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Whole body vibration exposures in metropolitan bus drivers: A comparison of three seats

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ABSTRACT

Using a repeated measures study design, three different seats were evaluated as 12 metropolitan bus drivers drove a standardized test route including city streets, old and new freeways, and a street segment containing 10 large speed humps. Three comparisons were made: (1) comparing seats made by different manufactures (Seats 1 and 2), (2) comparing seats with a standard foam (Seat 2) and silicone foam (Seat 3) seat pans, and (3) comparing WBV exposures based on individual factors such as seat pressure settings and body weight. Whole body vibration (WBV) exposures were measured using a tri-axial seat pan accelerometer and the attenuation capabilities of each seat were evaluated by comparing the vibrations measured at the floor and seat of the bus. There were significant WBV exposure differences between the various street types, which was shown across all seat types. The city street and older freeway segments had the highest WBV exposures with both segments producing WBV exposures slightly above the action limit for vibration dose value (VDV). Relative to Seat 2, Seat 1 performed better at attenuating impulsive and shock related WBV exposures; however, neither seat performed significantly better when average vibration (A_w) and VDV WBV exposures were compared. In addition, no performance differences were seen between the standard foam (Seat 2) and silicone foam (Seat 3) seat pans. Seat suspension stiffness (air pressure) was also examined, and the results indicated that the higher the seat air pressure the lower the A_w, VDV, and static compressive dose (S_{ed}) vibration exposures. This study provided a unique opportunity to evaluate on-the-job whole body vibration exposures in a standardized, controlled setting.

1. Introduction

Injuries to the back are considered the most significant non-lethal medical condition affecting the US workforce [1]. Throughout their lives approximately 80 percent of adults will experience back pain and 4–5 percent of the population has an acute low back pain episode every year [2]. Low back injuries require extensive treatment and often result in long periods of absence from work for the injured worker. Back injuries occurring at work account for 20 percent of all US workers' compensation claims, this translates to 33–41 percent of all workers' compensation costs, creating a drain on the economy totaling in the billions of dollars [3,4].

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One of the leading risk factors for the development of low back disorders is continuous exposure to whole-body vibration (WBV) [5]. WBV elevates spinal load as indicated by biomechanical and biological research [7,8]. Spinal loading causes muscle fatigue in the supporting musculature and has been shown to result in the intervertebral disc thinning and herniations [9–11]. WBV can also degrade other systems in the body hampering the function of the musculoskeletal, cardiovascular, cardiopulmonary, metabolic, endocrine, nervous and gastrointestinal systems [12]. There are also safety concerns associated with WBV, vibration frequencies which match the resonant frequency of the body have been shown to hamper a worker's ability to perform job tasks [13]. Extended periods of vibration exposure lead to worker irritability, fatigue, stress, and problems with concentration.

Numerous epidemiologic studies have shown an association between exposure to WBV in professional driving occupations and back pain [6,14,15]. A dose–response relationship has been established showing that increases in the duration of WBV exposure have been associated with an increased risk for injury [16]. Degenerative discs in the lumbar spine are 1.55 times more likely in professional drivers who have experienced high exposure to WBV over 0.6 m/s^2. The probability of lumbar degeneration has been shown to increase with an increase in WBV exposure [17]. The assessment methods for measuring time weighted average (TWA) WBV exposures and multiple shock exposure are described in ISO 2631-1:1997 and ISO 2631-5:2004, respectively, and provide guidance on the assessment of health effects. However, to date the assessment methods used to measure multiple shock exposures in ISO 2631-5 [18] is relatively new and has not been validated in the epidemiological literature.

Although it has been established that there is an exposure–response relationship between WBV and back disorders, the mechanisms are not currently well understood [19]. Previous research indicates a causal relationship between WBV exposure and the large number of low back disorders among public transit drivers [20,21]. In addition to low back pain, WBV causes discomfort and annoyance, influences the performance of work tasks, and presents other health risks in the form of pathological damage or physiological change [22].

Back disorders have been identified as the largest source of early permanent disability among mass transit operators [23]. In the greater Seattle Metropolitan area, transit drivers experienced a high number of low back claims when compared to other metropolitan employees. The main description for the cause of low back injuries were 'driving' and 'jarring/bouncing' accounting for 43 percent of all low back injuries. Safety officials indicate that the bus seat 'bottoming out' may be one possible source for injury. Seattle Metropolitan bus drivers are off of work longer than all other occupations within the same agency combined, missing 13 days compared to a median of 8 days for all other occupations. The rate of low back injury among bus operators was 3.4 percent, a rate which is consistent with the incidence of accepted back injury claims in Washington State for specialized (3.4 percent) and general (3.1 percent) freight trucking [24]. The 'jarring/bouncing' and 'bottoming out' of bus driver seats suggests that further investigation of impulsive vibration exposures is needed.

Seats can perform differently in their ability to attenuate vibration exposure for the driver. In some cases the seat can amplify the exposure and the understanding of seat performance is not well quantified [25]. Seat suspensions can be ineffective in attenuating vibration if they are not adjusted correctly. Drivers often incorrectly adjust the seats to the heaviest setting to gain height in the seat for improved vision which negates the seat vibration isolation effectiveness [26]. There can be a large variation in transmissibility between seats, selecting the right seat for a vehicle is an important factor in controlling exposures to whole-body vibration [25].

Impulsive exposures have recently been identified as a possible risk factor for low back disorders and the International Organization for Standardization (ISO) has published new guidelines for measurement and assessment of impulsive exposures [18]. The magnitude of the impulsive-related risk amongst bus drivers has not been well characterized. Currently there is a wide array of seats that can be selected for installation in Metropolitan busses.

Using a standardized test route, and calculating time-weight average (TWA) and impulsive WBV exposure parameters from ISO 2631-1 and ISO 2631-5, respectively, the purpose of this study was to determine whether there are performance differences in WBV attenuation between two bus seats made by two different major bus seat manufacturers. In addition, second goal of this study was to determine whether there were differences in WBV attenuation between a standard foam and silicone foam seat pan. Currently, based on King Country Metro repair records, the average life of a standard foam seat pan is 6 months, and after the foam fatigues, replacement of the seat pan is required. Silicone foam is being offered as an alternative seat pan material and is purported to have a fatigue life of 5 years. If the silicone foam seat pad has the same or better performance than the foam seat pad, then this may be a cost effective alternative due to its purported longer life. Beyond simply comparing seats, an additional goal of this study was to determine whether there were differences in WBV exposures based on road type. Finally, the last objective of this study was to determine whether there were differences in WBV exposures based on individual factors such as seat pressure settings and body weight.

