CHAPTER 25

Ergonomic Hazards and Controls for Elevating Devices in Construction

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CONTENTS

The construction industry sector has long been recognized for its high number and rates of nonfatal and fatal injuries. Data for 2007 from the survey of occupational injuries and illnesses, an occupational injury and illness database maintained by the U.S. Bureau of Labor Statistics (BLS), indicate that workers in the construction sector experienced the fourth highest number of injuries and illnesses with days away from work (135,350) and the highest rate of injuries and illnesses with days away from work (190.3 per 10,000 full-time workers) [1,2]. Falls accounted for 24% of the nonfatal injuries, while contact with objects and equipment and overexertion were associated with another 52% of the injuries in this sector. Preliminary fatality data for 2008 from the BLS, the Census of Fatal Occupational Injuries (CFOI), indicate that workers in the construction industry sector experienced the highest number of fatalities (969) and the fourth highest fatality rate (9.6 per 100,000 full-time equivalent workers) [3]. Nonetheless, the fatality rate in construction was still almost three times the overall fatality rate for all workers (3.6 per 100,000 full-time equivalent workers). Falls led to the largest number of fatalities within the construction industry sector (34%). Another 32% of the fatalities were due to contact with objects and equipment and highway incidents [4].

This chapter discusses the aforementioned injuries and their prevention for elevating devices at construction work sites. These devices—including aerial lifts, stilts, scaffolds, and mast work platforms—are widely used, and research further indicates increasing trends for their application in the construction industry. This chapter also identifies hazards and presents previous and current findings, focusing on four research studies conducted by National Institute for Occupational Safety and Health (NIOSH) for elevating devices. Because of the dynamic nature of construction tasks, safety professionals and ergonomists hesitate to evaluate and identify single risk factors associated with the use of elevating devices in the construction industry and prefer to consider the systematic risk involved with the use of this equipment [5]. This chapter promotes the recognition of these hazards and the use of the most advanced and current technologies for injury prevention and control, exposure simulation, and hazard evaluation—for example, computer simulation and force data collection through sensor technologies—to evaluate and control these hazards for this workforce.

25.1 AERIAL LIFTS

25.1.1 Injury Surveillance and Current State of Knowledge

Elevating devices are widely used for elevating workers, tools, and materials in various industries that require workers to work above ground level. The North American Industry Classification System does not have separate categories for elevating devices or aerial lifts but considers scaffold erection and dismantling, manufacturing, wholesaling, and rental as industrial classifications. Only scaffold erection and dismantling are considered specialty trade designations.

Because elevating devices are primarily and widely used in construction, many trade specialties (e.g., carpenters) and laborers in construction are involved with tasks related to the erection, dismantling, use, and deployment of elevating equipment. Because of these factors, a single industrial classification for elevating equipment does not exist, and research focused on fall prevention related to elevating equipment encompasses construction and related industries, rather than focusing on scaffolding or elevating equipment designations.

Aerial lifts constitute a common form of elevating equipment used in construction and related industries; this equipment is used for general construction tasks, masonry work, and related tasks. The applicable safety standard promulgated by the American National Standards Institute (ANSI) for safe use of this equipment is ANSI A92.2-1969. Because of the high degree of innovation and technical development in elevating devices at present, additional standards are under development.

The fall hazards associated with work on aerial lifts are well recognized within the scaffolding industry [6–9]. Surveillance reveals the increasing risk of severe injury and death associated with the adoption of this equipment in construction, telecommunications, and other industries. In addition, expert opinion within the user and manufacturing communities indicates great concern over the potential exposures involved with increasing vertical extension of newly developed equipment and the increased adoption of this equipment for nontraditional uses [10–13]. Industrial reports on aerial lifts indicate increasing use in various industries, including construction (7,583,000 employment), landscape services (705,900 employment), telecommunications (705,800 employment), warehousing and storage (595,700 employment), electric power transmission and generation (162,300 employment), and other industries [14].

There are two types of aerial lifts, mainly differing by design characteristics: boom lifts (articulating or telescopic), which support a work platform at the end of an extensible boom, or scissor lifts, which support a work platform at the top of an extensible, linked and folding support assembly (Figure 25.1). Aerial lifts can also be classified by their power sources,

Articulating boom lift telescopic boom lift

Scissor lift

FIGURE 25.1 Types of aerial lifts. (Reprinted with permission of Skyjack Inc., Guelph, Ontario, Canada.)

tire types, maximum elevated heights, wheelbases, and load capacities [6]. Tipovers of scissor lifts mostly occur while the lift is elevated over 15 ft, especially while the lift is moving [8]. Scissor lifts are available that can reach between 20 and 75 ft. At such heights, the stability of the lift and safety of the worker are of great concern. Scissor lifts that are designed to fit through doorways can have wheelbases as narrow as 17 in., decreasing their stability. The use of rollout platform extensions on the scissor lift platform also decreases stability since the extension extends beyond the wheelbase, affecting the center of gravity. Workers performing pulling or pushing activities while the platform is elevated can exert horizontal forces that the scissor lift is not designed to withstand [15]. This is a concern, especially when the platforms are extended horizontally beyond the base of the scissor lift [15].

