EVALUATION OF FALL HAZARDS ASSOCIATED WITH TWO CONSTRUCTION ELEVATED DEVICES

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This study identified fall risk factors for two construction elevated devices – scissor lifts and stilts. For scissor lifts, side forces that may lead to possible lift tipovers and falls were evaluated while participants performing simulated tasks on the lift at different elevations. Significantly greater lift accelerations were found when subjects performed tasks in the direction parallel with the lift at either 1.4 or 1.8 meters of height. For stilts, kinematics data were collected from construction workers while walking with stilts at 0.61 or 1.02 meter height settings. The increase in step width and a "lurching style" walking pattern with the foot swing out laterally suggests a wider base of support was needed to improve stability on stilts. The decrease in toe clearances on stilts increases tripping risks. This study suggested that workers may need to avoid excessive pushing or pulling in the direction parallel with the length of the lift to minimize lift instability. For workers who use stilts, it is imperative to ensure that floors are free of obstacles before putting on stilts.

Introduction

Falls are the leading cause of traumatic injuries in the construction industry. Falls from elevation can be largely attributable to the nature of construction work, which frequently requires workers to perform tasks at elevations. The use of aerial lifts in residential or commercial construction for tasks at high elevations is widespread and increasing. Major construction trades that use aerial lifts are electrical workers, construction laborers, painters, ironworkers and carpenters. In a study on deaths in construction related to personnel lifts between 1992 and1999, 339 deaths were identified – an approximate average of 42 per year (McCann, 2003). Among personnel lifts, scissor lifts and boom-supported lifts (61%) were most frequently involved in these deaths. In addition, falls (36%) and collapse/ tip-over (29%) were ranked as the top two causes of death (McCann, 2003). Another study of CFOI (Census of Fatal Occupational Injury) between 1992 and 2001 concluded that tip-over was the most frequent manner of fall incident and was responsible for 52% of scissor-lift-related fatalities (Pan *et al.*, 2005). For these cases, constructing/assembling/repairing activities contributed 54% of the tip-over incidents. Operator activites, such as pushing or pulling, may create excessive side pulls (forces) beyond that which the scissor lift can withstand. This is a concern, especially when the lift is elevated, parked on a slope, or with the deck extended horzontally beyond the base of support of the lift. To date, there has been little research on the stability of scissor lifts, particularly when they are under actual-use conditions.

One other unique item of elevated equipment commonly seen at building construction sites is stilts. Like scissor lifts, stilts raise workers above the ground level, to allow them to perform tasks at height, typically on the ceiling or upper half of a wall. They are used for a variety of construction tasks, such as painting, plastering, drywall installation, drywall finishing, acoustical ceiling installation, or light-duty building maintenance. The major difference between stilts and traditional elevated equipment, such as ladders and scaffolds is that stilts provide great mobility for workers to move freely from one location to another. The use of stilts is considered to be a high-risk activity leading to loss of balance and falls (Schneider and Susi, 1994). The State of California and the province of Ontario, Canada, have established legislation against the use of stilts as a preventive measure against occupational injuries. Beyond the perception that stilts are associated with high risks of falls, however, little research has been done to quantitatively demonstrate the hazards.

The objective of this study was to identify the fall risk factors associated with two elevated devices – scissor lift and stilts. The specific aims were (1) to determine how operators' activities affect the stability of scissor lifts; and (2) to identify the foot kinematics and compensatory movements for gait on stilts.

Study one – evaluation of fall hazards associated with scissor lifts

Experimental Design

Twenty healthy male construction workers (age: 42.3 ± 7.7 years) who had at least one year of experience in using scissor lifts for construction tasks participated in this study. Each subject performed pushing, pulling, or upright standing tasks at two locations on the scissor lift (main platform or extended platform) in three standing directions (parallel, perpendicular or diagonally to the length of the lift) at three lift heights (1.0, 1.4 or 1.8 meters). The order of administration of trials was randomized for each subject. The side forces and lift acceleration resulting from simulated tasks were collected.

Test procedures

The test procedure for upright standing involves standing quietly on the scissor lift platform and looking straight ahead for 30 seconds. For pushing and pulling tasks, the subject pushed or pulled a simulated drill placed in front of him at elbow height. The drill was secured to steel beams running from the ceiling to the floor of the laboratory. The subject was asked to push or pull the drill as hard as he can. The horizontal distance between the drill and the subject was adjusted accordingly to accommodate the variability of each individual's arm reach.

