

# 16

## *Aerial Lift Safety Research and Practice*

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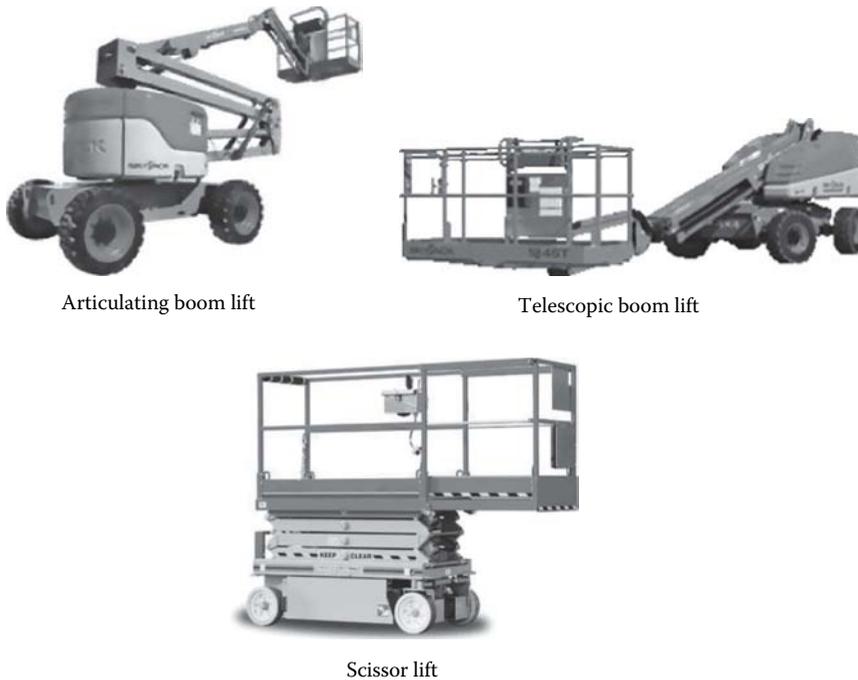
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**ABSTRACT** The increasing industrial use of aerial lifts has resulted in a corresponding increased risk of incidents with attendant injury and death. This chapter identifies factors contributing to those incidents, including hazardous surface conditions, aerial lift and worker motions, and the lack of use of safety systems. The chapter also describes current safety research on aerial lifts and other similar equipment.

### 16.1 Research on Aerial Lifts

The increasing industrial use of aerial lifts has resulted in a corresponding increased risk of incidents with attendant injury and death; there were over 300 deaths associated with the industrial use of aerial lifts between 1992 and 2003 [1]. To better understand the cause of aerial-lift incidents, the National Institute for Occupational Safety and Health (NIOSH), the National Safety Council (NSC), and the Center for Construction Research and Training (CPWR) joined together to review aerial platform fall, collapse, and tip-over data from three sources of information concerning incidents involving aerial lifts: the BLS



**FIGURE 16.1**  
Types of aerial lifts. (Reprinted with permission of SkyJack Inc.)

Census of Fatal Occupational Injuries (CFOI) (1992–2003), Occupational Safety and Health Administration (OSHA) incident investigation records (1990–2003), and NIOSH Fatality Assessment and Control Evaluation (FACE) reports (1985–2002) [1]. Results presented in this chapter represent data taken from these three databases, unless a specific source is indicated.

Analysis of data from these sources identifies factors contributing to those incidents, including hazardous surface conditions, aerial lift and worker motions, and the lack of use of safety systems. The following sections explore the results of NIOSH research focused on the use of scissor lifts, a type of aerial lift that supports a work platform on top of an extendable, linked, and folding support assembly. Aerial lifts generally include scissor lifts and boom lifts (Figure 16.1). Although NIOSH's research presently focuses on scissor lifts, the following sections will also describe incidents arising from the use of the other major type of aerial lift—the boom lift—which supports a work platform at the end of an extendable boom.

## 16.1.1 Scissor Lifts

### 16.1.1.1 Background

Scissor lifts are self-propelled, mobile work platforms that can be raised or lowered to various heights [1–3] but lack the ability to rotate. Scissor lifts are popular because their small footprint permits their use in tight areas [4], and they are generally considered to be more productive than other forms of elevating device, which can require extensive assembly and disassembly time, lack mobility, and are commonly perceived as imposing

constraints of reach, forceful loading, and postural instability upon users. Further, scissor lifts are generally perceived to effect reduction in physical demands on workers when compared to other traditional elevated devices, such as ladders [2], although the extent of physical demands on various body parts has not been extensively researched or comparatively established. However, despite the apparent reduction in exposure to some types of hazardous conditions, scissor lifts also present unique and substantial risks, particularly of falls to lower levels. Some of the hazards are inherent to the design and configuration of the lift itself; scissor lifts designed to fit through doorways can have narrow wheelbases, which decreases their stability. Rollout platform extensions on scissor-lift platforms also decrease stability, since they can reach beyond the wheelbase and thus affect the scissor lift's center of gravity. Further, horizontal worker motions and external kinetic forces can further destabilize the lift. For example, when a horizontal force of 623 newtons is applied while the lift is elevated over 5.49 meters, excess loading of the lift and subsequent tipover can occur [3]. These fall/collapse/tip-over hazards occur frequently and are easily overlooked by workers.

#### **16.1.1.2 Factors Contributing to Scissor-Lift Injuries and Deaths**

Descriptive results of a pertinent NIOSH study [1] shows that from 1992 to 2003, falls from scissor lifts caused 78 fatalities (CFOI data). Most of these deaths occurred in the construction industry (58 deaths, representing 74% of the total), at a construction site (41%), in an industrial zone (31%), or on a street or highway (30%). Consistent with the location of the incidents, the majority of scissor-lift falls recorded by OSHA and FACE investigations occurred while "constructing and repairing" (54%) or "painting and cleaning" (19%).

Tip-over and collapse of the scissor lift (known as *tip-overs*) caused over half of the falls (56% of the total, based on CFOI data), and falls from the scissor-lift platform caused the remaining incidents. The NIOSH/NSC/CPWR collaborative study collected information from the three source databases and identified several common factors associated with falls from scissor lifts. First, the study found that hazardous conditions largely contributed to falls from scissor lifts. For instance, the CFOI database shows that uneven or sloped ground or driving on or off a flatbed truck was cited as a factor in six tip-overs (14% of 44 scissor-lift tip-overs). That database also shows that driving into potholes, or over sidewalks or similar uneven edges, contributed to seven tip-overs (16%). In contrast, review of the information reported in the OSHA logs and FACE database show that 55% of fall reports cited surface conditions, and in the 16 fall incidents (55%) that cited surface conditions as contributing factors, seven cases involved potholes, and nine cases involved uneven or unstable ground [1].

The above-mentioned NIOSH/NSC/CPWR study also identified scissor-lift and worker movements as contributing to falls from scissor lifts. The OSHA/FACE databases cited scissor-lift motion in 42% of fall incidents. Also, scissor lifts had moved forward or backward in 18 of 78 (23%) of scissor-lift fatalities recorded in the CFOI database and in 18 (33%) of the 54 scissor-lift falls recorded in the OSHA/FACE databases. In addition, raising or lowering of the lift was cited in four (7%) of the total OSHA/FACE cases. Moreover, the study found that 25 (46%) of the OSHA/FACE fall reports cited worker movement as a contributory factor to the fall.

