Applied Ergonomics 122 (2025) 104402

Contents lists available at ScienceDirect

Applied Ergonomics

journal homepage: www.elsevier.com/locate/apergo

Vertical-dominant and multi-axial vibration associated with heavy vehicle operation: Effects on dynamic postural control

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A R T I C L E I N F O

Keywords:
Whole-body vibration
Falls

A B S T R A C T

Heavy vehicle operators suffer from increased fall risk, potentially due to exposure to whole-body vibration (WBV) that compromises postural control. This study aimed to characterize the relative impacts of multi-axial WBV vs. vertical-dominant WBV on dynamic postural control during sit-to-stand transition and stair descent, following prolonged vibration exposures. We also compared the effectiveness of a standard (single-axial passive suspension) seat with a multi-axial active suspension seat intervention. Vertical-dominant WBV adversely affected dynamic postural control. However, multi-axial WBV had no added adverse effects on postural control compared to vertical-dominant WBV. The multi-axial active suspension system did not outperform the standard seat in mitigating vibration effects on postural control during exposures but led to faster recovery during breaks between exposures. Overall, our results confirmed the negative effects of WBV on dynamic postural control but did not detect any additional negative effects associated with multi-axial WBV when compared to vertical-dominant WBV.

1. Introduction

Motor vehicle operators in the U.S. continue to suffer from a high prevalence of both fatal and non-fatal occupational injuries. Fall-related injuries, including slips, trips, and falls, continue to be a leading cause of morbidity and mortality among all injuries. In 2020, fall-related injuries accounted for approximately 10% of all fatal injuries in the transportation industry and 22% of all non-fatal injuries, with about half of those being among motor vehicle operators (Bureau of Labor Statistics 2021a, 2021b). Rates of fall-related injuries have been reported to be higher during vehicle egress as compared to ingress in the transportation and mining industries (Moore et al. 2009; Nicholson and David 1985). There are various potential causes leading to falls during egress, such as lack of adequate safety measures (e.g., steps and handholds), egress practice, and inclement weather (e.g., rain, snow, and ice) (Couch and Fraser 1981; Patenaude et al., 2001). However, some existing evidence indicates that postural instability may also be a significant risk factor for falls (Ahuja et al. 2005). Prolonged exposure to whole-body vibration (WBV) has been associated with loss of postural stability by increasing neuromuscular reaction times (Arora and Grenier 2013; Stamenkovic et al. 2014) and negatively impacting the visual, vestibular, and somatosensory systems (e.g., causing motion sickness, giddiness, or sensations of illusory movement) (Martin et al., 1981; Peli and García-Pérez 2003; Seidel and Heide 1986; Zahov and Medzhidieva 2005; Oullier et al., 2009). These altered sensory inputs are believed to be caused by biodynamic responses (i.e., accelerations) of the head, neck, and trunk, and may in turn disturb motor outputs through local spinal (Roll et al. 1980), vestibulo-spinal (Santos et al., 2008; Wilder et al., 1996), and vestibulo-ocular reflexes (Suvorov et al., 1989). In the lower body, cutaneous receptors under the feet have been shown to become less active after exposure to WBV (Ribot-Ciscar et al., 1996; R. D. Pollock et al., 2011). The vibration transmitted to the muscles and tendons of the lower extremities has been shown to activate muscle spindles and elicit a tonic vibration reflex (Carlucci et al. 2010). Thus, reflex contractions together with reduced sensitivity in vestibular and cutaneous receptors are believed to change the sensory integration of information in the central nervous system, resulting in a loss of postural stability following WBV exposure (Ribot-Ciscar et al., 1996; Liang et al., 2017). WBV exposure can thereby compromise postural control and increase the risk of fall-related injuries.

Off-road heavy equipment vehicle operators in the agricultural, construction, and mining industries may have a higher risk of falls since

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https://doi.org/10.1016/j.apergo.2024.104402
Received 19 February 2024; Received in revised form 17 September 2024; Accepted 7 October 2024
Available online 19 October 2024

they are exposed to a high level of WBV from driving on rough terrain (Kim et al. 2018; Marin et al., 2017). Furthermore, WBV exposure in off-road settings is multi-axial in nature, with significant fore-aft (X) and/or lateral (Y) axis components to the WBV exposure along with the vertical (Z) axis, which is the predominant exposure axis for on-road vehicles (Kim et al. 2018; Marin et al., 2017). Such multi-axial WBV experienced on off-road heavy equipment has been associated with a greater impairment of static postural stability compared to on-road vertical-dominant WBV (Park et al., 2021). Multi-axial WBV can also increase head acceleration (Kim et al. 2018), which may further impair vestibular system responses (Mansfield and Lundström 1999) and reduce postural stability. Moreover, current industry standard suspension seats (i.e., passive vertical suspension systems) in off-road heavy equipment are not effective in mitigating multi-axial WBV exposures, particularly the lateral component, which is more common with such equipment (Kia et al., 2022; Kim et al. 2018). Thus, the existing literature suggests that multi-axial WBV, characteristic of off-road vehicles, may impair postural stability to a greater extent than vertical-axis vibration. Yet, the nature of the additional impact of such multi-axial WBV exposure on postural control is poorly understood.

In terms of assessing postural control, a systematic review on the topic concluded that there was modest evidence to suggest a decrease in standing balance performance following exposure to seated occupational WBV (Mani et al. 2010). As documented in our recent study (Park et al., 2021), exposure to simulated WBV increased center-of-pressure (CoP) displacement and velocity during static standing on a firm surface, suggesting a deterioration in postural stability. While some studies have also found significant deteriorations in static balance following WBV, others have observed trends indicating decreased balance (by up to 61%) but without statistical significance (Yung et al., 2018); yet other studies have been unable to find any immediate short-term effects of occupational WBV on static balance (Ahuja et al. 2005; Pollard et al., 2017). However, these studies may not present a complete picture on postural control deterioration following WBV as they are limited almost exclusively to the study of static balance, under different visual/-vestibular conditions. Consequently, the current understanding of how occupational WBV affects postural control is limited with regards to dynamic tasks.

While static balance assessments measure the ability to maintain steadiness on a fixed, firm, and unmoving support surface (Prieto et al., 1996), postural control assessments in dynamic tasks focus on the ability to maintain balance, while transitioning between a static and dynamic state, by transferring the vertical projection of the center-of-mass (CoM) around the supporting base (A. S. Pollock et al., 2000; Bruijn and van Dieën, 2018). Hence, postural control assessments in dynamic tasks address distinctly different aspects of postural balance compared to static assessments. Previous investigations have also highlighted a limited correlation between static balance and postural control in dynamic tasks (Sell 2012; Karimi and Solomonidis 2011). Moreover, considering the higher prevalence of falls during egress, it is important to characterize the effects of WBV on postural control during dynamic activities involved in an egress, such as standing up from a vehicle seat or descending stairs.

Sit-to-stand transition is one of the main weight-bearing activities in daily life and is frequently encountered by operators of heavy vehicles directly preceding vehicular egress. This activity imposes a greater load on the lower limb joints compared to other activities, such as walking (Su et al. 1998). Successful execution of the sit-to-stand transition requires sufficient lower limb strength to efficiently propel the body forward and upward. Furthermore, precise motor coordination plays a crucial role in maintaining postural stability. Hence, an extended sit-to-stand transition time is associated with deteriorated postural control, as well as an increased risk of falls (Lord et al., 2002). Decreased ground reaction force (GRF) (e.g., reduced GRF peak-to-peak amplitude) can indicate decreased lower limb strength or muscular fatigue, thereby impaired sit-to-stand transition performance (Kera et al., 2022a).