Instrumentation

A commercially available 19-foot (5.8 m) electric scissor lift, which conforms to ANSI standards A92.6 for Self-Propelled Elevating Work Platforms was used for the study. The lift platform has a length and a width of approximately 1.62 m (64") and 0.73 m (29"), respectively, and a deck to extend the overall length to approximately 2.54 m (100"). Three triaxial accelerometers (Kionix KXM52-L50, +/- 5g, 264 mV/g, band: 0-3k) were mounted underneath the main platform of the scissor lift to determine the lift stability. A force sensor (Interface, Model: 1010ACK-250-B, Scottsdale, AZ) was incorporated into the simulated drill for pushing and pulling tasks. The data-collection frequency was set at 120 Hz.

Results

The greatest side force observed among 1080 trials was 141 lbs (627 Newton), which occurred when the subject performed a pushing task on the main platform in the direction parallel to the length of the lift at 72" height. Results from repeated measure ANOVA revealed that the height of the scissor lift did not affect the maximum side forces exerted by the subjects ($p=0.14$), implying high side forces may occur at any level of height. The interaction of standing direction and task was significant on maximum side forces ($p<0.0001$) as shown in Figure 1. Performing tasks in the direction parallel with the length of the lift created the greatest side forces ($p<0.001$). Significantly greater lift acceleration was also found while subjects performed tasks in a direction parallel with the lift at either 1.4 or 1.8 meters of height.

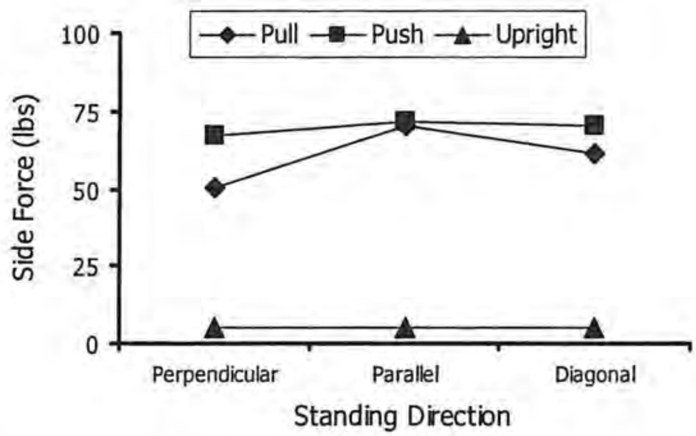

Figure 1 Comparison of side forces by task and standing location

Study two – evaluation of fall hazards associated with stilts

Experimental Design

Twenty healthy male construction workers (mean age 35.8±7.7 years) with more than 12 months of experience (mean: 9.5±7.7 years) in using stilts participated in the study. All subjects gave informed consent and underwent a health-history screening before the experiment. Subjects with body weights over 102.2 kg, exceeding the weight limit set by stilt manufacturers were disqualified. Each subject underwent 12 randomized gait trials under a combination of three experimental conditions: height, walking path, and tool carrying. The height levels were 0 meters (safety shoes), 0.61 meters (24 inches) on stilts, or 1.02 meters (40 inches) on stilts. They either walked straight or negotiated a turning path. For test conditions of tool carrying, subjects walked with or without holding a mud pan and a trowel in hands. The trajectories of heel and toe markers were examined. Gait characteristics including walking speed, stride period, step width, and double stance period (%) were evaluated. For stilts, the front and back markers on the stilt floor plate were treated as toe and heel markers, respectively.

Test procedures

Prior to the test, subjects were skill-tested by walking on stilts at 1.02 meter height. Anyone who did not demonstrate the ability to walk independently was disqualified for safety concerns. Subjects wore tight-fitting clothing, safety shoes, or stilts provided by the laboratory. Fifteen reflective spherical markers were placed on specific anatomical locations of the lower extremity. Six additional markers, three on each side, were placed on the stilts.

Subjects were tested on a 12-meter (40 feet) straight path or a curving path. For the latter, subjects walked half way down the same straight path then turned 45 degrees to the left onto another 4.6-meter long (15 feet) path. They walked in a self-selected manner at comfortable speed. For tool-carrying conditions, subjects walked in the same manners while holding a mud pan and a trowel in their hands. They wore a safety harness attached to an overhead rail system during the entire experiment.

Instrumentation
The stilts used for the study weighed 7.26 kg (16 lbs) and the height was adjustable from 0.6 to 1.02 meters (24 to 40 inches). A shoe plate was strapped onto the bottom of the workers' shoes with a strut tube running up the side of the leg and strapped right below the knee. Two lower strut tubes connected the shoe plate with a nylon floor plate. The lower tubes were spring loaded to provide forward and rearward stilt-walking actions. A six-camera motion analysis system (Peak Motion Analysis System, Peak performance Technologies, Englewood, CO) was used to collect kinematics data at 60 Hz.

