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Postural stability effects of random vibration at the feet of construction workers in simulated elevation

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ABSTRACT

The risk of falls from height on a construction site increases under conditions which degrade workers' postural control. At elevation, workers depend heavily on sensory information from their feet to maintain balance. The study tested two hypotheses: "sensory enhancement" – sub-sensory (undetectable) random mechanical vibrations at the plantar surface of the feet can improve worker's balance at elevation; and "sensory suppression" – supra-sensory (detectable) random mechanical vibrations can have a degrading effect on balance in the same experimental settings.

Six young (age 20–35) and six aging (age 45–60) construction workers were tested while standing in standard and semi-tandem postures on instrumented gel insoles. The insoles applied sub- or supra-sensory levels of random mechanical vibrations to the feet. The tests were conducted in a surround-screen virtual reality system, which simulated a narrow plank at elevation on a construction site. Upper body kinematics was assessed with a motion-measurement system. Postural stability effects were evaluated by conventional and statistical mechanics sway measures, as well as trunk angular displacement parameters.

Analysis of variance did not confirm the "sensory enhancement" hypothesis, but provided evidence for the "sensory suppression" hypothesis. The supra-sensory vibration had a destabilizing effect, which was considerably stronger in the semi-tandem posture and affected most of the sway variables.

Sensory suppression associated with elevated vibration levels on a construction site may increase the danger of losing balance. Construction workers at elevation, e.g., on a beam or narrow plank might be at increased risk of fall if they can detect vibrations under their feet. To reduce the possibility of losing balance, mechanical vibration to supporting structures used as walking/working surfaces should be minimized when performing construction tasks at elevation.

1. Introduction

Falls from elevation are a persisting occupational hazard, accounting for more than one third of all fatal incidents in the construction industry each year (BLS, 2008). Loss of balance was identified as one of the triggering events in fall incidents during construction work at height (Hsiao and Simeonov, 2001). The majority of fatal falls from scaffolding, building girders, and non-moving vehicles, (accounting for approximately one third of all fatal workplace falls), were described as loss of balance incidents (Webster, 2000). The risk of falling increases with the number of physiological, environmental, and task related conditions that degrade workers' balance (Hsiao and Simeonov, 2001). Understanding the factors that affect workers' postural stability at elevation and developing effective interventions to improve workers' balance may reduce the risk of fall incidents and injuries.

A promising approach for improving workers balance at height would be to enhance the sensory inputs from their feet (Simeonov et al., 2008). At elevated environments characterized with reduced visual cues, the workers' postural control system relies heavily on somatosensory information. Proprioceptive inputs from receptors in muscles and joints in the legs, and tactile inputs from receptors in the plantar surface of the feet are co-processed to maintain balance (Kavounoudias et al., 2001). The shoe acts as an interface between the foot and the surface of support, and shoe characteristics may modify the sensory information available to the foot, and affect postural stability, and therefore the risk of falling (Menz and Lord, 1999).

Numerous studies demonstrated the important contribution of cutaneous sensation, from the plantar surface of the feet, in the

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control of balance (Kavounoudias et al., 2001; Magnusson et al., 1990; Roll et al., 2002). Attenuation of the pressure receptors at the plantar surface of the foot has been associated with increased sway velocity (Meyer et al., 2004a) and more cautious walking patterns (Eils et al., 2004). Further, attenuation of pressure receptors altered postural response to lateral mechanical perturbations (Meyer et al., 2004b), and compensatory stepping reactions evoked by unpredictable multi-directional perturbation (Perry et al., 2000). These studies suggested that conditions which suppress sensation at the feet may reduce postural stability and increase the risk of falls under certain conditions.

Mechanical vibration applied to the foot sole was shown to effectively modulate the inputs from the tactile receptors and significantly affect balance (Kavounoudias et al., 2001; Roll et al., 2002). Workers are frequently exposed to vibration in construction environments both while operating heavy machinery and while working at heights (Suter, 2002). Vibrations form motorized equipment and hand tools on the construction site could be transmitted to the workers feet through structures used as walking/working surfaces. From a practical perspective, it is important to identify potentially dangerous vibration levels that could negatively affect workers' balance control on the worksite and develop strategies to avoid/eliminate such conditions.

In a related stream of literature it has been suggested that afferent nerve activation and mechanical facilitation at the foot sole may be beneficial for postural stability. Earlier studies demonstrated that mechanical facilitation from standing on a grid-like array of ball bearings increased afferent nerve activation and reduced postural sway (Okubo et al., 1980; Watanabe and Okubo, 1981). Mechanical facilitation of sensation from the plantar foot-surface boundaries by an array of small indentors has been shown to improve the efficacy of the stabilizing reactions evoked by unpredictable external perturbation in young and older healthy adults (Maki et al., 1999).

Recent research (Priplata et al., 2003) proposed and tested an innovative method to improve balance control of the elderly by reducing the threshold of the somatosensory inputs. Imperceptible random vibrations applied to the feet improved the feedback from the pressure receptors which lead to a more stable posture especially in conditions with reduced visual input (Priplata et al., 2003). A "sensory-enhancing" technology might be effective in improving workers' balance and thus reducing the risk of falls in elevated work environments. Research is needed to determine the effectiveness of this new technology in various environmental and postural conditions associated with construction work at height.

This study investigated the effects of different levels of random vibration applied to the plantar surface of the feet on the postural control of young and aging groups of construction workers while standing on narrow surfaces in the visually destabilizing conditions of a simulated height work environment. The study tested two hypotheses: "sensory enhancement" hypothesis: sub-sensory (undetectable) random mechanical vibrations at the plantar surface of the feet can improve worker's balance at elevation; and "sensory suppression" hypothesis: supra-sensory (detectable) random mechanical vibrations can have a degrading effect on balance in the same experimental settings.

2. Method

2.1. Participants

Six young (20–35 years-old) and six aging (45–60 years-old) male construction workers participated in the study. The average ages of the young and aging groups are 27.2 (S.D. = 3.3) and 51.2 (S.D. = 4.6) years, respectively. The average height, weight and shoe size (American) of the young group were 172.4 cm (S.D. = 11.7), 82.9 kg (S.D. = 17.8), and 10.6 (S.D. = 1.0), and correspondingly 180.4 cm (S.D. = 8.5), 80.2 kg (S.D. = 11.1), and 10.5 (S.D. = 1.8) for the aging group. The requirements for study participation were: at least 6-months experience of working at height, normal or corrected vision in both eyes, free of known balance problems, not fearful of heights, and no medication use or alcohol consumption in the last 24 h. All participants gave informed consent prior to the study and were compensated for their time. The study protocol was approved by the Institutional Review Board of the National Institute for Occupational Safety and Health (NIOSH).

