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Final Technical Report

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1.0 Executive Summary (recommended length 1 page):

Mining vehicle operators are exposed to various physical risks associated with musculoskeletal disorders (MSDs). Among the various physical risk factors, prolonged exposure to whole body vibration (WBV) is a leading risk factor for the development of MSDs especially in the low back regions among professional vehicle operators. Existing research suggests that occupational exposure to WBV is associated with increased musculoskeletal loading and muscular fatigue in the human spine.

Mining vehicle operators are known to be exposed to higher levels of WBV with more frequent impulsive shocks due to rough terrain as compared to on-road vehicle operators such as truck and bus drivers whose WBV exposures are mainly vertical, continuous oscillatory components. Moreover, previous studies have shown that mining vehicle operators' WBV exposures are multi-axial in nature, meaning that fore-aft (x-axis) and/or lateral (y-axis) vibration are often more predominant than the vertical (z-axis) vibration. These impulsive shocks and multi-axial components that the mining vehicle operators often experience can have a greater detrimental impact on the musculoskeletal health and increase the risk of LBP and MSDs further than vertical-dominant continuous oscillatory components.

Such high WBV exposure levels with frequent shocks and multi-axial components support previous findings that the mining vehicle operators have approximately 13 times higher incidence rate of absenteeism (960 cases per 10,000 Full Time Equivalents (FTEs)) due to low back injuries when compared to administrative workers in the same industry (74 cases per 10,000 FTEs). Moreover, this incidence rate of absenteeism for mining vehicle operators is even substantially higher than that for professional truck drivers who are ranked top among all the occupations with highest MSDs incident rates (162 cases per 10,000 FTEs) in the US.

Despite the potential adverse health effects associated with multi-axial WBV, its relative impact on musculoskeletal loading is poorly understood. Furthermore, the current industry standard approaches to reduce WBV exposures in most mining vehicles rely on passive vertical (Z-axis) suspension systems, which are found to be ineffective in reducing impulsive shocks and multi-axial components of WBV that mining vehicle operators are frequently exposed to.

Therefore, the objective of this study was to quantify the impact of mining vehicle specific (multi-axial) WBV on biomechanical loading of the neck and low back. This study also evaluated the efficacy of the multi-axial (lateral + vertical) active suspension seat in reducing mining vehicle specific WBV exposures and related biomechanical loading of the neck and low back relative to the industry standard passive air suspension seat. Our primary hypothesis was that mining vehicles' multi-axial WBV exposures will create greater biomechanical loading and muscle activity in the neck and low back compared to vertical-axial WBV exposures. We also hypothesized that the multi-axial active suspension seat would more effectively reduce overall WBV exposures and associated biomechanical loading compared to an industry-standard, vertical passive air suspension seat.

This study found that exposure to vibration (both vertical-dominant and multi-axial vibration) resulted in higher neck and low back joint torque compared to no vibration exposures. While the joint torque measures tended to be higher when exposed to the multi-axial vibration compared to the vertical-dominant vibration, these differences were less consistent across all the torque measures. In addition, the multi-axial active suspension seat more effectively reduced A(8) and VDV(8) exposure measures and some of the joint torque and muscle activity in the neck and low back regions.

The study findings may indicate the potential additional adverse effects of the multi-axial WBV on the biomechanical loading of the neck and low back regions compared to the vertical dominant WBV. The multi-axial active suspension seat was more effective in reducing WBV exposures and related joint torque in the neck and low back regions compared to an industry standard passive air suspension seat. However, given that the small differences in joint torque and lateral WBV exposures between the vertical passive air suspension (industry standard) and the newly-developed multi-axial active suspension, there is an urgent need to develop more effective engineering controls to mitigate mining vehicle operators' exposure to multi-axial WBV.

2.0 Problem Statement and Objective:

Mining vehicle operators suffer from a high prevalence of musculoskeletal disorders (MSDs). These operators are exposed to multiple risk factors for MSDs, including whole body vibration (WBV) and sedentary work (prolonged, static sitting). Mining vehicle operators are exposed to high levels of WBV exposures¹⁻³, one of the leading risk factors for the development of MSDs (especially, low back disorders) in professional vehicle operators.^{4,5} Current engineering controls to reduce WBV exposures rely on a passive vertical (z-axis) suspension system. However, in off-road vehicles such as mining vehicles, WBV exposures are multi-axial in nature, meaning that the predominant WBV exposure axis is not necessarily limited to the vertical (z-axis) but can be either fore-aft (x-axis) or lateral (y-axis).³ Therefore, the current industry standard seats with single-axial (vertical) passive suspension may be less effective in reducing the multi-axial components of WBV exposures among mining vehicle operators. Furthermore, because of the substantial mass of the torso and head, such multi-axial components of WBV exposure can not only substantially increase shear forces in the back and neck, but also muscle loads to counterbalance the inertia of the torso and head. Given the extended vehicle operation hours (i.e. prolonged exposed to multi-axial WBV)³, the increased muscle loads can cause overuse and damage to the low back and neck muscles. Therefore, mining vehicle operators exposed to multi-axial WBV are at even greater risks for MSDs, especially in the low back and neck as compared to on-road drivers whose WBV exposures are predominantly on the vertical axis (vertical-axial WBV).

The primary objective of this study was to determine whether there were differences between a single-axial passive suspension seat (current industry standard) and a new multi-axial active suspension seat in reducing the mining vehicle operators' exposures to WBV and the corresponding biomechanical loading. This primary objective was achieved by Aim 1 & 2: Determine the efficacy of different engineering controls (mining vehicle seat suspensions) in reducing the multi-axial WBV exposures in mining vehicles and the associated biomechanical loading on the musculoskeletal system. Using a repeated-measures design, we evaluated the WBV attenuation performance of the two main engineering controls (Aim 1) and two lower-cost alternative engineering controls (Aim 2) in a laboratory setting. Using actual field-measured mining vehicle WBV exposures^{3,41} played back into a large scale motion platform for four hours, we collected and compared WBV exposures (per ISO 2631-1 and 2631-5 standards), muscle activity, and joint torques in the neck and low back between a single-axial passive suspension and multi-axial active suspension seat (Aim 1). Lower-cost alternative passive seat suspension technologies were also evaluated in the similar manner (Aim 2).

3.0 Research Approach:

3.1. Aim 1: Determine the efficacy of single-axial passive and multi-axial active suspension seats in reducing the WBV exposures and biomechanical loading on the musculoskeletal system

3.1.1 Participants: Twenty healthy adults (18 males and 2 females) were recruited for this laboratory-based study via e-mail solicitation throughout a university community. The gender distribution was determined to reflect the demographic distribution of mining vehicle operators. The participants were recruited based on their responses to the eligibility screening questions. The eligibility criteria included no musculoskeletal pain in neck and back regions or medication use to treat such conditions for the past 7 days; no history of musculoskeletal disorders; a minimum of one year of driving experience; and not currently pregnant for any female participant⁴⁴. These criteria were determined to avoid potential risks for injuries from 4-hour exposure to the field-collected WBV on the motion platform in a laboratory setting and minimize the potential physical and physiological differences between the participants⁴⁵⁻⁴⁶. All of the experimental protocols were approved by the Oregon State University's Institutional Review Board. The participants' demographic information is summarized in Table 1.

Table 1. Mean (SD) demographic information [N=20].

	Height (cm)	Weight (kg)	BMI (kg/m ²)	Age (years)
Mean	176.4	81.8	26.2	28.3
SD	7.8	18.2	5.1	6.9

3.1.2 Experimental protocol: In a repeated-measures laboratory study, each participant was exposed to four different exposure conditions over four different days with a minimum of 24 hours between the conditions (Figure 1):

- (a) No WBV (control) with a vertical passive air suspension (i.e., industry standard) seat;
- (b) Vertical-dominant WBV with a vertical passive air suspension (i.e., industry standard) seat;

- (c) Multi-axial WBV with a vertical passive air suspension (i.e., industry standard) seat;
(d) Multi-axial WBV with a multi-axial (vertical + lateral roll) active suspension seat.

