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Evaluation of postural sway and impact forces during ingress and egress of scissor lifts at elevations

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Workers are at risk when entering (ingress) or exiting (egress) elevated scissor lifts. In this study, we recorded ground impact forces and postural sway from 22 construction workers while they performed ingress and egress between a scissor lift and an adjacent work surface with varying conditions: lift opening designs, horizontal and vertical gaps, and sloped work surfaces. We observed higher peak ground shear forces when using a bar-and-chain opening, with larger horizontal gap, with the lift surface more than 0.2 m below the work surface, and presence of a sloped (26°) work surface. Similar trends were observed for postural sway, except that the influence of vertical distance was not significant. To reduce slip/trip/fall risk and postural sway of workers while ingress or egress of an elevated scissor lift, we suggest scissor lifts be equipped with a gate-type opening instead of a bar-and-chain design. We also suggest the lift surface be placed no more than 0.2 m lower than the work surface and the horizontal gap between lift and work surfaces be as small as possible. Selecting a non-sloped surface to ingress or egress a scissor lift is also preferred to reduce risk.

1. Introduction

Scissor lifts (Fig. 1) are commonly found at many construction sites, and when used properly they can facilitate completion of many construction tasks. Over the past decade, the use of scissor lifts has increased significantly in industries such as construction, telecommunication, and warehousing and storage. Their growing popularity makes scissor lift safety an important issue. The scaffolding industry has long recognized fall hazards associated with work on scissor lifts (Burkart et al., 2004; Heath, 2006; McCann, 2003). A study of the Census of Fatal Occupational Injuries (CFOI) data found that falls from vertical lifts accounted for 44% of vertical-lift deaths, almost all involving scissor lifts (McCann, 2003). A later study conducted by the National Institute for Occupational Safety and Health (NIOSH) confirmed the increasing trend for fatalities associated with falls from scissor lifts and further identified that extensibility factors—the extended height of the lift or the vertical position of the worker—were significant contributing factors to 72% of scissor lift fatalities (Pan et al., 2007).

Scissor lifts are available that can reach between 6 and 15 m (20 and 50 ft). At such heights, the stability of the lift and worker are of great concern. According to the recent draft version of American National Standards Institute (ANSI) *A10.29* (2012), workers may enter and exit scissor lifts at heights greater than 1.8 m (6 ft) when the lift platform surface is adjacent to the elevated surface. The standard further specifies that if the lift platform is adjacent to the elevated surface, there shall not be a vertical gap larger than 0.2 m (8 inches) or a horizontal gap larger than 0.35 m (14 inches) between the lift platform and the adjacent surface. To date, there has been no scientific study on the manner in which the vertical and horizontal gaps were determined and how the distances between the lift platform and the adjacent surface may affect each worker's postural stability. In practice, scissor lifts are sometimes positioned at a vertical distance greater than that recommended by the ANSI standard (0.2 m or 8 inches).

Uneven surfaces can increase the risk of falling, especially during ingress and egress actions. Two types of uneven surfaces are typically encountered during the ingress and egress of a scissor lift.

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Fig. 1. A demonstration of the structure of scissor lifts (reprinted with permission of Skyjack Inc.).

One is the difference in elevation between the lift platform and the adjacent work surface; namely, the work surface is either higher or lower than the platform of the scissor lift. The second type of uneven surface is an inclined surface; namely, the adjacent work surface is sloped compared to the platform of the scissor lift. Both conditions can introduce significant safety concerns for the use of scissor lifts. First of all, a difference in surface elevation significantly increases the risk of slip and trip (Brauer, 2006). Second, a decided or large difference in surface elevations could significantly increase trunk instability and alter ground impact forces during worker foot contact (landing), which also increases the risk of falling (Fathallah and Cotnam, 1998, 2000). An inclined work surface introduces a higher risk of slipping due to increased ground shear forces and reduced ground compression forces (Zhao et al., 1987). Previous studies have shown that standing on inclined surfaces could reduce standing stability (Bhattacharya et al., 2002/2003; Lin and Nussbaum, 2012; Simeonov et al., 2003, 2009) and may cause changes to body postures and lower extremity biomechanics (Mezzarane and Kohn, 2007; Sasagawa et al., 2009). When walking on inclined surfaces, the pattern of walking as well as lower extremity biomechanics will also be altered (in comparison to walking on flat ground) in order to compensate for the increased risk of slip and fall (Leroux et al., 2002; McIntosh et al., 2006). Finally, when performing manual tasks (such as trunk bending and lifting) on inclined surfaces, previous studies have observed altered and unbalanced trunk biomechanical responses (Bhattacharya et al., 2002/2003; Hu et al., 2013, 2016; Jiang et al., 2005), increased magnitude of spinal loading (Shin and Mirka, 2004), and reduced trunk stability (Wade and Davis, 2009) among testing participants. These conclusions are consistent with the high incidence rate of fall-related fatal and nonfatal injuries reported in the roofing industry (Wade and Davis, 2005).

Additionally, there is a lack of quantitative data to demonstrate that potential risks may be associated with improper ingress and egress techniques, especially at heights. Measuring sway and other measures of postural instability at heights is difficult (Bain and Marklin, 2012). This is the first study in the literature to evaluate postural sway, effect of inclined surface, and impact force during ingress/egress to an elevated device—a scissor lift. This study also demonstrates how advanced experimental design can be used to develop scientific hypotheses, and responds to numerous requests from an industry-wide standards committee (i.e., ANSI A10.29) for methods that involve the safe use of a scissor lift.

The objective of this study was to evaluate postural sway and impact forces during various methods of ingress and egress scissor lifts at elevation. The first part of the study examined the effects of vertical and horizontal gaps between the lift platform and the adjacent surface on each worker's postural sway. These were evaluated on two types of scissor lift ingress/egress systems, known as "gate" and "bar and chain" designs. The gate design simply had subjects push a gate open to step onto the platform, whereas the bar and chain design challenged subjects to unhook the chain and bend laterally to pass a top rail while stepping toward the platform (Fig. 2(a)-(b)). The second part of the study focused on the effect of an inclined landing surface. The hypothesis was that the maximum interaction forces between human participants and landing surfaces resulting from various ingress/egress conditions are different and such differences can affect workers' postural sway at elevations and on inclined surfaces.