2.2. Independent variables

2.2.1. Plantar-vibration variable ("Vibration") – three levels

The variable *plantar vibration* (i.e., vibration applied directly to the undersurface of the foot) had three levels – no vibration, sub-threshold vibration, and supra-threshold vibration. During all tests the participants were standing on a pair of instrumented gel insoles (Fig. 1) – the insoles were not designed to be inserted in shoes and were not attached to the feet of the participants. The insoles were instrumented to induce random mechanical vibrations with frequency in the range 0–100 Hz. By controlling the signal power the individual vibration sensory threshold levels were first determined and used to calculate and set the test conditions. In the condition without vibration the subjects were standing on the insoles with the system turned off. In the sub-threshold vibration condition the system was turned on and the insoles vibrated (at 90% of threshold values) inducing imperceptible stimulation to the plantar surface of the feet. In the supra-threshold vibration condition the participants could detect small vibrations (at 120% of threshold values) applied to their feet. The supra-threshold stimulation condition simulated a scenario of a noisy work environment where vibrations caused by construction activities are transferred to the feet through the supporting structure. Scenarios may include: use of heavy motorized equipment (bulldozers, compactors) or a jack-hammer in the vicinity of a structure, or hand power tools (saws, drills), applied directly to a light or temporary structure used as a walking/working surface.

2.2.2. Standing posture variable ("Posture") – two levels

The variable *standing posture* had two levels – "standard" posture and "semi-tandem" posture. The standard posture is a standardized two-legged standing with heels separated by 8 cm and feet angled at 40° (Priplata et al., 2003). The semi-tandem posture, i.e., with left heel to the side and 5 cm back from the tip of the right big toe (Fig. 1), represents a posture required for standing on a narrow surface, i.e., a 25 cm scaffolding board or the top of

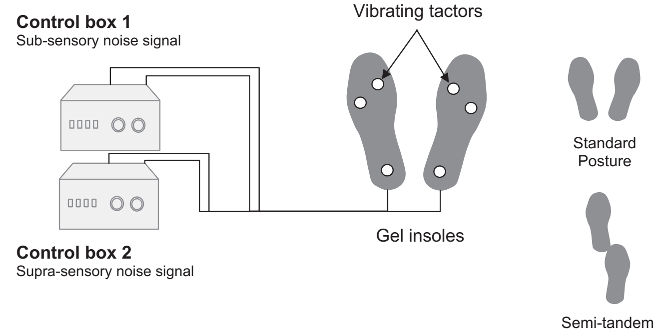

Fig. 1. The instrumented gel insoles experimental setup.

a wall, which is frequently encountered in construction work at elevation. The semi-tandem posture has been used in previous studies since it challenges the medial–lateral stability while minimizing the discomfort to the participants associated with standing in a standard tandem posture (Lord et al., 1999; Ravaioli et al., 2005).

2.2.3. Visual condition variable ("Visual") – two levels

The variable *visual* condition had two levels – eyes open or eyes closed in a simulated elevation in a surround-screen virtual reality (SSVR) system (Fig. 2). The eyes closed condition was used as a baseline. The elevated environment was a distant visual scene representing a view from the top of a partially completed three-story residential structure (Fig. 3). The virtual environment of elevation has been tested to have a similar destabilizing effect on balance as real height has (Simeonov et al., 2005).

2.2.4. Age variable ("Age") – two age groups

The variable *age* had two levels – two age groups – 20–35 and 45–60 year old participants were included in the study to determine the potential effects of age. Earlier research has demonstrated loss of plantar tactile sensitivity with age (Perry, 2006; Wells et al., 2003) and related decline in sensitivity to foot position (Robbins et al., 1995). In addition, it has been suggested that some sway characteristics increase with age in a linear fashion (Du Pasquier et al., 2003). Furthermore, in the work environment an increased risk of fatal falls occurs after the age 45, an age not commonly considered to be old (Agnew and Suruda, 1993). It is therefore reasonable to expect that any plantar-vibration effects may be more important for the balance control of the aging construction workers (Collins et al., 1995; Priplata et al., 2003).

2.3. Experimental procedure

On the day of the experiment the participants were briefed on the study objectives, methods, procedures, and potential risks. The participants changed into tightly fitting clothes, provided by the laboratory, to allow the accurate measurement of body movement by attached markers. The participants were then allowed time to experience the virtual environment, and were given the opportunity to get acquainted with the tasks and the test procedures.

At the beginning of the testing session the level of planter pressure sensory perception of the participants was determined with the Touch-Test™ Sensory Evaluators according the included test instructions. The individual vibration sensory threshold was determined for each foot using the instrumented gel insoles following a procedure used in earlier studies (Priplata et al., 2003). For the procedure the participants were standing in a standard posture while the vibration intensity in one of the gel insoles was gradually increased. The level at which the participants first felt the vibration was selected as a threshold. A retest was then done to ensure that a vibration signal at 90% of the threshold level was undetectable by the participants. For the postural stability tests, the level of the stimulus signal for each foot was adjusted to the sub-threshold (90%) value or to a supra-threshold (120%) value, or was turned off for the "no vibration" condition.

The participants were tested for 30 s while standing barefooted on the instrumented gel insoles. The participants were instructed to stand quietly and keep their arms to the side of their body. The experimental session included 12 test conditions replicated 3 times for a total of 36 trials. Three vibration levels ("no vibration", "sub-sensory vibration", and "supra-sensory vibration") were tested in 2 postural ("standard" and "semi-tandem") and 2 visual ("eyes closed" and "eyes open", i.e., virtual elevation) conditions. The test sequence was completely randomized and counterbalanced to reduce and average out any learning and fatigue effects.