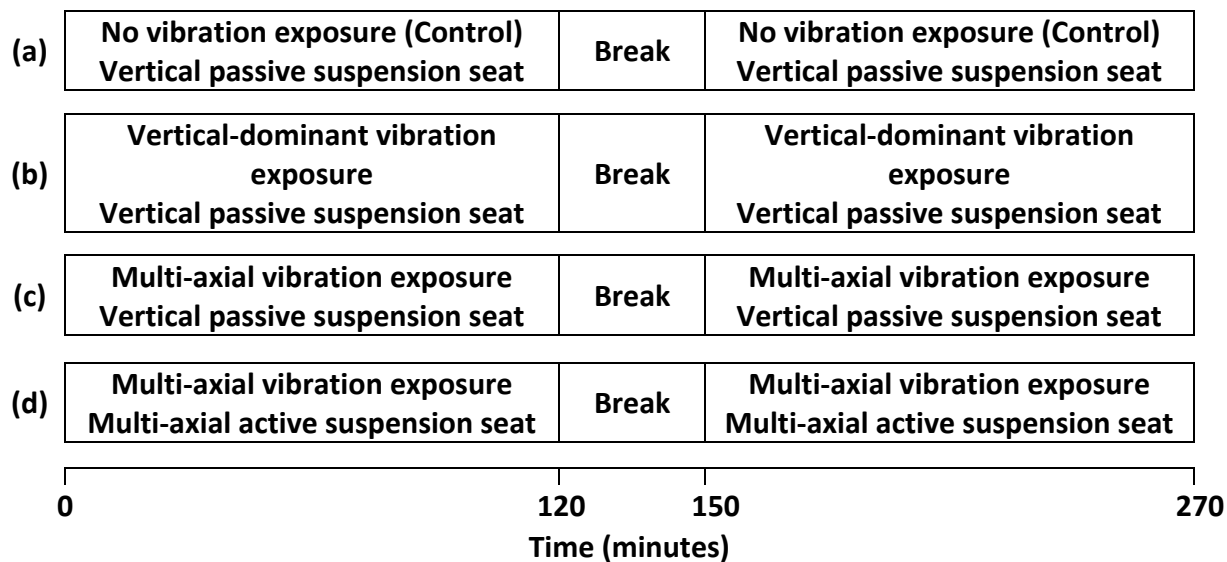


Figure 1. Experimental conditions (combination of exposure and seat): (a) No vibration as the control condition with a vertical axial passive air suspension seat; (b) Multi-axial vibration exposure reflecting mining heavy equipment operators' exposure with a vertical passive air suspension (i.e., industry standard) seat; (c) Multi-axial vibration reflecting mining heavy equipment operators' exposure with a multi-axial (vertical + lateral roll) active suspension seat; (d) Vertical-dominant vibration reflecting semi-truck drivers' exposure with a vertical passive air suspension seat (i.e., industry standard) seat. The order of the four conditions was randomized and counterbalanced across the participants.

The order of the conditions was randomized and counterbalanced to minimize any potential bias due to the order of the testing. To minimize variability and/or bias due to potential residual fatigue from the preceding experimental condition and individual physical activity, participants were asked to avoid any moderate-to-vigorous physical activity for 24 hours preceding each study. For each vibration exposure condition, participants were exposed to vibration for 2 continuous hours, had a 30-minute break, and continued for another 2-hour vibration exposure simulating 4 hours of driving with a 30-minute break in the middle. For the no-vibration condition (control), participants sat on the same vertical passive suspension seat without vibration or movement. Prior to the experiment on the first day, all the participants signed the consent form. Then, the participants were allowed to adjust the seat height such that participants' thighs were parallel to the ground and their feet rested firmly on the floor. The seat height was recorded and kept at a consistent height across all four experimental conditions. The seat back angle was kept at 100 degrees across all the exposure conditions in an attempt to control the participant's posture⁴⁷⁻⁴⁹. Participants were asked and reminded to maintain a standard driving posture without the steering wheel while sitting on the testing seats mounted on the motion platform and being exposed to WBV. To keep their posture consistent between the conditions, the participants were instructed to rest their hands on their laps and watch documentary films via a 55-inch LED flat screen mounted in front of the motion platform. The

location and height of the screen were set such that their neck postures and sitting eye heights were similar to those experienced during driving long-haul trucks or mining heavy equipment vehicles⁵⁰⁻⁵²).

While the participants were being exposed to WBV on the motion platform, we collected WBV in accordance with the International Organization for Standardization WBV 2631-1:1997 standards (ISO, 1997), kinematic data using 3-dimensional motion capture system, and muscle activity (electromyography) in the neck and low back regions.

3.1.3. Whole body vibration simulation

For the vibration exposures, two different field-measured vehicle vibration profiles were recreated using a 6-degree-of-freedom motion platform (MB-E-6DOF/24/1800KG; Moog Inc.; East Aurora; NY) (Figure 2). These two field-measured vehicle vibration profiles included vertical-dominant vibration collected at the floor of semi-trucks⁵²⁻⁵³ and multi-axial vibration collected from mining vehicles during professional drivers' actual regular operation⁵⁴. The ISO 2631-1:1997 WBV parameters for two input vibration exposures are summarized in Table 2.

Table 2. ISO 2631-1:1997 WBV parameters for two input vibration exposures: vertical-dominant vibration collected from on-road semi-trucks and multi-axial vibration collected from off-road mining vehicles. A (8) is root mean square weighted average vibration normalized to 8 hours; VDV(8) is vibration dose value normalized to 8 hours.

WBV Parameter	Axis	Vibration input	
		Vertical-dominant vibration	Multi-axial vibration
A (8) m/s ²	X	0.22	0.31
	Y	0.20	0.58
	Z	0.38	0.23
VDV (8) m/s ^{1.75}	X	5.23	7.74
	Y	4.00	13.68
	Z	8.45	6.26

For the vertical-dominant vibration (exposure condition (b) in Figure 1), we selected a 15-minute-long vibration profile from the tri-axial vibration data collected at the floor from 105 long-haul trucks⁵²⁻⁵³. To reflect actual semi-truck drivers' realistic WBV exposures, the 15-minute-long vibration profile was selected based on the average vibration exposure collected from the 105 long-haul trucks during regular truck operation in the field. The vibration profile was continuously looped and replayed to create the 2-hour exposure. The multi-axial vibration profile (exposure conditions (c) and (d) in Figure 1) was determined based on the field-measured tri-axial vibration data collected from 123 professional mining equipment vehicle drivers who operated 38 different types of mining equipment vehicles during their regular shifts⁵⁴. As a result, the 2-hour multi-axial vibration profiles used in this study were collected from 240-ton haul trucks, bulldozers, and scrapers. The profiles from each vehicle were 5 minutes long (15 minutes total from the three vehicles) and were continuously looped and replayed to create the 2-hour exposures. The raw acceleration data of the selected field-measured vibration profiles were filtered with high pass brickwall filter (discrete Fourier transform, zero low frequency component, and inverse discrete Fourier transform) and converted to displacement data by piecewise integration based on the methods described in our previous studies⁵⁰⁻⁵¹. The cutoff frequency of this filter ranged from 0 to 0.5 Hz. Then, the displacement data were imported to a motion platform control software

program (Replication software; Moog Inc.; Aurora, NY) and re-filtered iteratively to meet the limits of the motion platform. The differences in the average root mean square amplitude between the unfiltered and reproduce the field-measured vibration on the motion platform were approximately 10% mostly due to high frequency contents (> 30 Hz).

