Copyright © National Academy of Forensic Engineers (NAFE). Redistribution or resale is illegal.
Originally published in the Journal of the NAFE volume indicated below.

Journal of the National Academy OF Forensic Engineers®

http://www.nafe.org

ISSN: 2379-3252

DOI: 10.51501/jotnafe.v40i1

Vol. 40 No. 1 June 2023

Copyright © National Academy of Forensic Engineers (NAFE). Redistribution or resale is illegal.
Originally published in the Journal of the NAFE volume indicated on the cover page.

Nondestructive Forensic Investigation of a Scissor Lift Fatality

*By Michael Stichter, PhD, PE, DFE (NAFE 1162M), Zachary Ball, PhD, PE,
Carl Jewell, PhD, and Wade Lanning, PhD*

Abstract

After a worker was found fatally pinned between the top rail of a scissor lift and an overhead beam, rescue attempts were frustrated by unresponsive lift controls. In the investigation of this fatal accident, certain lift controls did not function or functioned intermittently. The intermittent nature of the malfunction indicated that the evidence was sensitive — likely to be disturbed if the device was disassembled using typical destructive techniques. Therefore, nondestructive techniques were required. This study discusses how X-ray imaging, computed tomography (CT), electrical testing, and engineering analysis of the lift and control system were used to investigate the causes and contributing factors of this fatal accident without disturbing sensitive evidence.

Keywords

Nondestructive, failure analysis, accident investigation, exemplar testing, scissor lift, control panel, lift controls, electrical, damage, safety devices, forensic engineering

Introduction and Background

Two construction workers (the victim and his colleague) were welding steel plates to overhead beams in a permit-required confined space (**Figure 1**). In order to reach the overhead beams, each worker was provided with a rented scissor lift. The workers were taking turns performing different tasks. One would weld while the other acted as “fire watch” and/or repositioned their lift to prepare for their turn at welding. No other workers were present in the confined space.

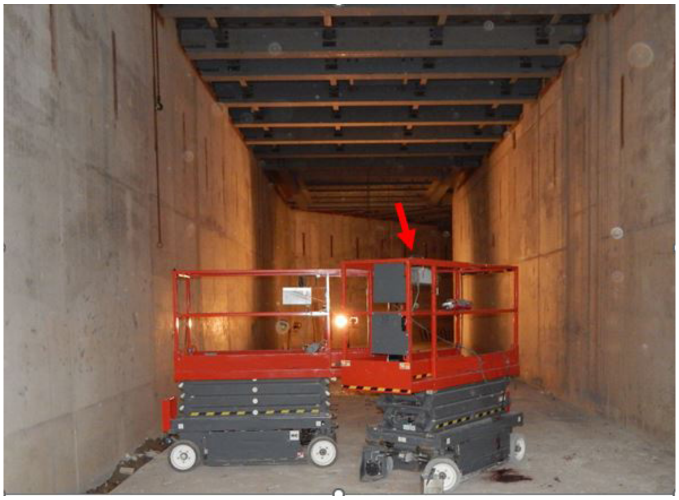

Figure 1
Photo from the incident scene showing the subject
scissor lift (red arrow), the other lift used in rescuing the victim,
and the overhead beams involved in entrapping the victim.

The accident occurred while the victim’s colleague was welding; he did not directly observe the accident. While the colleague was welding, the victim was expected to be on fire watch and/or repositioning his lift. After completing a series of welds, the colleague noticed that the victim’s lift was not moving. Further investigation revealed the victim was unresponsive and appeared to be pinned between the lift and an overhead beam. The colleague lowered his lift and ran to get help.

After a brief delay in getting access to the confined space, other construction workers and medical responders arrived and attempted to use the base controls on the scissor lift to lower the platform and rescue the victim. Unfortunately, the lift did not lower in response to the rescuers’ attempts to use the base controls. The colleague got back in the other scissor lift, raised it to reach the victim, and found the victim with his head pinned between the top rail of the lift and an overhead beam and his hand pushing against the upper control console joystick. The colleague moved the victim’s hand off of the joystick; then he operated the controls of both scissor lifts simultaneously to lower them to the ground. The victim died of severe crushing injuries to the head.

Michael Stichter, PhD, PE, 2288 Second Street Pike, Penns Park, PA 18943, (215) 598-9750, mstichter@arcca.com

Copyright © National Academy of Forensic Engineers (NAFE). Redistribution or resale is illegal.
Originally published in the Journal of the NAFE volume indicated on the cover page.

The authors and other investigators were tasked with evaluating the incident and determining how the victim became entrapped and why the subject lift's base controls were unresponsive during rescue attempts.

Post-Accident Interview

Investigators conducted interviews of witnesses. The victim's colleague was able to describe the position of the victim's body prior to freeing him from entrapment between the lift and the beam. The colleague described the position of the victim as if he was trying to look over the edge of the platform at the wheels of his scissor lift. When the colleague used his own lift to reach the victim, he found one of the victim's hands pressing the joystick on the upper control console in the forward/raise direction. The upper control console was positioned on the top rail of the lift platform (**Figure 2**). The colleague moved the victim's hand off of the controls; then he used the controls on both lifts simultaneously to lower them.

The joystick is designed to either make the lift platform raise/lower or the chassis move forward/backward, depending on the position of a selector switch. The colleague suggested that, while investigating control malfunctions, the victim had mistakenly attempted to move the lift forward — not realizing that the selector switch was in the raise/lower position, which resulted in the lift raising unexpectedly. The colleague also reported that, prior to the accident, the upper lift controls would sometimes "hesitate" or exhibit other malfunctions.

Figure 2
Photo from the accident scene, showing the control console of the subject scissor lift mounted on the top rail. The rail of a second scissor lift, used in an attempt to rescue the victim, is in the foreground. The top rail of the subject scissor lift is bent downward from the force exerted between the scissor lift rail, the victim, and an overhead beam.

Initial Inspection and Functional Testing of the Subject Lift

After the incident, the subject scissor lift was removed from the site, stored in a warehouse, and then examined/tested by investigators several months later. One of the upper rails was bent downward (**Figure 3**), indicating the contact point between the rail, the victim's body, and the overhead beam. Witness testimony and maintenance records indicated that the rail was not bent until after the incident. The force exerted by the lift during the incident bent the top rail and caused the victim's injuries.

