1.0 Cover Page

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Title: Evaluating the Effects of Multi-axial Whole Body Vibration Exposure on Postural Stability in Mining Heavy Equipment Vehicle Operators

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2.0 Executive Summary (recommended length 1 page):

Mining heavy equipment vehicle operators suffer from the highest occupational injury rates including musculoskeletal disorders (MSDs) [1, 2] and fall-related injuries [3-5]. Prolonged exposure to whole body vibration (WBV) has been shown to be associated with neuromuscular reaction time, visual and vestibular sensory system responses, and reduced postural stability that increases a risk of MSDs and fall-related injuries [6-10]. Previous studies have shown that mining vehicle operators are exposed to a high level of WBV exposures with impulsive shocks and multi-axial components [1, 2, 11, 12]. This means 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). Therefore, off-road vehicle operators may be at even greater fall-risks compared to on-road drivers whose WBV exposures are predominant on the vertical axis and are less impulsive.

Although previous studies have evaluated the effects of WBV on musculoskeletal injury [13-17] and postural stability [6-10, 18], little scientific research has examined the nature of the additional impact of multi-axial WBV on musculoskeletal and fall-related risk measures as compared to the vertical-dominant WBV exposure from on-road vehicles [19]. The objective of this study was to evaluate the effects of both vertical-dominant and multi-axial WBV on postural stability. We also aimed to investigate the potential efficacy of a newly-developed engineering intervention (multi-axial active suspension seat) in reducing multi-axial dominant WBV and its effects on postural stability.

In a repeated-measures laboratory experiment, we played actual field-collected vibration using a 6-degree-of-freedom motion platform (MB-E-6DOF/24/1800KG; Moog Inc.; East Aurora; NY) and simulated four experimental conditions: [(a) Vertical-axial dominant WBV exposure with a single-axial passive suspension seat, (b) Multi-axial WBV exposure with a single-axial active suspension seat, (c) Multi-axial WBV exposure with a multi-axial active suspension seat, (d) No WBV exposure (control)]. Measures of functional limits of stability, postural stability during standing balance, and anticipatory postural adjustments preceding gait initiation were collected at the start of each experimental condition, immediately after 2 hours and 4 hours of exposure and were compared across the different conditions.

The results of this study showed that center of pressure measures (velocity, displacement and sway area) significantly increased with multiaxial WBV, with the increase being significantly greater than in the vertical-dominant vibration and no-vibration (control) conditions. This finding confirms a main hypothesis of this study that multiaxial vibration exposures further impair postural stability as compared to the vertical dominant vibration. Furthermore, our study showed that the COP velocity and RMS displacement were significantly lowered in the multiaxial-suspension intervention condition compared to the multi-axial vibration condition. This indicates that the engineering intervention (multi-axial active suspension) evaluated in this study may have potential to reduce aspects of vibration that may subsequently deteriorate postural balance and therefore reduce fall-related injuries among professional mining vehicle operators.

3.0 Problem Statement and Objective:

Mining heavy equipment vehicle operators suffer from the highest occupational injury rates [1, 2]. Among all of the occupational injuries in mining industry, the fall-related injuries are the second largest components [3-5]. Previous studies have shown that prolonged exposure to whole body vibration (WBV) negatively affects postural stability [7-10] and increases the risk of falling, by increasing neuromuscular reaction times [6, 20-23] and adversely affecting the visual, vestibular and somatosensory systems [8,14,15,18,24-29].

In off-road mining vehicles, environmental factors such as rough terrain result in impulsive shocks [1, 2, 11, 12] and multi-axial WBV [2, 11] that are more severe than typical on-road vehicles. This means that in off-road mining vehicles the predominant WBV exposure is not necessarily limited to the vertical (z-axis) but can often include significant fore-aft (x-axis) and/or lateral (y-axis) WBV exposures [2, 11]. Because such multi-axial components of WBV exposures often have more detrimental effects on human responses [30-32], mining vehicle operators are at even greater injury risks compared to on-road drivers whose WBV exposures are predominantly on the vertical axis. However, limited research has been conducted on the additional impact of multi-axial WBV on fall-related injuries [2]. Moreover, the current industry standard approaches to reduce WBV exposures rely on passive vertical (Z-axis) suspension systems, which are less effective in reducing lateral components of WBV exposures and the associated injury risks among mining vehicle operators who chronically experience multi-axial WBV [33,34]. Therefore, to serve this critical need for applied research, our objectives in this application are to quantify the impact of multi-axial WBV exposure on postural stability, and to understand how this impact may be mitigated. This work supports our longer-term goal of reducing the prevalence of falling and related injuries among mining vehicle operators.