The tests were balanced across conditions (i.e., every treatment was preceded equally often by each other treatment) to reduce and average out any learning and fatigue effects. There was a 3-min rest interval between experimental conditions. The participants completed the test session in approximately 2 h and were compensated for their time. Before the start and at the end of the experimental session the participants completed two balance performance tests (NHTSA, 2000) to ensure that the virtual

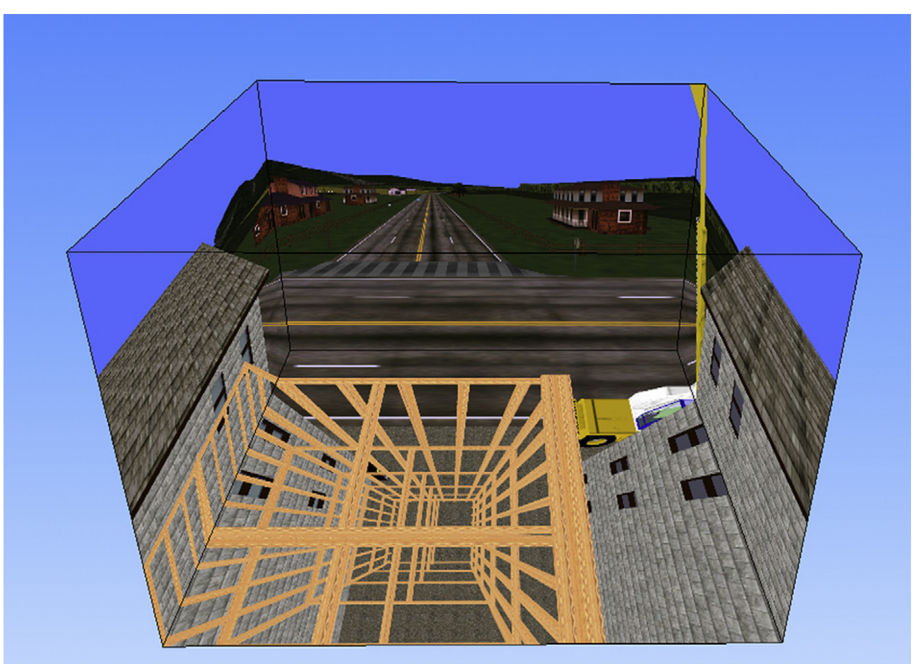

Fig. 2. The surround-screen virtual reality (SSVR) system with projected images of the simulated elevated construction environment.

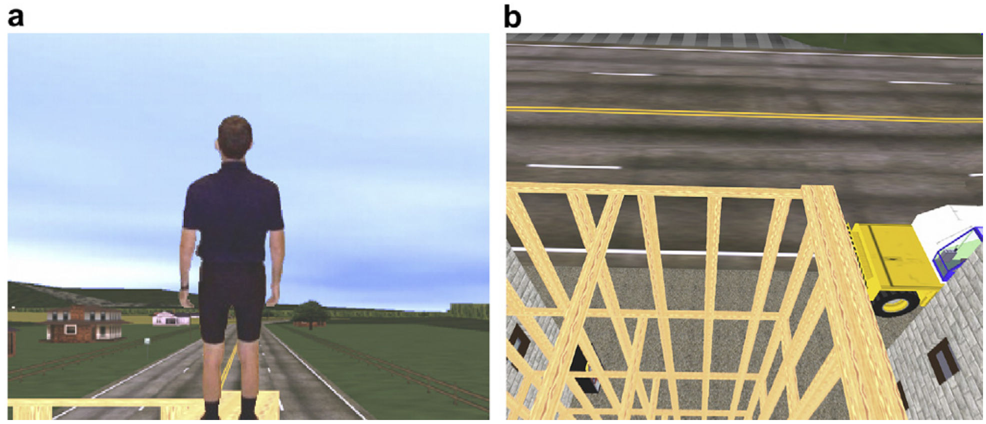

Fig. 3. a). Participant on a narrow plank at simulated elevation; b). View at the structure below.

environment exposure had no adverse effects. All participants passed the balance performance tests.

2.4. Equipment

2.4.1. Virtual reality system

A surround-screen virtual reality (SSVR) system was used to simulate the elevated construction environment. The projection-based SSVR system had three 3.6 m by 3.0 m walls and a 3.6 m by 3.6 m floor (Fig. 2). Four PCs, controlled the projected images at a resolution of 1024 by 768, and a 96 Hz stereo signal, for a 48 Hz effective scene refresh rate. The liquid crystal shutter glasses (Crystal Eyes-2, StereoGraphics Inc., San Rafael, CA) allowed a participant's field of view of approximately 100° in the horizontal and 50° in the vertical direction. The average time delay of the system was approximately 55 ms (Simeonov et al., 2005)

2.4.2. Kinematic measurement system

Body sway data were collected using an Optotrak (model 3020) motion-measurement system (Northern Digital Inc., Waterloo, Ontario) from one marker attached to the participant's right shoulder (placed on the acromio-clavicular joint). In addition, trunk angular displacement data were collected from two markers attached at the upper and lower back (a 3rd thoracic vertebra marker and a sacral marker). The data collection frequency was 100 Hz. Data-processing and calculation of the traditional sway variables were done with custom written programs using Visual Basic in Microsoft Excel. The "random walk" variables were calculated using an available Matlab algorithm (Collins and De Luca, 1993). The data was filtered with a fourth-order Butterworth filter with low cutoff frequency of 10 Hz

2.4.3. Vibrating insoles

The randomly-vibrating insoles are a replica (constructed at NIOSH) of the laboratory prototype developed and tested by the researchers in Boston University (Priplata et al., 2003). The insoles were molded with viscoelastic silicone gel (Silastic T-2 Moldmaking Rubber, Dow Corning, MI, USA). Three vibrating elements, called tactors (C-2, Engineering Acoustics, Winter Park, Florida, USA) were embedded in each insole (two under the forefoot and one under the heel) to propagate vibrations to the plantar foot surface (Fig. 1). Each insole receives a white noise signal, whose power is set independently (between 0 and 1000 arbitrary units) with potentiometers for each foot, from a control box. The white noise generator has a single-chip record and playback device (ISD2560P, Windbound Electronics Corporation, Taipei, Taiwan), in which a digitized uniform white noise signal, low-pass filtered to 100 Hz, is stored. Two control boxes were used in this study to selectively deliver a sub-sensory or a supra-sensory signal levels to the insoles without a need for readjustment of the controls. The construction and setup of the randomly-vibrating insoles was done in consultation and with direct help from the researchers in the Center of Biodynamics, Boston University, MA, who invented this new technology.