The incident unit was an electric-powered machine with a bay of four 6V batteries wired in series, which had to be replaced prior to testing (due to the old batteries having run down while in storage). Replacing the batteries was the only modification performed prior to the functional testing, which was deemed appropriate. This was due to the fact that the batteries were very unlikely to be a direct or indirect cause of the incident because the lift was able to raise at the time of the incident — low or defective batteries would have provided an inability to raise that is contradictory to all of the available evidence.

The investigators began the functional testing of the subject lift by following the pre-start checklist provided in the manufacturer's manual, which is fairly standard across manufacturers. This checklist was chosen because it is designed to notify the user of any issues with the unit prior to operation. During pre-start functional tests, the lift's electric motor was found to have failed. The motor was replaced in order to complete the functional tests. The original motor was preserved, and later examination determined that the motor failure was due to corrosion of the brushes while it was in storage. At the time of the incident, the subject lift was able to raise with sufficient force to

Figure 3
Photo from inspection of the lift several months after the accident. The top rail was bend downward where the victim was entrapped between the rail and an overhead beam.

Copyright © National Academy of Forensic Engineers (NAFE). Redistribution or resale is illegal.
Originally published in the Journal of the NAFE volume indicated on the cover page.

bend the top rail and fracture the victim's skull. The effect of the motor or battery failures discovered at later inspections would have made the lift unable to raise, preventing the incident. Thus, the condition of the motor could not have contributed to the incident.

After replacing the motor, functional testing continued. Investigators found that the control console was unable to cause the steering wheels to steer to the right, but could make the wheels steer left. Swapping the subject control console for an exemplar console corrected the problem, narrowing the cause of the issue to the subject control console. The subject control panel was preserved for nondestructive examination.

Investigators conducted electrical continuity tests between components of the control console and the pins in the console connector plug. As a result, they found a fault in the control for the lift to steer to the right. The steering switch itself functioned properly: it was normally open and connected its central pole to either the "steer right" or "steer left" terminals. The "steer left" terminal had normal electrical connectivity to a corresponding pin in the connector plug. However, there was no electrical connectivity between the terminal steering switch's "steer right" terminal and its pin in the connector plug. This testing narrowed the cause of the steering malfunction to a connectivity fault somewhere between the control console cable and its connector plug.

Photographs from the incident scene showed the subject scissor lift's front wheels were steered to the right (**Figure 4**). At the time of the accident, the lift was able to steer to the right. However, during functional testing, the incident control box was unable to steer the wheels to the right. This indicated an intermittent malfunction, of the lift's steering mechanism. An intermittent malfunction was consistent with the victim's colleague referring to "hesitation" and other (non-specific) control malfunctions prior to the incident.

As described earlier, rescuers claimed to have attempted to lower the scissor lift using the base controls, but the lift did not respond. Ultimately, the colleague used another lift to reach the victim and found him pinned against the control lever and platform rail with his right hand pressing the lever in the forward/raise position. Investigators found that the manufacturer of the subject lift issued a service bulletin approximately four years after the subject incident to scissor lift dealers describing a design flaw in the model and serial number of scissor lift involved in the incident. When the upper controls were held in the UP position, the flaw made the lower controls unable to lower the platform. This design defect explained why rescuers were unable to use the lower controls to rescue the trapped worker.

Figure 4
Photograph of the incident scene taken shortly after the incident, showing the subject lift's wheels turned to the right.

Rescuers claimed to have attempted to use the mechanical emergency lowering valve to lower the platform when it was stuck in the raised position, but were unable to get the platform to come down. In functional testing, investigators did not find any fault or malfunction with the emergency lowering valve.

As far as investigators were able to determine, the rescuers were unfamiliar with the lift's emergency lowering procedure. Before the emergency lowering valve could be used, a holding valve manual override knob on the lift cylinder had to be engaged. In interviews, rescuers did not demonstrate awareness of the holding valve manual override. Most likely, the rescuers failed to engage the holding valve manual override, which is why the emergency lowering valve did not cause the platform to come down. Rescuers did not attempt other means of lowering the platform, such as relieving pressure in the cylinder. Similarly, after initial failed attempts to use the lower controls to lower the platform, rescuers did not use the lower controls; instead they used the upper controls to lower the platform and free the trapped worker.

Investigators disagreed on how to proceed with investigation of the lack of electrical continuity found between

Copyright © National Academy of Forensic Engineers (NAFE). Redistribution or resale is illegal.
Originally published in the Journal of the NAFE volume indicated on the cover page.

control console and the pins in the connector plug. Some investigators wanted to proceed with destructive disassembly; others were concerned about preservation of the condition of the evidence and wanted to further document the condition of the plug and cord before risking disturbing evidence. The decision was made to not disassemble any additional components prior to the completion of 2D X-ray radiographs and CT scans.

Nondestructive examination methods were critical because the position of any loose or damaged conductors could be easily disturbed and raise questions about whether any faulty connections were the result of the disassembly process. The presence of intermittent electrical connections was indicated by witness testimony and the discrepancy in steering function observed between functional testing and scene photographs. However, the cause of the intermittent connections might be difficult to preserve while disassembling the components.

Nondestructive Radiography of the Control Console

Investigators performed nondestructive 2D X-ray radiography of the subject scissor lift platform control console. In the 2D X-ray radiographs (**Figure 5**), some of the wires in the cable connector appeared off-center relative to the pins, suggesting that they were not fully inserted into their terminals.