Surprisingly, the OSHA/FACE databases show that 83% of scissor-lift fall victims fell 3–8.8 m, yet only a small minority of the injury or fatality cases from the OSHA/FACE databases show that the workers were using safety protection, such as belts and harnesses.

In fact, only four of the 13 (31%) of the scissor-lift fall reports that mention fall protection show the use of such fall protection.

Indeed, the study found that mechanical failure was cited in only two scissor-lift cases (4%), suggesting that a majority of scissor-lift falls and resulting injuries and deaths may be considered to be related to operational variables and misuse scenarios and are preventable with appropriate training and safe-operation standardization procedures. When joined with careful analysis of the design variables of scissor lifts, and the inherent limitations of use under different conditions as a function of the design itself, virtually all of the injuries can be said to be preventable. Therefore, what is needed to effect the safe use of scissor lifts can be succinctly summarized as follows: A better understanding of scissor-lift design constraints under hazardous-exposure conditions; scissor-lift movements under normal and extreme conditions; worker movements, especially phase-amplifying movements that are cumulative and that contribute to tip-over and fall incidents; and the efficacy of safety systems designed to protect workers from such falls.

The current relevant regulations do not fully address these risk factors. Specifically, scissor lifts are “mobile scaffolds” as defined by 29 C.F.R. § 1926.451(g)(1)(vii) (OSHA) and thus require the use of guardrails or personal fall protection systems as a primary safety control system [1]. But these regulations were designed for the purpose of regulating scaffolding and not aerial lifts per se. In fact, the preamble to 29 C.F.R. § 1926.451 expressly states that the mobile scaffold section “does not apply to aerial lifts.” Expert opinion suggests that this requirement may not fully address hazards presented by scissor lifts, which are generally operated at different heights and conditions and for different work tasks than such normal suspension scaffolds. Accordingly, NIOSH has investigated these risk factors and presents the findings from the relevant studies below.

### **16.1.1.3 Scissor-Lift Behavior in Hazardous Conditions**

To conduct research into scissor-lift behavior under hazardous conditions without putting human subjects at risk, NIOSH researchers have developed computer simulations to model scissor-lift behavior under various potentially hazardous conditions. The NIOSH studies show that, although scissor lifts at static conditions are stable under certain circumstances, a static scissor lift may tip over when subjected to sufficient horizontal forces even if that scissor lift complies with all ANSI A92.6 safety limits [3]. The studies also show that decreasing the stiffness and increasing the tilt speed and tilt angle of a scissor lift generally reduces scissor-lift stability on sloped ground and during curb and pothole impacts. The studies further suggest that using a scissor lift on soft surfaces could cause tip-overs and that wind forces exceeding 20 m/s can potentially tip over a scissor lift.

#### *16.1.1.3.1 Computer Simulations of Static Scissor-Lift Behavior in Hazardous Conditions*

Nearly two-thirds of all scissor-lift tip-overs occur when the scissor lift is stationary, even when the scissor lifts at issue are designed and manufactured to withstand horizontal forces prescribed by ANSI safety standards [4]. To understand why such tip-overs occur, NIOSH studied how much horizontal force was required to tip over a scissor lift by developing a computer model of a stationary scissor lift, validating that model with experimental data, and then using this model to calculate the horizontal forces that would cause tip-over events. The results show that, although scissor lifts at rest are stable under certain circumstances, a static scissor lift may tip over when subjected to sufficient horizontal force even if that scissor lift complies with all ANSI A92.6 safety limits [4]. The results

also show that the use of outriggers may substantially strengthen a scissor lift's ability to withstand horizontal forces.

More extensive and detailed information on the procedure followed by NIOSH is given below. The first action that NIOSH researchers undertook to determine the forces acting on a scissor lift was to develop a computer model using information from manufacturer specifications. Researchers then conducted center-of-gravity and horizontal-stability tests under the ANSI A92.6 (2006) standard to validate the results predicted by the preliminary model. In order to determine the empirical center of gravity, researchers placed four force plates (Bertec Corporation, Columbus, OH) under the wheels of the scissor lift and tilted the lift using hand force-activated pump jacks and jack stands. Researchers recorded the platform height using a cable-extension transducer (Model PT5A-250-N34-UP-500-C25, Celesco Transducer Products, Inc., Chatsworth, CA). The researchers used a horizontal actuator (Series 247, MTS Systems Corporation, Eden Prairie, MN) to apply horizontal loads through a cable-and-sheaf arrangement. The researchers hung the sheaf from a 4,535.9 kg-capacity overhead crane and took load readings with a load cell (Model 661.20e-02, MTS Systems Corporation, Eden Prairie, MN) integrated with the hydraulic actuator. The modeling predictions agreed well with the experimental data with an error margin of less than 1% for the whole range of the lift height variations in three orthogonal directions [4].

Second, the researchers used the validated and refined computer model to calculate the amount of horizontal force that a scissor lift could withstand at different heights. The results show that a scissor lift (model 3219, SkyJack Inc., Guelph, ON, Canada) can be safely extended to a height between 3.49 and 5.49 m if applied forces are between 623 and 889 N [4].

#### *16.1.1.3.2 Further Computer Simulations of Dynamic Scissor-Lift Behavior in Hazardous Slope, Tilt, Curb Impact, and Pothole Conditions*

NIOSH researchers also developed a dynamic computer model of the scissor lift to identify factors in hazardous conditions that contribute to tip-over events. The model shows that on sloped ground, increasing the height and flexibility of the lift structure also increases the scissor lift's tip-over potential [5]. Accordingly, the lift should not be elevated on soft or uneven surfaces. Also, scissor lifts should be designed to be as stiff as possible to avoid tip-overs during curb impact and pothole depression impacts and to potentially use lower pothole guards (to reduce the dynamic impact) so as to avoid tip-overs during the latter events. The computer model also shows that both ground slope and the tilt speed of the lift affect the stability of the lift, and thus both the tilt angle and tilt speed of the lift could be measured and used to help prevent tip-overs. Further, the computer model confirms that low-frequency disturbances (such as repetitive-motion tasks) may cause scissor-lift tip-overs, and thus workers should avoid making periodic horizontal motions that could amplify the rocking motion and result in a tip-over. Therefore, the study suggests that certain periodic movements and horizontal forces/moments applied by workers may excite (increase) the resonate frequencies of the lift and may subsequently contribute to tip-over incidents. The results also suggest that increasing the flexibility of the lift structure while it is on sloped surfaces increases its tip-over potential, and the lift should thus not be elevated on soft, uneven, or other sloped surfaces.

The researchers equipped a scissor lift weighing 1170 kg with a deck extension carrying a rated load of 113 kg. They also installed five in-house packaged triaxial accelerometers on the main frame of the base; the second, third, and fourth scissor frames; and the main frame of the platform. The accelerometers' signals were sent to an in-house packaged data-acquisition system, which sampled the accelerometer data at 128 Hz [5].

The researchers simulated a curb impact by driving the scissor lift, both forward and backward, into a curb at 30° and 90° at the maximum heights allowed by the lift at two different speeds—5.80 m high while at 0.29 m/s and 2.08 m high while at 0.89 m/s. The researchers also simulated a pothole impact by driving one of the scissor lift's front wheels into a standardized pothole (0.60 m square and 0.10 m depth). The collected data from both the curb and pothole impact tests suggest that when the platform is fully elevated (2.08 m), the major cause of movement in the platform is pitching and rolling, arising from resonant low-frequency vibrations, particularly from 0.3 to 2.08 Hz, and can cause significant deformations of the scissor-lift substructures. By contrast, the data also show that such low-frequency vibrations do not occur at the lower heights of the scissor lifts and that high-frequency vibrations quickly dissipate and therefore are not likely to cause tip-overs.