2. Methods

The first goal of this study was to determine whether there were WBV exposure differences, over a standardized test route, using two different seats from two different seat manufactures. To enable a controlled comparison between seats, both seats used in the study were brand new. The two seats used in the study are shown in Fig. 1, the Recaro Ergo M (Seat 1) and USSC Q91 (Seat 2). Both seats have foam seat pans, air suspensions, and adjustable lumbar support.

Fig. 1. Seats selected for use in this study.

A second goal of this study was to determine whether there were WBV exposure difference based on the type of foam used to construct the seat pan. As a result a third seat was introduced to the study which was identical to Seat 2, except the foam seat pan in Seat 2 was replaced with a silicone seat pad (Seat 3).

The third and final goal of the study was to determine the extent to which individual factors affected WBV exposures. Individual subject factors such as seat pressure settings, which are a surrogate for seat suspension stiffness, and subject body weight were measured and analyzed.

2.1. *Bus and test route*

The standardized test route was designed to include three common road types encountered by bus drivers and included 12 km of city streets, 29 km of new freeway, 10 km of old freeway and a 1 km circular route containing 10 speed humps (4 m wide). The same 12.2 m New Flyer (manufactured in Winnipeg, Manitoba) low floor bus was used throughout the entire study. This is important as it has been shown in prior research that there are large variations in vibration magnitude within and between vehicle categories and types [27]. The runs were completed with no passengers other than the driver and two data collection staff (one or two researchers).

2.2. *Instrumentation*

2.2.1. *Whole body vibration measurement*

Fig. 2 shows the schematic and set up of the WBV data collection system. A Personal Digital Assistant (PDA)-based portable WBV data acquisition system was used to collect WBV exposures per ISO 2631-1 and 2631-5. Raw, unweighted tri-axial WBV measurements were collected at 640 Hz using a seat pad ICP accelerometer (model 356B40; PCB Piezotronics; Depew, NY) mounted on the driver's seat and simultaneous *z*-axis measurements were to be collected with an identical accelerometer mounted with a thin layer of beeswax, designed to secure the accelerometer to the floor of the bus, immediately adjacent to the driver's seat. Accelerometer calibrations were conducted prior to all data collection sessions using a Type 4294 Bruel & Kjaer Calibration Exciter with a 10 m/s^2 (rms), 159.2 Hz oscillation frequency. The system calibrations were evaluated using a LabVIEW program written to analyze and verify calibration exciter measurements.

As shown in Fig. 2, two Larson Davis HVM 100's loggers were used as accelerometer amplifiers and an HP H5555 Pocket-PC PDA with 2 Gigabytes of compact flash memory, an external battery pack, and a PCMCIA expansion pack instrumented with a 16 bit National Instruments data acquisition card (Model 6036E, National Instruments, Austin, TX) was used to collect the WBV signals. Using the serial port on the PDA, once every second, Global Positioning System (GPS) data (GPSmap76; Garmin; Olathe, KS) was also collected and integrated with the WBV exposure data to identify the location, velocity, and type of road associated with the WBV exposures.

2.2.2. *Seat pressure measurement*

Seat pressure was measured with an inline air gauge with a range from 0 to 621 kPa. Driver seat suspension stiffness was not controlled by the investigators. Based on personal preferences, the drivers selected their preferred seat suspension stiffness.

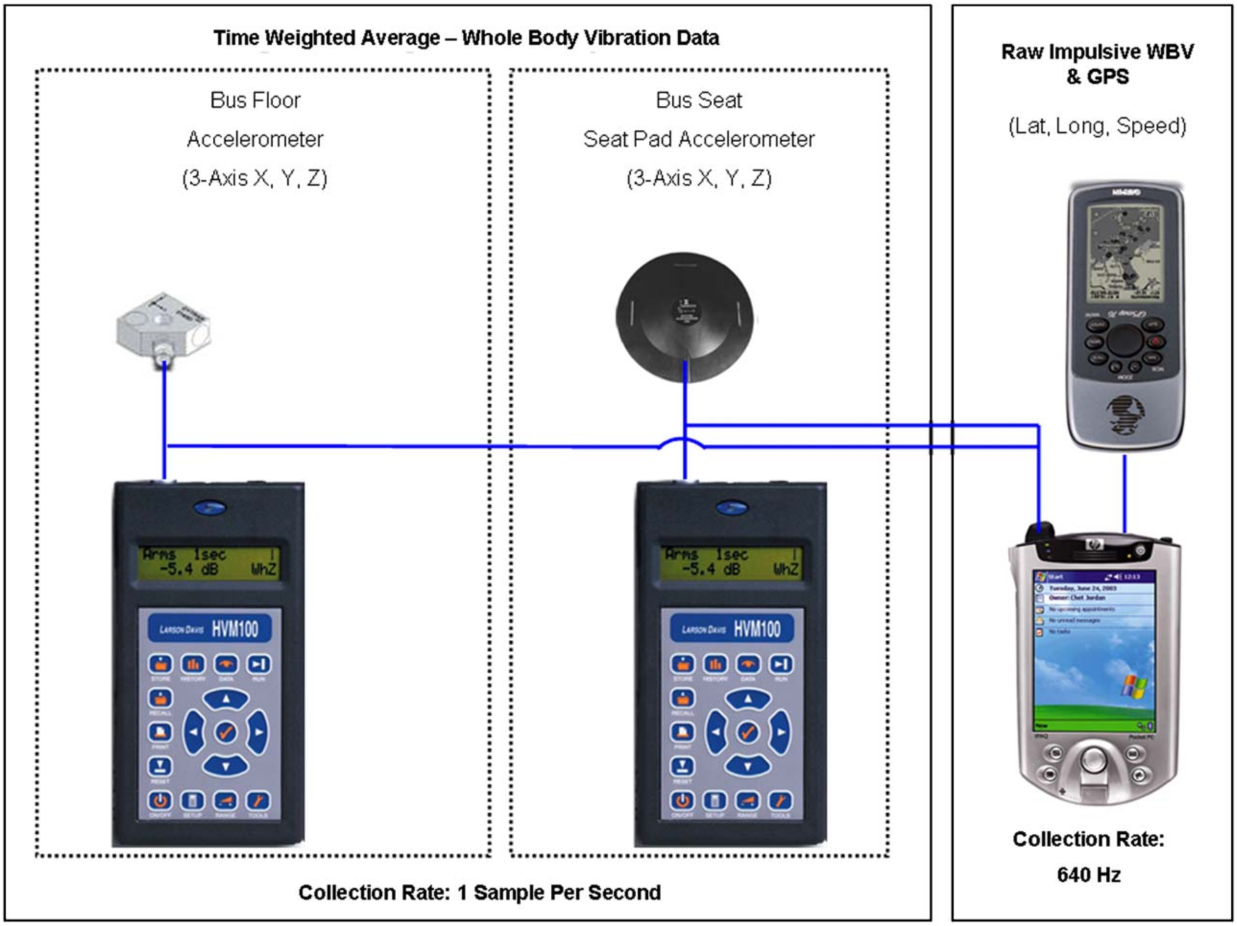

Fig. 2. Schematic of WBV Data Collection System.