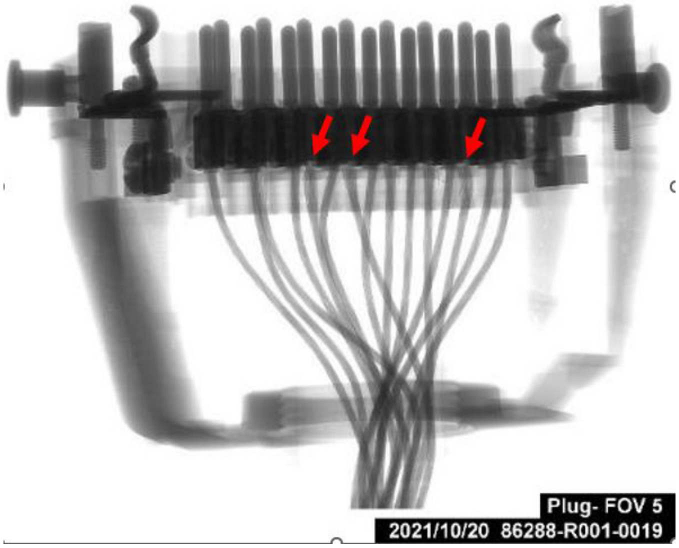

Figure 5
2D X-ray radiographs of the platform control console cable connector. Some of the wires appeared off-center relative to the pins, suggesting possible loose or detached connections. Further radiography was required to resolve the positions of the wires and identify which control functions were affected.

Investigators ordered a nondestructive 3D CT scan of the platform control console cable connector in order to better resolve the locations of the wire terminations in three dimensions. In the CT scans of the cable connector, the wires behind pins number 1 through 8 appeared to be fully inserted into the pin screw terminals (shown, but not labeled, in **Figure 6** and **Figure 7**). However, the wires behind pins 10, 11, and 15 were not secured in the pin screw terminals at all — they were either free-floating or resting against the outside of the terminals (**Figure 6** and **Figure 7**). Pins 12, 13, and 14 were partially withdrawn

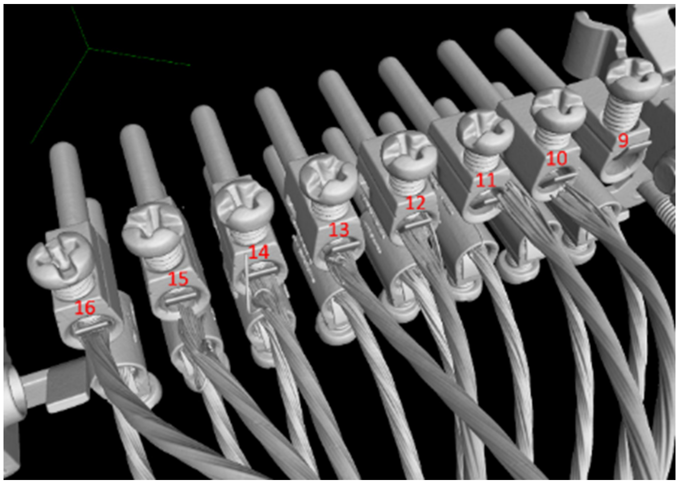

Figure 6
Top view of 3D CT scan of the subject platform control console cable connector. Numbers in red have been added to identify individual pins. Pins 1 through 8 (not numbered, located below pins 9 through 16 in this view) appeared fully secured within the screw terminals. Pins 10 to 15 were loose and withdrawn from the screw terminals. Pin 9 was left empty and had no corresponding wire.

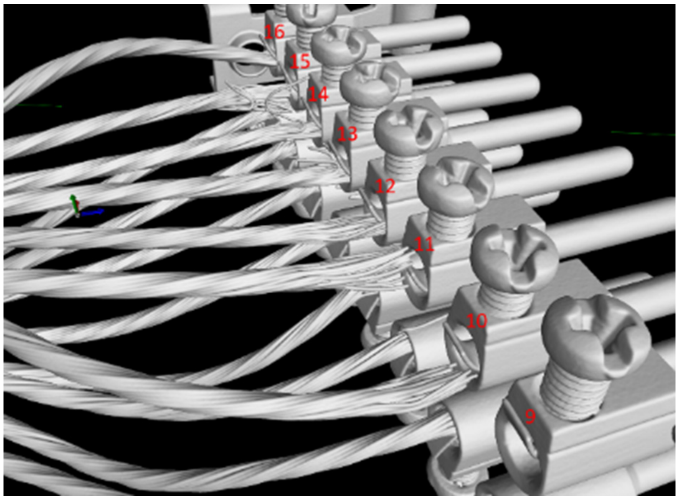

Figure 7
Side view of a 3D CT scan of the subject platform control console cable connector. Numbers in red have been added to identify individual pins. Pins 10 through 15 exhibited varying degrees of being withdrawn from the screw terminals.

Copyright © National Academy of Forensic Engineers (NAFE). Redistribution or resale is illegal.
Originally published in the Journal of the NAFE volume indicated on the cover page.

from their screw terminals. Out of pins 9 through 16 of the cable connector, only the wires behind pins 14 and 16 appeared fully inserted into and secured within the screw terminal. Pin 9 was not used (by design).

A slice of the 3D CT scan was used to measure the heights of the screws (i.e., how far they were tightened down) as shown in **Figure 8**. The threaded depth of the screw is directly correlated to clamping force of the wire as the screws for each wire connection were all the same size, and the wires were all the same gauge. The largest gap was the unoccupied pin 9 (measuring 3.4 mm between the top of the screw terminal and the bottom of the head of the screw). The next largest gaps were pins 15, 10, and 11 (measuring 2.31 mm, 2.28 mm, and 2.20 mm, respectively).

The reduced clamping force in the affected screw terminals would have made it easier for the wire to be pulled out from the terminal. Additionally, pin 14 was still partially inserted into the terminal, even though pin 13 and pin 15 on either side of it were more withdrawn from their respective terminals (**Figure 8**). If the sole cause of the withdrawal of the wires from the terminals was an excessive force, then one wire would not be expected to remain connected while the wires on either side failed. The fact that only some of the wires were withdrawn from the terminals indicates that those wires were not as firmly secured as the others in the connector.

Electrical connectors are typically designed with “strain relief” features that provide a mechanical connection between the cable and the connector. In this case, the two primary forms of strain relief were the “cable gland”-style connector that gripped the exterior of the cable as it entered the connector and the screw terminals that clamped the ends of the stranded wires in place. Cable glands (like those in the subject plug) grip the exterior of the cable insulation and transfer stress from the insulation to the body of the connector plug. Screw terminals grip the ends of the wire, forming a mechanical link from the wire to the plug pins. After nondestructive radiography of the console plug, the cable gland connector was disassembled, revealing evidence that the cable had been pulled through the cable gland (**Figure 9**).