2. Methods

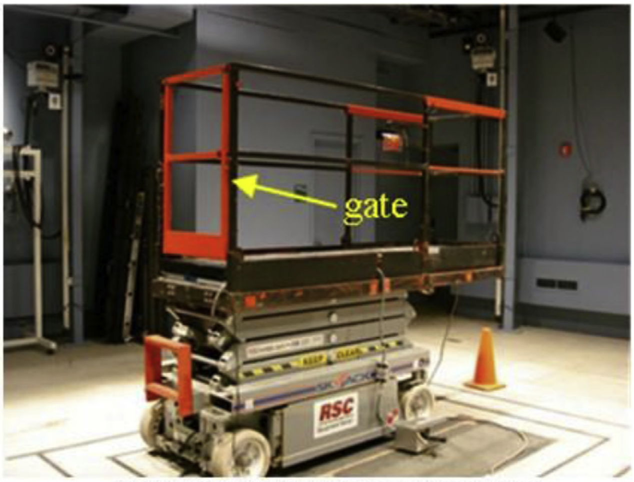
2.1. Participants

Twenty-two male construction workers, mean age of 28.5 ± 10.7 years, who had at least 1 year of experience working with scissor lifts were recruited from northern West Virginia. Their mean body weight was 82.8 ± 3.3 kg (182.5 ± 7.4 lbs), and mean body height was 1.82 ± 0.08 m (6.0 ± 0.29 ft). All participants completed a health-history screening before participating in the study to ensure they were free of a history of dizziness, tremor, vestibular disorders, neurological disorders, diabetes, chronic back pain, and falls within the past year resulting in injury with days away from work. Each participant gave informed consent according to the procedures approved by the NIOSH Institutional Review Board.

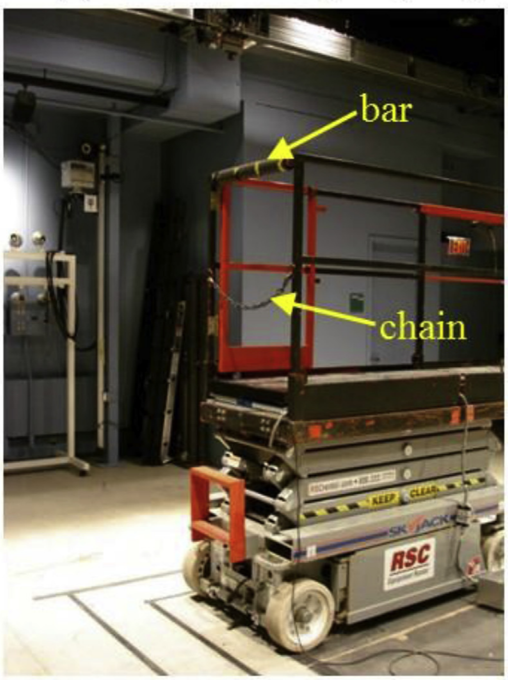
2.2. Laboratory setup

A commercially available 5.79 m (19 ft) electric scissor lift (Model SJIIIE 3219, Skyjack, Inc, Ontario, Canada) was used for the study. The SJIIIE 3219 scissor lift platform has a deck extension, a gate for ingress and egress, guardrails around its periphery, as well as toeboards on all sides (Fig. 1). This lift platform has a length and a width of approximately 0.73 and 1.6 m (29 and 64 inches), respectively, and a deck to extend overall length to approximately 2.54 m (100 inches). The guardrails, composed of a toprail and a midrail, have a height of 0.99 m (39 inches). The toeboard is about 0.15 m (6 inches) high. This type of scissor lift has a total load-bearing capacity of 249.4 kg (550 lbs). The separate rated load-bearing capacity on the main lift platform and 0.9-m (3-ft) deck are 113.3 and 136.0 kg (250 and 300 lbs), respectively. These specifications conform to ANSI standard A92.6 for Self-Propelled Elevating Work Platforms.

A test structure (Fig. 3(a) and (b)) was constructed to house measurement devices for capturing force data related to foot pressure from participants egress the aerial lift. This structure was designed to duplicate conditions found in worksites to be accessed by scissor lifts and served to capture force data typical of that found



(a) Scissor lift with a gate opening



(b) Scissor lift with a bar and chain opening

Fig. 2. Scissor lifts with a gate opening (a) and a bar and chain opening (b).

for workers who routinely step from aerial lifts onto construction or other work surfaces. One side of the test structure was adjacent to the scissor lift while the other side was connected to a mezzanine (2.7 m or 9 feet height). The participant accessed the mezzanine by climbing stairs at the rear of the test structure, then entered the test structure and the scissor lift. After the testing trials were completed, participants used the mezzanine and stairs to return to the ground floor. Each participant was protected from fall hazards comprehensively during the testing (e.g., safety net was constructed between the scissor lift and the test structure) (Fig. 3(c)).

The test structure was 2.4 m (8 ft) tall, constructed of wood (in the shape of rectangular prism), with a top surface area of 1.2 by 2.1 m (4 by 7 ft). It was constructed to house a force plate 0.9 by 0.6 by 0.08 m ($35\frac{1}{2}$ by $25\frac{5}{8}$ by $3\frac{1}{2}$ inches) level with the work surface. Guardrails were established along the sides of the top of the wood structure and one side of the structure was adjacent to the gate of the scissor lift for access to the lift. A force plate was secured to a lift table that was bolted to the top of the wood structure. The Bishamon lift table (Bishamon Lift-2K®; Port Washington, New York) (Fig. 3(a)) had a platform surface area of 0.9 by 1.2 m (36 by 48 inches), a capacity of 907 kg (2000 lbs), and an adjustable height of 0–0.76 m (0–30 inches). The height of the lift table was adjusted to achieve the desired vertical height for the experiment. A second force plate was placed on the top of the scissor lift platform for measuring the participant's baseline postural sway before egress the scissor lift. The scissor lift height was set at 3.04 m (10 ft) at all times.

Two three-dimensional Kistler™ force plates (Kistler Group, Winterthur, Switzerland), one on the lift platform and one on the lift table, were used to determine the impact forces and postural sway in each of the experimental conditions (Fig. 3(a)). Following standard calibration procedures for the Kistler, a comparison with data collected on the height of both the lift platform and lift table (on the test structure) with the data collected on the ground level was performed, and no significant differences were identified.

2.3. Experimental conditions and procedures

The height of the scissor lift was set at 3.04 m (10 ft) for all trials, and two experimental sessions were conducted on two different days. The rationale for testing at the 3.04-m (10-ft) height was that 83% of aerial lift falls, collapses, and tipovers occurred within the height categories of 3.04–5.79 m (10–19 ft) and 6.09–8.83 m (20–29 ft) (Pan et al., 2007).

In Experiment 1, participants performed 42 ingress and 42 egress trials while subject to three varying test conditions—lift type, vertical distance, and horizontal distance. Two types of scissor lifts were examined—one with a gate that could be opened for ingress or egress (hereinafter referred to as the “gate” condition) and the other with a bar and a chain on the side of the lift (hereinafter referred to as the “bar and chain” condition) (Fig. 2(a)-(b)). Seven different vertical landing positions (distance) were tested: same height as the lift (0 m); 0.1, 0.2, 0.3 m (4, 8, and 12 inches respectively) lower; and 0.1, 0.2, 0.3 m (4, 8, and 12 inches respectively) higher than the lift platform. The horizontal distance from the landing surface was 0.17, 0.35, or 0.53 m (7, 14, or 21 inches respectively) from the lift platform. Both the vertical and horizontal test distances we selected were based on the ANSI A10.29 draft standard (2012) for using aerial platforms in construction.

