Effectiveness of vertical visual reference for reducing postural instability on inclined and compliant surfaces at elevation

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ABSTRACT

Falls from elevation continue to be the most serious hazard for the workers in construction. Simple and cost effective technical approaches to improve workers' balance on sloped roofs and deformable/unstable platforms have potential to reduce the risk of falls. This study evaluated the effectiveness of simple vertical structures as visual references (cue) for balance improvement. Twenty-four construction workers were tested while standing on sloped and deformable surfaces at elevation and performing undemanding visual tasks with vertical structures positioned at different proximal locations. Workers' balance performance was assessed by sway parameters calculated from the center-of-pressure movement collected with a force platform. The study results indicate increased instability on the sloped and deformable surfaces at elevation, and show that a simple vertical structure, e.g., a narrow bar, can serve as a visual cue and assist workers' balance. Workers' balance improved linearly with cue proximity in the tested distance range both on the sloped and the deformable surfaces. At a moment of instability, workers can redirect their attention to a proximal structure, available in the line of sight, to assist balance control. These findings may be useful in modifying elevated work environments and construction procedures to improve workers' postural balance during various construction phases.

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1. Introduction

Falls are the leading cause of fatal injury in the construction industry – approximately 433 construction workers died from falls in 2006 (BLS, 2008). There are more than 7 million construction workers in US that are potentially exposed to fall hazards during a range of construction activities (BLS, 2007). Construction work on roofs has been associated with the highest number of fatal fall incidents (BLS, 2008). Residential construction, specifically roof installation, is an area where simple, practical and cost effective technical approaches to fall prevention are needed.

Losing balance is one of the major triggering events for fall incidents in roof construction (Cloe, 1979; Parsons and Pizatella, 1985). The control of balance is maintained through the integration of sensory information from the visual, vestibular, and somatosensory systems. The risk of falling increases with the number of conditions that degrade visual, vestibular, and somatosensory function (Tinetti and Speechley, 1989). Workers in roof construction perform a variety of tasks for extended periods of time on elevated and inclined work surfaces, and frequently on deformable or unstable surfaces. These environmental conditions, in combination with task-related and personal factors, i.e., attention diverting tasks, load handling and fatigue, tools and equipment, training and experience, may adversely affect workers' balance control systems and increase the risk of falling (Hsiao and Simeonov, 2001).

Recent studies demonstrated that in destabilizing conditions, such as on sloped and deformable surfaces at elevation, the availability of close visual structures in the periphery of the visual field improved workers' stability and restored sway parameters to their baseline values (Hsiao and Simeonov, 2001; Simeonov et al., 2003). Further, the presence of a vertical foreground object has been shown to improve the balance success rate in healthy young subjects, balancing near the limits of their individual abilities in a task of transfer to unipedal stance (Deyer and Ashton-Miller, 1999). These findings imply that proximal visual references can serve as visual anchors for postural stabilization during challenging tasks at height. Supporting such conjecture is the recently proposed "adaptive resource-sharing" view for the role of visual information in postural control (Mitra, 2004).

The "adaptive resource-sharing" model predicts that as a balancing task becomes more difficult, sway-induced information like optical expansion and motion parallax may start being recruited to aid balancing functions (Mitra, 2004). The optical flow parameters, optical expansion and motion parallax, are functions of the visual reference location relative to the observer and the visual background, as well as the head movement pattern and gaze

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direction (Warren et al., 1996). The body sway-related head movement depends on the task-defined postural and support conditions (Day et al., 1993). Increased head movement, associated with postural instability on the sloped and deformable surfaces at elevation, may enhance the potential effectiveness of an available visual reference.

The "adaptive resource-sharing" model further predicts a shift of attentional resources to balancing tasks of increasing difficulty (Mitra, 2004). Balancing on sloped surfaces with deficient visual inputs has been associated with increased attentional demand (Wade et al., 2006). An attentional shift to the task of maintaining balance will likely involve a more efficient use of the available visual information. It would be of practical importance to further investigate the effectiveness of a simple visual reference in the specific postural and support conditions at elevated construction site, such as on a sloped roof. The information would be helpful to the roofing industry in arranging work environments and construction procedures to reduce the risk of falls.

This study investigated the effects of visual reference location and visual attention (targeting) on workers' postural stability in simulated roof construction environments, including deformable and inclined surfaces at elevation. The study's main hypothesis is that in conditions of increased instability workers may benefit from an available close visual structure (cue) which can assist their balance control.

2. Method

2.1. Participants

Twenty-four male construction workers recruited from the Morgantown, WV area participated in the study. The participants had an average age of 37.9 years (S.D. = 8.6), average height of 178.7 cm (S.D. = 7.5), average weight of 87.4 kg (S.D. = 13.1). The requirements for study participation were: at least 6-months experience of working at height, 18 years of age or older, 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. Experimental design and study variables

The study used a repeated measures balanced design with experimental conditions summarized in Table 1.

2.2.1. Independent variables

2.2.1.1. Visual variables.

- *Visual cue distance* to the participant (three levels) – 1 m, 1.75 m, 2.5 m.
- *Visual targeting* task (two levels) – a) task: "look at the close cue", b) task: "ignore the close cue and look at the background".

2.2.1.2. Surface variables.

- *Surface slope* (four levels) – 0°, 18°, 26°, 34°;
- *Surface firmness* (two levels) – firm, deformable; applied only to a surface slope of 0°.

Table 1
Experimental conditions.

Surface conditions		Visual conditions							
		NV	NC	Cue distance/targeting					
				1 m		1.75 m		2.5 m	
Firmness	Slope			CNT	CT	CNT	CT	CNT	CT
Soft	0								
Firm	0								
Firm	18			×	×	×	×		×
Firm	26								
Firm	34			×	×	×	×		×

× indicates experimental conditions not included in the study design. NV, no vision (eyes closed); NC, no visual cue (distant visual background). CT (1, 1.75, 2.5), cue centrally located and targeted (at distance, m); CNT (1, 1.75, 2.5), cue centrally located and not targeted (at distance, m).

Detailed descriptions of the independent variables and the corresponding experimental conditions follow.

The tests were conducted on an elevated surface in the Division of Safety Research (DSR) High Bay Lab, simulating a roof environment on a one-story (3 m high) residential building (Fig. 1). The balcony is a part of the existing original structure in the lab, and is equipped with metal protective railing.