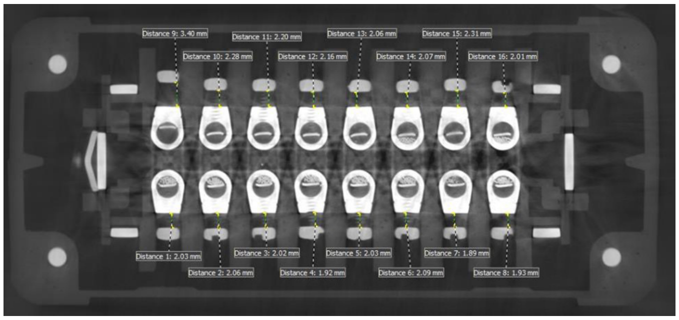

Figure 8
Slice of a 3D CT scan of the subject platform control console cable connector with threaded depth of the screws marked. Pins 1 through 8 had relatively tightly connected crew terminals. Pins 10 through 15 had relatively loose screw terminals with partially or fully withdrawn wires. The distance labels also correspond to the pin numbers.

Some, but not all, of the wires inside the connector in the subject platform control console pulled out of the screw terminals used in the cable connector (**Figure 6** and **Figure 7**). The screw terminals in pins 10, 11, and 15 had wires that withdrew completely, and pins 12, 13, and 14 were partially withdrawn. These pins did not provide adequate strain relief to hold their wires in place, but the other screw terminals successfully retained their wires. Pins 10 through 15 were not properly secured to the connector. If they were properly secured, then the connections between the cable and connector (the cable gland and the screw terminals) should have been stronger than the cable and its wires. When a properly secured connector fails, the cable and/or the wires fail rather than the strain relief. No such breakage or damage was visible in the 2D radiographs, CT scans, or physical inspection.

Each wire in the platform control console cable conveyed a different command from the platform control console to the lift. Investigators used wiring diagrams from the lift’s service and maintenance manual to identify the platform control console functions that were associated with the improperly secured wires found in the platform

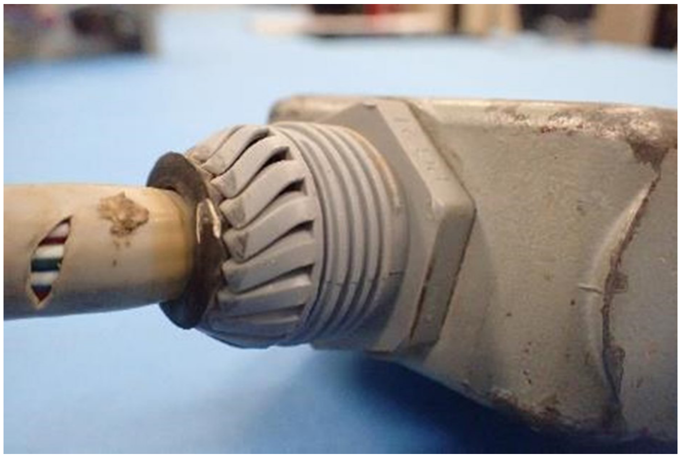

Figure 9
After nondestructive radiography, the cable gland connector on the control console plug was disassembled. The cable exhibited evidence of tension on the cable, such as movement of the cable within the gland and a tear in the outer insulation.

Copyright © National Academy of Forensic Engineers (NAFE). Redistribution or resale is illegal.
Originally published in the Journal of the NAFE volume indicated on the cover page.

control console connector. Pins 10 through 15 in the platform control console cable connector had wires that were not properly secured, and, as a result, were partially or fully withdrawn from the screw terminals connected to the pins (**Figure 6** and **Figure 7**).

The base controls were designed to override the platform control console in accordance with the requirements of ANSI/SAIA A92.6 (2006). The subject lift's override was accomplished by turning a key located at the base controls from a "platform control" position to a "base control" position. This would disable the platform controls and enable the base controls. However, due to an uncorrected design flaw, the platform control console was able to override the base controls if the platform control console joystick was in the up/forward position.

Since the wires to pins 10 through 15 were not properly connected to the screw terminals, the connection through those pins was interrupted, weak, or intermittent during operation of the lift. This affected a variety of signals sent from the platform control console to the lift, including:

- The speed with which the lift moved (raise/lower or forward/reverse) in response to the joystick (pin 12, withdrawn from terminal but still touching).
- The ability of the lift to move forward or up in response to the joystick controls (pin 10, withdrawn from terminal but still touching).
- Steering to the left (pin 14, partially inserted into terminal).
- Steering to the right (pin 15, fully withdrawn from terminal and not touching).
- Steering common, + voltage (pin 11, fully withdrawn from terminal but still touching).

Interruption of the connection on these pins would interfere with the operator's ability to control the lift from the platform control console and make the lift unpredictable and dangerous to operate. The console might work properly at times when the wires make contact, but malfunction when the wires were moved and would break contact with the terminals. This is consistent with statements that, prior to the accident, the lift controls would sometimes "hesitate" or malfunction.

Due to the intermittent nature of the connections, malfunctions could appear sporadically during inspections, functional tests, and use of the machine. For instance, the console could not steer to the right during functional testing because the wire to pin 15 was completely separated from its terminal, but the lift could still move forward because the wire to pin 10 was touching the terminal, even though it had been pulled loose. Because of the loose wires in the plug, important control console functions, including moving upward, movement speed, and turning right, would respond unpredictably. The steering malfunction is notable because, according to the colleague, the victim's body was positioned as if attempting to look over the edge of the platform down at the wheels. The victim may have been trying to look at the wheels in response to a steering problem.

Intermittent connections on the joystick pulse width modulation (PWM) output on cable connector pin 12 would have created a dangerous condition. PWM uses a series of digital pulses (i.e., a voltage that is either zero or maximum) that are processed in a microchip to achieve what is effectively an analog output (i.e., a voltage at a desired value between zero and maximum). The PWM output controlled how quickly the lift moved when either raising/lowering (by controlling a hydraulic proportional valve) or moving forward/backward (by controlling the drive system). An intermittent connection would interrupt and reconnect the signal to the speed control, causing the lift to move at unpredictable rates. The loose connection on pin 12 may have resulted in an unexpected rate of motion of the scissor lift's up/down movement and contributed to the victim being pinned against the ceiling beam.