In Experiment 2, participants were tested for a total of 12 ingress and 12 egress trials while subjected to three varying test conditions—lift type, vertical distance, and slope. The lift types varied between the two opening configurations (“gate” and “bar and chain”) described in the preceding paragraph. The vertical distance varied among three conditions: the same vertical height (0 m), the lift surface 0.2 m lower than the adjacent work surface (−8 inches), or the lift surface 0.2 m higher than the adjacent work surface (8 inches). The slope of the work surface was varied at either 0 or 26° (~6/12 pitch). This sloped surface was symmetrically placed with the lower edge facing the scissor lift. The selection of the slope of 6/12 pitch was undertaken because it is the most popular roof slope at which scissor lifts are used. During this experiment, the horizontal distance between the work surface and the scissor lift was fixed at 0.35 m (14 inches) from the exiting plane, and subjects were required to use a guardrail during ingress and egress. The horizontal distance reflected common working conditions (Kroemer and Grandjean, 1997).

The order of trials for each experiment was randomized for each participant, with an exception that we did not include the lift type in the randomization order due to the difficulties and time constraints of changing from a “gate” to a “bar and chain” opening.

Each subject's postural sway during the landing phase of each

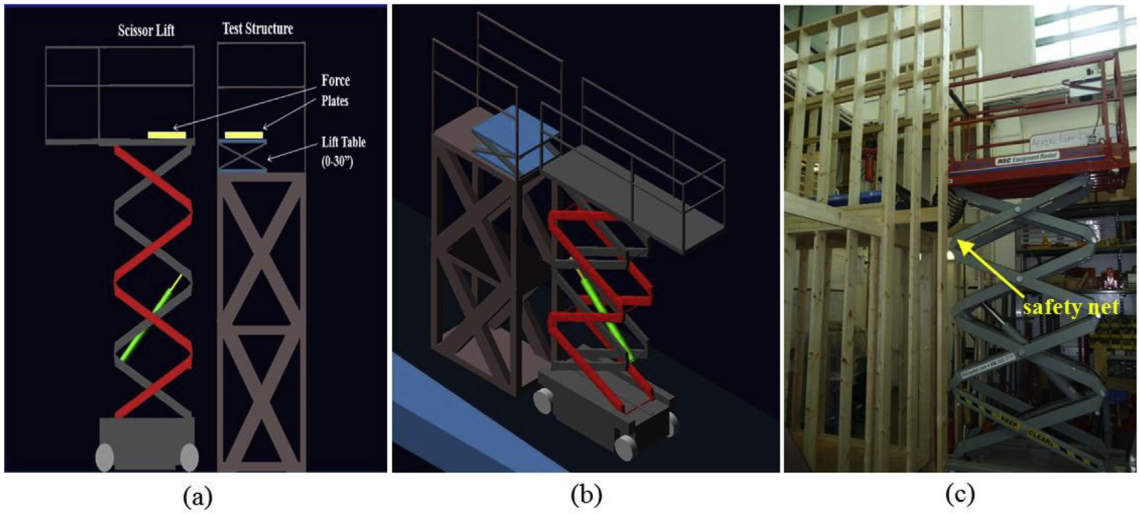


Fig. 3. A demonstration of the experimental Setup, including a side view (a), an aerial view (b), drawing and an actual picture (c) of the scissor lift and the test structure.

ingress or egress motion was quantified using center of pressure (CP) data registered on a force plate. Postural sway is a normal phenomenon in human beings. As postural sway movement causes the body's CP to approach one's stability boundary, as defined by the outer edges of the base of support, the potential for postural instability increases. In this study, two variables were derived from CP excursions and were used to quantitatively determine each subject's postural stability: postural sway distance in medial-lateral (ML) direction, and anterior-posterior (AP) direction (Bhattacharya et al., 2002/2003; Chiou et al., 2003; Pan et al., 2009).

For an egress trial (i.e. fully exiting the lift), it started with a participant standing quietly on the force plate within the scissor lift platform, upon a voice command, the participant went through the opening (either gate or bar and chain design) and stepped onto the adjacent work surface and stood quietly in a standardized foot placement (with their heels touching and feet at a 30° angle) for 30 s. In addition, participants were asked to visually focus on a "dot" placed at their eye level on the front wall. For an ingress trial (i.e. fully entering the lift), the same procedures were followed but with the participant going from the work surface through the opening to the scissor lift platform. For each trial, resultant landing forces registered on the force plate located on the landing surface were recorded; participants' postural sway right after ingress/egress were measured during the 30 s of quiet standing.

2.4. Independent variables

The independent variables for experiments in Experiment 1 were task (ingress or egress), lift opening type (gate or bar and chain), vertical distance (work surface is a vertical distance of −0.3 m [-12 inches], −0.2 m [-8 inches], −0.1 m [-4 inches], 0 m [0 inches], 0.1 m [4 inches], 0.2 m [8 inches], 0.3 m [12 inches] from the lift surface) and horizontal distance (work surface is 0.17 m [7 inches], 0.35 m [14 inches], or 0.53 m [21 inches] away from the lift platform). The independent variables for Experiment 2 were task (ingress or egress), lift opening type (gate or bar and chain), vertical distance (work surface is a vertical distance of −0.2 m [-8 inches], 0 m [0 inches], and 0.2 m [8 inches] from the lift surface), and slope (work surface was either 0 or 26°).

2.5. Dependent measures

Two groups of dependent variables were examined to evaluate the ingress and egress tasks. The first group included maximum impact forces in vertical (F_z) medial-lateral (F_x) and anterior-posterior (F_y) directions during landing. The second group of dependent variables characterized postural sway during the landing phase of ingress and egress motions. The maintenance of postural balance is a complex process that is achieved through the coordination among body segments and between the whole body and the environment. Anterior-posterior (AP) and medial-lateral (ML) sway were used to evaluate postural stability based on the participant's center of pressure excursions determined during the landing phase of ingress and egress motions from the scissor lift. AP and ML sway were defined as the sway distance in the anterior-posterior and medial-lateral direction during the first 30 s after landing (Bhattacharya et al., 2002/2003).

3. Statistical analysis

We used Minitab 17 (Minitab Inc., PA, USA) to perform all data analyses. Prior to any statistical testing, the normality assumption was examined using a probability plot. To stabilize variance, data were transformed to their natural logarithm when appropriate to achieve approximate normality of the statistical distributions.

