Evaluating Whole Body Vibration and Standing Balance Among Truck Drivers

Molly Halverson

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Committee:

Peter W. Johnson

June Spector

Han Kim

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Abstract

Evaluating Whole Body Vibration and Standing Balance Among Truck Drivers

Molly Halverson

Chair of the Supervisory Committee:

Associate Professor Peter W. Johnson

Department of Environmental & Occupational Health Sciences

Background: Over 60% of fatal fall-related occupational injuries occur in the long haul freight trucking industry. Exposure to whole body vibration (WBV) from driving or operating vehicles has been shown to negatively affect balance and may contribute to falls when entering or exiting the vehicle. Fall-related injuries are eight times more likely to occur upon exiting the vehicle than entering. It is hypothesized that WBV has a detrimental effect on postural stability upon truck egress and may be a contributing factor to falls when truck drivers egress their truck.

Methodology: Using field-collected WBV exposures from the floor of a truck cab, a three-dimensional vibrating platform (hexapod system) was used in a laboratory setting to expose eight truck drivers to two hours of simulated truck driving. The hexapod system provided an accurate and systematic method to simulate these vibrational exposures for the purpose of investigating whether balance changes occurred with prolonged exposure to WBV.

Using a repeated measures design, the truck drivers participated in two exposure levels: 1) sitting in an electromechanically active-suspension vibration-reducing seat, and 2) sitting in a standard passive, air-suspension truck seat. Based on field measurements, WBV exposures were expected to be approximately 50% lower in the seat with the electromechanically active-suspension. Seat order was randomized and counterbalanced. Immediately before exposure to WBV, after two hours of exposure, and five and ten minute post exposure, participants were asked to stand on a Wii balance board under two conditions, one with the eyes closed and the other with the eyes open. Each measurement lasted 30 seconds during which the standing balance center of pressure (COP) deviations were measured. In addition, a subcomponent of the Mini-BEST test, a qualitative clinical balance assessment tool, was performed to complement the quantitative force plate measurements.

Analysis: The association between exposure to WBV and postural instability was assessed pre- and post- WBV exposure, in the ten minutes post-exposure, and between the two different WBV exposures (the two seat conditions). Postural measurements of interest for the COP deviations focused on medio-lateral (ML) path length, anterior-posterior (AP) path length, and total path length. Secondary variables included the standard deviation of the AP and ML components. Other variables of interest included assessing the balance measurements with the eyes open/closed to determine whether the visual component of vibration, vestibular component, or both induced imbalance.

Results/Conclusions: Significant differences were found between all balance measurements (ML, AP, total path length) before and after WBV exposure for eyes open status but not eyes closed. Relative to the passive, air-suspension seat, the subjects' WBV exposures were roughly 50% lower with the active suspension seat. The decrease in WBV exposure associated with sitting in the active suspension seat did not affect postural balance when compared to the passive, air-suspension seat. After 10 minutes post exposure, balance measurements (path lengths) had returned to baseline in the eyes open balance measurements but were better (shorter than baseline) in the eyes closed measurement.

Specific aims:

1. To determine whether there were changes in postural stability after exposing truck drivers to two hours of simulated exposure to whole body vibration.
2. If there were changes in postural stability, determine whether the recovery of standing balance occurs in a short period of time.
3. To determine whether there were differences in postural stability after exposing truck drivers to different levels of whole body vibration.
4. To determine whether there was a visual component which may affect postural stability by comparing postural stability with the eyes open and the eyes closed.

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Background

Trucking Injuries:

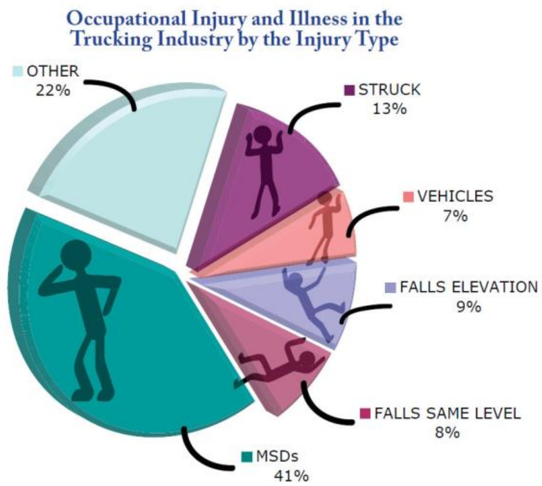
In Washington state alone, over 1.8 billion dollars were generated in 2005 by the for-hire transportation industry, which employs 48,000 workers. Following increased deregulation in the late 80s/early 90s, the number of small businesses and self-employed owners in the US with less than 6 trucks increased dramatically from 216,000 to 500,000 during the period of 1990 to 2000. This was followed by a decreased profit margin for these competing companies and decreased ability to provide safety training and equipment for drivers. Further, the average age of drivers in WA has increased from 39 to 42 since 1997, and trends continue to indicate an increasingly aging workforce.

Workers above the age of 45 were more likely to incur injuries requiring long periods before returning to work and increased claim costs compared to younger workers (Washington State Department of Labor and Industries WSDLI 2008). In addition, the truck driving population exhibits a higher percentage of obesity in comparison to that of the total population. Body weight in the form of BMI is a strong predictor of postural stability, accounting for up to 52% of the variance in balance between individuals (Hue et al 2007).

The trucking transportation industry remains a major contributor to yearly workplace injuries and fatalities. In the US during 1993 and 1994, over 70% of fatal fall related injuries were due to long haul freight trucking (Jones 2003). In 2003, 507 fatalities were reported to the Truck Transportation Industry and falls from non-moving vehicles were involved in 17 of the incidents (Bureau of Labor Statistics: US Department of Labor 2003).

Figure 1: Trucking Injuries

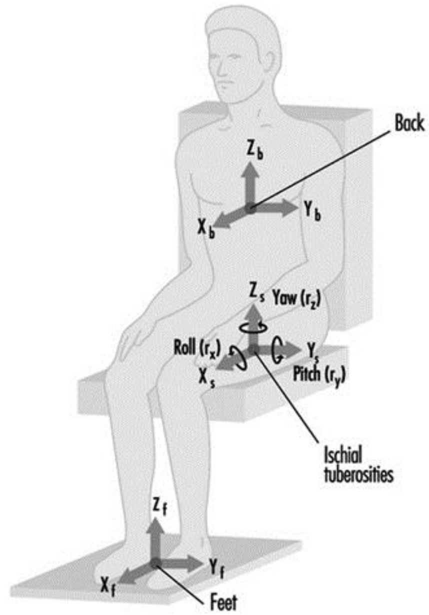
Source: Washington Department of Labor and Industries: Preventing Injuries in the Trucking Workplace



Annually, 1 out of every 13 truck drivers will suffer an occupation related injury that results in lost work time at an average cost of $30,000 per year (WSDLI 2008). When compared to all industries in the state of Washington, trucking injury rates are over double the state average. Falls were the second highest leading cause of occupational injury claims in the trucking industry at an average of $41,141 per incident (WSDLI 2011). Worker's compensation costs for falls from elevation were estimated to $68 million from 1997 to 2005, and falls from vehicles remain the greatest contributing source of those injuries (WSDLI 2008). Fall-related injuries are 8 times more likely to occur upon descending the vehicle than ascending (Ahuja 2005). The reasons behind this differential in fall risk are unclear; however, loss of balance associated with extended driving periods has been demonstrated a causal factor. (Ramakrishnan 2010).

Whole Body Vibration:

Figure 2: Axes of vibration for the seated driver, ISO 2631



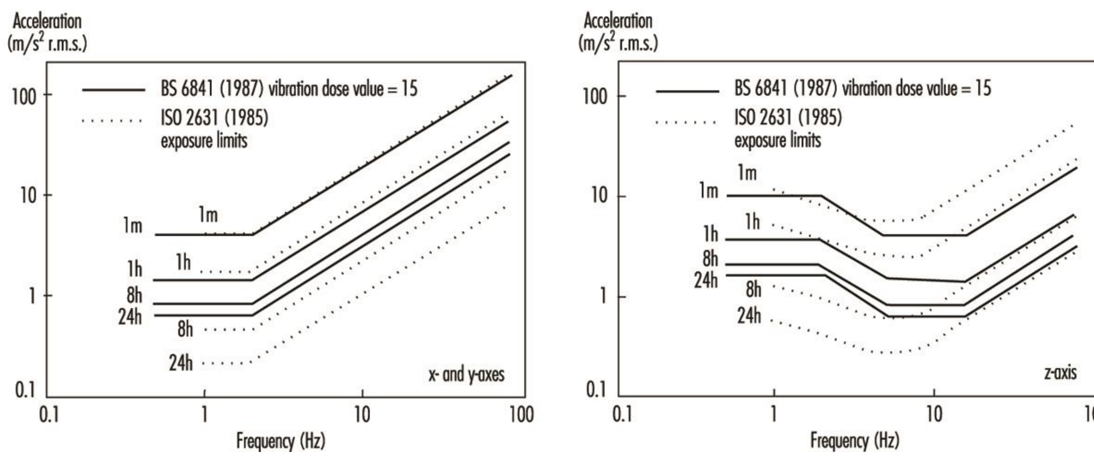
Occupational whole body vibration (WBV) has been linked to lower back injuries, visual and vestibular imbalances, as well as internal disturbances (Pope 1992). WBV is measured across three axes: Z measures head to toe, Y measures side to side, and X measures front to back. WBV in truck drivers is the result of motions created by translating engine components and the vehicle traveling over various types of road surfaces—correspondingly, factors such as age and maintenance of the vehicle along with environmental conditions can cause varying levels and frequencies of vibration even between the same models of vehicle (Hostens and Ramon 2003).

