

SPECIAL SECTION: Occupational Fall Prevention and Protection

Assessment of Fall-Arrest Systems for Scissor Lift Operators: Computer Modeling and Manikin Drop Testing

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Objective: The current study is intended to evaluate the stability of a scissor lift and the performance of various fall-arrest harnesses/lanyards during drop/fall-arrest conditions and to quantify the dynamic loading to the head/neck caused by fall-arrest forces.

Background: No data exist that establish the efficacy of fall-arrest systems for use on scissor lifts or the injury potential from the fall incidents using a fall-arrest system.

Method: The authors developed a multibody dynamic model of the scissor lift and a human lift operator model using ADAMS™ and LifeMOD™ Biomechanics Human Modeler. They evaluated lift stability for four fall-arrest system products and quantified biomechanical impacts on operators during drop/fall arrest, using manikin drop tests. Test conditions were constrained to flat surfaces to isolate the effect of manikin-lanyard interaction.

Results: The fully extended scissor lift maintained structural and dynamic stability for all manikin drop test conditions. The maximum arrest forces from the harnesses/lanyards were all within the limits of ANSI Z359.1. The dynamic loading in the lower neck during the fall impact reached a level that is typically observed in automobile crash tests, indicating a potential injury risk for vulnerable participants.

Conclusion: Fall-arrest systems may function as an effective mechanism for fall injury protection for operators of scissor lifts. However, operators may be subjected to significant biomechanical loadings on the lower neck during fall impact.

Application: Results suggest that scissor lifts retain stability under test conditions approximating human falls from predefined distances but injury could occur to vulnerable body structures.

Keywords: fall-arrest systems, fall from elevation, scissor lifts, computer modeling, manikin drop tests, head/neck injuries, fall hazard assessment

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INTRODUCTION

The scaffolding industry has long recognized the fall hazards and related injuries associated with work on scissor lifts (Burkart, McCann, & Paine, 2004; Heath, 2006; McCann, 2003; Pan et al., 2007). Construction, telecommunication, and other industries are experiencing an increasing risk of severe injury and death associated with the adoption of elevated, mobile devices such as the scissor lift. According to surveillance data, 72% to 74% of scissor lift fatalities occurred in the construction industry (Pan et al., 2007). A review of the Census of Fatal Occupational Injuries data by Pan et al. (2007) indicated that extensibility factors—the extended height of the lift or the vertical position of the worker as a result of extension of the lift—were significant contributing factors for fatal injuries (72% of the scissor lift cases). Falls/collapses/tip overs within the height categories of 10–19 ft and 20–29 ft were the cause of fatal injuries for 83% of cases involving scissor lifts, based on the Occupational Safety and Health Administration (OSHA) incident investigation records and National Institute for Occupational Safety and Health (NIOSH) Fatality Assessment and Control Evaluation reports (Pan et al., 2007).

Some scissor lift manufacturers suggest that fall-arrest systems be used to prevent fall incident injuries while working on scissor lifts. No body of scientific knowledge exists that establishes the efficacy of personal fall protection systems for use on scissor lifts. Also, the dynamic forces on an operator wearing a fall-arrest system have not been examined. Consequently, the utility of fall protection equipment on scissor lifts has not been universally accepted by safety and health experts as an effective safety and health control practice for reducing injury exposure for scissor lift operators.

Fall-arrest systems typically comprise four major components: a whole-body harness, a lanyard, an anchorage, and connectors (Ellis, 2001;

Riches, 2002). The whole-body harness is designed to distribute the dynamic forces, resulting during a fall, to the subpelvic region of the human body and to maintain an erect position with the head pointing upward. The interaction between the human body and the whole-body fall protection harness is one of the most important factors that affect the performance of the fall-arrest system (Hsiao, Bradtmiller, & Whitestone, 2003). The fitting of the harness to the body may influence the distribution of the impact force on the human body, thereby affecting impact kinetic energy exchange between the fall-arrest system and human body.

Crash test results of the automobile and aviation industries show that head/neck injuries may be caused by combined compressive forces, shear stresses, or moments that are transmitted to the spine via driver/pilot bodies (Deng & Goldsmith, 1987; Luo & Goldsmith, 1991; Stemper, Yoganandan, Pintar, Shender, & Paskoff, 2009; Yoganandan et al., 2000). At the moment of impact of a free-fall incident, the head/neck may be subjected to excessive combined compressive forces, shear stresses, and moments when a whole-body, fall-arrest harness is used. This may result in severe cervical vertebra injuries (Nightingale, McElhaney, Richardson, Best, & Myers, 1996).

Current OSHA regulations prohibit the securing of personal fall-arrest systems to guardrails (29 CFR 1926.502(d)(23)). The appropriateness of tie-off to the top guardrail of a scissor lift remains widely debated within standards committees, manufacturers' associations, and the user community (Boehler, McCann, Paine, Eckstine, Wingfield, personal communication, July 9, 2007). Also, the occupational safety literature does not address the underlying contribution of this anchorage point to fall-related injury, and the debate remains ongoing.

In 2009, NIOSH evaluated the structural and dynamic stability of a scissor lift subjected to significant fall-arrest forces generated by a dead-weight drop in a laboratory setting (Harris, Powers, Pan, & Boehler, 2010). In the current study, we examined the dynamic loading distribution and transfer to vulnerable structures of the human body during fall impact. To minimize study-design variables, the tie-off point

was kept to the same location as that used in the Harris study (the top rail of the platform), and a single test condition (upright manikin orientation during drop test) was used.

The objectives of this study were twofold: (a) to further evaluate the stability of the lift and the performance of various fall-arrest harnesses and lanyards using manikin drop tests and computer modeling and (b) to evaluate/predict the dynamic loading to the head/neck of a scissor lift operator caused by fall-arrest forces by using a dynamic simulation model that includes the scissor lift (Hartsell, 2010; Ronaghi et al., 2009) and the manikin.

METHOD

The study methods were designed to address three major concerns: (a) the kinetic energy transfer between the fall arrest system and the operator's body, (b) the dynamic interaction between the scissor lift structure and the operator's body during the fall arrest, (c) and the dynamic loading in the operator's head/neck complex during the fall impact.

In this study, drop tests were conducted with manikins; such tests are accepted as proxies for human fall impact. Maximum impulse loading and total loading on the manikin were determined by data recording onto an attached load cell; data served as inputs to injury-potential computer models. An additional computer model (for the scissor lift) was applied to evaluate the dynamic stability of the structure under sudden-load conditions. Using computer modeling, we were able to simulate the consequences of extreme working conditions and to predict internal forces in the human body, which cannot be obtained using the conventional experimental approaches for reasons of test-participant safety.

Apparatus, Experimental Task, and Test Conditions

A commercially available 5.79-m (19-ft) electric scissor lift (Model SJIIE 3219, SkyJack Inc., Ontario, Canada) was selected for testing at the NIOSH facilities in Morgantown, West Virginia, and Pittsburgh, Pennsylvania. This particular model has a mass of 1,170 kg and a load capacity of 250 kg. Based on manufacturers'



Figure 1. Experimental setup for drop test design using an ADAM manikin. Photo is the property of NIOSH.

sales records, this model was the most widely used lift at work sites (Ramsey, Parrish, & Whitehead, 2009). To limit design variables, the scissor lift was constrained to a single test orientation, a flat (0° slope) condition. Slope conditions and their effects on system stability were tested in the Harris study, under dead-weight drop conditions. The Harris study performed drops under axis-based tilt conditions specified to comply to the manufacturers' standard (interlock activation at 1.5° tilt above the horizontal plane [long axis] and 3.5° tilt above the horizontal plane [short axis]; American National Standards Institute [ANSI], 2006).