We conducted general linear model analyses of variance (ANOVAs) to evaluate the effect of different experimental conditions on each dependent variable. In this mixed model approach, the fixed effects included four independent variables (task, lift type,

Table 1
A summary of ANOVA results for Experiment 1.

Tests of Fixed Effects	Max F_X	Max F_Y	Max F_z	AP Sway	ML Sway
Lift Type	***	***	***	***	***
Task	***	***	***	***	***
Horizontal Distance	***		***	***	
Vertical Distance	***	***	***		
Lift*Task	***				*
Lift*Horizontal Distance	*		*		
Lift*Vertical Distance	***		***	*	
Task*Horizontal Distance	*	*		**	
Task*Vertical Distance			***	***	***
Vertical*Horizontal Distance					

*p < 0.05.
**p < 0.005.
***p < 0.0001.

vertical distance, and horizontal distance) for Experiment 1 and four independent variables (task, lift type, vertical distance, and slope) for Experiment 2; random effects included the individual participant. Simple effects analysis was performed among significant interaction effects.

Dependent variables that were statistically significant were selected for interpretation. For multiple comparisons, the Tukey-Kramer adjustment was used to determine significant differences among the experimental conditions. The significance level (α) for this study was set at 0.05.

4. Results

4.1. Experiment 1

Repeated measures ANOVAs showed that main effects significantly influenced most dependent variables (Table 1); changes in horizontal distance did not significantly influence F_y and ML sway, the influences of different vertical distances on AP and ML sway were also not significant. More specifically, as shown in Figs. 4 and 6, significantly lower peak ground shear forces (F_x and F_y) and sway in both AP and ML directions were observed when using gate opening (vs. bar and chain opening) and during egress (vs. ingress) of the scissor lift. However, the opposite trend was observed for the peak ground vertical impact force F_z (Fig. 5). A larger horizontal distance resulted in significantly higher peak F_x, F_z, and AP sway, especially in the 0.53-m [21-inch] gap condition. The lowest ML sway was observed at the 0.35-m [14-inch] condition, but the magnitude of ML sway distance in all three conditions (0.17 m [7 inches], 0.35 m [14 inches], and 0.53 m [21 inches]) was relatively low. Finally, significantly larger peak ground vertical (F_z) and shear (F_x and F_y) forces were observed when the scissor lift was lower than the work surface, especially when the difference in vertical distance was more than 0.2 m [8 inches].

4.2. Experiment 2

Results from Experiment 2 showed that main effects lift type significantly influenced all peak ground forces (F_x, F_y and F_z) and sway in both directions (Table 2). Similarly, slope significantly influenced all dependent variables except the peak vertical ground force F_z. Task significantly influenced F_y and F_z and vertical distance significantly influenced peak ground shear force F_x and peak vertical ground force F_z. More specifically, using gate opening (vs. bar and chain opening) and flat work surface (vs. 26-degree sloped work surface) resulted in significantly lower peak F_x, F_y, (Fig. 7) as well as AP and ML sway (Fig. 9), but higher peak F_z was observed when using gate opening (Fig. 8). When the scissor lift was lower than the work surface, significantly higher peak F_x and F_z were observed. Finally, egress from the lift generated significantly larger F_y. From Fig. 7(e), we can observe a clear interaction effect between task and slope on F_y. This phenomenon was mainly due to the generation of a much higher peak ground shear force in the AP direction when landing on a sloped surface. For the same reason, a smaller peak ground vertical force F_z was observed during egress (Fig. 8(b)).

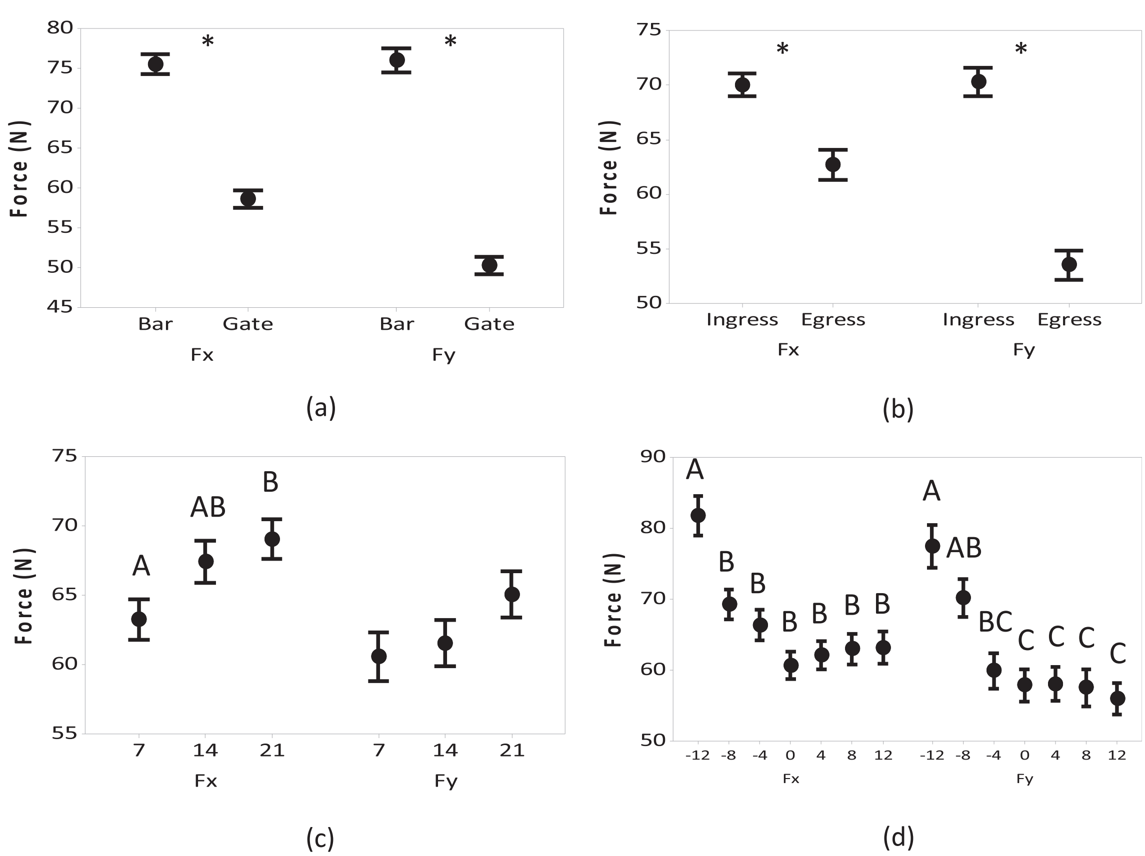


Fig. 4. Experiment 1: effects of lift type (a), task (b), horizontal distance (c), and vertical distance (d) on shear ground reaction forces F_x and F_y.
Note: Different letters and the asterisk mark denote values that are statistically different form one another. Bars indicate standard errors. Numbers on the X-axis in (c) and (d) are in inches.

