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Effects of foot placement on postural stability of construction workers on stilts

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ABSTRACT

Stilts are elevated tools that are frequently used by construction workers to raise workers 18–40 inches above the ground. The objective of this laboratory study was to evaluate the potential loss of postural stability associated with the use of stilts in various foot placements. Twenty construction workers with at least 1 year of experience in the use of stilts participated in this study. One Kistler™ force platform was used to collect kinetic data. Participants were tested under six-foot-placement conditions. These 6 experimental conditions were statically tested under all combinations of 3 levels of elevation: 0″ (no stilts), 24″ stilt height and 40″ stilt height. SAS mixed procedure was used to evaluate the effect of different experimental conditions. The results of the multivariate analysis of variance (MANOVA) and repeated measures of univariate analyses of variance (ANOVAs) demonstrated that stilt height, foot-placement direction, and foot-placement width all had significant effects on the whole-body postural stability. This study found that the higher the stilts were elevated, the greater the postural instability. A stance position with one foot placed forward of the other foot produced greater postural instability than a position with the feet parallel and directly beneath the body. This study found that placement of the feet parallel and directly beneath the body, with the feet positioned a half shoulder width apart, caused a greater amount of postural sway and instability than one and one-and-half shoulder width. This study also found that construction workers using the stilts could perceive the likely postural instability due to the change in foot placements.

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1. Introduction

Stilts (Fig. 1) are elevated tools that are frequently used by construction workers to raise workers 18–40 inches above the ground without the burden of erecting scaffolding or a ladder. Recent NIOSH studies (Pan et al., 1999, 2000) further supported these hypotheses and indicated that workers perceived greater fall potential and physical stress when using stilts. A study from Duke University indicated that stilts were responsible for about 12% of falls among drywall workers in North Carolina homebuilders (Lipscomb and Dement, 2005). The median number of lost workdays associated with injury from stilt usage was 73, which was at least twice the median number for wallboard taping and texturing workers. The highest median total dollar amount paid for a claim in construction was also for construction workers using stilts. The increased lost workday severity and high paid claim figures indicate that those injuries tend to be extremely severe in terms of economic impacts (Whitaker, 2006).

Potential injury-exposure hazards associated with stilts use in construction have been widely recognized (Pan et al., 1999, 2000; Schneider and Susi, 1994). Both nationally and internationally, the use of stilts was not recommended, and/or was prohibited outright in construction, in the State of California, in New York City, and in the Provinces of Ontario, Canada and Victoria, Australia. The International Union of Painters and Allied Trades (IUPAT) (1998) recommends the maximum safe height for stilts be limited to 24 inches for painter apprentice training. Various governmental and labor institutions (e.g., Ontario Ministry of Labor and IUPAT) demand in-depth biomechanical analyses related to stilt use. However, no reliable quantitative data exist to identify biomechanical hazards associated with stilts in different foot positions at this time.

Research findings in the published occupational safety literature on hazards associated with stilt use in construction have been disparate and limited. It has been hypothesized that construction workers on stilts (e.g., drywall finishers and painters) tend to use extra efforts to maintain balance, which would result in accumulated muscle fatigue in the lower extremities, and would eventually produce postural instability while holding a prolonged standing position (Pan et al., 1999, 2000; Schneider and Susi, 1994). Other

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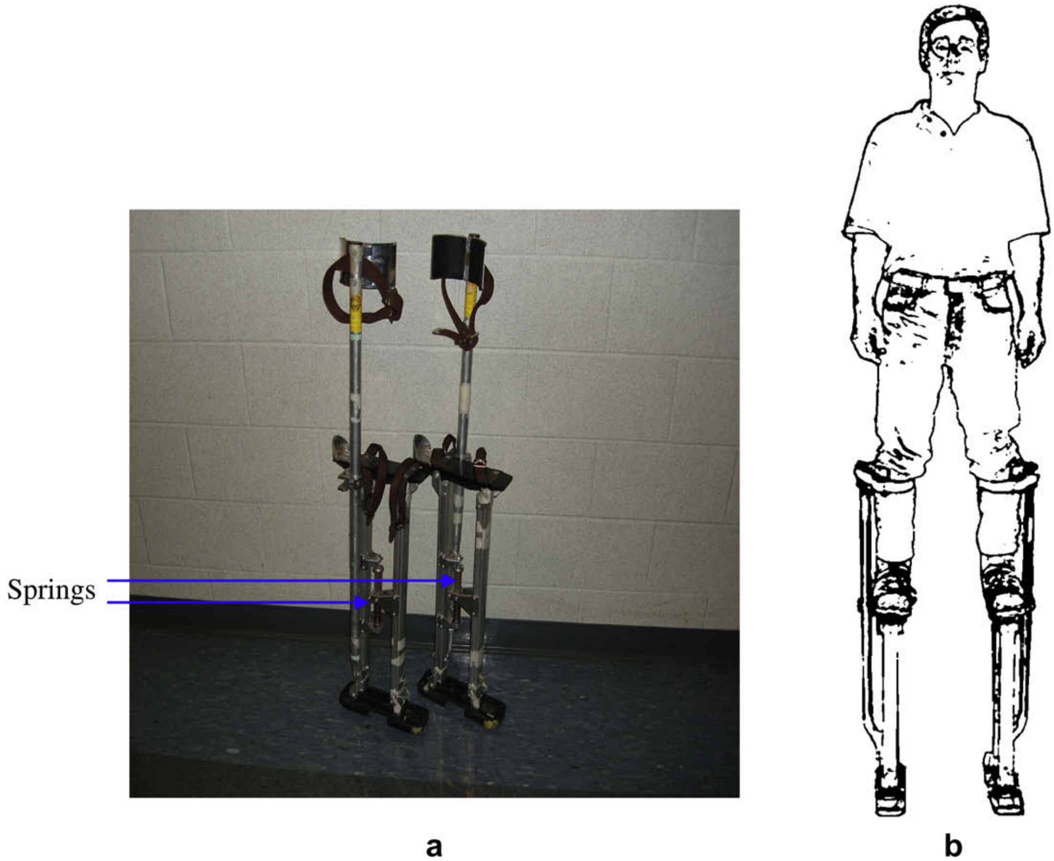

Fig. 1. (a) Stilts used for the present study; (b) standing posture of stilts.

