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Postural stability during task performance on elevated and/or inclined surfaces

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Abstract. The purpose of this study was to subjectively and objectively evaluate the postural stability of forty industrial workers while performing simulated industrial tasks on inclined and elevated surfaces under various combinations of environmental lighting and noise distraction conditions. The results suggest the following ordering for the effects of risk factors on objective measure of postural balance: (1) environmental lighting, (2) elevation of standing surface, (3) gender, (4) inclination of standing surface, (5) age. The task performed would be ranked highest had the data been analyzed across the three tasks. The postural sway length significantly increased with increasing elevations and inclination angles for the stationary and bending tasks implying body's perceived risk of fall deployed increase in postural muscle contraction. This compensatory mechanism indicated by increased sway length actually did reduce postural sway amplitudes with increasing elevation but for increasing inclination the postural sway amplitudes increased. While the objective measure of postural sway increased with the increasing combination of elevation and inclination, the subjective measure of stability did not show a significant two way interaction, implying that the participants were not able to perceive the combined risk to postural imbalance, causing potential inability to deploy appropriate postural muscle corrective actions.

Keywords: Elevation, inclination, postural stability, perceived sense of slip/fall, occupational safety

1. Introduction

Falls from elevations present significant potential for debilitating accidents, causing permanent disability or fatality. According to the Bureau of Labor Statistics [8], falls from an elevation constituted the sixth leading cause of injuries involving days away from work and accounted for more than 9% of workers' compensation claims [17]. The construction industry has one of the highest incident rate of falls, accounting for more than 80% of all reported incidents involving fatality, according to the National Institute for Occupational Safety and Health (NIOSH) database [18]. Within the construction industry, between 1981 through 1986, falls accounted for the highest fatality rate (25%), followed by electrocution

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(15%), and motor-vehicle-related accidents (14%) [16]. In 1995, in the construction industry, 97.9% of the fatal falls were to a lower level compared to 57.5% for nonfatal falls [19]. Due to the severity of accidents related to falls from an elevation, the associated costs are among the highest in the industry. In an analysis of accident profiles among New York industries, Cohen [12] found that falls were attributable to a combination of surface conditions and poor lighting. Sixty six percent of these accidents had occurred indoors, where the environmental lighting was poor, as is the case with new construction sites. In another study of NIOSH's Fatal Accident Circumstances and Epidemiology (FACE) report for 1987–1989, it was found that fatal falls have occurred from heights as low as three feet [7].

Generally, falls are preceded by a loss of upright stability. The ability of the worker to regain balance at an elevation would depend on his/her ability to adopt an alternate body posture, either by stepping or grabbing a support to bring his/her center of gravity within the base of support. However, this may be compounded by several other physical and psychophysical factors. For example, most construction work is performed at sites with compliant floor surfaces with surface contaminants that may contribute to slippage. Sufficient support area may not be available for the worker to take a step in order to prevent a loss of balance. Under such conditions, the worker would have to adopt a hip or ankle movement strategy to prevent a fall [15], which in turn may create additional shear forces at the shoe-floor interface causing a greater probability of slip.

The phenomenon of fall is dependent not only on physiological, environmental and frictional factors, but it is also influenced by one's perceptions (or higher center input) of how one would handle an impending fall. Therefore, any mismatch between subjective perception of an impending loss of balance and actual (as measured by objective measures) risk of fall may give rise to incidence of falls. This study provides an experimental design for investigating the interaction between standing surface elevation/inclination and other fall risk factors such as job-task, lighting, age, sex, and their impact on objective and subjective measures of postural balance.

2. Methods

2.1. Participants

A total of 40 participants were recruited for this study. The participants were recruited from Labor Unions, which represented a variety of trades. These included service trades such as maintenance and janitorial, commercial food service workers, construction workers and plumbers/pipe fitters. Stratified sampling from two age groups was performed: 22 to 29 years (younger) and 50 to 59 years (older). Each group was equally represented by both genders. All testing was carried out in the specially prepared facility described below. All participants were healthy and were subjected to physical examination to rule out the presence of any neurological, cardiovascular and musculoskeletal disease. The Institutional Review Board of the University of Cincinnati approved the test protocol and all participants completed an informed consent form prior to testing. All participants wore a whole body safety harness during the test.

2.2. Risk factors/treatment conditions (independent variables)

Inclined surface: Three levels of inclination were used, 0°, 14° and 26°. A majority of construction sites (both residential and commercial) use the above-mentioned roof inclination angles. Three specially designed inclined surfaces (described later in this section) were attached to the force plate to obtain the desired values of inclinations.

Elevated surface: 0 (or floor level), 30.48 and 60.96 cm above floor levels were used. In a workplace, it is not uncommon to have workers perform various tasks at elevations less than those found at the rooftop such as working while standing on a stepping stool or ladder (e.g. ceiling work, hanging drywall etc). Based on our preliminary studies, we have observed that elevations as low as 17.78 and 35.56 cm produce a significant increase in postural sway and increase activities of some of the postural muscle groups (anterior tibialis and gastrocnemius) [3]. A loss of balance occurring even at slight elevations might cause a serious injury or fatality. Bobick et al. [7] have reported that consequences of falls are always severe no matter how low the elevation. Three specially designed elevated surfaces (described later in this section) were attached to the force plate system to obtain the desired elevation levels.