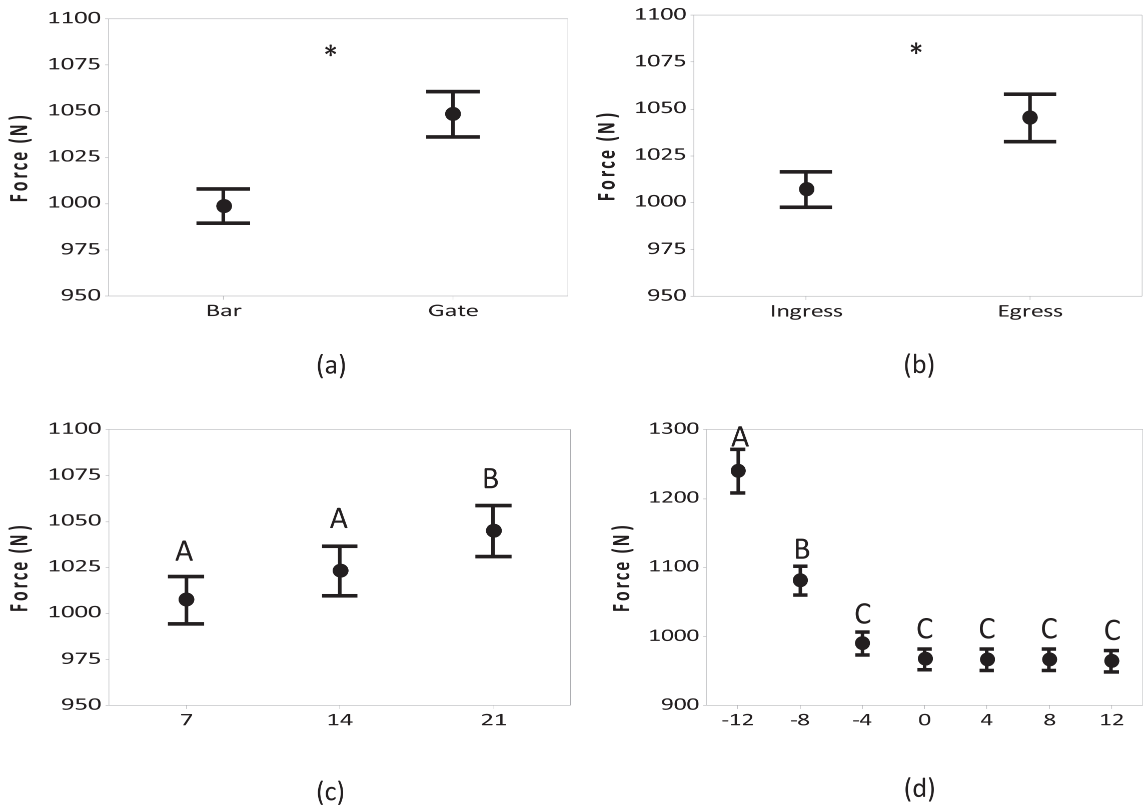


Fig. 5. Experiment 1: effects of lift type (a), task (b), horizontal distance (c), and vertical distance (d) on compressional ground reaction force F_z.
Note: Different letters and the asterisk mark denote values that are statistically different form one another. Bars indicate standard errors. Numbers on the X-axis in (c) and (d) are in inches.

5. Discussion

The objective of this study was to evaluate the risk of slip and fall and postural sway during various methods of ingress and egress scissor lifts at elevation. Due to the large number of testing conditions (i.e., 84 combinations from Experiment 1 and 24 combinations from Experiment 2), instead of making a comparison between different combinations, we made summarized comparisons between different levels of independent variables. The results of the Experiment 1 revealed a greater risk of slip and fall (greater peak ground shear forces F_x and F_y and greater sway in both AP and ML directions) when using a bar and chain opening as compared to a gate opening (Figs. 4(a) and Figure 5(a)). During data collection, it was noted that when subjects performed an egress task from a scissor lift with a bar and chain opening, first they would unhook the chain on the lift then bend at their waist or squat down in order to pass under the top rail (1.07-m [42.5-inch] height). They typically experienced a limited/confined inside space between rails (0.63-m or 25-inch width) while rotating/bending their body toward an open space to exit the lift. To enter a lift with the bar and chain opening, subjects needed to bend their upper body laterally to pass through the top rail while rotating toward the lift platform. These complex body movements resulted from the geometric constraints of the lift and job site environment and caused perturbations to the postural balance system immediately after ingress or egress (Singh et al., 2014; Winter, 1990). The ergonomic recommendations for the dimensions of confined space are to some extent based on anthropometric data, and the above-mentioned workstation design indeed is determined to be potentially hazardous (Bottoms, 1983; Kroemer and Grandjean, 1997). These complex motions associated with using bar and chain openings created non-vertical foot landing postures and, therefore, resulted in significantly larger peak ground shear forces. These motions also resulted in smaller peak ground vertical force, although such changes may not be physically meaningful (represent ~5% of change in vertical ground impact force). Entering into the lift also generated much larger ground shear forces and sways as compared to exiting from the lift. We believe such results are mainly due to the unstable nature of the lift surface. When stepping onto the elevated lift surface, a certain degree of sway and wobbling is generated due to the impact. Such ground motion likely generated the observed increase in peak ground shear forces as well as AP and ML sway (Figs. 4(b) and Figure 6(b)). The same mechanism could also result in reduced peak ground vertical force F_z due to more careful and slower motions when stepping onto the scissor lift (Fig. 5(b)). When the horizontal gap between the lift and the adjacent structural surface increased, participants demonstrated significantly increased peak ground vertical force and shear force in the AP direction and greater sway in the AP direction (Figs. 4(c), 5(c) and 6(c)). When larger horizontal distances occurred, the participant's landing foot became less vertically aligned to the landing surface, which resulted in larger ground shear forces. Crossing a larger horizontal distance also increased the CP sway in the direction of the motion (i.e., the AP direction). Finally, when the scissor lift surface was more than 0.2 m [8 inches] below the work surface participants demonstrated significantly higher ground shear forces (Fig. 4(d)). The larger vertical impact force when stepping down onto the scissor lift surface (Fig. 5(d)) likely generated an increase in ground shear force as well as sway. Some increase of CP sway in both AP and ML directions were also observed when there was a vertical gap between the lift surface and the adjacent work surface; however, such increases were not significant (Fig. 6(d)).