NIOSH, in collaboration with the National Safety Council and the Center for Construction Research and Training, conducted a surveillance study of aerial platform falls/collapses/tipovers across all industry classifications. Three databases were used to analyze aerial lift fall incidents: BLS CFOI data (1992–2003), Occupational Safety and Health Administration (OSHA) incident investigation records (1990–2003), and NIOSH Fatality Assessment and Control Evaluation (FACE) reports (1985–2002). Pan et al.'s [9] review of these surveillance systems 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 injury. These height factors accounted for 72% of the scissor lift cases in CFOI; 83% of cases investigated by OSHA/FACE involved falls/collapses/tipovers within the height categories of 10–19 and 20–29 ft [9]. In CFOI data, 45% of boom lift fatalities and 72% of scissor lift fatalities occurred in the construction industry; in OSHA/FACE data, 43% of boom lift fatalities and 74% of scissor lift fatalities occurred in construction (Figures 25.2 and 25.3). Based on the findings of this study [9] and the marketing lift sales information, NIOSH developed an aerial lift project focusing on a laboratory study of a commercially available, and the most popular, 19-ft electric scissor lift.

Another finding of interest from this study [9] relates to the human operator's stability/balance and related workstation design issues for aerial lifts. Workers typically position the

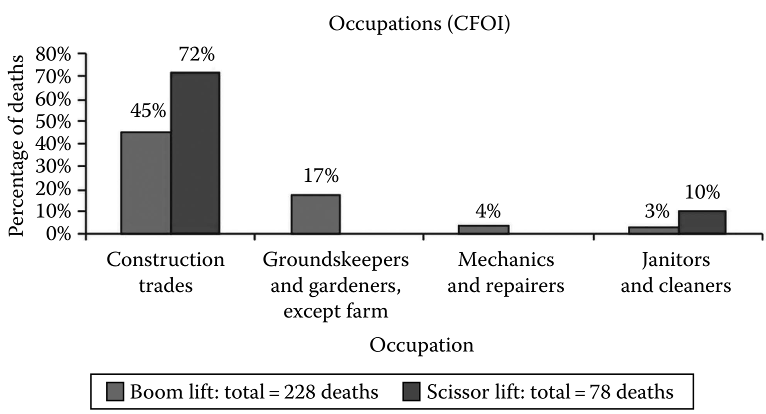


FIGURE 25.2 Occupations in aerial lift deaths, 1992–2003. (U.S. Bureau of Labor Statistics CFOI Research File.)

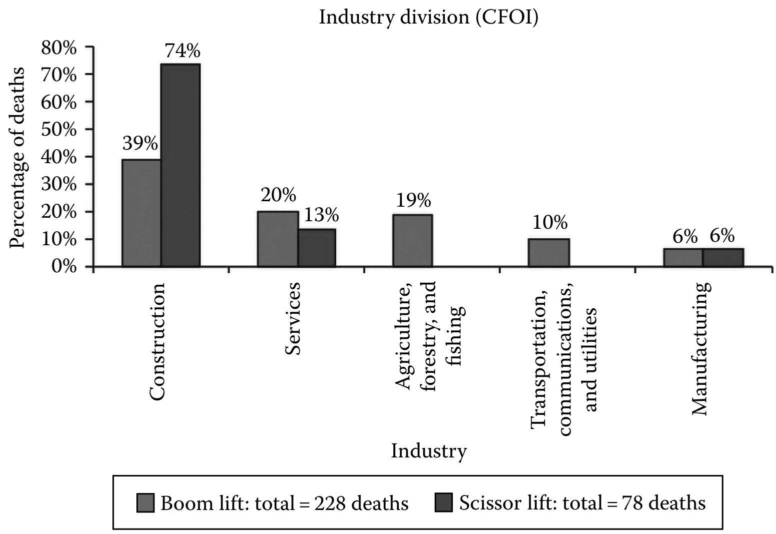


FIGURE 25.3 Industry divisions in aerial lift deaths (OSHA/FACE).