An Advanced Dynamic Anthropomorphic Manikin (ADAMTM, Veridian, Dayton, OH) was used as the human body test surrogate (Veridian, 1998). The manikin had a mass of 108 kg and a height of 1.88 m. Before the drop test, the scissor lift was fully elevated and the manikin was secured by an overhead crane. An energy-absorbing lanyard (EAL) was attached to a D-ring on the back of the harness on the manikin and anchored to the scissor lift guardrail (top rail) at a single anchorage point, as shown in Figure 1. The drop was controlled by an electromagnet

(Model SE-35352, Magnetic Products Inc., Highland, MI). Data on fall-arrest forces were captured by an interface load cell (Model SSM-S, Series 1000, Interface Inc., Scottsdale, AZ) in line with the EAL to measure the arrest forces. Logging of data and analysis occurred through data acquisition software (LabVIEW, National Instruments Corporation, Austin, TX) onto a laptop computer. Energy absorption effects of four different EALs, each from different manufacturers, were tested together with their safety harnesses. The manikin was dropped three times through each of the two free-fall distances, 1.83 m and 3.35 m. The 1.83-m (6-ft) drop represented the standard drop height as specified in ANSI/ASSE Z359.1 (ANSI, 2007). The 3.35-m drop represented a common misuse scenario in which operators stand on the midrail of the scissor lift. The kinematics of the human body and EALs during the impact were derived using the data of the time histories of the arrest force, which were measured experimentally.

Computer Modeling

The scissor lift simulation model was generated using multibody dynamics software (ADAMSTM, Version 2010, MSC Software Corporation, Santa Ana, CA) and refined based on data obtained in two dynamics tests—curb impact test and a depression (pothole) test—required by ANSI (2006). Mass distribution was verified using the lift's center of gravity, which was measured at four elevated heights. Connection stiffness and damping parameters were estimated based on the experimental data obtained individually from the two dynamics tests. The model was also validated and refined using the time histories of the lift dynamic responses measured in these physical experiments. Simulated operator information was then incorporated into the completed and validated scissor lift model (Figure 2) using LifeMOD Biomechanics Human Modeler (Version 2010, LifeModeler Inc., San Clemente, CA), which is a plug-in to the ADAMS software (Hartsell, 2010).

Modeling Analysis

The joint/segment properties of the human/operator model (Hybrid III manikin [2010], LifeModeler Inc., San Clemente, CA) was

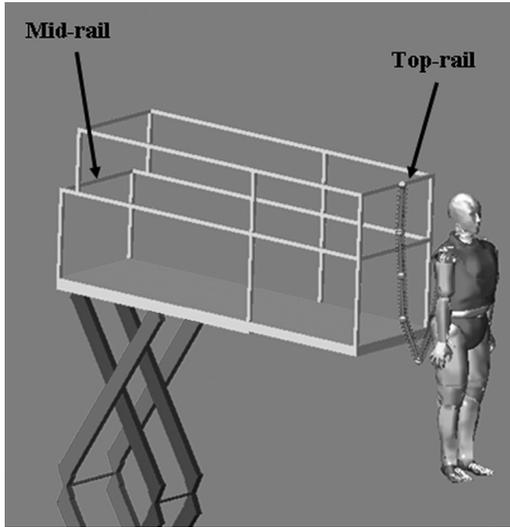


Figure 2. Computer model for simulating fall-arrest drop test with manikin.

divided into 15 body segments (e.g., head, neck, torso, left and right fore and lower arms, left and right hands, left and right upper and lower legs, and left and right feet). No muscles were included in the analysis. The model for this study was assumed to be a male having a height of 1.88 m and a mass of 108 kg (95th percentile) to match with our experimental test using the ADAM. All joints of the model were assumed to be at their neutral positions before the drop. Since this study was focused at the head/neck complex, the interaction between the harness and torso was simplified in the modeling.

Fall-arrest forces were collected for four fall-arrest systems supplied by separate manufacturers, and one fall-arrest system was chosen for modeling analysis. This particular manufacturer's product was chosen because the fall-arrest forces lie within the upper and lower values of all products tested and, based on manufacturers' sales records, was the most widely used in the industry.

The arrest force (i.e., the force in the EAL) was applied to the back of the torso at a location representing a typical D-ring location of the harness (Ellis, 2001; Figures 1, 3a). The head, neck, and torso are linked via the upper and lower neck joints (Figure 3b). Both neck joints were assumed to be spherical joints. The

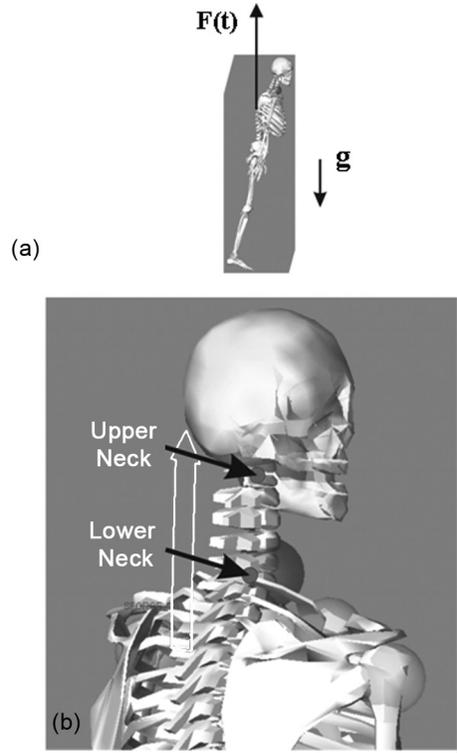


Figure 3. Simulation model of the fall impact. (a) Dynamic force balance in a typical fall-arrest test. (b) The head/neck complex of the model.

analysis was performed in a forward dynamic scheme. The force in the EAL and the gravitation were applied on the human model as external forces, whereas the dynamic responses of the head/neck complex were predicted.

RESULTS

Lift stability was evaluated using the rear-wheel vertical lift displacement (Figure 4) and tilt about the short axis in the horizontal plane of the scissor lift (Harris et al., 2010). Figure 5 shows the relationship between the rear-wheel vertical displacement and the bending stiffness of the scissor lift structure. It was observed that reducing the stiffness of the scissor lift structure decreases the stability of the lift.

The time histories of fall-arrest impact forces (Figures 5a, 5b) were measured by using four fall-arrest systems in three different trials (Figures 6, 7). These fall-arrest impact forces

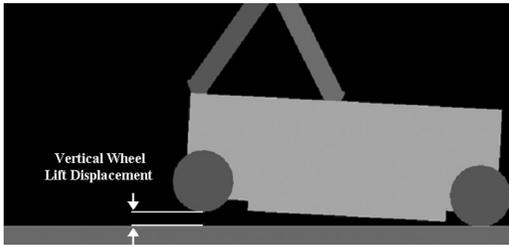


Figure 4. Stability from fall-arrest forces is measured by the vertical rear-wheel lift displacement.

were used to determine lift stability under a similar test scenario for one representative fall-arrest system (Figure 5c). Our results show that the deployment forces for lanyards from different manufacturers were moderately similar and independent of the drop height (1.83 m and 3.35 m; Figures 6, 7). Maximum arrest forces in all but one case (Figure 7) were found to be less than 8,000 N for both 1.83-m and 3.35-m drops. Repeated test trials for the same harnesses/lanyards produced similar results (Figures 6, 7).