2.3. Subjects

This study was designed to collect WBV measurements from 15 subjects divided equally across three groups by body weight. The drivers were systematically selected so there was equal representation of light-, middle- and heavy-weight drivers. As shown in Table 1, due to drop outs and hardware malfunction, data were collected from 12 subjects.

Table 1 also shows the demographic data of the bus driver population. The mean age of the participants was 50.8 (range 38–60) the mean weight of subjects was 80.9 km (range 49.4–116.1 kg) and an equal number of male and female drivers participated in the study. As shown in Table 1, half of the study participants were part-time drivers and half-were full time drivers with a mean driving time of 5.5 h per day (range 3–8) for the previous year of employment. The majority of drivers worked year round with a mean of 241.7 driving days per year (range 150–300). The majority of drivers had less than 10 years experience driving buses with a mean of 9.9 years (range 1–22). Drivers were also asked about their driving exposure outside of the workplace and it was determined that the study subjects averaged 2.8 h of car driving per day (range 1–4) with the yearly average totaling 308.3 h (range 150–350) per year.

2.4. Data analysis

The continuous data collected on the PDA were downloaded after each run to a PC and input into a LabVIEW routine (LabVIEW version 7.1; National Instruments; Austin, TX) which analyzed the WBV data from each run. To facilitate analyzing the data by road type, the individual start and stop times for each type of road segment was recorded. These start and stop times were then entered into the LabVIEW program to identify the beginning and end of the individual road segments.

The LabVIEW routine used a Matlab-based program to appropriately weight the continuous signals [28] and WBV calculations were performed as outlined in ISO 2631-1-1997 and 2631-5-2004. WBV measures were calculated over the whole route (all road segments) as well as by individual road segment.

Table 1
Subject demographic and driving information (n=12).

Category	Number	Percent
Gender		
Male	6	50%
Female	6	50%
Mean (±SD)	50.8 (±6.8)	
Age		
Weight (kg)		
≤70	5	42%
71–93	4	33%
≥94	3	25%
Mean (±SD)	80.9 (±19.8)	
Bus driving		
Starting age		
Mean (±SD)	40.4 (±9.2)	
Hours/day		
3–5	6	50%
6–7	3	25%
8–9	3	25%
Mean (±SD)	5.5 (±1.9)	
Days/year		
100–150	1	8%
200–250	10	83%
300+	1	8%
Mean (±SD)	241.7 (±35.9)	
Number of years		
0–9	7	58%
10–19	1	8%
20+	4	33%
Mean (±SD)	9.9 (±9.3)	
Car driving		
Hours/day		
0–1	2	17%
2–3	9	75%
3+	1	8%
Mean (±SD)	2.8 (±0.9)	
Days/year		
Mean (±SD)	308.3 (±59.7)	

The ISO 2631-1 [22] parameters evaluated and compared between seats, road types, seat settings and driver weights included:

Root mean square average vibration (A_w) calculated at the floor and at the seat pan of the bus (m/s^2):

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

Vibration dose value (VDV) which is more sensitive to impulsive vibration and reflects the total, as opposed to average vibration, over the measurement period at the seat pan and floor of the bus (m/s$^{1.75}$):

$$VDV = \left\{\int_0^T [a_w(t)]^4\,\mathrm{d}t\right\}^{1/4} \tag{2}$$

TWA Peak—the highest magnitude of A_w measured during the measurement period (m/s^2).

The ISO 2631-5 [22] parameters evaluated and compared between seats, road types, seat settings and driver weights included:

Average daily dose (D_k) is designed to be an estimate of daily vibration dose (m/s^2):

$$D_k = \left[\sum A_{ik}^6\right]^{1/6} \tag{3}$$

Static compressive dose (S_{ed}) measured in megapascals, which has been developed through biomechanical modeling to capture the linear relationship between peak acceleration and input shocks to responses in the spine (MPa).

$$S_{ed} = \left[\sum_{k=x,y,z} (m_k D_{kd})^6\right]^{1/6} \tag{4}$$

In addition to the WBV measures covered by Parts 1 and 5 of the ISO 2631 standard, the Raw (+) Peak—the highest vibration measured in the positive direction (Z-axis topping out), the Raw (−) Peak—the highest average vibration measured in the negative direction (Z-axis bottoming out) and seat effective amplitude transmissibility (SEAT) was calculated. The SEAT value provides a measure of how well a seat is suited to the spectrum of vibration entering the seat [25]. The calculation of the *SEAT* value for A_w and VDV are

$$SEAT\ A_w\ (\%) = \frac{A_{w_{seat}}}{A_{w_{floor}}} \times 100 \tag{5}$$

$$SEAT\ VDV\ (\%) = \frac{VDV_{seat}}{VDV_{floor}} \times 100 \tag{6}$$

2.5. Statistical analyses

The data segments analyzed with the LabVIEW routine created output files with all the desired summary measures. These files were then processed using Microsoft Excel to create time weighted averages based on segment and total route duration and then exported to JMP Statistical Discovery Software (Version 5.1.2; SAS Institute; Cary, SC).

In order to determine whether there were differences in WBV exposures between the seats made by different manufactures (Seats 1 and 2), repeated-measures analysis of variance (RANOVA) methods were used. The same methods were used to test whether there were differences between the standard foam (Seat 2) and silicone foam seat (Seat 3). Finally, differences in WBV exposures were evaluated based on individual factors of seat pressure settings and subject weights. Differences in seat pressures were evaluated by splitting the drivers into tertiles so there was roughly an even distribution of seat pressures across groups. The low pressure group had seat pressures $\leq$234 kPa, the medium pressure group was between 241 and 372 kPa, and the high pressure group was $\geq$379 kPa. Differences were considered significant when p-values were $<$0.05. Tukey-Kramer follow-up tests were used to identify differences across group means with a procedure-wise error of 0.05.

