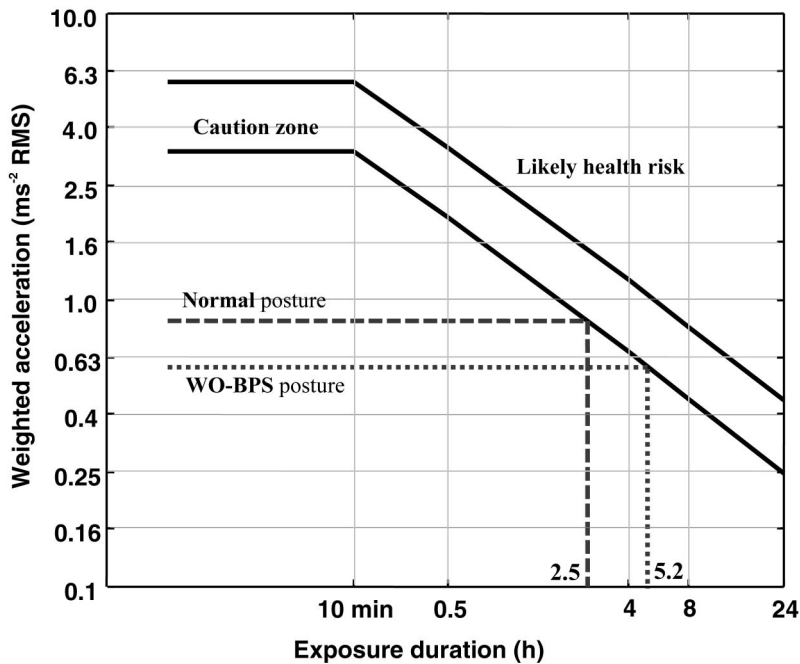


Figure 5. Root mean square (RMS) data for the lumbar spine in the z-axis applied to a graph (ISO 2631 – 1:1997) showing the human whole-body vibration exposure thresholds. The clear dashed line (– –) shows how long one may theoretically drive before entering the caution zone (where there is a possible health risk) with the Normal sitting design, while the dotted line (...) shows the same for the without back part of the seat (WO-BPS) sitting posture. Based on recording of the current study, the increase tolerance is 2.5 h daily.

WBV and, thus, reduce the risk for musculoskeletal injury related to WBV among long-term drivers of highway vehicles. As hypothesized, the WO-BPS sitting posture significantly reduced the drivers' exposure to WBV, in terms of substantial decreases seen in RMS and VDV in z-axis. Also confirmed is the hypothesis that the sitting contact pressure on the buttocks would be greatly reduced while using the WO-BPS posture to avoid a hard contact between the seat and buttocks. The results suggest that this softer contact area provides to the driver's body an increased damping effect on vibrations.

Results showed that the WO-BPS seating posture significantly reduced WBV along the z-axis for the body locations with the most concern for vibration-related musculoskeletal disorders, i.e. the lumbar spine and ITs, in long-term drivers of highway vehicles. The substantial decreases in the RMS and VDV along the z-axis in this area were found to be by 20–43%.

It is found in literature (Bovenzi 1998, Chen *et al.* 2003, Funakoshi *et al.* 2004) that typical WBV exposure levels of road vehicle drivers were at a RMS acceleration of $0.2\text{--}1.0\text{ ms}^{-2}$. The current study reports a mean value of RMS acceleration as $0.71\text{ (SE} \pm 0.05\text{) ms}^{-2}$ in the Normal posture of the tested new car seat, suggesting general consistence with results from other groups.

ISO 2631–1:1997 provides exposure guidelines in the form of a health guidance caution zone (figure 5). Exposure beyond this caution zone is 'likely to cause injury'.