Previous studies have demonstrated an increased risk of falls, fractures, and soft tissue injuries associated with poor equilibrium control (Bovenzi 1994, Jones 2003, Rozali 2009). Gait irregularities resulting from disorientation and altered visual perceptions are major factors resulting in falls (Lockhart 2008). Other potential injury mechanisms include the amplification of vibrations at certain frequencies traveling up and down the back which leading to spinal disc degeneration and spinal muscle fatigue due to the cyclic activity (Murtezani 2011). Low range frequencies, typically near 5-10 Hz, have produced evidence of amplification through the lower back via resonance (Kitazaki and Griffin 1998). Professional operators of heavy vehicles such as semi-trucks, helicopters, and buses are exposed to chronic vibrations at varying frequencies over the courses of their work periods (Bovenzi 1994, De Oliveira 2005). Researchers in Malaysia have observed levels of Z-axis vibration among military vehicle seats to correspond with resulting increased levels of back pain and transference through the spine (Rozali 2009, Tamrin 2007).

Posture and duration of vibration exposure have been evidenced to constitute the primary risk factors for back pain and imbalance among agricultural tractor drivers and truckers (Murtezani 2011, Ramakrishnan 2010). However, the links between WBV, back injury, and disrupted somatosensory and visual systems remain poorly understood and researched. Methods for evaluating the extent of spinal injury/discomfort and altered standing balance include pre- and post- workshift questionnaires, crude field medical sway tests, and force board plates to compare shifts and size changes in center of balance (Ramakrishnan 2010).

Currently, there are no Occupational Safety and Health Administration (OSHA) standards concerning vibration exposure (Occupational Safety and Health Administration 2008). The American Conference of Governmental Industrial Hygienists has suggested TLVs for whole body vibration over a daily period using a tabular formula to provide limits (ACGIH 1999). The most referenced set of guidelines for evaluating whole body vibration is "The International Standards Organization (ISO) Standard Guide for the Evaluation of Human Exposure to Whole-Body Vibration"—specifically ISO 2631—which provides general requirements for methods of evaluations and adverse health effects and defines exposure limits to be "set at approximately half the level considered to the threshold of pain (or limit of voluntary tolerance) for healthy human subjects". In the European Union (EU), the EU, Directive 2002/44/EC delineates minimum health and safety standards for levels of whole body vibration: an exposure action value of $0.5 m/s^2$ and an exposure limit value of $1.15\ m/s^2$ calculated over an eight-hour period using the highest RMS values (frequency weighted average) based on the primary axis of the vibration exposure:

Figure 3:Weighted ISO and British Standards (Source ??)



Measurements of vibration are typically made using accelerometers placed between the subject and the source of vibration. For seated exposures, the instruments are placed between the seat and the ischial tuberosities of the subject.

Balance Assessment Tools:

Balance assessment tools typically fall into one of two categories: clinical or research. Clinical balance tests are used by medical practitioners to evaluate whether a balance problem is present and, if discovered, to determine the root cause of the issue. These tests are primarily observational and based on the scorer's qualitative assessment of performance (Mancini and Horak 2010). The Mini-Balance Evaluation Systems Test (Mini-BESTest) provides a succinct balance test with high reliability and validity that is comparable to the standard Berg Balance Scale (King et al 2012). It is used in this study to corroborate the research tool assessments consisting of center of pressure measurements captured via force plates.

Force plates (platforms that measure coordinates of downward force applied over time) at are used in research settings to evaluate postural stability by analyzing coordinates of the center of pressure (COP) over a period of time. COP is defined as the point location of the ground reaction forces and the center of mass (COM) represents a point equivalent of the total body mass in 3D space (Winter, 1995). The vertical projection of the COM onto the 2D surface on the ground is called the center of gravity (COG). The COG is directly related to balance: specifically, the COG must reside within the base of support in order to maintain balance. The central nervous system adjusts the position of COP to control the COG. Since the COP has been demonstrated to closely and continuously follow the COG (Winter, 1995; Chang et al., 1999; Aoyama et al., 2006), the COP can be used to reliably estimate the COG, particularly in quiet standing or sway tasks (Morasso et al., 1999). Typically, the COP measurements are considered as both separate anterior-posterior (AP) and medial-lateral (ML) components along with a total path length summation (combined ML and AP path lengths).

The Nintendo Wii Balance Board is a video game control device that can serve as an inexpensive, accurate, and mass-produced force plate. Studies comparing the Wii board with laboratory grade force plates have demonstrated favorable results for the purposes of measuring center of pressure trajectories (averages and point estimates) within 5% of the ‘gold-standard’ baseline (Clark et al 2010, Huurnink et al 2013). Limitations include a relatively low sampling rate (50 Hz), a suggested maximum load of 1962 N (441 lbs. and adequate for truck driver weights), and an increased amount of noise (Pagnacco et al 2011).

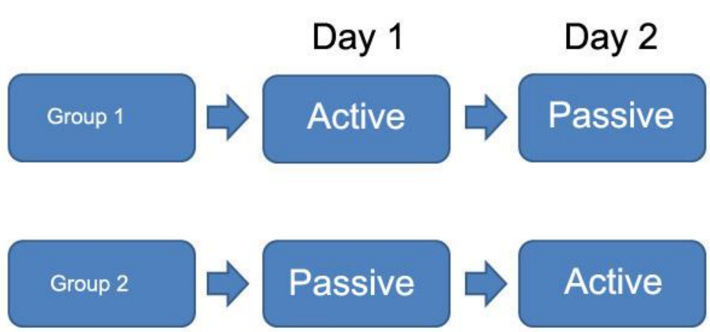
Six axis parallel motion devices have been used in previous studies to simulate vibrational exposures associated with a variety of heavy vehicle operations—mining, trucking, aviation, etc.—to a great degree of accuracy (Dickey 2010, Slota et al 2007). Readings taken from long haul work shifts can be programmed into the hexapod system to provide a systematic and repeatable exposure (Cornelius 1993, Dickey 2010).

Methods

Study Overview:

As can be seen in Figure 4, the overall study design consisted of a repeated measures cross-over design to examine effects of seated vibration exposure on the postural balance of male truck drivers and whether the WBV affected measures of postural balance. In a lab based setting, using a six degree of freedom vibrating platform called a hexapod (Moog Inc.; Kirkland, WA) a group of truck drivers were exposed to two hours of simulated WBV exposures collected from a semi-truck. In order to create a contrast in WBV exposures, the truck drivers sat in two different truck seats. On one day the truck drivers were exposed to WBV when they sat in an active suspension truck seat (Boseride; Bose Inc.; Framingham, MA) and on the complementing day when they sat in an industry standard, passive air-suspension truck seat. Prior results indicated that there would be roughly a 50% difference in WBV exposures between the two seats (Johnson, et. al., 2012)

Figure 4: Study Schedule



Subjects:

A group of 8 individuals were recruited to participate in the study. The age range of the subjects was 25-55 years with a mean age of 43.2 years. The average and standard deviation weight of the subjects was 236.5 and 43.9 lbs, respectively. The study was approved by the University of Washington's Human Subject Committee and all subjects gave their informed consent (HSD# 2857-E/G). Subjects were compensated with $100 for each day of their participation.

Study Design

Tri-axial truck floor vibration data from a freeway in Washington State were used as inputs to drive the hexapod (Figure 5). The hexapod was also equipped with mock steering wheels and pedals to better mimic WBV exposure during truck driving, An 8 minute segment of tri-axial truck floor vibration data was continuously repeated to create the two hours of exposure. The mean z-axis time weighted WBV exposure was 0.41 m/s^2. Hexapod systems have been used previously with great success to mimic a variety of occupational vibration exposures associated with heavy vehicle use and operation.

Vibration Measurements:

Figure 5: Hexapod mounted with the two truck seat seats, the active suspension seat is in the background and the passive suspension seat in the foreground.

With the subjects seated on the hexapod, the WBV they were exposed to was collected using a tri-axial seatpad accelerometer (model 356B40; PCB Piezotronics; Depew, NY) mounted on the truck seat. In addition, using an identical magnet mounted accelerometer secured to the floor of the hexapod, the z-axis WBV exposures were collected from the hexapod floor. The data acquisition system which collected the WBV exposure data consisted of an eight channel data recorder (model DA-40; Rion Co., LTD.;

Tokyo, Japan). The WBV exposures measurements were sampled at 1,280 Hz. The z-axis WBV exposures collected from the floor of the hexapod were compared to the actual input WBV exposures. In addition, to determine whether there were any differences in the WBV exposures when the subject sat on the two different truck seats, the WBV exposures when the subject sat on the active and passive suspension seat were compared.

Exposure session durations were two hours in length with two workers per session as shown in Figure 4/8. The two hour duration has been shown to be long enough to induce disruption in the somatosensory and visual systems (Slota et al 2007, Ahuja 2005). One set of measurements per subject was taken each day for two days to mimic a washout period similar to that of consecutive workday. The number of subjects recruited was consistent with previous studies where significant disturbances in posture were measured after exposure to whole body vibration (Ahuja et al 2005, Bovenzi 2009, Rozali 2009).

Before the experiment, subjects adjusted their seats to their desired seat height and back rest positions, armrests were used in all cases. Subjects were asked to mimic driving conditions and were directed to look forward to a large screen TV positioned to be in the line of sight in front of them. To keep drivers engaged and to reduce boredom, a movie was played on the large screen TV.