These findings highlight the value of performing nondestructive testing prior to any disassembly of components when their condition is both sensitive and critical to the investigation. Had the connector been disassembled during the functional testing, the status of the wires prior to disassembly would have been suspect as it may have been hypothesized that they became loose during the disassembly. Even if great care was taken during disassembly, the CT scans and 2D radiographs were valuable in documenting the state of the evidence — establishing that the loose wiring connections were present prior to disassembly. Nondestructive radiography was key to gathering forensic information while preserving the evidence.

After radiography, the connector was subsequently disassembled for further inspection, and wiring diagrams were used to identify the controls affected by loose and broken connections found in the connector. After removal

Copyright © National Academy of Forensic Engineers (NAFE). Redistribution or resale is illegal.
Originally published in the Journal of the NAFE volume indicated on the cover page.

of wires 1 through 8 from the cable terminal block by backing out each of the terminal screws, wires 10 through 15 were free without applying tension to the wires or backing out their respective screws (**Figure 10**).

Biomechanical Analysis of Injuries in the Subject Incident

The pattern of the victim's injuries and signs of external trauma indicated that he sustained a significant compressive force to his mandible and face[1-11]. The primary mechanism for bilateral laminar fractures in the cervical spine is a compressive force applied during extension[12-15]. The mechanism of injury for the victim's multiple facial fractures involved blunt force trauma to the face. The bones of the face are more resistant to fracture in frontal impacts as opposed to lateral[11]. The nasal bones are the most fragile bones of the face with reported tolerance levels for minor fractures as 25 to 75 pounds (lb)[6,11]. The maxilla (140 to 445 lb) and zygomatic arch (208 to 475 lb) show greater tolerance than the nasal bones, while the mandible (upward of 425 lb) is capable of withstanding greater amounts of force[11]. Given the pattern of injuries sustained by the victim, the sustained compressive force was most likely directed from the front as well as upward and laterally toward the left side of his face — most probably in excess of 400 lb.

Standards for Preventing Sustained Involuntary Operation (SIO) Accidents

Scissor lifts like the one involved in this case are one kind of mobile elevating work platform (MEWP), a machine for moving workers, tools, and materials to elevated working positions. The accident in this case was an entrapment accident, where an occupant became trapped between the machine and another object or structure. Entrapment accidents are one of the most common causes of reported fatalities involving MEWPs, along with falls from the platform, electrocutions, and equipment overturns[16].

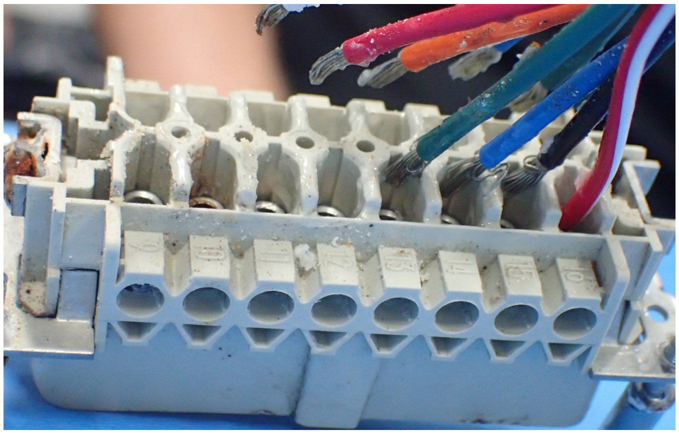

Figure 10
After nondestructive radiography, the cable terminal block was disassembled. The wires in terminals 1 through 8 were removed by backing out the screws on each terminal. Upon backing out the screw for terminal 8, the wires in terminal 10 through 15 slipped out of their respective terminals without applying tension to the wire or backing out the terminal screws.

This specific type of entrapment accident is referred to as sustained involuntary operation (SIO)[17-19]. In an SIO accident, the operator is pushed against the controls. The operator's body engages the controls, causing the MEWP to move, which further entraps the operator and jams the controls, creating a feedback loop. Since operators are unable to stop the motion of the lift or to free themselves, SIO accidents often make rescue of the operator difficult and result in fatal crushing and/or suffocation injuries.

The modern versions of standards, such as ANSI/SAIA A92.20 and ISO 16368, require design features such as overload protection, control console guards, and/or interlocks to interrupt the SIO feedback loop and reduce the likelihood and severity of SIO-type accidents[20-23]. However, the subject scissor lift did not have these features.

Multiple standards govern the design and safety features included on scissor lifts, including:

- ANSI/SAIA A92 series of standards
  (USA, Scaffolds and Access Industry Association)
- ISO 16368 standard (international)
- BS EN 280-1 (Europe / UK)
- CSA B354.6 (Canada)

The ANSI/SAIA A92 standards are the primary American standards for MEWPs, and major recent revisions include additional requirement for anti-SIO guarding. Historically, the ANSI/SAIA A92 standards were published as separate standards for different classifications of machine. These included ANSI/SAIA A92.3 (manually propelled lifts), A92.5 (boom lifts), A92.6 (self-propelled/ scissor lifts), and A92.8 (vehicle-mounted bridge inspection/maintenance lifts). However, ANSI/SAIA published a new suite of A92 standards that combined the standards for different types of machines, instead dividing them by topic. ANSI/SAIA A92.20 (design, safety, and testing), A92.22 (safe use), and A92.24 (training) were issued in December 2018 to replace the machine-specific ANSI/

Copyright © National Academy of Forensic Engineers (NAFE). Redistribution or resale is illegal.
Originally published in the Journal of the NAFE volume indicated on the cover page.

SAIA A92.3, A92.5, A92.6, and A92.8, which were withdrawn in June 2020[20]. The stated reason[23] for the change was to combine the requirements for MEWPs with similar configurations/uses and to bring the ANSI/SAIA standards into closer agreement with existing international standards such as ISO 16368[22].