Visual environment. The visual environmental conditions were designed to simulate an elevated construction environment, e.g., a residential roof. At elevation, construction workers frequently experience conditions in which the visual field does not include close visual structures – both in the central field and in the periphery. To simulate such "open space" conditions the participants were arranged to stand on a 3 m-high balcony and wear goggles that occluded the periphery of the visual field. The goggles restricted the visual field to approximately 50° in the vertical direction and 95° in the horizontal direction, which prevented the participants from seeing the protective railing and the edges of the balcony.

The visual background was the opposite wall of the laboratory at a distance of 9 m. The wall was painted in white and textured by the contours of the underlying beam-and-column structure; it included a large light-colored aluminum garage door with defined horizontal structural elements, which was surrounded by electrical conduits. The lighting in the lab was provided by the existing lighting fixtures, and represented an average daylight without
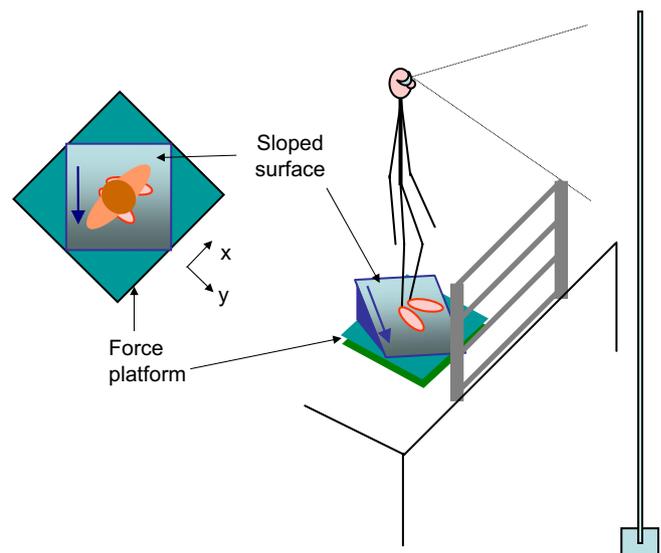

Fig. 1. Experimental setup on the 3 m-high balcony.

sunshine. This setup was used to test the effectiveness of a simple proximal structure as a control for visual stabilization. The proximal structure, used as a visual reference, was a movable vertical 4 cm × 4 cm × 600 cm wood bar, which contrasted with the visual background. The experimental design used tests without close visual reference as a baseline, and tests with eyes closed as a "control condition" for the effect of visual background.

Distance to visual cue. A single vertical bar 4 × 4 cm (Fig. 1) was tested as a visual cue. To determine the effect of visual cue distance the vertical bar was positioned at 1 m, 1.75 m and 2.5 m from participants' eyes. The cue distances were selected to represent a practical (without task interference in the grasping space) and effective distance range based on information from earlier studies (Paulus et al., 1989).

Visual targeting task. The visual targeting task had two levels: the participants either looked at the close visual cue, or in the alternative condition the participants ignored the close cue and looked at the visual background.

Surface Slope. The effects of surface slope were evaluated at three levels: 18°, 26°, and 34°. The three slopes represent a range of common residential roof slopes – from low-slope to steep-slope. Level surface (slope 0°) was used as a baseline condition. Standing on a sloped roof requires postural realignment at the ankle joints (Simeonov et al., 2003), and may quickly lead to localized muscle fatigue, which may challenge additionally the postural control system (Corbeil et al., 2003). To reduce the slope-related muscle strain, workers usually align their supporting leg at an angle to the slope direction. A standardized slope-related posture was used in this study to reflect the real-world practices and allow comparison among conditions. The slope-related posture is depicted in Fig. 1, and described in greater detail in Section 2.4. To further limit the uncontrolled and potentially confounding effects of fatigue, the number of the experimental conditions with slope exposure, especially on the steep slope, was minimized. All levels of the visual variables were tested only on the baseline slope (0°) and the intermediate slope (26°) levels, while the visual condition "not targeted on cue at 1 m" was tested on all surface slope levels (Table 1). The intermediate slope (26°) level was selected for full testing since it is the most common slope of roofs.

Surface Firmness. The subjects were tested while standing on two types of level surfaces: rigid and deformable. In the rigid surface condition the participants were standing directly on the force platform. The deformable surface condition simulated unstable support, i.e., from a structural element that can rotate, or materials that can bend, flex or compress. A 10 cm thick foam pad with density of approximately 80 kg/m^3 was placed on the force platform to simulate such condition.

2.2.2. Dependent variables

Three dependent variables derived from center of pressure (CP) measurements were used to quantitatively describe sway and determine postural stability. The variables were root mean square of CP displacement in medial–lateral (ML) and anterior–posterior (AP) directions, and mean velocity of CP displacement (V). ML and AP are suitable measures for average body sway (Bles et al., 1980), and V is an appropriate measure of postural stability (Le Clair and Riach, 1996).

2.3. Instrumentation

A portable strain-gauge-type force platform Accusway™ (Advanced Mechanical Technologies, Inc.,Watertown, MA) was used for CP measurements. The force platform is capable of measuring forces and moments along three orthogonal axes. Data were collected at a 50 Hz frequency with a laptop computer. The values of the dependent variables were derived from the CP

movement, which was calculated from the raw data. The force platform remained horizontal for all the tests and the inclined surfaces were achieved by positioning sloped blocks on top of the force platform. All the measures describing the CP movement were calculated in the horizontal plane. For the sloped surfaces, the calculation procedure used the CP coordinates to determine the effective elevation of the feet above the surface of the force platform. The estimated elevation was then used in the calculation of the next CP position, to reflect correctly the contribution of the horizontal forces.

2.4. Experimental procedure

Before the tests, the participants were briefed on the details of the study, completed a health questionnaire, and signed a consent form. The participants changed into NIOSH-provided socks and safety shoes (Model 604, Iron Age Corp., Pittsburgh, PA), and were then taken to the balcony in the DSR High Bay lab to start the experiment. The participants practiced the trials to familiarize themselves with the experimental procedure. The experimental procedure included a total of 30 experimental conditions (Table 1), which were randomly assigned for each subject. The participants stood quietly directly on the force platform surface or on a sloped or deformable surface that was positioned on the force platform, and performed a visual task for 60 s. There was a 2 min rest interval after each experimental condition and a 10 min sitting break after each 10 experimental conditions to reduce the possibility of fatigue. The participants completed the experimental procedures in approximately 2 h during a morning or an afternoon session.

On the level surfaces the participants stood straight with feet at 30° and heels together. On the sloped surfaces the subjects stood with a straight "supporting" right leg and foot at 45° to the left of slope direction. The "balancing" left leg was slightly bended at the knee with foot at 30° and heel touching the right foot. The sloped platform was oriented (at 45° to the force platform) such as the right "supporting" foot was aligned to, and the body of the participant was facing along the y-axis of the force platform (Fig. 1). These postural conditions allowed comparative assessment of sway variables in ML and AP directions relative to the participant's body (trunk) on different sloped surfaces. The slope-related posture was defined based on observations of roof construction video recordings and preliminary laboratory tests.