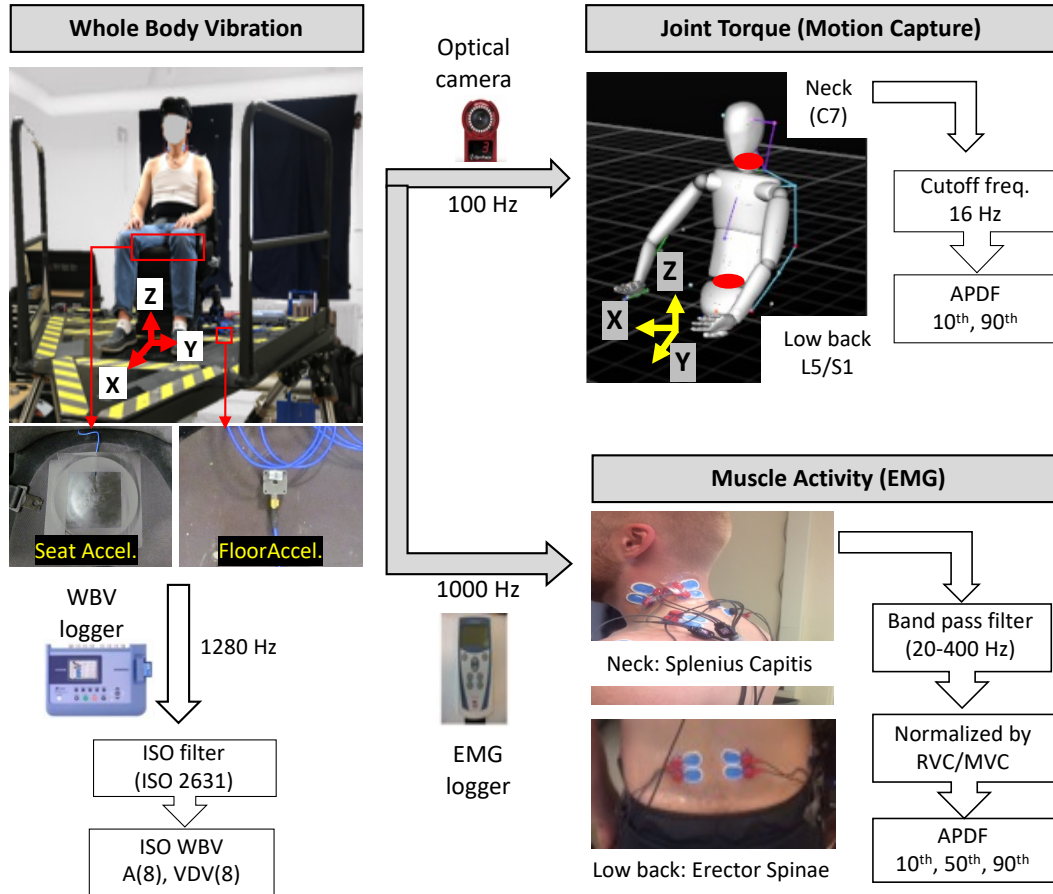
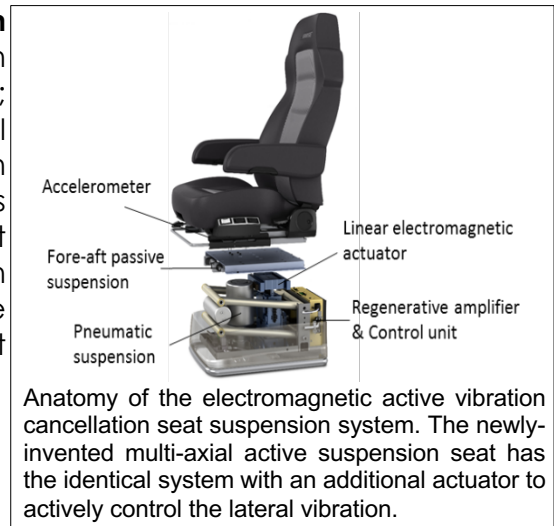


Figure 2. Experimental set up and schematic view of the data collection. On the left, the basicentric axes for whole body vibration measurements are shown in accordance with the ISO2631-1:1997 standard: X (fore-aft), Y (lateral), and Z (vertical). The defined axes for the biomechanical analysis (i.e., joint torque) are shown on the right: X (transverse - pitch), Y (sagittal - roll), and Z (vertical - yaw). Positive and negative values of the joint torque were determined using the right hand rule. A(8) is root mean square weighted average vibration normalized to 8 h; VDV(8) is vibration dose value normalized to 8 h; WBV, whole body vibration; Accl., accelerometers; Freq., frequency; RVC, reference voluntary contraction; MVC, maximum voluntary contractions; APDF, amplitude probability density function.

3.1.4. Suspension seats evaluated

Two different suspension seats were evaluated in this laboratory-based study: a multi-axial electromagnetic active suspension and a vertical passive air suspension seat.

The **multi-axial electromagnetic active suspension seat** evaluated in this study was a prototype suspension developed by Bose Corporation (BoseRide Prototype; Bose Corporation; Framingham, MA). This multi-axial active suspension seat continuously measures both vertical (Z) axis linear acceleration and lateral (Y) axis angular rate using a built-in inertial measurement unit (IMU) sensor. The built-in microprocessor uses seat position and acceleration data to control two highly responsive electromagnetic linear actuators. These control the seat travel and counteract the road-induced vibration disturbances. Due to far greater fidelity in frequency response, this multi-axial active suspension seat has shown greater efficacy in attenuating not only the low frequency vibration exposures but also the higher frequency, impulsive exposures that mining vehicle operators are frequently exposed to. Both of these exposures can be difficult for the traditional pneumatic seat suspension systems to effectively control. This makes the multi-axial active suspension seat a particularly well-suited engineering control for off-road vehicles used in the mining industry. This active suspension seat did not have X-axis suspension to attenuate fore-aft vibration.



To minimize potential confounding influence of different seat designs and maximize the blinding effect, we used the same multi-axial active suspension for the vertical passive air suspension seat by turning off the active components and locking the lateral suspension. This mimicked a conventional, industry standard passive air suspension seat^{44, 50}, the type of seat that is used in most mining vehicles. This allowed us to use only the passive seat components, an air spring and damper, to attenuate vertical vibration in a manner similar to most other conventional air suspension seats. **Single-axial (vertical) passive suspension seats** are current industry-standard seats that have passive pneumatic suspension that uses passive components of compressed air and dampers to attenuate vertical WBV, and have a fixed response based on the properties of these components. Due to fixed response and low resonant frequencies, passive pneumatic suspensions are found to be ineffective in reducing impulsive exposures (commonly experienced in off-road mining vehicles). This seat has been strategically chosen to have the same seat top as the multi-axial active suspension with the primary difference being the suspension under the seat. An advantage of having the same seat top is that any confounding associated with seat design and manufacturer should be minimized while the blinding effect can be maximized.

3.1.5 Outcome measures

3.1.5.1 WBV exposures

While the participants were exposed to the field-measured vibration on the motion platform for 4 hours, we collected raw tri-axial acceleration data at 1,280 Hz using an eight channel data recorder (DA-40; Rion Co. LTD; Tokyo, Japan) with a tri-axial seat-pad accelerometer (Model 356B40; PCB Piezotronics; Depew, NY) mounted on the testing seats and a tri-axial accelerometer (Model 352C33; PCB Piezotronics; Depew, NY) magnetically mounted to the floor of the motion platform in accordance with ISO 2631-1:1997 WBV standard. The raw acceleration data were processed and analyzed using a custom-built LabVIEW program

(v2018; National Instruments; Austin, TX) to calculate WBV exposure parameters in accordance with ISO 2631-1:1997 standards. The ISO WBV exposure parameters included:

- Root mean square weighted average vibration (A_w), which represents the average of occasional shocks and transient vibration experienced over the period of exposures. As shown in the equation below, A_w is an average vibration exposure measure.

$$A_w = \left[\frac{1}{T} \int_0^T a_w^2(t) dt \right]^{\frac{1}{2}}$$

- Vibration dose value (VDV), which is more sensitive to impulsive vibration and reflects the total vibration (i.e., cumulative dose), as opposed to average vibration. This means that a VDV value increases as the measurement/exposure time increases, which is different from A_w .

$$VDV = \left[\int_0^T \{a_w^4(t)\} dt \right]^{\frac{1}{4}}$$

These values were normalized to 8 hours: $A(8)$ and $VDV(8)$.

3.1.5.2. Joint torque

Joint torque (or moment) is a rotational force quantity that causes rotation about a joint (axis of rotation). This is particularly important in understanding how much stress is applied on the musculoskeletal systems because linear force (F) does not provide any specific information in terms of muscle activation or the stress on the bones involved in the articulation. To quantify joint torque in the neck (C7) and low back (L5/S1), kinematic data of the upper body were collected at 100 Hz using a 10-camera optical motion capture system (Flex 13; Optitrack; Natural Point, OR) during the two, 2-hour vibration exposure sessions. Twenty-seven reflective markers (14 mm diameters) were placed on participant's head, upper arms, lower arms, hands, trunk, and pelvis. Two additional (redundant) markers were added on the iliac bone to minimize the chance of losing view of the pelvis occluded markers due to the participants' seated posture. The raw kinematic data were processed with a digital zero-phase 4th order Butterworth filter with a cutoff frequency of 16 Hz to minimize potential motion artifacts due to vibration itself^{55,56}. Using the filtered kinematic data, the net joint torque about the neck (C7) and low back (L5/S1) was calculated in a biomechanics analysis software program (Visual3D; C-Motion Inc., Germantown, MD) using a top-down approach assuming no external loads were applied to the head and torso. That is, we assumed the seat back did not contribute any external forces to the torso above L5/S1 joint. The biomechanical analysis incorporated each participant's anthropometry. The net joint torques at the neck and low back were summarized as the 10th percentile, 90th percentile, and the range (i.e., difference between the 90th and 10th value). Given the nature of the vibration exposures, the peak joint torques (10th and 90th) were relatively symmetric around zero. Therefore, 10th and 90th percentile values represent two peak torque measures in each direction. Also, the range value (90th-10th) can show the overall peak-to-peak joint moments. Also, this approach can eliminate potential DC offsets. The similar parameters have been used for reporting range of motion in previous studies. Positive and negative values of the joint torque were determined using the right-hand rule. That is, in the transverse (X, pitch) axis, a positive value indicates extension torque while a negative value indicates forward flexion torque (i.e., opposite direction). In the sagittal (Y) axis, a positive value

indicates right-side torque (roll). In the vertical (Z) axis, a positive value indicates left axial rotation torque (yaw).