aerial lift platform directly adjacent to the work location to perform assigned work tasks at positions that are convenient and ergonomically adjacent to work, as opposed to positioning the platform beneath a work location and working overhead [16]. Work positions above shoulder height—especially for an increasingly aging workforce with musculoskeletal limitations—impose musculoskeletal demands that make it difficult to perform work while assuming this posture. Frequently, this workforce has additional limitations—for example, reduced vision requiring corrective bifocal lenses—which make overhead work more problematic when work tasks require changing visual focus. Common tasks for elevated workers frequently involve work practices that impose potentially destabilizing forces on the human body—for example, forces from excessive or awkward motions (jerking or forcing tools, excessive pressures on tools, over reaching, leaning over the edge or guardrail, and standing on the top rails or mid rails). These work practices and postural positions place the operator at increased risk of falls from the platform to a lower level and may additionally introduce overexertion hazards. Therefore, worker-preferred task locations/heights and work practices are extremely important to consider in the design of lifts. Also, since the platform/bucket constitutes a confined work space and operators need to perform tasks using awkward working postures, the use of fall protection systems (e.g., harness and lanyard) will generate significant issues in ergonomic design and health-impact considerations, especially during fall arrest situations [17–19]. When these awkward postural issues are combined with the application of significant task-related side forces in the horizontal direction, the potential for hazards associated with ejection and tripping incidents, as well as overexertion, significantly increases [5]. Improvement in control measures addressing operators' whole-body postural stability within the platform/bucket will be critical to prevent such fall/trip/ejection incidents [20].

The use of fall protection equipment on aerial lifts is generally recognized by aerial lift safety experts as one of the most effective safety control practices to reduce fall-risk exposure for operators [6]. However, results from this study [9] indicated that, for a significant percentage (82% for OSHA/FACE data) of fall-from-elevation incidents, safety controls did not protect workers because existing fall protection systems (e.g., guard rails, chains, gates/doors, belts, harnesses with or without lanyards) were not in use at the time of the incident. Only 4 out of 13 scissor lift injury/fatality cases from OSHA/FACE reports showed the use of additional personal fall protection systems (i.e., belts and harnesses). Findings from a field observation study found significant nonusage of existing fall protection systems and indicated that the majority of boom lift operators (16 out of 18) conducted tasks without using personal fall protection systems [21]. This finding supports data analysis of this study [9], which found 45% (18 of 39) of boom-lift-related fatalities recorded in OSHA/FACE reports involved nonuse of fall protection systems. This finding is also extremely significant, since OSHA regulations for working on boom lifts [1926.453(b)(2)(v)] require the use of personal fall protection systems, with the further requirement that the lanyard must be attached to the boom or basket [22]. However, no body of scientific knowledge establishes the efficacy of personal fall protection systems for use on scissor lifts, and the use of harnesses and lanyards is not required (OSHA-regulated scissor lifts are regulated as mobile scaffolds). Guardrails on the platforms are sufficient to meet the OSHA requirement [1926.451(g)(4)] for fall injury prevention for scissor lifts, and additional requirements for using personal fall protection systems currently are still under consideration by industry and standard committees (ANSI A92.6 and ANSI A10.29). The lack of universal standards regarding best practices for the use of fall protection standards represents a serious concern for the aerial lift industry. It should be noted that fall-arrest and fall-protection devices perform no function in the event of a tipover, and fall-protection devices do not constitute hazard-reduction devices in the event that the elevating platform tips over and propels the operator to the ground.

25.1.2 NIOSH Research Findings

NIOSH has conducted research into various conditions of exposure related to the use of aerial lifts. Constraints on this research chiefly are found in conducting research that puts human subjects at risk of fall injury. NIOSH researchers have responded to this risk by conducting a significant part of their research in the form of computer simulation and modeling of various hazardous exposures. Preliminary computer model development was conducted using input from the static test results of the center-of-gravity and horizontal-stability tests from the standard promulgated by ANSI A92.6 (2006) [23]. Additional human subject tests were conducted to collect side force information for the computer model [15]. The center-of-gravity (Figure 25.4) and horizontal-stability tests (Figure 25.5) generated data for developing a computer simulation model for the SkyJack model 3219 with manufacturer's lift part mass/geometric information using the SolidWorks™ software program. The computer model was generated based on data from automated dynamic analysis of mechanical systems software (*ADAMS*™ 2005, MSC Software Corporation, Santa Ana, CA). In order to calculate the center of gravity, four force plates (Bertec Corporation, Columbus, OH) were placed under the wheels of the scissor lift (Figure 25.4), and the lift was tilted using hand pump jacks and jack stands (Figure 25.4). Platform height

FIGURE 25.4 Center of gravity tests.