Environment lighting: Availability of proper visual cues is critical for maintenance of postural balance. In a poorly lit area, visual cues will be inadequate for the maintenance of balance. In a work environment, lighting has been found to be one of the critical factors related to accidents due to falls. In this study, participants were tested for postural balance under two extremely different lighting conditions, using illumination guidelines [13] for rough to moderately precise work: (1) Acceptable, good lighting: 320–800 lux (30–74 foot candles) and (2) Unacceptable, poor lighting: < 20 lux (< 2 foot candles). A light meter was used for measuring the lighting condition (in lux).

Distraction condition: Each trial was performed with and without an audio exposure to construction site noise. The distraction protocol was developed based on the audio channel of videographed construction site sounds where the workers were found to be working at elevated and/or inclined surfaces. This required reproduction of the environmental noise experienced by workers at the worksite under the laboratory conditions. The noise level (sound pressure) and the frequency response were reproduced with minimal loss in fidelity.

The distraction protocol for the study included the use of a radio frequency based (900 Hz) Wireless Remote Headphone (Optimus: Model 1682 K964) that was worn by the participant during the entire duration of the session. During the tasks requiring audible distraction (determined randomly), a prerecorded segment of construction noise was played into the headphones using a high performance sound system (Pioneer Stereo Deck model CT-W404R, Pioneer Stereo Receiver model SX-203). External speakers (Fig. 1; Panasonic model 7173) were used to amplify the voice of the facilitator providing instructions and other verbal commands to the participant. The actual control unit of the audio system was rack mounted in a mobile unit and was placed outside of the test enclosure to minimize cues to the participant during testing. The distraction was started 3 sec. prior to each 30 sec. test and was turned off 1 sec. second following the end of the test. At the culmination of the session, the headphones were connected to a battery charger for recharging.

Postural stability tasks: Three tasks were used and are described as follows. Stationary: The participant stood erect on the force platform for 30 s with hands at the hip. Bending: (i) The participant stood erect on the force platform for 12 s, then with voice command from the investigator, performed the following activities: (ii) rapidly bent upper trunk to touch the knees, (iii) stayed in this position for 5 s, and (iv) straightened back up for the remaining 13 seconds.

Reach task: (i) Participant stood erect on the force platform for 7 s, then with voice command from the investigator, performed the following activities: (ii) reached forward to pick up a weight attached to a $5.08 \times 10.16 \times 60.96$ cm^3 wood block (cumulative weight of 2.36 kg), brought it close to the belly, and replaced it on the shelf, (iii) repeated step (ii) for 4 cycles, (iv) reassumed the erect position for the remaining time. The shelf was placed at the knee height and at a functional reach distance away from the participant. The above tasks have been used in our previous studies [2,9,10].

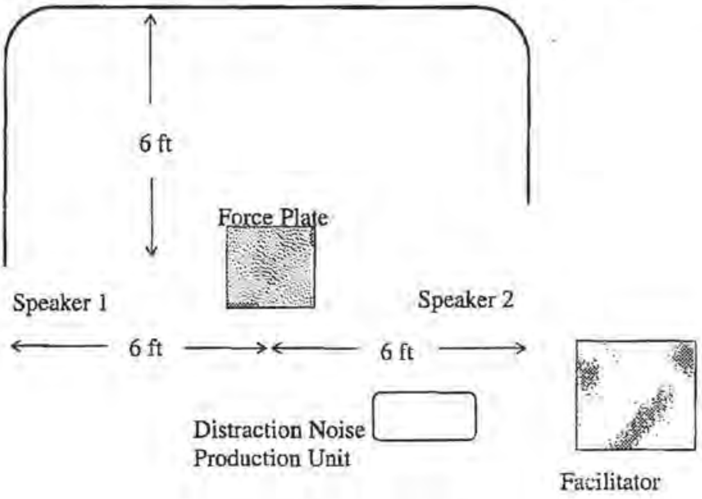


Fig. 1. Experimental set up.

2.3. *Testing facility and inclined/elevated surfaces*

The specialized enclosure unit consisted of three modular framework structures, made of lightweight aluminum that was fitted with fabric panels. Figure 1 provides a schematic representation of the enclosure system. These enclosure walls (panel) used a flat black felt-type fabric that forms a uniform viewing surface offering minimal visual cues. The aluminum panel framework pieces were interconnected with removable screw-knobs. The cloth panels, made of felt fabric on fire-resistant plastic sheath were lined with magnetic strips. Matching strips were found on the framework pieces. The enclosure framework was constructed to the height of the false ceiling (279.40 cm inches). A rigid roof structure, made of the similar material as the walls of the enclosure, was hung from the top to add uniformity to the appearance of the enclosure.

The roof of the enclosure extended up to and above the participant's head. The floor of the enclosure was covered with a low-pile black carpet to minimize further visual cues. This facility was equipped to include a specially designed overhead single-point safety harness hookup. This system accommodated a hook that allows the whole body safety harness to be attached to it while the participant stood on an inclined/elevated surface at various elevations performing the assigned study protocol.

A specially designed structure was constructed to provide all possible combinations of the three inclinations (0, 14°, and 26°) and elevations (0, 30.48 and 60.96 cm). The structure was made of cast iron and consists of seven independent pieces that could be combined to achieve the required inclination and elevation. The surfaces of the unit were sandblasted to increase the friction between the participants' shoe sole and the standing surface for a safer grip while standing. Special cotter pins were inserted at specific places to keep the modular structures together and prevent slip-outs and mechanical instability of the whole system. Special care was taken to ensure that there was minimal clearance for relative motion of the individual pieces, since this might introduce error in the force platform measurement. The participant was asked to step on the force platform before commencement of the task. A specialized ladder, with an easy access system, was constructed for the participant to mount the surface.