3. Results

3.1. Visual cue effects on elevated sloped surfaces

3.1.1. Visual cue and surface slope interactions

A 4 × 2 (Visual cue × Surface slope) ANOVA was performed for the sway variables ML, AP and V. The two surface slope levels included the baseline level surface (slope 0°) and the intermediate slope (26°). The four visual condition levels included a control condition with eyes closed, i.e., no vision (NV), a baseline condition without visual cue (NC), a centrally located and targeted visual cue at 1 m (CT1), and a centrally located not targeted visual cue at 1 m (CNT1). The analysis of these experimental conditions would reveal the effects of vision, close visual cue and the targeting task and their interaction with surface slope.

The ML sway analysis indicated significant main effects and interaction of visual cue and surface slope conditions (Table 2). The CNT1 and CT1 visual conditions progressively reduced the ML sway from its control (NV) and baseline (NC) values, and these effects were stronger on the sloped surface (Fig. 2(a)). The AP sway analysis showed a significant main effect of slope. The AP sway increased on the sloped as compared to level surface; and the slope-related increase in AP sway was significant for all visual

Table 2
Surface slope and visual condition effects – p values.

Source	ML Sway	AP Sway	Sway velocity
Main effects			
Slope (0, 26)	<.001*	0.001*	<.001*
Visual (NV, NC, CNT1, CT1)	<.001*	0.298	<.001*
Interactions			
Slope × Visual	<.001*	0.293	<.001*

* Statistically significant.

conditions. The analysis of V revealed significant main effects and interaction of visual cue and surface slope conditions. On the sloped surface the CNT1 and CT1 visual conditions progressively reduced V from its control (NV) and baseline (NC) values, while on the level surface these effects were not statistically significant (Fig. 2(b)).

A subsequent 3 × 3 (Visual cue × Surface slope) ANOVA was conducted for ML, AP and V, to determine the dose-response effects of visual cue by slope grade conditions. The analysis included the visual conditions NV, NC, CNT1, and the slope levels 18°, 26°, and 34° (Table 3). This analysis allowed evaluation of the slope grade effects, since the postural configuration was similar on all three slopes and the slope grade affected mainly the postural alignment at the ankle joints and the knee joint of the balancing leg.

The ML and V analysis indicated significant effects of visual cue and slope (Table 3). The AP analysis demonstrated a significant effect of visual cue and interaction of visual cue and slope, indicating some reduction in the AP values with increase of slope only for the NC visual condition but not for the other visual conditions. Overall, this analysis demonstrated similar visual effects on ML and V for all slope conditions, i.e., the effectiveness of a visual cue was independent of the slope steepness.

3.1.2. Cue distance, cue-targeting, and surface slope interaction

A 3 × 2 × 2 (Cue distance × Cue-targeting × Surface slope) ANOVA was performed for the sway variables ML, AP and V (Table 4). The cue distances included 1 m, 1.75 m, and 2.5 m, and the surface slope levels included 0° and 26°. The ML and V analyses revealed significant main effects of cue distance, cue-targeting and surface slope, and significant three way interactions. The AP analysis showed only a significant main effect of slope.

Since the visual cue effects were revealed only on the sloped surface, a subsequent 3 × 2 (Cue distance × Cue-targeting) ANOVA for ML and V were conducted using only the sloped surface (26°)

data. The analysis revealed a significant interaction of cue distance and cue-targeting for V ($F_{2,46} = 4.54$, $p = 0.016$) but not for ML ($F_{2,46} = 2.38$, $p = 0.104$). V decreased with the reduction of cue distance only when the cue was targeted; the changes were not significant when the cue was not targeted (Fig. 3).

A repeated measures linear regression analysis of the ML sway data revealed significant ($p = 0.0123$) association between the ML sway values (S_{ML}, cm) and cue distance (D, m) on the sloped surface:

$$S_{ML} = 0.048D + 0.472 \quad (r = 0.16) \tag{1}$$

3.2. Visual cue effects on elevated deformable surfaces

3.2.1. Visual cue and surface firmness interactions

A 4 × 2 (Visual cue × Surface firmness) ANOVA was performed for the sway variables ML, AP and V. The visual cue levels were NV, NC, CNT1, and CT1, while the surface firmness levels included firm and deformable support conditions. The analysis revealed significant main effects and interaction for visual cue condition and surface firmness for all sway variables (Table 5).

On the deformable support the CNT1 and CT1 visual conditions progressively reduced ML and V from their baseline (NC) values (Fig. 4(a), (c)), but caused some increase in the AP sway values (Fig. 4(b)). On the firm surface all the visual effects were considerably smaller (for ML), or not significant (for AP and V).

3.2.2. Cue distance, cue-targeting, and surface firmness interactions

A 3 × 2 × 2 (Cue distance × Cue-targeting × Surface firmness) ANOVA was performed for the sway variables ML, AP and V. The ML and V analyses revealed significant main effects of cue distance, cue-targeting and surface firmness, and significant interaction for cue distance and surface firmness. Only V analysis showed significant interaction for cue-targeting and surface firmness. The AP analysis demonstrated only a significant main effect of surface firmness (Table 6).

Overall, greater cue distances increased both ML and V independent of cue-targeting (Fig. 5(a), (b)), and cue-targeting reduced V independent of the cue distance (Fig. 6), but these effects were significant only on the deformable and not on the firm surface.

A repeated measures linear regression analysis of the ML sway data revealed significant ($p < 0.0001$) association between the ML sway values (S_{ML}, cm) and cue distance (D, m) on the deformable surface:
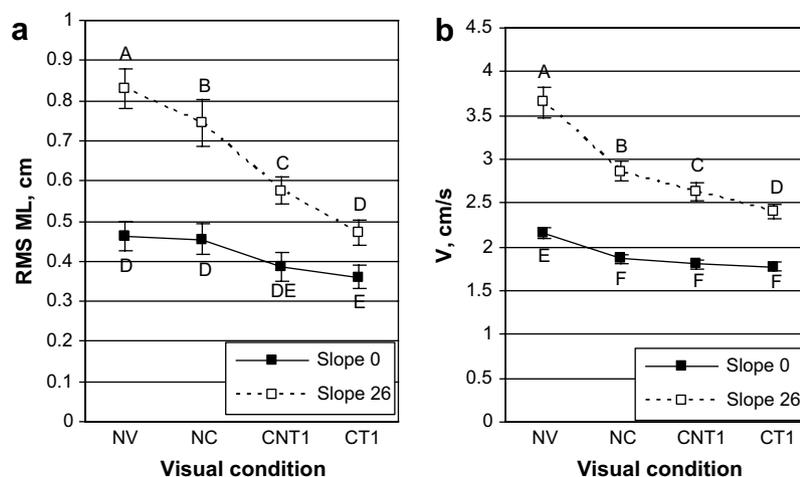

Fig. 2. Visual cue and surface slope interaction on ML and V. NV – no vision (eyes closed); NC – no visual cue (visual background); CT1 – cue targeted, at distance 1 m; CNT1 – cue not targeted, at distance 1 m; means with the same letter are not significantly different (Duncan); standard error represented by vertical bars or dotted lines.