Our central hypothesis is that exposure to multi-axial WBV increases the risk of falling more so than single-axial vertical WBV by altering sensory orientation derived from effective integration of visual, vestibular and somatosensory information, hence impairing postural stability. We also hypothesize that this risk can be more effectively mitigated by a multi-axial active suspension seat than the current industry standard of single-axial (vertical) passive suspension seats. Our rationale for this study is that if we can use an effective engineering control to reduce multi-axial WBV to levels previously unobtainable, we can alleviate the associated loss in postural stability and therefore lower risks for fall-related injuries among mining vehicle operators. To achieve our research objectives, we propose a repeated-measures laboratory study using 20 subjects in which we will replicate actual field-measured multi-axial vibration profiles and measure important aspects of postural stability in the following specific aims:

Specific Aim 1: Determine the relative impact of single- and multi-axial WBV exposure on postural stability. Our working hypothesis is that exposure to WBV with significant multi-axial components will, as compared to vertical-dominant WBV: (i) reduce functional limits of stability, (ii) increase sway during quiet standing (reduced standing balance) and (iii) prolong the duration of the preparatory imbalance phase and increase center-of-pressure displacement during the preparatory imbalance phase preceding functional tasks such as gait initiation and stair descent (impaired anticipatory postural adjustments).

Specific Aim 2: Determine the efficacy of single-axial passive and multi-axial active suspension seats in alleviating the adverse effects of multi-axial WBV on postural stability. Our working hypothesis here is that the use of a multi-axial suspension seat would alleviate the effects of multiaxial WBV on postural stability measures better than a single-axial passive suspension seat. Outcome measures will be the same as used in Specific Aim1.

4.0 Research Approach:

To achieve our research objectives, we conducted a repeated-measures laboratory study using 20 subjects in which we replicated actual field-measured vibration profiles and measured important aspects of postural stability.

4.1 Subjects:

A total of 20 participants (18 males and 2 females) were recruited for this laboratory study. Their mean (SD) age was 28 (4) years, and they were 177 (9) cm tall with body mass of 77 (13) kg. The gender distribution was determined based on mining vehicle operators' gender distribution. All participants were free of pain in neck, shoulder, and back regions (over past 7 days) with no history of musculoskeletal disorders. Pregnant women were excluded in order to avoid any unforeseen adverse effects due to the 4-hour WBV exposure. The experimental protocol was approved by the University's Institutional Review Board and all of the participants signed the consent form prior to the experiment.

4.2 Experimental protocol and procedures:

In a repeated-measures laboratory experiment, four experimental conditions [(a) Vertical-axial dominant WBV exposure with a single-axial passive suspension seat, (b) Multi-axial WBV exposure with a single-axial active suspension seat, (c) Multi-axial WBV exposure with a multi-axial active suspension seat, (d) No WBV exposure (control)] were administered over four different days with a minimum of 24-hours between the conditions (Figure 1). The order of the conditions were randomized and counterbalanced to minimize any potential bias due to the order of the testing. Each vibration exposure condition consisted of two 2-hour exposure sessions and a 30-minute mid-term break.

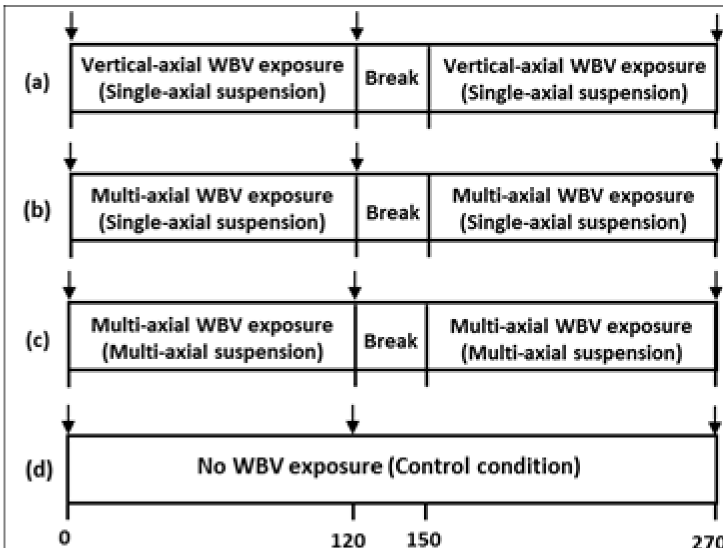

Figure 1. *Four experimental conditions: (a) Vertical-axial dominant WBV exposure with a single-axis suspension seat, (b) Multi-axial WBV exposure with a single-axis suspension seat, (c) Multi-axial WBV exposure with a multi-axial active suspension seat, (d) No WBV exposure (control). Arrows denotes times at which postural stability measures will be collected*

The seat height of each participant was measured on the first day and kept consistent across the subsequent conditions to minimize the potential effect of posture

[35, 36]. Participants were instructed to sit on the seat mounted on a motion platform and watch a monotonic documentary film while being exposed to vibration. The location and height of the display monitor was set such that their postures were similar to those during driving long-haul trucks or mining heavy equipment vehicles. During the exposure sessions, WBV measurements were collected from the seat and motion platform. In addition, tri-axial ground reaction forces and moments were collected at the start of each experimental condition, immediately after 2 hours and 4 hours of exposure.

4.2 Vibration Simulation:

A 6-degree-of-freedom motion platform was used to recreate two different types of actual field-collected vibration profiles in the laboratory (Figure 2). This large scale 6-DOF motion platform consists of 6 electric linear servo actuators which can replicate the same vibration exposure measured in the field. As this motion platform is based on electro linear servo actuators, it provides much greater precision and repeatability in motion control as compared to hydraulic actuator-based motion platforms.