2.4. *Outcome measurements (dependant variables)*

Objective measures of postural sway/instability: The postural sway was obtained with a force platform system. These kinetic measurements, which included the forces and moments exerted on the force platform, were collected using a piezoresistive force platform (Model OR-6-1000, Serial # 3371 manufactured by AMTI, Newton, MA) capable of measuring forces and moments in the three orthogonal directions. The details regarding the accuracy of the force plate are available in Bhattacharya et al. [4]. At the start of the session, the force platform was calibrated and checked to ensure that the measurement error of the plate was within the acceptable 2% range [4]. The force platform was placed flush with the floor. The signals from the plate were fed into an amplifier (AMTI, model SGA6). The signals coming out of the amplifier were then delivered to an IBM compatible 486 personal computer, using an A/D board and Peak Performance Software (Peak Performance Technologies Inc., Englewood, CO) for data collection at 60 Hz for 30-second duration. Collected data was further processed to calculate the movement patterns of the body's center of pressure (CP), which were then used to determine the variables of postural sway using custom software developed in our laboratory (KineLysis 1998–2002, All Rights Reserved, University of Cincinnati). Four variables were calculated for quantifying postural sway. These are: (1) Sway area (SA), which is the area of the projection of the body's CP on the horizontal (xy) plane due to sway; (2) sway length (SL), which is the distance traveled by the CP; (3) medio-lateral (ML or x-direction) excursion, which is the net deviation of the CP in the ML direction; and (4) anterior posterior (AP or y-direction) excursion, which is quantitated by measuring the net deviation of the CP in the AP direction. We have used these variables in several research studies in our laboratory [4–6,9–11]. An increase in all or any one of the above variables implies increased postural sway or instability.

Subjective measures of postural sway/instability: A short questionnaire-type rating scale was administered to determine the subjective perception of slip and/or potential fall (PSOF) of the participant during postural sway tests [10]. It consisted of simple questions (about their postural sway/balance), which the participant had to answer immediately after each test. The results from this test were used to see how the participant's subjective perception correlates with the objective measures of postural stability as measured by the various postural sway parameters. A high score (8 is the maximum score possible and 0 is the minimum score possible) implies a high subjective perception of slip or sway and/or fall. The PSOF scale has been validated and tested in other studies conducted in our laboratories [10,11].

2.5. *Data analysis strategy*

A repeat measure analysis of covariance (ANCOVA) was performed to analyze the kinetic and PSOF data. Four dependent postural sway variables, SA, SL, ML and AP sway, and PSOF scale were used in the ANCOVA. The sway variables were log normally transformed. The covariates of age, gender, and baseline sway variables and the height to weight ratio were the between-participant variables used to predict the postural sway outcomes. Age, gender and height to weight ratio were the covariates used in the PSOF ANCOVA model. Within participants, the experimental conditions of elevation, lighting, inclination and distraction were tested for their effect on postural stability and the PSOF scale. In addition, all possible two-factor interactions between the within-participant factors were investigated. The postural sway and PSOF data were analyzed within the three tasks performed by the participants (bending, reach and stationary tasks). Beginning from saturated models involving all covariates, within-participant factors and interactions, final models were derived through a backward elimination strategy of insignificant covariates and two-factor interactions. In the final models, only significant covariates and two-factor interactions were included, along with the within-participant main effects, which were not candidates for removal from the ANCOVA models. An alpha-level of 0.05 was used for all statistical tests.

Table 1
Demographics

	Male ($n = 20$)		Female ($n = 20$)	
	mean	s.d.	mean	s.d
Age (year)	39.15	15.08	39.50	14.90
Weight (kg)	89.89	18.05	73.88	14.54
Height (cm)	175.15	6.33	162.13	5.57
Left foot length (cm)	27.19	0.95	24.81	1.04
Right foot length (cm)	27.23	0.90	24.88	1.09
Left foot width (cm)	10.23	0.60	9.27	0.46
Right foot width (cm)	10.12	0.52	9.28	0.47
Foot reaction time (m. second)	45.25	8.11	45.20	5.11
Hand teaction time (m. second)	39.87	10.51	41.57	7.71

2.6. *Experimental procedures*

Each participant was tested in four sessions. The first session was used for (1) briefing about the content of the study and signing the consent form, (2) measurement of detailed anthropometry, (3) selection of the appropriate shirt and shorts provided by the laboratory, (4) selection of the appropriate shoes (Red Wing; model/style: GripTec Sole 2160), (5) detailed orientation of the participant to Protocol of the tasks and PSOF questionnaire (6) a demonstration of the distraction protocol, including a sample run of the noise wearing the headphones, and (7) measurement of the appropriate overhead lanyard length attachment (for the safety harness) to be used for each individual combination of elevation (0, 30.48 and 60.96 cm) and inclination (0°, 14°, and 26°). Sessions two through four were used for data acquisition on the various test conditions. The blocked design allowed the use of only one elevation to be tested during one session. At the start of a session, his/her blood pressure and heart rate was measured. Participants did not undergo testing if the participants reported the following during previous 48 hours: (1) Alcohol consumption, (2) excessive stress at work/home, (3) consumption of medication affecting nervous system, and/or demonstrated abnormally high cardiovascular activity. The participants were instructed to wear the designated shirt, shorts, and shoes, and were fitted with the appropriate full-body harness.