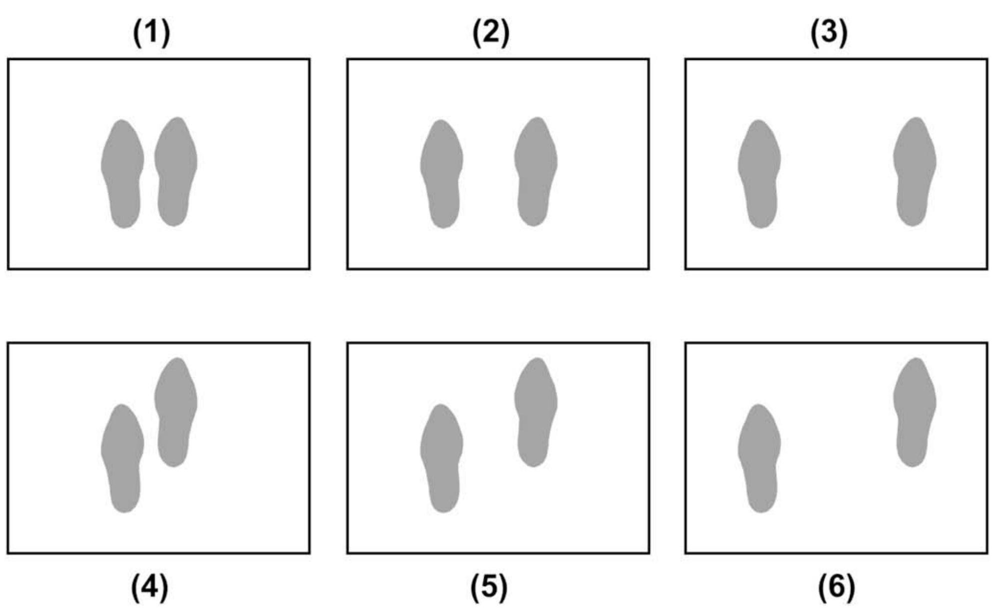

Fig. 2. Six-foot-placement test conditions at 3 levels (0″, 24″, 40″) of elevation. (1)–(3) are two-foot-parallel direction; (4)–(6) are one-foot-forward direction. (1) Standing, with feet at half of the individual's shoulder width, and directly beneath the body; (2) standing, with feet placed at participants' shoulder width and directly beneath the body; (3) standing, with feet placed at 1½ times shoulder width and directly beneath the body; (4) standing, with feet at half of the individual's shoulder width, and with the left foot beneath the body and the right foot placed forward a distance of half the individual's foot length; (5) standing, with feet placed at participants' shoulder width, and with the left foot beneath the body and the right foot placed forward a distance of half the individual's foot length; and (6) standing, with feet placed at 1½ times the participants' shoulder width, with the left foot beneath the body and the right foot placed forward a distance of half the individual's foot length. In these six test conditions the participant maintained an upright posture, with a zero degree of anterior or front lean angle (Holbein and Chaffin, 1997).

research findings have determined that postural stability and motor control mechanism were highly associated with various foot placements (Holbein and Chaffin, 1997; Winter et al., 1996, 1998). Independent research has attempted to identify and quantify issues related to standing and balance performance while conducting manual material handling or while undergoing rehabilitation procedures for neuromuscular injury; various additional research efforts have attempted to determine and evaluate fall hazards associated with foot placement (Gillette et al., 2002; Holbein-Jenny et al., 2007; Uhlir et al., 2000). Workers' foot placements are known to influence whole-body postural stability and lower-extremity joint force (Chiari et al., 2002; Escamilla et al., 2001; Gillette and Abbas, 2003; Moraes and Patla, 2005). As a result, alternative arrangements of foot placement are suggested as one of the main biomechanical implications from these studies; alternative foot placements are believed to increase postural stability and to reduce the incidence of fall-related injuries (Gillette and Abbas, 2003; Gillette et al., 2007; Holbein and Chaffin, 1997). The implications of findings from these research studies are that postural instability and fall risk as a result of stilt use requires further investigation especially because the main injury event involving stilt use is that of fall event (Susi and Flanigan, 2004). The objective of the current study is to evaluate the potential for loss of balance associated with the use of stilts under common-use conditions in construction, that is, assuming a standing position with combinations of foot placement and stilt height.

2. Methods

2.1. Participants

Twenty healthy male construction workers with mean (SD, standard deviation) of age 35.8 (SD = 7.7) years and at least one year of experience in stilt use (mean length of experience: 9.5 (SD = 7.7) years) participated in this study. The mean body weight, body height, and foot length were 80.9 kg (SD = 10.7), 179.0 cm (SD = 7.0), and 30.7 cm (SD = 1.0), respectively. Participants were required to undergo a health-history screening before joining the study. Participants with the following conditions were excluded from this study: history of dizziness, tremor, vestibular disorders, neurological disorders, cardiopulmonary disorders, diabetes, chronic back pain, chronic knee pain, chronic joint pain, and individuals who had fallen within the past year resulting in an injury with days away from work. A medical history with any of these conditions could influence the performance of the participant during testing. In addition, any subjects with body weights over 102.2 kg — exceeding the weight limit set by stilt manufacturers — were disqualified for safety reasons. On the day of experiment, prior to the test, subjects were skill-tested by walking on stilts at the 1.02-m (40-inch) height. Anyone who did not demonstrate the ability to walk at least 6 m (20 feet) steadily without momentary alternation in gait or progressing with hesitation was excluded.