In terms of egress, once operators transition from a seated position, stair descent is a common activity for heavy vehicle operators to safely transition from the vehicle cabin to ground level. Compared to stair ascent or level walking, stair descent poses a greater challenge due to the increased effort required to lower the CoM and propel oneself forward while avoiding potential falls. Moreover, the lack of visibility of steps and the ground, especially when descending stairs during egress, can hinder visual sensory cues and further challenge postural control during stair descent (Agyemang and Kinateder 2022; Jacobs 2016; Zietz et al. 2011; Lu et al., 2021). Effective stair descent, in addition to processing sensory information, requires substantial power absorption in the ankle and knee joints, resulting in increased energy demands compared to level walking (McFadyen and Winter 1988; Gorski 2004). Hence, deficit of sensory information or muscle weakness can lead to impaired stair negotiation, indicated by altered spatiotemporal gait measures (e.g., increased step width and double support time) or decreased dynamic stability (Bosse et al., 2012; Lee and Chou, 2007).

Therefore, to clearly delineate the effects of WBV exposure on fall-related injury risks, this study aimed to characterize the relative impacts of multi-axial WBV (characteristic of off-road vehicles) compared to vertical-dominant WBV (characteristic of on-road vehicles) on dynamic postural control during sit-to-stand transition and stair descent activities. We also included a static stance condition as a baseline. In addition, considering the limitations of current industry standard seat suspensions (vertical passive air suspension seat) in mitigating the lateral component of WBV, we aimed to evaluate the efficacy of an intervention (multi-axial active suspension seat) in alleviating postural control impairments following multi-axial WBV. The multi-axial active suspension seats are equipped with additional electromagnetic actuators to counteract both lateral and vertical components of WBV. They have been found to be more effective in mitigating WBV across different frequencies compared to current industry-standard seat suspensions (Kia et al., 2022; Kim et al. 2018). However, their effectiveness in alleviating the postural control impairments associated with WBV is unknown, which we aimed to evaluate in this study. Our hypotheses were that.

1. Exposure to WBV would lead to impaired postural control during sit-to-stand transition (e.g., increased sit-to-stand transition time and peak-to-peak force amplitude) and stair descent (e.g., decreased dynamic stability). We also expected an increase in COP-based postural sway measures during static stance on a foam surface.
2. Exposure to off-road vehicle multi-axial WBV would impair postural control more so than vertical-dominant WBV from on-road vehicles.
3. The use of a multi-axial active suspension seat would alleviate the effects of multi-axial WBV on postural control measures better than a single-axial passive suspension seat.

2. Methods

2.1. Participants

Twenty-two healthy adult participants (11 males and 11 females) were recruited for this laboratory-based study from the Oregon State University community via email solicitations. The means (standard deviations) of the participants' age, weight, and height were 30.3 (7.9) years, 79.1 (17.0) kg, and 173.3 (7.9) cm. Participants were recruited into the study if they 1) were 18–49 years-old; 2) had no musculoskeletal pain in the past 7 days and no history of musculoskeletal disorders in the neck, shoulder, and back regions; 3) had no self-reported visual or vestibular deficits that may influence normal balance control; and 4) were not pregnant.

2.2. Experimental protocol

The experimental protocol was approved by Oregon State University's Institutional Review Board. Informed consent was obtained from participants prior to experimental sessions. The experimental setup included a car seat located on a 6-degree-of-freedom high-fidelity motion platform (MB-E−6DOF/24/1800 KG; Moog Inc.; East Aurora; NY) to create realistic WBV exposures in a laboratory setting (Fig. 1 (a)). After demographic and anthropometric data were collected, the seat height was adjusted for each participant so that their feet could rest firmly on a force platform (AMTI OR6-7-1000, Watertown, MA, USA) mounted in front of the seat while their thighs were parallel to the force platform (Fig. 1 (a)). For each participant, the same seat height was maintained across all experimental conditions to control the participants' posture and its potential impact on postural control measures (Mazzà et al., 2004; Whitney et al., 2005; Zimmermann and Cook 1997). Next, reflective markers were placed on participants' upper and lower body to collect kinematic measures. During an initial practice session, the participants performed a series of postural control assessment tasks (Fig. 1) until they verbally confirmed their understanding of and proficiency with them and overall study protocols.

In a repeated-measures experiment, participants sat on the heavy equipment vehicle seat, mounted on the motion platform, and were exposed for a total of 4 h to each experimental condition (Fig. 2). This 4-h session was broken up into two sessions (exposure 1 and exposure 2) lasting 2 h each, with a 30-min break in between. This was repeated for four different WBV exposure conditions on four separate days: No WBV exposure, vertical-axial dominant WBV exposure with a single-axial passive suspension seat, multi-axial WBV exposure with a single-axial passive suspension seat, and multi-axial WBV exposure with a multi-axial active suspension seat intervention. A minimum 24-h gap was maintained between the experimental conditions to avoid any potential residual effects from a prior condition. The order of all conditions was randomized across participants to minimize any potential systematic bias due to the order of exposure conditions. During the two 2-h sessions, monotonic and neutral nature documentary films were displayed on a flat screen to keep participants' neck posture similar to driving postures while minimizing boredom. Immediately before and after each 2-h exposure, postural control was assessed during sit-to-stand transitions, static stance on a foam surface, and stair descent (Fig. 1). Altogether, the postural control assessments took about 5 min. In total, each experimental session lasted for 5 h, including the study protocol briefing, practice session, the two 2-h exposure sessions with a 30-min midterm break, and postural control assessments.

The sit-to-stand transition started with participants in a seated position on the vehicle seat with their bare feet resting on the force platform in front of the seat and their arms on their chests (Fig. 1 (a)). They were then instructed to stand up without using their arms as soon as they heard an auditory cue and to remain as still as possible for approximately 5 s until receiving another auditory cue (Norman-Gerum and McPhee 2020). We did not control the speed of the sit-to-stand transition to allow participants to perform the task at a self-selected speed (Jeon et al. 2021; Norman-Gerum and McPhee 2020; Petrella et al., 2021). The sit-to-stand transition was performed with eyes open condition and repeated three times (i.e., self-perturbation). Participants then were asked to self-evaluate their perceived confidence that they did not lose balance or become unsteady while performing the sit-to-stand transition tasks and verbally announced their confidence level on a scale of 0–10 (0: no confidence, 10: completely confident) (Powell and Myers 1995).

For the static stance task (Fig. 1 (b)), participants were asked to stand on a foam pad (thickness: 7.5 cm) placed on the force platform in front of the seat and remain as still as possible for 30 s, with their bare feet close together, arms resting on their sides, head facing straight ahead, and eyes open (Lin et al., 2008). The instruction to 'stand as still as possible' was issued to minimize inter-individual differences (Zok et al. 2008). The static task was performed once on a foam pad, with no repetition. Considering that healthy adults, like the participants in this study, primarily depend on somatosensory information to maintain their balance, a foam surface was used to challenge postural control during a static stance (Maitre and Paillard 2016) and improve the sensitivity of detecting the changes in postural control measures related to WBV. During the sit-to-stand transitions and static stance trials, tri-axial ground reaction force (GRF) and moments were collected using the force platform at a sampling rate of 1000 Hz.

Subsequently, participants were directed to dismount the motion platform and stand on a three-step staircase constructed according to OSHA 1910/25 standards (riser height = 18 cm, tread width = 90 cm, tread depth = 20 cm) at the ground level (Fig. 1 (c)). The top of the stairs was equipped with a force platform (AMTI BMS464508-2K-SYS, Watertown, MA, USA). The stair descent task started with participants standing upright on the force platform for 5 s in a comfortable position (arms resting on their sides and no restrictions on the distance between their feet). Then, as soon as they received an auditory cue, participants stepped down the staircase. This task was performed with eyes open condition and repeated twice. During the stair descents, tri-axial GRFs and ground reaction moments were collected at 1000 Hz using the force platform to evaluate anticipatory postural adjustments (APA) preceding stair descent. To evaluate postural control during the stair descent tasks, kinematic data were collected at 100 Hz using an optical motion capture system (Flex 13; Optitrack; Natural Point, OR) and reflective markers. The reflective markers were placed bilaterally on the radius styloid process, humerus lateral epicondyle, clavicle-acromion, anterior and