***Figure 2**. Experimental setup showing the motion platform for simulating WBV exposures*

For the multi-axial WBV exposures (exposure condition (b) and (c) in Figure 1), the vibration data profiles were chosen from tri-axial vibration data collected from 38 vehicles (11 different vehicle types) with 123 mining equipment operators. The multi-axial vibration profiles used in this study were selected in order to have significant lateral (Y-axis) vibration that reflects the average WBV parameters in a previous study. For the vertical-axial dominant vibration exposures, the most representative tri-axial acceleration data collected from long-haul trucks was selected to reflect the average WBV parameters of 105 long-haul trucks. The ISO 2631-1 WBV parameters for two input vibration exposures are shown in Figure 3. The selected field-measured vibration profiles were iteratively brick wall filtered and converted to displacement data by integration. The displacement data were imported (Replication software; Moog Inc.; Aurora, NY) to reproduce the same accelerations on the motion platform.

The two seats tested in this study included a single-axial (vertical) passive suspension seat (BoseRide; Bose Corporation; Framingham, MA) and multi-axial (vertical + lateral) active suspension seat (Prototype; Bose Corporation; Framingham, MA). The multi-axial active suspension seat continuously measures both vertical (Z-axis) and lateral (Y-axis) vibration using built-in accelerometers. The built-in microprocessor uses seat position and acceleration data to counteract the translational Z-axis (vertical) vibration and angular lateral (roll) acceleration by controlling electromagnetic linear actuators. The single-axial (vertical) passive suspension seat is a current industry-standard seat with passive pneumatic suspension that uses passive components of compressed air and dampers to attenuate vertical vibration.

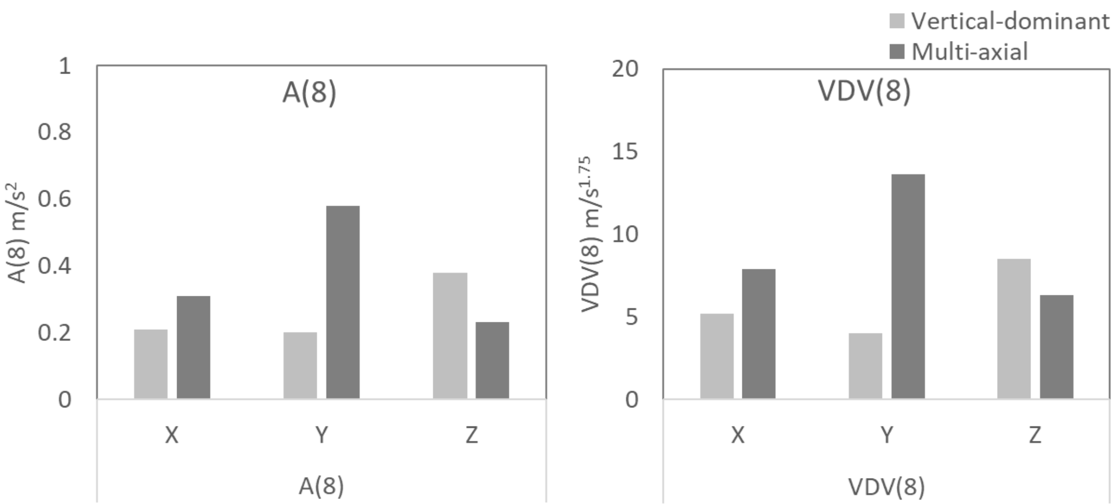

***Figure 3**. ISO 2631-1 WBV parameters of two input vibration profiles: vertical-dominant vibration collected from on-road semi-trucks and multi-axial vibration collected from off-road mining vehicles. A(8) is root mean square weighted average vibration normalized to 8 hours; VDV(8) is vibration dose value normalized to 8 hours.*

4.3 Measures:

Postural stability: In order to measure parameters related to postural stability, tri-axial ground reaction forces and moments were sampled at 100 Hz before WBV exposure, immediately after 2 hours and 4 hours of exposure using a force platform (AMTI OR6-7-1000, Watertown, MA, USA). At each of these time points, subjects were asked to stand still, perform maximal forward and backward leans, and initiate gait to measure the following parameters:

1. Functional limits of stability: Smaller functional limits of stability is related to impaired postural preparation for gait initiation [40, 41]. In order to measure this parameter, subjects were asked to stand near to the center of a force platform barefoot in an upright and natural neutral position for 5 seconds. Then, as has been done in previous studies assessing functional limits of stability [42], subjects were instructed to perform maximum forward lean and maximum backward lean for 5 seconds, starting from a natural neutral position. Subjects were asked to lean as far as possible at their comfortable speed, without lifting their toes or heels or flexing their hips, and to hold their maximum position for at least 5 seconds. During the trials, tri-axial ground reaction forces and moments were sampled at 100 Hz using a force platform (AMTI OR6-7-1000, Watertown, MA, USA), low-pass filtered (2nd order, zero-phase-lag, Butterworth, 5 Hz cut-off frequency), and transformed to obtain center of pressure (COP) values [43]. Functional limits of stability were quantified by the maximum COP displacement in the anterior-posterior (AP) direction with respect to the base of support [44]:

$$fLOSAP = maxFW - maxBW$$

where maxFW and maxBW represent the average AP COP over the first 5 s of stabilized, forward and backward leaning, respectively.