2.4.4. Sensory evaluators

The level of planter pressure sensory perception was determined for each foot using Semmes–Weinstein monofilaments – a set of 6 ("foot kit") Touch-Test™ Sensory Evaluators (North Coast Medical, Inc., Morgan Hill, CA). Each foot was tested three times at the first and fifth metatarsal heads and the heel, starting with the smallest monofilament. Subjects were eligible for the study if they could feel at any location a touch with an evaluator size up to "4.31" (force of 2 g or smaller), i.e., they were within the normal range of protective sensation.

2.5. Dependent variables

2.5.1. Sway velocity variables

The postural sway variables, calculated from the shoulder marker displacement in the horizontal plane, included: mean sway velocity, and mean sway velocity in the medial–lateral (ML) direction. Research has suggested ML sway parameters are considered to be valid measures of lateral stability and good fall predictors for the elderly. Examples include, lateral sway with eyes closed after mechanical perturbation (Maki et al., 1994), and ML sway in a near-tandem stability test with eyes open (Lord et al., 1999). Sway velocity is a sensitive sway parameter, giving a direct indication of the intensity of the posture control activity (Baratto et al., 2002). Further, sway velocity has been considered a valid measure of postural stability, and a potential fall predictor (Koleva et al., 2001; Robbins et al., 1998).

2.5.2. Random walk sway variables

Random walk variables of postural sway included the short-term diffusion coefficients and critical values calculated from the medial–lateral (ML) and radial (planar) displacement of a shoulder marker, using the stabilogram diffusion analysis (SDA) technique (Collins and De Luca, 1993). The SDA uses the average of the squared displacements between successive points separated by increasing time intervals (usually within the range 0 and 10 s) to create a plot which is characterized with two linear regions. The slopes of the two linear regions represent a short-term and a long-term diffusion coefficients, and define a critical time point which divide the two regions. The random walk variables have been shown to be sensitive to manipulation in a number of factors related to balance control, including vision, age, and sub-sensory mechanical vibration (Collins and De Luca, 1995; Collins et al., 1995; Priplata et al., 2003). Furthermore, the random walk variables have been demonstrated as more sensitive than the traditional sway parameters in detecting the effects of age on balance control (Norris et al., 2005).

2.5.3. Trunk angular displacement variables

The range of the ML and radial trunk angular displacements were calculated using two markers attached at the upper back (T3) and lower back (lumbar) of the participants. The trunk angular displacements were calculated as the arcsine of the ratio between the relative horizontal displacement and the vertical distance between the upper and lower trunk markers. The trunk angular displacement has been shown to correlate well with the movement of the whole body center of mass (Gage et al., 2004). During momentary instability in a tandem posture, a lateral trunk-tilting strategy may be used to regain balance.

2.6. Statistical analysis

The experimental conditions of the study included three within-participant factors – Vibration (sub-sensory, supra-sensory, no vibration), Posture (standard and semi-tandem), and Visual (eyes open and eyes closed in a simulated elevation), and one between-participant factor – participant's age group (young and aging).

The statistical analyses of the motion data included multivariate repeated measures analysis of variance (ANOVAs) on the full models, as well as on models of reduced complexity for the three subsets of dependent variables, including: general statistics and random walk sway measures, and angular trunk displacement measures.

To evaluate the effect of the experimental conditions, a multivariate repeated measures analysis was performed for each dependent variable using the mixed procedure in the Statistical Analysis System (SAS) software (SAS Institute Inc., Cary, NC, USA). For each dependent variable, the full model included all main effects, 2-factor and 3-factor interactions (4-factor interactions were not considered in this study). Three different covariance structures of observations within a participant were evaluated first for the full model: (1) direct product compound-symmetry, (2) direct product unstructured, and (3) direct product autoregressive. We selected an appropriate model based on Akaike's information Criterion (AIC), AICC (a modified criterion from AIC for use in small samples), and Schwarz's Bayesian Criterion for final analysis using the restricted maximum likelihood method.

To test the specific hypotheses and simplify the interpretation of the results, further analyses were performed on selected data subsets using two sensory levels. Bonferroni method was used to adjust p-values for multiple comparisons.

3. Results

A four way (Age $\times$ Posture $\times$ Visual $\times$ Vibration) ANOVA was performed for all the dependent variables. The results description gave priority to the dependent variables which revealed significant effects and interactions for the vibration condition since this was the main focus of the study.

3.1. Sensory threshold levels

3.1.1. Pressure sensory threshold levels

The average pressure sensory threshold level at the plantar surface of the feet, determined with the Touch-Test™ Sensory Evaluators before the start of the tests, was 3.67 (S.D. = 0.14) for the young group and 3.96 (S.D. = 0.38) for the aging group. All of the individual test results were below or equal to "4.31", i.e., within the normal range of protective sensation for a healthy population.

3.1.2. Vibration sensory threshold levels

The individual vibration sensory threshold levels, determined with the instrumented gel insoles, and used to set the test condition vibration values are summarized in Fig. 4a. The average vibration sensory threshold level of the aging group was significantly higher than that of the young group of workers ($p = 0.005$) (Fig. 4b).

3.2. Sub-sensory (undetectable) vibration effects

3.2.1. ML critical value (ML-Cv)

The 2 $\times$ 2 $\times$ 2 $\times$ 2 (Age $\times$ Posture $\times$ Visual $\times$ Vibration) ANOVA on ML-Cv showed only a significant main effect of posture

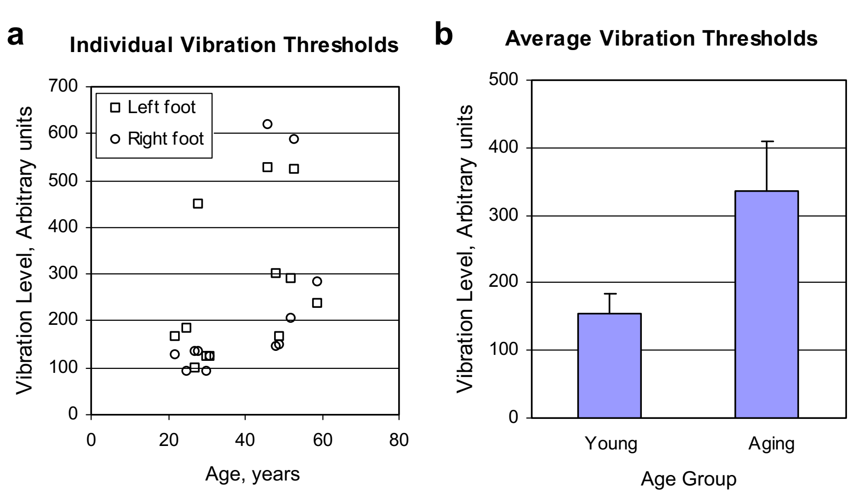

Fig. 4. Age effects on sensory thresholds. a). Individual vibration threshold values, including left and right foot values; b). Average vibration threshold values for the two age groups; standard error represented by vertical bars.