Table 3
Surface slope steepness and visual cue effects – p values.

Source	ML Sway	AP Sway	Sway velocity
Main effects			
Slope (18, 26, 34)	0.019*	0.616	<.001*
Visual (NV, NC, CNT1)	<.001*	<.001*	<.001*
Interactions			
Slope × Visual	0.699	0.020*	0.142

* Statistically significant.

$$S_{ML} = 0.101D + 0.475 \quad (r = 0.30) \qquad (2)$$

4. Discussion

The study's central finding, that a simple vertical structure, i.e., a wooden bar, can serve as visual reference and improve workers' stability in an elevated workplace, reflects the complex interaction of visual, postural and support conditions on human balance control.

4.1. The role of visual information for balance control is significant on sloped and deformable surfaces at elevation

The significant effect of surface slope on sway velocity demonstrates the increasing difficulty of balance control at steeper sloped surface, since the velocity variable more closely reflects muscle activity (Laughton et al., 2003). The results of this study extend the findings of previous research (Simeonov et al., 2003) to show that the destabilizing effects of elevated sloped surfaces increase with slope grade even in more comfortable ("preferred") standing postural orientations. In an earlier study (Simeonov et al., 2003), the increase in slope was associated with progressive increase in anterior–posterior (AP) instability for participants who were facing the slope in a standard posture. The current study suggests mostly increased medial–lateral (ML) instability with increase of slope for participants in a semi-lateral slope-related posture. Overall, the results of both studies support the logical inference that the major challenge for postural stability on a sloped surface (independent of posture) is in the slope direction.

Standing on a sloped surface modifies postural alignment and stretches/contracts the muscle groups at the ankle (Simeonov et al., 2003). To reduce muscle strain, ankle joint position must be optimized by rotation of the feet away from the slope direction. In such posture the load bearing down-slope leg is straight at the knee with the foot angled (in this study at 45°) to slope direction, while the leg adjacent to the slope (the up-slope leg) is bent at the knee and used predominantly for balancing. For the down-slope posture in this study, the foot of the supporting leg is plantar-flexed and inverted. The resulting modified effective range of ankle motion and reduced muscle force-producing potential (Chaffin and Anderson, 1991) in

Table 4
Surface slope, visual cue distance, and targeting effects – p values.

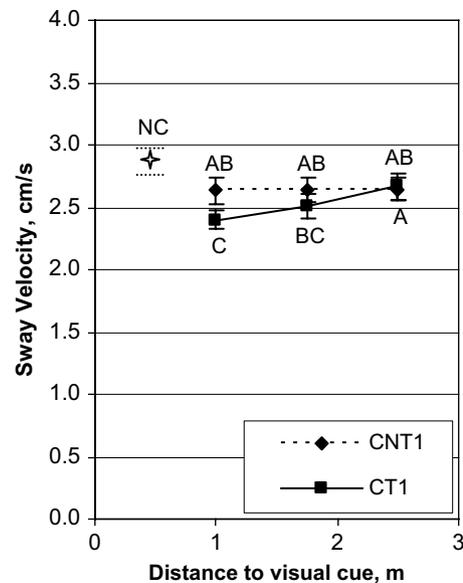| Source	ML Sway	AP Sway	Velocity
Main effects			
Slope (0, 26)	<.001*	0.012*	<.001*
Distance (1, 1.75, 2.5)	0.003*	0.498	0.015*
Target (No, Yes)	<.001*	0.635	0.028*
Interactions			
Slope × Distance	0.580	0.543	0.244
Slope × Target	0.381	0.352	0.096
Distance × Target	0.919	0.494	0.189
Slope × Distance × Target	0.017*	0.387	0.044*

* Statistically significant.

Fig. 3. Cue distance and cue-targeting interaction on *V* at slope 26°. NC – no visual cue (visual background); CT1 – cue targeted, at distance 1 m; CNT1 – cue not targeted, at distance 1 m; means with the same letter are not significantly different (Duncan); standard error represented by vertical bars or dotted lines.

both the AP and ML directions lead to decreased effectiveness of the ankle control strategy and increased overall postural instability. Furthermore, the modified pressure distribution under the feet and the stretched/contracted muscles at the ankle joint on the sloped surface may be associated with reduced effectiveness of the somatosensory (both exteroceptive and proprioceptive) inputs for balance control.

The surface slope and surface firmness interactions with visual cue condition for ML sway and sway velocity (Figs. 2(a), (b); 5(a,)(c)) reflect sensory re-weighting in conditions of postural instability. Both the sloped and the deformable surfaces hinder or considerably modify the somatosensory input from the feet interacting with the base of support and alter the effectiveness of the ankle control strategy. In these unreliable support conditions the posture control system re-weights the sensory information and relies more heavily on inputs from the visual system, which can provide essential proprioceptive information for precise balance control (Lee and Lishman, 1975).

Considering the inverted pendulum model for postural sway during quiet standing, the increased postural instability on the deformable and sloped surfaces is most likely associated with increased range of movement in the upper body and the head. This increased range of head movement allows enhanced visual input for self motion perception and balance control (Stoffregen, 1985; Day et al., 1993). The enhanced visual input on the sloped and the deformable surfaces as compared to the level and firm support, allowed for larger visual effects on the sway variables. The increased visual effects on the deformable surface in this study are

Table 5
Surface firmness and visual condition effects – p values.