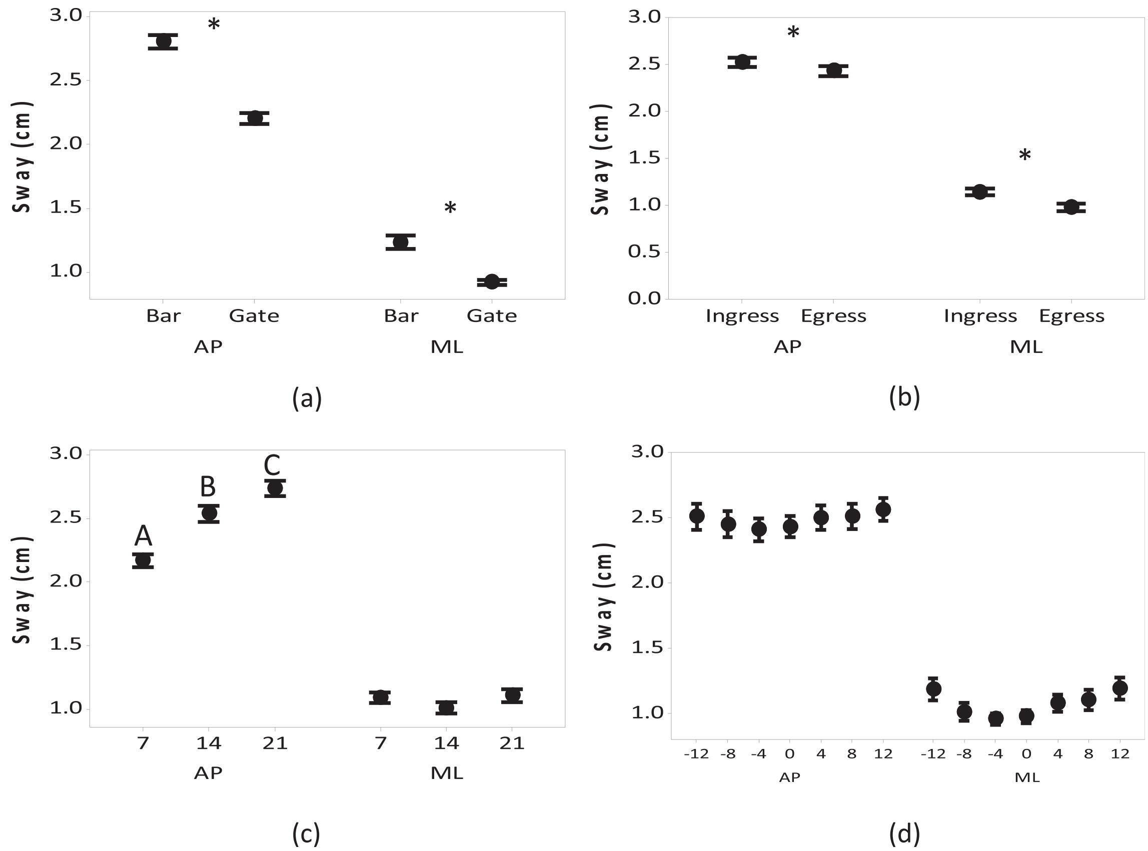


Fig. 6. Experiment 1: effects of lift type (a), task (b), horizontal distance (c), and vertical distance (d) on postural sway.
Note: Different letters and the asterisk mark denote values that are statistically different form one another. Bars indicate standard errors. Numbers on the X-axis in (c) and (d) are in inches.

Table 2
A summary of ANOVA results for Experiment 2.

Tests of Fixed Effects	Max F_X	Max F_Y	Max F_z	AP Sway	ML Sway
Lift Type	***	***	***	***	***
Task		***	***		
Slope	*	***		**	**
Vertical Distance	*		***		
Lift*Task	***		***		
Lift*Slope					*
Lift*Vertical Distance	**		***		
Task*Slope		***	***		
Task*Vertical Distance			*	*	
Slope*Vertical Distance					

*$p < 0.05$.
**$p < 0.005$.
***$p < 0.0001$.

In Experiment 2, similar to the Experiment 1, we also observed larger peak ground vertical force and smaller peak ground shear forces and CP sways when using a gate opening as compared to a bar and chain opening (Figs. 7(a), 8(a) and 9(a)). In addition, in agreement with previous research (Zhao et al., 1987), smaller peak ground vertical force (although not statistically significant) (Fig. 8(c)) and larger peak ground shear forces and sway were also found when the work surface was sloped vs. flat (Fig. 7(c), and Fig. 9(c)). Two conditions were tested: one involving no slope and one involving a 26-degree slope. Variable measures of sway and force may have been returned with variable measures of slope, but for the purposes of this project, no slope was contrasted with a decided slope condition. Greater indicators of postural instability—heightened ground shear force, increased medial-lateral and anterior-posterior sway—were found to be significantly associated with a sloped landing surface, and it is the finding of this study that sloped surfaces should not be used as landing surfaces (Jones and Hignett, 2007).

Many previous studies investigated sloped and inclined surfaces associated with trunk and whole-body kinematics during manual material handling and gait (Leroux et al., 2002; Shin and Mirka, 2004; Hu et al., 2013, 2016). Tasks involving an upward body motion created greater postural demands on the subjects (Kluzik et al., 2005, 2007; Mezzarane and Kohn, 2007). Ingress or egress onto a lift from a sloped surface placed greater postural demands on the subjects compared to a non-sloped landing surface. This study also identified results that were similar to those studies associated with inclined surfaces: increased the range of motion, elevated the muscle activation level (i.e., increase muscle strength requirement), deployed appropriate postural muscle corrective actions, and caused muscle fatigue in various test conditions (Bhattacharya et al., 2002/2003; McIntosh et al., 2006; McNitt-Gray, 1993; Mezzarane and Kohn, 2007; Yung-Hui and Wei-Hsien, 2005). A previous study on postural sway following prolonged exposure to an inclined surface (Wade and Davis, 2009) indicated that an individual was less stable directly after performing tasks on an inclined surface and highlighted the importance of optimal work-rest cycles. Several studies on postural stability of roofers suggested there might be an adaptation period associated with working on a sloped