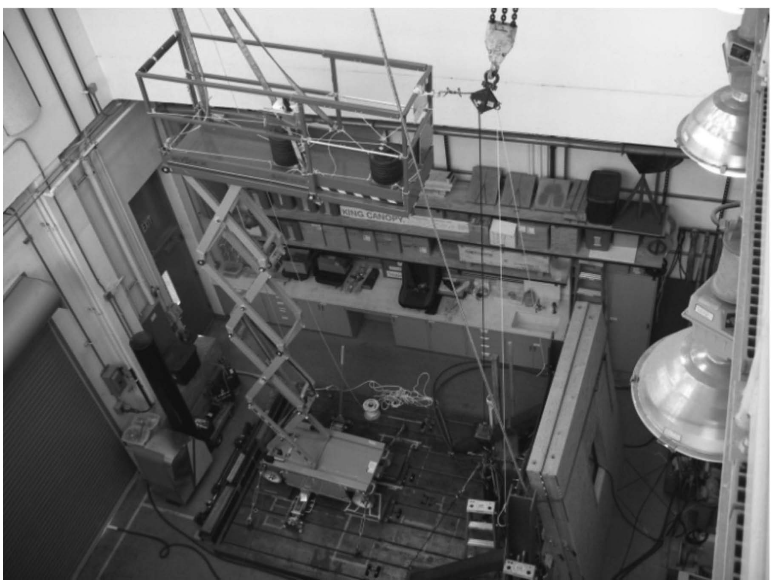


FIGURE 25.5 Horizontal stability tests.

was recorded using a cable-extension transducer (Model PT5A-250-N34-UP-500-C25, Celesco Transducer Products, Inc., Chatsworth, CA). A horizontal actuator (Series 247, MTS Systems Corporation, Eden Prairie, MN) was used to apply horizontal loads through a cable-and-sheave arrangement as shown in Figure 25.5. The sheave was hung from a 5-ton-capacity overhead crane. Load readings were taken via a load cell (Model 661.20e-02,

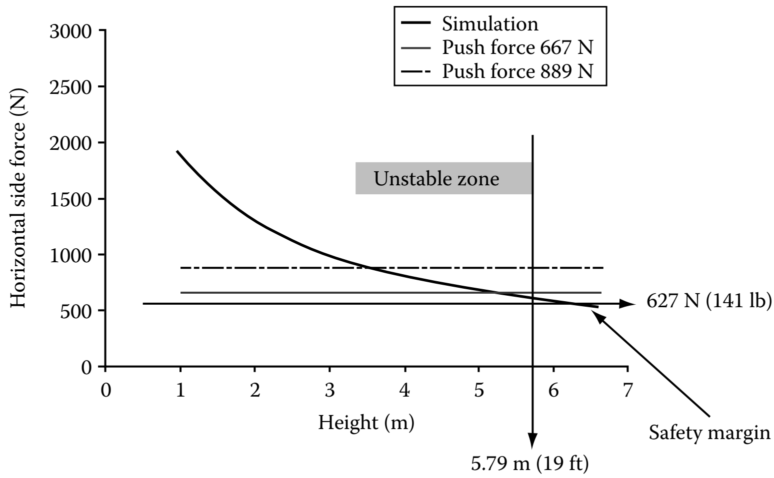


FIGURE 25.6 Stability prediction from the horizontal side forces and elevated heights or SkyJack Model 3219 scissor lift.

MTS Systems Corporation, Eden Prairie, MN) integrated with the hydraulic actuator. The modeling predictions agreed well with the experimental data with an error less than 1% for the whole range of the lift height variation in three orthogonal directions.

The NIOSH study team completed data collection for operations within the scissor lift platform. Results indicate that the scissor lift could lose static equilibrium when operated at an extended height above 5.49 m with the application of a horizontal force of 627 N, which is the maximum push force measured in the experiment simulating working conditions on the platform [15] (Figure 25.6). The study indicates that the scissor lift may tip over in the horizontal direction during normal operations with the excessive applied forces. If the applied forces are between 627 and 889 N, the scissor lift can be safely extended to a height between 5.49 and 3.49 m respectively [24].

25.1.3 Curb and Pothole Test Results

To quantify the fundamental dynamic characteristics of the lift, accelerations in three orthogonal directions on the platform and base were measured at the right-side base frame and main-platform frame, as shown in Figure 25.7. Two in-house packaged triaxial accelerometers (Model KXM52-1050, Kionix Inc., Ithaca, NY) were used for the measurement. A 20-cm-high granite slab of 956 kg was positioned tightly against a concrete curb (50 mm) at the back of the slab. As specified in the standards, a depression of 600 × 600 mm with a depth of 100 mm was constructed on the runway. In separate tests, each leading wheel was driven into the depression at its full speed for each given elevated height. The drive control was maintained at maximum until the leading wheel was driven into or over the depression. A data acquisition box was installed securely within the platform.