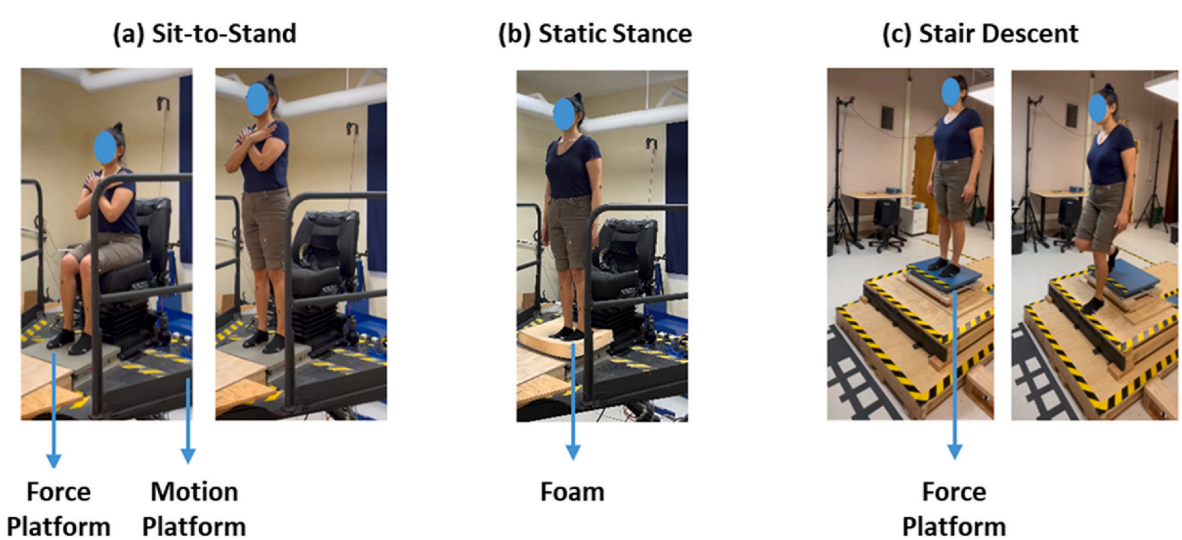

Fig. 1. Experimental setup for measuring postural control during (a) sit-to-stand transition, (b) static stance on foam, and (c) stair descent.

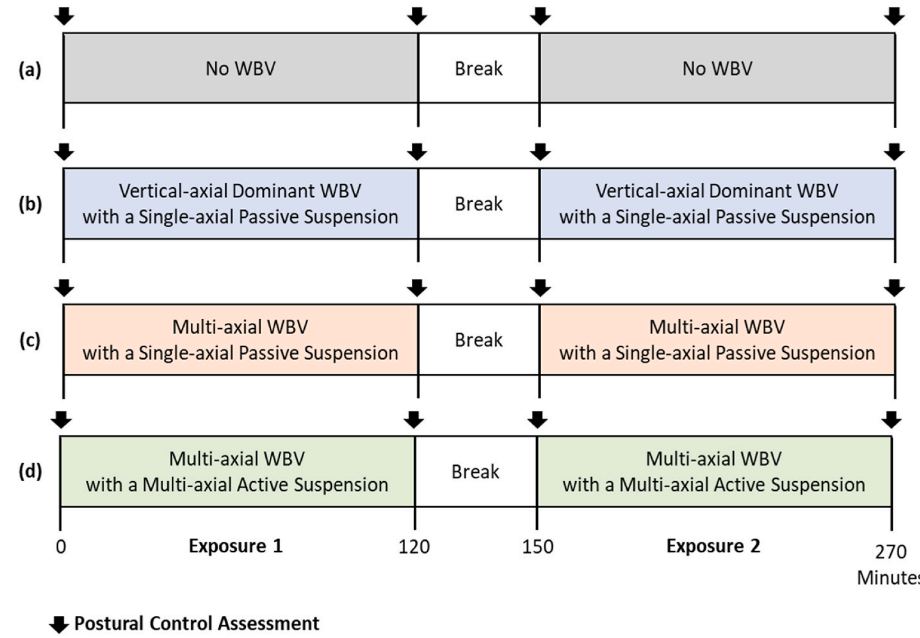

Fig. 2. Repeated-measure experiment design with four experimental conditions: (a) No WBV exposure, (b) vertical-axial dominant WBV exposure with a single-axial passive suspension seat, (c) multi-axial WBV exposure with a single-axial passive suspension seat, and (d) multi-axial WBV exposure with a multi-axial active suspension seat intervention. A minimum 24-h gap was maintained between the experimental conditions (4 days of data collection). The horizontal axis shows the time domain in minutes. Arrows denote times at which postural stability assessments were conducted.

posterior superior iliac spines, lateral knee condyle and ankle malleolus anatomical landmarks. Additionally, four tracking markers were placed on the front center of the thighs and shins, along with markers placed on each foot at the tip of second toe, heel, and the first and fifth metatarsals to establish the base of support (BoS).

2.3. Whole body vibration simulation and measurement

The motion planform (Fig. 1 (a)) was used to play two types of tri-axial vibration profiles collected from long-haul trucks and mining vehicles in field settings (Johnson et al., 2018; Kim et al., 2018a,b) as shown in Fig. 3. The detailed approaches for the WBV simulation are described in our previous studies (Kia et al., 2020, 2022). The vertical-dominant vibration, which had the vertical (Z) axis as the dominant axis, represented the exposures from long-haul trucks operated on paved terrain, including city streets, freeways, and interstate highways (Kim et al., 2016). The multi-axial vibration, in which WBV parameters were greater in the lateral (Y) and fore-aft (X) axes than in the vertical axis, represented the WBV exposures collected from various mining vehicles in off-road terrains and their corresponding vehicle movements (Kim et al. 2018; Dennerlein et al., 2022).

During the WBV simulations, vibration data (i.e., acceleration) were collected at the floor of the motion platform and the seat level using an 8-channel vibration acquisition system that consisted of a data logger (DA-40; Rion Co. LTD; Tokyo, Japan) and two accelerometers (Model 356B40; PCB Piezotronics; Depew, NY) at a sampling rate of 1280 Hz. The vibration data were processed and summarized per ISO 2631-1 WBV standards at the floor and seat levels (ISO, 1997) (Fig. 3).

2.4. Suspension seats

Two different suspension seats were evaluated in this study: a vertical passive air suspension seat (control) and a multi-axial electromagnetic active suspension seat (intervention). To minimize the potential confounding influence of different seat designs and maximize the blinding effect, we used the same seat (BoseRide Prototype; Bose Corporation; Framingham, MA, USA) with two suspension settings: vertical passive air suspension and multi-axial electromagnetic active suspension. 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 WBV. Due to its fixed response and low resonant frequencies, the passive pneumatic suspensions have been found to be ineffective in reducing impulsive exposures that are commonly experienced in off-road vehicles (Kim et al. 2018). The multi-axial active suspension seat continuously measures both vertical and lateral vibration using a built-in inertial measurement unit (IMU). The built-in microprocessor uses seat position and acceleration data to control two highly responsive electromagnetic linear actuators. These control seat travel and counteract the road-induced vibration disturbances. Due to far greater fidelity in frequency response, this multi-axial active suspension seat can effectively attenuate not only the low frequency vibration exposures but also the higher frequency impulsive exposures. Both of these exposures can be difficult for traditional pneumatic seat suspension systems to effectively control. In addition, this seat has a passive fore-aft mechanical suspension to isolate the fore-aft vibration. These features make the multi-axial active suspension seat a particularly well-suited engineering control for off-road vehicles such as construction, forestry, and mining vehicles.

