Evaluating whole-body vibration reduction by comparison of active and passive suspension seats in semi-trucks

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Truck drivers have one of the highest injury rates in the US workforce with the majority of injuries occurring in the low-back. Exposure to Whole Body Vibration (WBV) is thought to be a significant factor. This study compared difference in WBV exposures in sixteen drivers who drove a semi-truck over a standardized test route with a passive (air suspension) and electromagnetic vibration cancelling (active suspension) seat. Tri-axial WBV measurements of average weighted vibration (A_w), Vibration Dose Value (VDV), and Static Compressive Dose (S_{ed}) were collected and compared between the two seats. Vehicle speed and location was collected with GPS loggers. The results show when compared to the passive suspension seat, the active suspension seat reduced A_w ($p<0.001$) and VDV ($p<0.001$) vibrations exposures by roughly 50%, with impulsive exposures (S_{ed}) being reduced by approximately 20% ($p=0.02$). Based on the results the active suspension seat appears to have the potential to substantially reduce an operator's exposure to WBV.

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INTRODUCTION

Professional truck drivers provide a vital service to the US economy delivering approximately 95% of the nations' goods. Long-haul truck drivers represent one of the largest segments in the US transportation sector, a group who spend upwards of eleven hours a day (60 hours per week) in the seated driving position. This population represents one of the most often injured worker populations in the US workforce with the majority of the injuries occurring in the low-back. The US Bureau of Labor Statistics indicates that the transportation and warehousing sector, which includes all variety of truck drivers, had the highest Days Away From Work rate, ranks third in injury and illness incidence rate, and sixth in the total number of illnesses and injuries (BLS, 2010). Additionally, when drivers are injured they are out of work twice as long as the overall private industry average. One of the leading risk factors for this work population is whole-body vibration (WBV) exposure which has been shown to lead to low back disorders with prolonged exposure (Bernard, 1997; Troup, 1988).

Biomechanical research has found that prolonged WBV exposure leads to elevated spinal load (Fritz, 1997, 2000), causes muscle fatigue(Wilder et al., 1996), and has been linked to disc damage including herniations (Griffin, 1990). WBV exposure also results in cardiovascular, cardiopulmonary, metabolic, endocrinologic, nervous and gastrointestinal system damage (Thalheimer, 1996).

Using a standardized test route, and calculating time-weight average (TWA) and impulsive WBV exposure parameters from the ISO 2631-1 and ISO 2631-5 standards respectively, the purpose of this study was determine whether there are performance differences in WBV attenuation between an active suspension and a traditional passive suspension semi-truck seat.

METHODS

Two commercially available semi-truck seats were tested and evaluated in this study. The first semi-truck had an active suspension seat (BoseRide System, Bose Corp, Framingham, MA). The active suspension seat was equipped with an onboard computer and linear electro-magnetic force actuator that monitored and attempted to cancel the vibrations transmitted to the seat column and in real time.

The second semi-truck had a passive seat suspension system. The passive suspension, air-ride seat was the truck seat that currently is sold as standard equipment on the majority of new semi-trucks sold in the United States. Both seats used in the study were new and unused when installed in the semi-truck cabs at the start of the study.

WBV measurements were collected from sixteen experienced, full-time, semi-truck drivers recruited from the New England region of the United States. All drivers were male with an average age of 49.3 (SD 9.3) years, an average weight of 102.5 kg (SD 16.7 kg), an average height of 179.5 cm (SD 6.9 cm), and an average of 27.7 (SD 9.4) years of experience as truck drivers. All study procedures and collection methods were approved by the Human Subjects Committee at the University of Washington and subjects provide their informed consent prior to participating in the study. Subjects were financially compensated for their participation in the study.

As shown in Figure 1, two identical sleeper-cab semi-trucks with identical flatbed trailers, loaded with four concrete jersey barriers (total weight approximately 9,072 kg), were used in the study. One truck (Freightliner Inc., Model: CL120064S-T, Year: 2005) had 381,403 miles at the start of the study, and the other truck (Freightliner Inc., Model: CL120064S-T, Year: 2006) had 348,042 miles at the start of the study. Both trucks had 6 cylinder, 515 horsepower engines and 10 speed manual transmissions. Tires on both trucks had moderate wear with a recommended tire inflation of 105 psi.