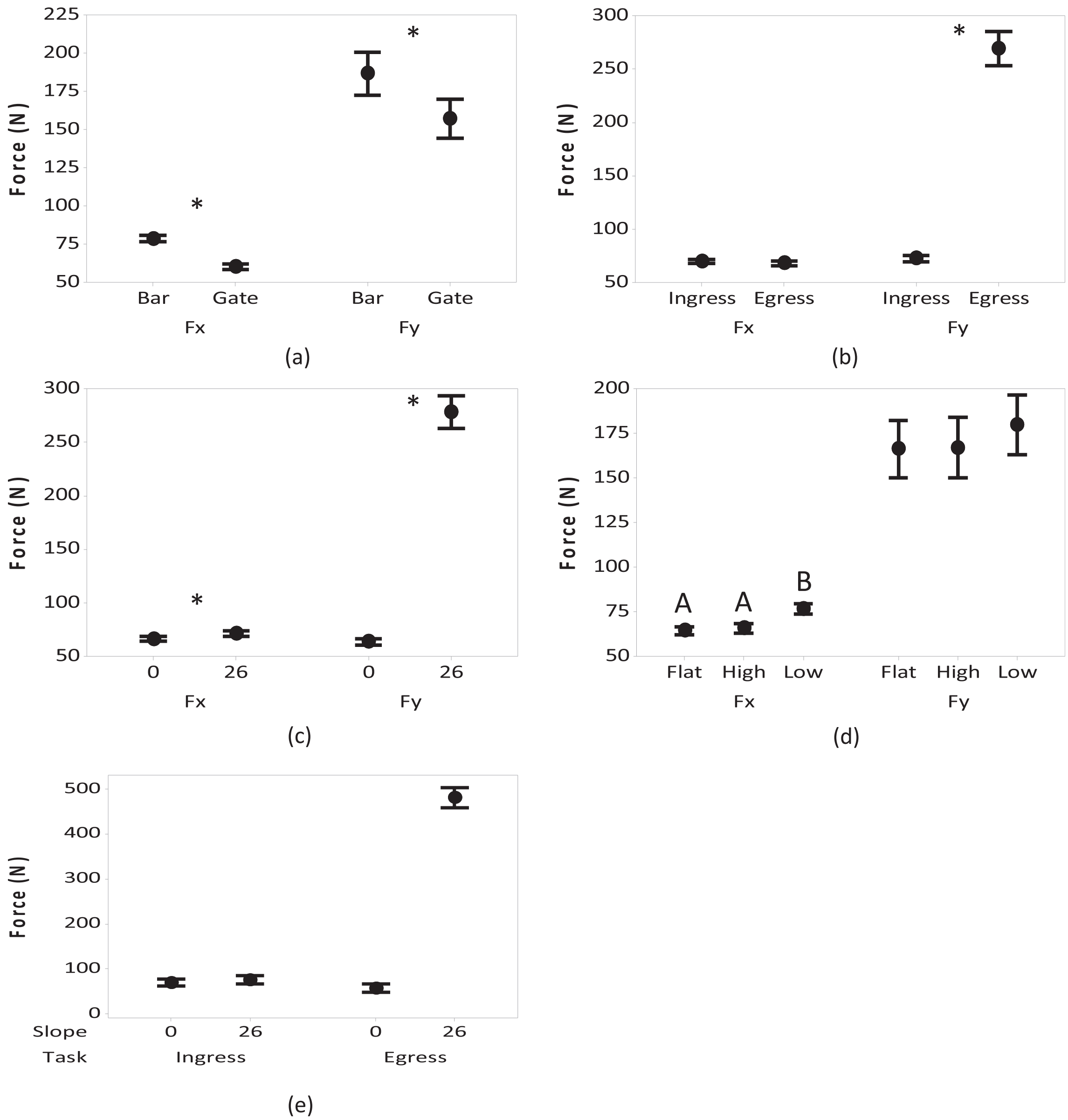


Fig. 7. Experiment 2: effects of lift type (a), task (b), slope (c), and vertical distance (d) on shear ground reaction forces F_x and F_y, and a demonstration of F_y at different slope and task conditions (e).
Note: Different letters and the asterisk mark denote values that are statistically different form one another. Bars indicate standard errors. Numbers in (c) and (e) are in degrees. Flat, high, and low in (d) represent 0 inches, 8 inches, and −8 inches, respectively, from the lift surface.

surface and more emphasis should be given to workers in the adaptation period after exposure to inclined surfaces (Choi and Fredericks, 2008; Hsiao and Simeonov, 2001; Simeonov et al., 2004).

This study demonstrated that ground impact forces and postural sway were significantly affected by scissor lift opening type, horizontal and vertical distances between the lift surface and the work surface, the slope of the work surface, and methods of adjusting the body while ingress or egress the lift. Future studies are needed to examine if the anthropometric size of the subjects affect the ingress/egress strategies and the resultant impact forces and postural sway. Such research could lead to an extension of the design criteria for structural components of the lift that have been demonstrated to significantly influence the human-machine interface. In addition, the body position at landing and performance execution in relation to the requirement of the lift should be further examined. The propensity toward falls as a function of excursions within and beyond the CP could also be examined (Bagchee et al., 1998; Chiou et al., 2003).

ANSI A10.29 draft standard (2012) states that “when transferring to an elevated surface, there should be sufficient vertical clearance to allow for movement of the platform as weight is transferred to or from the aerial lift, and the platform floor should be within 0.3 m (1 foot) horizontally of adjacent structure.” This statement in this draft standard was adopted from the regular scaffold standard, which may not be appropriate for aerial lifts (and especially so for scissor lifts). The current ANSI A92.6 Standard (2006) for Self-Propelled Elevating Work Platform [scissor lift] states that “if permitted by the manufacturer, the personnel shall only vacate or enter a raised aerial platform by following the