To test the hypothesis and assess the peak arrest forces and significant sudden impact to the neck/head region of lift operators during the drops, we examined experimental test data of arrest forces obtained from a representative fall-arrest system product for the 1.83-m and 3.35-m tests (Figure 8).

We observed a three-stage development of the fall-arrest force in an EAL during the activation and deactivation time periods of a free-fall event. The first stage was from the start of the manikin's fall to the start of the EAL's stretch. During this first stage, the manikin is in a state of free fall (1.83 m or 3.35 m) and the force on the EAL was negligible. In the second stage, the EAL is deployed and the arrest force stayed nearly constant. Theoretically, the EAL deployment force is associated with the EAL performance, independent of the drop height and manikin mass (Figures 6, 7). During the third stage, the EAL is fully deployed and further stretched and experienced a steep force increase because of a high-distance drop (3.35 m; Figure 8b). The third impact stage appears only in the case of intense impact (3.35 m).

By using the experimentally obtained arrest force (Figure 9), the time histories of the joint

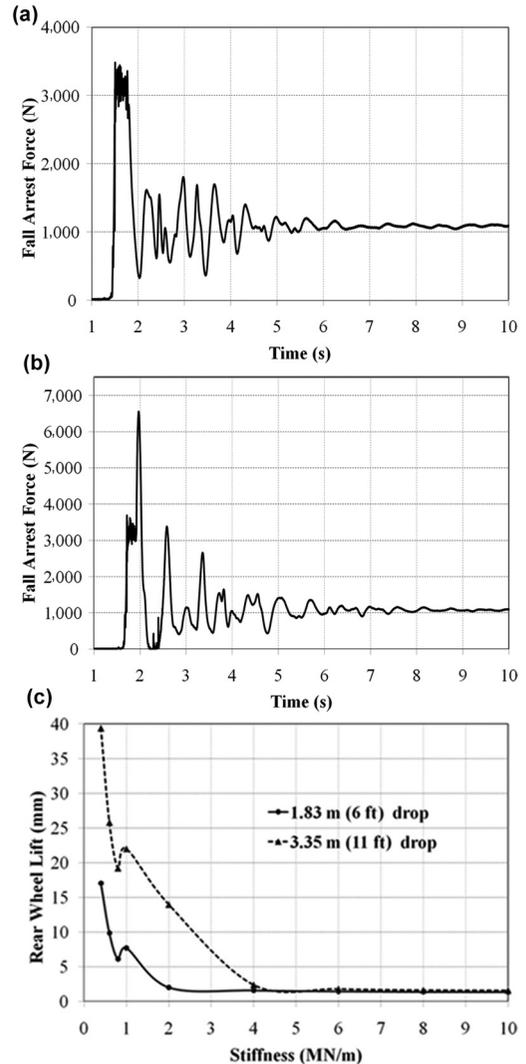


Figure 5. Effects of the fall-arrest impact force on the structural stability. (a) and (b) Time histories of the fall-arrest force for two different drop heights. (c) Vertical displacement of the scissor lift's rear wheel as a function of the structural stability stiffness.

angles of the head/neck complex were predicted by computer modeling. The joint angles at the upper neck and lower neck indicated that the head moved only in the sagittal plane during the fall impact for both drop tests. The head motion in the other two planes was negligible. The peak joint angle at the lower neck was about 6 and 3 times the angle at the upper neck for 1.83- and

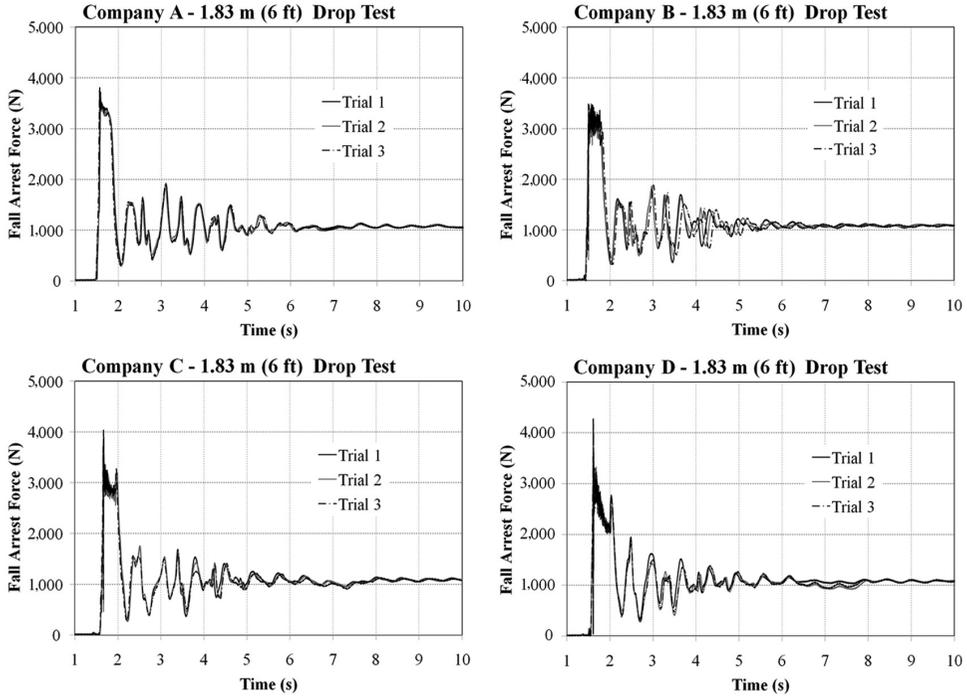


Figure 6. The time histories of the fall-arrest forces for four manufacturers' products for the 1.83-m (6-ft) drop test among three repeated trials.