The subject lift was manufactured in 2013 after international ISO 16368 standard began to explicitly require anti-SIO guarding but before ANSI/SAIA A92.20, which explicitly addressed anti-SIO guarding. Pre-A92.20 requirements were potentially relevant to preventing unintentional activation of controls but did not explicitly address the relevance of such guarding to prevent operator entrapment. ANSI/SAIA A92.6-2006, "American National Standard For Self-Propelled Elevating Work Platforms" has requirements for the controls.

The upper controls at the platform shall:

- 4.7.1(5) be protected against activation other than that initiated by the operator.

- 4.7.1(3) include a separate control that shall be continuously activated by the operator for upper directional controls to be operational, which can be released by the operator independently from the directional controls and render the upper controls inoperative when released.

The lower controls shall:

- 4.7.2(1) override upper controls for powered functions.

- 4.7.2(2) be provided for all powered functions except drive and steering.

- 4.7.2(4) be protected against activation other than that by the operator.

The newer ANSI/SAIA A92.20, "Design Calculations, Safety Requirements and Test Methods for Mobile Elevating Work Platforms," which replaced A92.6, has more explicit requirements for anti-SIO design:

- 4.7.1.2. All controls shall be designed to protect against inadvertent operation (any operation other than that intentionally initiated by the operator). Hand-operated controls in the platform shall be protected against sustained involuntary operation. This protection should either prevent further movement of the machine in the direction of trapping or allow the operator to reverse or stop the trapping movement.

- 4.7.1.3. The upper controls shall include a separate device(s) that shall be continuously activated by the operator for directional controls to be operational. This device(s) shall be capable of being released by the operator independent of the directional controls. When released, this device(s) shall render the directional controls inoperative.

- 4.7.3.1. The control devices shall be located on the work platform. Duplicate controls for all powered functions of the extending structure shall be provided at the base or ground level, except for drive or steering, and shall override control devices situated on the work platform. Control devices shall be readily accessible to the operator. Control boxes not permanently attached shall have their normal location and orientation clearly marked.

The subject lift was manufactured in 2013 — before the ANSI/SAIA A92 standards were restructured and language was added explicitly addressing the SIO hazard. Thus, features that would have detected an SIO event and stopped or reversed motion of the lift were not yet required by the applicable American standard when the subject lift was made. However, the lift did not meet the existing A92.6 requirements related to inadvertent activation of the upper controls.

- The joystick on the upper controls extended above the small handle/guard (**Figure 2**), making it inadequately guarded against inadvertent activation as required by A92.6 Section 4.7.1(5).

- Although the joystick did have an activation switch, it was integrated into the joystick grip rather than being a separate control. It is debatable whether a button on the joystick satisfies A92.6 Section 4.7.1(3). In the incident, the victim did not release this control even after he was entrapped.

- Due to a flaw in the wiring design, the lower controls could not override the upper controls as required by A92.6 Section 4.7.2(1), which delayed rescue of the victim.

The international ISO 16368:2010(E) standard was

Copyright © National Academy of Forensic Engineers (NAFE). Redistribution or resale is illegal.
Originally published in the Journal of the NAFE volume indicated on the cover page.

published in 2010 (prior to manufacture of the subject lift), and includes similar requirements to ASTM A92 for a separate activation control and protection of controls from inadvertent activation (Section 4.7.1) and for lower controls that override upper controls (Section 4.7.3). ISO 16368:2010(E) also requires that all signal-transmitting wiring be protected against damage (Section 4.11.3.2), which the exposed control cable of the subject lift (**Figure 2**) did not meet.

ISO 16368:2010(E) has additional requirements in Section 4.4.1.2 relevant to SIO incidents. All MEWPs are required to have a load-sensing system that activates when it detects a load between 100 percent and 120 percent of the machine's rated capacity. The system activates warning lights and an audible alarm. If the system is activated when the lift is raised 1 meter or 10 percent of its lift height (whichever is greater), then the system must prevent further upward motion once excessive load is detected. The standard notes that some means of moving the lift must still be available in order to release a trapped person[23]. Section 4.4.1.2.1 of ANSI/SAIA A92.20 duplicates the requirements for a load-sensing system from ISO 16368[23]. The subject lift did not have a load-sensing system.

Exemplar Testing of Alternative Design

Testing of an exemplar — a machine of identical design to the subject lift — allowed investigators to probe the design of the machine without risk of disturbing evidence. Even though testing can be potentially destructive to the exemplar, it is nondestructive with regard to the subject machine. The investigators also built and tested a technologically and economically feasible alternative design that would guard against the hazard of sustained involuntary operation (SIO) per the hierarchy of controls when designing a new product[24-27]. Before designing and adapting the alternative solution, testing on an exemplar was required to characterize the hazards associated with SIO in an unmodified exemplar scissor lift.

Investigators conducted testing of an exemplar lift matching the model and year of manufacture of the subject lift. They found that in the lowered position, the lift could exert in excess of 900 lb of force when raising the platform into contact with an overhead obstruction. Based on the test results at a 136.5-inch height, the lift could exert in excess of 2,100 lb of force when encountering an overhead obstruction. The increase in force was due to a change in the angle of the hydraulic actuators (lift cylinders) relative to the lift's "scissor" lift mechanism, which increased the magnitude of the moment (torque) created by the actuator acting on the scissor mechanism.

Because the moment is proportional to the perpendicular component of force acting on a lever arm, the magnitude of the moment increased as the scissor mechanism raised, causing the hydraulic actuators to rotate from an oblique angle to a more perpendicular angle with the arms of the scissor mechanism, increasing the resulting moment (torque) on the scissor arms and the total force exerted by the lift. The lift reached maximum force approximately 1 second after encountering an obstruction. **Figure 11** shows the orientation of the lifting cylinder and the cylinders when in the fully lowered and a partially raised position. The lifting cylinder becomes more vertical as the scissor lift mechanism extends.

The forces measured in testing the exemplar violated relevant ANSI and ISO standards. The subject and exemplar had a rated capacity of 550 lb. ISO 16368:2010(E); 4.4.1.2 requires lifts to be equipped with a "load-sensing system" that would activate if a force above the rated load and before 120 percent of the rated load is exceeded. The lift involved in the accident did not have such a system.