The treatment conditions were blocked within the three levels of elevation (0, 30.48 and 60.96 cm), i.e. each session consisted of one of the three levels of elevation (chosen in random order). The participant started the session by performing 3 baseline tasks (stationary, bending, reach) under ideal conditions (good light, no distraction, 0" elevation, 0° inclination). S/he then performed 18 tasks. Each test was followed by a 1 min. rest during which the participant dismounted the test platform on to a level surface placed adjacent to the test platform. At the end of each task, the participant was asked to evaluate his/her perceived sense of loss of balance, using the PSOF scale [10,11]. Data from the force plate was collected as per the description given in the above sections. A typical test session required about 2.5 hours for completion.

The lighting in the testing chamber was controlled using independent lighting controls. The lighting in the room was measured using a light meter (Sper Scientific; Model: 840021) and recorded. All the data collected were stored on computer mass media storage disks and duplicated for data safety. The stored data were later analyzed with our custom developed software before it was used for statistical analysis.

3. Results

Forty workers participated in this study. Half of the participants were male. Descriptive statistics for variables common to the participants are provided in Table 1. Male participants appeared to be slightly

Table 2
P-values for testing the effects of age, gender, elevation, lighting, inclination, and distraction on sway length, sway area, ML and AP

Effect	Bending task				Reach task				Stationary task			
	Sway length	Sway area	ML	AP	Sway length	Sway area	ML	AP	Sway length	Sway area	ML	AP
Baseline	0.0001	0.001	0.02	0.01	0.0001	0.0001	0.005	0.0001	0.0001	0.0001	0.006	0.0002
Age	0.03	0.11	0.02	0.12	0.39	0.28	0.23	0.44	0.03	0.49	0.09	0.49
Gender	0.01	0.01	0.05	0.02	0.25	0.05	0.41	0.02	0.05	0.01	0.006	0.002
Elevation	0.0001	0.0003	0.35	0.004	0.0001	0.0002	0.73	0.0001	0.0001	0.009	0.39	0.003
Lighting	0.0001	0.0001	0.0001	0.01	0.0001	0.0001	0.0001	0.02	0.0001	0.0001	0.002	0.001
Inclination	0.0001	0.02	0.14	0.01	0.21	0.0001	0.007	0.0001	0.0001	0.10	0.006	0.23
Distraction	0.97	0.87	0.97	0.69	0.95	0.9508	0.75	0.88	0.74	0.93	0.68	0.74
Elevation* Inclination		0.002	0.02						0.007			

Table 3
Geometric least square mean of sway length, sway area, ML and AP by task, age, gender, lighting, and distraction

Experimental condition	Bending task				Reach task				Stationary task			
	Sway length	Sway area	ML	AP	Sway length	Sway area	ML	AP	Sway length	Sway area	ML	AP
Age												
Young	84.56	12.17	3.76	6.34	157.87	26.16	5.36	9.59	48.44	2.88	2.02	2.39
Old	89.28	13.54	4.18	6.77	159.03	27.02	5.53	9.55	51.68	2.89	2.21	2.39
% change	5.6	11.3	11.2	6.8	0.7	3.3	3.2	−0.4	6.7	0.3	9.4	0.0
Gender												
Female	83.78	11.47	3.76	6.13	155.95	25.12	5.35	9.19	48.41	2.50	1.91	2.14
Male	90.33	14.36	4.17	7.00	160.99	28.13	5.54	9.97	51.72	3.33	2.33	2.68
% change	7.8	25.2	10.9	14.2	3.2	12.0	3.6	8.5	6.8	33.2	22.0	25.2
Lighting												
Good	80.38	11.88	3.70	6.41	146.04	24.27	4.97	9.45	47.28	2.69	2.05	2.30
Poor	94.15	13.87	4.24	6.69	171.91	29.11	5.98	9.70	52.95	3.10	2.17	2.48
% change	17.1	16.8	14.6	4.4	17.7	19.9	20.3	2.6	12.0	15.2	5.9	7.8
Distraction												
No	87.66	12.98	4.03	6.57	159.41	26.92	5.44	9.62	50.18	2.95	2.12	2.41
Yes	86.33	12.70	3.90	6.53	157.50	26.25	5.46	9.52	49.89	2.83	2.10	2.38
% change	−1.5	−2.2	−3.2	−0.6	−1.2	−2.5	0.4	−1.0	−0.6	−4.1	−0.9	−1.2

heavier than the average American man (83.2 kg ± 15.1 s.d.), and their stature was larger than the average American man (174.5 cm ± 6.6 s.d.) [18]. Female participants were heavier than the average American woman (66.4 kg ± 13.9 s.d.), and their stature was comparable to the average American woman (162.1 ± 6.0 s.d.) [14]

3.1. *Findings based on objective measures of postural balance*

The results of the ANCOVAs are shown in Table 2. The results presented were controlled for baseline data obtained on each day of the three testing days. The geometric means for the levels of each within-participant factor, significant within-participant interactions and the significant covariate effects are shown in Table 3 and Fig. 2 to Fig. 4.