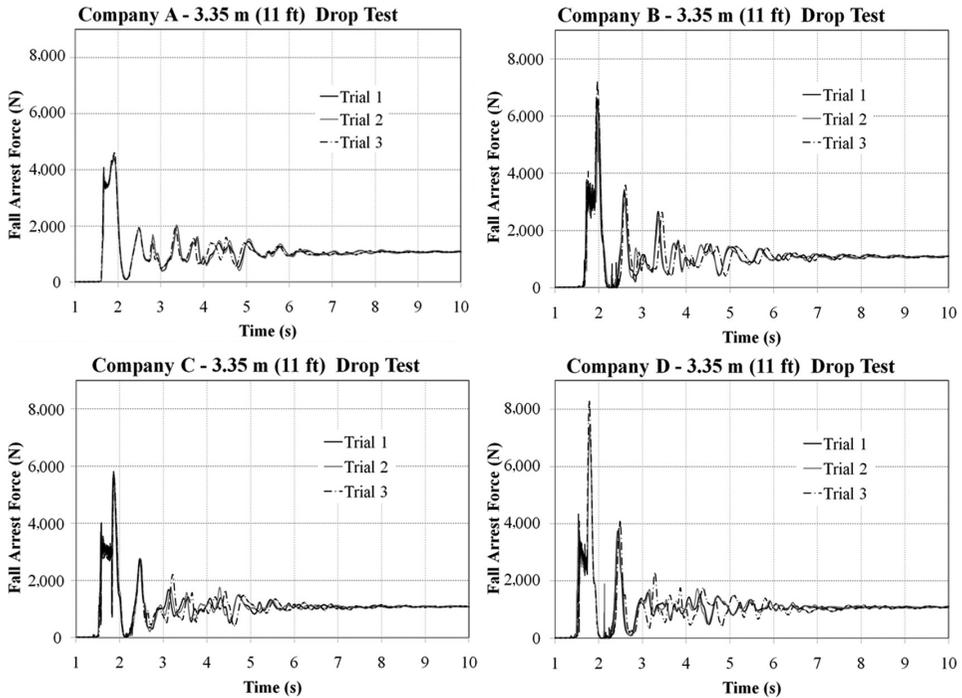


Figure 7. The time histories of the fall-arrest forces for four manufacturers' products for the 3.35-m (11-ft) drop test among three repeated trials.

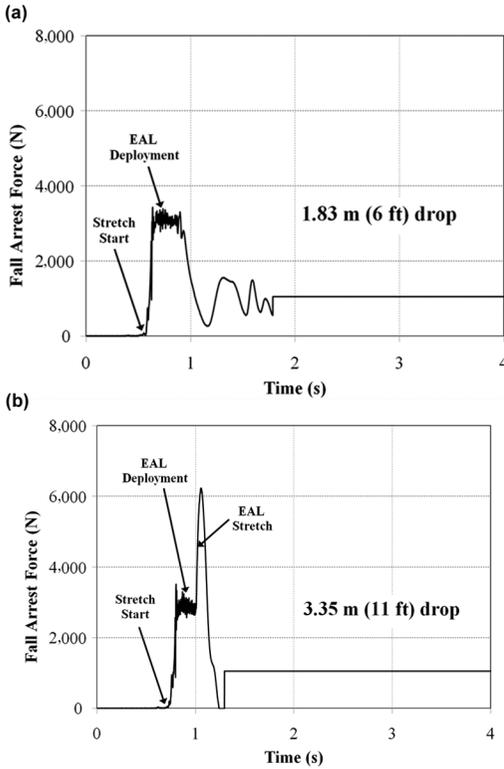


Figure 8. Characterization of the time histories of the fall-arrest forces used in the simulations for the (a) 1.83-m (6-ft) and (b) 3.35-m (11-ft) drop tests.

3.35-m drop tests, respectively, and for the 3.35-m drop test was about 2.2 times the angle for the 1.83-m drop test.

The predicted forces in the upper and lower neck joints (Figure 10) indicated that the head/neck complex experienced multiaxial loadings during the fall impact. The force in the superior/inferior direction is the axial force, and the negative and positive measurements represent compression and tension, respectively. The forces in the anterior/posterior and left/right directions are the shear forces. The shear force in the left/right direction is negligible, which is consistent with the head/neck joint motion (Figure 9). The peak shear forces in the lower neck are approximately 30% to 40% greater than those in the upper neck, whereas the peak axial forces in the lower neck are slightly greater than those in the upper neck. The peak shear force in the lower neck reached 200 and 268 N for the 1.83- and

3.35-m drop tests, respectively. The corresponding peak compressive force reached 166 and 360 N for the 1.83- and 3.35-m drop tests, respectively.

The simulation results showed that the head/neck complex is subjected only to the flexional joint moment during the fall impact (Figure 11). The joint moments in the frontal and transverse direction are negligible. The peak joint moments in the lower neck were substantially greater than those in the upper neck (approximately twice and 1.5 times greater for the 1.83- and 3.35-m drop tests, respectively). The maximal joint moment reached 29 and 68 N-m for the 1.83-m and 3.35-m drop tests, respectively.

Comparing the magnitudes of the resultant joint forces and moments in the upper and lower neck for the 1.83-m drop test with those for the 3.35-m drop test (Figure 12), the force and moment magnitudes for the 1.83- and 3.35-m drop tests are very similar during the period of EAL deployment. By the end of the EAL deployment, the joint force and moment magnitudes for the 3.35-m drop test show a steep increase, whereas there is no such peak for the results of the 1.83-m drop test.

We have evaluated the intensity of the dynamic loading in the head/neck in our fall impact tests using the neck injury criterion (Eppinger, Sun, Kuppa, & Saul, 2000), N_{ij} , which is generally accepted in automobile industries for the crash impact test analysis. N_{ij} is a dimensionless parameter that includes the combined effects of the bending and axial loading in the neck during the impact:

$$N_{ij} = \frac{F}{F_1} + \frac{M}{M_1}$$

where F and M represent the axial force and moment, respectively; F_1 and M_1 denote the intercept values of F and M , respectively. The intercept force and moment values represent the tolerance of the human body to the dynamic loading.

If we apply the intercept values proposed by Eppinger et al. (2000; i.e., $F_1 = 7440$ N and $M_1 = 162$ N-m for males), N_{ij} value for the current study has been estimated to be 0.21 and