For the curb tests, the wheel of the lift did not climb up the curb, and tipover did not occur. A large phase difference between the accelerations on the base and platform suggests that there is some flexibility in the scissor lift structure. However, the speed on the base before the impact was practically identical to that on the platform. The extension of the platform

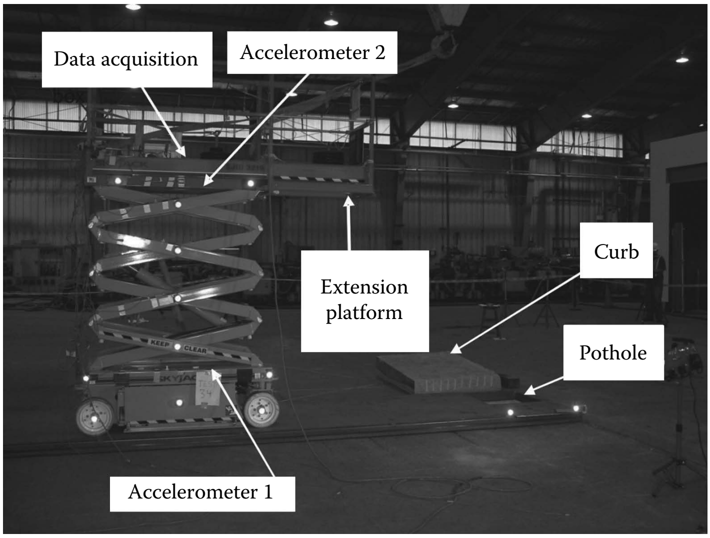


FIGURE 25.7 Two accelerometer locations, the curb test setup, and the pothole test setup.

reduced the bounce frequency ($F = 451$, $p < 0.001$). The impact angle affected the pitch and bounce resonance frequencies ($F \geq 13.5$, $p \leq 0.002$). The travel direction did not significantly influence the pitch and rolling resonance frequencies ($F \leq 1.6$, $p \geq 0.224$), but it marginally affected the bounce frequency ($F = 6.0$, $p = 0.026$). The maximum peak accelerations in the 90° impact test were larger than those in the 30° impact test ($F \geq 12.1$, $p \leq 0.001$). Because of the increased flexibility and reduced speed in the fully elevated test, the maximum peak accelerations in the full-height test were much less than those in the low-height test ($F \geq 450.3$, $p < 0.001$). The maximum rigid body roll angle was 2.3°, which was lower than the tipover angle (9.0°) calculated from the rationale for the theoretical criterion adopted in ISO 16368 [25,26]. The resonance frequencies of the lift at full height in the depression tests were also generally lower than those observed in the curb impact test ($p < 0.001$). This is because the lift base tilted when one wheel dropped into the depression such that the gaps between the wheels and ground were larger than those in the curb test. A very common scenario leading to a tipover event occurs as a general function of this situation: Lift stability is compromised as a result of a wheel entering a depression, causing the supporting plane of the lift base to move off a horizontal plane. Destabilization can occur as a result of this "tilted" plane, which translates into a greater degree of deflection for a platform at height.

The highest acceleration was found in the high-speed curb impact test. Therefore, the acceleration in a curb impact event is of major concern for the workers' stability within the platform. Appropriate fall protection systems should be used to prevent ejections. Another potential concern is that a tipover may occur while the scissor lift runs over a depression without a pothole guard [26].

25.1.4 Computer Simulation and Modeling Results

The computer simulation model (Figure 25.8) was developed based on experimental data obtained in standardized curb impact and pothole depression tests. These tests investigated

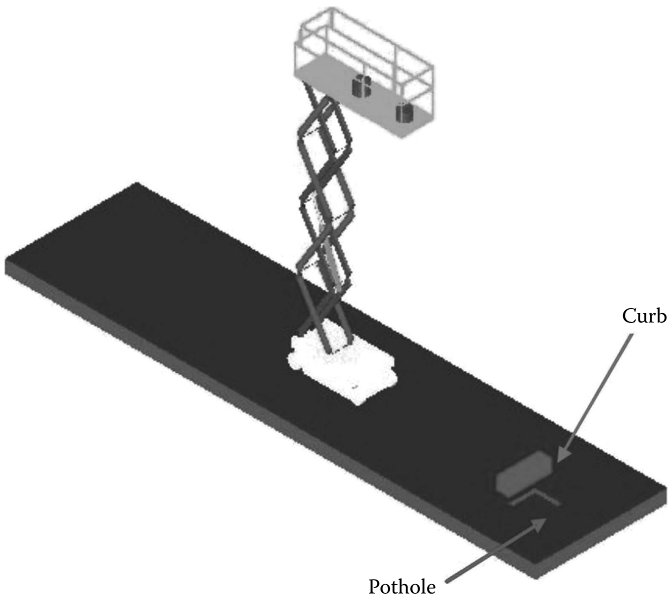


FIGURE 25.8 ADAMS model of the scissor lift with its full load and elevated at its full height (the curb block is de-actuated when the pothole test is simulated).