Participant's height, weight, and shoe size were measured; they then changed into safety shoes and tight-fitting black clothes (provided by the study) to minimize interference with the testing equipment and data collection. For safety, participants wore a bicycle helmet, safety shoes, and a vest-type harness. The harness was attached to a Gantry system (Exonic Systems™, Pittsburgh, PA) that was operated on rails using a remote control. The lanyard of the harness was properly adjusted for each participant to protect from falls without restricting movement during the experiment. This harness system was manually operated by a hand-held control pendant with a joystick. The gantry/harness system served as a safety control during the entire time of the experiment to reduce the chance of fall-related injury.

2.2. Experimental conditions

A set of 2 × 3 stance conditions were studied for three levels of stilt heights: 0 m (no silts), 0.61 m (24 inches), and 1.02 m (40 inches). These six stance conditions were combined at two levels of asymmetric foot-placement direction (parallel vs. forward) and three levels of foot-placement width as scaled against shoulder width (SW) (0.5 SW, 1 SW, 1.5 SW) as shown in Fig. 2. Thus, each participant performed a total of 18 trials. Before data collection, the participant was asked to acclimatize himself to the stilts and to make sure spring adjustment was properly set to counter-balance his weight, by walking about on the 24-inch and 40-inch stilts until the participant was comfortable with the stilts as configured.

For practicality, the order of the testing conditions was randomized by stilt height first, followed by trials under six stance conditions within each stilt height, also arranged in random order. Any potential correlation in measurements as a function of learning effects was accounted for in the experimental design, which required each participant to perform 18 trials under different experimental conditions.

2.3. Procedures

An informed-consent procedure was conducted prior to the collection of human participant data; all task procedures had previously been approved by the NIOSH Human Subjects Review Board. For each measurement in the test session, a participant was instructed to stand upright on a force platform for 30 s. Standing upright quietly was assumed to represent the baseline position (Bagchee et al., 1998; Bhattacharya et al., 1988). Subsequently, during the 30-s test, the participant's foot placement was standardized in six different ways based on each individual's shoulder width and foot length.

2.4. Apparatus

A force plate (Model 9287, Kistler™ Instrumentation Corporation, Amherst, NY) was placed flush with the floor. The participant stood on the plate with both feet/stilts placed within the force plate (as shown in Fig. 2). The ground reaction forces from the embedded plate were obtained at 600 Hz and amplified by the Kistler charge amplifier (Kistler, Type 9865B, Kistler Instrument Corp., Amherst, NY) and collected through the Motus Analog Acquisition Module (Peak Performance Technologies, Inc., Englewood, CO).

2.5. Dependent measures

The complexity of postural stability of a human body cannot simply be represented by just one variable. Seven variables and indices were selected to evaluate postural sway and propensity for postural instability based on the participant's center of

Table 1
Description of postural sway and propensity of postural instability parameters.

Variables	Description
Sway Speed	Mean velocity of the postural sway
ML Sway	Postural-sway distance in medial–lateral direction
AP Sway	Postural sway distance in anterior–posterior direction
Sway Area	The area of the region contains within the outer envelope of the COP movement in the *x*–*y* plane
Sway Length	The distance travels by the body's COP in the *x*–*y* plane
IPSB (Index of Proximity to Stability Boundary)	The closest distance of the body's COP travels to a person's stability boundary
SAR (Stability Area Ratio)	The ratio of sway area to the stability boundary

Table 2
Rating of perceived sense of postural instability (PSOPI) (Chiou et al., 2000).

1. How much did you feel your body sway (i.e., rotate, pivot)?				
A little		Some		A lot
0	0.5	1	1.5	2
2. Did you have any difficulty in maintaining balance?				
A little		Some		A lot
0	0.5	1	1.5	2
3. Did you feel at any time that you might fall?				
A little		Some		A lot
0	0.5	1	1.5	2
4. What would you say was the overall difficulty of this task?				
A little		Some		A lot
0	0.5	1	1.5	2

pressure (COP) data as measured on a force plate during the experiment. These seven variables and indices were: mean sway speed (Sway Speed); medial–lateral sway (ML Sway); anterior–posterior sway (AP Sway); stabilogram area (Sway Area); COP Path of Length (Sway Length); index of proximity to stability boundary (IPSB); and stability area ratio (SAR). These variables and indices have been used by others to evaluate workers' postural sway and the propensity for postural instability (Bagchee et al., 1998; Balasubramaniam et al., 2000; Chiari et al., 2002; Harris et al., 1993; Kilburn and Thornton, 1995; Maki et al., 1994; Pan et al., 2003; Winter et al., 1993, 1996). The first five COP-based postural-sway variables are self-explanatory. The IPSB measures how close the body's COP travels to a person's stability boundary, which is delimited as the outer perimeter of the feet (shoe) placement during the test period. The SAR considers the spread of the stabilogram during the task performance in comparison to the stability boundary, which is defined as the ratio of sway area to the stability boundary (Bagchee et al., 1998; Pan et al., 2003). A brief description of these variables is listed in Table 1.