2.5. Postural control assessment

2.5.1. Sit-to-stand transition

The collected tri-axial GRFs and ground reaction moments during the sit-to-stand transitions were low-pass filtered (2nd order, zero-phase-lag, Butterworth, 10 Hz cut-off frequency). The time series vertical GRFs were used to calculate sit-to-stand transition events (Fig. 4) following the protocols established in previous studies (Etnyre and Thomas 2007; Norman-Gerum and McPhee 2020). The outcome measures included reaction time, sit-to-stand time, and peak-to-peak amplitude of GRF. Reaction time in milliseconds was estimated as the duration between the moment the auditory cue was played and when the vertical GRF decreased more than 1% of the difference between the minimal and maximal vertical GRFs (refer to the time between Cue and Initiation events in Fig. 4). The sit-to-stand time in milliseconds was

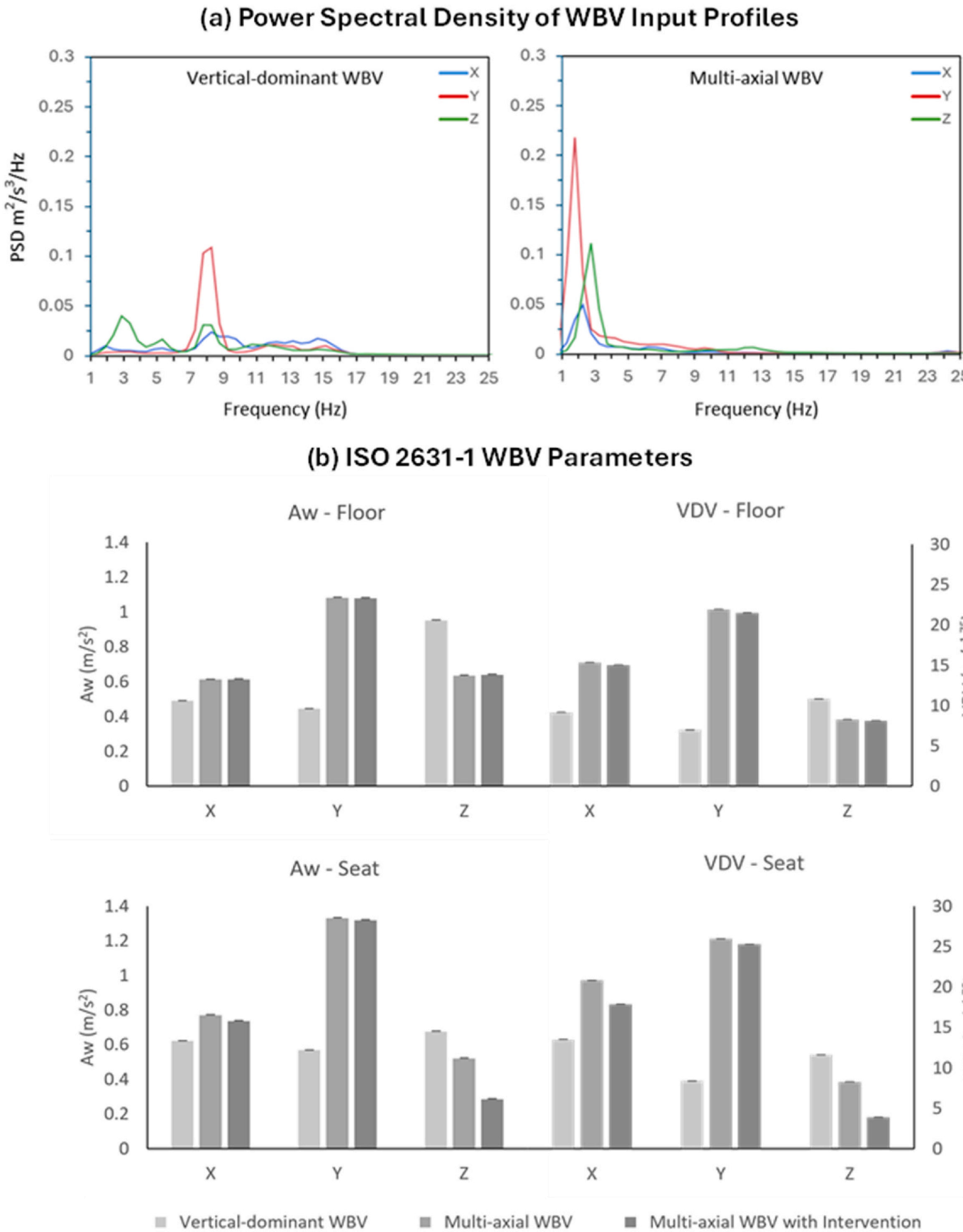

Fig. 3. (a) The power spectral density (PSD) of vertical-dominant (left) and multi-axial (right) input vibration profiles. (b) Means and standard errors (indicated by error bars) of WBV parameters measured per ISO 2631-1 WBV standards (ISO, 1997) [weighted average vibration (Aw) and vibration dose value (VDV)] in X (fore-aft), Y (lateral), and Z (vertical) axis [N = 22]. The top row shows input vertical-dominant and multi-axial WBV [with and without intervention (multi-axial active suspension seat)] measured at the floor of motion platform level. The bottom row shows the WBV parameters at seat level when exposed to WBV.

defined as the duration between initiating the sit-to-stand transition and adapting a steady stance (time between Initiation and Steady Stance events in Fig. 4). The GRF peak-to-peak amplitude was determined as the difference between the minimal and maximal vertical GRFs (reflecting differences in vertical GRFs at Counter and Peak in Fig. 4), normalized by body weight (%BW). Slower reaction time, slower sit-to-stand time, and lower amplitude of initiation to peak force can indicate inability to generate force quickly and control postural stability (Kera et al., 2020; Lord et al., 2002). Lastly, perceived confidence on balance during the sit-to-stand transition tasks was evaluated using a 10-point visual analog scale (0: no confidence, 10: completely confident).

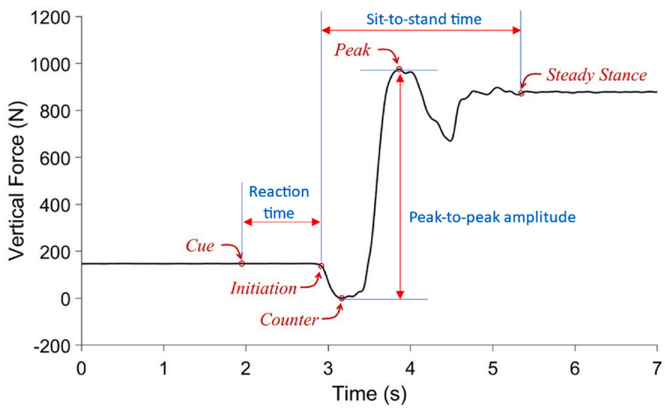

Fig. 4. An example of vertical ground reaction force time series during sit-to-stand transition.

2.5.2. Static stance

Center-of-pressure (CoP) values were calculated based on the filtered tri-axial GRFs and ground reaction moments collected during the static stance on foam. Postural balance measures were then calculated based on the CoP time series and displacement trajectories (Park et al., 2021; Lin et al., 2008; Prieto et al., 1996; Richman and Moorman, 2000). The main outcome measures included CoP root-mean-square (RMS) distance and sample entropy in the mediolateral (ML) and anteroposterior (AP) direction, in addition to elliptical sway area. An increase in CoP RMS distance and area can be interpreted as an overall degradation of an individual's ability to maintain balance (Lin et al., 2008; Prieto et al., 1996). Lower sample entropy values indicate a more predictable signal, while higher values indicate more randomness in the signal (Ramdani et al., 2009). Increased sample entropy shows an increase in efficiency or automaticity of postural control, whereas decreased sample entropy is usually correlated with greater attention or cognitive involvement in postural control (Donker et al., 2007; Stins et al., 2009).

2.5.3. Anticipatory postural adjustments (APA) preceding stair descent

The filtered GRFs and ground reaction moments recorded before the stair descent were employed to compute CoP values. The CoP trajectories and vertical GRFs were then used to compute the APA timings and amplitudes (Fig. 5) (Bonora et al., 2015; Park et al., 2021). APA onset was identified as the time when the CoP displacement in the ML direction exceeded twice the standard deviation of the vertical GRF during quiet standing (Mancini et al., 2009). Toe-off of trailing foot was identified as the moment when the reaction force reached zero. The timestamps for heel-off and toe-off of the leading foot were determined by assessing the CoP position relative to the onset of APA and the toe-off of the trailing foot (Bonora et al., 2015). The temporal parameter of imbalance duration was quantified as the time spanning from the APA onset to the heel-off of the leading foot. The unloading duration was defined as the time interval between the heel-off and toe-off of the leading foot. The imbalance and unloading amplitudes were quantified as CoP displacements during the imbalance and unloading phases in the ML and AP directions. In general, prolongation of both the imbalance and unloading phases of APAs and increases in the CoP displacement amplitudes during these phases can be interpreted as an overall deterioration of postural control (Callisaya et al., 2016).