Figure 6: Experimental set-up showing the large screen TV the subjects were supposed to watch while sitting on the hexapod

Subjective assessment of discomfort:

Surveys (Appendix 1) were dispensed among all truckers pre-and post- exposure to evaluate levels of neck, lower back, and shoulder pain and fatigue (0 - no pain/fatigue, 10 - severe pain/fatigue)

Balance Measurements:

Participants underwent both a quantitative and qualitative evaluation of balance to determine whether exposure to WBV had any effect on postural balance. As shown in Figure 8, these postural balance measurements were made before the exposure to WBV, after two hours of exposure to WBV and five and ten minutes post-exposure. If there were any changes in postural balance after the two hour exposure to WBV, the five- and ten-minute post exposure measurements were conducted to determine whether there was any recovery in postural balance shortly after the exposure.

Figure 7: Experimental protocol showing the postural measurements before and after the exposure to WBV

Quantitative Balance Measurement

The quantitative evaluation of postural balance consisted of standing on a Wii force platform (Nintendo; Redmond, WA, USA) two times for approximately 1 minute: once with eyes open and once with the eyes. The sequence of standing on the balance board with the eyes open and closed was randomized. Differences in pre-and post- WBV exposure served as the basis for the analysis to determine whether the WBV exposures affected the vestibular (inner ear), visual systems or both and altered perception off balance.

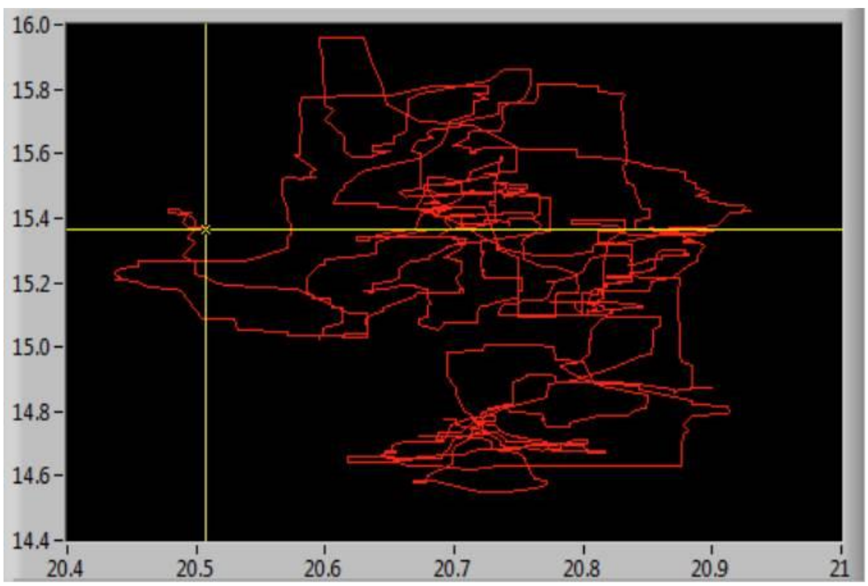
Figure 8: Wii fit platform showing the foot placement

As can be seen in Figure 8, subjects stood on the balance plate with their shoes on and their heels were positioned 10 to 15 cm apart angled 20 to 45 degrees away from the mid-sagittal plane. Subject stood on the balance plate with their shoes on since no differences have been found in balance scores between shoes on or off (Whitney and Wrisley 2004).   During the task, subjects were asked to look at a target image roughly at eye-level approximately 2 meters away to provide consistency across measurements.

Balance data from the Wii balance platform was transmitted via the balance platform's Bluetooth signal and saved at 50Hz on a laptop which used a Labview program to receive and record the postural data. After the balance data was collected a separate interactive Labview program was used select and analyze the postural data. Interactive cursors in the Labview program were used to select a 30 second segment from the 60 seconds of postural data and the medial-lateral, anterior-posterior, and total deviations from center of balance were calculated. The accuracy of the Wii platform was evaluated against a gold-standard AMTI force plate with resulting coefficient of correlation values >0.99 on both the anterior-posterior (AP) and medial-lateral (ML) coordinates, and multiple studies have been found that support our use of the Wii as a measure of balance (Young et al, 2011; Holmes et al, 2013).

Figure 9: Sample Labview Output of Total COP Balance Measurement

AP (cm)



ML (cm)

30 second COP path

Total Path Length: 17 cm
ML Path Length: 7.4 cm
AP Path Length: 12.2 cm

Qualitative Balance Measurement

After the quantitative balance measurements, a more qualitative postural balance assessment was performed using a brief medical evaluation of balance via a subset of tasks from the miniBESTest (Wade et al 2004) and used as a corroboratory tool. These qualitative medical balance tests include observations of any lateral deviations in pathing when the subject follows a set (3 meter) line, difficulties in unilateral balance (standing on one leg), pivot turn stability, and sit-stand balance evaluated with a 0 (severe) to 2 (normal) point scale (see Appendix 2 for the full evaluative miniBESTest tool). A total score of 0 indicates significant balance impairment, while a score of 12 indicates normal balance.

Lastly, a brief (3 question) Borg discomfort/fatigue questionnaire (Appendix 1) was given pre- and post-exposure. Previous anecdotal comments from field truck drivers regarding the lack of lower back and torso pain after testing the active suspension seat seemed to warrant further investigation to determine if any clear perceived differences between the two seats were present independent of balance measurements.

Data Analysis

The main effects which could be responsible for changes in posture included the exposure time (pre- and post-), washout time post vibration exposure (post, 5 and 10 min), and seat type (active suspension or passive suspension). Response variables and analyses focused on changes in center of pressure (COP), path length in medio-lateral (ML), anterior-posterior (AP), and both directions combined (total path length), and differences in variance between pre-and post-vibration.

To determine whether there were changes in postural balance pre- and post-exposure to the WBV and between the two WBV exposure conditions, as shown in Table 1, various repeated measures Analysis of Variance models were evaluated to determine which explanatory variables would be included in the final model. Independent variables which were not statistically significant ($p>0.05$) to results were excluded in the subsequent models. In addition, Dunnett's tests were also performed comparing the post-exposure (120min) measurements to the baseline (0min), 5 minute washout (125min), and 10 minute washout (130min) measurements for increased sensitivity to differences in means. The statistical program JMP was used to perform these analyses.

Possible effect modifiers, including—

- Seat type
- Time
- Visual feedback (eyes open or closed)
- Weight and BMI (higher BMI/weight individuals may be less able to maintain balance during descension)

—were examined using a multilevel stratified analysis examining possible interaction coefficients.

Table 1: Fixed effect variables and interactions in original model

	Eyes*	**Time***	**Seat**	**Day**	**Age**	**BMI**	**Weight**
Eyes*		x	x	x	x	x	x
Time*	x		x	x	x	x	x
Seat	x	x		x	x	x	x
Day	x	x	x				
Age	x	x	x				
BMI	x	x	x				
Weight	x	x	x				
Eyes x Seat		x					
Eyes x Age		x					
Eyes x BMI		x					
Eyes x Weight		x	x				

*Variables in final model

The variables included in the final model (R^2 from 0.65 to 0.80 depending on path length type) were Time (0min, 120min, 125min, 130min) (fixed effect) with Subject (S1-S8) set to random effect to account for variation between individuals and differences within measurements from the same individual and stratified by Eyes (Closed/Open) (effect modifier) as the balance measurements greatly differed depending on eye status.

Our data consisted of both independent and dependent samples that were initially analyzed separately for residual chronological differences to exclude confounding due to residual effects. Longitudinal multilevel analysis using repeated measures provided controls against factors that changed according to time. Differences in postural balance were expected between the two WBV exposure conditions, pre and post WBV exposure and in the ten washout periods after the exposure to WBV.

Hypothesis tests were based on the mean differences in postural stability between vibration levels, with and without the eyes open and as a function of time:

H_a: Significant difference in postural stability after 2 hours of exposure to WBV

H_a: Significant difference between postural stability pre-and post-shift between postural stability measurements with the eyes open and eyes closed.

H_a: Significant difference between postural stability depending on the magnitude of the WBV exposure (whether subject sat in the active suspension or passive suspension seats).

H_a: Significant difference between postural stability measured post WBV exposure and the measurements 5 and 10 minutes post WBV exposure.

Sample size (at least 8 individuals total) was roughly estimated prior to recruitment from a previous study (Ahuja YEAR) with similar methodology using $N = (4\sigma^2 \text{ x } (Z_{power} + Z_{critical}))/D^2$ at 0.05 significance and .80 statistical power, with an overall standard deviation in cm of 0.05 within individual sway and difference of at least 0.2 cm between pre- and post- shift. As we were measuring fairly large differences in COP path lengths between pre-and post-shift compared to smaller postural instability due to inherent variation within individuals, our sample size of 8, while not ideal due to time and cost constraints, was anticipated to provide reasonable power to detect differences, if they exist.