Elevation effect: Elevation significantly affected SL, SA and AP sway for all 3 tasks (Figs 2A to 2C). However, an increasing monotonic relationship with elevation was observed only for sway length during the bending and stationary tasks (Fig. 2A). Sway length was greatest for the highest elevation (60.96 cm)

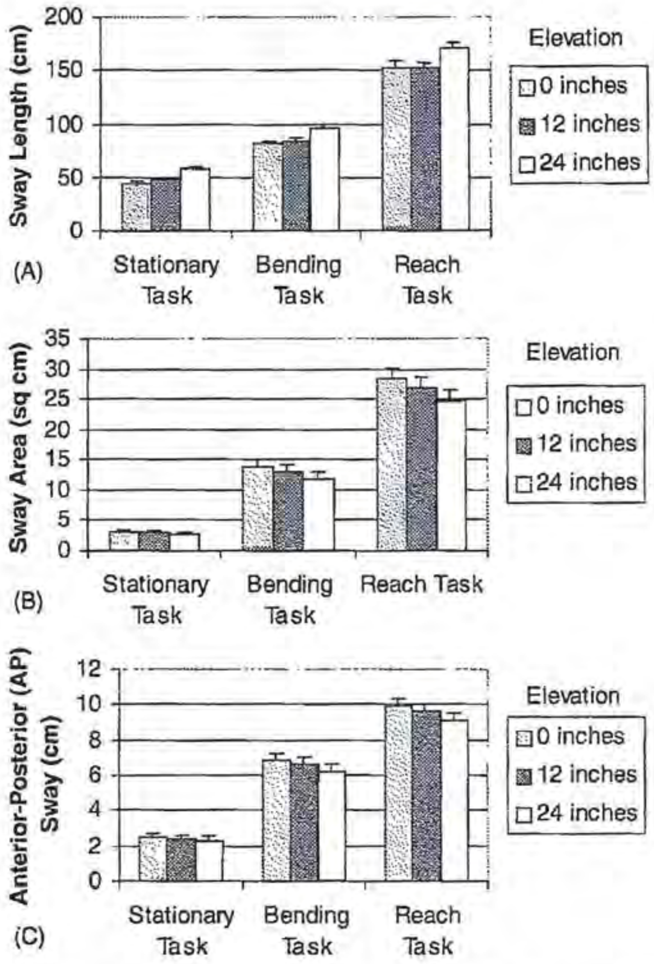


Fig. 2. A. Effect of elevation on postural sway length (SL) by task. (geometric mean of sway length (cm) with the 2 standard error range); B. Effect of elevation on postural sway area (SA) by task. (geometric mean of sway area (sq cm) with the 2 standard error range); C. Effect of elevation on anterior posterior (AP) sway by task. (geometric mean of AP sway (cm) with the 2 standard error range).

while participants performed the reach task; however the difference between the lower elevations (0 and 30.48 cm) was less than 1 cm for the reach task and not statistically different (Fig. 2A). The percent increase for SL for 30.48 and 60.96 cm with respect to 0 cm elevation was 3.1% and 16.8%, respectively, for the bending task and 7% and 28.9%, respectively for the stationary task. For the reach task, the 60.96 cm elevation showed an increase of 11.8% in SL with respect to 0 cm while at 30.48 cm SL was almost the same as that for the 0 cm. For all of the tasks, SA (range of decrease with respect to stationary task: 13.4% to 3.92%) and AP sway (range of decrease with respect to stationary task: 9.56% to 2.8%) actually decreased with increasing elevation (Figs 2B and 2C). With increasing elevation, ML sway also decreased but was not statistically significant.

Lighting effect: Lighting was found to affect all 4 postural sway outcomes for all 3 tasks performed. Sway length, SA, ML sway and AP sway invariably were found to increase in poor lighting as compared to good lighting (Table 3). In comparison to good light, the percent increase in sway responses were

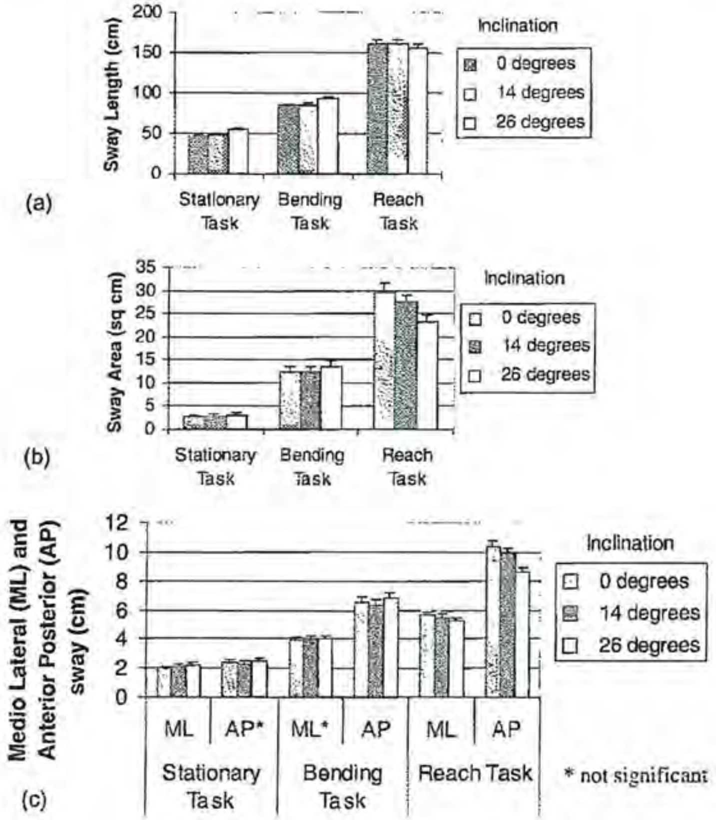


Fig. 3. A. Effect of inclination on postural sway length (SL) by task. (geometric mean of sway length (cm) with the 2 standard error range); B. Effect of inclination on postural sway area (SA) by task. (geometric mean of sway area (sq cm) with the 2 standard error range); C. Effect of inclination on anterior posterior (AP) and medio-lateral (ML) sway by task. (geometric mean of AP (cm) and ML (cm) with the 2 standard error range).

different depending upon type of task being performed in poor lighting. The values of percent increases in sway variable responses for poor lighting are given in Table 3.