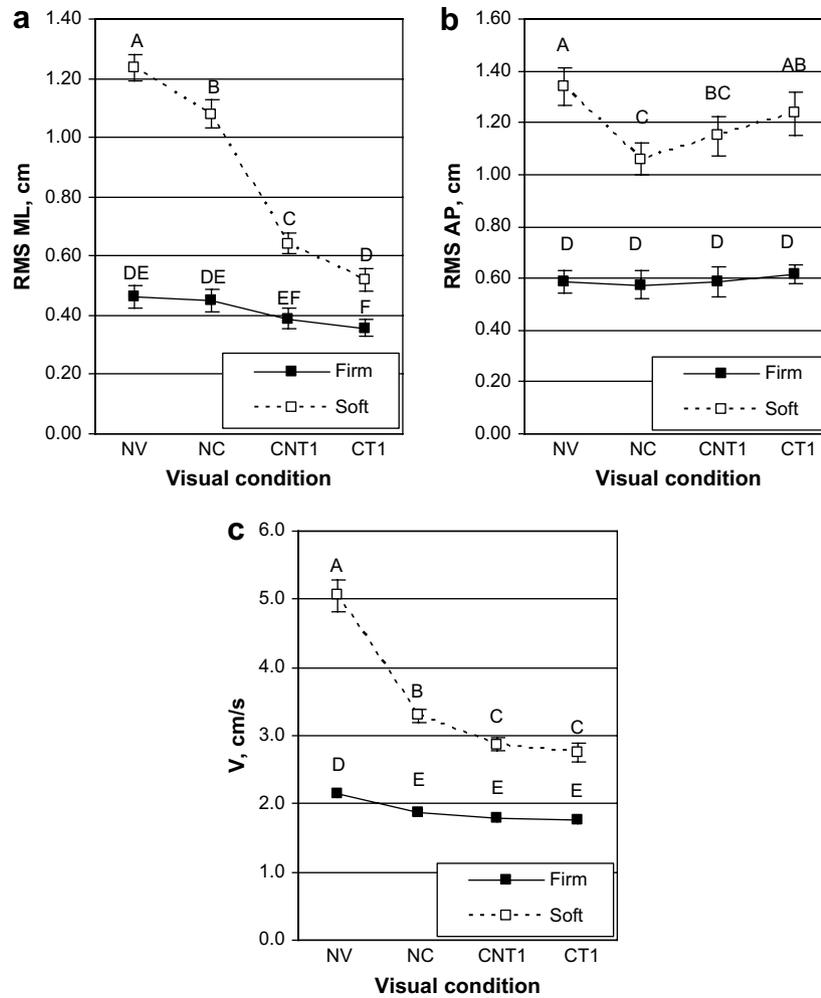| Source	ML Sway	AP Sway	Velocity
Main effects	p	p	p
Surface (Firm, Soft)	<.001*	0.001*	<.001*
Visual (NV, NC, CNT1, CT1)	<.001*	0.014*	<.001*
Interaction			
Surface × Visual	<.001*	0.015*	<.001*

* Statistically significant.

Fig. 4. Surface firmness and visual cue interaction on ML, AP and *V*. NV – no vision (eyes closed); NC – no visual cue (visual background); CT1 – cue targeted, at distance 1 m; CNT1 – cue not targeted, at distance 1 m; means with the same letter are not significantly different (Duncan); standard error represented by vertical bars.

consistent with earlier research on physiological height vertigo (Bles et al., 1980). Furthermore, the comparable visual effects for ML sway on slopes with different grade most likely indicate similar range of head motion determined by the similar postural configuration and foot position.

The balance control system can use information from the optical flow (the pattern of the visual motion at the moving eye) to reduce sway and sway velocity, i.e., the effort for balance control. The optical flow stimulus is a function of the observer's head position and velocity relative to the environmental 3-D structure (Kelly et al., 2005). Enhancing the proximal environment (the foreground) with simple vertical structures, i.e., bars will increase the available

optical flow stimulus. A centrally located visual cue, i.e., as was the setup in this study, provides enhanced visual inputs predominantly for ML sway and limited information for AP sway control. However, the enhanced visual input is useful for balance control only if and when it is interpreted as perceived self motion relative to the environment (Kelly et al., 2005). The required and sufficient conditions for extraction of self motion information from the available optical flow are not completely understood. Factors such as biomechanical stability, sensory state, task, and attention can affect this information processing (Prothero, 1998).

4.2. Adequacy of using goggles in testing the effect of visual reference at elevation

The laboratory experimental setup for this study used goggles to eliminate the existing close cues from the periphery of participants' visual field, and in this way simulate the open space conditions existing at an elevated construction workplace, such as a residential roof. A previous study (Simeonov et al., 2003) used similar experimental setup and demonstrated that the modified visual field from the use of goggles had relatively small effect on sway parameters in the presence of close frontal visual references. Earlier research has reported that visual stabilization of posture can be achieved with slightly reduced visual fields because of the large redundancy among the different parts of the visual field in reducing body sway (Paulus et al., 1984). In addition, visual control of posture is

Table 6
Surface firmness, visual cue distance and targeting effects – *p* values.

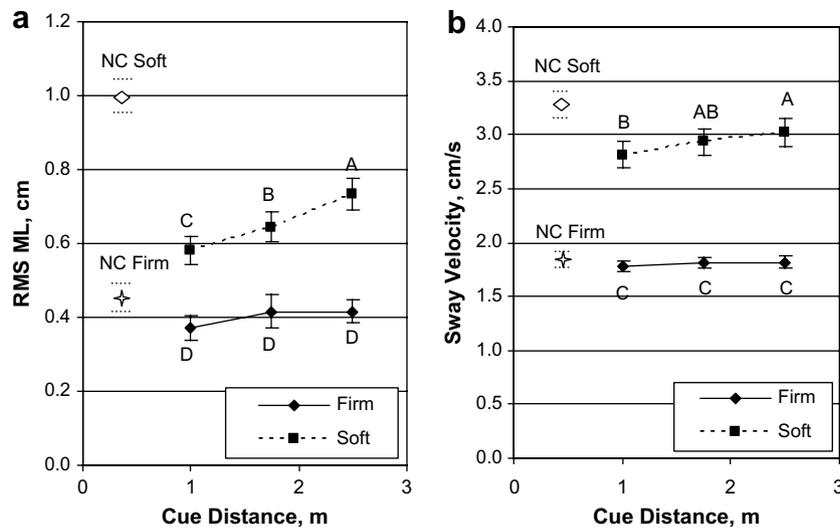| Source	ML Sway	AP Sway	Velocity
Main effects			
Surface (Firm, Soft)	<.001*	<.001*	<.001*
Distance (1, 1.75, 2.5)	<.001*	0.397	<.001*
Target (No, Yes)	<.001*	0.741	0.002*
Interactions			
Surface × Distance	<.001*	0.356	0.028*
Surface × Target	0.168	0.336	0.025*
Distance × Target	0.379	0.387	0.524
Surface × Distance × Target	0.660	0.635	0.863

* Statistically significant.