2. Standing balance: Postural stability during quiet standing were assessed using a modified version of the Clinical Test of Sensory Integration for Balance [7, 8, 45]. Briefly, subjects were asked to stand as still as possible for 10 seconds barefoot near the center of a force plate eyes open with arms at the side and looking straight ahead. During all trials, tri-axial ground reaction forces and moments were sampled at 100 Hz using a force platform (AMTI OR6-7-1000, Watertown, MA, USA), low-pass filtered (2nd order, zero-phase-lag, Butterworth, 5 Hz cut-off frequency), and transformed to obtain COP values. The median power frequency, mean velocity, RMS distance, and COP sway area were calculated according to procedures described in previous studies [46, 47]. Increases in these traditional COP-based sway measures are typically interpreted as an overall deterioration of postural control [41, 46, 48, 49].

3. Anticipatory postural adjustments preceding gait initiation: Anticipatory postural adjustments (APAs) represent the transient phase between quiet standing and dynamic conditions such as walking. This parameter was measured using the earlier protocols measuring APA strategies [50, 51]. Briefly, subjects were instructed to stand upright for 5 s in a comfortable position with the arms laying on their sides without any restrictions on the distance between their feet and walk along a straight trajectory for about 3 m for the gait initiation task. During all trials, tri-axial ground reaction forces and moments were sampled at 100 Hz using force platforms (AMTI OR6-7-1000, Watertown, MA, USA), low-pass filtered (4th order, zero-phase-lag, Butterworth, 10 Hz cut-off frequency), and transformed to obtain COP values [43].

COP trajectory and vertical ground reaction force were used to analyze the APAs, from APA onset to the instant of foot contact of the leading foot. APA onset was identified using the COP medial/lateral (ML) displacement with the threshold set as twice the standard deviation (SD) of the signal during the quiet standing period preceding task initiation [52]. The foot contact of the leading limb was identified as the instant when the vertical ground reaction force of the second force platform exceeds a threshold of 6.5% of body weight [53]. Temporal parameters, including APA, swing phase, and step duration, in addition to spatial parameters, including imbalance and unloading phase amplitude in ML (AP) direction, were computed from the COP displacement to characterize APA timing and amplitude using the earlier protocols [54]. Prolongation of the imbalance and unloading phases of APAs indicates postural stability deterioration.

4.4 Data Analysis:

Dependent measures for assessing postural stability were functional limit of stability ($fLOSAP$), COPmedian power frequency, COPmean velocity, COPrms distance, COParea obtained from standing balance trials, and the APA temporal and spatial parameters from gait initiation trials. Normality of the data was assessed using a combination of graphical methods and Shapiro-Wilk statistical test. Generalized linear mixed model (GLMM) was used to determine the effects of exposure conditions, measurement time, and interaction of these two fixed effects on the corresponding outcome variables to test our hypotheses. Random intercepts were introduced to account for within-subject correlations. Based on our hypothesis, we expected to find a statistically significant effect of the interaction of condition and time on the postural stability measures. When such significant interaction effects were found, linear contrast analyses were set up for specifically testing which pairs of conditions were associated with a significant change in dependent measures from pre-to-post exposures. All statistical analyses were performed using JPM® Pro (Version 14, SAS Institute Inc., Cary, NC). As interaction effects are typically harder to detect, Type I error rate of 5% and 10% were considered acceptable for statistical significance for main effects and interaction effects respectively.

5.0 Results, Summary of Accomplishments, Conclusions and Impact Assessment:

Results

Descriptive summaries of all COP-based measures for standing balance in all experimental conditions are presented in Table 2. While median power frequency (MF) of COP did not significantly differ with time or condition, all the remaining COP measures showed significant changes. The mean velocity and RMS displacement of COP increased significantly with time (i.e. pre to post exposure) along both the Anterior-Posterior (AP) and Medial-Lateral (ML) directions, and so did the COP area (Table 1). Specifically, post hoc analysis indicated that significant increase in mean velocity along ML (p=0.002) and AP (p=0.001) directions, RMS displacement along ML (p=0.007) and AP (p=0.041) directions, and elliptical sway area (p=0.028) occurred following multi-axial vibration exposures. Following the vertical-dominant vibration condition, only mean velocity in the AP direction (p<0.001) and elliptical sway area (p=0.027) showed significant increase. Significant condition × time interaction effects were found for the mean velocity in ML direction and for the RMS displacement of COP in the ML direction. These are graphically shown in Figures 4.

Post-hoc analysis of the significant interaction effects revealed that increase in COP mean velocity and RMS displacement along ML direction following multi-axial WBV exposure was significantly higher than the increase in these measures following no WBV (p=0.005, and p=0.04 respectively) and vertical-dominant WBV condition (p=0.015 and p=0.05). The increase in in COP mean velocity and RMS displacement along ML direction following multiaxial WBV exposure were also significantly higher than that following the intervention condition (p=0.005 and p=0.006, respectively). That is, the multi-axial active suspension seat significantly reduced the change in COP mean velocity and displacement in ML direction from pre- to post exposure, compared to the multiaxial vibration condition with the conventional passive air suspension seat. Furthermore, changes in COP mean velocity and displacement in ML direction from pre to post exposure was not significantly different between no WBV and vertical-dominant WBV condition (p=0.596 and 0.784, respectively).