3. Results

3.1. WBV results comparing seats and seat attenuation

3.1.1. Comparison of different seat manufacturers (Seat 1 versus Seat 2)

The left portion of Table 2 compares the seats of the different manufacturers (Seats 1 and 2). As presented in Table 2, there were no differences between seats in average vibration exposures (A_w). However, according to ISO 2631-1, when crest factors are above 9, this indicates impulsive exposures were likely encountered, A_w may be underestimated and should be interpreted with caution. As an alternative, the vibration dose value (VDV) is recommended for evaluation when impulsive exposures are present. As revealed in Table 2, there were no differences between seats in VDV exposures. The only differences between seats were in TWA Peak and Raw (+) Peak exposures. The positive (+) and negative (−) raw peak

Table 2
Mean (SEM) WBV measurements over the whole route comparing Z-axis floor and seat measured exposures by seat type (n=12).

Parameter	Accelerometer location	p-Value, Seat 1 versus 2	Seat 1	Seat 2	Seat 3	p-Value, Seat 2 versus 3
A_w (m/s^2)	Floor	0.12	0.45 (±0.01)	0.43 (±0.01)	0.48 (±0.02)	0.02
	Seat	0.72	0.41 (±0.01)	0.40 (±0.02)	0.40 (±0.01)	0.89
Crest factor	Floor	0.40	19.8 (±1.63)	21.7 (±1.48)	14.9 (±0.98)	0.001
	Seat	0.001	9.25 (±0.44)	11.6 (±0.34)	11.9 (±0.52)	0.45
VDV (m/s$^{1.75}$)	Floor	0.79	12.0 (±0.38)	12.2 (±0.43)	11.9 (±0.77)	0.13
	Seat	0.98	9.26 (±0.27)	9.24 (±0.42)	9.33 (±0.36)	0.69
TWA peak (m/s^2)	Floor	0.65	8.70 (±0.73)	9.14 (±0.63)	7.15 (±0.85)	0.08
	Seat	0.01	3.59 (±0.17)	4.43 (±0.25)	4.59 (±0.25)	0.36
Raw (+) Peak (m/s^2)	Floor	0.13	44.0 (±4.81)	52.5 (±2.36)	37.4 (±7.58)	0.0004
	Seat	0.004	5.37 (±0.24)	6.89 (±0.40)	7.04 (±0.41)	0.68
Raw (−) Peak (m/s^2)	Floor	0.11	47.3 (±5.23)	58.9 (±4.50)	32.3 (±3.58)	0.0004
	Seat	0.51	6.33 (±0.29)	6.65 (±0.38)	6.55 (±0.46)	0.92
D_k (m/s^2)	Floor	0.54	14.0 (±1.06)	13.3 (±0.67)	12.4 (±1.10)	0.51
	Seat	0.01	9.01(±0.39)	11.5 (±0.84)	12.1 (±0.74)	0.23
Speed (km/h)	–	0.13	55.7 (±1.56)	53.1 (±1.58)	57.5 (±1.03)	0.04

measures were designed to indicate when the seat topped out or bottomed out. Table 2 shows that Seat 1 did a better job at attenuating Raw (+) Peak exposures; however, there were no differences between the two seats in attenuation of Raw (−) Peak exposures. The differences in performance between seats in the peak measurements, and the crest factors as well, suggest that there is a difference in the performance of seat suspensions. Finally, the daily acceleration dose (D_k), measured at the seat pan, was significantly lower for Seat 1 when compared to Seat 2. This measure, part of ISO 2631 Part 5, is designed to give a prediction of long term health effects related to spinal compression.

3.1.2. Foam (Seat 2) versus silicone (Seat 3) seat pan

As shown in Table 2, there was virtually no difference in exposures between the seat with the standard foam seat pan (Seat 2) and the silicone foam seat pan (Seat 3). The only significant differences measured were at the floor with the Aw, Raw (+) Peak and Raw (−) Peak values being different.

3.1.3. Floor versus seat

Not shown in Table 2 are the *p*-values comparing the floor versus the seat WBV exposures. In all instances, with the exception of crest factor, the seats significantly attenuated all WBV exposures. When comparing across the floor measured vibrations in Table 2, another observation was many of the differences in floor measured vibration (A_w, TWA Peak, Raw (+) Peak, Raw (−) Peak) approached significance. This may indicate that either the floor is not completely rigid and there may be a complex interaction between the floor and seat affecting the floor measured vibrations and/or the slight difference in speeds under which the seats were tested (4.4 km/h) was enough to effect the floor measured vibrations.

Table 3 shows the SEAT values and peak ratios for all the seat configurations evaluated in this study. For the A_w and VDV, the seats transmitted between 83.6–92.3 percent and 76.3–80.4 percent of the vibration measured at the floor to the seat

Table 3
Mean (SEM) SEAT values and peak ratios comparing *Z*-axis floor and seat measures by seat type (*n*=12).

Parameter	*p*-Value, Seat 1 versus 2	Seat 1, SEAT (%)	Seat 2, SEAT (%)	Seat 3, SEAT (%)	*p*-Value, Seat 2 versus 3
A_w (m/s^2)	0.66	90.4 (±2.5)	92.3 (±3.4)	83.6 (±3.8)	0.10
VDV (m/s$^{1.75}$)	0.76	77.9 (±3.5)	76.3 (±3.3)	80.4 (±4.5)	0.48
Parameter	*p*-Value, Seat 1 versus 2	Peak ratio (%)	Peak ratio (%)	Peak ratio (%)	*p*-Value, Seat 2 versus 3
Raw (+) Peak (m/s^2)	0.55	15.2 (±3.2)	13.2 (±0.7)	25.8 (±4.4)	0.014
Raw (−) Peak (m/s^2)	0.145	16.1 (±2.6)	11.9 (±0.9)	24.0 (±3.4)	0.003

Table 4
Mean (SEM) WBV tri-axial measurements comparing seat measured exposures by road type (*n*=12).