A short questionnaire-type rating scale (Chiou et al., 2000) including four questions regarding the perceived sway and instability under different experimental conditions was also collected from each participant (Table 2). The perceived-instability score

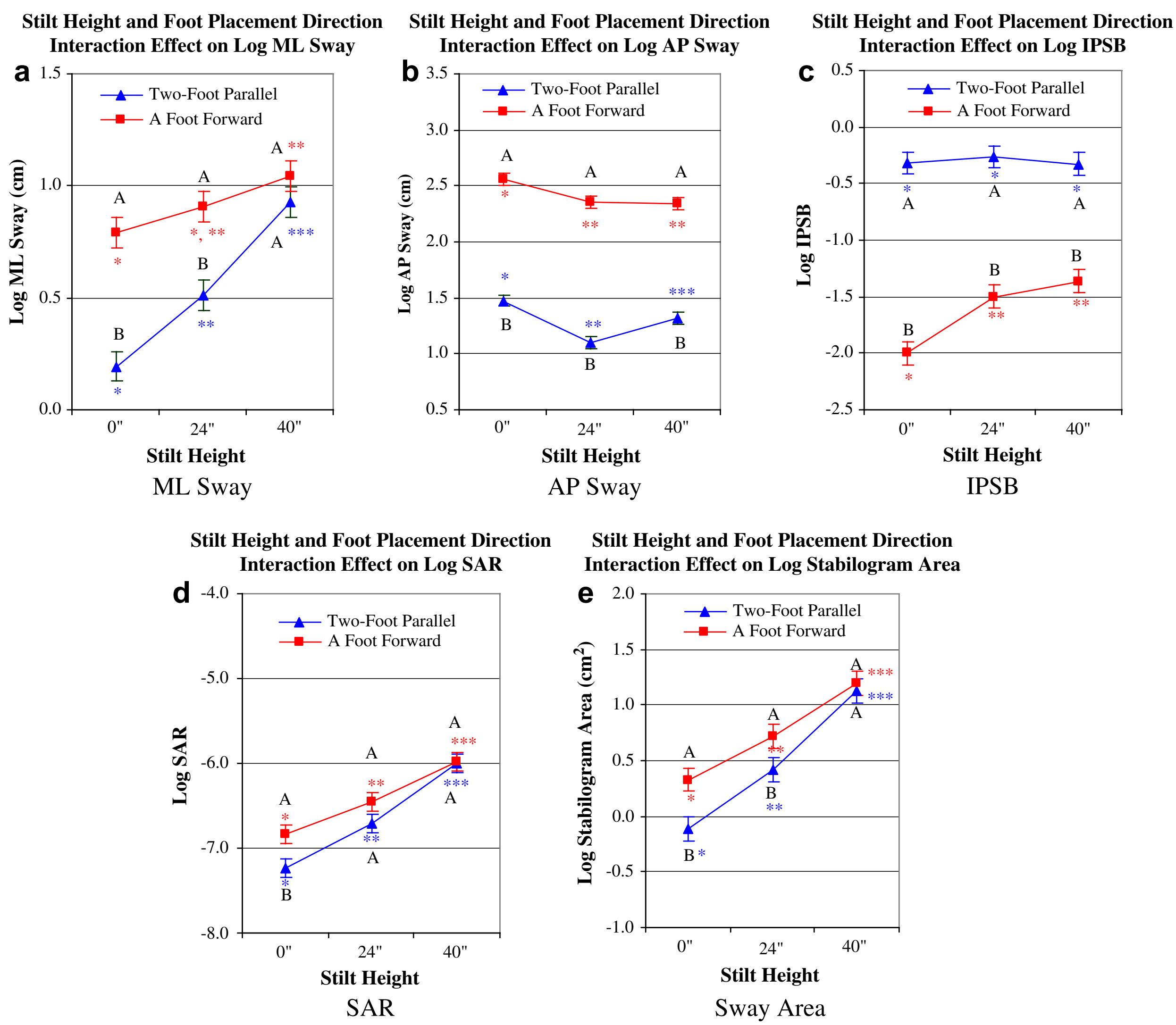

Fig. 3. (a)–(d) The ML sway, AP sway, IPSB and SAR were affected by the interaction of stilt height and foot-placement direction. Within each stilt height, same letter indicates no statistical significance between levels of foot-placement direction. Different asterisks (* and **) indicate a significant difference between stilt height levels within each foot-placement direction. Vertical bars in the graph represent standard errors. (e) The Sway Area was affected by the interaction of stilt height and foot-placement direction. Within each stilt height, same letter indicates no statistical significance between levels of foot-placement direction. Different asterisks (* and **) indicate a significant difference between stilt height levels within each foot-placement direction. Vertical bars in the graph represent standard errors.

used a 5-point scale (0, 0.5, 1, 1.5, 2) for each question for the subjects' perception of postural sway and instability. Zero score meant that the participant perceived low instability and two meant high instability. The descriptions of the perceived-instability scores are: 0 = low instability, 1 = some instability, 2 = high instability. The sum of the 4 answers defined the subject's perceived sense of postural instability (PSOPI); this measure was developed for this study and was in general agreement with the self-rating propensity for slip measurement developed by Chiou et al. (2000). The rating scale was administered immediately after each static-postural-stability condition to determine workers' perceived sense of stability during each experimental condition.

2.6. Statistical analyses

SAS/STAT software (SAS, 2004) was used to perform all data analyses. Before any statistical testing, we checked the normality assumption using a probability plot. To stabilize variance, a natural logarithm transformation was applied to all seven potential fall measures, and the transformed variables were used to perform parametric tests.

Initially, a multivariate analysis of variance (MANOVA) was performed using mixed model by treating each participant as a random factor and experimental conditions as fixed factors to evaluate the overall effects of different experimental conditions on seven potential fall measures. A General Linear Model (GLM) procedure with the appropriate *F*-tests was constructed for main effects and interactions using the effect-by-participant interaction as the denominator for the test (Hays, 1994).