3.1.5.3. Muscle Activity (*Electromyography*)

Electromyography (EMG) measures muscle response or electrical activity in response to a nerve's stimulation of the muscle. EMG has been extensively used to objectively quantify muscular loading or determine the onset of muscle fatigue or abnormality. To measure muscular loading associated with vibration exposures, muscle activity was bilaterally collected at 1,000 Hz from splenius capitis (SPL – neck muscle), sternocleidomastoid (SCM – neck muscle), trapezius (TRAP – neck/shoulder muscle), and erector spinae (ES – low back muscle) using a 8-channel electromyography (EMG) data logger with a hardware pre-amplifier bandpass filter of 15-500 Hz (ME6000; Mega Electronics; Kupio, Finland) and Ag/AgCl surface electrodes (N-00-S/25; Ambu; Ballerup, Denmark). Skin preparation, muscle identification and electrode placement were conducted in accordance with the European recommendation for surface electromyography⁵⁷.

The collected EMG data were processed with a band pass filter of 20-400 Hz and then rectified and averaged using a 125-millisecond moving window. The bandwidth of 20-400 Hz was chosen in order to minimize the motion artifacts from the WBV exposures⁵⁸. At the end of an experimental day, the maximum voluntary contractions (MVCs) from SPL, SCM, and TRAP, and the submaximal reference voluntary contractions (RVCs) from ES were collected to normalize the EMG data. The RVC was chosen to reduce injury risks as the low back is more susceptible to injuries. The MVCs in the SPL and SCM muscles were collected while the participants performed the self-resistant maximal flexion/extension, bilateral bending and axial rotation of their neck^{50,59}. The TRAP MVCs were collected during continuous shoulder shrug on each side in an upright seated posture against isometric manual resistance by a researcher^{60,61}. ES RVCs were obtained during 30° truck forward flexion without any external resistance⁶². Each participant performed three 5-second MVCs/RVCs in each muscle with a 2-minute rest between the contractions. Among the three contractions, the maximum of the highest root mean square signal over a 1-second period was identified and used to normalize the EMG data. The normalized EMG data were summarized as amplitude probability density function (APDF): the 10th (static), 50th (median) and 90th percentile values (peak)⁶³.

3.1.6 Statistical analysis

Our independent and dependent variables for our two main hypotheses are summarized in Table 3. Prior to hypothesis testing, the normality of the dependent variables was tested using the combination of histograms, quantile-quantile plots, and Shapiro-Wilk tests. While most data followed normal distributions, muscle activity data were heavily skewed and therefore transformed with logarithm. Then, linear mixed models (R 4.0.1, R Core Team; Vienna, Austria) were used to test our hypotheses with an alpha level of 0.05, which is the most-widely used threshold probability for determining statistical significance. The normally distributed data were summarized with means and standard errors; the skewed (non-normal) data were summarized with median and interquartile values (25th, 75th percentile).

- Hypothesis 1: the multi-axial vibration exposure would create greater joint torque and muscle activity in the neck and low back compared to the vertical-axial vibration and no vibration (control) exposure. Participants sat in the same vertical passive air suspension seat across the three conditions (i.e., comparing conditions (a), (b), and (c) in Figure 1). The dependent variables were joint torque about neck (C7) and low back (L5/S1) and muscle activity (SPL, SCM, TRAP, and ES). The vibration condition (3 levels: (a) no, (b)

vertical-dominant, and (c) multi-axial vibration) was included as a fixed effect, and 'participant' was included as a random effect in the mixed model. Any statistical significance was followed up with Tukey's HSD tests.

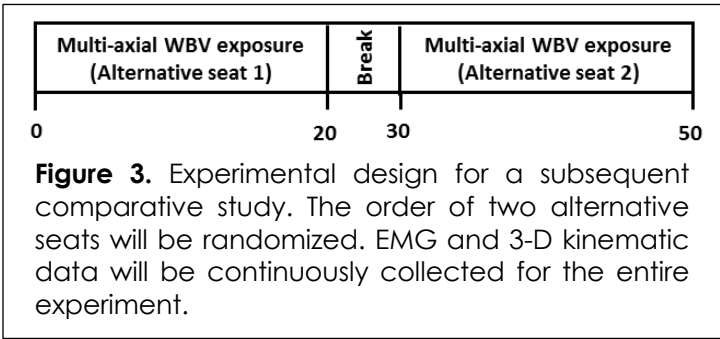
- Hypothesis 2: the multi-axial active suspension seat would create a greater reduction in overall WBV exposure and related biomechanical loading measures (i.e., joint torque and muscle activity) compared to an industry-standard vertical passive air suspension seat under the same multi-axial vibration exposure (i.e., comparing condition (c) and (d) in Figure 1). The dependent variables were ISO WBV parameters [A(8) and VDV(8)], joint torque about neck (C7) and low back (L5/S1), and muscle activity (SPL, SCM, TRAP, and ES). The seat condition (2 levels: vertical passive air suspension and multi-axial active suspension seat) was included as a fixed effect, and 'participant' was included as a random effect in the mixed model.

Table 3. The dependent and independent variables in the mixed models to test two main hypotheses: (1) the multi-axial vibration exposure would create greater biomechanical loading (i.e., joint torque and muscle activity at the neck and low back) compared to the vertical-axial vibration and no vibration exposure; (2) the multi-axial active suspension seat would more effectively reduce overall WBV exposure and related biomechanical loading compared to the single-axial passive air suspension seat.

Hypothesis	Dependent variable	Independent variable	
		Fixed effect	Random effect
(1)	<ul style="list-style-type: none"> • Joint torque about neck (C7) and low back (L5/S1) • Muscle activity (SPL, SCM, TRAP, and ES) 	Vibration exposure condition (3 levels: no, vertical-dominant, and multi-axial vibration)	Participant
(2)	<ul style="list-style-type: none"> • ISO WBV parameters [A(8) and VDV(8)] • Joint torque about neck (C7) and low back (L5/S1) • Muscle activity (SPL, SCM, TRAP, and ES) 	Seat condition (2 levels: Vertical passive and multi-axial active suspension)	Participant

3.2. Aim 2: Evaluate other affordable alternative engineering controls (seating technologies) to reduce WBV exposure and associated biomechanical loadings on the musculoskeletal system.

Using the field-measured mining vehicle vibration data (multi-axial WBV exposure) that was the same exposure used in Aim 1: Conditions (c) and (d) in Figure (1), we completed a subsequent comparative study to assess the vibration attenuation performance of two additional commercially available off-road vehicle seats mounted on the motion platform (Figure 3).



Alternative off-road vehicle seats tested included a passive pneumatic suspension (MSG97AL; Grammer) and a semi-active suspension (MSG97EAC; Grammer). Different from the multi-axial active suspension seat (tested in Aim 1) that cancels the floor-measured vibration using the electro-magnetic actuator (considered as fully active), this **semi-active seat** (MSG97EAC; Grammer) is equipped with a pneumatic semi-active suspension to attenuate vertical z-axis vibration. The semi-active pneumatic suspension is designed to adjust the pressure of the compressed air in the air damper based on the floor-measured vibration. Because it only adjusts the pressure of the air damper rather than actively counteract the vibration, it is considered as semi-active. Another difference (compared to the active suspension in Aim 1), this seat has the passive mechanical spring-based lateral (side-to-side) suspension that is design to isolate linear translational acceleration as compared to the active roll suspension that addresses angular acceleration. One benefit of this semi-active suspension seat is cost-effectiveness due to the simpler mechanical and electronical structures. Moreover, as it is designed to attenuate low-frequency vibration that are common in off-rod vehicles, this semi-active seat can be a cost-effective alternative intervention seat as compared to the fully-active electromagnetic seat evaluated in Aim 1.