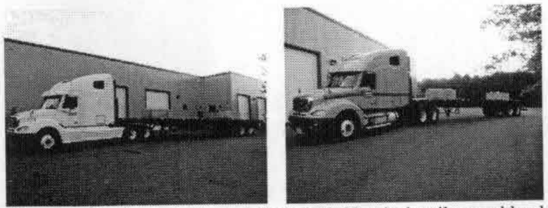

Figure 1: Trucks tested in the study with identical trailers and loads.

Test Route

The test route was 59.2 kilometers and included common road types encountered by semi-truck drivers (rough road, stop and go driving, two lane highways, and freeways). The weather was clear and warm for all of the data collection which occurred over a weekend which meant that the trucks were not subject to weekday morning and afternoon traffic congestion. Truck speed was determined by traffic conditions and subject driving style. The data was collected in parallel with one semi-truck leading and the other semi-truck following closely behind to insure that traffic conditions and truck speeds were similar across the two seat conditions during the paired runs. Drivers were asked to complete the route twice, once in the semi-truck with the active suspension seat and once in the semi-truck with the passive suspension seat. Midway through the study, after eight subjects, the seats were swapped between the semi-trucks to minimize any potential confounding associated with either semi-truck (vehicle specific vibration, wear and tear, rides differences, etc.).

Instrumentation

An eight channel data recorder (model DA-40; Rion Co., LTD.; Japan) was used as the data acquisition system to collect WBV exposures per ISO 2631-1 and 2631-5. Raw, unweighted tri-axial WBV measurements were collected at 1,280 Hz per channel using a seat pad ICP accelerometer (model 356B40; PCB Piezotronics; Depew, NY) mounted on the driver's seat and simultaneous tri-axial measurements were collected with an identical magnet mounted accelerometer secured to the floor of the truck, under the driver's seat. Accelerometer calibrations were verified 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 the accelerometers matched the vibration frequency and magnitude created by the vibration calibrator.

The data recorder stored the collected data on a 2 Gigabyte compact flash memory card (Extreme III; San Disk; Milpitas, CA). Once every second, Global Positioning System (GPS) data was collected with a GPS logger (Model DG-100; GlobalSat; Chino, CA) to record the vehicle speed and location. Using an interactive program (LabVIEW 2009; National Instruments; Austin, TX) the WBV and GPS data were synchronized and combined into one output file.

Data Analysis

The synchronized vibration and GPS data from each run were processed and analyzed by a second interactive LabVIEW routine. To facilitate analyzing the data, using the beginning and ending GPS coordinates from the test route, a second LabVIEW program calculated the various WBV measures.
The ISO 2631-1(Standardization, 1997) and 2631-5(Standardization, 2004) parameters were calculated by the LabVIEW program and compared between seats. These vibration parameters measured at the seat and floor of the vehicle included: 1) the root mean square average weighted vibration (A_w), measured in m/s^2; 2) the Vibration Dose Value (VDV), measured in $m/s^{1.75}$, which is more sensitive to impulsive vibration exposures and reflects the cumulative rather than the average vibration; and 3) the Static Compressive Dose (S_{ed}) measured in mega-pascals. Signal crest factors were calculated per ISO 2631-1. Per the standard, Crest Factors were calculated based on the ratio of the

maximum instantaneous peak value of the frequency-weighted acceleration to its r.m.s. value (A_w). Crest factors above 9 indicate that A(8) may be underestimating the exposure and that VDV(8) should be the measure of focus.

All vibration exposures were normalized to 8 hours (A(8), VDV(8), $S_{ed}(8)$) to facilitate comparisons between seats and between past and future studies.

Finally, the Seat Effective Amplitude Transmissibility (SEAT) values were calculated from A(8) and VDV(8). The SEAT values were the ratio of the vibration measured at the seat pan divided by the vibration measured at the floor of the vehicle and are a measure of the percentage of the vehicle vibration attenuated by the seat suspension.

Data Processing and Statistical Analyses

The data analyzed with the LabVIEW routine created output files with all the desired vibration summary measures. These files were then exported to JMP Statistical Discovery Software (Version 8.0.1; SAS Institute; Cary, SC) for statistical analysis.

In order to determine whether WBV exposure differences existed between the seats (active and passive suspension) repeated-measures analysis of variance (RANOVA) methods were used. The WBV exposures parameters that were compared included A(8), VDV(8), and $S_{ed}(8)$, differences were considered significant when p-values were less than 0.05.

