

Control and Perception of Balance at Elevated and Sloped Surfaces

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Understanding roof-work-related risk of falls and developing low-cost, practical engineering controls for reducing this risk remain in high demand in the construction industry. This study investigated the effects of the roof work environment characteristics of surface slope, height, and visual reference on standing balance in construction workers. The 24 participants were tested in a laboratory setting at 4 slopes (0°, 18°, 26°, and 34°), 2 heights (0, 3 m), and 2 visual conditions (with and without visual references). Postural sway characteristics were calculated using center of pressure recordings from a force platform. Workers' perceptions of postural sway and instability were also evaluated. The results indicated that slope and height synergistically increased workers' standing postural instability. Workers recognized the individual destabilizing effects of slope and height but did not recognize the synergistic effect of the two. Visual references significantly reduced the destabilizing effects of height and slope. Actual and potential applications of this research include the use of temporary level work surfaces and proximal vertical reference structures as postural instability control measures during roofing work.

INTRODUCTION

Falls from roofs account for about one third of all fatal fall incidents in the construction industry each year (Bureau of Labor Statistics [BLS], 1999). In addition, injury statistics indicated that 3843 serious injuries (involving days away from work) were associated with construction-related falls from roofs in 1995 (BLS, 1998). Typical injuries caused by falls from roofs are extremely severe, require long periods of treatment and recovery, and result in substantial medical cost (Gillen, Faucett, Beaumont, & McLoughlin, 1997). Losing balance has been determined to be one of the triggering events for fall incidents in roof construction (Cloe, 1979; Parsons & Pizatella, 1985).

Loss of balance occurs when one or several modes of the proactive and reactive mechanisms of human balance control are disrupted during human-environment interactions (Horak, Henry, & Shumway-Cook, 1997; Patla, 1997; Woollacott & Tang, 1997). Control of balance is main-

tained through integration of sensory information from the vestibular, visual, and somatosensory systems, with high redundancy among the systems (Diener & Dichgans, 1988). Balance control is typically exercised at the level of the most accurate sensory input available to the sensory systems (Fitzpatrick & McCloskey, 1994; McCollum, Shupert, & Nashner, 1996). For instance, in familiar postures on firm and stable support, the balance control system relies mainly on somatosensory inputs, and visual information may not be needed or actively used for balance control. However, degraded visual inputs may cause instability in challenging support conditions (Lee & Lishman, 1975). Adequate recognition of increased instability is critical for the timely modification of a postural strategy to prevent loss of balance.

Multiple factors in roof construction environments may affect workers' balance control and increase their risk of falling (Hsiao & Simeonov, 2001). Steep slope, height, and lack of visual references are typical characteristics of roof

environments. The closest references for visual stabilization on roofs can be provided by the roof surface if it is included in the workers' visual field. However, workers standing close to roof edges may have to rely mainly on vestibular and somatosensory inputs to maintain balance. In such sensory-deprived conditions, sloped roof surfaces may further affect workers' stability and increase the risk for loss-of-balance incidents.

It is well known that inclined surfaces increase the risk of slipping incidents because of the increased friction demand (McVay & Redfern 1994; Sun, Walters, Svensson, & Lloyd, 1996; Zhao, Upadhyaya, & Kaminaka, 1987), but research on the effects of surface slope on balance control is limited. Emerich, Bhattacharya, Succop, and Bagchee (1993) reported that participants' postural stability decreased in response to increased roof inclination. How the inclination effect interacts with visual references remains to be investigated. Previous research has also demonstrated that height can affect balance control. At elevation, the observer's field of view is often deficient of close visual structures. It has been suggested that height vertigo is associated with conditions deficient in close visual references, and the destabilizing effect of height is the same at different altitudes when the height environments are equally deficient in close visual references (Bles, Kapteyn, Brandt, & Arnold, 1980; Brandt, Arnold, Bles, & Kapteyn, 1980; Lee & Lishman, 1975). However, again, whether height and visual reference interact with surface inclination to affect balance, and whether these effects can be correctly perceived, has not been well explored.

The objective of this study was to investigate the effects of surface slope, height, and close visual references and their interactions on the control and perception of standing balance in construction workers. Understanding these underlying causes and effects will be useful in developing effective prevention strategies to reduce the incidence of falls from roofs.

METHODS

Participants

The participants were 24 healthy male construction workers with at least 6 months' experience working at heights. Participants in the

study were recruited via classified advertisements and letters to the local unions. They were between 21 and 57 years old with an average age of 31 years, average body weight of 90.5 kg ($SD = 15.2$ kg), and average height of 179 cm ($SD = 6.5$ cm). Exclusion criteria for study participation were acrophobia, height vertigo, history of dizziness, neurological disorder, abnormal vision, and uncorrected vision. The experimental protocol for the study was approved by the Institutional Review Board of the National Institute for Occupational Safety and Health (NIOSH). All participants gave informed consent prior to the study and were compensated for their time.