Table 1. Mean (SD) of postural sway measures [mean power frequency (MF), mean velocity (MV), RMS displacement (RMSD), and sway area (AREA)] in the different conditions: No WBV, vertical-dominant WBV, multi-axial WBV, and multi-axial WBV with an intervention seat. ML and AP indicates Medial-Lateral and Anterior-Posterior directions, respectively. *P*-values were calculated from the repeated measures ANOVA (*CON*: condition, *TIME*: time, *CON* × *TIME*: condition × time). Significant differences are highlighted in bold.

	No WBV		Vertical-dominant		Multi-axial WBV		Multi-axial WBV with intervention seat		*p*-Value		
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	*CON*	*TIME*	*CON* × *TIME*
MF_ML (Hz)	0.37 (0.16)	0.31 (0.11)	0.33 (0.13)	0.31 (0.13)	0.30 (0.15)	0.40 (0.22)	0.33 (0.18)	0.39 (0.15)	0.879	0.924	0.300
MF_AP (Hz)	0.36 (0.18)	0.30 (0.18)	0.27 (0.12)	0.28 (0.13)	0.27 (0.11)	0.29 (0.15)	0.30 (0.14)	0.21 (0.05)	0.381	0.299	0.525
MV_ML (mm/s)	4.90 (2.25)	5.36 (1.11)	5.06 (1.81)	6.09 (0.96)	3.84 (1.18)	7.60 (2.18)	5.73 (2.39)	6.20 (2.08)	0.546	**< 0.001**	**0.012**
MV_AP (mm/s)	7.11 (2.61)	9.11 (2.29)	7.22 (2.46)	11.01 (3.98)	7.57 (1.82)	11.27 (2.75)	7.66 (1.60)	11.27 (3.25)	0.286	**< 0.001**	0.448
RMSD_ML (mm)	1.80 (0.83)	2.36 (0.62)	2.17 (0.77)	2.86 (1.15)	1.44 (0.51)	3.13 (1.25)	2.04 (0.81)	2.21 (0.39)	0.295	**< 0.001**	**0.045**
RMSD_AP (mm)	2.96 (1.18)	4.26 (1.14)	3.76 (1.70)	5.11 (1.67)	3.62 (1.40)	5.45 (1.68)	3.32 (1.22)	5.86 (2.42)	0.115	**< 0.001**	0.836
AREA (mm^2)	107.09 (76.70)	165.65 (40.45)	143.31 (80.73)	245.35 (109.82)	95.47 (57.47)	273.16 (118.12)	119.37 (63.13)	235.03 (124.97)	0.086	**< 0.001**	**0.272**