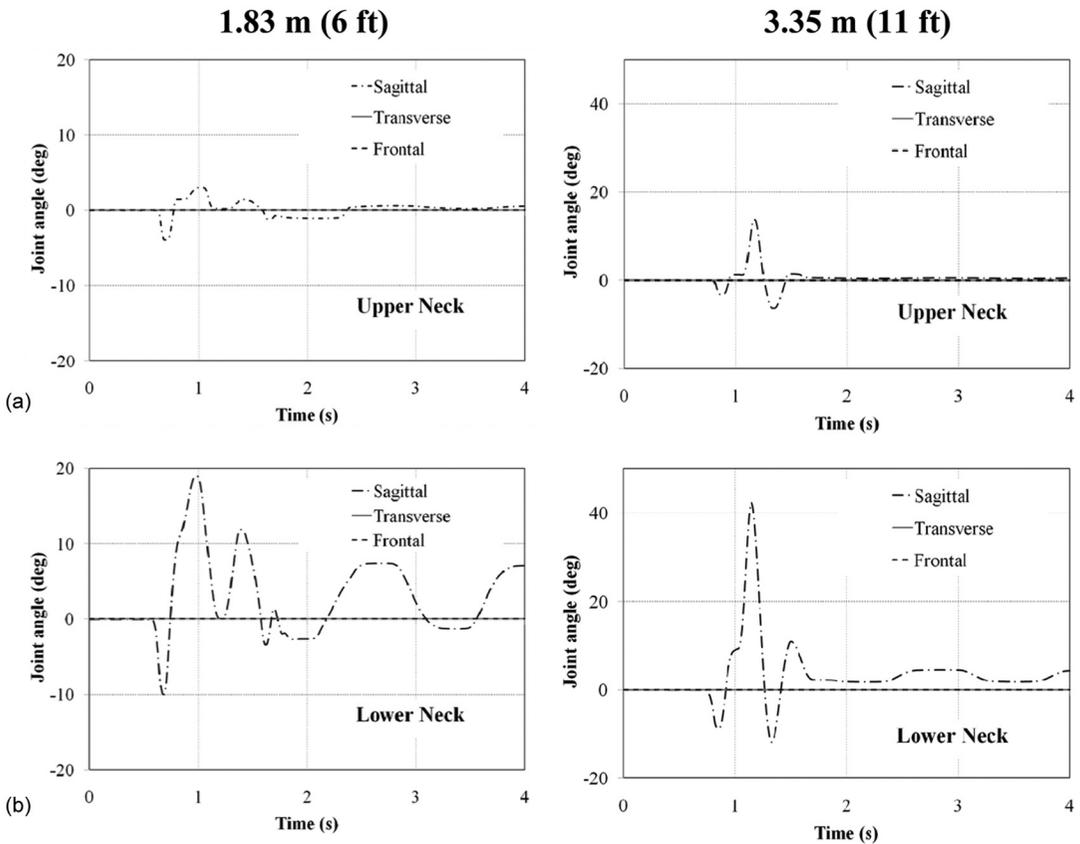


Figure 9. Time histories of the neck joint angle during the fall impact. (a) Upper neck joint measurements for the 1.83-m (6-ft) and 3.35-m (11-ft) drop tests. (b) Lower neck joint measurements for the 1.83-m (6-ft) and 3.35-m (11-ft) drop tests.

0.47 for the 1.83-m and 3.35-m drop tests, respectively. $N_{ij} = 1.0$ represents the injury threshold. Because load tolerance varies by participants' body morphology and other variables, a single-measure injury threshold may not be applicable to all persons subjected to sudden loads. The level of exposure that represents an acceptable risk of injury for the majority of participants may represent an elevated risk of injury for vulnerable populations.

DISCUSSION AND CONCLUSION

Various standard-setting committees (ANSI A10.29, 10.32, A 92.6, and Z359) have considered the benefits of using fall-arrest systems on scissor lifts as part of a fall injury protection program. Using dead-weight drop tests, the Harris et al. (2010) study indicated that guardrails

may be useful to serve as anchorage points under certain specific task conditions without increasing the risk of scissor lift tip overs. When a fall-arrest system is anchored to the top rail of a guardrail system, the guardrail will sufficiently absorb energy generated during a fall-arrest incident (Wu, Powers, Harris, & Pan, in press). This study also could not produce scissor lift tip over during manikin drops using various fall-arrest systems anchored to the guardrail. The above-mentioned findings associated with the use and application of fall-arrest systems (i.e., guardrail, anchorage point, harness/lanyard) apply specifically to the scissor lift model we tested and modeled.

Our simulation results indicate that a reduction of the stiffness below certain critical values may substantially increase the scissor lift's tip

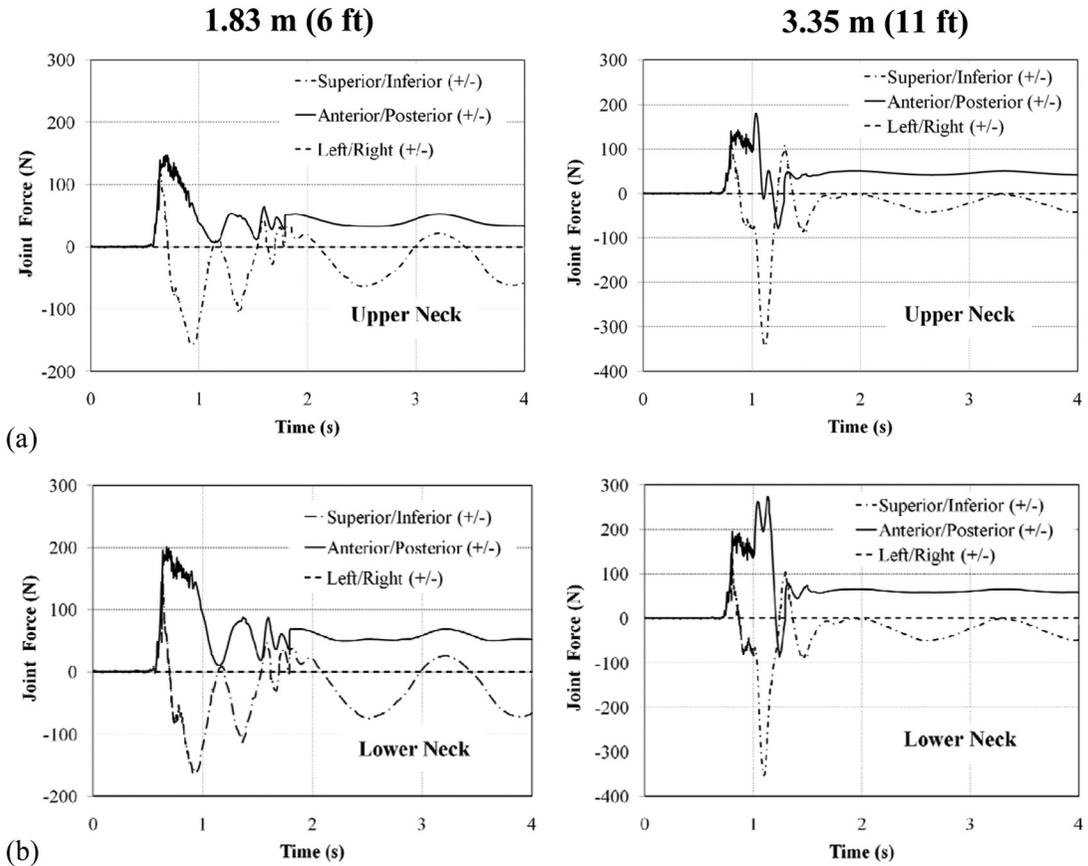


Figure 10. Time histories of the neck joint force during the fall impact. (a) Upper neck joint measurements for the 1.83-m (6-ft) and 3.35-m (11-ft) drop tests. (b) Lower neck joint measurements for the 1.83-m (6-ft) and 3.35-m (11-ft) drop tests.

over potential (Figure 5). A refined scissor lift model was used that included rigid body dynamics for operational joints and other related lift structures. Further investigation is needed using modifications to the computer model that represent more realistic conditions of the scissor lift, such as significant stiffness reduction resulting from damage to joints/structures of the lift because of aging and normal wear. The effects of such deterioration were observed in automobile suspension systems (Dukkupati, Pang, Qatu, Sheng, & Shuguang, 2008) subjected to extreme weather, poor maintenance, soft ground operational conditions, or any combination of these factors (Hartsell, 2010).

The top two standards OSHA recommends for preventing fall injuries and hazards in the construction industry are 29 CFR 1926.501 for

fall-arrest systems and 26 CFR 1926.451/452 for scissor lifts (OSHA, 2010). This study addressed the use of these standards (ANSI A92.6). All maximum arrest forces were less than 8,000 N for the 1.83-m drops as required by ANSI Z359.1 (ANSI, 2007; Figure 6). Properties of the computer simulation model, such as stiffness and damping, were determined from the static and dynamic experimental tasks required by the ANSI A92.6 and ISO 16368 standards (ANSI, 2006; International Organization for Standardization, 2003).

