Equipment Design

Scissor Lift Safety

An initiative to model static stability

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SCISSOR LIFTS ARE ELEVATING PLATFORMS that can be raised or lowered to various heights. The platform can be positioned horizontally beyond the base. These lifts are increasingly being used in various industries because they are mobile and provide workers access to elevations to perform required tasks (Burkart, McCann & Paine, 2004).

NIOSH, in collaboration with National Safety Council (NSC) and Center to Protect Workers' Rights (CPWR), conducted a surveillance study of aerial platform falls/collapses/tipovers across all industry classifications. This study showed that approximately two-thirds of fatal and nonfatal incidents involving scissor lifts occurred in the construction industry (Pan, Hoskin, Lin, et al., 2005). A scissor lift is regulated by OSHA as a mobile scaffold and by the agency's general industry requirements for scaffolds. Manufacturers have relied on the tests and safety features described in consensus standards published by ANSI and Scaffold Industry Association (SIA) for self-propelled elevating work platforms (e.g., A92.6-1999) to ensure proper scissor lift performance.

Because of market demands to increase the vertical reach of lifts, the results of certain design changes—such as higher center-of-gravity (CG) positions and limited size and weight of the base of support for the lift—have created an increased risk of fall/collapse/tipover incidents (McCann, 2003; Pan, Hoskin, McCann, et al., 2007). Review of these incidents indicated that approximately two-thirds were reported at a height range of 3.05 to 8.84 m (Pan, et al., 2005). One-third of the incidents involving scissor lifts were identified as occurring while there was dynamic movement of the lifts in the horizontal plane as the workers were conducting assigned tasks within the platform (Pan, et al.) and two-thirds of the incidents occurred under static conditions. The contribution of specific factors leading to loss of stability under static work conditions was of greatest importance.

Understanding the etiology of tipover-related

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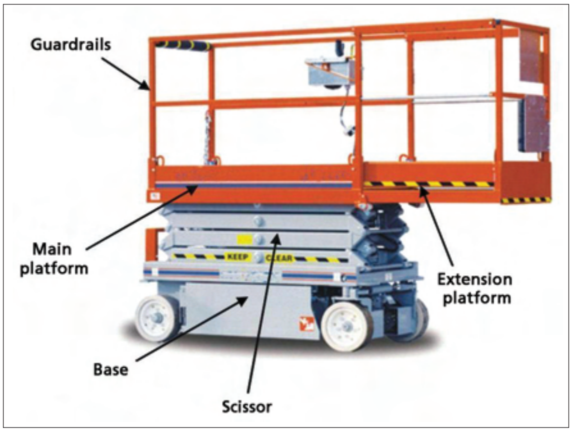
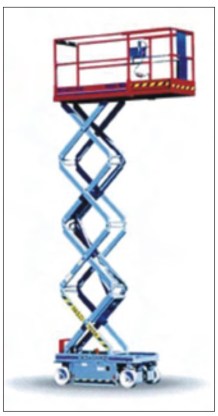
Photo 1 (top): This analysis involved several major components of the scissor lift.

Photo 2 (below): The scissor lift analyzed in this study can be raised 5.79 m from its stowed position.





injuries was the primary focus of this study. The applied horizontal tipping loads depend on the CG position and the total weight of the lift. Lift manufacturers, relying on the required horizontal load test from ANSI A92.6, would consider these safety margin tests robust enough for the performance of normal tasks during standard operations, but the safety margin would be significantly degraded if loading forces were additively combined with load-generating hazards and stability-reducing factors associated with specific task operations (e.g., side force), tribological characteristics (e.g., wet floor) and nature of the work surface (e.g., slope), as well as environmental factors (e.g., wind effects).

Computer modeling and simulation have been used to evaluate heavy equipment crash incidents and fall/instability scenarios, and could effectively help engineers and SH&E professionals develop an improved design (Abo-Shanab & Sepehri, 2005; Huston, 1987; Gerritsen, Van Den Bogert & Nigg, 1995; Lee, 1998; Mohan & Zech, 2005; Tamate, Suemasa & Katada, 2005). The authors could not locate published literature on computer simulations or models of the safety margins of scissor lifts and related elevated equipment.