Subsequently, more extensive statistical testing was performed by repeated measures univariate analyses of variance (ANOVAs) using SAS MIXED procedure to take into account the covariability of performance of the same participant. For each dependent variable, various models were evaluated first to find the appropriate covariance structure of observations for the same participant. These covariance structures include (1) compound-symmetry, (2) unstructured, and (3) autoregressive. A model that provided the best fit based on Akaike's Information Criterion (AIC), AICC (a modified criterion from AIC for use in small samples), and Schwarz's Bayesian Criterion (BIC) was selected for final analysis.

From the analyses, dependent variables (Sway Speed, ML Sway, AP Sway, Sway Area, Sway Length, IPSB, SAR) that had both practical use and statistical significance were selected for result interpretation. Independent variables included experimental conditions of stilt height (Height), foot-placement width (Width), and foot-placement direction (Direction). For multiple comparisons, the Tukey–Kramer (Kramer, 1956) adjustment was used to determine significant differences among the experimental conditions.

To evaluate the effect of the experimental conditions on perceived instability and the relationships between the perceived instability and fall-potential measures, both parametric and nonparametric approaches were used. First, the sum of all four perceived-instability scores was calculated and the total scores were used as the dependent variable in the repeated measures analysis of variance (ANOVA) as described above.

Next, with nonparametric approaches, the Spearman rank correlation coefficient was calculated to explore the relationship between the perceived-instability scores and seven fall-potential measures. The Kruskal–Wallis tests were further used to examine if fall-potential measures were significantly different among different perceived-instability classes (0, 0.5, 1.0, ≥1.5). Since the total perceived-instability scores in excess of 1.5 were rather scarce, this group was further combined into a single class.

3. Results

3.1. Effect on fall-potential measures

Our results from MANOVA using all seven dependent variables showed significant overall main effects of stilt height, foot-placement width, and foot-placement direction on fall potential (Wilks' lambda, $p < 0.0001$). The first-order interaction effects of Height with Width, Height with Direction, and Width with Direction on fall potential were also significant (Wilks' lambda, $p < 0.0001$). There was no significant second-order interaction among Height, Width, and Direction.

Subsequent univariate analyses of variance indicated similar effects of the experimental conditions on fall-potential variables. Significant main effects were observed for (1) stilt heights on ML Sway, AP Sway, IPSB, SAR, and Sway Area; (2) foot-placement width on Sway Speed, ML Sway, SAR, Sway Area, and Sway Length; and (3) foot-placement direction on ML Sway, AP Sway, IPSB, SAR, and Sway Area (Figs. 3–5).

Significant first-order interaction effects were also observed for (4) stilt height and foot-placement direction on ML Sway, AP Sway, Sway Area, IPSB, and SAR (Fig. 3(a)–(e)); and (5) foot-placement width and direction on ML Sway (Fig. 4).

The results using medial–lateral sway (ML sway) showed significant main effect of Height ($F_{2,38} = 47.72$, $p < 0.0001$), Width ($F_{2,38} = 94.75$, $p < 0.0001$), and Direction ($F_{1,19} = 79.09$, $p < 0.0001$) on fall potential. The first-order interactions of Height with Direction ($F_{2,38} = 11.23$, $p = 0.0001$) and Width with Direction ($F_{2,38} = 6.40$, $p = 0.0040$) were also significant.

Construction workers wearing stilts had significantly higher mean ML sway than with no stilts. This instability increased substantially with increasing stilt height. This stilt height affected the magnitude of the ML sway differently in different foot-placement directions. For example, at 0″- and 24″-stilt height, standing with one-foot forward showed significantly higher mean ML sway than for standing in parallel direction, but no significant differences were observed at the 40″-stilt height (Fig. 3(a)).

In addition, construction workers standing with foot placement at narrower widths and with one-foot-forward placements were

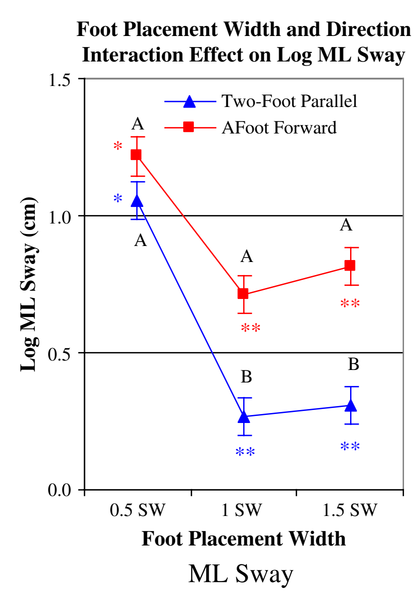

Fig. 4. The ML Sway was affected by the interaction of foot-placement width and foot-placement direction. Within each foot-placement width, same letter indicates no statistical significance between levels of foot-placement direction. Different asterisks (* and **) indicate a significant difference between foot-placement width within each foot-placement direction. Vertical bars in the graph represent standard errors.