Results
Table 1 shows general gait characteristics for different walking heights. Subjects walked significantly slower during gait on stilts ($p < 0.001$) with the mean stride period increased from 1.24 sec of no stilts to 1.59 and 1.69 seconds for 0.6 m (24") and 1.02 m (40") stilts, respectively. Significantly lower walking speed (1.03 m/sec vs. 1.25 m/sec) was also observed for turning path compared with straight path ($p<0.001$). The double stance period (%), representing the percent of time of a gait cycle in which both feet or stilts were in contact with the floor, was significantly increased for gait with stilts ($p < 0.001$). A greater double stance period was also found for gait on a turning path (21.5% vs. 20.6%). The step width was significantly increased from 15 cm for no stilts to as much as 25 cm on stilts ($p<0.0001$).

Table 1 Means and standard errors for gait parameters

		Safety	Stilt height	
		Shoes	0.6-meter	1.02-meter
Gait cycle parameters	Average speed (m/sec)	1.25 (0.16)	1.08 (0.15)	1.03 (0.16)
	Stride period (sec)	1.24 (0.08)	1.59 (0.15)	1.69 (0.17)
	Double stance period (%)	20.0 (2.1)	21.6 (3.5)	22.6 (3.3)
	Step width (m)	0.15 (0.05)	0.24 (0.08)	0.25 (0.10)

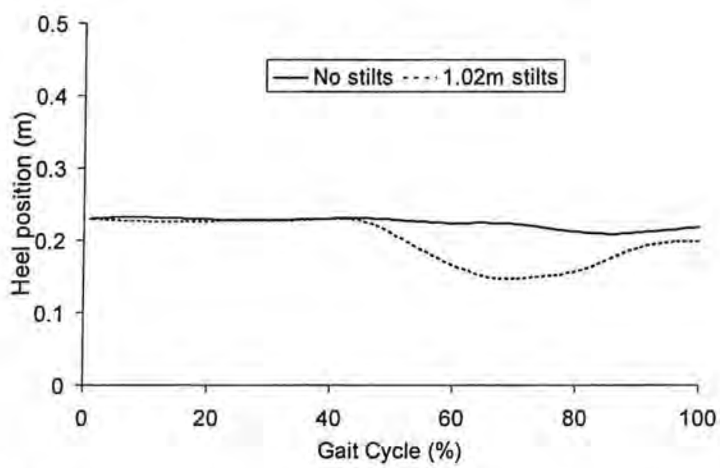

Figure 2 Medio-lateral position of the right heel as a function of the gait cycle

Figure 2 illustrates the position of the right heel marker in the medio-lateral direction as a function of gait cycle, with heel contact at 0% and the subsequent heel contact at 100%. The position of heel for no stilts conditions remained essentially the same medio-lateral position – around 0.23 m. For gait on stilts, the stilt was at 0.23 m in the beginning of the gait cycle but swung 8 cm outward during swing phase. The effect of height was found significant on minimum toe clearance during mid-swing ($p<0.0001$). The toe clearances for stilt conditions were consistently lower than those of no stilts throughout the entire gait cycle. No significant effect was found for tool carrying.

Discussions and Conclusions

This study investigates fall hazards associated with two commonly used elevated devices in construction. Results from this study provide information on how operator activities, standing direction and location affect the stability of scissor lifts, as well as insights on gait characteristics and kinematics mechanisms by which gait on stilts is accomplished.

Performing construction tasks on a scissor lift can create a side force of as much as 141 lbs, under test conditions simulating normal tasks which involved a pushing activity in the direction parallel with the length of the lift. The effect of lift height did not affect the maximum side forces exerted by the subjects, implying high side forces may occur at any level of lift height. The maximum lift acceleration during sudden forceful exertions was more than 1.4 g as observed in the current study. Such acceleration may perturb subjects' postural stability and result in loss of balance leading to a fall. The peak trunk accelerations during successful recovery efforts were reported to be in a range of 1.02 to 1.33 g (Brown *et al.*, 2001; Betker *et al.*, 2006). The maximum magnitudes of the acceleration observed in this study falls beyond this range. Subjects' postural instability may be further challenged if the scissor lift is parked on a slope or uneven ground. To minimize lift instability, workers may need to avoid excessive pushing or pulling in the direction parallel with the length of the lift.

For gait on stilts, the functional changes in walking speed, stride period, step width, and double stance period (%) reflect the adaptations adopted by workers to maintain dynamic balance. The increase in balance demand is evident in the increases in step width and double stance period (%). The increase in step width suggests a wider base of support was needed to improve stability on stilts. The lengthened double stance period (%) indicates a longer time was required for the body to re-establish stability from one step to another. The trajectory of heel markers for gait on stilts suggests a "lurching style" walking pattern with the foot swing out laterally, providing a wider base of support. The decrease in toe marker clearance of the swing limb implies that workers may be more likely to trip on objects on the floor. Therefore, workers should inspect the work environment before putting on stilts, to ensure the floors are free of obstacles.

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