The researchers then created an ADAMS/View computer model based on the collected data; other measurements taken of the scissor lifts' wheels; and dimensions, connection points, mass properties, and centers of mass (CM) calculated through the scissor lifts' schematics. The researchers successfully validated the CM values generated by the model, which were consistent with CM values measured during a tilt-table experiment of the scissor lift at four different heights. The researchers further validated the computer model's predicted acceleration values upon curb and pothole impacts, which also closely agreed with experimental acceleration measurements. The researchers used the computer model to determine the tip-over threshold under four hazardous conditions. In so doing, the researchers treated the tip-over threshold as a function of the scissor lift's vertical stiffness because vertical stiffness controls the rolling and pitching motions of the scissor structure and platform. Thus, the researchers used the effect of the scissor structure's stiffness as an independent variable for most of the simulations.

In this study, the researchers first applied the model to determine the effect of scissor-lift stiffness on tip-over threshold when the scissor lift was on sloped ground. The results showed that, if the lift platform was elevated, the tip-over threshold primarily depended on the height of the platform but that a scissor lift's stiffness also affected its stability. Although increasing stiffness generally increases the tilt tip-over angle, once the stiffness value approaches the limit identified from physical experiments [5] to a stiffness value that is roughly double to that limit, the tilt tip-over angle remains constant and undifferentiated, equivalently recording the same level of stability. Further, the model shows that a marginal change (<15%) from normal stiffness results in only a slight change (<1.0%) in tilt tip-over angle but that reducing the scissor lift's normal stiffness by more than 60% significantly reduces the tilt tip-over threshold (>5.0%). Consequently, using the lift on soft soil and other deformable surfaces such as bridged wood boards or metal sheets—which are effectively sloped surfaces—could be hazardous, particularly if workers create periodic motions close to the resonance frequency of the scissor lift that amplify the rocking motion and can result in a tip-over.

Second, the researchers used the model to simulate the effect of a scissor lift's tilting and rocking speed on tip-over threshold. The results showed that if the tilt speed is low, the tip-over threshold is close to the quasi-static tip-over threshold. However, the tip-over threshold is substantially reduced when the tilt speed is greater than 2.5 degrees/second, because dynamic energy can increase the tip-over potential. Accordingly, both the tilt angle and tilt speed—not just the tilt angle—should be monitored to avoid tip-overs.

Third, the researchers used the model to determine the effect of stiffness on the tip-over threshold during curb impact. Although the stiffness of the scissor lift did not substantially affect the tip-over threshold of the impact speed, the results show that to reduce the tip-over potential, it is better to keep the scissor-lift structures as stiff as possible.

Finally, the researchers used the model to determine the effect of stiffness on the tip-over threshold of pothole guardrail height. The results show that reducing the stiffness of the scissor lift, in turn, requires lowering the pothole guardrail height to control the tilt angle within the stable limit, because reducing the stiffness makes the lift's center of gravity move further toward the tilt direction. Consequently, the results suggest that pothole guardrails should be designed to be as low as possible [5].

#### **16.1.1.4 Drop Tests Evaluating Personal Fall Arrest System Efficacy, Personal Fall Arrest Systems' Impact on Workers, Fall Impact on the Stability of Scissor Lifts, and Methodologies for Evaluating the Biomechanical Risk Factors**

Personal fall arrest systems, which prevent workers from falling by catching them on a lanyard attached to the scissor lift, are not required by regulation because guardrails on the platforms meet the OSHA requirements for fall injury prevention for scissor lifts. (See 29 C.F.R. § 1926.451(g)(4)). Additional requirements for using personal fall arrest systems currently are still under consideration by industry and standard committees (ANSI A92.6). Indeed, the impact of these fall arrest systems on the stability of a scissor lift is unknown. Further, the effectiveness of personal fall arrest systems for scissor lifts and their impact on the head, neck, and torso of a worker when activated is also largely unknown. The following studies show that personal fall arrest systems under the test conditions below are not likely to cause scissor lifts to tip over and that forces exerted on the human body fall within the acceptable limits defined by applicable industry standards. Given that workers did not use personal fall arrest systems in most falls from scissor lifts that resulted in fatalities, these results suggest that perhaps aerial lift standards should consider amending the use of personal fall protection equipment to include personal fall arrest systems.

##### *16.1.1.4.1 Drop Test Results (Dead Weight Drop)*

Presently available fall arrest systems prevent worker falls from scissor lifts by anchoring a harness worn by the worker to the scissor lift with an energy-absorbing lanyard. To determine whether the use of a fall arrest system imposes forces on a scissor lift exceeding 1800 lb (the maximum force allowed by ANSI Z359.1-2007) or can otherwise cause a scissor lift to tip over, another NIOSH study [6] measured the structural and dynamic stability of aerial lift work platforms by dropping different weights anchored to different anchorage points on a scissor lift from different heights and observing whether the scissor lift tip-over occurred or the structure subsequently experienced component and complete failure. The results showed that the specific scissor lift used in this study (model 3219, SkyJack Inc., Guelph, ON, Canada) can withstand many different levels of fall arrest forces when fully elevated and deployed on an incline and that the use of a personal fall system will not likely cause the scissor lift used in this study to tip over [6]. The results also showed that such fall arrest systems are not likely to cause the scissor lift to tip over even if anchored to locations unapproved by the scissor lift manufacturer, such as the mid- and top rails of a scissor lift [6].

For this study, the researchers first identified combinations of weights and free-fall heights that would generate specific fall arrest forces—2224 N; 4,448 N; 6,672 N; 8000 N; and 10,675 N—by tying weights to a rigid beam with Nystrom ropes, dropping those weights, and collecting fall arrest data. The researchers used a load cell (1361.8 kg, S-type, Interface Inc., Scottsdale, AZ) to record the maximum arrest force, a string potentiometer (635 cm, Model PT5D, Celesco Transducer Products, Inc., Chatsworth, CA) to record positions of the

drop-test fixture, and an electromagnet (317.5 kg, Model SE-35352, Magnetic Products, Inc., Highland, MI) to activate the drop-test fixture. The researchers collected generated data with a laptop computer equipped with a data acquisition card (Model DAQCard-6036E, National Instruments Corporation, Austin, TX) running the LabVIEW data acquisition application (National Instruments Corporation, Austin, TX).

Using these same weights and heights and similar equipment, researchers repeated the experiment but dropped the weights anchored to the mid right point of a scissor lift (model SJIII3219, SkyJack Inc., Guelph, ON, Canada). Since the scissor lift neither tipped over nor suffered any structural failure, the researchers then applied the height and weight combinations generating the maximum 10,675-N arrest force for the five other anchor points—(1) mid left, (2) back right, (3) back left, (4) front right, and (5) front left. Once again, the scissor lift neither tipped over nor suffered any significant structural failure or deformation during any of these tests.

The researchers therefore repeated the experiment using the maximum 10,675-N arrest force but dropped weights anchored to the midpoints of the rails, which are the weakest points and thus the “worst-case anchorage points”—(1) right mid rail of the main platform, (2) left mid rail of the main platform, (3) right top rail of the main platform, (4) left top rail of the main platform, (5) right mid rail of the extension platform, (6) left mid rail of the extension platform, (7) right top rail of the extension platform, and (8) left top rail of the extension platform. Although all the anchor points on the respective rails deformed, the scissor lift did not tip over during any of these tests.