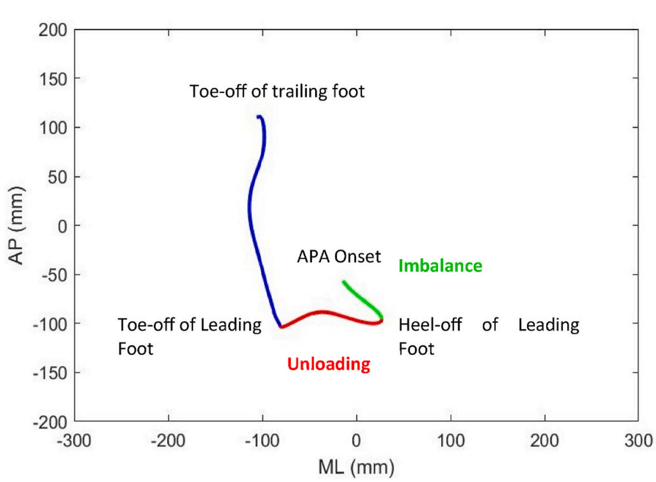

Fig. 5. An example of CoP displacement in the ML and AP directions during anticipatory postural adjustments (APA) preceding stair descent. APA onset, heel-off and toe-off of the leading foot (right foot) and the toe-off instant of trailing foot (left foot) are shown. [Imbalance phase: from APA onset to heel-off of leading foot; unloading phase: from heel-off to toe-off of leading foot].

2.5.4. Stair descent

The raw kinematic data collected during the stair descent tasks were filtered by a digital zero-phase 4th order Butterworth filter with a cutoff frequency of 6 Hz (Motive 2.0; Optitrack; Natural Point, OR). The filtered kinematic data were used to compute spatiotemporal gait measures (i.e., step width, swing time, and double support time) as well as dynamic stability (i.e., margin of stability [MoS] in both ML and AP directions) during stair descent. Heel-off and toe-off events during the stair descent task were detected using a coordinate-based algorithm (Zeni et al. 2008). Subsequently, swing time and double support time were estimated. Step width was defined as the distance between two consecutive heel strike positions in the medial–lateral direction. Larger step width, shorter swing time, and prolonged double support time can indicate postural adaptation and coping strategy to maintain deteriorated dynamic postural control during stair descent (McAndrew Young and Dingwell, 2012; Kwon et al., 2018).

Whole-body center of mass (CoM) was calculated using a nine-segment model (bilateral shank, thigh, upper arm, and forearm as well as trunk) (Tisserand et al., 2016). In addition, the BoS borders were defined based on markers on the calcaneus, the 1st metatarsal head, the 2nd distal phalanx, and the 5th metatarsal head of each foot. MoS is defined as the minimum distance between extrapolated CoM and BoS borders (Hof et al. 2005; Sivakumaran et al., 2018). MoS measures used in this study included the minimum of MoSs during swing phase (i.e., from toe-off of the trailing foot on the force platform to the heel-strike of the trailing foot on the 2nd platform) and MoS at heel-strike (e.g., heel-strike of the trailing foot on the 2nd platform), in both the ML and AP directions. Decreased MoS can indicate deteriorated dynamic stability during stair descent (Hof et al. 2005; Sivakumaran et al., 2018).

2.6. Statistical data analysis

The dependent variables (i.e., outcome measures) are summarized in Table 1. The independent variables were *CONDITION* (4 levels: No WBV, vertical-dominant WBV, multi-axial WBV, and multi-axial WBV with intervention) and *TIME* (4 levels: 0, 120, 150, 270 min). A repeated-

Table 1
Dependent variables collected from postural control assessments.

Tasks	Dependent variables
Sit-to-Stand transition	Reaction time, Sit-to-stand time, GRF peak-to-peak amplitude, Perceived confidence
Static stance	CoP RMS distance (ML and AP), CoP sample entropy (ML and AP), CoP area
Anticipatory postural adjustments preceding stair descent	Imbalance duration, Unloading duration, Imbalance amplitude (ML and AP), Unloading amplitude (ML and AP)
Stair descent	Step width, Swing time, Double support time, MoS (ML and AP) during swing and at heel strike

measures analysis of variance (ANOVA) was used to determine the main and interaction effects of *CONDITION* and *TIME* on each outcome measure. Sex-associated interaction effects were explored initially. As the interaction effects of *CONDITION*, *TIME*, and *SEX* were not significant for most of outcome measures, *SEX* was excluded in the final ANOVA model. Parametric model assumptions were assessed using Shapiro-Wilk tests, and data transformations were performed to meet these assumptions as relevant (Table 2). Partial eta-squared (η_p^2) was used to quantify effect sizes for the main and interaction effects. Given the study goals, the subsequent presentation of results and the discussion emphasizes the interaction effects of *CONDITION* and *TIME*. When such significant interaction effects were found, linear contrast analyses were set up for specifically testing the relative impacts of vertical-dominant WBV (vs. No WBV), multi-axial WBV (vs. vertical-dominant WBV), and multi-axial WBV with intervention (vs. multi-axial WBV) on changes in each of the outcome measures following exposure 1, break, exposure 2, and total (exposure 1 + break + exposure 2). Summary results were back-transformed and are presented in the original units as least-squares means (95% confidence intervals) unless stated otherwise. All statistical analyses were completed using JMP® Pro (v. 16.0, SAS Institute Inc., Cary, NC), with statistical significance noted when $p < 0.05$.

3. Results

Table 2 summarizes ANOVA results, regarding *CONDITION* and *TIME* effects; these results are presented below in more detail for each group of outcome measures. Summaries of *post hoc* linear contrast analyses for the relative impacts of vertical-dominant WBV (vs. No WBV), multi-axial WBV (vs. vertical-dominant WBV), and multi-axial WBV with intervention (vs. multi-axial WBV) on changes in each of the outcome measures following exposure 1, break, exposure 2, and total (exposure 1 + break + exposure 2) are included in the Appendix (Tables A1, A2, and A3).

3.1. Sit-to-stand transition

During sit-to-stand transition, significant interaction effects of *CONDITION* and *TIME* were observed in GRF peak-to-peak amplitude (Table 2). Specifically, a decrease in GRF peak-to-peak amplitude following total exposure was larger in vertical-dominant WBV than in both No WBV and multi-axial WBV conditions (Fig. 6, Table A1, and Table A2). Furthermore, multi-axial WBV with intervention led to a greater decrease in GRF peak-to-peak amplitude following both break and total exposure as compared to multi-axial WBV condition (Fig. 6 and Table A3).

3.2. Static stance

During upright stance on a foam surface, CoP RMS distance in the AP direction showed significant interaction effects of *CONDITION* and *TIME* (Table 2). Linear contrast analyses showed that a decrease in CoP RMS distance in the AP direction following a break was larger in No WBV than in vertical-dominant WBV condition (Fig. 7 and Table A1). Conversely, an increase in this measure was greater in multi-axial WBV than in multi-axial WBV with intervention conditions (Fig. 7 and Table A3).

3.3. APA preceding stair descent and stair descent

During anticipatory postural adjustments prior to stair descent, significant interaction effects of *CONDITION* and *TIME* were seen in imbalance amplitude in the ML direction only (Table 2). Specifically, vertical-dominant WBV led to a larger increase in imbalance amplitude in the ML direction following total exposure as compared to both No WBV and multi-axial WBV conditions (Fig. 8, Table A1, and Table A2).

Table 2
Summary of ANOVA results for the main and interaction effects of *CONDITION* and *TIME* on each set of outcome measures. Any transformations used on the outcome measures are specified. For each effect, entries are p values (η_p^2), and significant interaction effects are highlighted in bold font ($p < 0.05$).