Parameter	Axis	City streets	Speed humps	New freeway	Old freeway	*p*-Value
A_w (m/s^2)	*X*	0.14 (±0.01)	0.17 (±0.01)	0.11 (±0.01)	0.13 (±0.01)	<0.0001
	Y	0.11 (±0.01)	0.15 (±0.01)	0.11 (±0.01)	0.12 (±0.01)	<0.0001
	Z	0.36 (±0.01)	0.36 (±0.01)	0.43 (±0.01)	0.51 (±0.01)	<0.0001
Crest factor	*X*	14.1 (±1.54)	8.4 (±0.50)	8.8 (±0.25)	7.4 (±0.27)	<0.0001
	Y	13.9 (±0.72)	7.3 (±0.33)	8.4 (±0.22)	8.3 (±0.27)	<0.0001
	Z	14.5 (±0.63)	11.8 (±0.49)	8.2 (±0.22)	6.9 (±0.23)	<0.0001
VDV (m/s$^{1.75}$)	*X*	3.4 (±0.16)	4.1 (±0.22)	2.5 (±0.14)	2.7 (±0.17)	<0.0001
	Y	2.9 (±0.09)	3.3 (±0.08)	2.1 (±0.06)	2.4 (±0.07)	<0.0001
	Z	9.4 (±0.24)	9.6 (±0.37)	8.9 (±0.18)	10.3 (±0.22)	<0.0001
TWA Peak (m/s^2)	*X*	2.2 (±0.55)	1.4 (±0.11)	1.0 (±0.05)	0.9 (±0.06)	0.007
	Y	1.0 (±0.09)	1.1 (±0.06)	0.9 (±0.02)	0.9 (±0.03)	<0.0001
	Z	5.2 (±0.26)	4.2 (±0.23)	3.5 (±0.11)	3.5 (±0.11)	0.008
Raw (+) Peak (m/s^2)	*X*	15.0 (±1.52)	7.7 (±1.65)	11.6 (±3.71)	14.7 (±7.21)	0.45
	Y	20.4 (±7.57)	4.6 (±0.13)	9.0 (±2.51)	10.7 (±3.86)	0.10
	Z	8.1 (±0.42)	6.7 (±0.56)	5.2 (±0.15)	5.0 (±0.15)	0.01
Raw (−) Peak (m/s^2)	*X*	17.5 (±1.85)	8.0 (±1.60)	12.1 (±3.78)	14.6 (±7.25)	0.27
	Y	20.9 (±7.77)	4.6 (±0.22)	9.1 (±2.48)	10.3 (±3.85)	0.08
	Z	8.3 (±0.38)	5.9 (±0.33)	5.2 (±0.18)	5.1 (±0.19)	0.004
D_k (m/s^2)	*X*	7.3 (±1.47)	6.4 (±0.39)	3.9 (±0.27)	4.2 (±0.31)	0.004
	Y	4.0 (±0.21)	4.6 (±0.18)	2.5 (±0.10)	2.7 (±0.12)	<0.0001
	Z	12.8 (±0.77)	13.2 (±0.85)	8.9 (±0.26)	9.4 (±0.28)	0.03
S_{ed} (MPa)	–	0.45 (±0.03)	0.42 (±0.03)	0.29 (±0.03)	0.30 (±0.03)	<0.0001
Speed (km/h)	–	28.3 (±0.89)	29.9 (±0.69)	82.6 (±1.26)	82.9 (±1.64)	<0.0001

pan, respectively. There were no differences in A_w and VDV transmissions between Seats 1 versus 2 and Seats 2 versus 3. Peak ratios were also compared and all seats did well in lowering the transmission of peak values from the floor to the seat. Interestingly, the seat with the silicone foam seat pan, Seat 3, transmitted more of the peak vibration.

3.2. WBV results comparing road types

WBV exposures measured across the different road segments was compared across four ISO 2631-1 time weighted vibration exposure parameters (A_w, crest factor, VDV and TWA Peak), two ISO 2631-5 impulsive exposure parameters

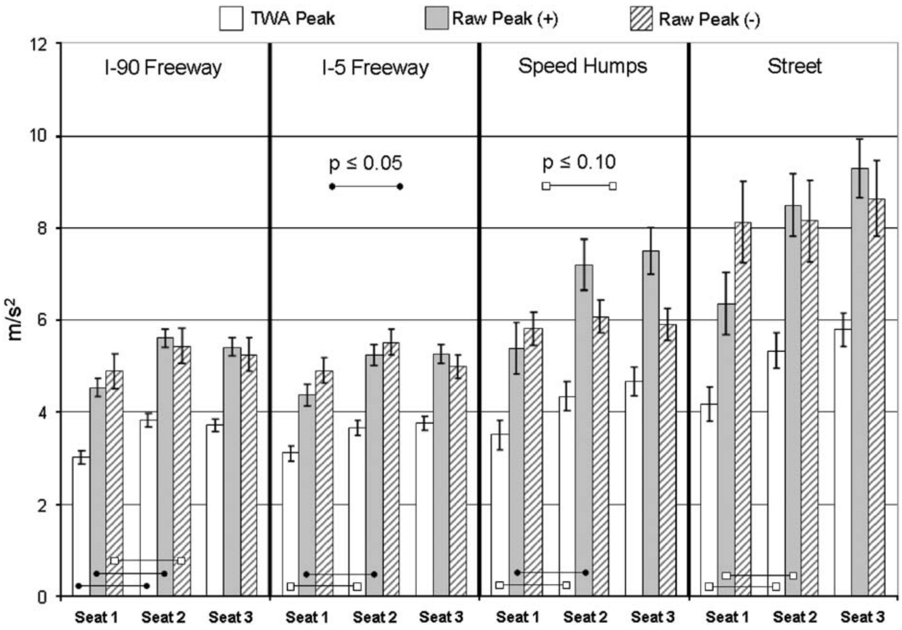

Fig. 3. Mean (SEM) time weighted average TWA Peak, Raw (+) Peak, and Raw (−) Peak by seat grouped by road type (*n*=12).