Next, the researchers repeated this experiment to evaluate the stability of the scissor lift where workers improperly stood on either the mid-rail or top rail of the scissor lift and fell from those heights. The researchers dropped a 128-kg weight from a height of 3.53 m while it was anchored to the (1) right mid rail of the main platform and (2) right top rail of the main platform, and dropped that same weight from a height of 3.10 m while it was anchored to the (3) right mid rail of the extension platform and (4) right top rail of the extension platform. Again, although all the anchor points on the respective rails deformed, the scissor lift did not tip over during any of these tests.

Finally, the researchers also tested whether the scissor lift would remain stable under three conditions when in its least stable orientation, at a tilt of 1.5° about the long axis of the lift. First, the researchers evaluated whether the tilted scissor lift met the Canadian Standards Association (CSA) B354.4-02 industry standard [7], which requires a scissor lift to remain stable when arresting the force from a 136-kg weight, falling 1.2 m while anchored to the least stable position (the front right point). Second, the researchers tested the tilted scissor lift’s stability by applying 10,675-N arrest force to anchor points on its front right, mid span of the mid rail, and mid span of the top rail. Third, the researchers tested whether the tilted scissor lift would remain stable if a person weighing 128 kg and of 95th percentile nipple height (1.364 m) improperly stood on the mid rail of the lift and fell 3.53 m while anchored by an energy-absorbing lanyard to the mid span of the mid rail or 3.10 m from the mid span of the top rail of the tilted scissor lift. During these three tests, the tilted scissor lift neither tipped over nor experienced any significant structural failure or deformation [6].

#### *16.1.1.4.2 Drop Test Results from Alternative Anchor Points (Manikin Drop)*

Personal fall arrest systems work by attaching the worker with a lanyard to an anchor point on the scissor lift platform. Some scissor-lift work platforms contain lanyard anchor points on the floor of the platform, but using these floor anchor points may limit the worker’s mobility since the worker may not be able to travel the length of the work platform without

disconnecting the lanyard from either the floor anchor point or the worker's harness. Prior research suggests that the mid rail and top rail of a scissor lift work platform support forces associated with a person falling from within the platform and the lift is stable during such a fall and will not tip over [6]. The results here show that under certain (but not all) the test conditions here described, the use of unapproved scissor-lift anchor points may not result in a tip-over event.

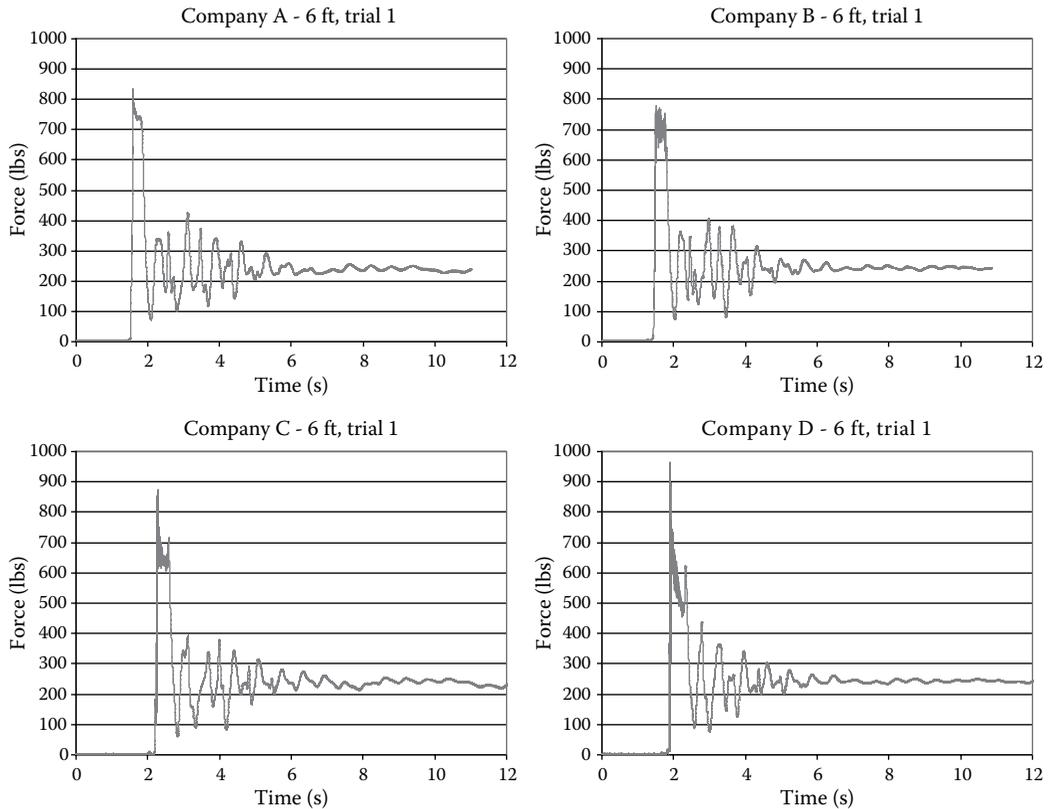
In this study, NIOSH researchers investigated the performance of four personal arrest fall systems when those systems were attached to anchor points on the top rail of the work platform of a scissor lift. Specifically, the researchers used personal arrest fall systems from DBI/Sala (ISAFE™ Model 1102000 harness and 1240006 lanyard), Elk River (Construction Plus™ Model 48113 harness and lanyard), MSA (Workman™ Model 10072479 harness and Model 10072474 lanyard), SafeWaze (Safelight™ Model 10910 harness and Model 209512 lanyard), and Skyjack (model SJIII3219). The researchers attached each harness onto an Advanced Dynamic Anthropomorphic Manikin (ADAM, Veridian, Dayton, OH), which was 1.88 m and weighed about 100 kg, and attached the respective harness and energy-absorbing lanyard to the top rail of the short axis of the scissor-lift work platform. The researchers dropped the manikin three times from two heights: 1.83 m (the standard drop height specified in ANSI/ASSE Z359.1-2007) and 3.35 m (to simulate a common misuse scenario in which operators stand on the mid rail of the scissor lift).

Preliminary analysis of the collected data showed that, during the standard 1.83-m drop height simulation, all four personal fall arrest systems kept the maximum arrest force (MAF) exerted on the manikin below 8700 N with 99% confidence and, therefore, met the ANSI and OSHA standards limiting MAFs to that amount. (See ANSI Z359.1-2007; OSHA § 1926.502(d)(16)(ii).) However, during the 3.35-m misuse simulation, only two of the four personal fall arrest systems met those ANSI and OSHA standards with 99% confidence [6].

Subject to further testing and validation, these preliminary results suggest that manufacturers may consider providing alternative anchor locations to permit better worker mobility through the work platform but that workers should be cautious when climbing the mid rail, since a fall from over 1.83 m could result in a MAF exceeding the ANSI and OSHA standards.

It should be noted that suspension trauma can occur while the worker is in a suspended position. Even though the MAF may not result in immediate health consequences, workers should not remain suspended for a sufficient period of time to engage trauma suspension; therefore, it may be necessary to work in pairs. Further information on this health hazard can be found in Turner et al. [8].