Table 1
ANOVA results for sub-sensory vibration effects – p-values.

	Shoulder-velocity		Shoulder-random walk				Trunk angular	
Effects	ML-V	V	ML-Cv	ML-Ds	R-Cv	R-Ds	ML-Tar	R-Tar
Age group (young, aging)	0.360	0.581	0.908	0.807	0.304	0.315	0.557	0.987
Posture (standard, semi-tandem)	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*
Visual (eyes closed, eyes open)	0.014*	0.027*	0.541	0.790	0.844	0.005*	0.839	0.375
Vibration (no, sub-sensory)	0.189	0.678	0.092	0.768	0.384	0.508	0.822	0.854
Age group × Posture	0.153	0.528	0.119	0.820	0.369	0.657	0.045*	0.477
Age group × Visual	0.029*	0.071	0.157	0.437	0.020	0.005*	0.128	0.924
Age group × Vibration	0.296	0.872	0.709	0.866	0.564	0.700	0.419	0.702
Posture × Visual	0.006*	0.004*	0.145	0.752	0.551	0.024*	0.816	0.373
Posture × Vibration	0.357	0.289	**0.043***	0.837	0.116	0.371	0.781	0.590
Visual × Vibration	0.417	0.412	0.607	0.895	0.759	0.404	0.357	0.093

* indicates statistically significant effects; the significant vibration-related effects are in bold.

($p < 0.001$), and a significant interaction of posture and vibration ($p = 0.043$) (Table 1). ML-Cv was increased in the semi-tandem posture as compared to the standard standing posture. The sub-sensory vibration under the feet reduced slightly but not significantly ML-Cv in the standard posture, and increased it in the semi-tandem posture (Fig. 5).

3.2.2. *Sway variables with interactions not involving vibration*

The 2 × 2 × 2 × 2 (Age × Posture × Visual × Vibration) ANOVA revealed significant posture and visual interactions on ML-V ($p = 0.006$), V ($p = 0.004$), and R-Ds ($p = 0.043$), and age and visual interactions on ML-V ($p = 0.029$), R-Cv ($p = 0.020$), and R-Ds ($p = 0.005$) (Table 1). Eyes closed as compared to “eyes open”, i.e., virtual elevation condition increased significantly ML-V, V, and R-Ds only for standing in the semi-tandem but not in the standard posture. Standing with eyes closed as compared to “eyes open”, i.e., virtual elevation condition, caused increase of ML-V, R-Cv, and R-Ds, only in the aging workers.

3.3. *Supra-sensory (detectable) vibration effects*

3.3.1. *Sway velocity (V)*

The 2 × 2 × 2 × 2 (Age × Posture × Visual × Vibration) ANOVA for the sway variable V revealed significant main effects of posture

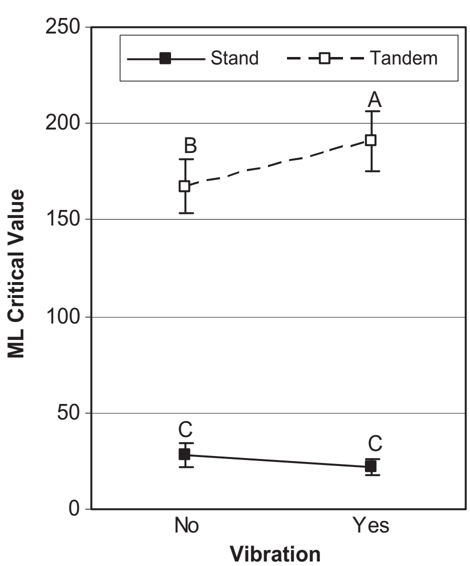

Fig. 5. Interaction of vibration (sub-sensory noise) and posture on diffusion sway characteristic ML Critical Value. Within each posture, means with the same letter indicate no statistical significance between the vibration levels (Bonferroni). Standard error represented by vertical bars.

($p < 0.001$) and visual ($p = 0.009$), as well as a significant interaction of posture and vibration conditions ($p = 0.029$) (Table 2). Standing in a semi-tandem posture increased V as compared to the standard standing posture. Eyes closed increased V as compared to the “eyes open”, i.e., virtual height condition. The supra-sensory vibration under the feet increased sway velocity in the challenging semi-tandem posture but not in the standard posture (Fig. 6).

3.3.2. *ML critical value (ML-Cv)*

The 2 × 2 × 2 × 2 (Age × Posture × Visual × Vibration) ANOVA on ML-Cv demonstrated significant main effects of age ($p = 0.020$), posture ($p < 0.001$), and vibration ($p = 0.018$), as well as a significant interaction of posture and vibration ($p = 0.016$) (Table 2). The group of aging workers had on average 50% higher ML-Cv as compared to the group of young workers. ML-Cv value was nearly 6 times higher for the tandem standing posture as compared to the standard standing posture. Supra-sensory vibration increased significantly ML-Cv, however the increase was statistically significant only in the semi-tandem posture (Fig. 7a).

3.3.3. *Radial critical value (R-Cv)*

The 2 × 2 × 2 × 2 (Age × Posture × Visual × Vibration) ANOVA showed only a significant main effect of posture ($p < 0.001$) and a significant interaction of posture and vibration ($p = 0.001$) (Table 2). Overall, R-Cv was higher in the semi-tandem posture as compared to the standard standing posture. The supra-sensory vibration under the feet increased significantly R-Cv only in the semi-tandem posture (Fig. 7b).