Defining the static stability boundary of the scissor lift is essential for safe operation since the CG position and weight of the lifts vary with working conditions; operators may apply excessive horizontal forces while performing under various working conditions involving slope, friction and wind load, causing the lift to lose stability.

For the purpose of this study, the static instability of the scissor lift was analyzed using computer simulation. The objectives of this study were to 1) develop a model simulating the variation of the scissor lift's CG during normal operation; 2) experimentally measure the CG position at three different heights to validate the theoretical model; and 3) calculate the safety margin of the horizontal forces that can be applied to the scissor lift.

Study Method

Many scissor lifts are available on the market and each can perform various tasks. For this study, the SkyJack model SJIII 3219 compact scissor lift with standard equipment was selected (Photos 1 and 2). A simulating scissor lift model was developed via a collaborative research partnership between NIOSH and SkyJack Inc. (manufacturer) using Automated Dynamic Analysis of Mechanical Systems software (2005 version), a simulation software for analyzing static and dynamic of mechanical systems.

The SJIII 3219 has a deck extension, guardrails around its periphery and toeboards on all sides. This platform is 1.63 m long and 0.74 m wide. The deck extension increases the platform to an overall length of 2.54 m. The guardrail systems are composed of a toprail and a midrail. The toprail has a height of 0.99 m, while the toeboard is 0.15 m high. This type of scissor lift has a total capacity of 2.5 kilo-Newtons (kN), including two people and materials. The rated load on the main platform and 0.91 m deck extension are 1.3 kN and 1.1 kN, respectively. These specifications conform to ANSI A92.6 for self-propelled elevating work platforms.

This model was used for both laboratory testing and computational simulations using the analysis software. The model meets the test requirements of ANSI 92.6-1999. All tests conducted in the study complied with this standard's requirements as well. The SJIII 3219 model has a 0.81 m width and can be elevated vertically to 5.79 m from its stowed position.

Modeling & Simulation

Computer modeling was performed in two steps. First, the global structure of the aerial lift was decomposed into three substructures: base, scissor and platform (Figure 1). The dimensions and total mass of these three substructures were modeled according to the manufacturer's component design drafts. The mass distributions of the substructural models were adjusted so that the computed total mass and CG positions agreed with the manufacturer's specifications.

Second, the three substructural models were assembled and the global CG position of the scissor lift was computed as a function of the lift height; the theoretical predictions were then compared with the experimental data collected in the lab test. The equipment manufacturer provided the geometric drawings (in SolidWorks format) along with the material properties of each component of the scissor lift.

The major components of the structure were simulated in sufficient detail to capture the manufacturing and testing data without compromising the model's accuracy. The most complex substructure is the base, which was modeled using a simple geometric representation with some Boolean volumes for the wheels and hydraulic actuator. The wheels are attached to the base through struts and mounts. Mounts are fixed to the base while the struts are attached to the wheels. A stiff spring-damper connects mounts to struts.

The front wheels can swivel about the axis passing

PHOTOS COURTESY SKYJACK INC.

through the struts. A stiff spring-damper was applied between strut and mount with a step function defining its motion to swivel wheels while in motion. The hydraulic actuator attached to the bottom portion of base uses a sinusoidal function to elevate the scissor lift to the proper height. The wheels were attached to struts and connected to the base through a mount. The front axle has two hydraulic motor-driven wheels, steerable by a hydraulic cylinder. A step function describes the path that the scissor lift can follow.