Fig. 5. Surface firmness and visual cue distance interaction on ML and *V*. NC – no visual cue (visual background); means with the same letter are not significantly different (Duncan); standard error represented by vertical bars or dotted lines.

homogeneous for the entire visual field (Straube et al., 1994), and both central and peripheral vision can use the optical flow structure pattern produced by optical expansion and motion parallax to control posture (Bardy et al., 1999). Therefore, the experimental design using goggles in this study is both adequate and practical in testing the effect of visual references at elevated environments.

4.3. Visual cue proximity and visual cue-targeting improve postural stability on sloped or deformable surfaces at elevation

The significant interaction between cue distance and cue-targeting for sway velocity on the elevated sloped surface (Fig. 3) implied a "facilitatory control" (Stoffregen et al., 1999). The human posture control system reduced sway velocity only when the close cue was targeted, i.e., to facilitate the (supra-postural) visual task. The lack of such interaction for the ML sway amplitude, however, implied an autonomous control, as suggested by the "adaptive

Fig. 6. Surface firmness and visual cue-targeting interaction on *V*. NC – no visual cue (visual background); means with the same letter are not significantly different (Duncan); standard error represented by vertical bars or dotted lines.

resource-sharing view" for the use of visual information (Mitra, 2004). These combined results suggest that the posture control system takes advantage of the available visual information by partially redirecting attention to the proximal visual cue. Although an elevated sloped surface is challenging for postural stability, the need for visual information to reduce sway amplitude while on the elevated sloped surface is not imminent; the posture control system uses primarily proprioceptive inputs under the situation, and is likely to use the visual information for stabilization only if needed.

On the elevated deformable surface, the balance control is more seriously challenged; the somatosensory (exteroceptive) input is not reliable and the visual information is critical for maintaining balance. The lack of cue distance and cue-targeting interaction on sway amplitude and sway velocity (Figs. 5(a), (b) and 6) indicates that the posture control system used the visual information from the proximal cues to reduce the sway variables independent of the (supra-postural) visual task. These results are consistent with the adaptive resource sharing view (Mitra, 2004). In the more unstable conditions the visual attention was redirected by the posture control system to support a higher priority task – avoid loss of balance (i.e., survive), as was suggested earlier (Simeonov et al., 2003).

The results of the current study indicated that the visual cue effects on ML sway appear to follow linear relations to eye-cue distance (see Equations (1) and (2)). The results further suggested that the effective range for the vertical visual reference most likely extends beyond the maximum tested distance of 2.5 m, both on the sloped and the deformable surfaces. These findings are consistent with earlier research on physiological height vertigo (Bles et al., 1980), and visual stabilization of posture (Paulus et al., 1984), which suggested that the limited distance range for an effective visual reference is based on the limited resolution of the retina, and is directly related to the level of postural instability and the associated head motion. Further studies, with application of eye/gaze-tracking coupled with kinematic methods which assess the real range of head movement, will allow establishing more accurate relations and determining the effective ranges of visual references associated with specific set of postural and support conditions.

The study results demonstrate that visual effects are different for sway amplitude and sway velocity (Fig. 2(a) and (b); Fig. 4(a), (b)), and (c). On the sloped surface, the increased sway amplitude reflects the dynamics of the new postural configuration and may indicate modified balance control strategy which includes increased
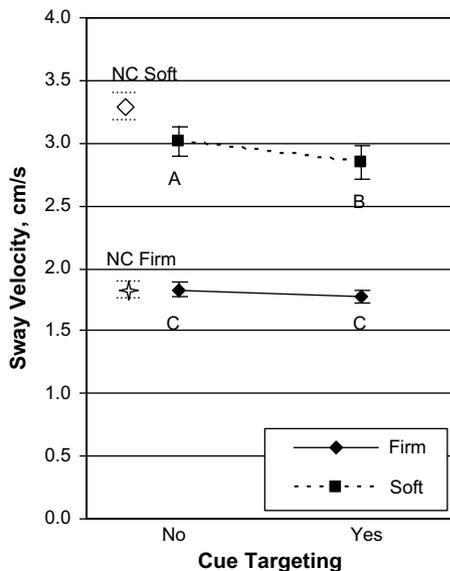
exploration at the boundaries of the support surface; while the increased sway velocity reflects intensified muscle activity, i.e., higher instability. On the deformable surface, the results for ML and AP sway are consistent with the stochastic optimal control theory, i.e., balance control involves and requires a certain level of variability for exploration and pick up of sensory information (Todorov and Jordan, 2002). The deformable surface may require increased sway variability for the pick-up of sensory information. For the visual targeting task the ML sway is reduced in proportion to the visual cue distance, while the AP sway is increased to provide the required variability. However, this is only valid for variables describing sway amplitude but not for variables related to sway velocity, which represent the intensity of balance control and stability.

4.4. Relevance of the study findings to the workers' risk of falling

The current study evaluated visual effects on workers' postural sway characteristics during standing tasks, while most fall incidents can be considered as consequence of balance failure during dynamic events, such as walking or postural transitioning. Earlier research has suggested that postural control system utilizes the same control mechanisms under quiet-standing and dynamic conditions (Lauk et al., 1998). Furthermore, the same visual information, i.e., motion parallax and radial expansion, is used to control both standing posture and posture during locomotion (Bardy et al., 1996), and to guide locomotion (Warren et al., 2001). Reduced quality of visual perception, i.e., visual acuity and contrast sensitivity, has been associated with increased risk of falls in the elderly (Lord et al., 1991). In addition, some postural sway measures have been shown in the literature to be predictive of falls. For example, sway velocity have been proposed as a measure of fall probability (Koleva et al., 2001) and was found to correlate well with the risk of falling in the elderly (Fernie et al., 1982); increased medial–lateral sway was a good predictor of falls in the elderly (Maki et al., 1994), as well as for falls in an occupational setting (Vouriot et al., 2004). This information supports the relevance of this study to the understanding and modifying/enhancing environmental characteristics of elevated workplaces that may contribute to fall initiation.

4.5. Practical aspects and considerations

The study findings suggest the potential benefit of including the information on visual cues in a comprehensive fall prevention program. Workers can benefit from receiving adequate training in recognizing the role of visual references in elevated work environments, which would result in enhanced balance through modifications of work environment and improved worker behavior. For example, when facing the roof eaves the workers may want to avoid looking into the open space while in unstable postures; rather, they are suggested to direct their visual attention to a proximal roof structure. Any temporary or permanent vertical elements, e.g., scaffolding poles, ventilation pipes, lightning poles, antenna masts, and chimneys, may provide visual reference in a roof environment, and be beneficial for workers' stability. Whenever practical, light vertical structures may be installed at the roof perimeter at the early stage of construction, and serve as visual cues to improve workers' balance. Furthermore, some of the conventional fall protection systems used in roof construction, i.e., railing systems and pole anchors, serve not only as fall-protection devices, but also provide a proximal visual reference for balance enhancement.