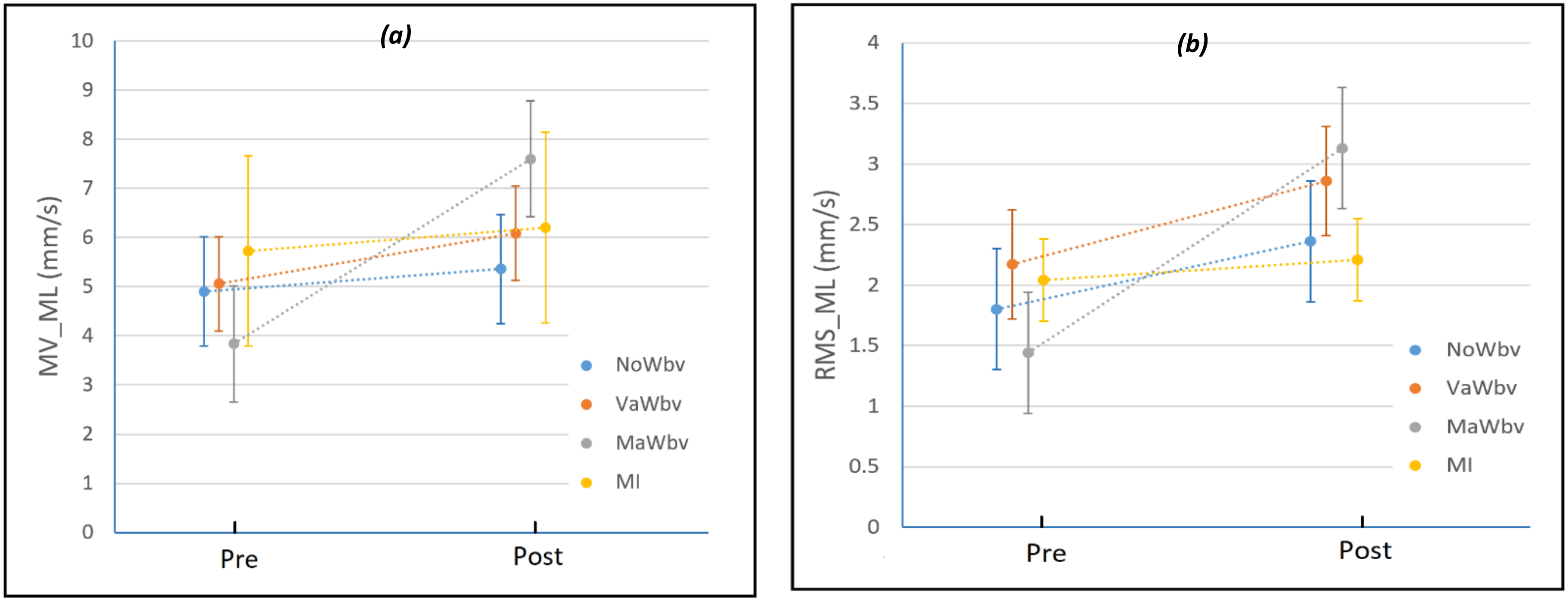

Figure 4 *Condition x Time interaction effects on (a) mean velocity and (b) RMS displacement in medial-lateral direction. Conditions include no WBV (NoWbv), vertical-dominant WBV (VaWbv), multi-axial WBV (MaWbv) and multi-axial WBV with the intervention seat (MI). Error bars indicate standard deviation.*

Descriptive measures for functional limit of stability and anticipatory postural adjustment (APA) measures for gait initiation are shown in Table 2, along with results from statistical analysis. While several trends were apparent in the data, there was large inter-subject variance in most measures. Of the APA measures, the only significant change was observed in the amplitude of unloading phase in ML direction, which showed a significant interaction between condition and time (Table 2). Post-hoc analysis revealed that while the control and vertical axis vibration condition were not different from one another, the amplitude of unloading phase was increased significantly in multi-axial WBV condition compared to control (No WBV) and multi-axial WBV with the intervention conditions ($p = 0.05$ and $p=0.04$, respectively, see figure 5).

Table 2. Mean (SD) of functional limit of stability (FLoS) and APA measures [Imbalance phase duration and amplitude (IMB_DUR and IMB_AMP), Unloading phase duration and amplitude (UNL_DUR and UNL_AMP) in the different conditions: No WBV, vertical-dominant WBV, multi-axial WBV, and multi-axial WBV with an intervention seat. ML and AP indicates Medial-Lateral and Anterior-Posterior directions, respectively. *P*-values were calculated from the repeated measures ANOVA (*CON*: condition, *TIME*: time, *CON* × *TIME*: condition × time). Significant differences are highlighted in bold.

	No WBV		Vertical-dominant		Multi-axial WBV		Multi-axial WBV with intervention seat		*p*-Value		
	Pre	Post	Pre	Post	Pre	Post	Pre	Post	*CON*	*TIME*	*CON* × *TIME*
FLoS_AP (ms)	136.05 (22.86)	131.30 (26.68)	134.04 (31.03)	135.68 (26.41)	136.66 (16.16)	123.54 (24.71)	126.38 (17.44)	129.33 (22.29)	0.227	0.932	0.882
IMB_DUR (ms)	690.36 (331.10)	1009.90 (412.12)	858 (341.23)	1012.55 (242.78)	770.89 (400.84)	749.90 (308.95)	868.64 (335.87)	651.27 (333.02)	0.511	0.389	0.098
UNL_DUR (ms)	341 (77.32)	328.90 (40.83)	351.58 (126.86)	320.63 (53.47)	338.78 (56.49)	334.10 (71.61)	314.27 (34.09)	357.00 (96.16)	0.995	0.933	0.461
IMB_AMP_ML (mm)	43.93 (13.96)	52.55 (19.72)	48.87 (19.02)	43.04 (25.95)	41.41 (9.23)	56.14 (10.15)	45.77 (15.10)	41.52 (14.36)	0.388	0.833	0.122
IMB_AMP_AP (mm)	35.24 (16.20)	38.82 (11.37)	32.71 (16.60)	30.84 (17.51)	30.18 (10.41)	29.49 (12.76)	36.51 (17.95)	24.47 (11.71)	0.983	0.134	0.321
UNL_AMP_ML (mm)	146.65 (25.91)	154.20 (38.73)	151.69 (24.13)	148.19 (45.42)	159.34 (18.44)	182.41 (19.27)	140.49 (29.16)	142.46 (26.00)	0.122	0.091	**0.081**
UNL_AMP_AP (mm)	30.85 (20.73)	20.93 (13.74)	16.07 (12.85)	19.78 (12.71)	33.21 (11.78)	21.38 (17.68)	32.35 (13.61)	22.68 (16.34)	0.512	0.105	0.612