Outcome measures	Data transformation performed	Main and interaction effects		
		CONDITION	TIME	*CONDITION × TIME*
Sit-to-stand transition				
Reaction time	–	0.448 (0.002)	**0.002 (0.016)**	0.973 (0.003)
Sit-to-stand time	–	**< 0.001 (0.029)**	**< 0.001 (0.019)**	0.081 (0.016)
GRF peak-to-peak amplitude	Log	0.182 (0.005)	**< 0.001 (0.039)**	**0.009 (0.023)**
Perceived confidence	–	**< 0.001 (0.072)**	**< 0.001 (0.244)**	0.168 (0.043)
Upright stance				
CoP RMS distance in ML	Log	0.143 (0.018)	**0.009 (0.039)**	0.930 (0.013)
CoP RMS distance in AP	Log	0.391 (0.011)	0.384 (0.011)	**0.022 (0.064)**
CoP sample entropy in ML	Square root	0.320 (0.011)	**0.001 (0.053)**	0.971 (0.009)
CoP sample entropy in AP	Square root	0.296 (0.012)	0.300 (0.013)	0.203 (0.041)
CoP area	Log	0.374 (0.011)	**0.008 (0.040)**	0.080 (0.051)
APA prior to stair descent				
Imbalance duration	–	0.622 (0.002)	0.203 (0.008)	0.584 (0.012)
Unloading duration	–	0.157 (0.009)	0.885 (0.001)	0.678 (0.011)
Imbalance amplitude in ML	Square root	0.066 (0.012)	0.554 (0.003)	**0.031 (0.029)**
Imbalance amplitude in AP	Square root	0.556 (0.003)	0.921 (0.001)	0.283 (0.018)
Unloading amplitude in ML	Square root	0.303 (0.006)	0.836 (0.001)	0.400 (0.015)
Unloading amplitude in AP	Square root	**0.029 (0.014)**	0.772 (0.002)	0.212 (0.019)
Stair Descent				
Step width	–	**0.036 (0.014)**	0.822 (0.001)	0.808 (0.009)
Swing time	–	0.119 (0.010)	**0.047 (0.013)**	0.303 (0.017)
Double support time	–	**0.001 (0.028)**	0.852 (0.001)	0.902 (0.007)
MoS in ML during swing	–	0.737 (0.002)	0.430 (0.004)	0.454 (0.014)
MoS in AP during swing	–	0.190 (0.008)	0.212 (0.007)	0.864 (0.007)
MoS in ML at heel strike	–	0.828 (0.001)	0.860 (0.001)	0.837 (0.008)
MoS in AP at heel strike	–	0.313 (0.006)	**0.047 (0.013)**	0.643 (0.011)

•CoP – center of pressure; RMS – root mean square; APA - anticipatory postural adjustments; MoS – margin of stability; ML – mediolateral; AP – anteroposterior.

An increase in this measure following exposure 2 was also greater in vertical-dominant WBV than in No WBV condition (Fig. 8 and Table A1).

4. Discussion

This study examined the effects of on-road vertical-dominant WBV

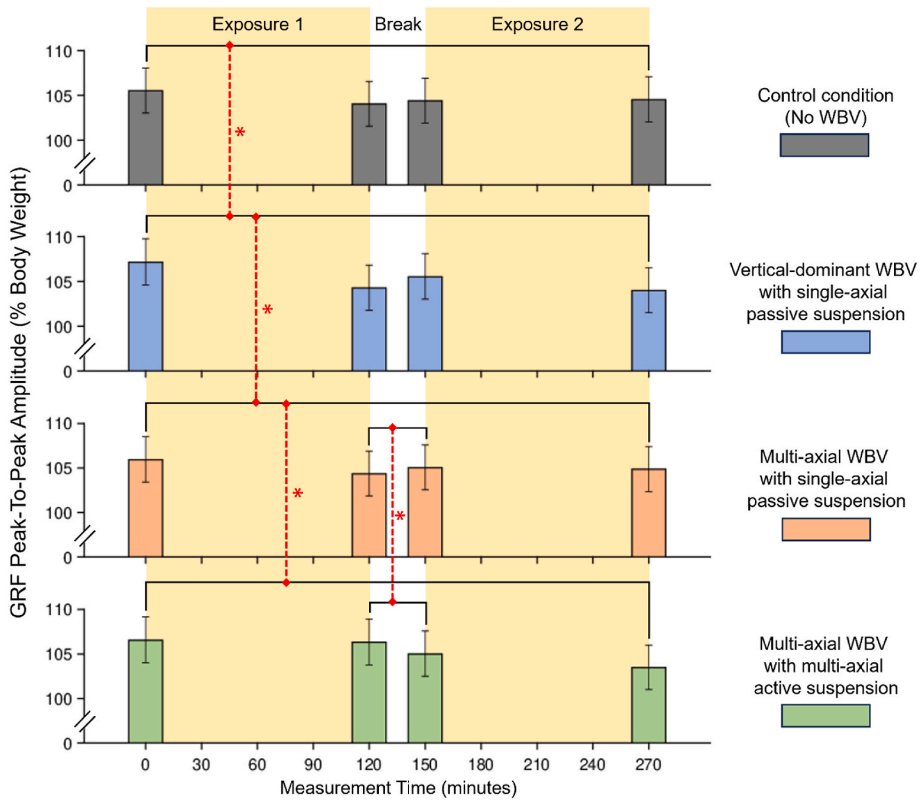

Fig. 6. Changes in normalized ground reaction force (GRF) peak-to-peak amplitude (% body weight) during sit-to-stand transition by four experimental conditions. Data are presented as least-squares means with error bars indicating 95% confidence intervals. Significant differences found from *post hoc* linear contrast analyses are denoted by * ($p < 0.05$).

and off-road vehicle multi-axial WBV on postural control using a comprehensive set of measures for assessment. The effectiveness of a multi-axial active suspension seat in mitigating WBV-associated impairment in postural control was also assessed. Overall, our results indicate that vertical-dominant WBV negatively affected postural control, especially during sit-to-stand transition and APA preceding stair descent. However, comparing the effects of vertical-dominant WBV, the lateral component of multi-axial of WBV did not impose additional adverse effects on postural control. Furthermore, the multi-axial active suspension seat did not exhibit superior performance in mitigating the effects of multi-axial WBV on postural control compared to the vertical-axial passive suspension seat.

4.1. *Effects of vertical-dominant WBV on postural control (hypothesis 1)*

Sitting while being exposed to vertical-dominant WBV resulted in a more pronounced decrease in GRF peak-to-peak amplitude during sit-to-stand transition compared to sitting without WBV (Fig. 6). Decreased GRF amplitude is indicative of inability to generate force quickly and maintain postural stability, thereby implying impaired postural control during sit-to-stand transition (Kera et al., 2020; Lord et al., 2002). Muscular load and fatigue caused by prolonged exposure to vertical-dominant WBV (Kia et al., 2020, 2022; Kim et al., 2018a,b; Troxel et al., 2016) may have contributed to diminished force exertion capabilities and a reduction in GRF peak-to-peak force amplitude. Such changes can be indicative of a higher risk of losing balance (Cameron et al., 2003; Kera et al., 2022b; Simpkins and Yang 2022). Vertical-dominant WBV also led to a greater increase in imbalance amplitude in the ML direction compared to the control condition (No WBV) during APA prior to stair descent (Fig. 8). Increased imbalance amplitude can suggest deteriorated APA (Callisaya et al., 2016). Hence, our first hypothesis was confirmed. Also, these results suggest that vertical-dominant WBV, common in on-road vehicles, can have adverse impacts on dynamic postural control during sit-to-stand transition and APA prior to stair descent, which may lead to increased risk of falls during vehicle egress.