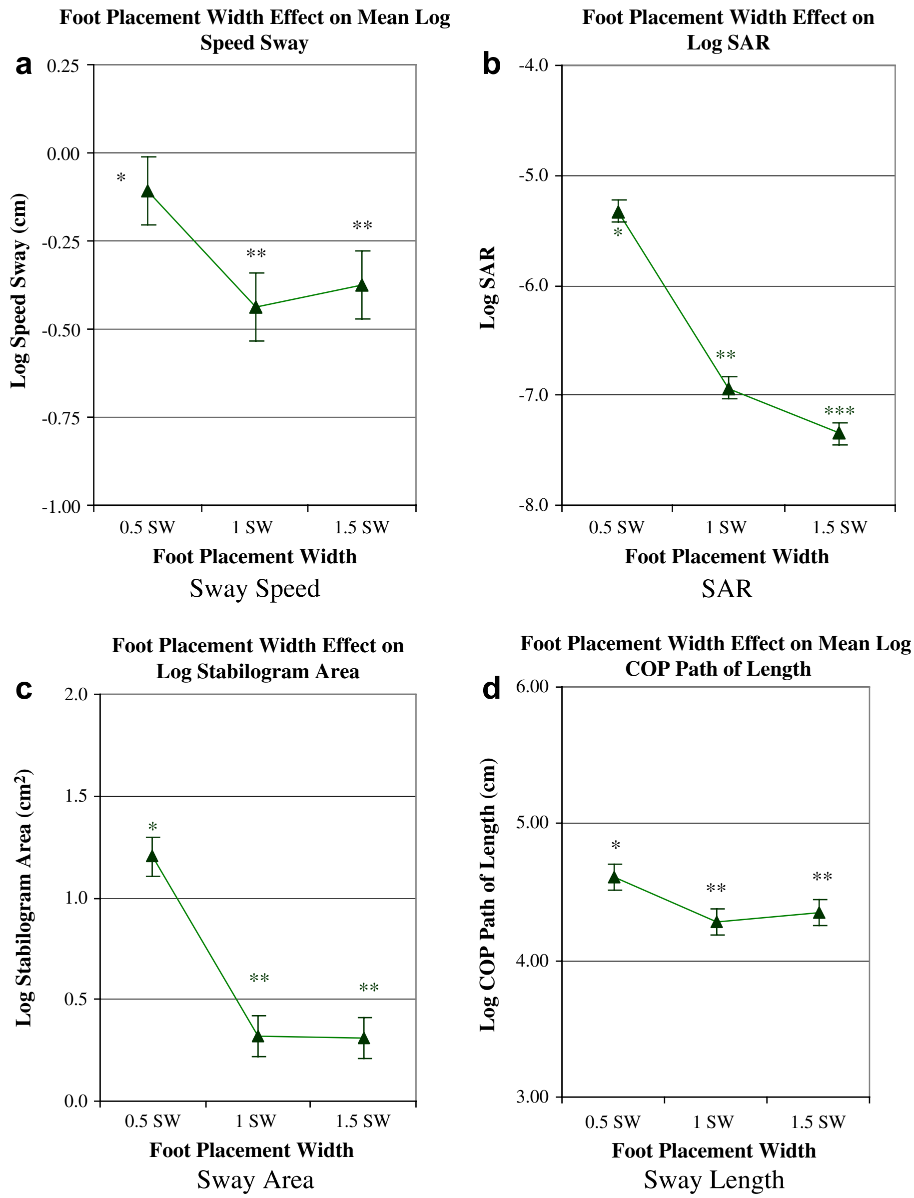

Fig. 5. (a)–(d) The Speed sway, SAR, Sway area, and Sway Length were affected by the foot-placement width. Different asterisks (* and **) indicate a significant difference between foot-placement width. Vertical bars in the graph represent standard errors.

found to exhibit degraded postural stability. Foot-placement width affected the magnitude of the ML sway differently in each foot-placement direction. For instance, construction workers had the largest ML sway value at 0.5 SW, followed by 1.5 SW, and 1 SW. Standing with one-foot forward showed significantly higher ML sway than standing in parallel placement at both 1 SW and 1.5 SW, but no significant differences were found at 0.5 SW (Fig. 4).

Other variables also shared these typical properties of Height, Width, and Direction effects. In particular, our results showed similar patterns of Height and Direction interaction effects on ML sway, AP sway, IPSB, SAR, and Sway Area (Fig. 3(a)–(e)). Therefore, an increasing value for ML sway, SAR, and Sway Area, which implied increasing postural instability, was observed when using stilts. This behavior is more severe at one-foot-forward placement as compared to placement in parallel direction. Similarly, a higher value of ML sway caused an increasing loss of balance when standing at narrower width and was consistent with the results from perceived-instability scores. Of all seven measurements, Sway Length was the only measurement that did not show any significant differences in Height and Direction. This could be due to relatively large variations in the measurements and thus a reduction in the power to detect any differences.

3.2. *Perceived instability*

3.2.1. *Relationship between perceived-instability scores and experimental conditions*

Results of perceived instability are consistent with fall-potential measures as shown in Fig. 6(a) and (b). Significant main effects of Height ($F_{2,36} = 24.07$, $p < 0.0001$), Width ($F_{2,36} = 73.09$, $p < 0.0001$), and Direction ($F_{1,18} = 8.71$, $p = 0.0085$) and interactions of Height with Width ($F_{4,70} = 4.35$, $p < 0.0001$) and Width with Direction ($F_{2,\ 36} = 5.86$, $p = 0.0063$) on perceived-instability scores were observed.

Construction workers felt less stable when standing with foot placement at 0.5 SW and wearing 40″- or 24″-height stilts than those not using stilts. Similarly, these workers felt that it was more difficult to maintain postural balance when standing at 0.5 SW and in the one-foot-forward placement. The Height and Direction