Results

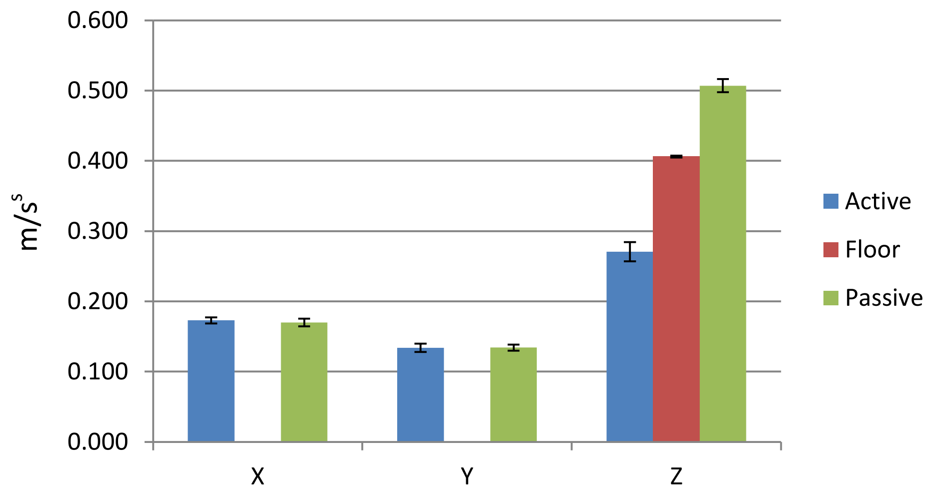
WBV Exposure Data

There were significant differences and a substantial contrast in WBV exposures between different seat types. As can be seen in Figure 10, there were no differences in the *x*- and *y*-axis exposures. The average weighted vibration for the active and passive, air-suspension seats was 0.25 (SE ±0.014) and 0.51 (±0.009) m/s^2 respectively (see Table 2). The mean *z*-axis vibration measured at the hexapod floor was 0.41 (SE ±0.002) m/s^2. Due to equipment difficulties, the floor measured vibrations were based on a subsample of four measurements collected on the second day. The industry standard, passive air-suspension seat was found to amplify the *z*-axis floor measured WBV exposures by 20.8% (±0.1%), while the active suspension seat reduced WBV exposures by 33.6% (±0.2%).

Table 2: The mean (± standard error) z-axis WBV exposures measured from the seats and at the floor of the hexapod. SEAT stands for Seat Effective Amplitude Transmission and is the percentage of the floor measured vibration transmitted to the seat of the operator. A(8) is an RMS based averaging of raw acceleration signal.

		Active Suspension	Passive Suspension	p-value
A(8) [m/s^2]	**Seat**	0.25 ± 0.014	0.51 ± 0.0.009	< 0.0001
	Floor	0.41 ± 0.002	0.41 ± 0.002	-
	SEAT	67% ± 0.1	120.8%± 0.2	< 0.0001

Figure 10: Tri-axial average weighted WBV exposure when sitting on the Hexapod grouped by seat type. Only z-axis exposures were measured from the floor of the Hexapod [n = 8 for x-, y- and z- seat, n = 4 for z-floor]. Vertical bars represent standard errors?



Balance Measurements

A total of 123 balance measurements were collected out of an expected 128. 2 subjects each missed a measurement section of the washout period (4 measurements missing) due to having to use the restroom immediately after the two hours of exposure to the whole body vibration. One subject had a repeated eyes open instead of eyes open/closed measurements (1 measurement missing).

The Wii force plate data returned coordinates along the X (medial-lateral) and Y (anterior-posterior) axis for each point measurement taken. The following equations (See Equation 1-3) were used to find the total distance traveled by the COP along for the medial-lateral (ML) and anterior-posterior (AP) axis, and then calculated the total combined distance travelled.

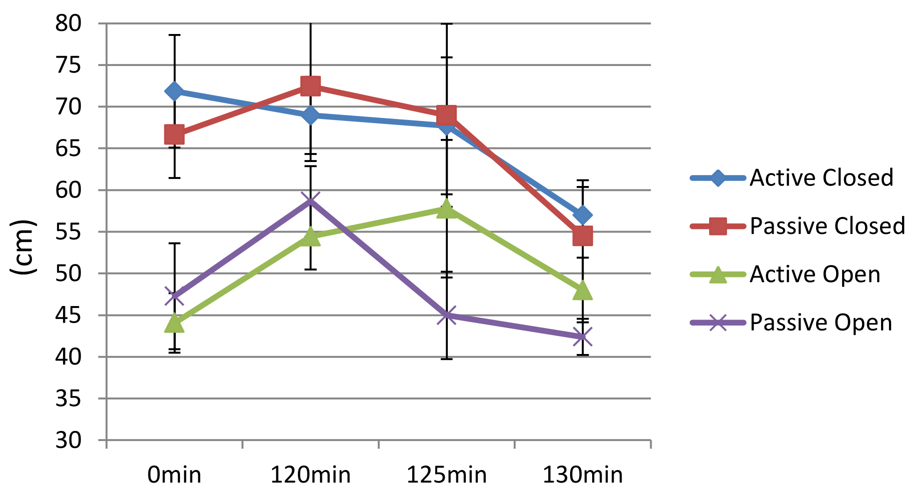
Equation 1:
ML Path Length = $\sum(|X_2-X_1| + |X_3-X_2|...|X_n-X_{n-1}|)$
where n denotes the total number of COP samples.

Equation 2:
AP Path Length = $\sum(|Y_2-Y_1| + |Y_3-Y_2|...|Y_n-Y_{n-1}|)$

Equation 3:
Total Path Length = $\sum [\surd (|X_2-X_1|^2 + |Y_2-Y_1|^2) + \surd (|X_3-X_2|^2 + |Y_3-Y_2|^2) +... \surd (|X_n-X_{n-1}|^2 + |Y_n-Y_{n-1}|^2)]$

Postural balance differences based on WBV Exposures

Figure 11: Total Path Length by Seat Type and Eyes Open/Closed (averages from all subjects?). Vertical bars represent standard errors?



As shown in Figure 11 and Tables 3, 4, 5, and 6, the repeated measures analysis of variance displayed no significant differences in balance measures between the two seats before and after the two hours of exposure to WBV (p = 0.48 eyes open, p = 0.99 eyes closed); however there was a small time-lag- in balance recovery during the washout period (125min) after subjects sat in the active suspension seat with eyes open. As a result of the lack of differences between the two seat conditions, and given there was not a significant condition by time interaction for the balance measures with the eyes open and the eyes closed, the balance measures from the two seating conditions were combined for all subsequent analyses. This minor time-lag with the eyes open was apparent in all three postural measures (AP, ML, Total) and remained insignificant (p>0.05).

Table 3: RANOVA model of Eyes/Seat/Time and the associated p-values and (F-ratios) [n = 8]

	Eyes Closed			**Eyes Open**		
	Medial Lateral	**Anterior Posterior**	**Total**	**Medial Lateral**	**Anterior Posterior**	**Total**
Time	0.056(2.7)	0.003(5.6)	0.002(5.7)	0.11(2.1)	0.02(3.8)	0.03(3.5)
Seat	0.51(0.43)	0.94(0.01)	0.98(<0.00)	0.73(0.12)	0.27(1.2)	0.35(0.91)
Seat x Time	0.80(0.33)	0.64(0.56)	0.78(0.37)	0.08(2.4)	0.19(1.7)	0.13(2.0)

Table 4: Mean (±standard error) Medial Lateral Path Length in centimeters by Seat Type [n = 8]

	Eyes Closed			**Eyes Open**		
	Active	**Passive**	**p-value**	**Active**	**Passive**	**p-value**
0min	16.8 (±2)	17.4 (±1)	0.98	13.4 (±1)	15.9 (±2)	0.97
120min	19.6 (±3)	17.9 (±2)	0.99	17.0 (±2)	20.1 (±2)	0.91
125min	16.4 (±1)	16.6 (±1)	0.71	18.7 (±4)	14.1 (±2)	0.48
130min	16.3 (±1)	14.2 (±2)	0.96	15.9 (±2)	13.6 (±1)	0.99

Table 5: Mean (±standard error) Anterior Posterior Path Length in centimeters by Seat Type [n = 8]

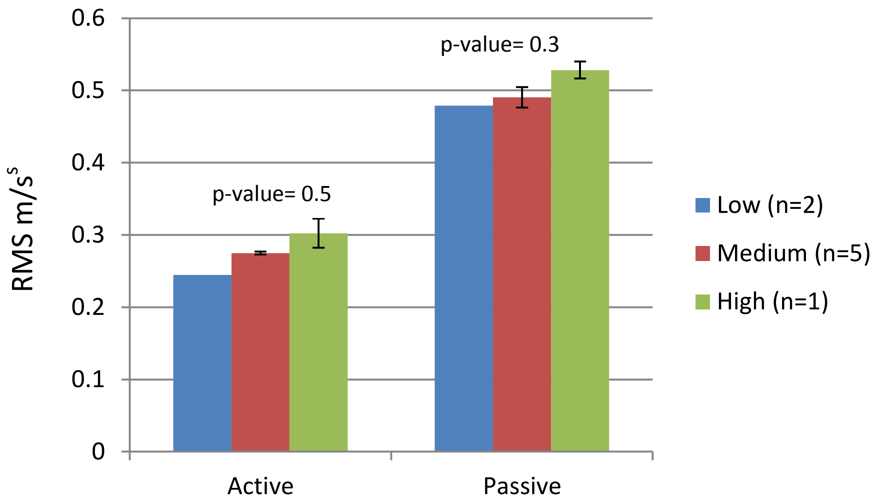
	Eyes Closed			**Eyes Open**		
	Active	**Passive**	**p-value**	**Active**	**Passive**	**p-value**
0min	64.6 (±6)	58.7 (±5)	0.97	37.3 (±4)	38.9 (±5)	0.99
120min	60.3 (±4)	64.9 (±9)	0.99	46.2 (±3)	48.7 (±3)	0.99
125min	60.7 (±8)	61.7 (±11)	0.99	48.8 (±7)	38.0 (±4)	0.34
130min	49.7 (±4)	48.2 (±6)	0.99	39.9 (±3)	35.4 (±2)	0.99

Table 6: Mean (±standard error) Total Path Length in centimeters by Seat Type [n = 8]

	Eyes Closed			**Eyes Open**		
	Active	**Passive**	**p-value**	**Active**	**Passive**	**p-value**
0min	71.8 (±7)	66.6 (±5)	0.99	44.1 (±4)	47.3 (±6)	0.99
120min	69.0 (±5)	72.4 (±9)	0.99	54.4 (±4)	58.6 (±4)	0.99
125min	67.7 (±8)	69.0 (±11)	0.99	57.8 (±8)	45.0 (±5)	0.32
130min	57.0 (±3)	54.5 (±7)	0.99	48.0 (±4)	42.4 (±2)	0.99

Further, we analyzed WBV exposures by weight (H=greater than 300lbs M=200-300lbs, L=200lbs or less) to examine possible bottoming out effects or increase in vibration in the seats, and no change in z-axis vibration levels were found when subjects were grouped by weight (p-value = 0.890) as in Figure 12.