Nonetheless, the effects of vertical-dominant WBV on the postural control measures were relatively small. Briefly, the effects of the changes in GRF peak-to-peak amplitude during sit-to-stand transition observed in this study were small: 3% decrease in the vertical-dominant WBV compared to 1% decrease in No WBV (Fig. 6). These changes were relatively smaller than other studies analyzing clinical changes. For example, this measure was 19% lower among patients with sarcopenia (vs. non-sarcopenia) (Kera et al., 2022a), 14% lower among older males (vs. young males) (Smith et al., 2020), and 9% lower among elderly with locomotive syndrome (vs. elderly without locomotive syndrome) (Yamako et al., 2023). Moreover, vertical-dominant WBV increased imbalance amplitude in the ML direction by 21–33% during stair descent, as compared to 8–20% decrease in No WBV (Fig. 8). To the best of our knowledge, only one study, which assessed APA preceding stair descent using CoP data, did not show significant differences between individuals with patellofemoral osteoarthritis and asymptomatic controls (Wyndow et al., 2019). Given that prior work using these measures have predominantly considered clinical conditions where such differences may be amplified, whether the small but statistically significant changes observed with vibration exposure in this study hold practical meaning is not currently clear.

In relation to other postural control measures used in this study, such as those assessed during static stance on a foam surface and stair descent, vertical-dominant WBV did not lead to significant differences in postural control when compared to No WBV condition. Several potential factors may account for these observations. First, exposure to vertical-dominant WBV may not compromise sensory information or muscle strength substantially enough to affect static stance. Second,

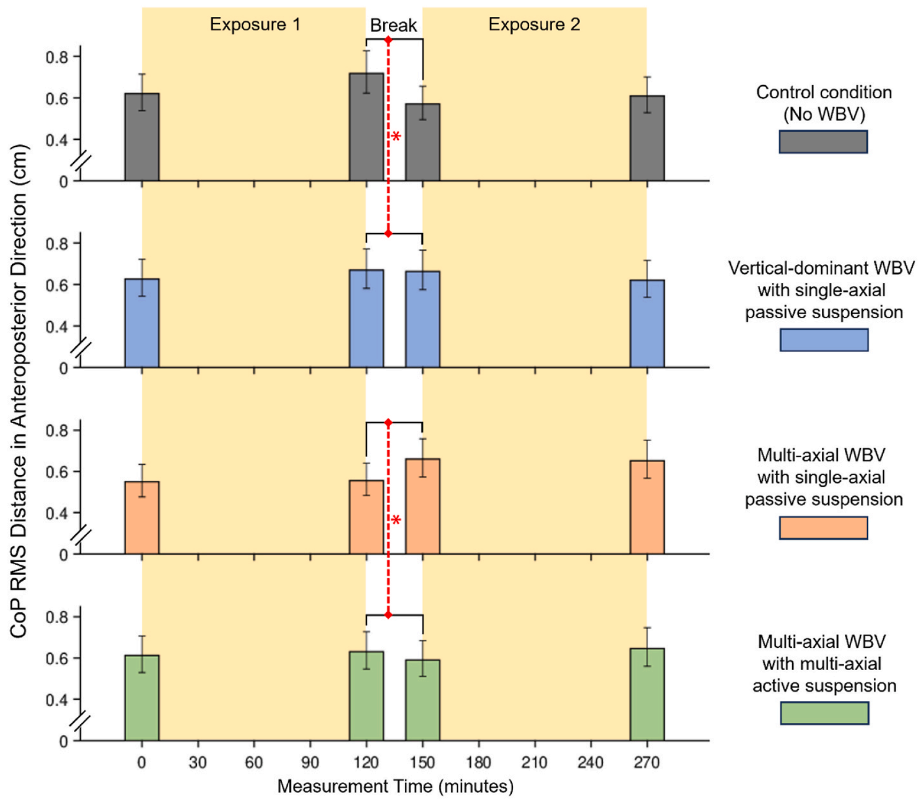

Fig. 7. Changes in the center of pressure (CoP) RMS distance in the anteroposterior (AP) direction during upright stance by four experimental conditions. Data are presented as least-squares means with error bars indicating 95% confidence intervals. Significant differences found from *post hoc* linear contrast analyses are denoted by * ($p < 0.05$).

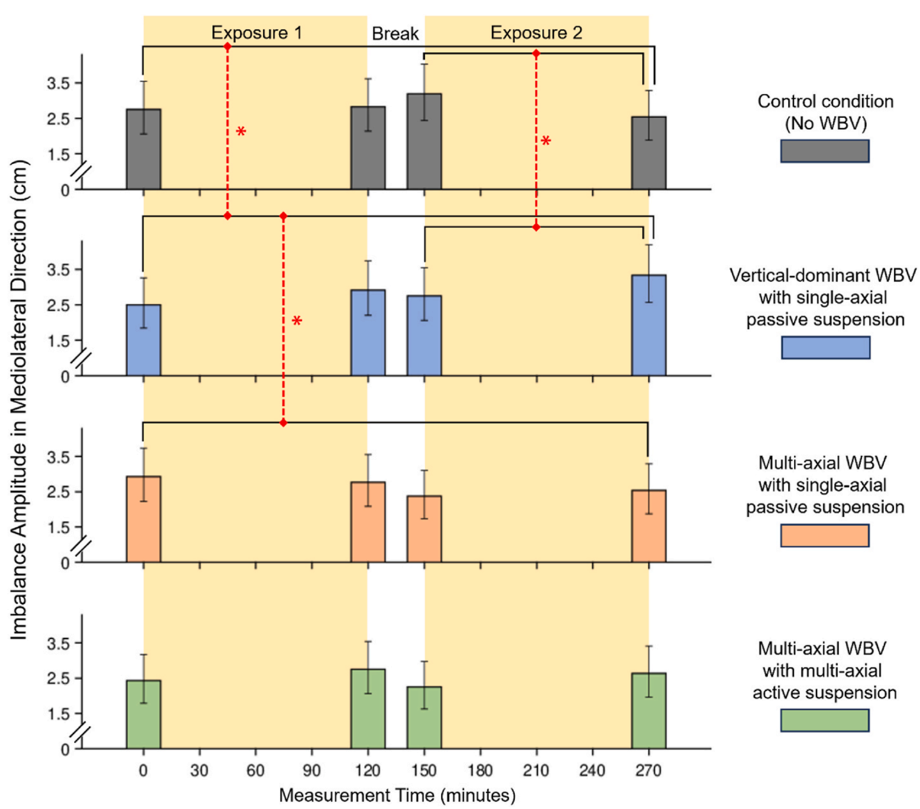

Fig. 8. Changes in imbalance amplitude in the ML direction during anticipatory postural adjustments prior to stair descent by four experimental conditions. Data are presented as least-squares means with error bars indicating 95% confidence intervals. Significant differences found from *post hoc* linear contrast analyses are denoted by * ($p < 0.05$).

participants may have recovered from the effects of WBV exposure by the time that static stance and stair descent tasks were conducted, as these were the last tasks we tested (Kowalski et al. 2021; Johanson et al., 2011). Third, given that the stairs used in this study were designed with a wider width and lower height compared to those typically found in heavy vehicles, the stair descent task in this study may have been less demanding than typical egress from heavy vehicles.

4.2. Comparing the effects of multi-axial and vertical-dominant WBV on postural control (hypothesis 2)

As compared with vertical-dominant WBV, multi-axial WBV did not present more detrimental effects on postural control. Instead, vertical-dominant WBV led to a greater decrease in GRF peak-to-peak amplitude compared to multi-axial WBV during sit-to-stand transition (Fig. 6). Furthermore, imbalance amplitude in the ML direction during APA prior to stair descent increased more with vertical-dominant WBV compared to multi-axial WBV (Fig. 8). For the remaining postural control measures utilized in this study, multi-axial and vertical-dominant WBV did not have distinctly different effects on postural control. These results fail to support our second hypothesis. These findings are also somewhat contradictory to our previous findings, where we observed that multi-axial WBV led to greater impairments on postural control (than vertical-dominant WBV) during static stance on a firm surface (Park et al., 2021), as opposed to the foam surface used in this study. Hence, our results suggest that the lateral component of multi-axial WBV from off-road vehicles may not have additional adverse effects on dynamic postural control during sit-to-stand transition and stair descent when compared to vertical-dominant WBV experienced in on-road vehicles.