Experimental Design

The study used a repeated-measures design with three independent variables: surface slope, height, and visual reference (Hays, 1994). Each participant received the same 16 treatments ($4 \times 2 \times 2$); the order of these treatments among participants was balanced to control order effects. Three consecutive trials per experimental condition were used. The experimental procedure also included a baseline phase conducted at ground level with eyes closed while standing on sloped surfaces.

Surface slope. Four levels of roof slope were evaluated: flat (0°), 4/12 ($\sim 18^\circ$), 6/12 ($\sim 26^\circ$), and 8/12 ($\sim 34^\circ$). The slope 4/12 represents a low-slope type of roof, 6/12 is classified as steep (Occupational Safety and Health Administration, 1999), and 8/12 represents a very steep roof surface. Workers frequently perform tasks on roofs within this range of surface slopes without using any additional support devices (e.g., roof brackets or roof ladders). For the tests, sloped platforms constructed from 3/4-inch (1.9-cm) plywood and painted with slip-resistant paint were positioned on a force plate.

Height. Tests were conducted on an elevated surface, 3 m in height, in the NIOSH laboratory in Morgantown, West Virginia. The laboratory is equipped with a 3-m-high balcony. The balcony has metal protective railings, thus minimizing the psychophysiological effects from elevation exposure in this study. Tests at ground level (0 m) were also conducted.

Visual reference. To simulate an elevated workplace without close visual references, the

participants wore goggles that restricted their visual field to approximately 50° in the vertical direction and approximately 95° in the horizontal direction. With goggles, the participants were not able to see the protective railing, the edge of the balcony, or the close visual references that were constructed for the study. The closest objects that could be seen were at a distance of more than 5 m.

In the alternative test condition (without goggles), the participants could see everything in the periphery of their visual field. Both on the balcony and on the ground floor of the lab, the closest visual references in the periphery were two vertical planks (4 × 8 × 230 cm) symmetrically located 76 cm away from the eye and angled 53° from horizontal gaze direction.

To standardize the visual conditions at ground level, where close visual structures are normally available, we asked the participants to stand in front of a white poster with random contrasts (black rectangles of different shape, size, and orientation) at a distance of 120 cm. The tests at ground level included conditions both with and without goggles to account for the effect of the modified visual field on balance (Paulus, Straube, & Brandt, 1984). In addition, the experimental design included baseline tests at ground level with eyes closed.

Instrumentation. For center-of-pressure measurements we used the portable strain-gauge-type force platform Accusway™ (Advanced Mechanical Technologies, Inc., Watertown, MA), which is capable of measuring forces and moments along three orthogonal axes. Data were collected with a portable personal computer at 50 Hz frequency. The values of the dependent variables were derived from the center of pressure (CP) movement, which was calculated from the raw data. In the calculations of CP movement, the elevated position of the feet relative to the surface of the forceplate for standing on sloped platforms was taken into consideration because it could affect the contribution of the horizontal forces.

Dependent variables. Eight dependent variables derived from CP measurements were used to quantitatively describe sway and determine postural stability. The variables were root mean square (RMS) of CP displacement in medial-lateral (ML) and anterior-posterior (AP) direc-

tions, mean velocity of CP displacement (V), the sway velocity components in the medial-lateral and anterior-posterior directions (V_{ML} and V_{AP}), the mean power of AP sway in low- and high-frequency bands (LFP_{AP} and HFP_{AP}), and perceptions of postural sway and instability (P). RMS represents a suitable measure for average body sway over a certain period and allows an easy comparison to be made between the effects of different experimental conditions (Bles et al., 1980). Sway velocity is considered to be a valid measure of postural stability (Robbins, Waked, & Krouglicof, 1998) and correlates well with risk of falling (Fernie, Gryfe, Holliday, & Llewellyn, 1982).

Power spectrum for AP sway was obtained with a standard fast Fourier transform procedure. The power spectrum had a frequency resolution of 0.05 Hz and was calculated for the frequency range of 0 to 3 Hz. For statistical analysis and interpretation, the spectrum was divided into two frequency bands: 0 to 1 Hz = low frequency (LFP_{AP}) and 1 to 3 Hz = high frequency (HFP_{AP}). The mean values of the power in these frequency bands were used as dependent variables. Previous research has demonstrated that high-frequency components of sway (> 1 Hz) are influenced mainly by somatosensory inputs whereas vision affects sway in the frequency range below 1 Hz (Diener & Dichgans, 1988). Increased mean power frequency of sway is associated with higher muscle stiffness in response to increased postural threat (Adkin, Frank, Carpenter, & Peysar, 2000; Carpenter, Frank, & Silcher, 1999).