4.5.1. Limitations of the study

The short duration of the exposure to the experimental conditions (a visual task for 60 s) does not reveal the possible effects of postural adaptation and fatigue. Longer exposures to elevated and sloped surfaces associated with work tasks on roofs may lead to fatigue and thus further increase worker's postural instability (Corbeil et al., 2003) and the reliance on visual references (Vuillerme et al., 2001). The experimental conditions involved only a static posture task, which may limit the direct implication of the findings for a broader range of dynamic tasks and activities; however, as discussed above, in general the study findings should be relevant for reducing the workers' risk of falling.

To simulate an open space on the lab balcony, the study used goggles to restrict the subject's visual field. The lab dimensions may have been too small, even with the restricted field of view, to adequately represent an open space; some elements of the lab structure may have been detected and thus utilized as a visual anchor by the participants during instability tests on sloped and deformable surfaces. A virtual model of elevation in a surround screen virtual reality system, which can be augmented with real structures, is suggested as a more flexible alternative experimental setup (Hsiao et al., 2005; Simeonov et al., 2005).

The targeting task used in this study, was not attention intensive, which may have allowed for an easy attention transfer. A study with more demanding supra-postural visual tasks will provide additional insights to the effect of cue-targeting on balance control (Fraizer and Mitra, 2008). It should also be noted that the postural challenges used in this study were mild, not injury- or life-threatening. A more challenging situation can be simulated in the future in a virtual environment to further advance the knowledge on cue-targeting process. It has been suggested, that in potentially dangerous situations with increased risk of injury, the task of balance maintenance always has a priority (Shumway-Cook et al., 1997). In extreme conditions, if balance is threatened, any supra-postural task will be interrupted and not resumed until balance is recovered to a satisfactory degree (Riccio et al., 1992; Riccio and Stoffregen, 1992).

Individual differences in balance performance were not addressed in this study. It is understandable that some workers may benefit more than others from the visual cues at elevated workplaces, and it is likely that these will be the workers that are more susceptible to falls (Vouriot et al., 2004). Recent research has indicated that some individuals have well-established, preferred, sensory strategies for controlling postural orientation (Kluzik et al., 2005). Moreover, some workers may be less sensitive to changes in proprioceptive information and depend more on gravity as a reference frame to control their posture. Such individuals may be better adapted to the challenging work environments at elevation. Nevertheless, all workers may benefit from available visual cues since the vestibular thresholds for perception of postural sway are an order of magnitude above the visual thresholds (Fitzpatrick and McCloskey, 1994).

The balcony used in the experimental setup for this study was equipped with protective railing which may have minimized the psycho-physiological effects from the elevation exposure. Previous research has demonstrated that height-related anxiety is associated with a stiffening strategy for balance control (Adkin et al., 2000). However, experienced construction workers, e.g., roofers, may be less susceptible to the psycho-physiological effects of elevation exposure, since they usually underestimate the risk associated with their job (Zimolong, 1985).

5. Conclusions

The study results indicate increased instability on the sloped and deformable surfaces at elevation, and show that a simple proximal vertical structure, e.g., a wooden bar, has the potential to serve as a visual reference and assist workers' balance in these challenging conditions. The stabilizing effects of a vertical visual

cue appear to follow linear relations to the eye-cue distance both on the sloped and deformable surfaces, and these effects increase for closer cues. During instances of instability, workers' attention might be redirected to the available visual cues to assist balance control. These findings may be useful in modifying elevated work environments and construction procedures on sloped roofs and deformable/unstable platforms, e.g., by early erection of light vertical structures or guardrails, to improve workers' postural balance during various construction phases. In addition, these results may be used to develop a lay language material on the use of visual cues as part of workers' safety training.

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References

Adkin, A.L., Frank, J.S., Carpenter, M.G., Peysar, G.W., 2000. Postural control is scaled to level of postural threat. Gait & posture 12, 87–93.

Bardy, B.G., Warren Jr., W.H., Kay, B.A., 1996. Motion parallax is used to control postural sway during walking. Exp. Brain Res. 111, 271–282.

Bardy, B.G., Warren Jr., W.H., Kay, B.A., 1999. The role of central and peripheral vision in postural control during walking. Percept Psychophys. 61, 1356–1368.

Bles, W., Kapteyn, T.S., Brandt, T., Arnold, F., 1980. The mechanism of physiological height vertigo. II. Posturography. Acta Otolaryngol. 89, 534–540.

BLS, 2007. Workplace injuries and illnesses in 2006. News Release USDL 07–1562. Bureau of Labor Statistics, US Department of Labor. Available from. <http://www.bls.gov/iif/oshwc/osh/os/osnr0028.pdf> (accessed 07.08.08).

BLS, 2008. Census of fatal occupational injuries 2006 (revised data). Table A1. Fatal occupational injuries by industry and event or exposure. Bureau of Labor Statistics, US Department of Labor. Available from. <http://www.bls.gov/iif/oshwc/cfoi/cftb0214.pdf> (accessed 07.08.08).

Chaffin, D.B., Anderson, B.J., 1991. Occupational Biomechanics, second ed. Wiley, New York.

Cloe, W.W., 1979. Occupational Fatalities Related to Roofs, Ceilings, and Floors as Found in Reports of OSHA Fatality/Catastrophe Investigations. Occupational Health and Safety Administration, U.S. Department of Labor, Washington DC.

Corbeil, P., Blouin, J.S., Begin, F., Nougier, V., Teasdale, N., 2003. Perturbation of the postural control system induced by muscular fatigue. Gait & posture 18, 92–100.

Day, B.L., Steiger, M.J., Thompson, P.D., Marsden, C.D., 1993. Effect of vision and stance width on human body motion when standing: implications for afferent control of lateral sway. J. Physiol. 469, 479–499.

Deyer, T.W., Ashton-Miller, J.A., 1999. Unipedal balance in healthy adults: effect of visual environments yielding decreased lateral velocity feedback. Arch. Phys. Med. Rehabil. 80, 1072–1077.

Fernie, G.R., Gryfe, C.I., Holliday, P.J., Llewellyn, A., 1982. The relationship of postural sway in standing to the incidence of falls in geriatric subjects. Age Ageing 11, 11–16.