Testing of an exemplar lift revealed that the type of lift involved in the accident could exert dangerous levels of force too quickly for the operator to react and save himself. In order to test whether a safety device could have prevented the accident, investigators designed and built a simple anti-SIO device that triggered the lift's emergency stop when a pressure sensor on the top rail was activated (**Figure 12**), motivated by the Design Order of Precedence[27]. The device stopped the lift and reduced the force exerted on the overhead obstruction to 50 to 225 lb of force, depending on how far forward the control joystick was pressed. Note: The angle of the joystick controlled a pulse width modulation (PWM) signal that modulated the

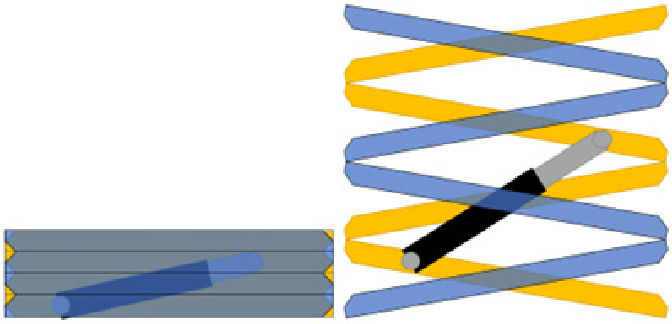

Figure 11

Sketch of a scissor lift mechanism in the lowered (left) and raised (right) position. Note that in the raised position, the lift cylinder and scissor arms rotate to be more nearly perpendicular to one another.

Copyright © National Academy of Forensic Engineers (NAFE). Redistribution or resale is illegal.
Originally published in the Journal of the NAFE volume indicated on the cover page.

position of the hydraulic proportional valve — and thus the speed with which the platform moved upward or traveled forward or reverse.

The investigators determined that the absence of an anti-SIO device was a contributing factor to the accident — and that if such a device was equipped, it would have reduced the severity of the victim's injuries and increased his chances of survival. Although an anti-SIO device as described above is not explicitly required by the ANSI/SAIA standards, at the time of manufacture the testing showed, in conjunction with biomechanical analysis of the injuries sustained in the subject incident, that the upward force developed by the subject lift was well above the force necessary to cause fatal injuries to the head without this device and is limited to survivable forces when such a device is implemented.

Summary

A witness at the scene stated that the victim was positioned as though he was looking down at the wheels on the lift. This would be consistent with the victim reacting to a steering malfunction by observing the lift wheels while the victim manipulated various controls to see which responded.

Faulty connections in the upper control console plug would result in unpredictable changes in the speed of the lift's motion in response to the joystick. It is likely that the accident was the result of the lift moving upward faster than expected, pinning the victim between the lift and an overhead beam. The victim's body was trapped such that it pushed the joystick forward, causing the lift to continue to move upward and resulting in SIO of the lift controls and fatal injuries to the victim. The lift lacked control guarding against inadvertent activation that would reduce the likelihood of trapping the operator in an SIO feedback loop.

A design flaw in the lift's wiring prevented the lower controls from overriding the upper controls, as required by ISO and ANSI standards applicable at the time the lift was manufactured. The lift also lacked overload protection features required by ISO and later ANSI standards. Testing of an exemplar lift found that a raised scissor lift could exert in excess of 2,100 lb when encountering an obstruction — and that a simple anti-SIO device could reduce the force to 225 lb or less, greatly decreasing the risk of injury or death.

Conclusion

Conducting a forensic failure analysis of an intermittent malfunction requires special care to avoid losing vital evidence. In this case, nondestructive radiography allowed investigators to detect and document evidence that would have been disturbed by disassembling the part for visual examination. This would have left investigators in doubt of the significance of finding loose screw terminals.

Nondestructive radiography revealed that wires had been withdrawn from the screw terminals without altering the condition of the plug. This case illustrates that nondestructive radiography can be an effective strategy for investigating intermittent failures or malfunctions. The investigator must consider that whatever causes a failure to be intermittent or difficult to reproduce may also leave sensitive evidence that is best examined by nondestructive

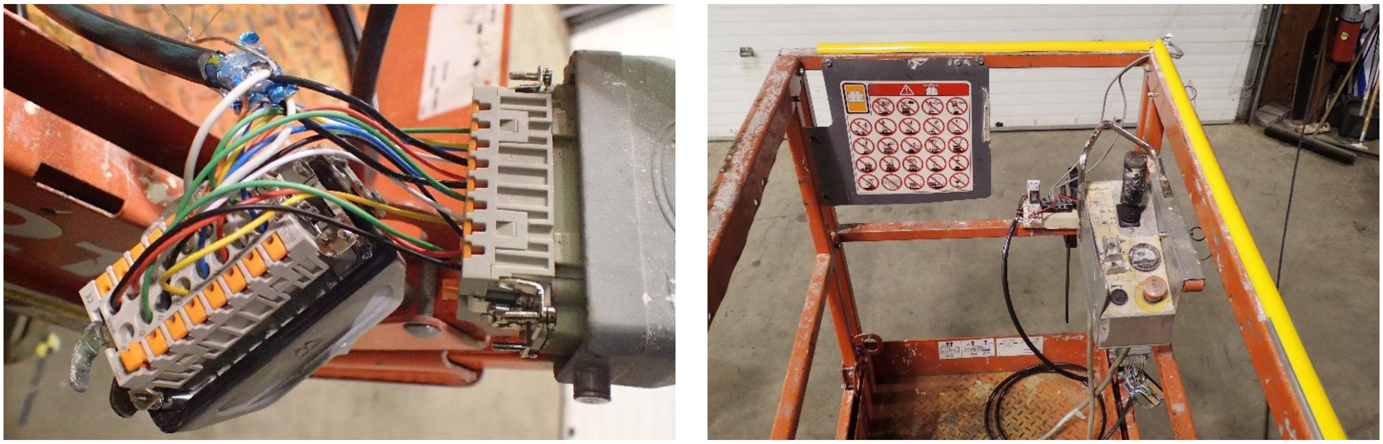

Figure 12
Exemplar test setup including left and upper guardrail sensors and circuitry to cut off power.
The alternative solution allowed for a plug-and-play connector along with a force sensor signaling to a basic circuit that stopped the upward movement of the lift when it came into contact with a hazard.