The **passive pneumatic suspension seat** (MSG97AL; Grammer) is an off-road vehicle seat which suspension's components and structures are similar to the passive suspension tested in Aim 1, but tuned to attenuate lower-frequency vibration. This passive suspension seat is identical to the semi-active suspension seat (being compared in Aim 2) in the design, structure, and materials. The only difference is that this passive suspension seat does not have capability to adjust the pressure of compressed air in the air damper. An advantage of having the same seat design and structure (except for the suspension) is that any confounding associated with seat design and manufacturer should be minimized while the blinding effect can be maximized. The order of the seat conditions was randomized to minimize potential systematic bias due to the seat order.

Using the methods described in Aim 1, we determined whether there were differences in muscle activity and net joint torques on the low back and neck regions. The impact of this aim was to identify other less-costly commercially-available seats (relative to the multi-axial active suspension seat) to reduce WBV exposures in mining vehicle operators.

4.0 Research Findings and Accomplishments:

4.1 Aim 1: The objectives of Aim 1 were two fold: 1) to determine whether mining vehicles' multi-axial WBV exposures will create greater biomechanical loading and muscle activity in the neck and low back compared to vertical-axial WBV exposures; 2) the multi-axial active suspension seat would more effectively reduce overall WBV exposures and associated biomechanical loading compared to an industry-standard, vertical passive air suspension seat. This study found that exposure to vibration (both vertical-dominant and multi-axial vibration) resulted in higher neck and low back joint torque compared to no vibration exposures. While the joint torque measures tended to be higher when exposed to the multi-axial vibration compared to the vertical-dominant vibration, these differences were less consistent across all the torque measures. In addition, the multi-axial active suspension seat more effectively reduced A(8) and VDV(8) exposure measures and some of the joint torque and muscle activity in the neck and low back regions.

Effects of WBV on biomechanical loading (Hypothesis 1): Exposure to both vertical-dominant and multi-axial WBV resulted in higher joint torque as compared to no vibration (control) condition (Table 4). This finding is in line with the previous studies showing that exposure to WBV increased neck and low back biomechanical loading^{27,28,50,64-66}. Moreover, these increased biomechanical loading measures with WBV exposure support previous epidemiological studies that have shown the association between WBV and musculoskeletal discomfort/disorders^{4,10,54,67}. This supports the mechanical pathway where exposure to WBV can increase risks for musculoskeletal pain and disorders.

While the statistical significance levels varied and the differences were relatively small, the results showed a consistent trend that the joint torque in the neck and low back regions were higher when exposed to mining vehicles' multi-axial WBV than those when exposed to on-road semi-trucks' vertical-dominant WBV. This trend can be due to the non-vertically induced inertia of the torso that was higher when exposed to the multi-axial WBV compared with the vertical-dominant WBV, given substantial mass of the head and torso⁶⁸⁻⁷⁰ to counterbalance. This indicates that mining vehicles' multi-axial WBV can further increase musculoskeletal loading on the neck and low back relative to on-road semi-trucks' vertical dominant WBV and therefore mining vehicle operators may be at greater risk for musculoskeletal disorders, especially considering a strong association between occupational WBV exposure and musculoskeletal disorders with a clear dose-response relationship^{5,71-73}.

The muscle activity in the neck muscles (SPL, SCM, and TRAP) tended to be lower with the multi-axial active suspension seat (Table 5). Some of these differences reached the statistical significance, especially on the left side. While the right-side erector spinae muscle activity was not different between two suspension seats ($p > 0.096$), there were significant differences in the left-side erector spinae muscle activity between the seats ($p < 0.018$).

Table 4. Mean (Standard error) of 10th percentile, 90th percentile, and range (90th – 10th) joint torque (Newton-meters: Nm) in the low back (L5/S1) and neck (C7) across the three experimental conditions: (a) No vibration with a vertical passive air suspension seat; (b) Vertical-dominant vibration with a vertical passive air suspension seat; (c) Multi-axial vibration with a vertical passive air suspension seat.

Hypothesis 1 (Vibration effects on joint torque)						
Vertical passive suspension seat						
Joint torque (Nm)	Axis*	Percentile	(a) No vibration (Control)	(b) Vertical-dominant vibration	(c) Multi-axial vibration	P-value**
Neck (C7)	Transverse (X - pitch)	10 th	-4.05 (0.07)	-4.03 (0.06)	-4.23 (0.05)	0.06
		90 th	-3.93 ^A (0.06)	-3.61 ^B (0.05)	-3.73 ^B (0.05)	0.001
		90 th -10 th	0.12 ^A (0.04)	0.43 ^B (0.01)	0.50 ^B (0.03)	<0.0001
	Sagittal (Y - roll)	10 th	0.10 (0.10)	-0.09 (0.11)	-0.17 (0.08)	0.11
		90 th	0.38 (0.10)	0.27 (0.09)	0.34 (0.09)	0.73
		90 th -10 th	0.28 ^A (0.05)	0.36 ^A (0.04)	0.51 ^B (0.04)	<0.0001
	Vertical (Z - Yaw)	10 th	-0.11 ^A (0.07)	-0.23 ^A (0.07)	-0.47 ^B (0.05)	<0.0001
		90 th	0.13 ^A (0.06)	0.08 ^A (0.06)	0.29 ^B (0.09)	0.008
		90 th -10 th	0.24 ^A (0.08)	0.32 ^A (0.03)	0.76 ^B (0.07)	<0.0001
	Transverse (X - pitch)	10 th	1.94 ^A (0.56)	0.13 ^B (0.64)	0.83 ^B (0.74)	<0.0001
		90 th	3.62 ^A (0.57)	3.72 ^A (0.6)	5.17 ^B (0.62)	<0.0001
		90 th -10 th	1.68 ^A (0.18)	3.59 ^B (0.24)	4.34 ^C (0.26)	<0.0001
Low back (L5/S1)	Sagittal (Y - roll)	10 th	-0.96 ^A (0.2)	-2.02 ^{AB} (0.33)	-2.12 ^B (0.39)	0.005
		90 th	0.78 ^A (0.23)	3.35 ^B (0.58)	3.51 ^B (0.33)	<0.0001
		90 th -10 th	1.75 ^A (0.15)	5.37 ^B (0.72)	5.62 ^B (0.5)	<0.0001
	Vertical (Z - yaw)	10 th	-0.34 ^A (0.14)	-1.89 ^B (0.35)	-2.1 ^B (0.28)	<0.0001
		90 th	0.61 ^A (0.1)	1.25 ^B (0.21)	1.46 ^B (0.29)	0.004
		90 th -10 th	0.95 ^A (0.1)	3.14 ^B (0.51)	3.56 ^B (0.51)	<0.0001

* The defined axes for joint torque are shown in Figure 2. Positive and negative values of the joint torque were determined using the right hand rule.

**P-values were calculated from a mixed model with three vibration conditions as the fixed effect and the participant as the random effect (hypothesis 1). The same vertical passive air suspension seat was used across three vibration exposure conditions. Different superscript letters across rows indicate statistically significant differences from the post-hoc comparisons at $\alpha=0.05$ ($p < 0.05$).

Table 5. Median [25th , 75th percentile] values of the normalized muscle activity (APDF: 10th, 50th, 90th) on splenius capitis, sternocleidomastoid, trapezius, and erector spinae among three exposure conditions: (a) No vibration with the vertical passive air suspension seat; (b) Vertical-dominant vibration with the vertical passive air suspension; (c) Multi-axial vibration with the vertical passive air suspension seat. Each of the amplitude probability density function (APDF) percentile values indicates the following: 10th percentile (static muscle activity), 50th (median – central tendency of the muscle activity) and 90th percentile values (peak muscle activity)