4.3. Efficacy of the multi-axial active suspension seat (hypothesis 3)

For multi-axial WBV exposures, using a multi-axial active suspension seat (intervention) did not demonstrate superior performance in alleviating the impact of multi-axial WBV on postural control compared to the vertical-axial passive suspension seat (the current industry standard). Rather, multi-axial WBV with multi-axial active suspension led to a larger decrease in GRF peak-to-peak amplitude during sit-to-stand transition compared to multi-axial WBV with single-axial passive suspension (Fig. 6). These results can be attributed to the fact that the multi-axial active suspension seat did not substantially outperform the single-axial passive suspension seat in reducing the lateral component (Y-axis) of WBV (Fig. 3), or due to the fact that the lateral component of vibration associated with multi-axial WBV itself did not significantly compromise postural control compared to vertical-dominant WBV. Some previous studies have also reported the limited efficacy of the multi-axial active suspension seat in mitigating lateral WBV (Kia et al., 2022; Park et al., 2021). However, interestingly, the multi-axial active suspension seat led to significantly better recovery in postural sway measures associated with static stance during the break between the successive 2-h long exposures to WBV, compared to the standard single-axial passive suspension seat (Fig. 7). Hence, while the seat did not produce differences in pre-post postural control measures during each vibration period, its use seems to have promoted recovery of postural control during the breaks.

Although these results fail to support our third hypothesis and further emphasize the need for more effective interventions that can reduce the lateral component of WBV, the potential for a multi-axial active suspension seat to promote faster recovery from the detrimental effects of WBV needs to be better understood.

4.4. The effects of a break on postural control

Vibration exposures did not significantly affect CoP RMS distance in the AP direction during static stance when compared to No WBV (sitting without vibration). However, this measure recovered at a significantly better rate in No WBV condition than in the other WBV conditions during the 30-min break, following the first exposure (Fig. 7). This is in accordance with results from previous studies, indicating that incorporating breaks between prolonged sitting can effectively mitigate muscular fatigue (Thorp et al., 2014; Kar and Hedge 2020; Ding et al., 2020), subsequently reducing the risks associated with postural control loss (Kowalski et al. 2021; Johanson et al., 2011). These results collectively highlight the value of having periodic breaks in drivers' work schedules to prevent potential postural control impairment, and that exposure to WBV may cause slower recovery in postural control measures compared to prolonged sitting without WBV exposure.

4.5. Limitations

There were a few limitations to our study. First, this study was conducted in a controlled laboratory setting in which the environment (e.g., road conditions, noise, traffic, WBV) and tasks (i.e., driving) may be different from actual driving conditions. For example, participants in this study were not engaged in driving tasks but instructed to watch monotonic nature documentaries while exposed to WBV. Previous investigations have shown that cognitively demanding tasks can increase trunk sway (Arippa et al., 2022; Leban et al., 2017), which may in turn affect postural control. However, in an effort to make our WBV exposure more realistic, this study utilized actual field-measured vibration data collected during regular vehicle operations (from on-road semi-trucks and off-road mining vehicles), to better simulate a professional vehicle operator's daily WBV exposures. Therefore, the WBV exposures in this laboratory study were far more realistic, especially when compared to previous WBV studies (Arora and Grenier 2013; Martin et al., 1981; Stamenkovic et al. 2014). Second, this study did not examine the long-term effects of WBV exposure on postural control. A longitudinal study may be needed to investigate changes in postural control through cumulative exposures to WBV as professional vehicle operators are regularly exposed to hours of WBV over the course of their careers. Third, because this study included a comprehensive set of postural control measures, potential balance recovery over the course of the postural control assessments may have diminished the effects of WBV on the measures collected later in the experimental sessions. A previous study showed that postural balance itself can recover when dynamic movements are performed (e.g., sit-to-transition, static standing, and gait initiation) and so impairments in balance may diminish with delayed assessment (Pollard et al., 2017). Lastly, the sit-to-stand transition in our study, adapted from clinical postural control assessments, may differ from real-world scenarios of egressing a vehicle. In vehicle egress, drivers may use their arms, have different body orientations, and may not fully stand due to the low-rise ceiling, unlike the conditions in our study and clinical assessments. Also, the dynamic postural control assessments in this study have been primarily used in clinical settings to understand the association between postural control measures and increased fall risks. Therefore, these measures may not be directly compared to those in clinical settings or linked directly to fall risks. However, they can provide valuable insights into the effect of WBV on postural control during high-risk dynamic activities such as egressing from a vehicle.

5. Conclusions

We found that exposure to vertical-dominant WBV has negative effects on postural control during sit-to-stand transition and APA preceding stair descent, thereby potentially explaining the increased risk of falls during vehicle egress. Moreover, vertical-dominant WBV was associated with slower recovery in postural sway (i.e., CoP RMS distance in the AP direction) during a break between exposures, when compared to the control condition (No WBV). We found that multi-axial WBV, however, did not impose additional adverse effects on postural control as compared with vertical-dominant WBV in our static and dynamic tasks. Moreover, using the multi-axial active suspension system did not exhibit superior performance in mitigating the effects of multi-axial WBV during exposure, but was associated with faster recovery during the break between exposures, when compared with the current industry standard suspension seat.

CRediT authorship contribution statement

Kiana Kia: Writing – review & editing, Writing – original draft, Visualization, Software, Project administration, Methodology, Investigation, Formal analysis. **Jangho Park:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis. **Allen Chan:** Writing – review & editing, Writing – original draft, Investigation. **Divya Srinivasan:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Methodology, Funding acquisition, Conceptualization. **Jeong Ho Kim:** Writing – review & editing, Writing – original draft, Validation, Supervision, Software, Resources, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Acknowledgements

This research was supported by a research grant from the National Institute for Occupational Safety and Health (R21OH011538-01). The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes for Occupational Safety and Health. The authors would like to thank Mina Salehi Sedeh from Oregon State University's Occupational Ergonomics and Biomechanics Laboratory for assisting in data collection.

Appendix

Table A1
Summary of *post hoc* linear contrast analyses for the relative impacts of vertical-dominant WBV (vs. No WBV) on changes in each of the outcome measures following exposure 1, break, exposure 2, and total (exposure 1 + break + exposure 2). Table entries are *p* values, and significant differences are highlighted in bold ($p < 0.05$).

Outcome measures	Vertical-dominant WBV vs. No WBV			
	Exposure 1	Break	Exposure 2	Total
Sit-to-stand transition				
GRF peak-to-peak amplitude	0.160	0.354	0.085	**0.028**
Static stance				
CoP RMS distance in AP	0.467	**0.044**	0.226	0.936
APA prior to stair descent				
Imbalance amplitude in ML	0.426	0.234	**0.005**	**0.016**

Table A2
Summary of *post hoc* linear contrast analyses for the relative impacts of multi-axial WBV (vs. vertical-dominant WBV) on changes in each of the outcome measures following exposure 1, break, exposure 2, and total (exposure 1 + break + exposure 2). Table entries are *p* values, and significant differences are highlighted in bold ($p < 0.05$).

Outcome measures	Multi-axial WBV vs. Vertical-dominant WBV			
	Exposure 1	Break	Exposure 2	Total
Sit-to-stand transition				
GRF peak-to-peak amplitude	0.183	0.547	0.162	**0.033**
Static stance				
CoP RMS distance in AP	0.613	0.095	0.621	0.100
APA prior to stair descent				
Imbalance amplitude in ML	0.174	0.550	0.366	**0.004**

Table A3
Summary of *post hoc* linear contrast analyses for the relative impacts of multi-axial WBV with intervention (vs. multi-axial WBV) on changes in each of the outcome measures following exposure 1, break, exposure 2, and total (exposure 1 + break + exposure 2). Table entries are *p* values, and significant differences are highlighted in bold ($p < 0.05$).

Outcome measures	Multi-axial WBV vs. Multi-axial WBV with intervention			
	Exposure 1	Break	Exposure 2	Total
Sit-to-stand transition				
GRF peak-to-peak amplitude	0.175	**0.046**	0.160	**0.041**
Static stance				
CoP RMS distance in AP	0.873	**0.031**	0.351	0.291
APA prior to stair descent				
Imbalance amplitude in ML	0.241	0.780	0.572	0.145

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