Figure 12: Mean (standard error) Z-axis RMS Vibration by Seat and Weight Category



As measures of quality control, Days 1 and 2 were compared for differences in path length measurements (ML, AP, total) at all time points (0min, 120min, 125min, 130min), and did not differ significantly (See Figure 13 and Table 7).

Figure 13: Mean (±standard error) Total Path Length by Day

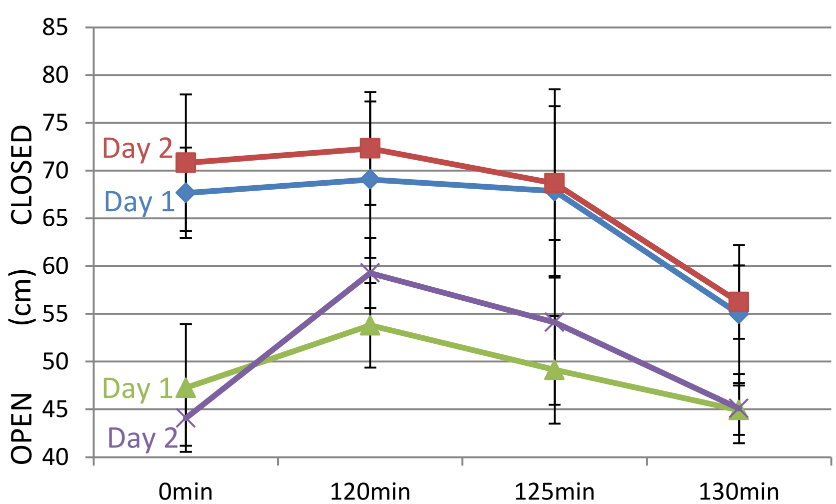


Table 7: Mean (±standard error) Total Path Length in centimeters by Day [n = 8]

	Eyes Closed			**Eyes Open**		
	Medial Lateral	**Anterior Posterior**	**Total**	**Medial Lateral**	**Anterior Posterior**	**Total**
Day 1	17.0 (±2)	56.4 (±6)	64.0 (±6)	15.9 (±2)	40.3 (±3)	48.4 (±3)
Day 2	16.6 (±2)	60.2 (±6)	67.4 (±6)	16.1 (±2)	42.7 (±3)	50.6 (±3)
p-value	0.86	0.19	0.26	0.86	0.34	0.47

Postural balance differences based on visual feedback

Since there were no differences in balance measures between the two WBV exposure conditions (seat conditions), the balance measures were combined for the final analysis. As can be seen in Figure 14 and as shown in Tables 8 and 9 (pre- (0 min) and post- (120 min) WBV exposure measures), WBV exposure was associated with a significant increase in the AP and total path lengths (p-values <0.05) and near significance (p-value = 0.053) for ML path length when eyes were open, but no difference in path lengths when comparing pre-and post- WBV exposure with eyes closed. The differences between pre- and post- WBV exposure balance measurements were consistently larger when the eyes open measurements were compared to eyes closed.

Figure 14: Mean (±standard error) Path Lengths in centimeters by Eyes Open/Closed [n = 8]. Data points with dissimilar characters (i.e. A vs. B) were significantly different from each other while points sharing characters (i.e. A vs. A,B) were not significantly different.

Medial Lateral   Anterior Posterior   Total

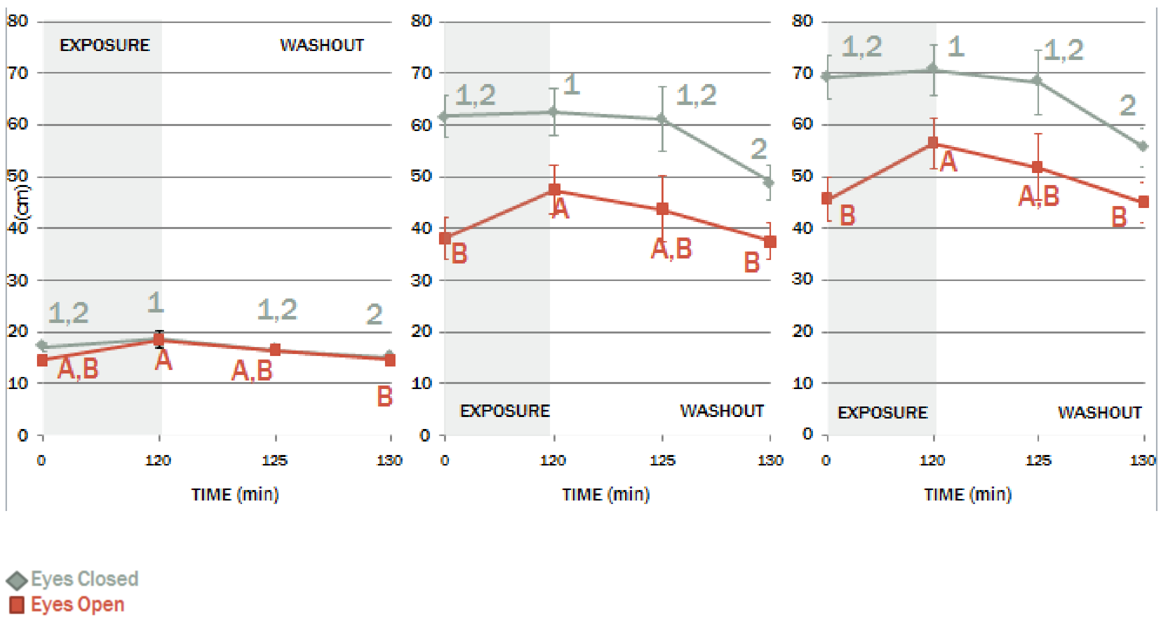


Table 8: Dunnett's Method tests (p-values) for significance with 120min path length measurements set as baseline for comparison to 0min/125min/130min measurements

	Eyes Closed			**Eyes Open**		
	Medial Lateral	**Anterior Posterior**	**Total**	**Medial Lateral**	**Anterior Posterior**	**Total**
0 min	0.5	0.9	0.9	0.05	0.02*	0.02*
120 min	-	-	-	-	-	-
125 min	0.2	0.9	0.8	0.26	0.41	0.31
130 min	0.02*	0.009*	0.006*	0.045*	0.009*	0.009*

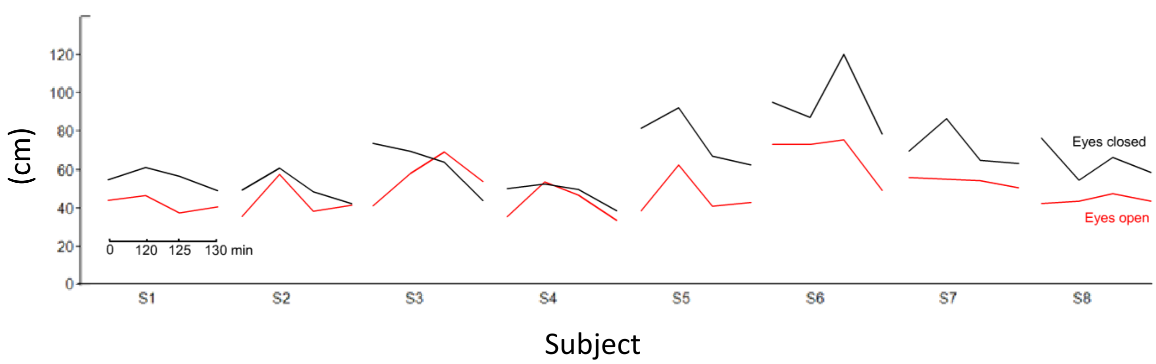
Table 9: Mean (±standard error) Path Lengths in centimeters by Eyes Open/Closed [n = 8]

	Eyes Closed			Eyes Open		
	Medial Lateral	**Anterior Posterior**	**Total**	**Medial Lateral**	**Anterior Posterior**	**Total**
0 min	17.1 (±1)	61.7 (±4)	69.2 (±4)	14.6 (±1)	38.1* (±3)	45.7* (±4)
120 min	18.7 (±2)	62.6 (±5)	70.7 (±5)	18.5 (±1)	47.5 (±2)	56.5 (±3)
125 min	16.4 (±1)	61.2 (±6)	68.2 (±6)	16.4 (±1)	43.6 (±4)	51.6 (±4)
130 min	14.7* (±1)	47.91* (±3)	54.6* (±4)	14.6* (±2)	37.2* (±2)	44.7* (±2)

*p-value<0.05

There were also differences in the balance measurements between the eyes open and the eyes closed within the recovery/washout period (comparing 120 min, 125 min and 130 min). With the eyes closed, the 130 min balance measurements were consistently and significantly lower than the pre exposure measurements (0min) across all subjects. In contrast, with the eyes open, the 130 min balance measurements returned to the pre-exposure (0min) values.

Figure 15: Total Balance Path Lengths for Eyes Closed (top) and Open (bottom) by Subject and grouped by Time.