Hypothesis 1 (Vibration effects on muscle activity)					
Vertical passive suspension seat					
Muscle	APDF Percentile	(a) No vibration (Control)	(b) Vertical-dominant vibration	(c) Multi-axial vibration	P-value*
Splenius capitis (SPL)	Left	10 th 1.6 ^A [0.7, 2.0]	3.1 ^B [1.0, 5.0]	2.2 ^{AB} [1.0, 4.0]	0.017
		50 th 2.2 ^A [0.9, 3.7]	4.0 ^B [1.3, 6.0]	3.2 ^{AB} [1.5, 5.3]	0.039
		90 th 3.8 ^A [2.4, 8.2]	7.9 ^B [3.0, 10.2]	5.7 ^{AB} [3.3, 11.6]	0.005
	Right	10 th 0.8 [0.4, 2.0]	1.5 [1.0, 2.8]	1.0 [0.4, 3.8]	0.083
		50 th 1.3 [0.8, 4.0]	2.9 [1.4, 5.3]	1.5 [0.8, 4.1]	0.181
		90 th 3.0 [1.9, 5.8]	3.9 [2.4, 7.7]	4.5 [2.6, 10.0]	0.148
Sternocleido- mastoid (SCM)	Left	10 th 5.0 [3.9, 9.3]	6.9 [3.9, 8.2]	7.9 [3.6, 10.4]	0.115
		50 th 8.2 ^A [5.7, 13.8]	10.6 ^{AB} [7.3, 16.4]	13.2 ^B [7.0, 17.1]	0.030
		90 th 20.8 [15.5, 31.3]	21.9 [10.7, 38.0]	27.7 [15.2, 34.8]	0.121
	Right	10 th 5.6 [2.7, 7.7]	6.2 [4.2, 10.3]	6.0 [4.0, 11.8]	0.106
		50 th 7.8 [3.8, 11.9]	9.9 [5.7, 14.3]	10.4 [5.1, 14.3]	0.133
		90 th 14.9 [5.6, 32.7]	16.5 [8.1, 23.1]	17.2 [7.0, 24.4]	0.481
Trapezius (TRAP)	Left	10 th 0.9 [0.3, 2.7]	1.0 [0.4, 4.6]	1.5 [0.6, 1.8]	0.050
		50 th 1.2 ^A [0.4, 3.4]	2.3 ^{AB} [1.0, 5.9]	2.6 ^B [1.9, 4.9]	0.027
		90 th 5.7 [3.0, 12.6]	6.7 [2.0, 13.1]	7.3 [6.1, 9.0]	0.136
	Right	10 th 0.9 [0.2, 2.4]	0.9 [0.5, 1.7]	1.5 [1.0, 3.8]	0.268
		50 th 1.9 [0.5, 8.2]	1.0 [0.6, 5.5]	2.9 [1.1, 5.2]	0.676
		90 th 4.5 [1.0, 12.2]	4.4 [1.0, 12.9]	4.8 [3.0, 8.3]	0.983
Erector spinae (ES)	Left	10 th 7.7 [5.8, 52.3]	13.0 [3.9, 37.3]	11.3 [5.4, 35.7]	0.204
		50 th 8.6 [6.6, 59.8]	25.0 [6.2, 48.4]	17.2 [6.1, 46.9]	0.950
		90 th 27.2 [18.7, 67.9]	26.8 [13.5, 59.5]	46.7 [14.3, 60.0]	0.613
	Right	10 th 5.4 [2.8, 31.1]	14.6 [5.5, 21.9]	9.9 [4.6, 18.4]	0.921
		50 th 6.4 ^A [3.6, 34.8]	30.6 ^B [19.2, 89.1]	18.4 ^B [11.0, 24.8]	0.018
		90 th 29.8 [14.0, 60.0]	39.8 [26.1, 109.0]	26.4 [23.4, 47.7]	0.380

* P-values were calculated from a mixed model with the vibration conditions as the fixed effect and the participant as the random effect (hypothesis 1). The same vertical passive air suspension seat was used across three vibration conditions. Different superscript letters across rows indicate statistically significant differences from the post-hoc comparisons at $\alpha=0.05$ ($p < 0.05$).

Effects of different suspension seats on WBV exposure and biomechanical loading (Hypothesis 2): The results showed that the multi-axial active suspension much more effectively reduced mining specific multi-axial vibration exposures than the vertical passive air suspension (Table 6). The observed superior performance of the multi-axial active suspension seat in attenuating WBV is consistent with previous studies^{12,44,51,52,72}. These studies also demonstrated limited vibration attenuation performance of vertical passive air suspension seats, which suspension mechanisms were similar to the passive suspension seat tested in this study. This limited performance of the passive air suspension can be due to passive suspension seat's low resonant frequencies which could have been matched with low resonant frequency of the mining road's disturbance^{14,15}. Passive suspension seats' relatively slow reaction to counteract the rapid transient exposures, which are common in mining vehicle operation, could have also been a contributing factor for the vertical passive suspension seat's poor performance in vertical (Z) axis vibrations⁵¹.

The X-axis A(8) and VDV(8) values were slightly lower (< 5%) with the multi-axial active suspension compared to the vertical passive air suspension seat. While these differences appeared to be practically small, this trend was supported by the lower neck and low back joint torque with respect to transverse (X) axis (flexion-extension) when compared to the vertical passive air suspension seat. The observed superior performance of the multi-axial active suspension seat was also mirrored in lower neck muscle activity with the multi-axial active suspension seat. These effects on the muscle activity were more dominant on the left side of body, which can be contributed to the presence of lateral (Y) axis WBV exposures and sagittal (Y) axis joint torque⁵¹. Overall, these results indicate that the multi-axial active suspension may have potential to reduce overall WBV exposure and related biomechanical loading of the neck and low back while it needs further engineering improvements.

Table 6. Comparisons of mean (Standard error) ISO-2631 WBV parameters [daily equivalent weighted average vibration A(8) and daily equivalent vibration dose value VDV(8)] between the vertical passive air suspension and multi-axial active suspension seat under the same multi-axial vibration exposure.

WBV Parameter	Axis	Floor	Hypothesis 2 (Seat effects on WBV)		
			Multi-axial vibration exposure		P-value*
			(c) Vertical passive suspension seat	(d) Multi-axial active suspension seat	
A(8) m/s ²	X	0.31	0.38 (0.003)	0.37 (0.003)	0.009
	Y	0.58	0.70 (0.007)	0.71 (0.006)	0.034
	Z	0.23	0.24 (0.002)	0.10 (0.008)	<0.001
VDV(8) m/s ^{1.75}	X	7.74	9.2 (0.11)	8.8 (0.96)	0.007
	Y	13.68	16.6 (0.17)	16.8 (0.15)	0.136
	Z	6.26	5.6 (0.08)	3.1 (0.41)	<0.001

* P-values were calculated from a mixed model with two seat conditions (i.e., vertical passive air suspension and multi-axial active suspension seat) as the fixed effect and the participant as the random effect (Hypothesis 2). The same multi-axial vibration exposure was used for both seat conditions.

The WBV results also showed that both of the tested suspension seats amplified the fore-aft (X) and lateral (Y) axis A(8) and VDV(8) WBV exposures (~12-24% relative to the floor). This indicates that either that the multi-axial active suspension seat's additional lateral suspension may not effectively reduce the lateral (Y) axis WBV exposures, or the current ISO-recommended linear accelerometers used to measure the WBV exposures, may not be capturing the reduction in lateral (Y) axis roll motions and angular accelerations which may be occurring with the multi-axial active suspension seat. Given the higher biomechanical loading associated with multi-axial WBV exposures, the limited performance of the vertically passive seat in reducing non-vertical WBV indicates that there is a critical need to further improve and develop new engineering controls to more effectively reduce overall non-vertical WBV exposures and associated biomechanical loading, especially for mining vehicle operators.

The results found limited differences in the joint torque and muscle activity measures between the two seats (Tables 7 and 8).

Table 7. Mean (Standard error) of 10th, 90th percentile, and range (90th – 10th) joint torque in the low back and neck between two suspension seats: (c) Multi-axial vibration with a vertical passive air suspension seat; (d) Multi-axial vibration with a multi-axial active suspension seat.

Hypothesis 2 (Seat effects on joint torque)					
Joint torque (Nm)	Axis*	Percentile	Multi-axial vibration exposure		P-value***
			(c) Vertical passive suspension seat	(d) Multi-axial active suspension seat	
Neck (C7)	Transverse (X - pitch)	10 th	-4.23 (0.05)	-4.08 (0.03)	0.10
		90 th	-3.73 (0.05)	-3.83 (0.04)	0.08
		90 th -10 th	0.50 (0.03)	0.25 (0.02)	<0.0001
	Sagittal (Y - roll)	10 th	-0.17 (0.08)	-0.14 (0.09)	0.74
		90 th	0.34 (0.09)	0.37 (0.11)	0.63
		90 th -10 th	0.51 (0.04)	0.52 (0.04)	0.93
	Vertical (Z - Yaw)	10 th	-0.47 (0.05)	-0.36 (0.05)	0.08
		90 th	0.29 (0.09)	0.37 (0.06)	0.55
		90 th -10 th	0.76 (0.07)	0.73 (0.06)	0.28
Low back (L5/S1)	Transverse (X - pitch)	10 th	0.83 (0.74)	0.42 (0.59)	0.61
		90 th	5.17 (0.62)	4.29 (0.54)	0.02
		90 th -10 th	4.34 (0.26)	3.87 (0.21)	0.03
	Sagittal (Y - roll)	10 th	-2.12 (0.39)	-3.4 (0.44)	0.02
		90 th	3.51 (0.33)	3.37 (0.44)	0.65
		90 th -10 th	5.62 (0.5)	6.77 (0.78)	0.21
	Vertical (Z - yaw)	10 th	-2.10 (0.28)	-1.74 (0.22)	0.21
		90 th	1.46 (0.29)	1.80 (0.23)	0.36
		90 th -10 th	3.56 (0.51)	3.54 (0.40)	0.87

* The defined axes for joint torque are shown in Figure 2. Positive and negative values of the joint torque were determined using the right hand rule.