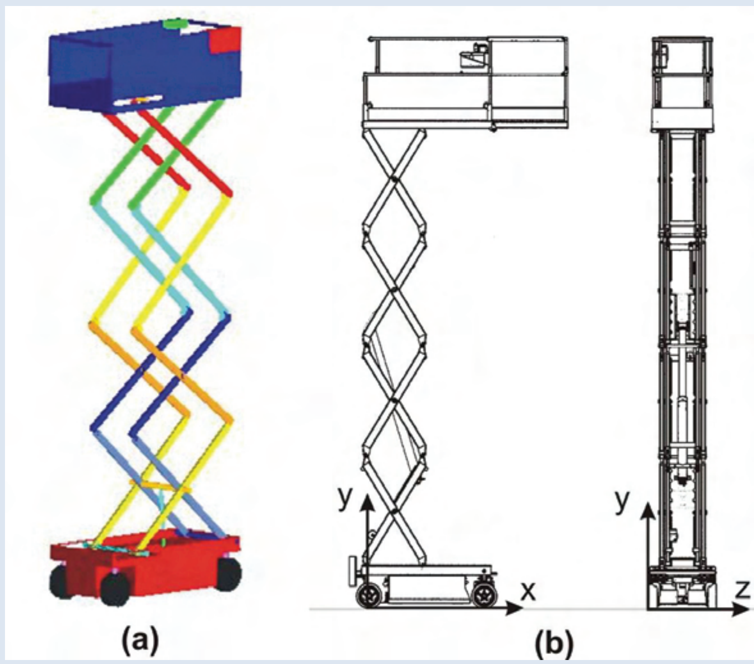
Laboratory Testing

CG for the scissor lift was experimentally determined at four different heights—stowed position, 1 m, 1.52 m, 2.14 m and 3.05 m. In addition, horizontal stability tests were conducted at these heights following ANSI/SIA A92.6-1999 requirements. To calculate CG in x and z directions (as shown in Figure 1), four force plates (Bertec) were placed under the wheels of the scissor lift (Photo 3). To calculate the CG in the y direction, the lift was tilted using hand pump jacks and jack stands (Photo 4). Platform height was recorded using a cable-extension transducer (Model PT5A-250-N34-UP-500-C25, Celesco).

A horizontal actuator (Series 247, MTS) was used to apply horizontal loads through a cable-and-sheave arrangement (as shown in Photo 3). The sheave was hung from a 5-ton-capacity overhead crane. Load readings were taken via a load cell

Figure 1

Modeling of Scissor Lift & Three-Axes Orientation



Abstract: *Scissor lifts are used in many industries because they are mobile and provide access to elevated work tasks. Tipover during stationary operation is a common incident. In the present study, a simulation model was used to calculate the location of the center of gravity and the safe operational margins due to applied horizontal forces to the scissor lift under static conditions. The results indicate that even if all ANSI regulations covering scissor lift operations are strictly followed the lift can still tip over if the horizontal forces exerted by a worker on the lift exceed the manufacturer safety limits as specified in the ANSI A92.6 standards. The use of outriggers increases the base area of a scissor lift, which consequently improves the stability and safe operation.*

Photo 3 (above): To calculate CG in x and z directions (as shown in Figure 1), four force plates were placed under the wheels of the scissor lift.

Photo 4 (right): The scissor lift was tilted with hand pump jacks and jack stands to measure the CG in the y direction.

(Model 661.20e-02, MTS) integrated with the hydraulic actuator.

Calculation of Safe Operational Margins

Assuming that a worker/operator applies a pull or push force while working from the platform when the scissor lift is at a height H_l (as illustrated in Figure 2), the maximum horizontal forces in the x and z directions that will not tilt the scissor lift can be estimated using the following equations:

Equation 1

$$F_x \leq \frac{W(C_x + X_{ext})}{H_l + H_h}$$

Equation 2

$$F_z \leq \frac{W(C_z + Z_{ext})}{H_l + H_h}$$

where:

•W is the total weight of the system including the worker's body weight;

•C_x and C_z are the CG position in the x and z direction, respectively;

•H_h is the height of the elbow of the worker;

•F_x and F_z are the horizontal forces in x and z direction, respectively;

•X_{ext} and Z_{ext} implicate the outrigger extension length in x and z direction, respectively.

According to the manufacturer, the total system weight was 10,791 N. The height of the elbow for a typical construction worker was assumed to be 1.21 m based on the results from the NIOSH aerial-lift-study human-subject-data analyses (Pan & Chiou, 2005). The CG position in both x and z directions are a function of the lift height; consequently, the maximum safe horizontal forces in x and z direction will vary with changing lift height.

Study Results

The positions of the CG in x, y and z directions were calculated using the proposed model as a function of the height of the scissor lift. The model predictions were compared with the results from laboratory testing, which were shown as the discrete points in Figure 3. The modeling predictions agreed well with the experimental data with an error of less than 1% for the whole range of the lift height variation in three orthogonal directions (Table 1, p. 48). The modeling and experimental results show that as CG in x direction decreased, the CG in y direction increased, while the CG in z direction remains constant with increasing lift height.