Fitzpatrick, R., McCloskey, D.I., 1994. Proprioceptive, visual and vestibular thresholds for the perception of sway during standing in humans. J. Physiol. 478 (Pt 1), 173–186.

Fraizer, E.V., Mitra, S., 2008. Methodological and interpretive issues in posture-cognition dual-tasking in upright stance. Gait & posture 27, 271–279.

Hsiao, H., Simeonov, P., 2001. Preventing falls from roofs: a critical review. Ergonomics 44, 537–561.

Hsiao, H., Simeonov, P., Dotson, B., Ammons, D., Kau, T.Y., Chiou, S., 2005. Human responses to augmented virtual scaffolding models. Ergonomics 48, 1223–1242.

Kelly, J.W., Loomis, J.M., Beall, A.C., 2005. The importance of perceived relative motion in the control of posture. Exp. Brain Res. 161, 285–292.

Kluzik, J., Horak, F.B., Peterka, R.J., 2005. Differences in preferred reference frames for postural orientation shown by after-effects of stance on an inclined surface. Exp. Brain Res. 162, 474–489.

Koleva, R.K., Widom, A., Garelick, D., Harris, M., 2001. Posture sway and the transition rate for a fall. Physica A 293, 605–615.

Laughton, C.A., Slavin, M., Katdare, K., Nolan, L., Bean, J.F., Kerrigan, D.C., Phillips, E., Lipsitz, L.A., Collins, J.J., 2003. Aging, muscle activity, and balance control: physiologic changes associated with balance impairment. Gait & posture 18, 101–108.

Lauk, M., Chow, C.C., Pavlik, A.E., Collins, J.J., 1998. Human balance out of equilibrium: nonequilibrium statistical mechanics in posture control. Phys. Rev. Letters 80, 413–416.

Le Clair, K., Riach, C., 1996. Postural stability measures: what to measure and for how long. Clin. Biomech. (Bristol, Avon) 11, 176–178.

Lee, D.N., Lishman, J.R., 1975. Visual proprioceptive control of stance. J. Hum. Mov. Sci. 1, 87–95.

Lord, S.R., Clark, R.D., Webster, I.W., 1991. Visual acuity and contrast sensitivity in relation to falls in an elderly population. Age Ageing 20, 175–181.

Maki, B.E., Holliday, P.J., Topper, A.K., 1994. A prospective study of postural balance and risk of falling in an ambulatory and independent elderly population. J. Gerontol. 49, M72–84.

Mitra, S., 2004. Adaptive utilization of optical variables during postural and suprapostural dual-task performance: comment on Stoffregen, Smart, Bardy, and Pagulayan (1999). J. Exp. Psychol. Hum. Percept. Perform. 30, 28–38.

Parsons, T.J., Pizatella, T.J., 1985. Safety Analysis of High Risk Activities Within the Roofing Industry. PB-85163236. U.S. National Technical Information Service, Springfield, VA.

Paulus, W., Straube, A., Krafczyk, S., Brandt, T., 1989. Differential effects of retinal target displacement, changing size and changing disparity in the control of anterior/posterior and lateral body sway. Exp. Brain Res. 78, 243–252.

Paulus, W.M., Straube, A., Brandt, T., 1984. Visual stabilization of posture. Physiological stimulus characteristics and clinical aspects. Brain 107 (Pt 4), 1143–1163.

Prothero, J.D., 1998. The Role of Rest Frames in Vection, Presence and Motion Sickness. University of Washington.

Riccio, G.E., Martin, E.J., Stoffregen, T.A., 1992. The role of balance dynamics in the active perception of orientation. J. Exp. Psychol. Hum. Percept. Perform. 18, 624–644.

Riccio, G.E., Stoffregen, T.A., 1992. An ecological theory of motion sickness and postural instability. Ecol. Psychol. 3, 195–240.

Shumway-Cook, A., Woollacott, M., Kerns, K.A., Baldwin, M., 1997. The effects of two types of cognitive tasks on postural stability in older adults with and without a history of falls. J. Gerontol. A Biol. Sci. Med. Sci. 52, M232–240.

Simeonov, P.I., Hsiao, H., Dotson, B.W., Ammons, D.E., 2003. Control and perception of balance at elevated and sloped surfaces. Hum. Factors 45, 136–147.

Simeonov, P.I., Hsiao, H., Dotson, B.W., Ammons, D.E., 2005. Height effects in real and virtual environments. Hum. Factors 47, 430–438.

Stoffregen, T.A., 1985. Flow structure versus retinal location in the optical control of stance. J. Exp. Psychol. Hum. Percept. Perform. 11, 554–565.

Stoffregen, T.A., Smart, L.J., Bardy, B.G., Pagulayan, R.J., 1999. Postural stabilization of looking. J. Exp. Psychol. Hum. Percept. Perform. 25, 1641–1658.

Straube, A., Krafczyk, S., Paulus, W., Brandt, T., 1994. Dependence of visual stabilization of postural sway on the cortical magnification factor of restricted visual fields. Exp. Brain Res. 99, 501–506.

Tinetti, M.E., Speechley, M., 1989. Prevention of falls among the elderly. N. Engl. J. Med. 320, 1055–1059.

Todorov, E., Jordan, M.I., 2002. Optimal feedback control as a theory of motor coordination. Nat. Neurosci. 5, 1226–1235.

Vouriot, A., Gauchard, G.C., Chau, N., Benamghar, L., Lepori, M.L., Mur, J.M., Perrin, P.P., 2004. Sensorial organisation favouring higher visual contribution is a risk factor of falls in an occupational setting. Neurosci. Res. 48, 239–247.

Vuillerme, N., Nougier, V., Prieur, J.M., 2001. Can vision compensate for a lower limbs muscular fatigue for controlling posture in humans? Neurosci. Lett. 308, 103–106.

Wade, C., Davis, J., Marzilli, T.S., Weimar, W.H., 2006. Information processing capacity while wearing personal protective eyewear. Ergonomics 49, 955–967.

Warren Jr., W.H., Kay, B.A., Zosh, W.D., Duchon, A.P., Sahuc, S., 2001. Optic flow is used to control human walking. Nat. Neurosci. 4, 213–216.

Warren, W.H., Kay, B.A., Yilmaz, E.H., 1996. Visual control of posture during walking: functional specificity. J. Exp. Psychol. Hum. Percept. Perform. 22, 818–838.

Zimolong, B., 1985. Hazard perception and risk estimation in accident causation. In: Eberts, R.E., Eberts, C.G. (Eds.), Trends in Ergonomics/Human Factors II. Elsevier, Amsterdam, pp. 463–470.