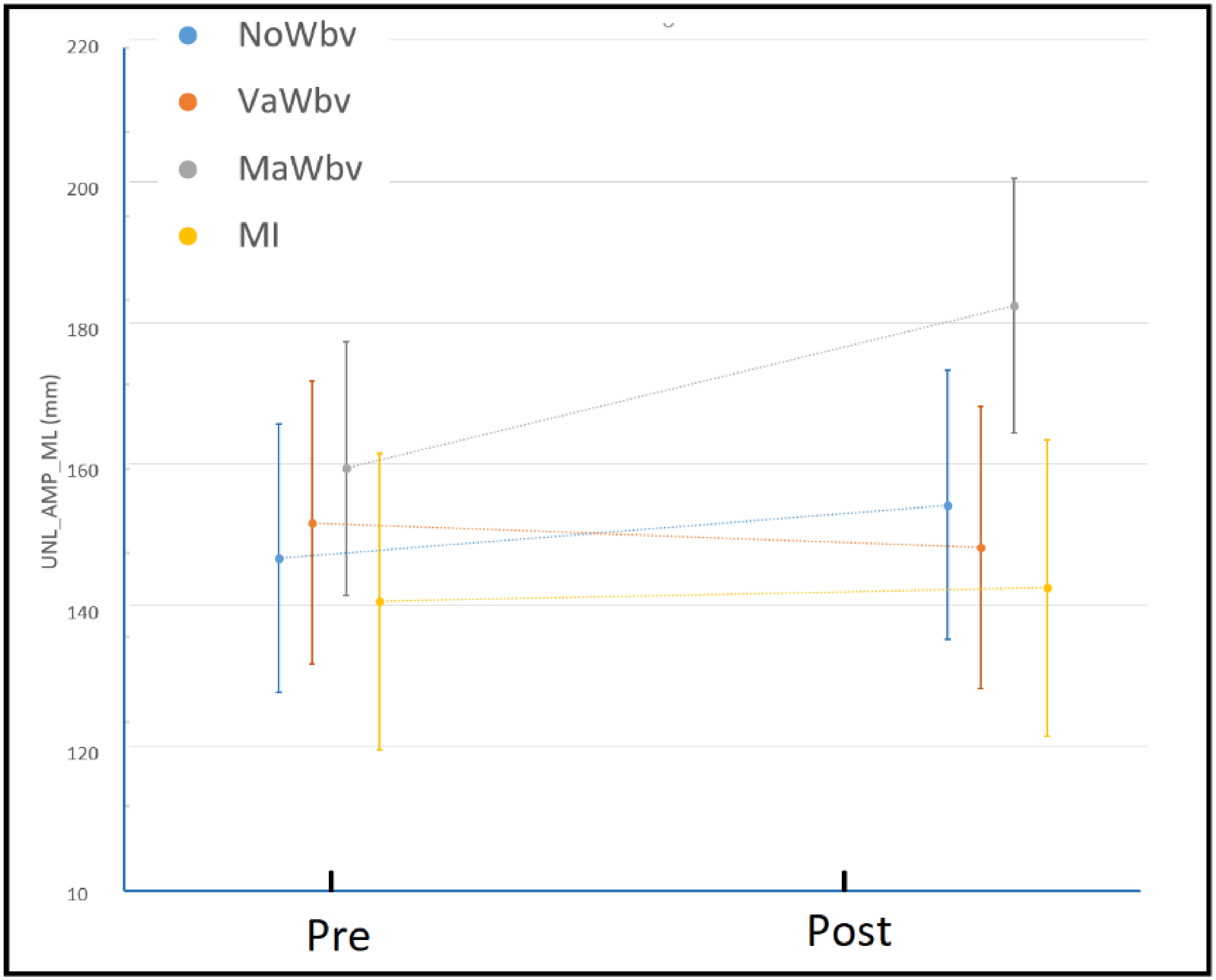

Figure 5 *Condition x Time interaction effects on unloading phase amplitude in medial-lateral direction. Conditions include no WBV (NoWbv), vertical-dominant WBV (VaWbv), multi-axial WBV (MaWbv) and multi-axial WBV with the intervention seat (MI). Error bars indicate standard deviation.*

Discussion

This study comparatively evaluated the effects of exposure to different WBV conditions on postural balance during quiet standing and gait initiation among a young and healthy participant group. For standing balance, no significant differences were found for COP median frequency parameters across the exposure conditions. Frequency domain analysis of COP trajectory has been shown to be useful for evaluating postural disturbances caused by specific diseases or clinical conditions [55]. That we didn't find any significant differences in this measure might be either due to the short measurement time utilized in our protocol, or the possibility that the frequency domain measure of COP is not responsive enough to postural sway changes associated with vibration exposures. Others have also reported the median frequency to be the least reliable of all the traditional COP-based measures commonly reported in the literature [56, 57]. The results in our study on vertical-dominant vibration increasing specific postural sway measures such as COP RMS displacement are similar to the results reported by earlier studies [7].

All the other COP measures that included mean velocity, RMS displacement and sway area significantly increased with multiaxial vibration, and post-hoc analysis indicated that the increase in these measures in the multiaxial vibration condition was significantly greater than both those in the vertical-dominant vibration and no-vibration (control) condition. Thus our hypothesis on the potential for multiaxial vibration exposures to further impair postural stability even compared to the vertical dominant vibration condition has been confirmed. Furthermore, our analysis also indicated that the COP velocity and RMS displacement were significantly lowered in the multiaxial-suspension intervention condition compared to the multi-axial vibration condition, thereby showing promise that the engineering intervention explored in this study may have the ability to reduce aspects of vibration that may subsequently deteriorate postural balance.