Using the numerically calculated CG positions, the safe horizontal forces in x and z directions were predicted using Equations 1 and 2 (Figure 4, p. 48). The outrigger extension X_{ext} and Z_{ext} are assumed to be zero in these calculations. The horizontal forces that could be safely applied on the lift decreased dramatically with increasing lift height.

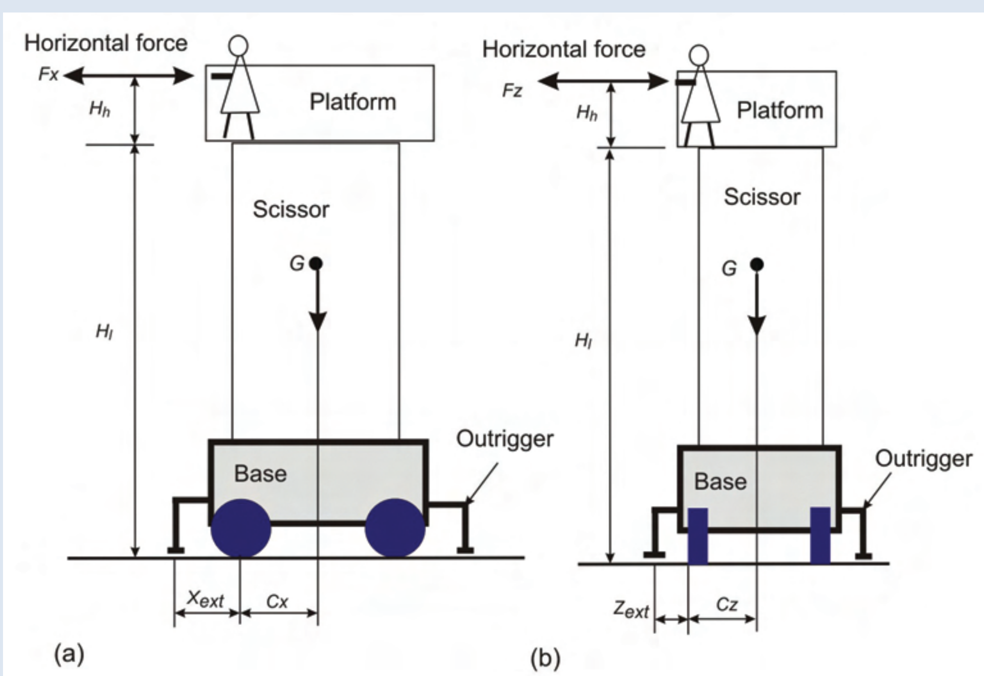
Discussion

The scissor lift tipover from a stationary state during operation represents a frequent scenario in lift-related incidents. The NIOSH team collected data for operations within the scissor lift platform and the results indicate that the scissor lift could lose static equilibrium when operated at an extended height above 5.49 m with the application of a horizontal force of 623 N—which is the maximum push force measured in the experiment simulating working conditions on the platform (Pan & Chiou, 2005). Scissor-lift operators could easily neglect these hazards when they are concentrating on their jobs.

The tipover risk due to the excessive horizontal force has not been discussed in the safety manual published by Association of Equipment Manufacturers (2002). Considering the force variations in the human subject tests, it would be feasible to consider the maximum horizontal forces in an engineering design in a range from 667 to 889 N. The results of this study show that even if all ANSI A92.6 safety limits on lift operations

Figure 2

Modeling Analysis of Static Stability



are strictly followed, the lift can still tip over if the horizontal operational forces exceed the manufacturer safety limits in z direction (Figure 4b, p. 48).

The use of outriggers would increase the safety limits. However, outriggers will limit the equipment's mobility. One advantage of using outriggers is that doing so increases the scissor lift support area—and the lift's stability will be enhanced as the support area increases. The scissor lift is more stable in x (longitudinal) direction due to greater axis span in comparison to z direction (Figure 4a, p. 48).