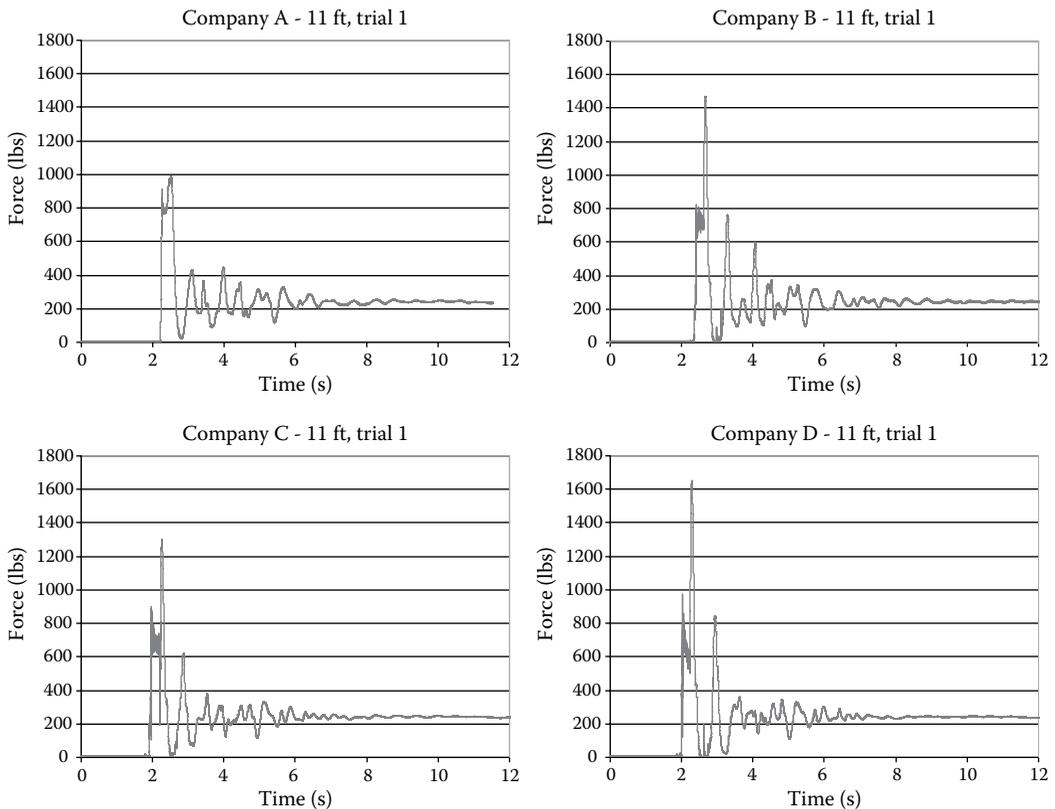
During the deceleration distance of a fall, the fall arrest system absorbs the kinetic impact energy, thereby reducing the impact force on the human body. The kinetic energy dissipated during the fall impact is an important parameter that characterizes the dynamic performance of the fall arrest system. The impact kinetic energy was either not considered or not correctly estimated in the literature. In the current study, a systematic approach was used to evaluate the energy dissipated in the energy-absorbing lanyard (EAL) and in the human body during the fall impact. The kinematics of the human body and the EAL during the impact were derived by using the data of the time histories of the arrest force, which was measured experimentally. The proposed method was used to analyze the experimental data of a 6-ft drop test and an 11-ft drop test. The preliminary results indicate that the distribution of the kinetic energy in the EAL and the falling body depends on the intensity of the impact: the portion of the kinetic



**FIGURE 16.2**  
Arrest forces for four different lanyards/harnesses for 6-ft drops.

energy dissipated in the EAL for higher-impact force is more than that for lower-impact force. The following preliminary findings (Figures 16.2 through 16.7) are summarized as follows [9]:

1. Lanyard deployment forces among four manufacturers are all similar (~800 lbs) (Figures 16.2 and 16.3).
2. Maximum arrest forces vary but are all under 1800 lbs (6-ft and 11-ft drops) (Figures 16.2 and 16.3).
3. Deployment forces do not correlate to the drop distances (6-ft and 11-ft drops) (Figures 16.2 and 16.3).
4. Repeated test trials for the same harnesses/lanyards produce similar results (Figures 16.4 and 16.5).
5. Arrest forces calculated using the kinematic data agree well with those measured directly via a force sensor (Figure 16.6), and the accelerations calculated using the force data agree well with those measured directly (Figure 16.7). These analyses indicated that the kinematics of the falling surrogate can be determined using measured arrest force, and vice versa: the arrest force in the EAL can also be determined using the accelerations measured at the surrogate. Detailed calculations



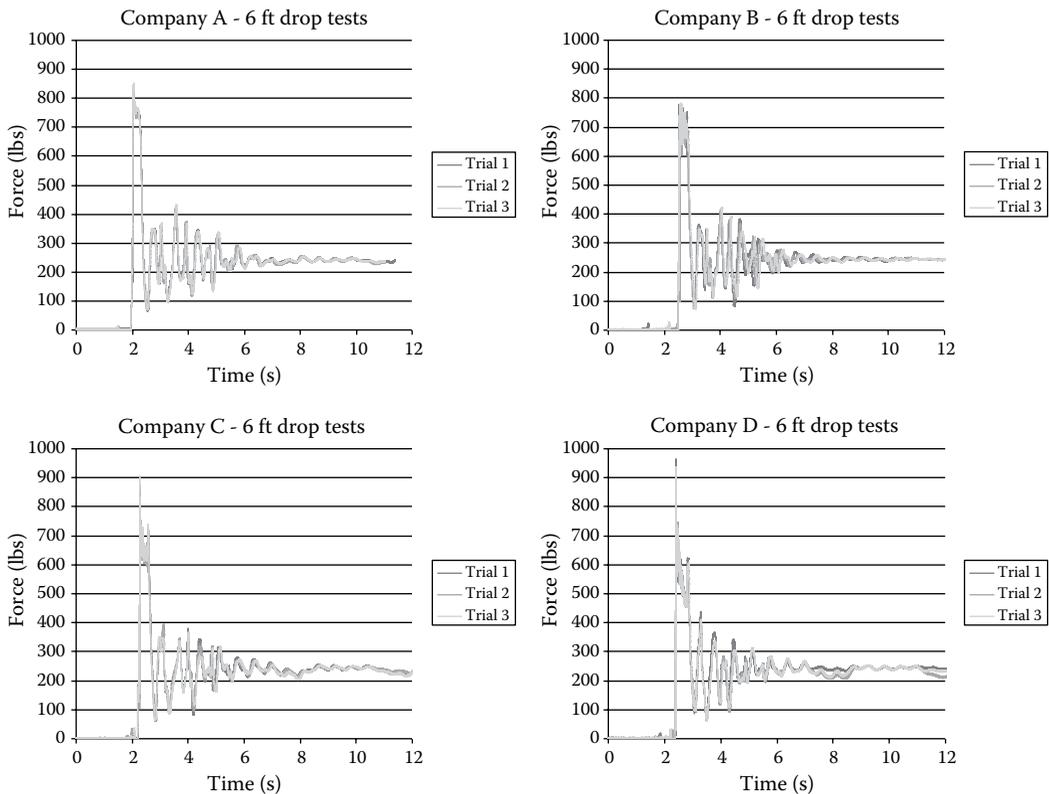
**FIGURE 16.3**  
Arrest forces for four different lanyards/harnesses for 11-ft drops.

and equations (acceleration, velocity, and displacement) used for this component are listed in Wu's summarized manuscript [10].