In the drop/fall arrest tests, the speed of the manikin just prior to impact was approximately 5.9 m/s for the 1.83-m drop test and 8.1 m/s for the 3.35-m drop test (Wu et al., in press). The impact speed of the fall-arrest tests used in the current study were comparable to those in the vehicle impact tests by Yoganandan et al. (2000),

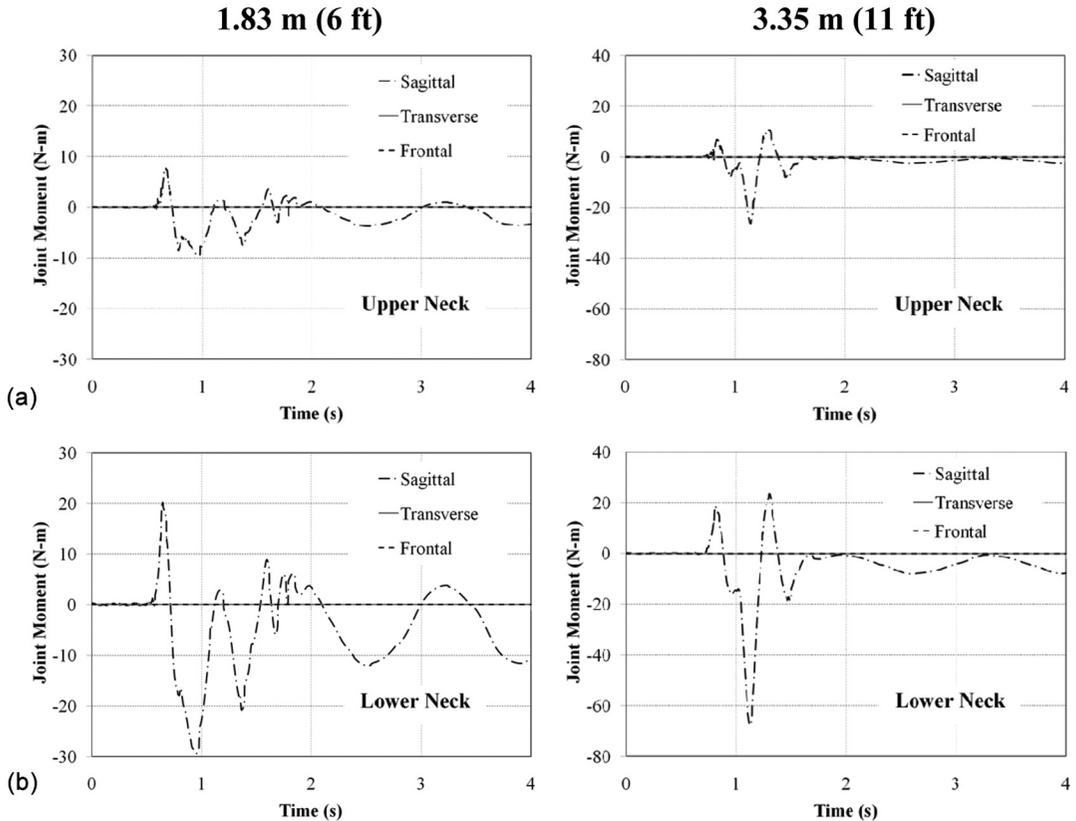


Figure 11. Time histories of the neck joint moment during the fall impact. (a) Upper neck joint measurements for the 1.83-m (6-ft) and 3.35-m (11-ft) drop tests. (b) Lower neck joint measurements for the 1.83-m (6-ft) and 3.35-m (11-ft) drop tests.

who performed impact tests using cadaver specimens at a speed of 4.3 to 6.6 m/s. Yoganandan et al. measured the dynamic joint loading in the impact and found the peak compressive force was 100 to 254 N, the peak tensile force was 369 to 904 N, the peak shear force was 257 to 525 N, and the peak moment was 22 to 46.6 N-m. Our simulation results indicated that during the 3.35-m drop tests (Figures 10, Figures 11) the neck will be subjected to maximal compressive force of 360 N, maximal shear force of 260 N, and maximal joint flexion moment of 68 N-m. By comparing the neck joint loadings in the current study with those in the vehicle impact tests, we found that the compressive force and joint moment in the fall impact tests were greater than those in the vehicle impact tests, whereas the shear force for both tests were similar. The tensile loading in the neck was very small during the

fall impact and extremely high during the vehicle impact tests. For these two tests, the direction of the impact (superior/inferior direction in the fall impact tests and anterior/posterior direction in the vehicle impact tests) affected the degree of internal forces in the neck.

The neck injury criterion factor ($N_{ij} = 0.47$) for the 11-ft drop test in our study is comparable to that observed in the vehicle impact tests ($N_{ij} = 0.57$) and the ambulance crash test results ($N_{ij} = 0.2-0.6$) by Green et al. (2010), although it is still well below the injury threshold. It should be noted that the N_{ij} for females may be higher since females have a lower tolerance to dynamic loading than do males (Eppinger et al., 2000; National Highway Transportation Safety Administration, 2008).

The criteria for neck injuries under complex loading conditions have been well established

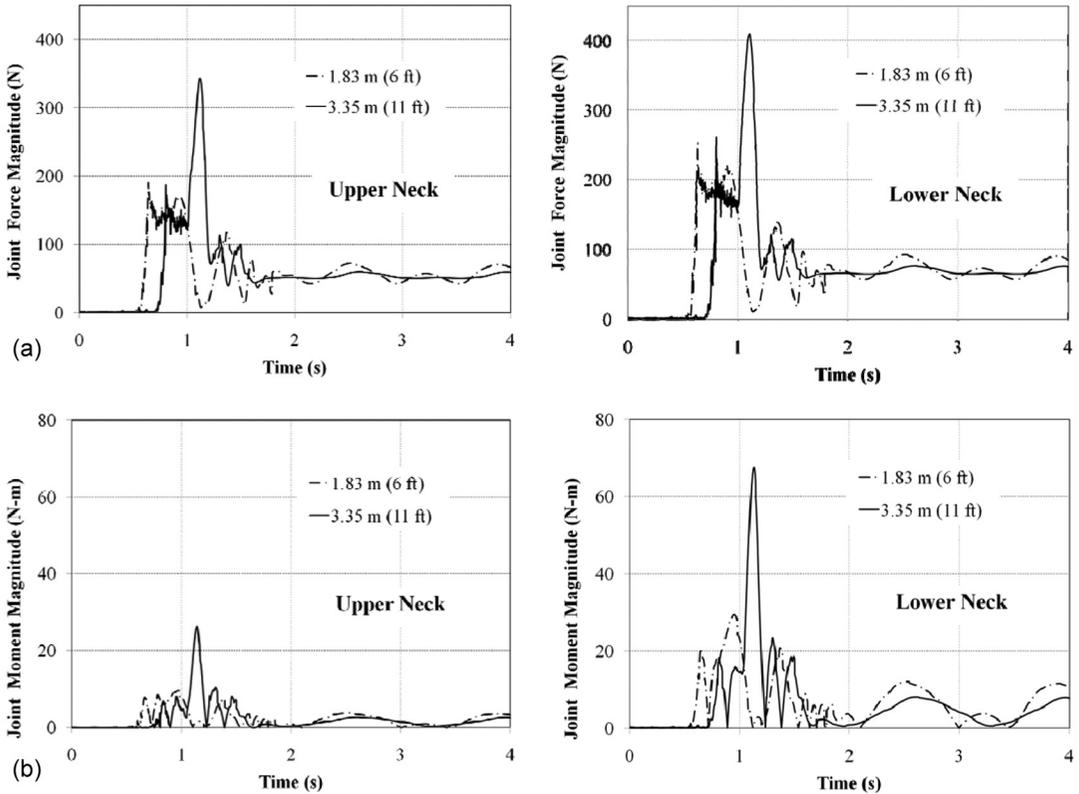


Figure 12. Time histories of the neck joint loading magnitudes for the 1.83-m (6-ft) drop tests compared with those for the 3.35-m (11-ft) drop tests. (a) Joint force magnitudes for the lower and upper neck. (b) Joint moment magnitudes for the lower and upper neck.