Practical Applications

Most scissor lifts on the market are not equipped with outriggers, extendable axles or stabilizers. These modeling analyses show that outriggers increase safety when the scissor lift is elevated above two-thirds of its full extension. According to the calculations using Equations 1 and 2, the maximum horizontal force (in x or z direction) that could be applied onto the system could safely be doubled if outriggers with a length of 50% of the base dimension were used. As another equipment improvement, horizontal-overload-detecting sensor devices could be developed for use on the lift.

The geometric data provided by the equipment manufacturer were input in the modeling analyses to generate reliable CG results. The data generated have been validated with the discrete experimental results produced by laboratory testing.

This model can predict the CG in three orthogonal directions for the entire 5.79 m height. Although the results of this simulation were obtained through static modeling, the computer model can perform and analyze dynamic predictions for more sophisticated scenarios—for example, driving into a pothole or curb, and dynamic push/pull forces exerted on the platform.

A computer model was developed to simulate the variation of the position of CG as a function of the aerial lift height. The theoretical predictions have been validated to be in line with discrete experimental data. Based on the numerically predicted CG data, the safety margins of the horizontal forces that can be applied to the scissor lift are functions of lift height may be determined.

The study indicates that the scissor lift may tip over in the horizontal z direction during normal operations with the excessive applied forces. If the applied forces are between 623 and 889 N, the scissor lift can be safely extended to a height between 5.49 and 3.49 m, respectively.

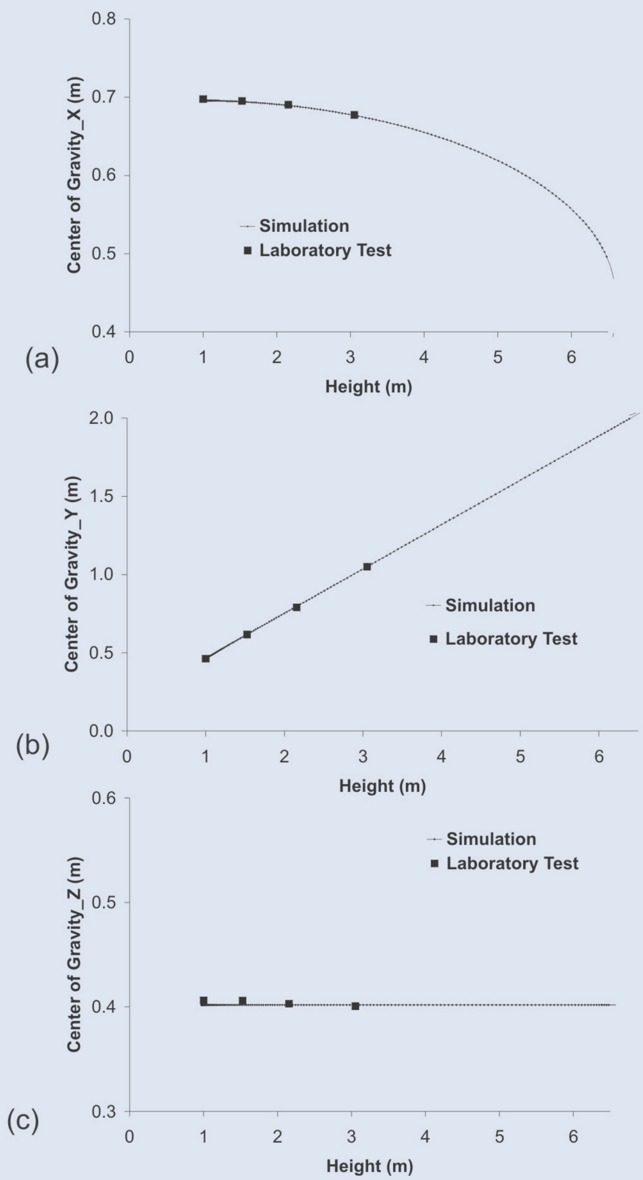
Recommendation

Workers need to be aware that excessive horizontal force is a critical factor in scissor lift tipovers. To ensure safe operation when the lift is extended to more than half of the fully elevated height, workers should be cautious in performing a full-power horizontal push or pull action on the lift platform. Any pull or push action should be applied with caution. These recommendations should also be emphasized in lift training programs.