3.3.4. *R diffusion coefficient (short) (R-Ds)*

The 2 × 2 × 2 × 2 (Age × Posture × Visual × Vibration) ANOVA showed significant main effects of posture ($p < 0.001$), visual ($p = 0.010$), and vibration ($p = 0.010$), as well as a significant interactions of age and visual ($p = 0.027$) and posture and vibration ($p = 0.008$) (Table 2). Standing in a semi-tandem posture increased R-Ds as compared to the standard standing posture. Standing with eyes closed increased R-Ds as compared to the “eyes open”, i.e., virtual elevation condition, only in the aging workers. Supra-sensory vibration under the feet increased R-Ds but only in the semi-tandem posture (Fig. 7c).

3.3.5. *ML trunk angular range (ML-Tar) and R trunk angular range (R-Tar)*

The 2 × 2 × 2 × 2 (Age × Posture × Visual × Vibration) ANOVA for ML-Tar and R-Tar showed only a significant main effect of posture ($p < 0.001$, $p < 0.001$) and a significant interaction of posture and vibration ($p = 0.019$, $p = 0.041$) (Table 2). Overall, ML-Tar and R-Tar were both higher in the semi-tandem posture as compared to the standard standing posture. The supra-sensory

Table 2
ANOVA results for supra-sensory vibration effects – *p*-values.

Effects	Shoulder-Velocity		Shoulder-Random Walk				Trunk angular	
	ML-V	V	ML-Cv	ML-Ds	R-Cv	R-Ds	ML-Tar	R-Tar
Age group (young, aging)	0.136	0.611	0.020*	0.027*	0.967	0.790	0.114	0.302
Posture (standard, semi-tandem)	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*
Visual (eyes closed, eyes open)	0.014*	0.009*	0.724	0.057	0.681	0.010*	0.542	0.918
Vibration (no, supra-sensory)	0.307	0.073	**0.018***	0.378	0.085	**0.010***	0.646	0.230
Age Group Posture	0.273	0.859	0.218	0.314	0.512	0.890	0.245	0.357
Age group × Visual	0.510	0.099	0.656	0.319	0.106	0.027*	0.846	0.570
Age group × Vibration	0.646	0.147	0.543	0.809	0.770	0.111	0.336	0.628
Posture × Visual	0.007	0.060	0.405	0.250	0.402	0.132	0.482	0.201
Posture × Vibration	0.119	**0.029***	**0.016***	0.327	**0.001***	**0.008***	**0.019***	**0.041***
Visual × Vibration	0.382	0.159	0.107	0.981	0.297	0.703	0.250	0.477

* indicates statistically significant effects; the significant vibration-related effects are in bold.

vibration under the feet increased ML-Tar and R-Tar only in the semi-tandem posture, while in the standard standing posture the supra-sensory vibration reduced them slightly but not significantly (Fig. 8a and b).

4. Discussion

The study results did not support the "sensory enhancement" hypothesis but provided evidence for the "sensory suppression" hypothesis. The results further indicated that plantar vibration increased the postural sway variables predominantly in the unstable semi-tandem posture but not in the standard standing posture.

4.1. Sub-sensory (undetectable) vibration effects

The lack of a significant main effect of vibration indicates that sub-sensory random vibration did not provide a consistent balance improvement across all test conditions. The interaction of vibration and posture on the random walk sway variable ML-Cv indicated a noticeable (but not statistically significant) ML balance improvement with sub-sensory random vibration in the normal standing posture (Fig. 6). This is in line with earlier research which found improved balance performance from sub-sensory stimulation in healthy young individuals during normal standing with eyes closed (Priplata et al., 2003). However, further comparison of the individual results in the current study showed that the effect was evident only in some but not in all of the participants. The lack of consistent sub-sensory vibration effects across all participants may be due to unreliable sensory threshold estimation procedure or to considerable differences in the individual balance control strategies.

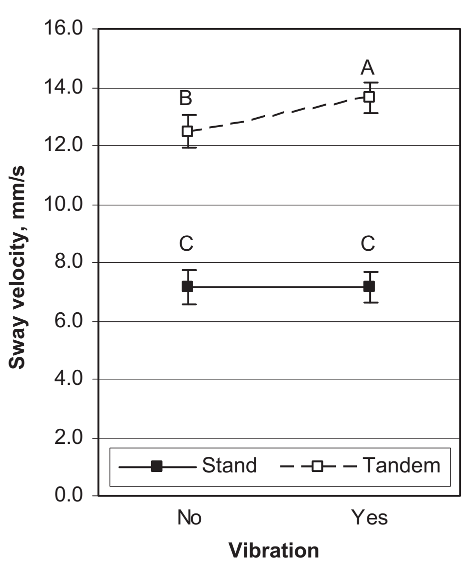

Fig. 6. Interaction of vibration (supra-sensory noise) and posture on general statistic sway variable Sway velocity. Within each posture, means with the same letter indicate no statistical significance between the vibration levels (Bonferroni). Standard error represented by vertical bars.

The significant vibration by posture interaction on ML-Cv further indicated reduced postural stability with sub-sensory random vibration in the semi-tandem posture (Fig. 6). It is likely that the postural control activity in the semi-tandem posture may have modified the intensity of random vibration at the plantar surface of the feet. During the semi-tandem standing, postural stability is challenged, and the ML balance is maintained by an ankle eversion/inversion control movements, i.e., similar to the "foot-tilt" control strategy in one-leg standing (Hoogvliet et al., 1997). The "foot-tilt" movements are associated with quick change in pressure in the ML direction at the plantar surface of the forefoot. These changes in pressure may have increased the perceived intensity of the vibrations transmitted by the forefoot tactors, and thus exceeded the sensory thresholds established during quiet standing in the standard posture. Consequently, the perceived random vibration applied to the semi-tandem posture most likely lead to impaired proprioception and reduced postural stability.

The study findings indicate a need for further improvement of the sensory-enhancing technology. The following directions for improvement may be beneficial. First, the output levels of the tested insole prototype may be sensitive to the continuous change in pressure under the foot. New technical solutions are needed to deliver stimulation levels, independent of pressure changes, e.g., tactors capable of delivering tangential instead of normal vibrations to the plantar surface of the foot may be more appropriate for the development of sensory-enhancing insoles. Second, the procedure of sensory threshold estimation may need further improvement – because of differences in tactile perception thresholds at different plantar locations (Nurse and Nigg, 1999; Wells et al., 2003), it has been recently suggested to set the amplitude of all tactors individually (Hijmans et al., 2007).