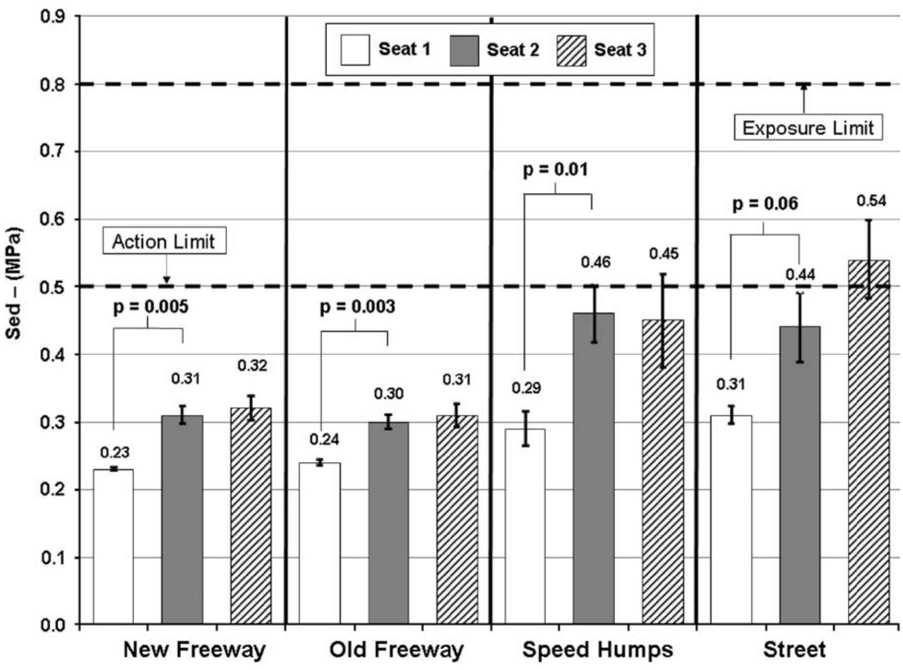

Fig. 4. Mean (SEM) daily static compressive stress (S_{ed}) across seats grouped by road type (*n*=12).

(D_k and S_{ed}), and two other impulsive exposure parameters (Raw (+) Peak and Raw (−) Peak). Since there were very few differences between seats, Table 4 shows the vibration exposures, averaged across all seats, grouped by road type.

As can be seen in Table 4, with the exception of crest factor (which is a normalized measure) and the raw positive and negative peak measures, *z*-axis exposures were the highest and the *y*- and *x*-axis exposures were lower. The *y*-axis exposures (side-to-side) tended to be slightly higher than the *x*-axis (fore-aft) exposures. In general, most WBV exposures were low and below recommended exposure limits; however, there were a few exceptions. The *z*-axis measures for A_w was highest and above the 0.5 m/s^2 action limit for the older freeway segment. However, given that the *z*-axis crest factors were above 9 in the street and speed hump segments, this indicates that impulsive exposures were encountered, the A_w exposures should be interpreted with caution, and the VDV evaluated. Table 4 shows that there were significant differences across road types in *z*-axis VDV measurements, with the VDV exposures above the action limit in the street, older freeway and speed hump segments.

Differences in peak exposures between seats grouped by road type, are shown in Fig. 3. The results show that there were some differences between Seats 1 and 2, but no significant differences between Seats 2 and 3. Across all seats, the highest peaks (TWA Peak, Raw (+) Peak, and Raw (−) Peak) were measured on the street segment while the lowest peak measurements were on the freeways.

There were significant differences in S_{ed} exposures between seats, these exposures are shown by road type in Fig. 4. The highest exposures for static compression were exhibited in the street segment with the silicone seat (Seat 3), Seat 2 was intermediate, and Seat 1 had the lowest static compressive doses. With the exception of the streets, the seat with the foam seat pan (Seat 2) performed similarly to the seat with the silicone seat pan (Seat 3) and Seat 1 always had significantly lower S_{ed} values than Seat 2.

3.3. Seat settings

Seat pressures were evaluated as one determinant of vibration exposure. A statistical analysis of seat pressure by seat and road type did not reveal any significant differences across road types, in addition, since seat pressure did not differ by road types, seat pressure results were averaged over the whole route. As shown in Fig. 5, when evaluating ISO parameters that have exposure action limits, drivers who set their seat suspension in the low pressure range ($\leq$234 kPa) experienced higher average vibration exposures ($A_{w\ z}$), vibration dose values ($VDV_{\ z}$), and static compression doses (S_{ed}). For the impulsive measures, vibration exposures decreased with higher seat pressures and the lowest seat pressures always resulted in the highest exposures. Further examination revealed that Seats 2 and 3 were all in the low and medium pressure categories and the high pressure category was exclusive to Seat 1. As a result, the drop in A_w and VDV exposures between the low and medium pressure categories was exclusively a result of Seats 2 and 3, the same seat with different seat pads. However, the drop in S_{ed} exposures in the high pressure category was a result of Seat 1.

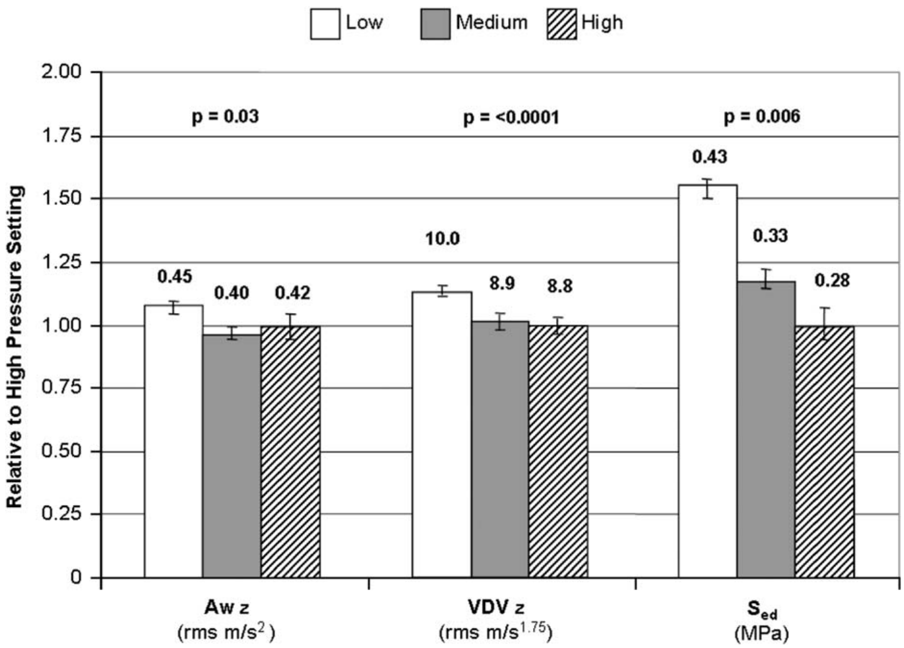

Fig. 5. Mean (SEM) WBV exposures grouped by seat pressure. Data normalized to the high pressure seats to facilitate comparisons. Actual exposure values above each bar.