***P-values were calculated from a mixed model with two seat conditions (vertical passive and multi-axial active) as the fixed effects and the participant as the random effect (Hypothesis 2). The same multi-axial vibration exposure was used for both seat conditions.

Table 8. Median [25th, 75th percentile] values of the normalized muscle activity on splenius capitis, sternocleidomastoid, trapezius, and erector spinae between two seats: (c) Multi-axial vibration with the vertical passive air suspension seat; (d) Multi-axial vibration with the multi-axial active suspension seat.

		Hypothesis 2 (Seat effects on muscle activity)		
		Multi-axial vibration exposure		P-value**
Muscle	APDF Percentile	(c) Vertical passive suspension seat	(d) Multi-axial active suspension seat	
Splenius capitis (SPL)	Left	10 th	2.2 [1.0, 4.0]	1.6 [0.8, 3.8] 0.049
		50 th	3.2 [1.5, 5.3]	3.0 [1.0, 5.2] 0.251
		90 th	5.7 [3.3, 11.6]	5.7 [2.0, 8.2] 0.147
	Right	10 th	1.0 [0.4, 3.8]	3.5 [0.9, 5.0] 0.560
		50 th	1.5 [0.8, 4.1]	3.9 [1.0, 6.6] 0.469
		90 th	4.5 [2.6, 10.0]	4.4 [2.4, 9.1] 0.603
Sternocleido-mastoid (SCM)	Left	10 th	7.9 [3.6, 10.4]	6.9 [3.0, 10.1] 0.096
		50 th	13.2 [7.0, 17.1]	9.2 [5.6, 9.2] 0.016
		90 th	27.7 [15.2, 34.8]	23.1 [12.4, 35.8] 0.485
	Right	10 th	6.0 [4.0, 11.8]	5.5 [5.0, 6.5] 0.167
		50 th	10.4 [5.1, 14.3]	8.7 [6.4, 9.8] 0.183
		90 th	17.2 [7.0, 24.4]	12.0 [9.3, 20.1] 0.374
Trapezius (TRAP)	Left	10 th	1.5 [0.6, 1.8]	0.6 [0.2, 1.5] <0.001
		50 th	2.6 [1.9, 4.9]	2.2 [1.0, 3.7] 0.349
		90 th	7.3 [6.1, 9.0]	8.1 [4.0, 11.7] 0.285
	Right	10 th	1.5 [1.0, 3.8]	1.0 [0.4, 4.1] 0.372
		50 th	2.9 [1.1, 5.2]	2.3 [0.9, 5.3] 0.468
		90 th	4.8 [3.0, 8.3]	4.4 [2.3, 6.6] 0.340
Erector spinae (ES)	Left	10 th	11.3 [5.4, 35.7]	16.0 [9.2, 48.3] 0.018
		50 th	17.2 [6.1, 46.9]	27.2 [15.2, 85.0] 0.002
		90 th	46.7 [14.3, 60.0]	38.5 [19.5, 105.6] 0.003
	Right	10 th	9.9 [4.6, 18.4]	10.8 [5.5, 16.3] 0.644
		50 th	18.4 [11.0, 24.8]	17.1 [6.4, 33.5] 0.330
		90 th	26.4 [23.4, 47.7]	23.1 [7.6, 44.1] 0.096

** P-values were calculated from a mixed model with two seat conditions (vertical passive and multi-axial active) as the fixed effects and the participant as the random effect (Hypothesis 2). The same multi-axial vibration exposure was used for both seat conditions.

4.2 Aim 2: In this aim, we evaluated other affordable alternative engineering controls (off-road vehicle suspension seats) to reduce WBV exposure and associated biomechanical loadings on the musculoskeletal system.

Effects of two other seats on Biomechanical Loading: Comparing two suspension seats showed that the range (90th – 10th) neck moments in three axes were approximately up to two times higher with the semi-active seat compared to the passive seat (Table 9). However, despite the lack of statistically significant differences, low back moments in three axes were lower with the semi-active compared to seat P.

Table 9. Mean (standard error) of 10th, 50th, and 90th percentile and range (90th – 10th percentile) joint moments in the neck (C7) and low back (L5/S1) across the two seat conditions: semi-active suspension seat (Seat SA) and passive multi-axial seat (Seat P). The defined axes for the biomechanical analysis and positive and negative values of the moments were determined using the right hand rule.

Joint	Axis	Percentile	Seat		P-value
			Seat SA	Seat P	
Neck (C7)	Transverse (X)	10th	-4.49 (0.06)	-4.38 (0.05)	0.08
		50th	-4.07 (0.04)	-4.09 (0.05)	0.29
		90th	-3.16 (0.39)	-3.74 (0.05)	0.21
		90th-10th	1.33 (0.41)	0.64 (0.02)	0.14
	Sagittal (Y)	10th	-0.81 (0.42)	-0.26 (0.10)	0.26
		50th	0.09 (0.07)	0.15 (0.12)	0.45
		90th	0.99 (0.41)	0.60 (0.13)	0.29
		90th-10th	1.80 (0.82)	0.86 (0.09)	0.27
	Vertical (Z)	10th	-0.60 (0.11)	-0.61 (0.09)	0.76
		50th	0.16 (0.07)	-0.01 (0.09)	0.03
		90th	0.97 (0.11)	0.59 (0.10)	0.003
		90th-10th	1.58 (0.16)	1.20 (0.07)	0.02
Low back (L5/S1)	Transverse (X)	10th	0.36 (1.05)	1.06 (1.06)	0.29
		50th	3.12 (0.99)	3.96 (1.04)	0.38
		90th	5.71 (1.06)	6.64 (0.98)	0.39
		90th-10th	5.35 (0.71)	5.58 (0.59)	0.86
	Sagittal (Y)	10th	-4.56 (0.76)	-4.43 (0.73)	0.74
		50th	-0.72 (0.54)	-0.58 (0.40)	0.86
		90th	3.22 (0.54)	3.52 (0.54)	0.74
		90th-10th	7.78 (0.77)	7.95 (0.98)	0.93
	Vertical (Z)	10th	-0.92 (0.23)	-1.21 (0.20)	0.48
		50th	0.24 (0.13)	0.14 (0.14)	0.69
		90th	1.41 (0.14)	1.44 (0.22)	0.96
		90th-10th	2.32 (0.28)	2.65 (0.31)	0.49

*P-values were calculated from mixed models with seat (two seats) as the fixed effect and the participant as the random.

The results showed no statistically significant differences in the neck (splenius capitis and trapezius) and low back (erector spinae) muscle activity across the two seats (Table 10). Despite the lack of statistically significant differences, the peak (90th percentile) neck back muscle activity were approximately 50% lower with the semi-active seat compared with the passive seat.

Table 10. Median [25th, 75th percentile] normalized muscle activity on splenius capitis (%MVC), trapezius (%MVC), and erector spinae (%RVC) across the two seat conditions: semi-active suspension seat (Seat SA) and passive multi-axial seat (Seat P).