The simulations were performed by assuming operation in ideal conditions—the lift rests on level, solid ground and the effects of structural flexibility and wind are negligible. In the real world, however, all these effects exist and will affect the equipment's static stability. Therefore, a more conservative safety factor should be applied when using the predicted maximum horizontal forces in the practical cases. ■

Figure 3

Predicted Positions of the CG Compared With Laboratory Experimental Measurements



Note. *Predicted positions of the CG in (a) x, (b) y and (c) z directions are compared with the laboratory experimental measurements.*

Table 1

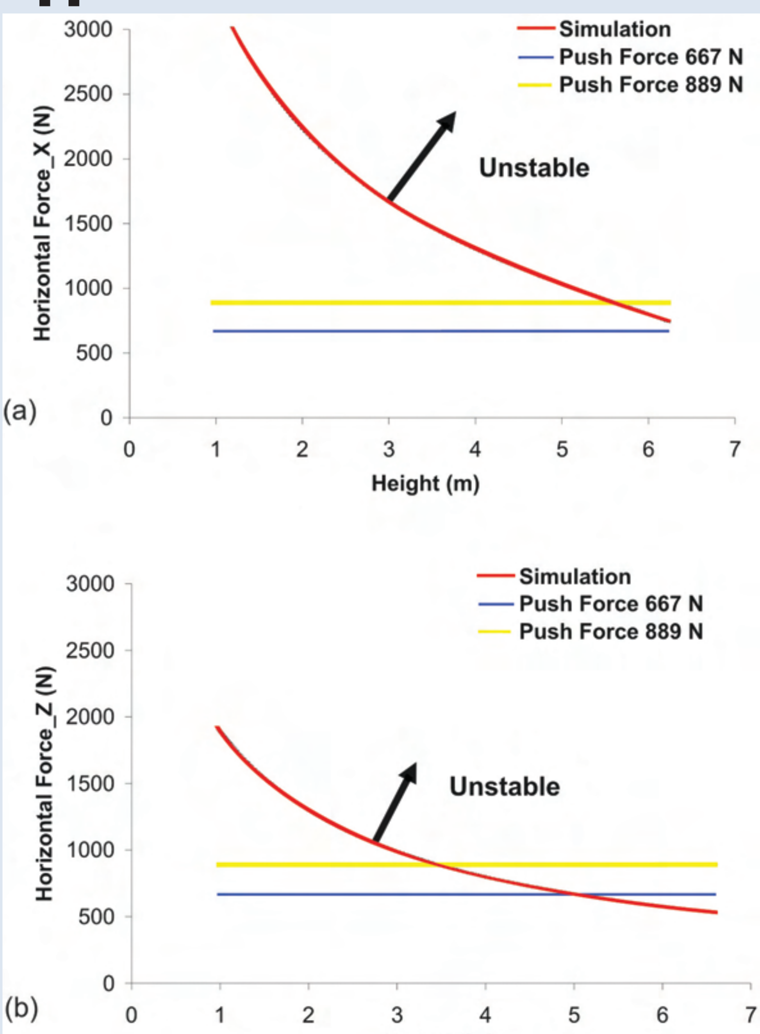
Comparison of Theoretically Predicted CG With Those Measured Experimentally

Height	Center of Gravity_X Test	Simulation	Error (%)	Center of Gravity_Y Test	Simulation	Error (%)	Center of Gravity_Z Test	Simulation	Error (%)
0.997	0.698	0.696	< 1	0.463	0.463	< 1	0.406	0.402	< 1
1.52	0.695	0.694	< 1	0.618	0.616	< 1	0.406	0.402	< 1
2.15	0.691	0.689	< 1	0.791	0.795	< 1	0.403	0.402	< 1
3.05	0.678	0.677	< 1	1.051	1.049	< 1	0.401	0.402	< 1

Note. *Measured in meters.*

Figure 4

Predicted Maximum Horizontal Forces That Can Be Safely Applied Onto the Platform



Note. *Predicted maximum horizontal forces that can be safely applied onto the platform: (a) x direction; (b) z direction. The predicted forces have been compared with a range of 150 to 200 lb (667 to 889 N) feasible forces in the scissor lift tipovers.*

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