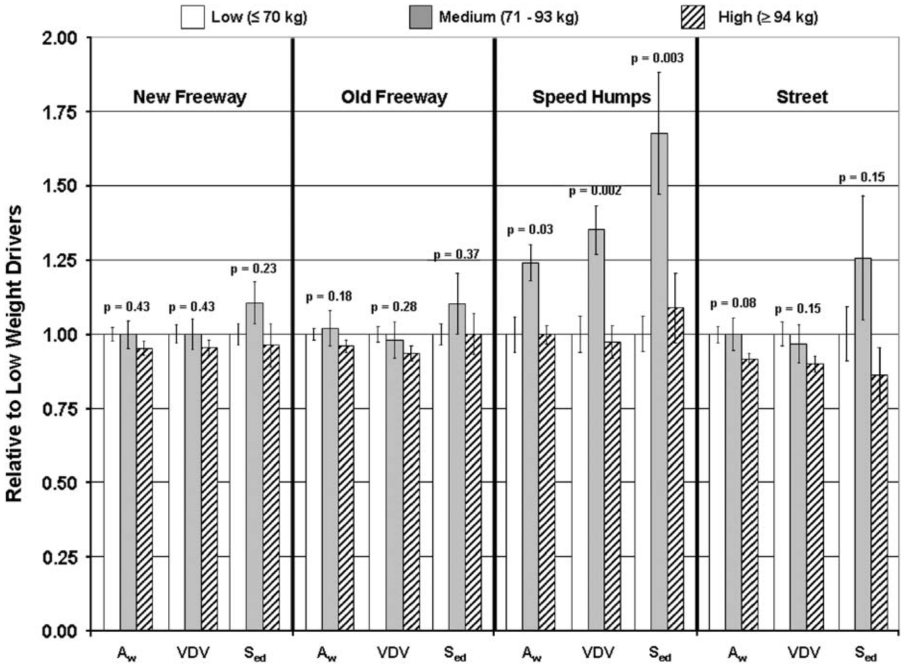

Fig. 6. Mean (SEM) bus Bus WBV exposures by driver weight grouped by road type (n=12). Data normalized to low driver weights to facilitate comparisons.

3.4. Driver weights

Driver weights were also evaluated as a determinant for WBV exposure. Analysis of the weight-related behavior across seat and road types did not produce any significant results by road or seat type, therefore, Fig. 6 presents results averaged across all seats by road type. As shown in Fig. 6, again evaluating ISO parameters that have exposure action limits, medium weight drivers experienced higher average vibration exposures ($A_{w\ z}$), static compression doses (S_{ed}), and vibration dose values ($VDV_{\ z}$). However, within each road type, driver weight categories across the low ($\leq$70 kg), medium (71–93 kg), heavy ($\geq$94 kg) were not statistically significant except for the speed hump segments. In the speed hump segments, medium weight drivers had significantly higher exposures.

4. Discussion

In a standardized controlled setting, this study evaluated and compared two different seats and two types of seat foam for attenuated WBV exposures. Seat 1 performed significantly better than Seat 2 in the attenuation of impulsive WBV exposures; however, no seat performed better on all road types. There were significant differences in WBV exposures across the various road types. As a result, a possible administrative control could involve assigning routes based on road type with the goal of limiting or distributing WBV exposures based on road type. There were significant differences in WBV exposures based on seat pressure settings with higher seat pressure settings attenuating more of the WBV exposures. Driver weight did not show a significant effect in this study, this may be a result of small sample size and the need for more measurements in the exploration of the relationship between driver weight and WBV exposure. The study was conducted in North America, however, the results of this study may translate to European bussed which fall under the current European Directive 2002/44/EC [29].

4.1. WBV results comparing seats

The WBV exposure differences between Seats 1 and 2 showed that the seats performed similarly in attenuating TWA WBV exposures; however, Seat 1 performed better in attenuating impulsive exposures. The results also indicated that no seat performed universally well on all road segment types. In the future, it would be interesting to evaluate the performance of commercially available semi-active seat suspensions.

The WBV exposures between Seats 2 and 3 were not significantly different from one another. One interesting result was that there were significant differences between Seats 2 and 3 in the transmission of peak vibrations from the floor to the seat. The denser silicone foam appears to transmit more of the peak vibration signal to the operator. The other interesting aspect associated with comparing Seats 2 and 3 was that there were significant differences between floor measured vibration levels. This may suggest that the floor is not completely rigid and/or there may be a complex interaction between the floor and seat affecting the floor measured vibrations.

4.2. WBV results comparing road types

This study found significant differences in vibration exposure across the road types with z-axis street segment exposures near or slightly above the established action limit (9.1 $m/s^{1.75}$) for VDV. A_w z-axis exposures were below the action limit (0.5 m/s^2) as established by ISO 2631-1. However, as indicated in ISO 2631-1, A_w measurements with crest factors above 9 should be interpreted with caution. This was the case with the WBV data collected from the street segments.

High VDV z-axis exposures were also present in the older freeway segment and above the action limit. The continuous nature of WBV exposures combined with the large number of impulsive exposures from expansion joints indicates that both TWA and impulsive WBV exposures were present on the freeway segments. The exposure differences between the different road types indicate that one potential work organization measure could be route rotation so that drivers do not spend excessive time on noxious routes and/or drive on different segments to vary the exposure to continuous and impulsive vibration exposures. It is noteworthy that the freeways had the highest A_w exposures due to the continuous nature of the WBV exposures. This was due to the on/off nature of the street WBV exposures associated with alternating WBV exposures between moving/driving and being idle at stoplights. The freeway routes represent a fairly constant exposure which leads to less idle time than the street segments, however, the street segments have more starts and stops from stop lights and bus stops.

4.3. Seat settings

This study also found significant differences in vibration exposure across at different seat pressures; therefore driver selected seat suspension pressure (stiffness) appears to be an important determinant of exposure as measured in the z-axis A_w, S_{ed}, and VDV. The results of this study showed there were significant differences between seat pressure levels and WBV exposures demonstrating that lower seat pressures resulted in higher vibration exposures. This finding suggests that increasing seat suspension stiffness may be one method for reducing overall vibration exposures on the type of bus tested in this study. However, increasing seat stiffness is likely dependent on the vehicle suspension and road type. In the future, it would be interesting to more systematically control and evaluate bus driver seat pressure. In addition, it may be interesting to compare pedestal bus driver seats (stiff/rigid seats) against the current air suspension seats.

4.4. Driver weights

Driver weights did not have a significant affect on exposures among this population of bus drivers. The small sample size may have limited the ability of this study to draw meaningful conclusions about how subject weights effect WBV exposures. In future studies a larger sample size with even numbers of subjects in each weight class will help to better characterize the effect of subject weight on WBV exposure.

4.5. Limitations of the study

One potential limitation in the study was due to practical limitations associated with switching seats, as a result, seat order was not randomized. All subjects tested the seat in the same order (Seats 1–3).