the effects of the lift structural flexibility on the tipover thresholds of road surface slope, curb impact speed, and pothole guardrail height. The mass distribution of the model was validated using lift center of gravity measured at four elevated heights. The connection stiffness and damping parameters of the model were estimated based on the experimental data obtained from an impact test and a depression test of the scissor lift. The model was also validated and refined using the time histories of the lift dynamic responses measured in these physical experiments [27]. The modeling results indicate that decreasing the stiffness of the scissor lift generally reduces both static and dynamic stabilities of the lift. This study showed that lift instability could be achieved by increasing the flexibility of the scissor-lift ground system, which includes severe wear (e.g., aging lifts) and decoupling of structural joints, damage to the joints resulting in decoupling of rigid frame members, and the use of the lift on deformable or uneven surfaces (e.g., soft ground). This information will be used to determine the future tasks associated with refining this multibody model simulation and may contribute to more finite element analyses and better evaluation techniques.

Simulated operator information was also incorporated into the completed scissor lift model using 2009 LifeMOD Biomechanics Human Modeler (LifeModeler Inc., San Clemente, CA), which is a plug-in to ADAMS. Using this joint human/lift model, various hazardous working conditions were simulated (i.e., pothole, curb, tilting/slope, gusting wind, and fall-arrest loading using a fall-protection harness/lanyard) (Figures 25.9 through 25.12). These hazardous working conditions cannot be tested on a human subject, even in well-controlled laboratory events; however, the simulation model of the lift/operator can appropriately assess the contributions of each individual hazard to the incidents or the combined effects from these hazards. In other words, outcomes of this study component can provide users with an effective tool for better incident investigations.

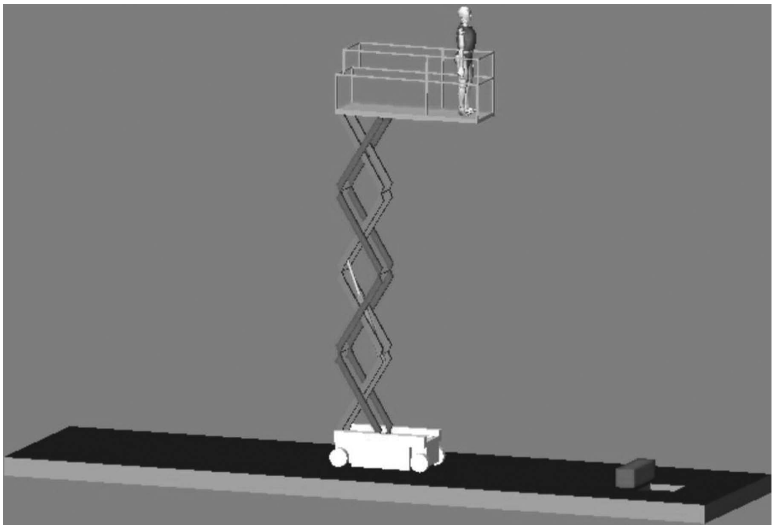


FIGURE 25.9 ADAMS/LifeMOD model of the scissor lift with an operator.

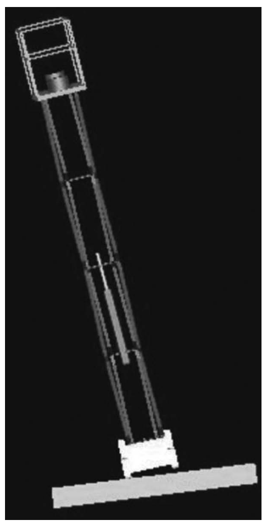


FIGURE 25.10 ADAMS simulation of tilting and slope conditions.

For example, a simulation was to determine the lateral tipover threshold for an applied wind load. For this simulation, the scissor lift was positioned on a level surface and no other external forces were applied. Based on ISO 16368 Section 5.2.3.3, the initial wind speed was assumed to be 12.5 m/s. The corresponding wind forces were calculated for the base, lifting mechanism, platform, guardrail assembly, and operator. Table 25.1 shows the wind forces calculated for various wind speeds.

It was assumed that an operator (113 kg) was on the main platform and another worker (113 kg) was on the extension platform. The wind forces were then applied horizontally to the center of each component. The scissor lift was raised to a maximum platform height of 5.8 m. At a wind speed of 12.5 m/s, the scissor lift did not tip over. The wind speed was then

FIGURE 25.11 ADAMS simulation of gusting wind conditions.