Copyright © National Academy of Forensic Engineers (NAFE). Redistribution or resale is illegal.
Originally published in the Journal of the NAFE volume indicated on the cover page.

means to avoid losing valuable information. While this case study focused on loose wiring connections, the same principles can be applied to other types of failures, such as blockages in hoses, stuck/seized valves, and other conditions where disassembling the part would cause the investigator to disturb the as-found condition and lose potentially critical information.

Acknowledgements

The authors would like to acknowledge Jeremy Robbins of ARCCA with assistance in testing the exemplar scissor lift and assembling the anti-SIO safety device.

References

1. K. U. Schmitt, P. F. Niederer, and F. Walz, Trauma Biomechanics: Introduction to Accidental Injury. Berlin: Springer, 2004.
2. W. C. Whiting and R. F. Zernicke, Biomechanics of Musculoskeletal Injury. Leeds: Human Kinetics, 2008.
3. E. A. Luce, T. D. Tubb, and A. M. Moore, “Review of 1,000 major facial fractures and associated injuries,” Plastic and Reconstructive Surgery, vol. 63, no. 1, pp. 26–30, 1979. doi:10.1097/00006534-197901000-00005.
4. C. St. Hilaire et al., “Facial fractures and associated injuries in high- versus low-energy trauma: All are not created equal,” Maxillofacial Plastic and Reconstructive Surgery, vol. 42, no. 1, 2020. doi:10.1186/s40902-020-00264-5.
5. N. Yoganandan and F. A. Pintar, “Biomechanics of temporo-parietal skull fracture,” Clinical Biomechanics, vol. 19, no. 3, pp. 225–239, 2004. doi:10.1016/j.clinbiomech.2003.12.014
6. J. Cormier et al., “The tolerance of the nasal bone to blunt impact,” Annals of advances in automotive medicine/Annual Scientific Conference, vol. 54, pp. 3-14, 2010.
7. D. Raymond, C. Van Ee, G. Crawford, and C. Bir, “Tolerance of the skull to Blunt ballistic temporo-parietal impact,” Journal of Biomechanics, vol. 42, no. 15, pp. 2479–2485, 2009. doi:10.1016/j.jbiomech.2009.07.018.
8. T. L. Jackson, “Effect of American football helmet chin strap placement on measures of blunt impact,” Honors Theses, University of Southern Mississippi, 2018. [Online]. Available: https://aquila.usm.edu/honors_theses/606.
9. M. Vander Vorst, J. Stuhmiller, K. Ho, N. Yoganandan, and F. Pintar, “Statistically and biomechanically based criterion for impact-induced skull fracture,” Annual Proceedings Association for the Advancement of Automotive Medicine, vol. 47, pp. 363 – 381, 2003.
10. C. Chang, Y. Chen, S. Noordhoff, and C. Chang, “Maxillary involvement in central craniofacial fractures with associated head injuries,” The Journal of Trauma: Injury, Infection, and Critical Care, vol. 37, no. 5, pp. 807–811, 1994. doi:10.1097/00005373-199411000-00017.
11. B. Pappachan and M. Alexander, “Biomechanics of cranio-maxillofacial trauma,” Journal of Maxillofacial and Oral Surgery, vol. 11, no. 2, pp. 224–230, 2012. doi:10.1007/s12663-011-0289-7.
12. R. R. Crowell et al., “Cervical injuries under flexion and compression loading,” Journal of Spinal Disorders, vol. 6, no. 2, 1993. doi:10.1097/00002517-199304000-00013.
13. D. J. Maiman et al., “Compression injuries of the cervical spine,” Neurosurgery, vol. 13, no. 3, 1983. doi:10.1097/00006123-198309000-00007
14. A.A. White III, M. M. Panjabi, Clinical Biomechanics of the Spine, Philadelphia: J.B. Lippincott Company, 1990.
15. F. A. Pintar et al., “Dynamic characteristics of the human cervical spine”, Proceedings Stapp Car Crash Conference, vol. 39, pp. 195–202, 1995.
16. “IPAF Global Safety Report” International Powered Access Federation, 2022. [Online]. Available: https://www.ipaf.org/en-us/resource-library/ipaf-global-safety-report.
17. C. Leah, D. Riley, A. Jones, “Mobile elevated work platform (MEWP) incident analysis”, Research Report RR961, Health and Safety Laboratory for the Health and Safety Executive, United Kingdom, 2013.

Copyright © National Academy of Forensic Engineers (NAFE). Redistribution or resale is illegal.
Originally published in the Journal of the NAFE volume indicated on the cover page.

18. "SAIA - Secretariat for the A92 Series of Standards," SAIA, https://www.saiaonline.org/a92 (accessed Jan. 27, 2023).

19. A. Jones, S. Bates, "Mobile elevated work platforms", Research Report RR960, Health and Safety Laboratory for the Health and Safety Executive, United Kingdom, 2013.

20. Self-Propelled Elevating Work Platforms, ANSI/SAIA A92.6-2006, 2006.

21. Safety Requirements for Industrial Scissor Lifts, ANSI MH-1:2012, 2012.

22. Mobile Elevating Work Platforms – Design, Calculations, Safety Requirements and Test Methods, ISO 16368:2010, May 2010.

23. Design, Calculations, Safety Requirements and Test Methods for Mobile Elevating Work Platforms (MEWPs), ANSI/SAIA 92.20-2018, 2018.

24. "Hierarchy of controls," Centers for Disease Control and Prevention, https://www.cdc.gov/niosh/topics/hierarchy/default.html (accessed Aug. 11, 2022).

25. Guidelines for Addressing Occupational Hazards and Risks in Design and Redesign Processes, ANSI/ASSE Z590.3-2011, R2016.

26. F. A. Manuele, On the Practice of Safety. Hoboken, NJ: John Wiley & Sons Inc., 2013.

27. R. L. Brauer, Safety and Health for Engineers. Hoboken, NJ: Wiley, 2016.