In addition to the physical sway measurements, a modified 11-point rating scale was used to determine the perceptions of postural sway and instability (P ; Chiou, Bhattacharya, Lai, & Succop, 1998). The participant answered four simple questions immediately after each test: How much did you feel your body sway? Did you have any difficulty in maintaining balance? Did you feel at any time that you would fall? What would you say was the overall difficulty of this task? When answering these questions, the participants had to choose a number, ranging from 0 (*not at all*) to 10 (*a lot*), that closely reflected their perceptions. The perceived sense of postural sway and instability was defined as the sum of the four answers. A high score implied

a high subjective perception of postural sway and instability. Experimental conditions in which participants underestimate their actual postural instability may indicate increased risk for loss of balance.

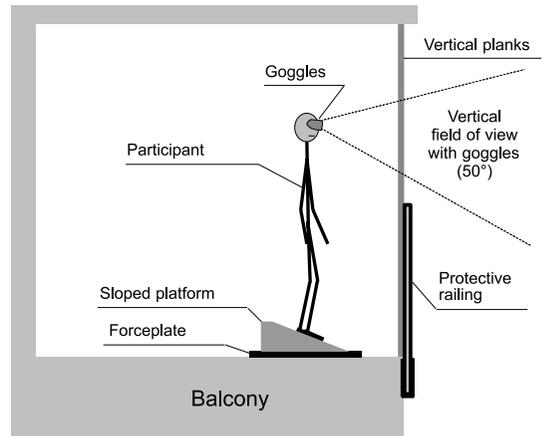
Experimental Procedure

Upon arrival, the participant was briefed on the details of the study, filled out a health questionnaire, and signed an informed consent form. He then changed into socks and safety shoes (Model 604, Iron Age Corp., Pittsburgh, PA) provided by the laboratory and was taken either to the ground level or to the 3-m-high balcony of the laboratory to start the experiment. Before starting the tests, the participants had 3 practice trials to familiarize themselves with the experimental procedure. They performed 3 consecutive trials per experimental condition for a total of 48 trials, including 24 at the ground level and 24 at the balcony. To change the experimental condition, the investigator positioned a sloped platform on the force plate, and the participant put on or removed the goggles to control for the visual reference.

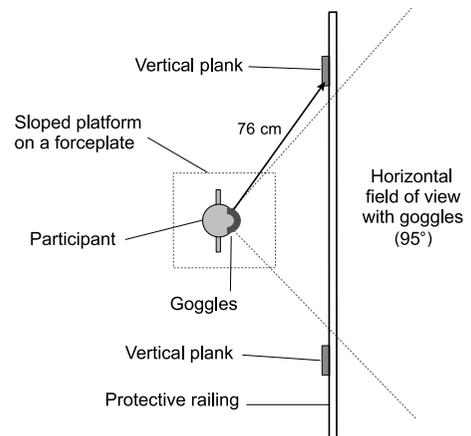
For each trial data were collected for 30 s while the participant stood on the sloped platform facing the slope (or stood directly on the force plate at 0° slope), looking straight forward with his heels together, feet angled at 30°, and hands by the hips (Figure 1). Between experimental conditions the participant had a seated rest period of 3 min to reduce the possibility of fatigue. During the rest period, the participant was asked to rate his perceptions of postural sway and instability for the evaluated experimental condition. At the end, 12 baseline tests with eyes closed were performed at the ground level, at four slope levels with three consecutive trials. The slope levels were randomly assigned within each participant. The participant completed the experiment in approximately 3 h, compensated for his time, and then dismissed.

Statistical Methods

Analysis of variance (ANOVA) was used to determine differences between the experimental conditions. The analysis was performed with the general linear model (GLM) procedure in SAS software (SAS Institute Inc., Cary, NC). Normality of the residuals was examined to en-



A



B

Figure 1. Experimental setup. (a) View from the side. (b) View from above. Participant standing on a sloped platform, positioned on a forceplate, at the 3-m high balcony in the lab, and wearing goggles to control the presence of close visual references.

sure nonviolation of ANOVA underlying assumptions. Dependent variables were assessed assuming within-subject variation as a random effect. The Student-Newman-Keuls multiple-range test was used to investigate pairwise comparisons between levels of experimental conditions when significance was demonstrated in the ANOVA model.