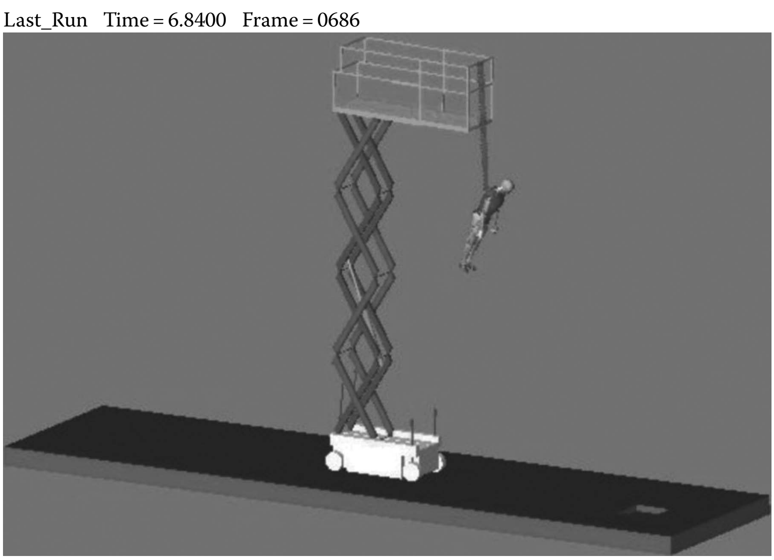


FIGURE 25.12 ADAMS/LifeMOD simulation of drop test in which a manikin is dropped from a fully elevated scissor lift to test lift stability. *Note*: Physical tests were done on different lift platform locations at NIOSH laboratories, not just the recommended anchorage points. Top rail is commonly used, but not recommended. Lift remained stable even under adverse (extreme) test conditions.

TABLE 25.1 Wind Forces for Components of the Scissor Lift

	Wind Forces (N)—Adjusted for 1.1 Multiplication Factor										
Wind Speed (m/s)	**Wind Pressure**	**Base**	**Lift Frame Member**	**Platform**	**Guard-rail 1**	**Guard-rail 2**	**Guard-rail 3**	**Guard-rail 4**	**Guard-rail 5**	**Guard-rail 6**	**Operator**
12	92.16	109.72	19.87	22.24	2.05	1.46	3.51	3.51	8.20	8.65	70.96
12.5	100	119.05	21.56	24.14	2.23	1.58	3.81	3.81	8.90	9.39	77.00
14	125.44	149.34	27.04	30.28	2.79	1.98	4.78	4.78	11.17	11.78	96.59
16	163.84	195.05	35.32	39.54	3.65	2.59	6.24	6.24	14.58	15.38	126.16
18	207.36	246.86	44.71	50.05	4.61	3.28	7.90	7.90	18.46	19.47	159.67
19	231.04	275.05	49.81	55.76	5.14	3.65	8.80	8.80	20.57	21.70	177.90
20	256	304.77	55.19	61.79	5.70	4.05	9.75	9.75	22.79	24.04	197.12

increased until tipover occurred. Tipover occurred at a wind speed of 20 m/s (44.7 mph) (Figure 25.11). Also, the wind speed threshold increased to 23 m/s for one person (113 kg) on the main platform.

25.1.5 Drop Test Results (Dead Weight Drop) [28]

The object of this study was to measure structural and dynamic stability of aerial lift platforms under dynamic load conditions, through the application of weights dropped from the platform surface. A load cell (3000 lb S-type, Interface Inc., Scottsdale, AZ) was used to record the maximum arrest force, a string potentiometer (250 in., Model PT5D, Celesco Transducer Products, Inc., Chatsworth, CA) recorded positioning of the drop test fixture, an electromagnet (700 lb, Model SE-35352, Magnetic Products, Inc., Highland, MI) activated the drop test fixture, and data were logged onto a laptop computer equipped with a data acquisition card (Model DAQCard-6036E, National Instruments Corporation, Austin, TX) running the LabVIEW data acquisition application (National Instruments Corporation, Austin, TX).

Two fall conditions were tested: 6-foot falls and 11-foot falls. The latter represented a common misuse scenario, in which operators stand on the midrail. Fall arrest loads of 2400 lb were selected to exceed the ANSI Z359.1 standard, which calls for loads of 1800 lb. Various anchorage point locations were chosen in the platform. To determine the free-fall height for these tests, the lanyard attachment point to a fall arrest harness was assumed at approximately chest height for a 95th percentile worker, 53.7 in. (1.364 m) (MIL-STD-1472D, 1989). Total fall height was 139 in. (3.53 m) when anchored to the midrail and 122 in. (3.10 m) when anchored to the toprail. The scissor lift maintained structural and dynamic stability for all drop tests under various test conditions (Figure 25.13).