Postural balance differences by suspected confounders/effect modifiers:

No significant differences between balance measurements were found when stratified by BMI as shown in Tables 10, 11, and 12 and Figure 16. Subjects were divided into 3 categories (Low 25-30 BMI, 30-35 BMI, and High 35+ BMI).

Figure 6: Mean (±standard error) Total Balance Path Lengths for Eyes Closed (left) and Open (right) by BMI

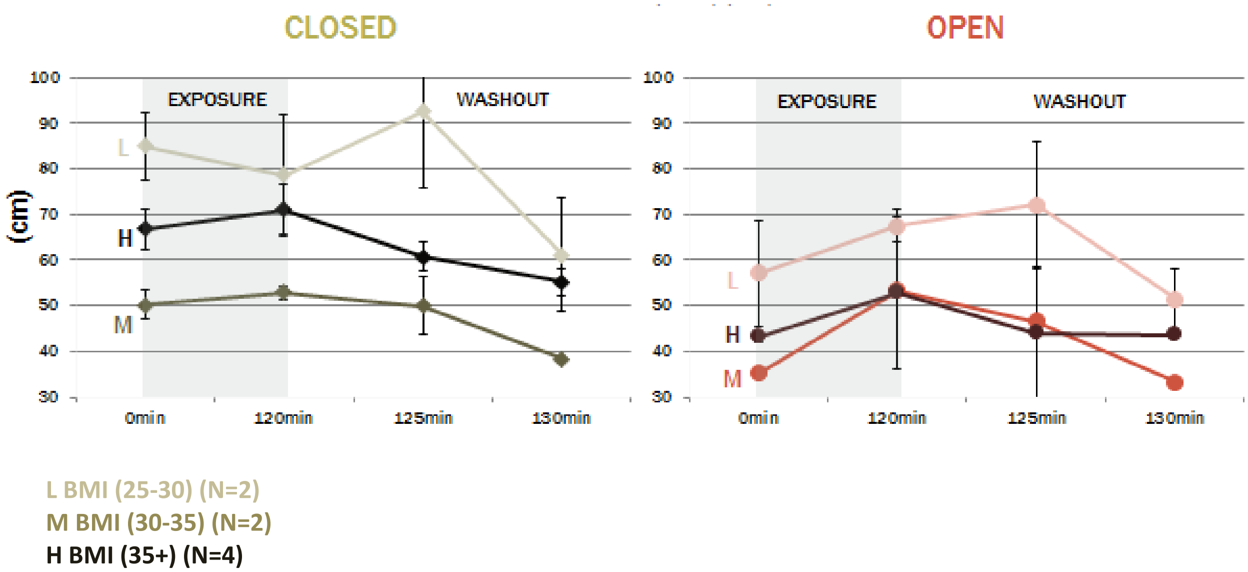


Table 10: Mean (±standard error) Medial Lateral Path Length in centimeters by Eyes Open/Closed and BMI [n = 8]

	Eyes Closed p-value = 0.98			Eyes Open p-value = 0.48		
	25-30 BMI	**30-35 BMI**	**35+ BMI**	**25-30 BMI**	**30-35 BMI**	**35+ BMI**
0 min	20.0 (±1)	12.4 (±0.2)	16.9 (±1)	19.6 (±4)	12.5 (±2)	13.1 (±1)
120 min	21.8 (±2)	11.8 (±0.2)	18.9 (±2)	23.8 (±1)	18.1 (±8)	16.5 (±1)
125 min	19.7 (±2)	11.8 (±0.2)	16.1 (±1)	26.7 (±6)	14.0 (±6)	12.6 (±1)
130 min	16.6 (±4)	9.4 (±0.2)	15.2 (±1)	18.1 (±4)	11.7*	13.6 (±1)

*too few subjects for standard error due to missing data/small n of BMI group

Table 11: Mean (±standard error) Anterior Posterior Path Length in centimeters by Eyes Open/Closed and BMI [n = 8]

	Eyes Closed p-value = 0.98			Eyes Open p-value = 0.48		
	25-30 BMI	**30-35 BMI**	**35+ BMI**	**25-30 BMI**	**30-35 BMI**	**35+ BMI**
0 min	76.8 (±7)	44.2 (±3)	59.1 (±4)	46.6 (±10)	28.4 (±0.3)	36.6 (±2)
120 min	68.9 (±13)	47.7 (±2)	63.1 (±5)	55.3 (±4)	44.3 (±13)	45.0 (±2)
125 min	84.5 (±17)	44.8 (±70)	53.6 (±3)	59.0 (±11)	39.8 (±12)	37.9 (±3)
130 min	53.5 (±11)	33.6*	48.6 (±3)	41.9 (±5)	27.2*	36.8 (±5)

*too few subjects for standard error due to missing data/small n of BMI group

Table 12: Mean (±standard error) Total Path Length in centimeters by Eyes Open/Closed and BMI [n = 8]

	Eyes Closed p-value = 0.98			Eyes Open p-value = 0.48		
	25-30 BMI	**30-35 BMI**	**35+ BMI**	**25-30 BMI**	**30-35 BMI**	**35+ BMI**
0 min	84.9 (±7)	50.2 (±3)	66.8 (±4)	57.2 (±1)	35.3 (±12)	43.2 (±3)
120 min	78.7 (±13)	52.8 (±2)	71.1 (±6)	67.5 (±17)	53.3 (±4)	52.8 (±3)
125 min	92.5 (±17)	50.0 (±6)	60.7 (±3)	72.0 (±14)	46.5 (±14)	44.0 (±3)
130 min	61.2 (±13)	38.3*	55.2 (±3)	51.4*	33.4 (±7)	43.6 (±1)

*too few subjects for standard error due to missing data/small n of BMI group

Subjects were also stratified by age into three categories, and no results of significance were found when examining the differences between balance measurements across the four time periods (age by time interaction listed as **Δ** p-value) in Tables 13, 14, and 15. However, mean balance measurements by age at each measurement point (i.e. 120min 25-35 yrs vs. 120min 50+yrs) did differ significantly as seen in the total balance path length in Figure 17.

Figure 7: Mean (±standard error) Total Balance Path Lengths for Eyes Closed (left) and Open (right) by Age

Table 7: Mean (±standard error) Medial Lateral Path Length in centimeters by Eyes Open/Closed and Age [n = 8]

	Eyes Closed p-value = 0.03 Δ p-value = 0.92			Eyes Open p-value = 0.05 Δ p-value = 0.87		
	25-35 yrs	**40-50 yrs**	**50+ yrs**	**25-35 yrs**	**40-50 yrs**	**50+ yrs**
0 min	13.9 (±2)	13.9 (±2)	13.9 (±3)	12.7 (±1)	14.3 (±1)	17.2 (±5)
120 min	15.7 (±3)	15.7 (±3)	15.7 (±3)	18.9 (±4)	15.7 (±5)	23.7 (±1)
125 min	14.1 (±1)	14.1 (±1)	14.1 (±1)	13.3 (±2)	16.3 (±5)	20.2 (±7)
130 min	12.6 (±2)	12.6 (±2)	12.6 (±2)	12.0 (±0.4)	14.7 (±3)	16.6 (±1)

Table 8: Mean (±standard error) Anterior Posterior Path Length in centimeters by Eyes Open/Closed and Age [n = 8]

	Eyes Closed p-value = 0.03 Δ p-value = 0.39			Eyes Open p-value = 0.05 Δ p-value = 0.60		
	25-35 yrs	**40-50 yrs**	**50+ yrs**	**25-35 yrs**	**40-50 yrs**	**50+ yrs**
0 min	42.7 (±2)	61.5 (±3)	81.0 (±6)	47.3 (±1)	38.3 (±3)	47.3 (±10)
120 min	49.7 (±2)	59.4 (±5)	81.9 (±11)	56.3 (±5)	43.9 (±2)	56.3 (±3.0)
125 min	43.0 (±3)	56.8 (±3)	95.7 (±18)	47.9 (±5)	46.1 (±4)	47.9 (±13)
130 min	34.5 (±2)	47.8 (±4)	61.8 (±6)	37.3 (±3)	39.6 (±3)	37.3 (±2)

Table 9: Mean (±standard error) Total Path Length in centimeters by Eyes Open/Closed and Age [n = 8]

	Eyes Closed p-value = 0.03 Δ p-value = 0.57			Eyes Open p-value = 0.05 Δ p-value = 0.68		
	25-35 yrs	**40-50 yrs**	**50+ yrs**	**25-35 yrs**	**40-50 yrs**	**50+ yrs**
0 min	49.9 (±1)	69.1 (±4)	88.9 (±6)	35.4 (±1)	45.7 (±3)	56.0 (±12)
120 min	56.9 (±2)	68.0 (±6)	89.8 (±11)	55.4 (±7)	51.5 (±3)	67.9 (±4)
125 min	49.8 (±3)	64.0 (±3)	102.8 (±18)	42.2 (±6)	53.9 (±5)	57.7 (±17)
130 min	40.9 (±2)	53.8 (±4)	70.4 (±6)	38.5 (±3)	47.0 (±4)	45.9 (±3)

Qualitative balance and discomfort results

The truncated Mini-BESTest scores ranged between 11-12 out of a total of 12 points (see Table 16). The difference between 11 and 12 on the clinical balance test was of statistical but not clinical significance. The Borg Discomfort Questionnaire (Appendix 1) did not display any significant scale changes (p-value >0.05) between pre- and post-WBV (0.25 Lower Back, 0.1875 Neck, 0.094 Shoulders, on average) out of a total of 10 points (see Table 16).