RESULTS

RMS of AP Sway

RMS of AP sway analysis demonstrated a significant two-way interaction for height and

visual reference, $F(1, 23) = 16.3, p < .001$, and a significant main effect for slope, $F(3, 69) = 3.2, p = .028$ (see Table 1). AP sway was 30% greater at height than at ground level when close visual references were not available. The effect of height on AP sway was reduced to 7.7% when close visual references were presented (Figure 2a). Exclusion of the close visual references at ground level increased AP sway by 20.5%, whereas at height the difference was 45% (Figure 2a). Increase of surface slope resulted in a progressive increase of AP sway. AP sway at 34° slope was 18.6% larger than that at 0° slope (Figure 2b).

RMS of ML Sway

RMS of ML sway analysis showed significant main effects for height, $F(1, 23) = 12.5, p = .002$, and visual references, $F(1, 23) = 15.8, p < .001$ (see Table 1). Height increased ML sway by 11%, and close visual references reduced ML sway by 15%.

Velocity of Sway

Velocity of sway (V) analysis demonstrated significant two-way interactions for slope and height, $F(3, 69) = 7.3, p < .001$; slope and visual reference, $F(3, 69) = 6.1, p = .001$; and height and visual reference, $F(1, 23) = 13.3, p = .001$ (see Table 1). Surface slope increased the effect of height on V : At 0 slope height increased V by 11.2%, and the effect of height increased to about 20% at the 26° and 34° slopes (Figure 3a). Surface slope also increased the effect of visual references: At 0° slope close visual references reduced V by 11.2%, whereas at 34°

slope this effect was 19.8% (Figure 3b). Visual references reduced the effect of height. V was 19.7% greater at 3 m height than at ground level when no close visual references were presented; the effect of height was reduced by nearly half (10.3%) when visual references were available (Figure 3c).

Comparative analysis of sway velocity in the anterior-posterior and medial-lateral directions revealed that slope had considerably larger effects on V_{AP} than on V_{ML} . The ratio V_{AP}/V_{ML} increased dose dependently with slope, revealing a directional effect of slope on balance, $F(3, 69) = 108.55, p < .001$ (Figure 4).

Power Spectrum of AP Sway

Analysis of the mean power in the 0- to 1-Hz (low-frequency) range of the AP sway power spectrum (LFP_{AP}) demonstrates a significant two-way interaction of height and visual reference, $F(1, 23) = 19.8, p < .001$, and significant main effects for slope, $F(3, 69) = 4.7, p = .005$ (see Table 2). Height increased LFP_{AP} by 73.1% in conditions without close visual references. The effect of height on LFP_{AP} was reduced to 21.7% when close visual references were available. Slope increased LFP_{AP} : At 34° slope, LFP_{AP} was 50% greater than that at 0° slope.

Analysis of the mean power in the 1- to 3-Hz (high-frequency) range of the AP sway power spectrum (HFP_{AP}) demonstrates significant two-way interactions for slope and height, $F(3, 69) = 6.0, p = .001$, and slope and visual reference, $F(3, 69) = 5.6, p = .002$ (see Table 2). Surface slope increased the effect of height on HFP_{AP} : At 0° slope, height increased HFP_{AP} by 66.9%,

TABLE 1: ANOVA of Sway Characteristics

Source	df	RMS _{AP} Sway		RMS _{ML} Sway		Velocity of Sway	
		F	p	F	p	F	p
Main Effects							
Slope	3	3.22	.028	2.2	ns	37.72	<.001
Height	1	39.53	<.001	12.48	.002	28.62	<.001
Visual reference	1	122.18	<.001	15.78	<.001	53.09	<.001
Interactions							
Slope × Height	3	2.1	ns	1.34	ns	7.29	<.001
Slope × VisRef	3	1.07	ns	0.38	ns	6.09	.001
Height × VisRef	1	16.27	<.001	1.08	ns	13.03	.001
Slope × Height × VisRef	3	1.96	ns	1.68	ns	0.96	ns