(e.g., Bostrom, Haland, & Svensson, 2000; Eppinger et al., 2000). For the fall impact, the neck was subjected to a combined loading of compression and flexional bending. Using Eppinger approach, $N_{ij} = 0.092$ and 0.212 for the 1.83- and 3.35-m drop tests, respectively, which are at the lower end of the injury index range (0.2–1.3) of the frontal impact tests of the vehicle crash test. Yang, Begeman, Muser, Niederer, and Walz's (1997) study indicated that the coexistence of the shear force and axial compressive force will result in a reduction of the shear stiffness of the vertical spine. They hypothesized that this mechanism of combined shear and compression effects can induce excessive stretch in the facet joint, leading to neck pain and injury.

In the current study, the manikin was dropped from the fully elevated platform of a scissor lift,

and a portion of the potential drop energy was dissipated in the structure. Consequently, the impact dynamic energy absorbed in the manikin would be smaller than those in the rigid anchorage drop tests at the same drop height with no other elevated devices (e.g., scissor lift) associated with it. Since this study identified significant, sudden biomechanical impact to the head/neck region, similar to what was found in the vehicle crash impact studies, the potential exists for serious spinal cord injuries as seen in vehicle crash incidents (Viano & Parenteau, 2008). The cervical spine (C1–C7; i.e., neck area) is the most maneuverable region of the spine (Ashton-Miller & Schultz, 1988; White & Panjabi, 1978). The lower neck (C5–C7), as identified from this study, experiences the most biomechanical loading during the fall-arrest incident. Unfortunately, this lower neck region

is also the most vulnerable to injuries (e.g., C5–C7 vertebrae fractures) in the upper spine (Deakin, 1993; Delahaye, 1982; Henzel, 1967; Teyssandier & Delahaye, 1967).

One limitation of this study is that biomechanical loading on the head/neck region was determined from a single lanyard-harness assembly. Testing was undertaken with a single assembly based on the fact that four different assemblies produced similar, convergent data, but more extensive selection of lanyard-harness assemblies could conceivably produce differing and divergent data. Further research could focus on more extensive selection of assemblies, with the intent of determining differing levels of biomechanical loading characteristics under similar conditions.

A useful line of inquiry would focus on elevated anchorage points or advanced EALs and harnesses that can increase the amount of energy reduction that occurs before energy is transferred to the human body. Numerous mechanisms of energy dissipation can be found, including advanced energy-absorbing materials, tear-away structures, elastomeric materials, elevated anchorage points, and similar engineering interventions. Advancements in the nonoccupational use of energy-absorbing structures, such as various sports applications, and in material science can all be applied to good effect.

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] (Panjabi, Ito, Ivancic, & Rubin, 2005; Panjabi, Wang, & Delson, 1999) might be followed 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.

In addition, a single elevating platform (SkyJack Model 3219 scissor lift) was used for the tests. This lift is widely deployed in industrial applications (approximately 200,000 units in use in 2009) and is generally considered to be the most widely used work platform (Genie,

personal communication, March 9, 2005; SkyJack, personal communication, March 9, 2005, April 22, 2006, and March 6, 2011). In addition, published material (Ramsey et al., 2009) indicates that the lift is generally comparable to seven other lifts of this class (19-ft narrow electric scissor lift) being used in industrial applications today. The injury data also indicate that more than 80% of fatal-injury incidents occurred within the operational range of this platform (Pan et al., 2007). However, the lift still represents a single product, and other elevating platforms could conceivably be responsible for the generation of differing levels of force transfer to the human body as a function of system rigidity, tie-off height, and other variables. Because of highly dynamic environmental issues—for example, issues of weather exposure, lift configuration under work zone or building entry conditions, various conditions of use (including overreaching and improper standing or other misuse conditions) related to work zone configurations and behavioral issues, changing work conditions, and common workarounds—development of engineering products that will meet the entire range of prioritized fall hazards is a challenging task for design engineers. In addition, the challenge to meet demands of anticipated hazard loads without overengineering fall-protection systems, with attendant task-interference issues, will remain substantial. Purposeful research related to the requirements of OSHA Standard 1926.453(b) (2)(viii), addressing the requirements for moving scaffolds, could also be undertaken to prevent exposures related to common misuse conditions. Future research should consider extending the current research to additional models of scissor lifts.

Another limitation of this study is that all drops were conducted in the upright manikin posture; it is unknown how other manikin postures (e.g., inverted falls, sideways falls) will affect the biomechanical loadings on the head/neck region.

Because of the weight/capacity limitations of the scissor lift used in this study, rarely will this platform be deployed in the field with multiple occupants. Therefore, the extrapolation of our findings to elevating platforms with multiple

occupants should be done with caution, as elevating platform characteristics for such platforms might differ under conditions with multiple occupants. In addition, dynamic test procedures followed by ANSI A92.6 recommendations and associated computer modeling were performed (Hartsell, 2010). Numerous other avenues of research could profitably be followed here because questions of dynamic actions of the lift or occupants, task performance, slope and motion, body orientation during falling, propulsion of occupants on sudden platform motion, and various other avenues of research suggest mechanisms of injury causation, and these mechanisms are at this point little understood. Future research efforts can address these situations and variables.

In summary, this study provides scientific, quantitative data for fall-arrest systems used on the SkyJack Model SJIIE 3219 electric scissor lift. The results show that the use of a fall-arrest system with an EAL and whole body harness did not cause structural instability of this scissor lift during a fall-arrest incident under the test conditions (i.e., flat surface, single occupant, and static working condition) evaluated in this study. Impact forces of the four fall-arrest systems used in the current study met the ANSI Z359.1 standard requirement. The performance of one fall-arrest system was further evaluated by quantifying biomechanical loadings on the operator's head/neck complex during drop/fall-arrest incidents. Future research should continue to explore the potential for internal injury associated with these fall-arrest systems during fall incidents with different anthropometric factors (e.g., weight, height, gender) and the criteria for selection and adoption of safer fall-arrest systems for use in highly dynamic, elevated, high-stakes work environments.

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KEY POINTS

- The fully extended scissor lift maintained structural and dynamic stability for all manikin drop test conditions.
- The maximum arrest forces from four manufacturer's harnesses/lanyards were all within the limits of the ANSI Z359.1 standard, and lanyard deployment forces were all similar.
- Significant biomechanical loadings on the lower neck region during the drops were identified.