Table 10: Questionnaire Results

Mean ± SD	Lower Back	Neck	Shoulders	MiniBESTest
Pre	0.94	0.81	1.09	11.75
Post	1.19	1	1	12
Difference	0.25 ±1.0	0.19 ±1.3	-0.09 ±1.5	0.25 ±0.44
p-value	0.17	0.28	0.40	0.02*

Discussion

The balance differences due to vibrational exposure differed significantly depending on whether eyes were open or closed. All COP balance path lengths (AP, ML and Total) were significantly greater with eyes closed compared to the path lengths with the eyes open. However, the changes in pre- and post-WBV exposure COP balance path lengths were substantial and statistically significant with the eyes open. This is consistent with previous research findings examining seated vibration (Ahuja 2005). This suggests that visual information is potentially inconsistent with sensory information in other modalities (i.e., proprioceptive and vestibular senses), which overall contributes to balance instability after extended exposure to WBV. COP balance measurements with eyes closed yielded little to no differences when comparing pre- and post-WBV measurements, but displayed a significant drop in all path lengths 10minutes post-exposure.

The path length changes pre- and post-exposure were consistent with other balance studies which have typically found the greatest changes in AP path (Ahuja 2005, Slota et al 2007, Oullier et al 2008). The increases between pre- and post-WBV balance measurements (3.91cm ML, 9.39cm AP, and 10.87cm total) were similar to differences in other studies examining balance measurements between stroke and control patients (10 to 15cm) (Sawacha et al 2013, Pyoria et al 2004), though both studies displayed large variability between individuals.

Though focused on a different demographic, studies examining risk of falls among the elderly have displayed associations between increased COP movement and likelihood of falling independent of age (Muir et al 2013, Pajala et al 2008, Brauer et al 1999). Increased body sway while attempting to maintain stillness ('quiet stance') as during balance measurements in this study has been used to predict elderly fallers (Campbell et al 1989, Lord et al 1993), though the specific metrics of COP vary (path length/velocity/amplitude, etc.) depending on study. In a review of balance literature, the axis found to have the best predictive ability was in the ML direction (Piirtola and Era 2006), which in our study displayed the smallest absolute differences ($Mean_{post}$-$Mean_{pre)}$ (~4cm ML between pre- and post- WBV exposure), but similar changes in amplitude to AP and total path length ($Mean_{post}/Mean_{pre}$) (1.23x ML, 1.25x AP, 1.24x Total). A large prospective study (Pajala et al 2008) evaluating falls among elderly women using velocity and path amplitude for ML/AP measurements as explanatory variables found that the group with largest COP measurements displayed significantly (2-4x) increased risk for indoor falls in comparison to the lowest group (1.1x increase in ML velocity, 1.23x increase in AP velocity). While not directly measuring the same factors in this study (velocity/amplitude vs. path length), their velocity calculations were a sum of overall path length divided by length of time measured, which would correlate well to the distance traveled calculated in this study.

The changes in pre- and post-WBV exposure balance measurement were nearly identical across the two WBV exposure conditions (active verses passive seat). This lack of difference pre- and post WBV exposure was surprising considering the active suspension seat reduced the z-axis WBV exposures by roughly 50%. One explanation for the lack of a difference in balance changes between the two conditions may be due to vibrations entering the subject from other sources such as through the feet placed on mock pedals on the floor of the hexapod or through the hands which gripped a mock steering wheel. Alternatively, the active suspension seat may have mediated the higher frequency vibrations (5 Hz and above) while doing less to alleviate the low frequency vibrations (2 Hz and below) that may have been the primary cause of vibration induced instability. Another explanation would that there may be a lower threshold of vibration exposure above which balance differences remained relatively stable.

The lag in apparent washout duration of WBV in the active suspension seat was also an unexpected finding. While not statistically significant, the trend in all three path measurements displayed a consistency that may warrant further study with smaller time increments between measurements to better characterize the washout period and either provide corroborating data or refute the apparent time-lag in the data.

Another unusual result involved the differences between eyes open and eyes closed measurements for the 130min washout period. The balance measurements at 130min (AP and total) with eyes closed were uniformly much lower than the pre-exposure/baseline measurements for all subjects. In contrast, balance measurements with eyes open followed the expected pattern of an increase at the post-exposure (120min) measurement followed by a gradual decrease in path lengths during the 10 minute washout period (125 min and 130 min), five- and ten-minutes post-exposure, reaching pre-exposure baseline levels at 130min.

While differences between balance measurements with the eyes open and eyes closed have been seen in previous studies (Ahuja 2005, Oullier et al 2008), the distinct improvement in postural balance with the eyes closed at the end of the 10 minute washout period was surprising and is likely due to a higher level of 'comfort' or experience associated with the short duration (10 minutes) between measurements in the washout period compared to the 120 minute difference pre- and post-exposure.

Neither BMI, body weight, nor age had a significant effect on changes in balance measurements, though overall mean path lengths were different when stratified by age group, suggesting that while the oldest age category (50+yrs) exhibited more baseline instability than the youngest (25-35yrs) category, the seated WBV lead to a similar range of effects.

The discomfort questionnaires did not display any significant differences between seats or when comparing pre- and post-exposure results. This was somewhat contrary to expected findings as many of the drivers verbally commented on the increased comfort of the active seat. The improvement of clinical balance test scores was statistically significant, but the difference was small (only a 0.25 increase out of a 12 point scale) thus may not have clinical significance. Furthermore the shortened version of the Mini-BESTest used in this study may need further validation for clinical assessments.

Limitations/Biases

The primary limitation of this study involved its small sample size of 8 subjects that may have failed to provide adequate study power for certain trends such as washout period effects and seat type. Nonetheless, significant changes in balance were found between pre- and post-WBV exposure and these changes may have injury prevention implications for the trucking industry. One way to address this finding may be to develop an egress policy upon the end of a long drive period that requests drivers remain inside the cab with engine turned off for 5-10 minutes and perform tasks (such as paperwork) that can be completed while seated before exiting.

Neither subjects nor researchers were blinded to the type of seat, and it was possible that this may have biased results away from null if subjects expected better balance after the exposure to the WBV when sitting in the active suspension seat. Another limitation was the lack of seated control condition, where subjects simply sat for a two hour period, not exposed to WBV and the same battery of postural measurements were performed. Long periods of sitting may lead to an increase in path length measurements regardless of WBV exposure.

While statistical significance was found in changes of balance measurement pre- and post- WBV exposure, the clinical significance of these differences (4-10cm increase over a 30 second period) was less clear, primarily due to lack of similar quantitative data regarding occupational imbalance in other controlled laboratory or field settings.

Alternates to ‘quiet stance’ measurements such as balance during simple tasks or dynamic balance measurements may better reflect the patterns in COP changes that result in falls as drivers are primarily falling when exiting vehicle. The hexapod system with 2 hours of WBV may not have accurately reflected the workshift exposures, primarily regarding duration of WBV as the frequencies and amplitudes of vibration were recreated faithfully.

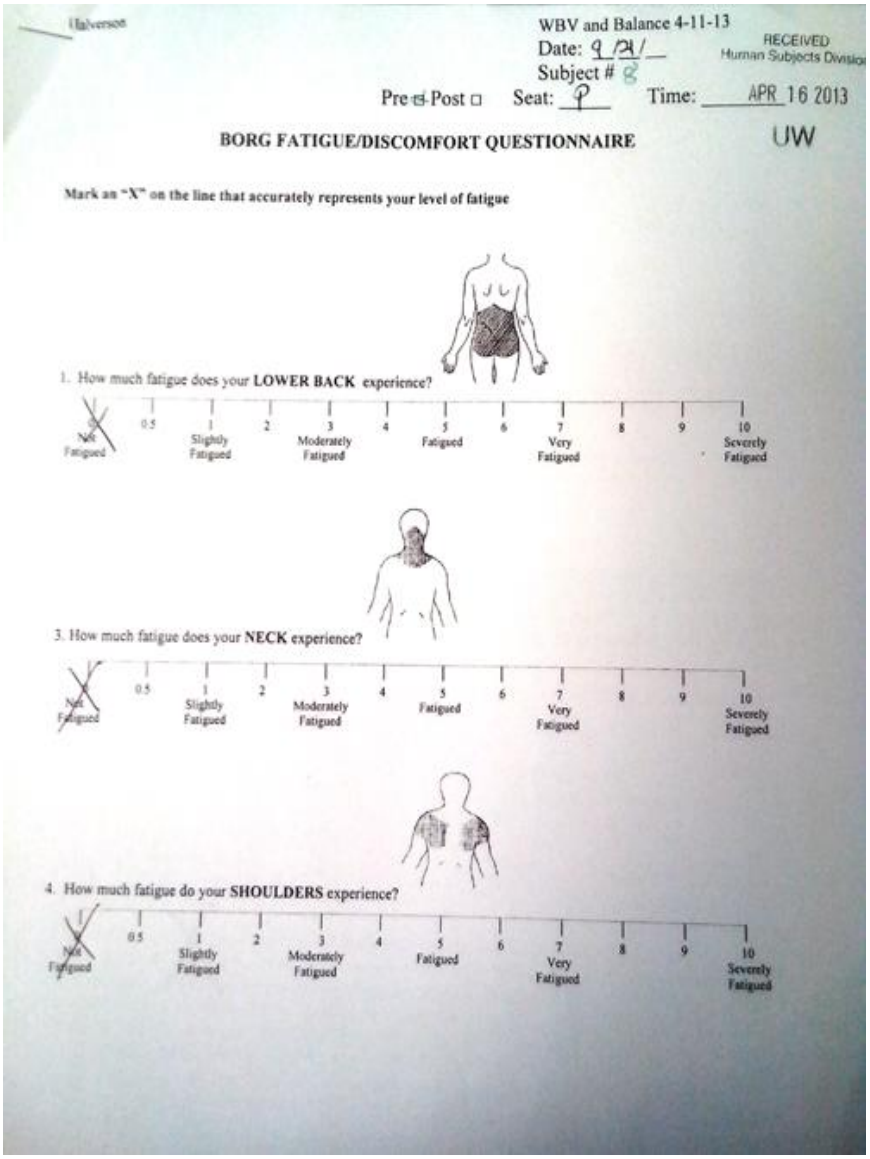
Conclusion

Exposure to vehicular WBV was associated with a significant increase in imbalance when eyes were open, particularly for the AP and total path lengths. In addition, these changes in balance were reversible by 10 minutes post exposure. This has potential administrative control implications for reducing fall risks among truck drivers during egress. After completing a route, a policy that results in drivers remaining seated for up to 10 minutes after driving sessions could potentially minimize fall injuries. The active suspension seat effectively reduced Z-axis vibrations by 50%, though this exposure reduction did not produce any difference in post WBV exposure measurement compared to the passive suspension seat.