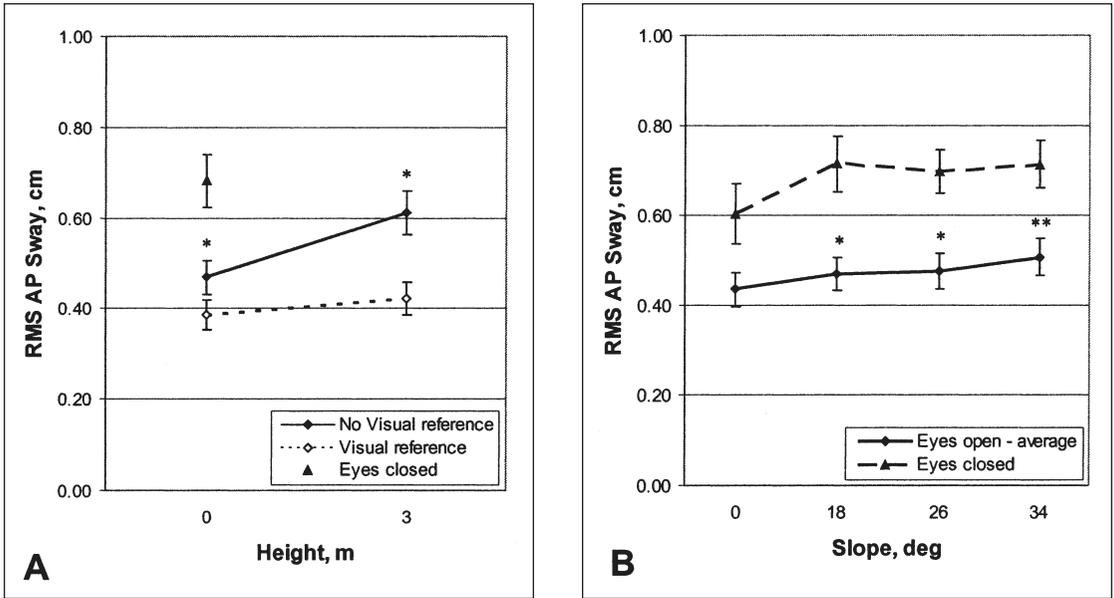


Figure 2. Anterior-posterior sway. (a) Height and visual reference interaction. * Indicates a significant effect of visual reference at the specific height. (b) Effect of slope. *, ** Indicate a significant difference between the groups. Vertical bars represent standard errors.

whereas at 26° slope the effect was 107.0%. Surface slope also increased the effect of visual reference on HFP_{AP} . At 0° slope, visual reference reduced HFP_{AP} by 32%, whereas at 34° slope the reduction was 41%.

Perception of Postural Sway and Instability

Analysis of perceptions of postural sway and instability (*P*) demonstrated a significant two-way interaction for slope and visual references, $F(3, 69) = 25.9, p = .005$, and a significant main effect for height, $F(1, 23) = 5.0, p < .035$ (see Table 3). Slope increased the effect of visual references on *P*: At 0° slope visual references reduced *P* by 27.5%, whereas at 26° slope the reduction was 38.6% (Figure 5). Participants perceived higher postural instability (22%) when at height than when at ground level.

DISCUSSION

The study results demonstrated that roof environment characteristics (slope and height) synergistically increased workers' standing postural instability. Their interaction affected the velocity and high-frequency components of body sway and occurred predominantly in the

anterior-posterior direction. The amplified instability caused by the Slope × Height interaction was not well perceived by the workers, although they recognized the effects of slope and height. The destabilizing effects of height and slope were significantly reduced in the presence of visual references.

The analysis of AP sway characteristics in this study has provided insight concerning the role of visual and somatosensory inputs in balance control. Because the environment at height is known to be associated with reduced visual information for balance control (Bles et al., 1980; Brandt et al., 1980), the interaction effects of height and slope on the velocity and high-frequency components of AP sway probably reflect the interaction between visual and somatosensory controls of balance (i.e., increased role of visual demands under less stable or restricted postural and/or support conditions). It has been reported that destabilizing visual environments have a larger effect on balance on deformable surfaces (Redfern, Moore, & Yarsky, 1997; Simeonov & Hsiao, 2001) and that visual inputs are more effective in reducing sway velocity at narrower stance width (Day, Steiger, Thompson, & Marsden, 1993).