The sample size (n=12) was relatively small. Testing more subjects would increase the ability to determine if there were any systematic WBV exposure effects associated with driver weight. Two drivers dropped out and as a result the weight distribution of subjects was not balanced. This may have affected the analysis of subject weight on the z-axis A_w, S_{ed}, and VDV exposure as presented in Fig. 6.

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References

[1] W.S. Marras, Occupational low back disorder causation and control, *Ergonomics* 43 (2000) 880–902.
[2] D.A. Plante, M.G. Rothwell, H.M. Tufo, Managing the quality of care for low back pain, in: J. Frymoyer (Ed.), *The Adult Spine: Principles and Practice*, second ed., Lippincotte-Raven, Philadelphia, 1997.
[3] G.B.J. Andersson, M.H. Pope, J.W. Frymoyer, S.H. Snook, Epidemiology and cost, in: M.H. Pope, G.B.J. Andersson, J.W. Frymoyer, D.B. Chaffin (Eds.), *Occupational Low Back Pain: Assessment, Treatment, and Prevention*, Mosby Year Book, St. Louis, 1991, pp. 95–113.
[4] B.S. Webster, S.H. Snook, The cost of 1989 workers compensation low back pain claims, *Spine* 19 (1994) 1111–1116.
[5] J.D.G. Troup, Clinical effects of shock and vibration on the spine, *Clinical Biomechnical* 3 (1988) 277–281.
[6] National Institute of Occupational Safety and Health (NIOSH). Musculoskeletal Disorders (MSDs) and Workplace Factors: A Clinical Review of Epidemiological Evidence for Work-Related Musculoskeletal Disorders of the Neck, Upper Extremities, and Low Back. NIOSH: PB 97 141, 1997.
[7] M. Fritz, Estimation of spine forces under whole-body vibration by means of a biomechanical model and transfer functions, *Aviation Space and Environmental Medicine* 68 (1997) 512–519.
[8] M. Fritz, Description of the relation between the forces acting in the lumbar spine and whole-body vibrations by means of transfer functions, *Clinical Biomechanics* 15 (2000) 234–240.
[9] D.G. Wilder, A.R. Aleksiev, M.L. Magnusson, M.H. Pope, K.F. Spratt, et al., Muscular response to sudden load. A tool to evaluate fatigue and rehabilitation, *Spine* 21 (1996) 2628–2639.
[10] M.J. Griffin, *Handbook of Human Vibration*, Academic Press, London, 1990.
[11] E. Thalheimer, Practical approach to measurement and evaluation of exposure to whole-body vibration in the workplace, *Seminars in Perinatology* 20 (1996) 77–89.
[12] G.J. Gruber, H.H. Ziperman, *Relationship between Whole-Body Vibration and Morbidity Patterns among Motor Coach Operators*, National Institute of Occupational Safety and Health, Cincinnati, Ohio, 1992.
[13] D.E. Wasserman, *Human Aspects of Occupational Vibration*, Elsevier, New York, 1987.
[14] M.H. Pope, G.B.J. Andersson, J.W. Frymoyer, D.B. Chaffin (Eds.), *Occupational Low Back Pain: Assessment, Treatment and Prevention*, Mosby Year Book, St. Louis, 1991.
[15] National Research Council, *National Research Council. Institute of Medicine. Panel on Musculoskeletal Disorders and the Workplace. Commission on Behavioral and Social Sciences and Education. Musculoskeletal Disorders and the Workplace: Low Back and Upper Extremities*, National Academy Press, Washington, DC, 2001.
[16] K. Teschke, A. Nicol, H. Davies, S. Ju, Whole body vibration and back disorders among motor vehicle drivers and heavy equipment operators: a review of the scientific evidence. Report to: Workers Compensation Board of British Columbia, Vancouver, BC, 1999.
[17] S. Schwarze, G. Notbohm, H. Dupuis, E. Hartung, Dose–response relationships between whole-body vibration and lumbar disk disease a field study 48 on 388 drivers of different vehicles, *Journal of Sound and Vibration* 215 (4) (1998) 613–628.
[18] International Organization for Standardization, ISO 2631-5. Mechanical vibration and shock—evaluation of human exposure to whole body vibration—Part 5: Method for evaluation of vibration containing multiple shocks, 2004.
[19] J.C. Chen, W.R. Chang, T.S. Shih, C.J. Chen, W.P. Chang, L.M. Dennerlein, L.M. Ryan, D.C. Christianni, Predictors of whole-body vibration levels among urban taxi drivers, *Ergonomics* 46 (11) (2003) 1075–1090.
[20] M. Bovenzi, Low back pain disorders and exposure to whole-body vibration in the workplace, *Seminars in Perinatology* 20 (1) (1996) 38–53.
[21] M.L. Magnusson, M.H. Pope, D.G. Wilder, B. Areskoug, Are occupational drivers at an increased risk for developing musculoskeletal disorders?, *Spine* 21 (6) (1996) 710–717.
[22] International Organization for Standardization, ISO 2631-1. Mechanical vibration and shock—evaluation of human exposure to whole body vibration—Part 1: General requirements, 1997.
[23] E. Johanning, Back disorder intervention strategies for mass transit operators exposed to whole-body vibration-comparison of two transit system approaches and practices, *Journal of Sound and Vibration* 215 (4) (1998) 629–634.
[24] B. Silverstein, D. Adams, J. Kalat, Work-related musculoskeletal disorders of the neck, back, and upper extremity in Washington State, 1994–2002, Technical report number 40-8a-2004, Safety and Health Assessment and Research for Prevention (SHARP), Washington State, Department of Labor and Industries, December 2004.
[25] G.S. Paddan, M.J. Griffin, Effects of seating on exposures to whole-body vibration in vehicles, *Journal of Sound and Vibration* 253 (1) (2002) 215–241.
[26] P. Donati, Survey of technical preventative measures to reduce whole-body vibration effects when designing mobile machinery, *Journal of Sound and Vibration* 253 (1) (2002) 169–183.
[27] G.S. Paddan, M.J. Griffin, Evaluation of whole-body vibration in vehicles, *Journal of Sound and Vibration* 253 (1) (2002) 195–213.
[28] L. Zuo, S.A. Nayfeh, Low order continuous-time filters for approximation of the ISO 2631-1 human vibration sensitivity weightings, *Journal of Sound and Vibration* 265 (2003) 459–465.
[29] Directive 2002/44/EC of the European Parliament and of the Council of 25 June 2002 "on the minimum health and safety requirements regarding the exposure of workers to the risks arising from physical agents (vibrations)". OJ L 177, 6.7.2002, p. 1.