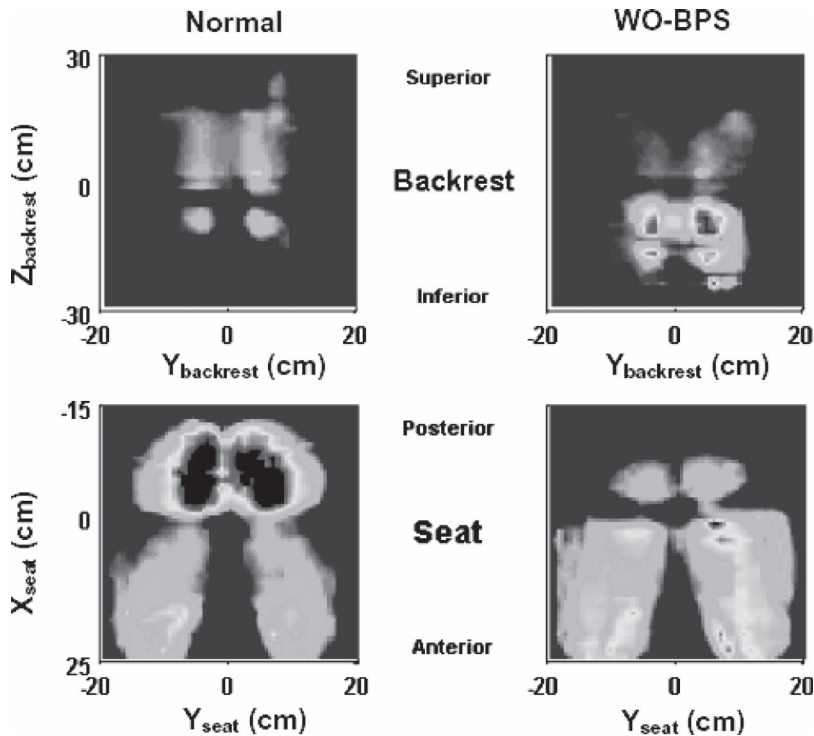


Figure 6: Pressure images of the backrest (top) and the seat (bottom). A comparison between Normal (left) and without back part of the seat (WO-BPS) seating

Based on RMS data of the lumbar spine in the z-axis for Normal and WO-BPS posture from this study, it suggests that the new seating design at the WO-BPS posture benefits vehicle drivers in terms of more than 2.5 extra hours daily driving before reaching the caution zone.

The VDV used in the ISO 2631 – 1:1997 standard has been found to correlate well with driver ratings of road roughness, particularly for rough rides. Griffin (1990) suggested that the VDV is a useful measure of increasing discomfort with increasing duration of exposure and a good indicator of subjective reaction to shocks. Therefore, the decrease of VDV at WO-BPS posture in this study shows the potential of implementing this seating concept in reducing discomfort associated with exposure to WBV during extended periods of driving. Decreases in VDV during the WO-BPS trials also demonstrate the reduction in low-frequency vibration as well as the dampening effect during bumpy road conditions, with the new seating design at WO-BPS posture.

Significant reductions of both RMS and VDV in the WO-BPS condition were found only along z-axis, and no significant differences were found at any body locations in the other axes, except along x-axis at elbow. However, since vibration can be transmitted to the driver's upper limbs from sources other than the seat, e.g. through the hand gripping on the steering wheel, this reduction of RMS acceleration and VDV recorded at elbow should not be simply attributed to the changing of the sitting posture.

Pressure mapping images suggest a possible mechanism that the WO-BPS design, by providing a soft contact between the body and seat, provides a dampening effect to

Table 1. The percentage changes of interface pressure parameters from Normal posture to without back part of the seat (WO-BPS) posture on 17 healthy subjects (mean $\pm$ SE).

	Pressure parameters	Whole cushion	Anterior cushion	Middle cushion	Posterior cushion
Seat	Change:				
	TCA (%)	-2.8 ± 1.8	14.7 ± 2.9	10.7 ± 3.4	-53.4 ± 4.6
	<i>P</i>	<0.05	<0.001	<0.01	<0.001
	<i>t</i>	1.81	-5.34	-3.48	9.74
	<i>DF</i>	16	16	16	16
	AP (%)	12.8 ± 3.4	44.6 ± 4.3	18.0 ± 7.7	-39.5 ± 3.3
	<i>P</i>	<0.01	<0.001	<0.05	<0.001
	<i>t</i>	-3.67	-13.73	-2.25	9.63
	<i>DF</i>	16	16	16	16
	PP (%)	-6.8 ± 4.7	77.2 ± 15.2	-5.2 ± 5.2	-50.0 ± 4.0
	<i>P</i>	<0.05	<0.001	<0.05	<0.001
	<i>t</i>	1.78	-7.4	1.79	12.35
	<i>DF</i>	16	16	16	16
Backrest	Change:				
	TCA (%)	91.5 ± 36.4			
	<i>P</i>	<0.001			
	<i>t</i>	-9.66			
	<i>DF</i>	16			
	AP (%)	27.7 ± 5.4			
	<i>P</i>	<0.001			
	<i>t</i>	-4.94			
	<i>DF</i>	16			
	PP (%)	28.2 ± 10.4			
	<i>P</i>	<0.05			
	<i>t</i>	-2.57			
	<i>DF</i>	16			

TCA = total contact area; AP = average pressure; PP = peak pressure. Data are given for these parameters both on seat and backrest. Changes of the TCA, AP and PP are also given for three regions on the seat, i.e. the anterior, middle and posterior regions. *p*-values are given for statistical significance of such changes.

vibration. The significantly decreased pressure on the ITs and the increased pressure on the thighs indicate that, in the WO-BPS posture, the thighs play a more important role of supporting the driver's body weight while the generally concentrated load on ITs is significantly evened away. The dampening effect might be attributed to two aspects of what is seen on the pressure map. First, eliminating the hard contact between ITs and the seat cushion broke the direct transmission pathway of the mechanical vibration from car seat to spinal column through the pelvic bone. Instead, the vibration was transmitted to the upper body mainly by way of the thighs, which may have a different vibration absorption mechanism.