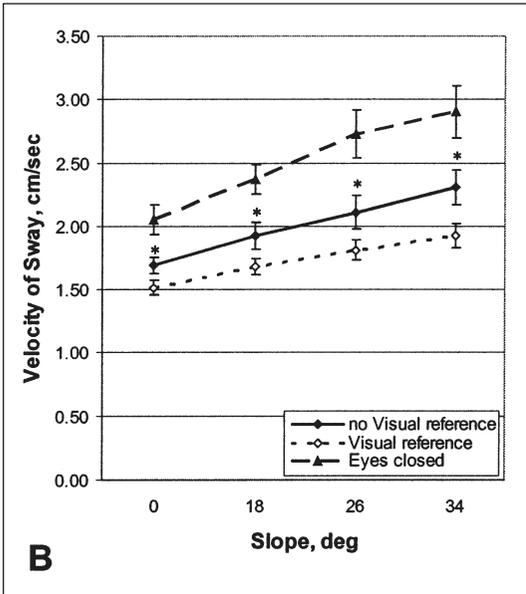
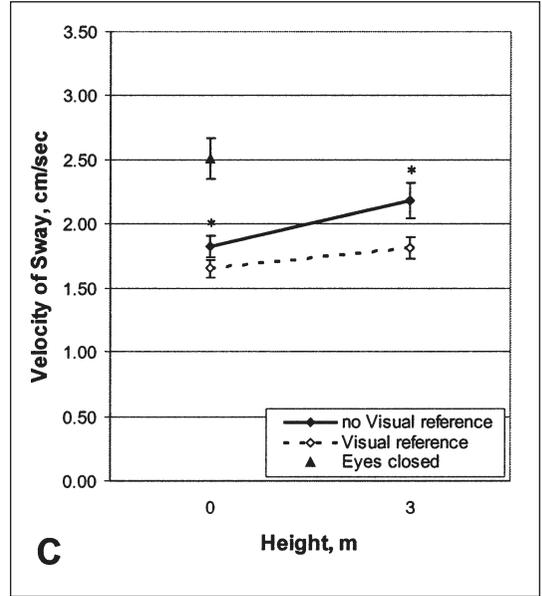
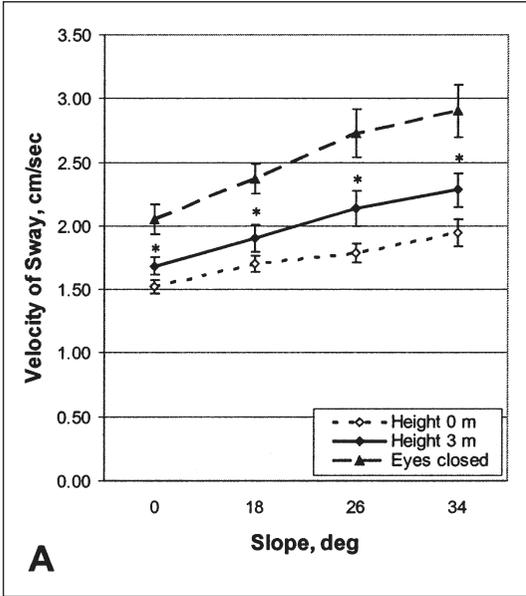


Figure 3. Velocity of sway. (a) Slope and height interaction. * Indicates a significant effect of height at the specific slope. (b) Slope and visual reference interaction. * Indicates a significant effect of visual reference at the specific slope. (c) Height and visual reference interaction. * Indicates a significant effect of visual reference at the specific height. Vertical bars represent standard errors.

In addition, leaning posture has been found to increase the effect of vision on some characteristics of unperturbed postural sway (Riley, Mitra, Stoffregen, & Turvey, 1997). A sloped surface affects balance by altering the somatosensory input as a result of modified postural alignment and reduced effective base of support. To provide postural alignment on a slope, the ankle joints become plantar- or dorsiflexed, or inverted or everted, depending on body orienta-

tion. This causes stretching or contraction of the groups of muscles that control movement of the ankle joints and thus is involved in the control of balance. The resulting increased stiffness and muscle activity at the ankle joints probably cause an increase in sway velocity, given that sway velocity reflects the dynamic muscle forces at the ankle joints (Kunkel, Freudenthaler, Steinhoff, Baudewig, & Paulus, 1998).

In the current study the participants were instructed to stand facing downslope without bending their knees, which caused plantarflexion at the ankle joints equal to slope angle. This affected the major muscles involved in the control of balance in the AP direction (the slope direction), contracting the plantarflexors (soleus and gastrocnemius) and stretching the dorsiflexors. The effective range of AP movement at the ankle joint was shifted and reduced, and the plantarflexors' contraction capability was diminished because of the nonoptimal force-producing length of the contracted muscles (Chaffin & Anderson, 1991).

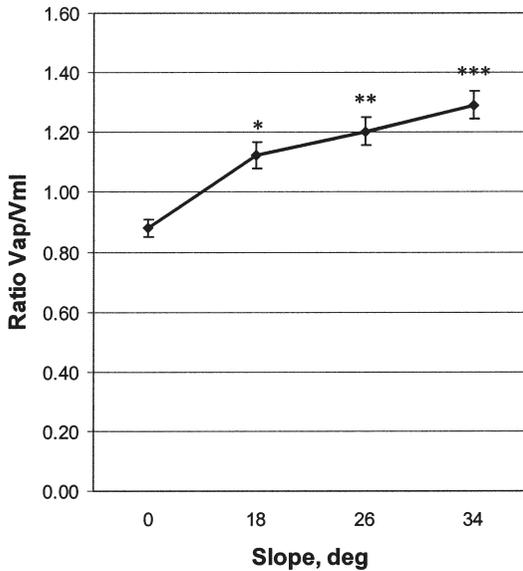


Figure 4. Directional effect of slope — the ratio of sway velocity components in anterior-posterior and medial-lateral direction (V_{AP}/V_{ML}) as a function of slope. *, **, *** Indicate a significant difference between the groups. Vertical bars represent standard errors.