RESULTS

There was no difference in driving speed between the trucks with the active and passive suspension seats when driving over the test route (34.4 vs 34.5 km/h; $p = 0.88$). Figure 2 shows the differences in vibration exposures between active and passive suspension seats from driving over the test route. The most prominent performance differences between seats were in the z-axis, with the active suspension seat reducing vibration exposures between 19 - 55% more than the passive suspension seat. In general, the differences in x- and y-axis exposures between seats were small, averaging 8%. With respect to the various z-axis vibration exposure measures, the active suspension seat was most effective in reducing the ISO 2631-1 A(8) and VDV(8) exposures, exposures derived from time-weighted averages. The data showed that all crest factors were above 9, this indicated that impulsive exposures were likely present in the data and A(8) exposures may underestimate the actual exposures.

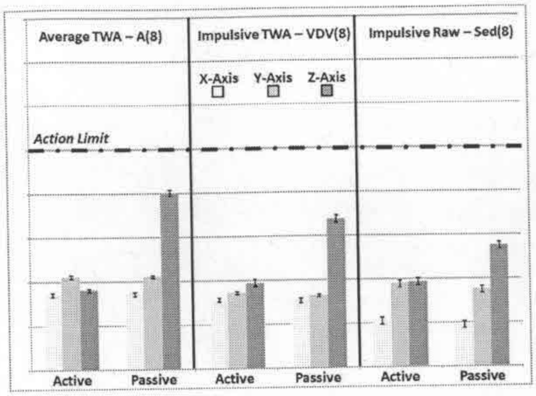

Figure 2: 8-Hour equivalent truck exposure by axis and seat (n=16).

Z-axis Seat Effective Amplitude Transmissibility (S.E.A.T.) values were calculated (Figure 3) for the active and passive suspension seats the percentage to compare the percentage of the floor measured vibration transmitted to the seat pan. The active suspension seat attenuated nearly two-thirds of the floor transmitted A(8) vibration and more than half of the VDV(8) vibration. Conversely the passive seat only attenuated approximately 5% of A(8) and 7% of VDV(8) vibration when seat exposures were compared to the measurement at the vehicle floor. This indicates that in this exposure scenario the active suspension seat is more efficient than the passive seat at canceling the vibration exposures.

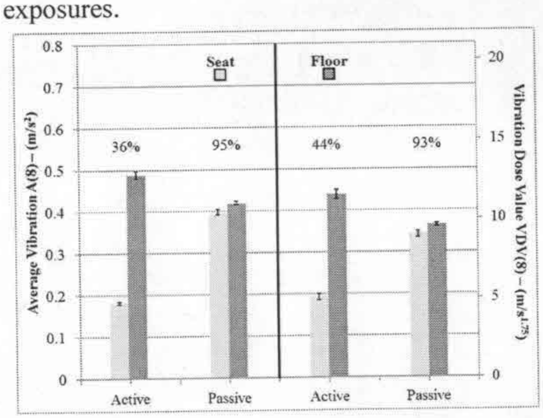

Figure 3: Z-axis S.E.A.T. values comparing the active and passive suspension seat (n=16).

Additionally, with respect to the static compressive dose ($S_{ed}(8)$), an ISO 2631-5 impulse exposure measure derived from the raw vibration data from the x-, y- and z axes, the active suspension seat outperformed the passive suspension seat ($p = 0.02$), reducing the impulsive static compressive dose exposure an additional 22%.

DISCUSSION

This study used three parameters that are part of the ISO 2621 Part 1 (A(8) and VDV(8)) and Part 5 (Sed(8)) standards to quantify relative vibration exposure levels between an active and passive suspension seats. Using a standardized test route, the results of this study demonstrated that, relative to the passive suspension seat, the active suspension seat substantially reduced WBV exposures. The reduction in WBV exposures ranged between 19 to 55% and were dependent on the WBV exposure measures (e.g. A(8), VDV(8), Sed(8)). When compared to traditional passive suspension seats the 19 to 55% exposure reduction with the active suspension seat was fairly substantial, and could feasibly reduce the incidence of low back pain in semi-truck driving populations. The exposure reduction with the active suspension seat does come at a cost, the active suspension seat costs approximately $6,000 USD compared to the passive suspension seat which costs approximately $800 USD. However, the cost of the active suspension seat can is small relative to the average costs of a low back injury (Over $30,000 USD).