In terms of functional limit of stability in the AP direction, there was no statistically significant difference in the pre-exposure to post-exposure values across the different vibration conditions. There may be two possible explanations for this: 1. The maximal leaning task was done predominantly by subjects leaning at their ankles, without bending other parts of their body. This task may hence be affected more by ankle stability than by stability changes occurring due to fatigue or other vibration-related effects on the more proximal joints in the body (e.g., trunk and hips). 2. From our standing balance results, it seems that multiaxial vibration exposure affects balance more significantly in the ML direction than in the AP direction. Hence in future studies, leaning protocols that involve not only the ankle joint, and that include multiple leaning directions, may have more potential to discriminate multi-axial vibration-related changes in voluntary leaning and associated functional stability.

During gait initiation, anticipatory postural adjustments (APAs) were measured in this study and quantified using a combination of spatial and temporal outcome variables. To the best of our knowledge, these measures have previously only been used in neurophysiological investigations of aged or neurologically impaired populations. Our study is the first attempt to utilize these measures to explore vibration-related changes in functional balance capacity. There were no statistically significant differences in the duration of the imbalance or unloading phase preceding and following any vibration condition. However, when looking at the amplitude of COP displacement during these phases, the COP displacement amplitude in ML direction during the unloading phase was significantly greater in the multi-axial vibration condition compared to control and vertical axis conditions, and significantly lower during the multi-axial suspension intervention condition. Future studies need to verify whether the observed increased in unloading phase amplitude of COP displacement translates to poorer functional stability during walking tasks. Measures of global stability such as dynamic margin of stability or local dynamic stability (such as maximal Lyapunov exponents) may be useful to examine gait stability in individuals following vibration exposures.

Limitations

There were a few limitations to our study. First, there were several dependent measures for standing balance and gait initiation, many of which are correlated. While this may have slightly increased the chances of finding statistical significance, we would like to emphasize the exploratory nature of this study, which required us to attempt to quantify a broad number of outcomes. Hence, a subsequent study should confirm our findings. Second, the duration for which postural stability may be affected following different vibration exposures has not been established in the literature. Due to the number of outcome measures in our study, it is possible that some subjects may have recovered by the time gait initiation was run (following static balance and functional limit of stability trials). Third, while this study models the change in balance responses with time as a linear process, there may be some nonlinear changes in postural stability measures across time. Finally, as this was a laboratory-based study where external factors including environmental factors were controlled and consistent across conditions, this study does not account for external factors that may influence fall risk. Therefore, in future studies, it may be important to evaluate the relative importance of other factors vs. impaired postural stability on fall risk during vehicle egress.

Conclusions

In conclusion, this relationship between WBV and postural stability may be a contributing factor in explaining the disproportionally higher fall-related injuries (up to 8 times) during egress as compared to ingress of vehicles [7]. However, future studies need to investigate whether the observed change in postural stability measures (even though statistically significant) is biologically significant in terms of increasing fall-risks, and how it may vary with longer-term exposures characteristic of a typical work shift lasting 8 or more hours. Whether these results from static balance trials transfer across conditions (e.g. conditions requiring dynamic balance), and how long individuals take to recover from postural stability decrements, are also key factors yet to be determined in order to establish a firm causal link between WBV-related decrement in postural stability and increased fall-risk among off-road vehicle operators. Finally, there are significant confounding factors such as foot placement, equipment egress design, physiological and environmental elements that play a role in a possible fall incident that should not be overlooked when considering the bigger picture of fall-risk during vehicle egress for on-road and off-road vehicle operators.

Summary of Accomplishment and Impact Assessment

Our major accomplishment is that this study has advanced the current knowledge on the effects of WBV on postural stability. Although previous studies have evaluated the effects of WBV on postural stability [6-10, 18], these studies are limited in that the vibration exposure is not realistic or too short to represent long driving hours of mining vehicle operators. Furthermore, although the multi-axial components of WBV, common exposure among mining vehicle operators, are expected to have more detrimental effects on human responses [30-

32], little scientific research has examined the nature of the additional impact of multi-axial WBV (common in mining vehicles) on postural balance and fall-related risk measures as compared to No vibration exposure or the vertical-dominant WBV exposure from on-road vehicles. By using 4-hour exposure of field-measured vibration, this study successfully showed not only that multi-axial WBV exposure had greater effects on postural balance compared to no vibration and the vertical-dominant WBV exposure, but also that such greater effects may be mitigated by a multi-axial active suspension seat. These findings support our rationale that the proposed engineering control (i.e., multi-axial active suspension seat) can mitigate impaired postural balance following WBV and therefore lower a risk for fall-related injuries among mining vehicle operators. This can provide a solid scientific basis for developing new engineering controls to reduce mining vehicles' multi-axial WBV and help in better targeting such future interventions to reduce fall-related injuries and associated musculoskeletal disorders among mining vehicle operators. Lastly, our study provides the first ever-data on novel APA measures during gait initiation among healthy subjects, both after prolonged sitting (control condition), as well as after different vibration conditions. Hence, our results will benefit the larger scientific community by providing pilot data that future studies can use for design, including for sample size calculations. Given the significant proportion of fall-related injuries and their substantial economic burden in mining industry, the impact of our study is expected to be substantial impact on mining vehicle operators and mining industry by reducing adverse effects of WBV on postural balance and related fall risks, and therefore improving occupational health and well-being of mining vehicle operators.

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