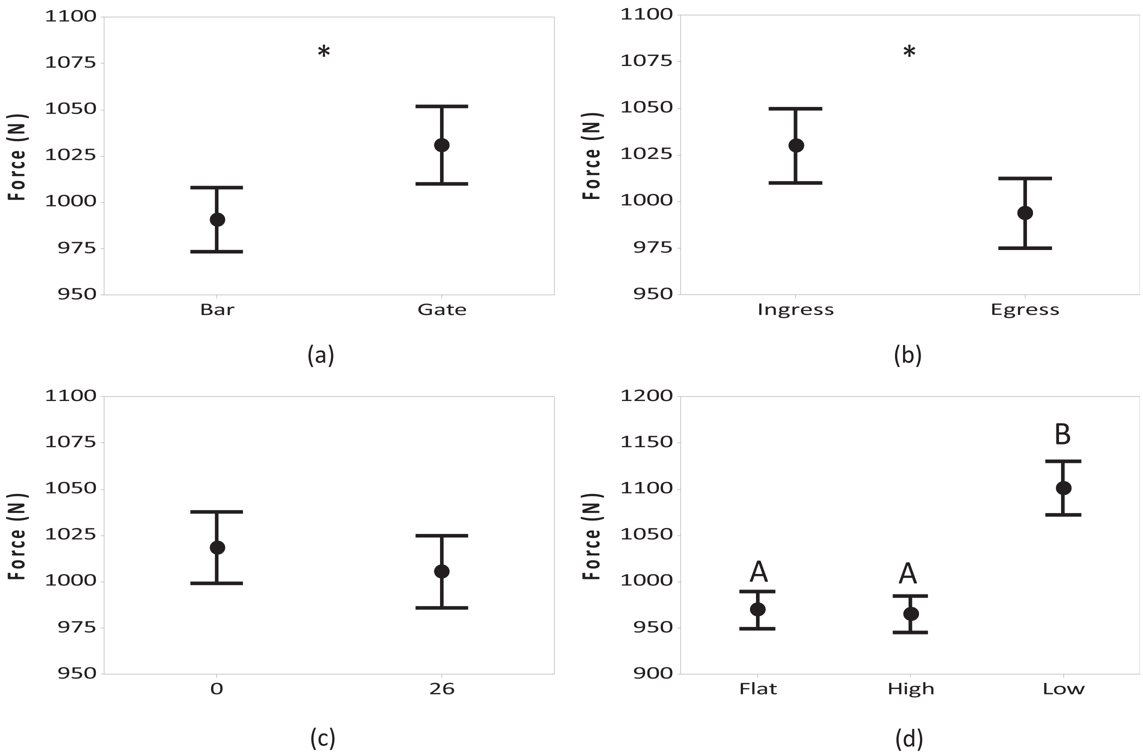


Fig. 8. Experiment 2: effects of lift type (a), task (b), slope (c), and vertical distance (d) on compressional ground reaction force F_z.
Note: Different letters and the asterisk mark denote values that are statistically different form one another. Bars indicate standard errors. Numbers in (c) are in degrees. Flat, high, and low in (d) represent 0 inches, 8 inches, and −8 inches, respectively, from the lift surface.

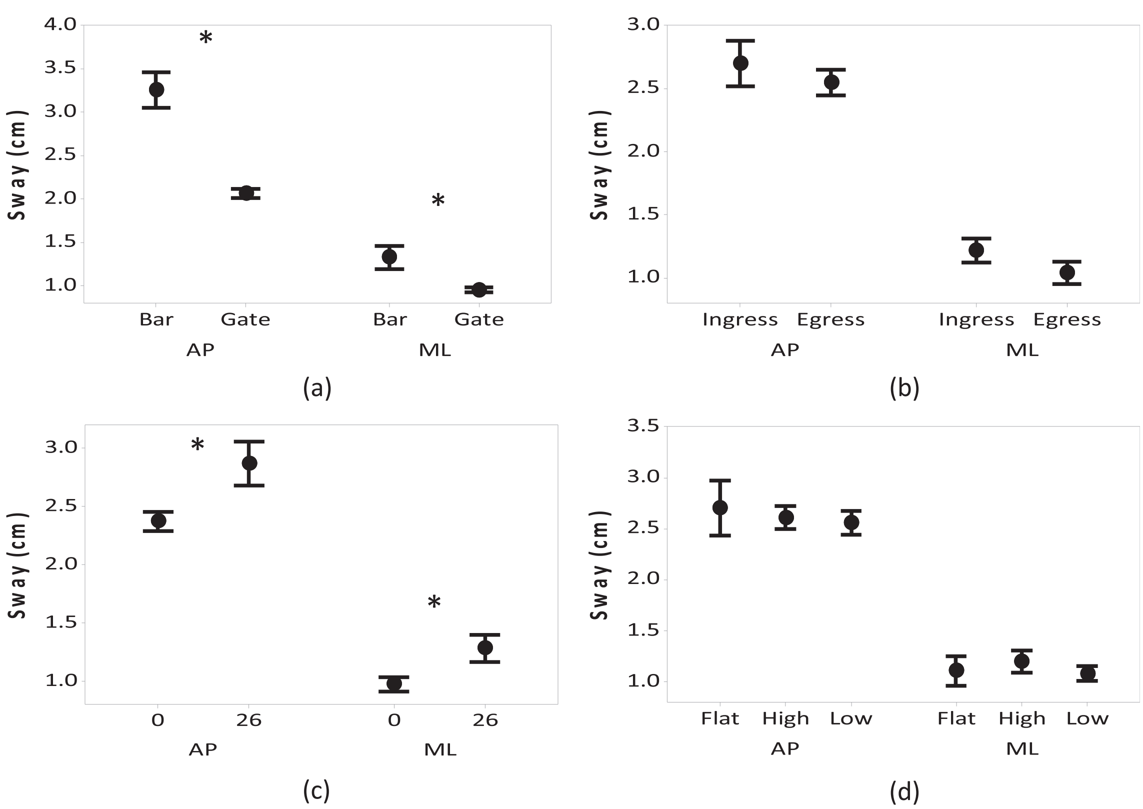


Fig. 9. Experiment 2: effects of lift type (a), task (b), slope (c), and vertical distance (d) on postural sway.
Note: The asterisk mark denotes values that are statistically different form one another. Bars indicate standard errors. Numbers in (c) are in degrees. Flat, high, and low in (d) represent 0 inches, 8 inches, and −8 inches, respectively, from the lift surface.

guidelines and instructions provided by the manufacturer." The results of this study will provide useful quantifiable information for developing safe "ingress and egress procedures at an elevation" for scissor lifts. These study findings can also be applicable for other construction elevated devices, heavy construction vehicles, trucks, mining equipment, and agricultural tractors (Bottoms, 1983; Moore et al., 2009; Pan et al., 2012).

It is inherently problematic to conduct fall-related research without putting human subjects at risk for fall-related injuries. Common risk hazard exposures, when duplicated in experimental conditions, would require implementation of protective measures for human study participants by the NIOSH Institutional Review Board (IRB). Any concerns that the IRB might have had regarding hazardous exposures to subjects in this study were dealt with through modifications in the experimental design, which was developed to overcome these scientific obstacles and return actionable and useful information, allowing for advanced methods of analysis that would allow the contribution of individual variables to be determined. This study demonstrated that impact forces and postural sway were significantly affected by various ingress and egress methods. Findings from this study will be used to suggest safer work practices to prevent fall injuries from elevations during the use of scissor lifts, and provide input to revise the ongoing ANSI A10.29 standard section in the use of aerial lifts as an elevator (Chiou et al., 2015).

6. Conclusions

In summary, this study quantifies the ground impact forces and postural sway effects that are identified for subjects during ingress and egress when the adjacent work surface is sloped, through gates or bar-and-chain openings, and at horizontal and vertical distances from the landing surface. The findings from this research suggest that, to reduce the risk of slip and fall, (1) scissor lifts should have gates in preference to bar and chain openings, (2) the adjacent work surface should be non-sloped, (3) the lift platform surface should be less than 0.2 m (8 inches) lower than the landing surface, and (4) the horizontal distance between a lift platform surface and the adjacent work surface should be less than 0.35 m (14 inches).

Disclaimers

The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health (NIOSH). Mention of company names or products does not imply endorsement by NIOSH.

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