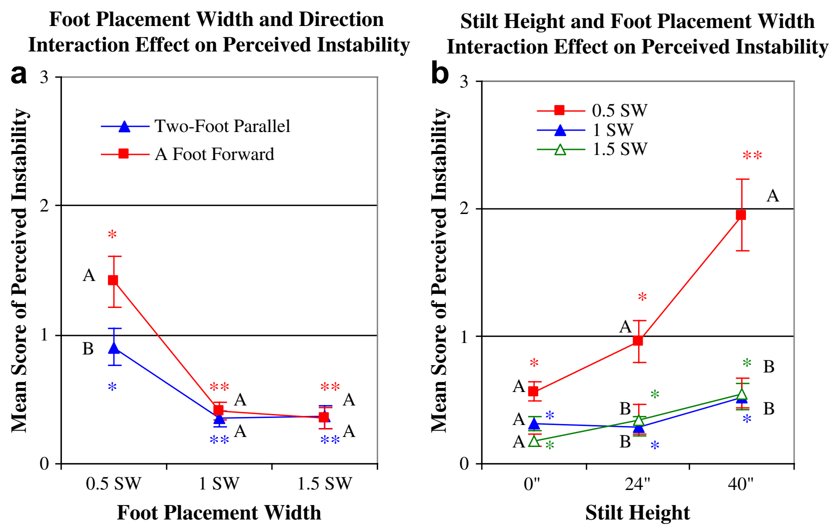

Fig. 6. (a) The perceived instability was affected by the interaction of foot-placement width and foot-placement direction. Within each foot-placement width, same letter indicates no statistical significance between levels of foot-placement direction. Different asterisks (* and **) indicate a significant difference between foot-placement width within each foot-placement direction. Vertical bars in the graph represent standard errors. (b) The perceived instability was affected by the interaction of stilt height and foot-placement width. Within each stilt height, same letter indicates no statistical significance between levels of foot-placement width. Different asterisks (* and **) indicate a significant difference between stilt height within each foot-placement width. Vertical bars in the graph represent standard errors.

effects diminished when foot placement was widened to 1 SW or 1.5 SW.

3.2.2. Relationship between perceived-instability scores and fall-potential measures

Table 3 shows Spearman correlation coefficient between the perceived-instability scores and seven fall-potential measures. Our results indicated a higher perceived-instability score with a larger Sway Speed, ML Sway, SAR, Sway Area, and Sway Length ($p < 0.0001$). The strongest correlation between perceived-instability score and fall-potential measures were SAR, followed by Sway Area, ML Sway, Sway Speed, and Sway Length.

Table 4 set out the mean values of seven fall-potential measures for each perceived-instability score class. Using the Kruskal–Wallis test, our results showed significant differences in fall-potential measures among four perceived-instability classes.

4. Discussion

The objective of this study was to evaluate potential loss of postural stability associated with the use of stilts in a stationary standing position under various common foot placements, which were identified at construction worksites. The results from the multivariate analysis of variance followed by the univariate analysis of variance demonstrated significant effects of experimental conditions on postural stability. Findings from this study support the hypothesis that standing with 6 discrete foot placements using stilts caused differential postural-stability results. This study suggested that a parallel foot placement directly beneath the body reduced postural instability more than a placement with the right foot placed forward to the left foot. These findings are especially important for those construction tasks involving confined working spaces, within which workers (e.g., drywall carpenters and painters) are frequently required to perform tasks within shoulder-width range (e.g., in closets and bathrooms). Results of this study also generally suggest that construction workers should not select the one-half shoulder-width foot-placement position, because this placement produced the greatest amount of postural sway and instability, exceeding both the one shoulder-width and one-and-half shoulder-width placements.

Sway length was the only one of the seven postural instability variables and indices that did not show significant and consistent results for static-posture stance test statistics for each condition. Some researchers suggested that sway length may not be a good parameter to evaluate postural balance; instead, sway length may be a good indicator for the evaluation of psychological and physiological workload, and fatigue-related sensory and functional variability (Holbein-Jenny et al., 2007; Seliga et al., 1991).

The phenomenon of fall is dependent not only on physiological, environmental, and frictional factors, but it is also heavily influenced by one's perceptions, or higher center input, of how one would handle an impending fall. Previous studies have provided evidence that the body's response to prevent a fall is not entirely reflexive in nature; rather, it utilizes a pre-programmed central-nervous-system-based sequence of postural corrective measures based upon perception of threat to subject's postural balance (Cordo and Nashner, 1982; Bhattacharya et al., 2002/2003, 2007). It is theorized that perception of postural instability should elicit compensatory response by the higher centers to reduce postural sway, and in the event of mismatch–between perceived versus actual risk of postural imbalance–this response could give rise to instability and incidence of an unexpected fall.

The PSOPI, which defines subjects' perceived sense of postural instability, was used to integrate the subjects' perception of postural sway and instability associated with task conditions (Chiou et al., 2000). In the current study, the test conditions of height, width, and direction were found to be highly correlated with the measures of PSOPI, implying that workers were able to correctly perceive the contribution to fall potential occasioned by these task conditions. However, certain combination of interaction

Table 3
Correlation between perceived-instability score and fall-potential measurements.

	Sway Speed	ML Sway	AP Sway	IPSB	SAR	Sway Area	Sway Length
Perceived-instability scores	0.4025 ($p < 0.0001$)	0.4845 ($p < 0.0001$)	0.15012 ($p = 0.0061$)	−0.1986 ($p = 0.0003$)	0.5832 ($p < 0.0001$)	0.5718 ($p < 0.0001$)	0.3674 ($p < 0.0001$)

Table 4
Fall-potential measures and perceived-instability scores.