Inclination effect: The inclination angle was significantly related to SL, SA and AP sway for the bending task (Figs 3A to 3C). Sway area was greatest (8.15% higher than 0 degrees) for the largest inclination angle (26 degrees) during the bending task; however, the two lesser inclines did not differ statistically from one another. For the stationary task, the inclination angle was significant for SL and ML sway only. Similar to elevation effect, SL increased monotonically as the inclination angle increased for both the bending and the stationary tasks. The percent increases in SL with respect to 0 degree inclination were 10.5 and 1.3% for 26 and 14 degrees, respectively, for the bending task, and 19.7 and 4.7% increase, respectively, for the stationary task. For the reach task three sway variables were significantly affected by the inclination. All four sway variables for the reach task decreased (range of decrease in responses for 26 and 14 degrees with respect to 0 degrees was 0.27 to 21.8%, respectively) monotonically as inclination angle increased.

Distraction effect: Distraction was not found to be significantly related to any of the sway variables and all variables, except for ML (in the reach task), decreased for all task types performed (Table 3).

Cofactor effects: In addition to these findings for the within-participant variables, the covariates also were found to often affect the sway outcomes. The baseline SL, SA, ML sway and AP sway were found to be significantly and positively related to the comparable outcome for all 3 tasks (Table 2). Age was a significant predictor of SL for the bending and stationary tasks, while ML sway was significant for the stationary task only. Except for AP sway for stationary and reach tasks, all variables showed a greater sway for the older age group (Table 3). For the stationary task, the older worker group's SL, SA, and ML were 6.7, 0.35, and 9.4 % respectively, higher than that for the younger group. For the bending task, the older worker group's SL, SA, ML and AP were 5.6, 11.25, 11.17 and 6.8% higher, respectively, than that for the younger group. Gender was found to significantly affect SL, SA, ML sway and AP sway during the bending and stationary tasks (Table 3). For the reach task only the AP sway was affected by gender. For these models, males demonstrated greater sway (range of percent higher: 6.8% to 33.2 %) than did females (Table 3). The height to weight ratio was not found to be related to postural sway and was removed from all of these models.

Interaction effect: Inclination and elevation were found to be significantly interacted in three of the postural sway models, affecting SA and ML sways during the bending task and SL during the stationary task (Figs 4A to 4C). There was a monotonic increase in SA only for the increasing inclination under the 30.48 cm elevation condition for the bending task (Fig. 4A). For 0 and 60.96 cm elevations increasing inclination decreased the SA at 14 degrees and increased at 26 degrees. The SA was greater at 0 cm elevation for both 0 degree and 14 degree inclinations than those at 30.48 and 60.96 cm elevations. At 26 degrees inclination, the SA response was almost the same for 0 and 30.48 cm elevations but decreased substantially at 60.96 cm inches elevation. The ML sway response was comparable to that for the SA at 60.96 cm elevation with increasing inclinations (Fig. 4B). However, at 0 cm elevation the ML sway response decreased with increasing inclination. At 30.48 cm elevation, like the SA response, the ML sway increased with increasing inclinations.

The interaction of inclination and elevation during the stationary task was quite interpretable, since SL was found to increase monotonically as either condition increased, while holding the other constant (Fig. 4C). For example, sway length increased from 41.28 to 42.56 to 51.69 cm (range of percent increase from 0 degree: 3% to 25%) as the inclination angle increased from 0 to 14 to 26 degrees, respectively, while the participants stood at ground level. Similarly, SL increased from 41.28 to 44.16 to 54.80 cm (range of percent increase from flat surface: 7% to 33%) as the elevation increased from 0 to 30.48 to 60.96 cm, respectively, and the participants stood on a flat (0 cm elevation) surface.

3.2. *Findings based on subjective measures of postural balance (perceived sense of fall)*

Statistically significant changes in perceived sense of fall were found for inclination ($p = 0.0001$), task ($p = 0.015$), light ($p = 0.0001$) and noise distraction ($p = 0.0017$). The repeated measures analysis of variance for between participant effects on perceived sense of fall (PSOF) showed no significant association, therefore, the between participant covariates (age, gender and height/weight) were dropped in the final model. There was no significant 2-way interaction among any of the experimental conditions. A higher score on PSOF scale implied an increased subjective sense of postural imbalance. The PSOF score for the 26-degree inclination was significantly larger when compared to that for 14-degree (127% larger) inclination and no inclination (182% larger) (Fig. 5A). The PSOF scores of the bending (22% greater) and the reach (21% greater) tasks were found to be significantly greater when compared to the stationary task (Fig. 5B). Poor lighting increased PSOF score by 57% (PSOF score for good lighting: 0.75; poor lighting: 1.18) compared to good lighting. The presence of noise distraction caused only