#### 16.1.1.4.3 Measuring Personal Fall Arrest System Performance By Dissipated Kinetic Energy

A personal fall arrest system reduces the impact force on the human body by absorbing kinetic energy resulting from a fall. Because the amount of absorbed kinetic energy is highly relevant to how well that safety system performs, NIOSH developed a systematic approach to evaluate the energy dissipated in the energy-absorbing lanyard and in the human body during a fall impact by deriving the kinematics of the human body and the EAL during impact from experimental arrest force data. The results confirm that arrest-force data can be used to predict the dynamics of a falling body. The results also show that increasing fall heights from 1.83 m to 3.35 m greatly increases the impact force on the human body even if a personal safety system is used [11].

The researchers first tested whether arrest-force data could be used to predict the dynamics of a falling body. In so doing, researchers equipped an Advanced Dynamic Anthropomorphic Manikin (ADAM™, Veridian, Dayton, OH), which was 108 kg in weight and 1.88 m in height, with a harness and an EAL (Workman™ Model 10072479 harness and Model 10072474 lanyard, MSA the Safety Company, Cranberry Township, Pennsylvania). Using the harness and EAL, the researchers attached the manikin to a scissor lift (Model SJIII3219, SkyJack, Guelph, ON, Canada) at the scissor lift's maximum height of 5.79 m.



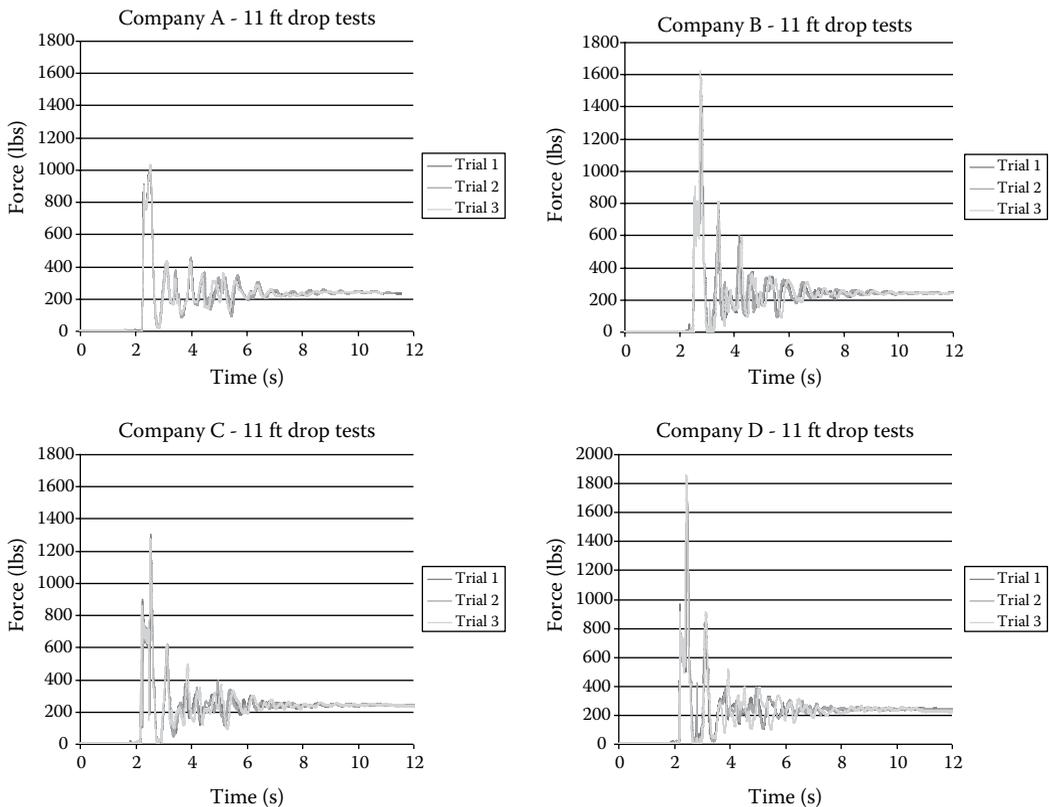
**FIGURE 16.4**

Arrest forces associated with three repeated trials for four different lanyards/harnesses for 6-ft drops.

The researchers then collected acceleration data from the manikin's three built-in uniaxial accelerometers (EAX series, Entran Devices Inc., Hampton, VA) located in the head, the middle of the spine, and the torso and arrest force data from a load cell (13.4 kN, S-type, Interface Inc., Scottsdale, AZ) connected inline to the lanyard. The researchers then dropped the manikin from heights of 1.83 m and 3.35 m, the latter being the drop distance that an operator standing on the mid rail of the scissor lift would fall.

The researchers found that the arrest force data collected from the load cell closely matched arrest forces calculated by using the acceleration data collected from the manikin's sensors. The researchers also used the arrest force data collected from the load cell to calculate the acceleration, speed, and displacement of the falling manikin. Those calculated values also closely agreed with the data collected directly from the manikin's sensors. Consequently, these results show that arrest force data can be used to predict the dynamics of a falling body.

Second, the data collected from the manikin and the load cell showed that increasing the drop height from 1.83 m to 3.35 m also increased the total impact energy by 42%, decreased the kinetic energy dissipated in the EAL from 92% to 84%, and increased the kinetic energy dissipated into the manikin by 193%. Consequently, increasing the drop height from 1.83 m to 3.35 m caused the amount of potential drop energy consumed in the manikin-harness-EAL system during a fall to decrease from 97% to 81%, causing the manikin to absorb much more energy. These results were confirmed by another drop test

**FIGURE 16.5**

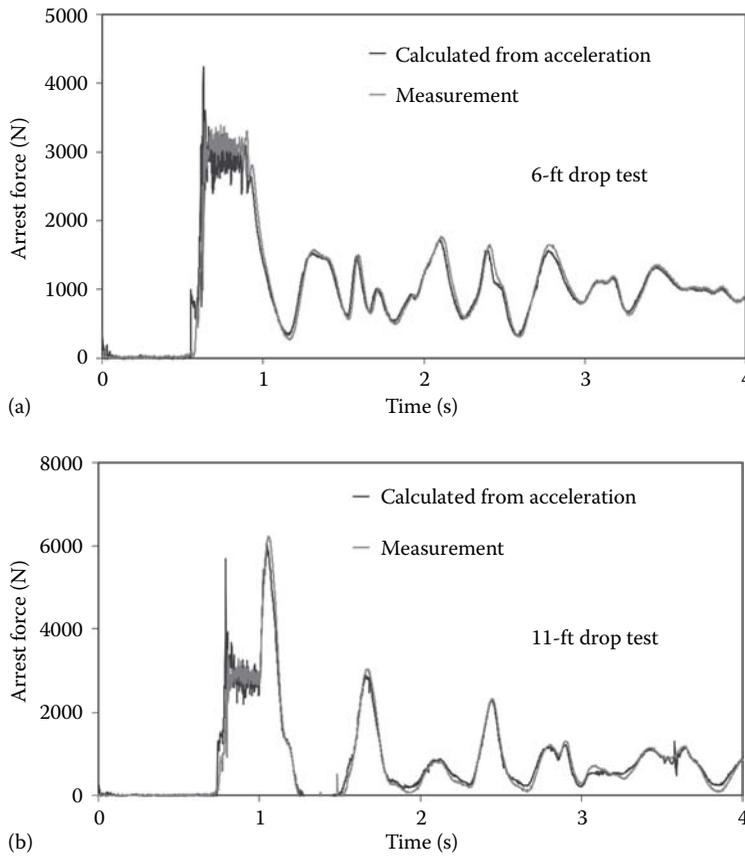
Arrest forces associated with three repeated trials for four different lanyards/harnesses for 11-ft drops.

using a rigid weight instead of the manikin. In other words, increasing fall heights greatly increases the impact force on the human body even if a personal safety system is used [11].