Comparing the Part 1 parameters, A(8) is a time weighted average measure which is designed to pick up average vibration exposures in the x, y, and z axes. The VDV(8) is a measure more sensitive to impulsive exposures and should be used in favor of the A(8) when measures have crest factors above 9 (crest factors were above 9 for both seats in this study) indicating the presence impulsive exposures. $S_{ed}(8)$ is the Part 5 parameter designed to combine tri-axial vibration into a single value which is more sensitive to impulsive shocks, this measure cannot be calculated without raw signal data. The active suspension seat performed consistently better across all parameters in this study.

This study was limited in that the measurements were made equivalent to an 8 hour day, this could over estimate exposures for local drivers who are on the clock around eight hours per day (with breaks), and potentially underestimate exposure for long haul drivers who drive up to 11 hours per day. Additionally, the exposure examination may also represent a best case scenario as both seats were brand new, the truck was loaded at the time of the study, and an extended sleeper cab was used which meant the truck had a longer wheel base. Further research with active suspension seats is warranted to determine if these results can be replicated in other driving exposure scenarios.

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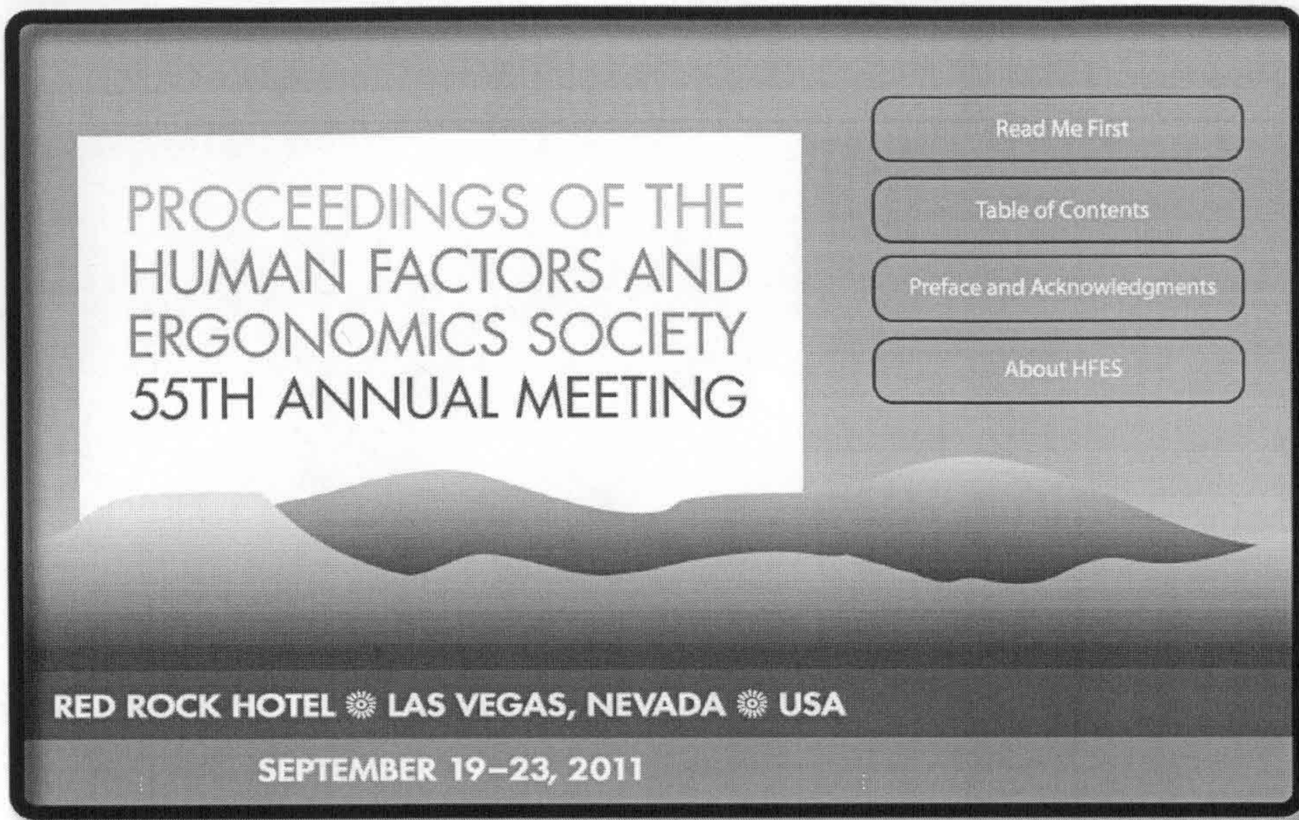
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