It is also worth mentioning that slope reduced the effective base of support (i.e., the area of the footprint projection on a horizontal plane). For the standing posture in this study, the effective base of support was reduced in the slope direction as the cosine of the slope angle. The reduced effective base of support limited the safe range of movement of the body center of gravity and thus increased postural instability.

The increased postural activity (sway) at elevated and sloped surfaces may reflect both more intensive balance control and more active postural exploration (Riccio, 1993) during instability in a phase of postural adaptation to these challenging conditions. The increased velocity and high-frequency components of CP movement probably reflect pickup of somatosensory information from the base of support to assist balance control. However, postural activity (exploration) for increased pickup of visual information (i.e., by increased movement of the upper body and head) was not indicated, given that the CP movements in the low-frequency band were not significantly increased; again, this is probably attributable to the reduced base of support and the limited range of movement on the sloped surface.

The participants in this study perceived the destabilizing effect of height and slope but did not perceive the significantly amplified instability at elevated and inclined surfaces. These findings imply that participants perceived muscle activity (proprioceptive input) as a stronger indicator of instability than integrated visual and somatosensory input. Workers' perceptions of sway and instability were well correlated with the high-frequency components of AP sway ($r = .92$) and AP sway velocity ($r = .96$), which are associated with muscle activity. This finding is consistent with that of Adkin et al. (2000), who reported that perception of increased postural threat has been associated with increased mean frequency of sway. The perceptions of sway and instability, however,

TABLE 2: ANOVA of Low- and High-Frequency Components of Sway Power Spectrum

Source	df	0-1 Hz		1-3 Hz	
		F	p	F	p
Main Effects					
Slope	3	4.68	.005	27.13	<.001
Height	1	44.21	<.001	12.42	.002
Visual reference	1	93	<.001	15.18	<.001
Interactions					
Slope × Height	3	2.17	ns	6	.001
Slope × VisRef	3	1.65	ns	5.56	.002
Height × VisRef	1	19.77	<.001	3.67	ns
Slope × Height × VisRef	3	2.4	ns	0.67	ns

TABLE 3: ANOVA of Perceptions of Postural Sway and Instability

Source	df	Perceptions	
		F	p
Main Effects			
Slope	3	25.93	<.001
Height	1	5.01	.035
Visual reference	1	19.66	<.001
Interactions			
Slope × Height	3	0.57	ns
Slope × VisRef	3	4.65	0.005
Height × VisRef	1	1.43	ns
Slope × Height × VisRef	3	1.49	ns

were less correlated with the low-frequency components of AP sway ($r = .76$) and AP sway amplitude ($r = .78$), which are affected by visual factors. The discrepancy between true instability and perception of balance at elevated and inclined surfaces may constitute an increased risk factor for loss of balance associated with roof work.

The presence of close visual references effectively improved balance by reducing the destabilizing effect of height, as demonstrated by

the significant Visual Reference × Height two-way interactions for AP sway, sway velocity, and low-frequency components of sway. The destabilizing effect at height without close visual references is similar to that of an eyes-closed condition, which completely eliminates visual stabilization. Furthermore, visual reference reduced the effect of slope on both sway velocity and the high-frequency components of sway. These interactions reflect the increased effectiveness of visual information for balance control in unstable postural and support conditions, such as on a sloped surface.

Interestingly, the interactions of visual factors, including height and visual reference, with surface slope in this study were significant for sway velocity but not for sway amplitude. This is consistent with a report indicating that visual information can be used to reduce and optimize dynamic muscle action (sway velocity), even though sway amplitude was less affected (Kunkel et al., 1998).

This study used goggles as a means of controlling the presence of visual references. One may suspect that the confounding factor (i.e., reduced field of view) can spuriously account for the reported destabilizing effect of environment without close visual references (i.e., at height). However, the small differences in AP sway and sway velocity between the tests with and without goggles at ground level demonstrated that the effect of the modified visual field was relatively small, too small to account for the great stabilizing effect of visual reference at height.