#### 16.1.1.4.4 Drop Test Results Regarding Stability of Lift, Performance of Fall Arrest Systems, and Impact to the Head and Neck of a Scissor-Lift Operator (Manikin Drop)

This study evaluated lift the stability and performance of fall arrest harnesses and lanyards using manikin drop tests and a computer model. This study also predicted the dynamic loading to the head and neck of a scissor lift operator caused by fall arrest forces by using a dynamic simulation model including the scissor lift and the manikin. The results suggest that the particular personal fall arrest systems tested under the experimental conditions described below exert forces on the human body within acceptable limits defined by applicable industry standards [11].

To test the four personal arrest systems, researchers equipped the respective personal fall arrest system harnesses on an Advanced Dynamic Anthropomorphic Manikin (ADAM™, Veridian, Dayton, OH), which had a height of 1.88 m and weight of 108 kg. The researchers attached each of the respective four energy-absorbing lanyards to the manikin's harness and anchored each EAL to the scissor-lift guardrail (top rail) of a model SJIII3219 scissor lift (Skyjack Inc., Guelph, ON, Canada). Each EAL was also connected to an interface load cell (Model SSM-S, Series 1000, Interface Inc., Scottsdale, AZ), which measured arrest forces. The researchers dropped the manikin three times from two heights: 1.83 m (the



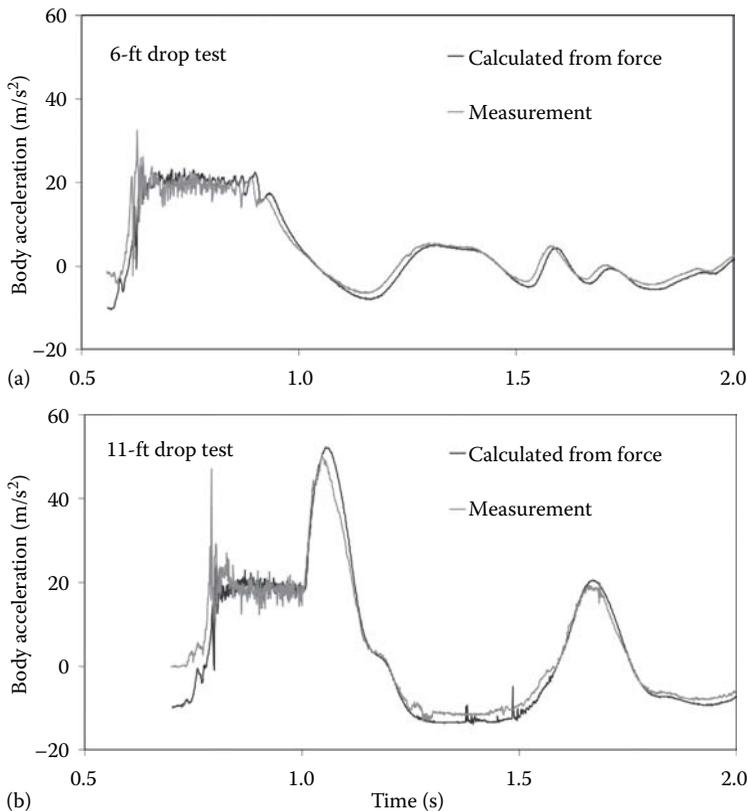
**FIGURE 16.6**

Calculated arrest forces and load cell measurement for 6-ft drop (a) and 11-ft drop (b).

standard drop height specified in ANSI/ASSE Z359.1-2007) and 3.35 m (to simulate a common misuse scenario in which operators stand on the mid rail of the scissor lift).

The researchers developed a scissor-lift simulation model using multibody dynamics software (ADAMS™, Version 2010, MSC Software Corporation, Santa Ana, California), which was refined and verified using experimental data obtained from dynamics tests. The simulated operator information was incorporated into a completed and validated scissor-lift model using the LifeMOD Biomechanics Human Modeler (Version 2010, LifeModeler, Inc., San Clemente, California), a plug-in to the ADAMS software. The researchers evaluated the stability of the simulated scissor lift in the fall arrest by applying the collected drop data from one of the widely used personal fall arrest systems to the simulation and predicting how much the rear wheel of the lift was vertically displaced and horizontally tilted about the short axis. From the collected data for one such widely used personal fall arrest system, the researchers also modeled the impact of the force on the joint and segments of a human body by applying the measured arrest force based on a computer model of the human torso divided into 15 body segments: head, neck, torso, left and right forearm and upper arms, left and right hands, left and right upper and lower legs, and left and right feet.

The results from the drop tests showed that the maximum arrest force exerted by the four personal arrest systems was less than 8000 N for both the 1.83 m and 3.35 m drops

**FIGURE 16.7**

Calculated body accelerations and accelerometer measurements from ADAM for 6-ft drop (a) and 11-ft drop (b).

and therefore complied with the ANSI Z359.1 standard (2007), which requires all maximum arrest forces to be less than 8000 N for 1.83 m drops. Further, the data generated by the scissor-lift simulation model showed that the scissor lift was stable during the arrest of a fall under the test conditions of a scissor lift on a flat surface with one occupant in a static working position. Consistent with other NIOSH studies [4], the data also showed that reducing the stiffness of the scissor-lift structure decreases the stability of the scissor lift and may substantially increase the scissor lift's tip-over potential.

The data generated by the simulation of the arrest forces on a joint-and-segment model showed that, during the 3.35-m drop tests, the neck will be subject to a maximal compressive force of 360 N, a maximal shear force of 260 N, and a maximal joint flexion moment of 68 N-m, some of which are greater than forces imposed on the neck during vehicle-impact tests. The simulation of a 3.4-m drop also generates a neck injury criterion factor comparable to the figure observed in vehicle-impact tests and ambulance crash-test results [10,11]. Although some of these results are well below the injury threshold, the sudden arrest forces upon the neck and head could still potentially result in serious spinal cord injuries. Future studies that concentrate on soft tissue-injury outcomes might very well indicate dimensions of fall protection that could fruitfully be developed by focused research on this mechanism of injury and injury prevention. Research following the model of the Intervertebral Neck Injury Criterion [IV-NIC] might be considered [12,13]. Specifically, the contribution of improper adjustment of fall protection to injury

mechanisms is undetermined, and research to quantify the role of this equipment adjustment factor is relevant and appropriate.

#### **16.1.1.5 Future Scissor-Lift Studies**

The draft ANSI standard A10.29 [14] provides that workers may enter and exit an aerial platform at heights greater than 1.8 m when the aerial platform surface is adjacent to the elevated surface. The draft standard further specifies that if the platform is adjacent to the elevated surface, no vertical gap will be larger than 20.3 cm or no horizontal gap will be larger than 35.6 cm between the aerial lift platform and the adjacent surface. But, to date, there has been no published scientific justification regarding the values of these gaps and how the distances between the lift platform and the adjacent surface may affect workers' postural stability and fall propensity.