More studies regarding the effect of seat type on length of time to baseline balance and better characterization of this washout period would be useful to determine possible work practices. Another potential study would examine balance measurements between workers with a prior history of fall injuries upon egress compared with controls before and after WBV exposure. A similar study with controlled exposures over a variety of frequencies and amplitudes would describe dose-response equivalent for WBV that may assist in occupational vibration guidelines/limits.

Appendix 1

Sample Borg Questionnaire:



Halverson

WBV and Balance 4-11-13
Date: 9/24/__
Subject # 8
Pre ☒ Post ☐ Seat: 9 Time: ____

RECEIVED
Human Subjects Division
APR 16 2013
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BORG FATIGUE/DISCOMFORT QUESTIONNAIRE

Mark an "X" on the line that accurately represents your level of fatigue

1. How much fatigue does your **LOWER BACK** experience?

0 Not Fatigued — 0.5 — 1 Slightly Fatigued — 2 — 3 Moderately Fatigued — 4 — 5 Fatigued — 6 — 7 Very Fatigued — 8 — 9 — 10 Severely Fatigued

3. How much fatigue does your **NECK** experience?

0 Not Fatigued — 0.5 — 1 Slightly Fatigued — 2 — 3 Moderately Fatigued — 4 — 5 Fatigued — 6 — 7 Very Fatigued — 8 — 9 — 10 Severely Fatigued

4. How much fatigue do your **SHOULDERS** experience?

0 Not Fatigued — 0.5 — 1 Slightly Fatigued — 2 — 3 Moderately Fatigued — 4 — 5 Fatigued — 6 — 7 Very Fatigued — 8 — 9 — 10 Severely Fatigued

Appendix 2

Sample miniBESTest of Dynamic Balance:

1. SIT TO STAND

(2) Normal: Comes to stand without use of hands and stabilizes independently.

(1) Moderate: Comes to stand WITH use of hands on first attempt.

(0) Severe: Impossible to stand up from chair without assistance –OR- several attempts with use of hands.

2. RISE TO TOES

(2) Normal: Stable for 3 sec with maximum height

(1) Moderate: Heels up, but not full range (smaller than when holding hands)-OR-noticeable instability for 3 s

(0) Severe: < 3 sec

3. STAND ON ONE LEG

Left *Time in sec Trial 1:*________*Trial 2:*________

(2) Normal: 20 s

(1) Moderate: < 20 sec

(0) Severe: Unable

Right *Time in sec Trial 1:* _______*Trial 2:*_________

(2) Normal: 20 s

(1) Moderate: < 20 sec

(0) Severe: Unable

4. COMPENSATORY STEPPING CORRECTION- FORWARD

(2) Normal: Recovers independently a single, large step (second realignment step is allowed)

(1) Moderate: More than one step used to recover equilibrium

(0) Severe: No step, OR would fall if not caught, OR falls spontaneously

5. COMPENSATORY STEPPING CORRECTION- BACKWARD

(2) Normal: Recovers independently a single, large step

(1) Moderate: More than one step used to recover equilibrium

(0) Severe: No step, OR would fall if not caught, OR falls spontaneously

6. COMPENSATORY STEPPING CORRECTION- LATERAL

Left

(2) Normal: Recovers independently with 1 step

(crossover or lateral OK)

(1) Moderate: Several steps to recovers equilibrium

(0) Severe: Falls, or cannot step

Right

(2) Normal: Recovers independently with 1 step

(crossover or lateral OK)

(1) Moderate: Several steps to recovers equilibrium

(0) Severe: Falls, or cannot step

Appendix 3

Alternate Measurements Collected:

Multivariate Correlations:

0 min

	Closed			Open		
	ML Path	AP Path	Total Path	ML Path	AP Path	Total Path
X STDEV	0.60	0.58	0.58	0.74	0.85	0.86
X VAR	0.59	0.61	0.60	0.78	0.89	0.90
Y STDEV	0.66	0.61	0.62	0.78	0.91	0.91
Y VAR	0.64	0.62	0.62	0.82	0.93	0.94

120 min

	Closed			Open		
	ML Path	AP Path	Total Path	ML Path	AP Path	Total Path
X STDEV	0.84	0.46	0.56	0.62	0.72	0.69
X VAR	0.79	0.38	0.47	0.58	0.62	0.61
Y STDEV	0.55	0.72	0.73	0.65	0.69	0.69
Y VAR	0.56	0.67	0.69	0.69	0.71	0.72

125 min

	Closed			Open		
	ML Path	AP Path	Total Path	ML Path	AP Path	Total Path
X STDEV	-0.01	-0.03	-0.03	0.87	0.78	0.81
X VAR	-0.17	-0.11	-0.12	0.81	0.73	0.76
Y STDEV	0.27	0.68	0.67	0.92	0.91	0.92
Y VAR	0.29	0.73	0.72	0.93	0.92	0.93

130 min

	Closed			Open		
	ML Path	AP Path	Total Path	ML Path	AP Path	Total Path
X STDEV	0.51	0.46	0.47	0.56	<0.00	0.15
X VAR	0.34	0.32	0.32	0.39	-0.15	-0.02
Y STDEV	0.81	0.65	0.68	0.47	0.70	0.70
Y VAR	0.77	0.62	0.65	0.43	0.69	0.68

Average of the correlations from time measurements:
0 min to 120min

	Closed			Open		
	ML Path	**AP Path**	**Total Path**	**ML Path**	**AP Path**	**Total Path**
X STDEV	0.76	0.40	0.43	0.72	0.69	0.72
X VAR	0.73	0.30	0.36	0.69	0.66	0.70
Y STDEV	0.60	0.58	0.61	0.63	0.71	0.71
Y VAR	0.60	0.55	0.59	0.63	0.66	0.68

120min to 130 min

	Closed			Open		
	ML Path	**AP Path**	**Total Path**	**ML Path**	**AP Path**	**Total Path**
X STDEV	0.56	0.24	0.29	0.55	0.40	0.45
X VAR	0.43	0.12	0.26	0.39	0.23	0.28
Y STDEV	0.57	0.65	0.67	0.59	0.64	0.64
Y VAR	0.54	0.63	0.65	0.58	0.62	0.63

Running the same mixed model with the X/Y STDEV and VAR yielded the following results:

Mean (cm) ± Standard Error

	Closed			Open		
	X STDEV	**X VAR**	**ML**	**X STDEV**	**X VAR**	**ML**
0min	0.285 (±0.023)	0.089 (±0.014)	17.1 (±2)	**0.281 (±0.039)**	**0.102 (±0.034)**	14.6 (±2)
120min	0.305 (±0.041)	0.119 (±0.037)	18.7 (±2)	0.304 (±0.030)	0.106 (±0.019)	18.5 (±2)
125min	0.306 (±0.051)	0.127 (±0.054)	16.4 (±2)	0.335 (±0.051)	0.148 (±0.045)	16.4 (±2)
130min	0.293 (±0.045)	0.114 (±0.036)	14.7 (±25)	0.340 (±0.068)	0.181 (±0.084)	14.6 (±2)
p-value	0.75	0.69	0.06	0.79	0.60	0.06

	Closed			Open		
	YSTDEV	Y VAR	AP	Y STDEV	Y VAR	AP
0min	0.822 (±0.1)	0.716 (±0.1)	61.7 (±6)	0.567 (±0.1)	0.359 (±0.1)	38.1 (±3)
120min	0.835 (±0.1)	0.751 (±0.1)	62.6 (±6)	0.797 (±0.1)	0.693 (±0.1)	47.5 (±3)
125min	0.835 (±0.1)	0.758 (±0.1)	61.2 (±6)	0.717 (±0.1)	0.572 (±0.1)	43.6 (±3)
130min	0.691 (±0.1)	0.523 (±0.1)	47.91 (±6)	0.673 (±0.1)	0.503 (±0.1)	37.2 (±3)
p-value	0.004*	0.02*	0.01*	0.03*	0.047*	0.01*

Dunnett's Method p-values:

	Closed			Open		
	X STDEV	X VAR	ML	X STDEV	X VAR	ML
0min	0.98	0.95	0.5	0.94	0.99	0.05
120min	-	-	-	-	-	-
125min	0.85	0.80	0.2	0.97	0.88	0.26
130min	0.98	0.99	0.02*	0.94	0.54	0.045*

	Closed			Open		
	YSTDEV	Y VAR	AP	Y STDEV	Y VAR	AP
0min	0.98	0.96	0.9	0.012*	0.019*	0.02*
120min	-	-	-	-	-	-
125min	0.97	0.96	0.9	0.45	0.47	0.41
130min	0.01*	0.03*	0.01*	0.13	0.16	0.01*

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