It has been reported that visual stabilization of posture can be achieved with slightly reduced

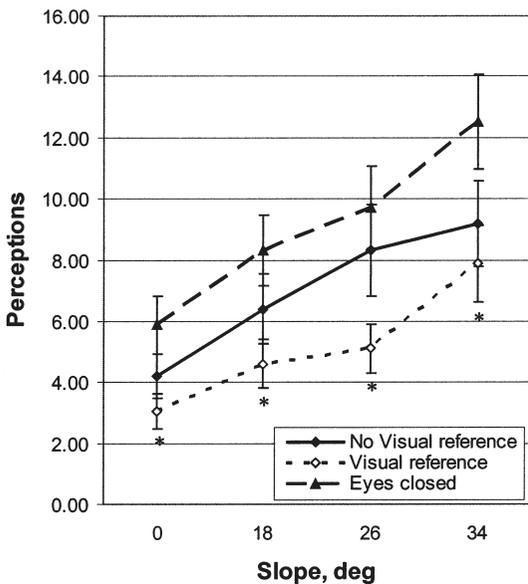


Figure 5. Perceptions of postural sway and instability – slope and visual reference interaction. * Indicates a significant effect of visual reference at the specific slope. Vertical bars represent standard errors.

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 homogeneous for the entire visual field (Straube, Krafczyk, Paulus, & Brandt, 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, Warren, & Kay, 1996, 1999). Therefore, the experimental design (using goggles in this study) is practical and adequate in testing the effect of visual references at elevated environments.

The use of visual reference has a practical application in maintaining balance at elevated and sloped surfaces. It has been suggested, in studies on postural control during performance of precise visual tasks, that close visual references reduce sway only when they are attended (Stoffregen, Pagulayan, Bardy, & Hettinger, 2000; Stoffregen, Smart, Bardy, & Pagulayan, 1999). Maintaining postural stability is not entirely automatic, and the attentional demands of a balance task increase with the difficulty of the task (Lajoie, Teasdale, Bard, & Fleury, 1993). It is likely that in the sensory-deprived and highly challenging postural conditions at elevated and sloped surfaces, participants may have devoted more of their attention to the nearby visual references.

Shumway-Cook, Woolcott, Kerns, and Baldwin (1997) proposed that the principle of "posture first" operates when the central nervous system needs to distribute limited attentional resources between a balance task and a concurrent cognitive task. A number of experimental studies have provided evidence for the validity of this principle (Marsh & Geel, 2000; McIlroy et al., 1999; Teasdale, Bard, LaRue, & Fleury, 1993). In real sloped-roof environments, which are characterized by both high postural demands and high risk of injury from a fall, more attentional resources will be directed or redirected to the task of maintaining or restoring balance, especially in the initial period of workers' postural adaptation and in inexperienced workers. In such conditions visual references, if available, may assist postural stabilization and serve as an effective balance control. However, there is strong evidence that shifting attention away from a visual stimulus reduces but does not

abolish visual detection and discrimination performance (Braun, 1998; Braun & Julesz, 1998). Close visual structures, even when not explicitly attended, might be noticed and used if needed by redirecting visual attention.

The extent to which the findings of this study can be generalized may be limited by the short duration of exposure to the experimental conditions, as compared with real roof work durations. Further research involving longer or repeated exposures may help to assess the interactions of postural adaptation (which may lead to stabilization) and fatigue (which may cause further postural deterioration) in the challenging roof environment. Additional research can be performed to address the possible effects on balance of other environmental factors commonly encountered in roof construction (e.g., wind, temperature, and humidity).

Furthermore, the participants in this study were involved only in a static postural task. Future studies should be expanded to assess the effects of these roof environment factors on workers' postural stability during simulated dynamic tasks such as reaching, lifting, walking, and carrying. Experiments in simulated construction environments with eye or gaze tracking and application of the dual-task paradigm may further improve understanding of the role that visual factors and attention play in balance control and, therefore, lead to new fall prevention strategies.

CONCLUSION

The elevated and sloped surfaces in roof work environments synergistically induced significant instability on standing balance in construction workers. Workers' perceptions of instability did not accurately reflect the increased destabilizing effects of height on sloped surfaces, which may further increase their risk of losing balance. Balance on elevated and sloped surfaces was improved in the presence of close visual references.

The findings have practical implications. Temporary structures that provide level work surfaces can significantly reduce the effort for balance control (and thus reduce the risk of loss-of-balance incidents) and could be useful in preventing falls on steep slopes. For example,

further evaluation of the effectiveness of scaffolding boards with roof jacks is merited. Close visual references can further reduce postural instability and, thus, the potential for loss-of-balance incidents on roofs. Installing or using a temporary nearby vertical reference structure may be useful as an additional postural instability control measure during roof work.

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