4.2. Supra-sensory (detectable) vibration effects

The detectable vibration applied to the feet of construction workers in the simulated construction environment caused significant increase across all groups of variables. Most likely the perceivable levels of random vibration masked the sensory information from the pressure receptors at the plantar surface of the feet, thus eliminating a critical sensory input for maintaining

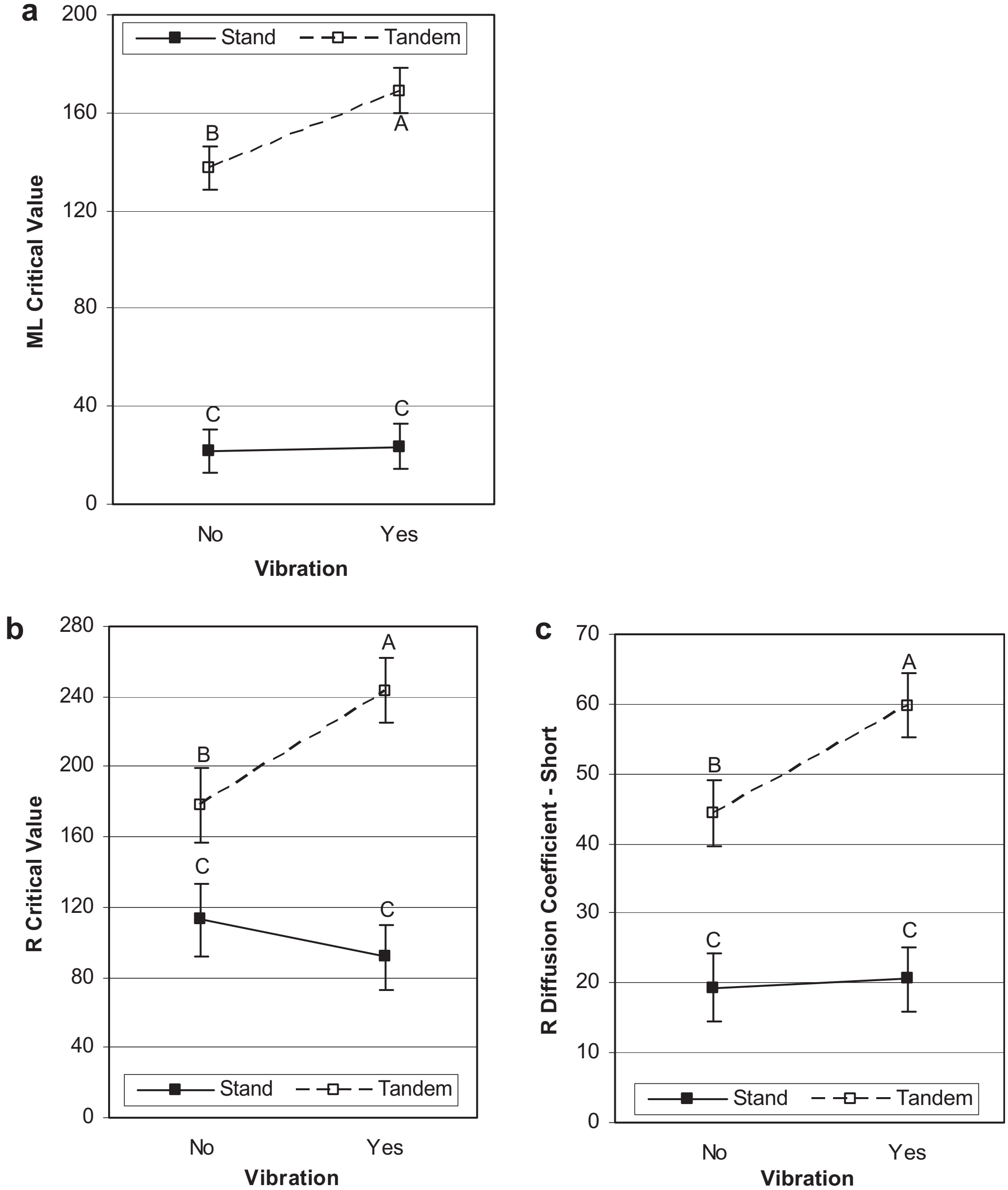

Fig. 7. Interaction of vibration (supra-sensory noise) and posture on diffusion sway characteristics. a). ML Critical Value; b). R Critical Value; c). R Diffusion Coefficient – Short. Within each posture, means with the same letter indicate no statistical significance between the vibration levels (Bonferroni). Standard error represented by vertical bars.

balance in a semi-tandem posture at elevation. These results are consistent with previous research indicating the importance of the sensory information from the plantar surface of the feet for control of standing balance in conditions deficient of visual information (Meyer et al., 2004a; Roll et al., 2002).

Furthermore, the destabilizing effect of the detectable vibrations was significant only in the semi-tandem posture (Figs. 7 and 8). These results are in agreement with earlier research (Meyer et al., 2004a) showing increase of sway velocity from loss of plantar sensation for unipedal standing but not for normal standing in healthy participants. Also, consistent with earlier research (Meyer et al., 2004a) is the increase in the short-term diffusion coefficient (R-Ds) from loss of plantar sensation, which reflects changes in the open-loop control of balance, and thus indicates that plantar feedback may be used by the posture control system to determine the appropriate level of background muscle activity and maintain balance in the challenging semi-tandem posture at height.

4.3. Age and visual conditions effects

The results indicated a significant effect of age on the plantar sensory thresholds. Consistent with earlier research (Perry, 2006), the plantar-vibration sensory thresholds of the aging workers were significantly higher as compared to those of the young workers. The results also revealed significant main effects of age in two of the random walk variables (only in the supra-sensory vibration analysis) – the aging workers group had a higher ML-Cv and ML-Ds as compared to the young workers group, which is in agreement with the findings of a previous study (Norris et al., 2005). The lack of other age main effects and age and vibration interactions may be due to the fact that the group of aging workers was active and physically fit.