Total perceived-instability scores	N	Mean (SD) of fall-potential measures						
		Sway Speed	ML Sway	AP Sway	IPSB	SAR	Sway Area	Sway Length
0	146	1.377 (2.911)	1.924 (1.269)	7.021 (4.247)	0.559 (0.272)	0.001 (0.002)	1.534 (1.154)	155.498 (327.241)
0.5	95	2.179 (3.656)	2.383 (1.211)	8.111 (4.695)	0.488 (0.295)	0.003 (0.003)	2.409 (1.747)	245.096 (411.331)
1.0	40	1.539 (3.523)	2.868 (1.113)	8.750 (4.420)	0.439 (0.295)	0.003 (0.003)	3.223 (2.008)	173.164 (396.297)
1.5+	51	1.529 (2.598)	3.896 (1.316)	8.381 (3.917)	0.424 (0.253)	0.007 (0.005)	5.605 (3.115)	169.838 (293.128)
p Value[a]		<0.0001	<0.0001	0.0341	0.004	<0.0001	<0.0001	<0.0001

[a] Kruskal–Wallis test.

between foot-placement width and foot-placement directions provided varying responses of perceived risk (as measured by PSOPI) to postural balance as compared to the actual risk to postural balance measured by the ML sway variable. For example, in Fig. 6(a) it can be observed that the 0.5 shoulder-width (SW) foot-placement condition was perceived to be more threatening to postural balance for a foot-forward direction condition than for a two-foot-parallel direction. This higher perceived risk for a foot-forward-direction condition elicited appropriate compensatory response to reduce the actual postural sway, and therefore, in Fig. 4, as expected, there is no statistical difference in measured postural balance between the two-foot-placement directions. While in the case of the 0.5 shoulder-width (SW) condition we saw an example of a good match between perceived risk and the response measures needed to maintain postural balance, the foot-width conditions of 1 SW and 1.5 SW indicate mismatch, as further explained in the next paragraph.

While a foot-forward direction produced significantly higher postural sway for foot-placement-width conditions of 1 SW and 1.5 SW than for parallel foot placement (Fig. 4), the perceived risk of postural instability as documented by PSOPI was not able to discriminate the relative risk of foot-placement direction (Fig. 6(a)). This exhibits a mismatch between perceived sense of instability and the corresponding response of the postural-balance compensatory mechanism during the use of stilts. It is not clear, however, whether the mismatch between objective measure of postural balance for these two-foot-placement conditions and the perceived sense of instability is due to low sensitivity of the perception scale used or that the test condition used was beneath the threshold needed to elicit proper postural-balance compensatory responses.

PSOPI, a measure used for this study, was of interest because it was felt to offer an alternative measure to instrumentation- and sensor-based stabilogram measurements, which require laboratory conditions and extensive calibration and setup. If self-reported instability measurements were in general agreement with data generated from stabilograms, then the PSOPI would offer additional potential for field- and worksite-based data recording and measurement. Results from PSOPI and COP-based data were generally correlated. Further research would be needed to establish the degree to which this correlation was found under various test and workplace conditions; however, it appears that workers' postural balance while using stilts can be adequately identified either through the use of the perceived sense-of-rating scale or through the objective measurements of postural stability.

A significant interaction between Width and Direction was found for the PSOPI. This interaction clearly indicated that with the change in foot-placement width from half shoulder-width to either one or one-and-half shoulder width, while maintaining a test condition with two-foot-parallel placement, decreased perceived instability more considerably (Fig. 6(a)). Also, a significant interaction between Height and Width was identified for the perceived sense of postural instability. This interaction evidently showed that with the change in stilt height from 24″ to 40″ while maintaining a one-and-half-shoulder-width test condition, perceptions of postural instability increased dramatically (Fig. 6(b)).

Five out of seven postural sway and stability variables and indices were further significantly correlated with the perceived sensation of postural-stability rating scale. Therefore, results of this study should be able to produce further understanding of the factors critical to maintaining postural stability on stilts. The total scores for postural stability were relatively low (which is to be expected, since subjects were motionless under the static upright-body-stance condition, without any loading and task), and conversely, significant correlations were identified between the perceived and measured postural sway and stability variables. This pattern indicated that workers using stilts may be able to detect their postural sway and instability conditions and may further be able to control their balance performance. This study did not measure fatigue-related musculoskeletal injury potential, which could be a critical issue when the static use of stilts was sustained over a prolonged work duration (Pan et al., 2000).

Construction workers wearing stilts had significantly higher postural sway and instability than those with no stilts. This instability increased substantially with increasing stilt height. In addition, regardless of the foot placement (i.e., Width and Direction), when the stilt height reached the highest elevation setting – 40″ – a significant degree of high postural sway and instability was identified. This finding can support the recommendation from the painter's union (IUPAT, 1998) of 24″ as a safe height setting for occupational stilt use.

In summary, it was the finding of this study that stilt height, foot-placement width, and foot-placement direction all had significant effects on postural sway and stability. Wearing stilts (24″ and 40″ – heights) created higher postural instabilities than no stilts. Postural instabilities were increased with increasing stilt height and forward foot-placement direction. Also, half-shoulder-width foot placement was the most hazardous condition in terms of fall-risk factors. The impact of stilt height on postural sway and instability was slightly different among different widths of foot placement, and between a "foot forward" and "parallel" foot-placement direction/position. Among construction workers wearing stilts and standing with two feet parallel and directly beneath the body, using a range of foot positions, the position with feet larger than one shoulder-width apart (1 SW) showed less postural sway and instability. Foot position directly beneath the body (parallel foot position) reduced postural sway and instability more than a placement with one foot placed forward to the other foot (forward direction). However, these reductions could not overcome the height impact of stilt use.

5. Conclusion

This study suggests that users should keep stilts at the lower height settings – the higher the stilts, the more difficult it is to maintain balance. This study also suggests that workers should use proper standing posture with stilts–keep feet parallel and directly beneath the body, and place them one or one-half shoulder-width apart.

Another important implication of this study is that the perceived rating scale provides a generally validated, simple tool to evaluate possible fall hazards. Even in a sophisticated laboratory setting, it may be difficult to establish the degree of sway- and postural-stability-related fall exposures obtaining from the use of elevating assistive devices. The difficulties in quantifying these hazards at construction worksites are apparent and perceived ratings may function as proxies for laboratory-based studies.

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