REFERENCES

- American National Standards Institute. (2006). *Self-propelled elevating aerial work platforms* (ANSI/ASSE A92.6). New York, NY: Author.
- American National Standards Institute. (2007). *Safety requirements for personal fall arrest safety systems, subsystems and components* (ANSI/ASSE Z359.1). New York, NY: Author.
- Ashton-Miller, J. A., & Schultz, A. B. (1988). Biomechanics of the human spine and trunk. *Exercise and Sports Sciences Review*, 16, 169–204.
- Bostrom, O., Haland, Y., & Svensson, M. (2000). Neck injury criterion (nic) and its relevance to various possible injury mechanisms. In N. Yoganandan & F. Pintar (Eds.), *Frontiers in whiplash trauma: Clinical and biomechanical* (pp. 456–467). Amsterdam, Netherlands: IOS Press.
- Burkart, M. J., McCann, M., & Paine, D. M. (2004). Aerial work platforms. In *Elevated work platforms and scaffolding* (pp. 239–300). New York, NY: McGraw-Hill.
- Deakin, R. S. (1993). Military aircrew head support system. *Journal of Aircraft*, 30, 100–104.
- Delahaye, R. P. (1982). *Physiopathology and pathology of affections of the spine in aerospace medicine* (AGARD-AG-250(Eng)). Neuilly-sur-Seine, France: Advisory Group for Aerospace Research & Development.
- Deng, Y. C., & Goldsmith, W. (1987). Response of a human head/neck/upper-torso replica to dynamic loading—physical model. *Journal of Biomechanics*, 20, 471–486.
- Dukkipati, R. V., Pang, J., Qatu, M. S., Sheng, G., & Shuguang, Z. (2008). *Road vehicle dynamics*. Warrendale, PA: SAE International.
- Ellis, J. N. (2001). Aerial lifts and platforms. In *Introduction to fall protection* (pp. 115–118). Des Plaines, IL: American Society of Safety Engineers.
- Eppinger, R., Sun, E., Kuppa, S., & Saul, R. (2000). *Supplement: Development of improved injury criteria for the assessment of advanced automotive restraint systems, II*. Washington, DC: U.S. Department of Transportation, National Highway Traffic Safety Administration.
- Green, J. D., Yannaccone, J. R., Current, R. S., Sicher, L. A., Moore, P. H., & Whitman, G. R. (2010). Assessing the performance of various restraints on ambulance patient compartment workers during crash events. *International Journal of Crashworthiness*, 15, 517–541.

- Harris, J. R., Powers, J. R., Pan, C. S., & Boehler, B. (2010). Fall arrest characteristics of a scissor lift. *Journal of Safety Research, 41*, 213–220.
- Hartsell, J. (2010). *The development of a dynamic scissor lift model* (Unpublished master's thesis). West Virginia University, Morgantown.
- Heath, F. G. (2006, May–June). Accident waiting to happen. *Lift and Access*, pp. 46–50.
- Henzel, J. H. (1967). *The human spinal column and upward ejection acceleration: Appraisal of biodynamic implications* (Rep. No. AMRL-TR-66-233). Pensacola, FL: U.S. Aerospace Medical Research Laboratory.
- Hsiao, H., Bradtmiller, B., & Whitestone, J. (2003). Sizing and fit of fall-protection harnesses. *Ergonomics, 46*, 1233–1258.
- International Organization for Standardization. (2003). *Mobile elevating work platforms—design calculations, safety requirements and test methods* (ISO 16368, 2003(E)). Geneva, Switzerland: Author.
- Luo, Z. P., & Goldsmith, W. (1991). Reaction of a human head/neck/torso system to shock. *Journal of Biomechanics, 24*, 499–510.
- McCann, M. (2003). Death in construction related to personnel lifts, 1992–1999. *Journal of Safety Research, 34*, 507–514.
- National Highway Transportation Safety Administration. (2008). *Title 49, CFR Pt. 571.208, occupant crash protection*. Washington, DC: Author.
- Nightingale, R. W., McElhane, J. H., Richardson, W. J., Best, T. M., & Myers, B. S. (1996). Experimental impact injury to the cervical spine: Relating motion of the head and the mechanism of injury. *Journal of Bone and Joint Surgery, 78*, 412–421.
- Occupational Safety and Health Administration. (2010). *Top 10 most frequently cited standards for fiscal 2010 (Oct. 1, 2009 to Sept. 30, 2010)*. Retrieved from http://63.234.227.130/Top_Ten_Standards.html
- Pan, C. S., Hoskin, A., Lin, M., McCann, M., Fern, K., & Keane, P. (2007). Aerial lift fall injuries: A surveillance and evaluation approach for targeting prevention activities. *Journal of Safety Research, 38*, 617–625.
- Panjabi, M. M., Ito, S., Ivancic, P. C., & Rubin, W. (2005). Evaluation of the intervertebral neck injury criterion using simulated rear impacts. *Journal of Biomechanics, 38*, 1694–1701.
- Panjabi, M., Wang, J., & Delson, N. (1999). Neck injury criterion based on intervertebral motions and its evaluation using an instrumented neck dummy. In *Proceedings of the IRCOBI Conference* (pp. 179–190). Zurich, Switzerland: International Research Council on Biomechanics of Injury.
- Ramsey, G., Parrish, K., & Whitehead, E. (2009, March). Sharp scissors: Analyzing the 19-foot-tall elevator class. *Lift and Access*, pp. 24–36.
- Riches, D. (2002). Analysis and evaluation of different types of test surrogate employed in the dynamic performance testing of fall-arrest equipment. *Health and Safety Executive, 411*. http://www.hse.gov.uk/research/crr_pdf/2002/crr02411.pdf
- Ronaghi, M., Wu, J. Z., Pan, C. S., Harris, J., Welcome, D., Chiou, S., . . . Dong, R. G. (2009). Scissor lift safety—An initiative to model static stability. *Professional Safety, 54*(4), 43–48.
- Stemper, B. D., Yoganandan, N., Pintar, F. A., Shender, B. S., & Paskoff, G. R. (2009). Physical effects of ejection on the head-neck complex: Demonstration of a cadaver model. *Aviation, Space, and Environmental Medicine, 80*, 489–494.
- Teyssandier, M. J., & Delahaye, R. P. (1967). Les Fractures Du Rachis Chez Le Parachutiste [Fractures of the spine in the parachutist]. *Aeronautical and Space Medicine, 6*(24), 19–23.
- Veridian. (1998). *Advanced Dynamic Anthropomorphic Manikin (ADAM) operations and maintenance manual*. Dayton, OH: Author.
- Viano, D. C., & Parenteau, C. S. (2008). Analysis of head impacts causing neck compression injury. *Traffic Injury Prevention, 9*, 144–152.
- White, A. A., & Panjabi, M. M. (1978). *Clinical biomechanics of the spine*. Philadelphia, PA: Lippincott.
- Wu, J. Z., Powers, J. R., Harris, J. R., & Pan, C. S. (in press). Estimation of the kinetic energy dissipation in fall arrest system and human body during fall impact. *Ergonomics*.
- Yang, K., Begeman, P., Muser, M., Niederer, P., & Walz, F. (1997). *On the role of cervical facet joints in rear end impact neck injury mechanisms* (970497). Troy, MI: Society of Automotive Engineers.
- Yoganandan, N., Pintar, F. A., Stemper, B. D., Schlick, M. B., Philipppens, M., & Wisman, J. (2000). Biomechanics of human occupants in simulated rear crashes: Documentation of neck injuries and comparison of injury criteria. *Stapp Car Crash Journal, 44*, 189–204.

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