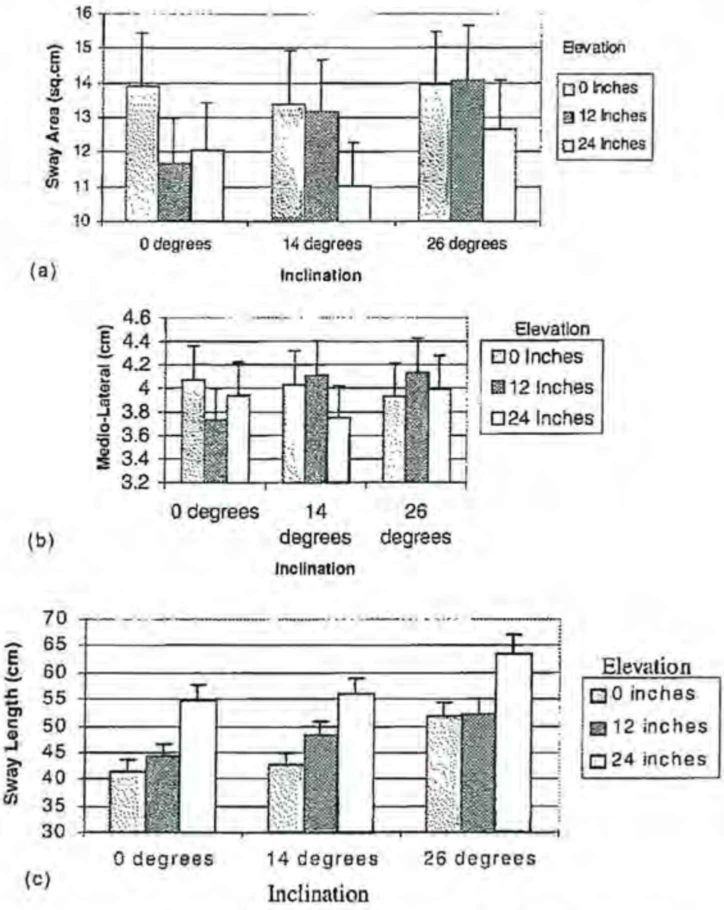
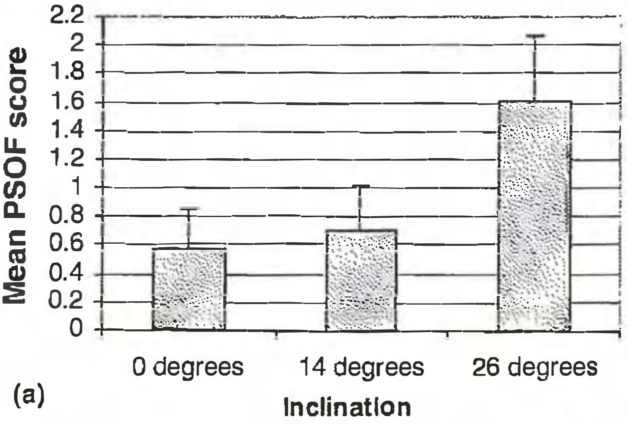


Fig. 4. A. Interaction of inclination and elevation on postural sway area (SA) for the bending task (geometric mean of sway area (sq cm) with the 2 standard error range); B. Interaction of inclination and elevation on medio-lateral (ML) sway for the bending task (geometric mean of ML sway (cm) with the 2 standard error range); C. Interaction of inclination and elevation on postural sway length (SL) for the stationary task (geometric mean of sway length (cm) with the 2 standard error range).

a 6.5% increase (PSOF score with distraction: 0.99; without distraction: 0.93) in PSOF score. In the present study, the experimental conditions elicited subjective responses to utilize only a part of the PSOF scale, which may be due to insensitivity of the scale and/or level of environmental risk factors presented to the participant.

4. Discussion

Several extrinsic and intrinsic factors contribute to the maintenance of upright balance for humans. While intrinsic factors consist of muscle strength, age, gender, reaction time, health status, medication and exposure to neurotoxic chemicals, extrinsic factors include environmental lighting, surface conditions (contaminants, compliance, coefficient of friction between the shoe-surface interaction), and other physical factors affecting the participants' ability to maintain balance. Since a fall or near fall is usually preceded by a momentary loss of balance, determination of factors leading to loss of balance is vital to



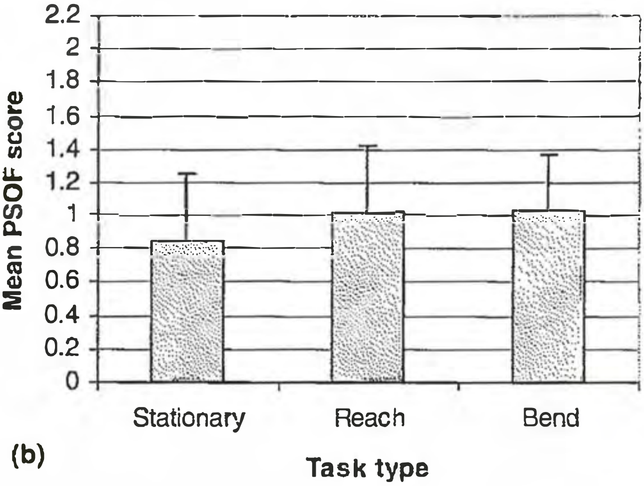


Fig. 5. (a) Effect of inclination on PSOF (arithmetic mean and the 2 standard error range); (b) Effect of task on PSOF (arithmetic mean and the 2 standard error range).

the fall prevention. Working on an elevated and/or inclined surface may introduce several intrinsic as well as extrinsic factors that would compromise the worker's postural stability. Roofers and construction workers frequently experience these surfaces that modifies their proprioceptive afferent input to balance maintenance. This may compromise their ability to maintain safe balance and the ability to regain upright stability in the event of a momentary loss of balance. The results from the study indicate a significant effect on postural stability during task performance on elevated and inclined surfaces (Figs 2 and 3).