However, this finding may raise the concern that the thighs might be brought to a higher vibration exposure level. Since vibration from both IT and knee was seen to be decreased in the WO-BPS posture (decrease at IT was significant), it is very unlikely that the bony structure in the thighs (femurs) is subjected to significantly higher vibration. Therefore, it leaves the concern of sustaining higher vibration to the soft tissue on the thighs due to increased contact between the thighs and the seat cushion. Several studies have been carried out on the biological and physiological effect of vibration on soft

tissues (Bovenzi *et al.* 2000, Kerschman-Shindl *et al.* 2001, Curry *et al.* 2002, Zhang *et al.* 2003) and both beneficial and risky effects were found. However, those that caused injury were found to be in the high frequency range and with large magnitude, which fell out of the range of vibration from driving a regular passenger vehicle. Moreover, these studies showed that vibration was found to cause blood vessel damage or decrease of tissue perfusion at the parts of the body composed of less soft tissue, such as the fingers (Bovenzi *et al.* 2000) and rat tails (Curry *et al.* 2002), which resembled nothing close to the thigh soft tissue during sitting. On the other hand, vibration with low frequency and low magnitude was found to increase the muscle blood flow and has been used in strength training (Kerschman-Shindl *et al.* 2001, Zhang *et al.* 2003, Mester *et al.* 2005).

It has been reported that the WO-BPS posture restores normal curvature of the spine by decreasing the ischial supporting load and increasing lumbar support (Makhsous *et al.* 2003a). Quantitative pressure measurements in this study confirm that the WO-BPS posture places significantly less pressure on load-bearing regions of the buttocks whilst driving.

In this study, the experimental seat resembled almost exactly the shape and the fabric seat cover of the native seat and all data were acquired with the same apparatus from the same experimental seat in different postures in the same vehicle. Therefore, possible discrepancies from vehicle, seat and experimental set-up were avoided. However, the fact that the study was carried out on a single vehicle can also impose a limitation on generalizing the findings to other vehicles.

As stated earlier, the possible benefit of the current seat design, presumably from the WO-BPS posture, to the vehicle drivers, was primarily established on the general accepted hypothesis that occupational drivers are at high risk of developing chronic musculoskeletal disorders in the lumbar spine due to continuous exposure to WBV. However, some other factors have been suggested by researchers as possible causes of low back disorders in vehicle drivers. Lewis and Griffin (1996), and Johnson and Neve (2001) identified the differential vertical motion between seat back and the squab, which induced continuous strains in the lower lumbar region, as a possible additional source of low back disorders in road vehicle operators. These authors also proposed a seat back suspension design to decrease such differential motions. If this additional cause of LBP has been proved to be true, simply reducing the exposure to WBV, as demonstrated in the current study, might not provide sufficient protection from the occupational low back disorders in vehicle drivers. Further study on clear identification of the aetiological factors of LBP in drivers will help to clarify this concern. A driver seat that integrates the current WO-BPS design and the idea of seat back suspension could possibly be a better solution.

Although it is felt that this new seating design demonstrates promise in reducing WBV and driving-related lumbar spine injuries, further investigation into material design is necessary. Little thought or effort was put into the suspension or cushioning of the seat at the time the experiments were performed. As a result, the frame of the seat itself was extremely rigid compared to most car seats. Although the transmissibility test showed that the new seat performed comparable to seats used in production cars today, it is felt that there is significant room for improvement in this area. The authors hope to further modify this seating design by adding a layer of viscoelastic foam on the seat cushion and designing a new suspension system. In addition, this seating concept needs to be further investigated to better understand how it responds to a variety of vehicles, different driving speeds and various road conditions.

In a laboratory test with similar experimental seat design, the author found decreased muscular effort from lower back muscles for trunk stabilization when the occupants used

WO-BPS posture (Makhsous *et al.* 2003a). This finding suggests another potential benefit of this sitting mechanism in reducing back muscle fatigue during long-time sitting and driving. Further investigation on the effects of WO-BPS posture on reducing lower back muscle activities for vehicle drivers is necessary.

It is a limitation that this study was conducted on a small group of participants ($n = 9$) without low back disorders. However, *post-hoc* power analysis revealed that this study had a statistical power over 80% for RMS acceleration at four (ITs, lumbar spine, elbow, and ankle) out of all six recording locations, and for VDV at two (ITs and ankle) out of six recording locations. Therefore, the results from this study are valid.

Other factors such as the short recording time of each driving trial and using a restricted road condition may limit the generalization of the research findings from this study. As the investigation moves further into the effectiveness of the new seating design in reducing WBV, it will be possible to perform longer laboratory tests using a shaker with a well-controlled vibration, which simulates normal vibration conditions based on real-life measures as recorded from different vehicles, speeds and road conditions. It is expected that with a higher level of precision and repeatability introduced to the study under such a well-controlled laboratory test, more consistent and less varying results would be obtained to better understand how the WO-BPS posture may change the frequency of vibrations. Eventually, testing will be expanded to not only address the musculoskeletal vulnerability of drivers, but also many other risks, such as motion sickness, fatigue, drowsiness and general discomfort related to WBV and driving. Biomechanical and mathematical models can also be the alternative way to investigate the effect of this new car seat design on WBV exposure in vehicle drivers (Fritz 2000).

Finally, long-term quantitative and qualitative field tests with a larger sample size and using different seat frames should be performed to see if the new design is a practical and effective application to everyday life for drivers.

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