NIOSH is presently testing whether interaction forces between workers and landing surfaces are different under various entrance or exit conditions and whether such differences affect workers' postural stability on an elevated lift [15]. To do this, NIOSH is investigating the postural instability and impact forces when a worker enters and exits elevated scissor lifts. First, this ongoing study examined the effects of vertical and horizontal gaps between the lift platform and the adjacent surface on workers' postural stability on two types of scissor lift entrance and exist systems. Second, this study examined the effect of an inclined landing surface on workers' postural stability.

The researchers used a 5.8-m electric scissor lift and its platform (Model SJIIE 3219, Skyjack, Inc., Guelph, ON, Canada), which has a deck extension, a gate for entrance and exit, peripheral guardrails, and toe boards on all sides. This platform was about 162.6 cm wide and 73.7 cm long and had a deck that extended the platform's overall length to about 254 cm. The guardrails, which are composed of a top rail and a mid rail, were 99.1 cm in height, and the toe boards were about 15.2 cm high. The platform held a three-dimensional force plate (Kistler™, Amherst, New York) to measure the participants' baseline postural stability before exiting the scissor lift. The researchers also constructed a test platform with sides protected by guardrails, such that one end was adjacent to the scissor lift while the other open end was connected to a mezzanine. The test platform housed a three-dimensional force plate (Kistler™, Amherst, New York) to collect force data and was supported by a lift table (Bishamon Lift-2 K®, Bishamon Industries Corporation, ON, Canada) that could adjust the height of the test platform from 0 to 76.2 cm.

Since most aerial lift incidents occur when scissor lifts are elevated between 3 and 8.8 m, the researchers elevated the scissor lift to 3 m at all times. Force data was collected while 22 construction workers exited the scissor lift and entered the test platform, and alternatively, reversed the procedure so that they exited the test platform and stepped onto the scissor lift. Testing involved measurement of force exerted onto a force platform following the actions of researchers in removing a barrier, which depended upon the lift type (one with a gate, the other with a bar and a chain).

Measured force as an indicator of center of pressure and of postural instability was also a function of the test platform's vertical and horizontal landing distance. The vertical distance was chosen to represent five test conditions—the test platform was set at identical height as the scissor-lift platform (0 cm vertical displacement) and then adjusted to different vertical positions (10.2 cm lower, 20.3 cm lower, 30.5 cm lower, and 30.5 cm higher). Horizontal distance between the aerial lift test platform and the test structure (i.e., the construction building) was also a test variable, with the horizontal distance between the aerial lift and the test building set at 17.8 and 35.6 cm. All of these test conditions were chosen to

represent various scenarios at a construction site. The researchers further collected data after adjusting the lift type (as before), the test platform's vertical landing distance (with the test platform at the same height, 20.3 cm lower or 20.3 cm higher than the scissor-lift platform), and the test platform's slope ( $0^\circ$  and  $26^\circ$ ). The researchers also traced the participants' shoe prints prior to the experiments and standardized them so that their heels were touching and feet were at a  $30^\circ$  angle.

Preliminary analysis of the collected impact force data suggests that positioning the scissor lift higher than the landing surface increases the vertical forces on the feet and the impact force to the ankles and knees. The preliminary results also suggest that workers experience more postural instability when they exit or enter from a sloped surface and that entering the scissor lift generally imposes more postural demands on the workers than exiting the scissor lift. The preliminary results also indicate that entrance or exit of scissor lifts with a bar/chain opening created greater postural instability in participants. The final results from this study will be used to suggest safer work practices to prevent injuries from scissor-lift falls [15].

## 16.1.2 Boom Lifts

### 16.1.2.1 Background and Injury Surveillance

Boom lifts are self-propelled, mobile work platforms, which, unlike scissor lifts, have platforms extending beyond the wheelbase of the supporting structure, which may be further extended with telescoping or articulating booms [1]. From 1992 to 2003, boom lifts accounted for nearly 60%–75% of fatalities arising from aerial lifts. The CFOI database shows that the plurality of these deaths occurred in the construction industry (45%), on a road (30%), or at an industrial location (15%) while “constructing and repairing” (42%) and “logging, trimming, and pruning” (26%).

### 16.1.2.2 Injury Surveillance

Tip-overs and collapse of the boom lifts (collectively, *boom tip-overs*) cause nearly half of the falls (46%). Falls from the basket, bucket, or platform of the boom lift caused about 27% of the remaining falls, and ejection from the boom lift caused about 28% of the remaining falls from 1992 to 2003. The NIOSH study [1] collected information from three different databases and identified several common factors associated with falls from boom lifts. First, the study found that mechanical failures, including failures of the lift structure, largely contributed to falls from boom lifts (33% of CFOI boom-lift events and 47% of OSHA/FACE investigations). The study also shows that collisions with vehicles and falling trees caused 14% of boom tip-overs and 13% of boom-lift ejections. Further, the study shows that failure to use a harness or belt and lanyard to tie off while performing tasks was reported in 18% of boom-lift fatalities. The OSHA/FACE databases also showed that surface conditions were cited in 35% of boom-lift cases, including the floor of a building, platform, ramp, sidewalk, or street (45%) or the ground or soil level (42%).

The fall height in 35% of boom-lift incidents recorded in CFOI and 42% recorded in OSHA/FACE ranged from 3 to 8.8 m. The OSHA/FACE database cited forward or backward boom-lift motion in 16% of fall incidents and elevating or lowering of the boom lift in 25% of all boom-lift falls. Moreover, the study found that 20 (22%) of OSHA/FACE fall reports cited worker motion (e.g., working postures) as a contributory factor to the fall.

Significantly, despite OSHA regulations mandating the use of fall protection in boom lifts (see § 1926.453[b][2][v]), the study shows that in 45% of boom-lift fatalities recorded in

the OSHA/FACE reports, no such fall protection was used. Indeed, although fall protection was specifically mentioned in 55 (66%) of OSHA/FACE incident reports, fall protection was not in use during 82% of these incidents.

Boom-lift fatalities account for nearly 60%–75% of all aerial lift fatalities and warrant further investigation. Accordingly, these factors are potential avenues for future research.

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## **16.2 Ongoing Aerial Lift Research and Practice Summary**

A hazard recognition simulator has been developed by NIOSH using Unity simulation software (version 4.5.3, Unity Technologies, CA). This web-based simulation will allow users to perform simulated work procedures with a SkyJack 3219 scissor lift and SJ46 AJ boom lift (SkyJack, Inc., Guelph, ON, Canada). Task-based hazards will be generated using an actual model of an aerial lift as seen from the point of view of an operator or, alternatively, from a third-person point of view. Users will be able to load a web page from a remote location and use the simulator to remotely control the simulated aerial lift; frequently encountered hazards will be introduced into the simulation. Users will drive the lift to complete tasks such as (1) basic maneuvers driving the lift, (2) basic maneuvers including complications such as avoiding crushing and trapping areas, and (3) avoiding tip-over hazards (e.g., potholes). This simulator approach has potential applications to other models and types of aerial lifts. User manuals and practice tools for the computer simulation model are planned so as to generate a model user package for safety officers.

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## **Disclaimer**

The findings and conclusions presented herein are those of the authors and do not necessarily represent the views of NIOSH. Mention of any company names or products does not constitute the endorsement by NIOSH.

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