The SL increases were noted with increasing elevations for all three tasks implying that the body's perceived risk of fall deployed an increase in postural muscle contractions (Fig. 2A). This finding is consistent with that of a previous study [1] where it was also reported that during stationary standing at different heights, the postural SL monotonically increased. We demonstrate that standing and completing simple tasks such as bending or reaching at various heights elicits larger compensatory responses by the motor control. This compensatory mechanism, indicated by the increased SL, did reduce the postural sway amplitudes measured by SA, ML and AP (Figs 2B and 2C). While the perceived sense of fall score was not significant for the elevation factor, the PSOF score for the 60.96 cm elevation was higher than that for the 0 cm, but the 30.48 cm elevation actually showed a lower PSOF score. This implies a lack of perception of loss of balance at an elevation while the objective measures of amplitude of sway variables (SA, ML and AP) showed a "real" imbalance (Figs 2B and 2C). This mismatch could be due to insensitivity of the PSOF tool used and/or the body's inability to sense a lower level threat posed by 30.48 cm elevation test condition.

The postural sway length monotonically increased as the inclination angle increased for stationary and bending tasks (Fig. 4C), which is comparable to that observed for the elevation effect (Fig. 3A). Such an increase is consistent with the observed monotonic increase in the PSOF score, implying increased perception of risk of imbalance (Fig. 5A). Like the elevation effect, under such an increased perceived risk of imbalance, an increased SL response to increasing inclined angles was expected (Fig. 4C). However, unlike the elevation effect, the increased SL was not sufficient to decrease the sway amplitudes (SA, ML and AP) with increasing levels of inclination angles for stationary and bending tasks (Figs 4A and 4B). On the contrary, the sway amplitudes actually increased with increasing inclination angle, implying that deployment of postural muscle contraction was inadequate to reduce the postural sway amplitude while performing stationary and bending tasks on inclined surfaces. The response for SL during the reach task was not significant and actually reduced for the 26-degree angle (with respect to 0 degree). However, sway amplitudes (SA, ML and AP) were decreasing monotonically with increasing inclination (Figs 4A and 4B).

The interaction between inclination and elevation effect with SL during the stationary task found as *both* factors increased (higher elevations and greater inclination angle), the postural sway increased even more than could be expected from these factors individually under the assumption of a linear additive model. Such an increase in SL implies overcompensation by the postural muscles to overcome the psychophysical "fear" of loss of balance as the elevation and inclination increased together. While the objective measure of postural sway increased with the increasing combination of elevation and inclination, the subjective measure of PSOF did not show a significant two way interaction, implying that participants were not able to perceive the combined risk to postural imbalance, causing potential inability to deploy appropriate postural muscle corrective actions.

As poor environmental lighting affects one of the major physiological afferents (i.e. visual input) necessary for postural balance, all four postural sway variables were detrimentally influenced. The poor environmental lighting condition had a significantly detrimental impact on SL (increased with respect to that for the good lighting), implying perceived risk of imbalance was higher, which is supported by the results of PSOF score being higher for poor lighting than for the good lighting condition (Tables 2 and 3). However, unlike the elevation effect, the poor lighting associated increase in SL was not adequate to reduce the sway amplitudes (SA, ML and AP). The above effect of lighting on postural balance during task performance on inclined and elevated surface is comparable to those reported by us previously for task performance on flat surface at floor level [11]. Based on percent increases in the SL, SA and ML variables (Table 3) in the poor lighting condition (compared to the good lighting condition) the reach task, bending task and stationary task were ranked first, second and third, respectively.

5. Conclusions

In summary, the conclusions reached from this experimental research were:

1. Standing on an elevation elicits a compensatory mechanism, indicated by the increased sway length, which reduces the postural sway amplitudes measured by total sway area, medio-lateral and anterior posterior sway.

2. Standing on increasing inclinations increased all postural stability variables for the stationary and bending tasks, however decreased them for the reach task implying that higher center induced voluntary motions associated with the reach task were providing protective measures to minimize the sway amplitudes
3. The interaction between inclination and elevation effect imply a synergistic relationship of these two factors.
4. Poor lighting detrimentally influenced all four postural sway variables. The results imply that the reach and bending tasks require more reliance on having good environmental lighting compared to the stationary task for postural balance.
5. The perceived sense of fall indicates that sometimes a mismatch may occur between the perceived risk and the objective measure of postural balance. This perception mismatch while a worker is on an elevated and inclined surface may increase the risk of losing his/her balance and falling, resulting in severe injuries or even fatality.
6. For the purpose of rank ordering, based on objective measures of postural balance, the following ordering for the magnitude of the effects of these experimental factors and covariates on postural balance is suggested: (1) lighting; (2) elevation; (3) gender; (4) inclination; (5) age. The tasks performed would also have been found to be highly significantly different had the data been analyzed across these three tasks. This result is expected, and has been demonstrated in our previous studies that have investigated the effects of the task factor, with the postural sway being greatest during the reach task, followed by the bending and stationary tasks [11].

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