The visual condition affected only some of the postural control variables – ML-V, V, and R-Ds. These variables were higher for eyes closed as compared to eyes open in the simulated height condition. However, these differences were relatively small, thus indicating

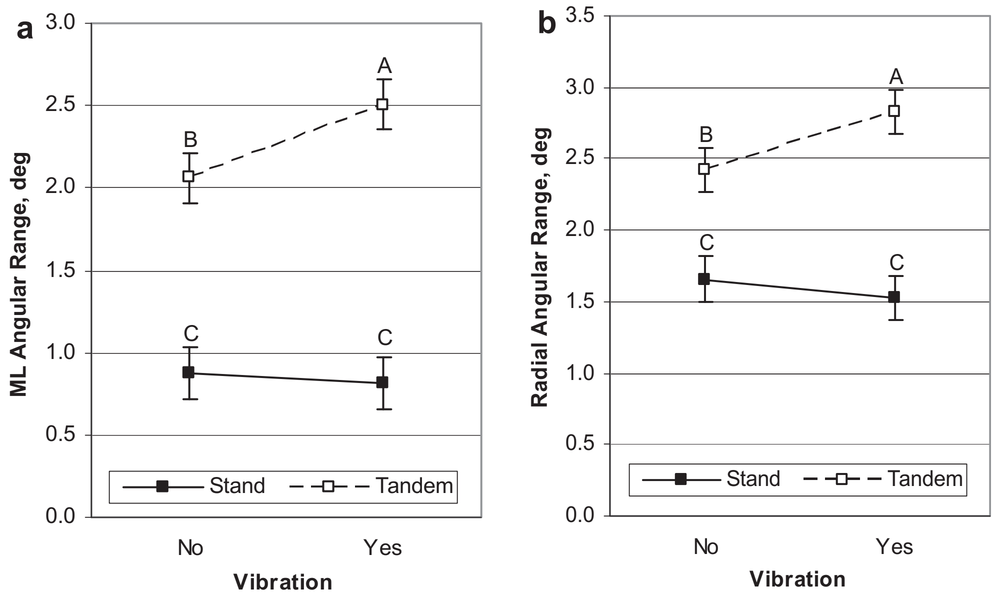

Fig. 8. Interaction of vibration (supra-sensory noise) and posture on trunk angular displacement variables. a). ML Angular Range; b). Radial Angular Range. Within each posture, means with the same letter indicate no statistical significance between the vibration levels (Bonferroni). Standard error represented by vertical bars.

that postural stability at simulated elevation was very similar to that in no vision condition. These findings are consistent with earlier research comparing postural stability at real and virtual heights (Simeonov et al., 2005) and more recent studies of VR effects on balance (Horlings et al., 2009). The similarity in the stability levels between the two visual conditions may further explain the lack of significant interactions between visual and vibration conditions on any of the postural stability variables.

The reduced number of age- and visual-related interactions in the supra-sensory analysis (Table 2) as compared to the sub-sensory analysis (Table 1), however, may be an indirect indication of some vibration-related effects. For example, the missing age and visual interactions on ML-V and R-Cv, and posture and visual interactions on V, and R-Ds, (present in Table 1, but not in Table 2), suggest that these effects were likely overwhelmed by the dominant destabilizing effects of the elevated (detectable) vibration.

4.4. Some methodological notes and practical implications

The sway variables in this study were derived from single shoulder marker displacement data, while commonly postural sway variables are calculated from COP movement using a forceplate. The vibration, applied under the feet of the participants in this study, prevented the use of a forceplate, since it could interfere with the data accuracy. However, it has been previously reported that displacement data obtained from markers attached to various single points on the body (including the shoulder) are highly correlated with COP displacement data and accurately quantify quiet stance (Priplata et al., 2003). Therefore, it is reasonable to consider this study as adequately related to the corresponding COP-based postural control literature. It should be noted however, that the sway information from the upper body movement is most likely not as sensitive (as the information from a force platform) to reveal the postural control activity of the muscles at the ankle joints.

The three groups of variables in this study revealed different aspects of the plantar-vibration effects on balance control. The vibration-induced increase of average sway velocity indicated an overall increase in control activity compensating the increased postural instability (Baratto et al., 2002). The higher random walk critical value coefficients suggested greater delay in utilization of the close-loop feedback mechanisms of balance control, which represents a more unstable condition (Collins et al., 1995). Further, the increased trunk angular displacement ranges corresponded to greater trunk tilt compensatory movements counterbalancing larger momentary instabilities. Taken together, these effects consistently indicate the increased postural instability associated with the detectable vibration applied to the participants' feet.

This laboratory study did not address many of the environment and task related factors often present on a construction worksite (e.g., wind, temperature, humidity, sloped surfaces, and personal protective equipment) which could potentially affect balance (Hsiao and Simeonov, 2001) and interact with the effects of vibration. Work shoes are an example of personal protective equipment that may have damping effects and reduce the vibration power transmitted to the foot from a walking/working surface. Wearing high-cut (boot-style) shoes have shown stabilizing advantage (Simeonov et al., 2008), and may help compensate some of the vibration-related instability. Further research is needed to characterize the role of shoes and other work environment and task related factors on vibration-induced postural instability, and develop corresponding industry-based practical applications and recommendations.

4.5. Limitations of study

The interpretation of the results of this study may be limited by the short exposure to the experimental conditions as compared to the real construction work durations. The short exposure durations will not allow evaluation of long-term postural adaptation effects that may improve stability or fatigue effects, which may result in additional postural deterioration in the challenging environments. Further, since the tests were performed at simulated elevation, the possible psychological effects on balance may be slightly degraded, as compared to real height exposures (Simeonov et al., 2005). Finally, the current prototype of the randomly-vibrating insoles does not allow performance and evaluation of dynamic tasks, e.g., walking, which will limit the interpretation of the results to predominantly pseudostatic postural conditions.

5. Conclusions

While sensory-enhancing may be a promising approach for improving worker balance performance and reducing their risk of falls from elevation in the challenging construction environments, the results of this study could not confirm the effectiveness of the tested technology at this point. Further research is suggested to improve the existing sensory-enhancing technology and develop procedures for reliable and effective sensory stimulation.

Sensory suppression associated with elevated vibration levels at a construction site may increase the risk of losing balance. Construction workers at height might be at elevated risk of fall if they can detect vibrations under their feet. This risk may be significantly increased when they are in a more unstable posture, i.e., on a beam or narrow plank. To reduce the possibility of losing balance, mechanical vibration to the supporting structures used as walking/working surfaces should be minimized when performing tasks at elevation.

Disclaimer

The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

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