Muscle	Axis	Percentile	Seat		P-value*
			Seat SA	Seat P	
Splenius capitis (SPL) %MVC	Left	10th	2.62 [1.99, 12.39]	2.78 [2.18, 9.5]	0.93
		50th	4.12 [3.58, 11.18]	4.07 [3.58, 8.79]	0.87
		90th	7.21 [6.34, 8.33]	7.14 [6.35, 8.77]	0.48
	Right	10th	3.78 [2.27, 10.99]	3.64 [1.93, 9.5]	0.85
		50th	6.69 [3.7, 19.15]	5.88 [3.78, 18.33]	0.77
		90th	8.32 [5.03, 11.74]	8.20 [5.64, 12.79]	0.79
Trapezius (TRAP) %MVC	Left	10th	0.65 [0.37, 2.01]	0.60 [0.37, 1.88]	0.94
		50th	2.28 [0.72, 3.79]	2.12 [0.87, 4.75]	0.71
		90th	4.62 [1.98, 14.06]	4.51 [2.27, 8.55]	0.93
	Right	10th	0.98 [0.43, 3.21]	1.12 [0.45, 4.21]	0.45
		50th	2.59 [0.98, 4.98]	3.91 [0.99, 5.31]	0.61
		90th	5.58 [3.44, 17.51]	6.22 [2.88, 14.68]	0.72
Erector spinae (ES) %MVC	Left	10th	9.19 [3.65, 13.52]	9.04 [5.04, 21.33]	0.64
		50th	9.19 [4.88, 18.65]	12.01 [7.84, 14.05]	0.68
		90th	10.42 [8.6, 23.45]	19.01 [11.89, 21.73]	0.40
	Right	10th	12.35 [3.52, 14.88]	7.18 [2.46, 13.42]	0.23
		50th	20.06 [5.85, 27.26]	13.05 [3.79, 16.91]	0.07
		90th	11.64 [9.70, 30.62]	17.47 [8.27, 29.73]	0.21

*P-values were calculated from mixed models with seat (two seats) as the fixed effect and the participant as the random.

Effects of two other off-road vehicle seats on WBV: The average weighted vibration [A(8)] and vibration dose value [VDV(8)] parameters showed that the off-road vehicle semi-active suspension seat tended to have lower WBV exposures in X (fore-aft) and Y (lateral) axis as compared to the off-road passive suspension seat (Table 11). However, no differences were found in Z (vertical) axis between the seats.

Table 11. Comparisons of mean (Standard error) ISO-2631 WBV parameters [daily equivalent weighted average vibration A(8) and daily equivalent vibration dose value VDV(8)] between the off-road passive air suspension and semi-active suspension seat under the same multi-axial vibration exposure.

WBV Parameter	Axis	Floor	Aim 2 (Seat effects on WBV)		
			Multi-axial vibration exposure		P-value*
			Off-road passive suspension seat	Semi-active suspension seat	
A(8) m/s ²	X	0.78	0.94 (0.03)	0.87 (0.01)	0.01
	Y	1.38	1.65 (0.02)	1.58 (0.02)	0.01
	Z	0.68	0.68 (0.12)	0.67 (0.01)	0.97
VDV(8) m/s ^{1.75}	X	24.9	31.9 (1.5)	28.6 (0.8)	0.02
	Y	36.4	41.7 (0.4)	41.7 (0.6)	0.95
	Z	11.9	14.4 (3.3)	10.0 (0.3)	0.22

* P-values were calculated from a mixed model with two seat conditions (i.e., the off-road passive air suspension and semi-active suspension seat) as the fixed effect and the participant as the random effect (Aim 2). The same multi-axial vibration exposure was used for both seat conditions.

4.3 Limitations: Despite the well-controlled laboratory experiment, there were some limitations that are worthy to note. First, the study results were based on 4-hour truck and mining vehicle vibration exposures. Future studies that use more realistic duration (e.g., 8 hours per day over multiple days) and amplitude (more severe exposures) of WBV exposures would be merited. In addition, while this laboratory-based study allowed us to quantify various biomechanical loading measures (joint torque and muscle activity) which are difficult to collect in a field setting, the simulated vibration exposures on a motion platform may have been less realistic as compared to the real mining operation due many environmental factors such as vehicle type, controller manipulation, and terrain. To overcome such limitations, this study used real field-measured vehicle vibration profiles collected during drivers' regular operation while controlling other environmental factors. Lastly, the participants' average weight (81 kg) and BMI (26.2 kg/m²) were less than general truck driver population⁷⁴ and mining populations⁷⁵. While the effects of weight and BMI on the WBV-related biodynamic responses across different studies are inconsistent^{76,77} future studies using participants with weights and BMI's similar to mining vehicle operators, may identify weight-related biomechanical effects that influence multi-axial WBV exposures.

5.0 Publication Record and Dissemination Efforts: We have disseminated the study results via conference proceedings and presentations. Currently, we are working on two journal papers (one in revision) to disseminate results. We plan to share the study results with National Mining Association, state-level mining associations, equipment manufacturers, and mining companies. The list of our publications is shown below:

Peer-reviewed journal articles

- Kia K, Bae H, Johnson PW, Dennerlein JT, Kim JH (In revision) Evaluation of Vertical and Multi-axial Suspension Seats for Reducing Vertical-dominant and Multi-axial Whole Body Vibration and Associated Neck and Low Back Joint Torque and Muscle Activity, *Applied Ergonomics*
- Kia K*, Johnson PW, Dennerlein JT, Kim JH (In Preparation) Effects of Whole Body Vibration on Biomechanical Stress. *Applied Ergonomics*
- Kia K*, Fitch, SM*, Newsom, SA, Kim, JH (2020) Effect of whole-body vibration exposures on physiological stresses: Mining heavy equipment applications, *Applied Ergonomics*, vol. 85, 103065
- Park JH, Kia K*, Fitch SM*, Srinivasan D, Kim JH (2021) Postural balance effects from exposure to multi-axial whole-body vibration in mining vehicle operation, *Applied Ergonomics*, vol. 91. 103307

Peer-reviewed conference proceedings/presentations

- Kia K*, Fitch SM*, Johnson PW, Dennerlein JT, Kim JH (2019) Comparisons of Single-axial and Multi-axial Suspension Seats in Reducing Whole Body Vibration and Related Biomechanical Stress: Mining Vehicle Application. 31st Annual International Occupational Ergonomics and Safety Conference. New Orleans, LA.
- Kia K*, Johnson PW, Fitch SM*, Dennerlein JT, Kim JH (2019) Comparisons of whole body vibration exposures and related musculoskeletal stress between single-axial passive and multi-axial active suspension in a mining vehicle application. 10th International Scientific Conference on the Prevention of Work-Related Musculoskeletal Disorders. Bologna, Italy.
- Kia K*, Fitch SM*, Newsom S, Kim JH (2019) Physiological and Muscular Stress Associated with Multi-axial Whole-Body Vibration Exposure in Mining Heavy Equipment Vehicle Environment. 2019 International Meeting of the Human Factors & Ergonomics Society. Seattle, WA.
- Park JH, Kia K*, Fitch SM*, Srinivasan D, Kim JH (2019) Effects of Multi-axial Whole Body Vibration Exposures on Postural Stability. 2019 International Meeting of the Human Factors & Ergonomics Society. Seattle, WA.
- Kia K*, Johnson PW, Fitch SM*, Dennerlein JT, Kim JH (2019) Evaluation of Multi-axial Active Suspension to Reduce Whole Body Vibration Exposures and Associated Biomechanical Loading in Mining Heavy Equipment Vehicle Operators. 2019 International Meeting of the Human Factors & Ergonomics Society. Seattle, WA.

6.0 Conclusions and Impact Assessment: A main accomplishment is that this study was the first to employ measurement of validated biomechanical measures to quantify the effects of mining specific WBV exposures in order to better understand musculoskeletal disorder mechanisms associated with mining-specific WBV exposure. By quantifying the relative impact of different types of WBV exposures (vertical dominant vs. multi-axial) on biomechanical stress, we were able to fulfill the first objective of this study. The study findings may indicate the potential

additional adverse effects of the multi-axial WBV on the biomechanical loading of the neck and low back regions compared to the vertical dominant WBV. The multi-axial active suspension seat was more effective in reducing WBV exposures and related joint torque in the neck and low back regions compared to an industry standard passive air suspension seat. However, given that the small differences in joint torque and lateral WBV exposures between the vertical passive air suspension (industry standard) and the newly-developed multi-axial active suspension as well as the alternative semi-active suspension seats, there is an urgent need to develop more effective engineering controls to mitigate mining vehicle operators' exposure to multi-axial WBV.

7.0 Recommendations for Future Work: Because this study was the first study that employed the actual field-measured vibration for relatively long exposure duration (4 hours), we chose the interquartile ranges of the field-measured WBV exposures in order to avoid any potential injuries from the exposures. However, given the limited biological responses to the WBV exposures used in this study, our subsequent studies will use more robust and representative WBV exposure that reflects 8-12 hour exposures and real-world intensity by including peak exposures (i.e., the 90-95th percentile values of real WBV exposure that mining vehicle operators experience). Moreover, based on the limitations (discussed earlier), future studies using participants with weights and BMI's similar to mining vehicle operators, may identify weight-related biomechanical effects that influence multi-axial WBV exposures.

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