25.1.6 Drop Test Results (Manikin Drop) [29]

This study measured drop forces on an anthropomorphic manikin (ADAM™, Veridian, Dayton, OH) (Figure 25.14) under loads mediated by four safety harnesses. Acceleration forces were measured by embedded triaxial accelerometers (Kionix, Inc., Ithaca, NY), which were positioned at three locations—head, middle of spine, and torso. A load cell

FIGURE 25.13 Lift tilting angles setup during the drop tests (1.5° on the left and 3.5° on the right).

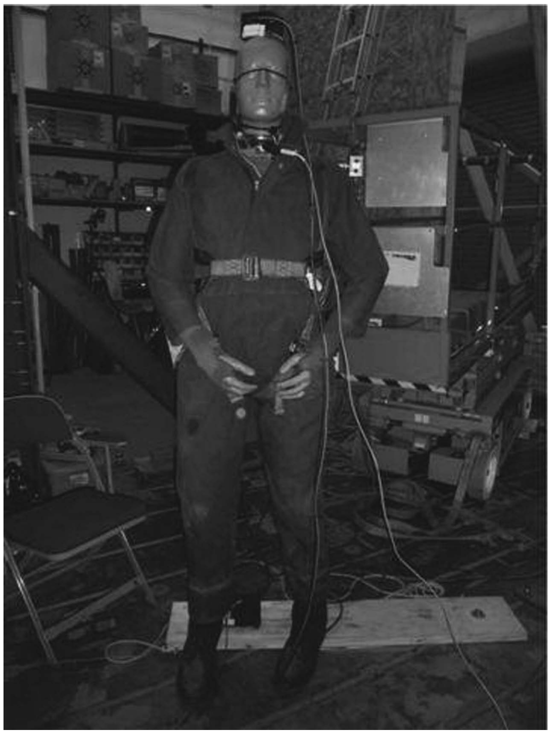


FIGURE 25.14 The advanced dynamic anthropomorphic manikin (ADAM) system.

(Model SSM-S, Series 1000, Interface, Inc., Scottsdale, AZ) was placed in line with the safety lanyard to measure the arrest force; lanyards were secured at an anchorage point at the bottom of the scissor lift platform. A high-speed camera (Phantom v4.3, Vision Research, Inc., Wayne, NJ) was used to record the drop test. An electromagnet (700 lb, Model SE-35352, Magnetic Products, Inc., Highland, MI) secured and released the drop test fixture to the hook of a 5-ton overhead crane, and data were collected on a laptop computer equipped with a data acquisition card (Model DAQCard-6036E, National Instruments Corporation, Austin, TX) running a LabVIEW data acquisition application (National Instruments Corporation, Austin, TX). The ADAM was dropped three times from each of the 2 heights, 6 and 11 ft (see dead weight drop tests in the previous section).

During the deceleration phase of a fall, the personal fall arrest system (PFAS) absorbs the kinetic impact energy, thereby reducing the impact force on the human body. The kinetic energy dissipated during the fall impact is an important parameter that characterizes the dynamic performance of the PFAS. The impact kinetic energy was either not considered or not correctly estimated in the literature. In the current study, we developed a systematic approach to evaluate the energy dissipated in the energy absorbing lanyard (EAL) and in the human body during the fall impact. The kinematics of the human body and EAL during the impact was derived using the data of the time histories of the arrest force, which was measured experimentally. We applied the proposed method to analyze the experimental data of a 6-ft drop test and an 11-ft drop test. The preliminary results indicate that the distribution of the kinetic energy in the EAL and the falling body depends on the intensity of the impact: The portion of the kinetic energy dissipated in the EAL for higher impact force is more than that for lower impact force [30].

25.1.7 Future Studies for Aerial Lifts

As stipulated in draft standard *A10.29* of the ANSI, workers may enter and exit an aerial platform at heights greater than 6 ft when the aerial platform surface is adjacent to the elevated surface. The standard further specifies that if the platform is adjacent to the elevated surface, there shall not be a vertical gap larger than 8 in. or a horizontal gap larger than 14 in. between the aerial lift platform and the adjacent surface. To date, there has been no published scientific justification on the manner in which the vertical and horizontal gaps were determined and how the distances between the lift platform and the adjacent surface may affect workers' postural stability and fall propensity. Additionally, there is a lack of quantitative data to demonstrate that potential risks may be associated with improper exiting and entering techniques, especially at these heights. The purpose of this ongoing study is to determine workers' postural stability under various conditions and methods of exiting and entering scissor lift platforms at elevations. In addition, partial results of this experiment—that is, maximum forces and moments resulting from exiting the scissor lift platform and on the positions of workers' centers of gravity—will provide information for the update and development of a computer simulation model for predicting the overall stability of aerial lifts. This would be considered in a long-term NIOSH aerial lift project.

25.2 STILTS

25.2.1 Background

Falls and overexertion are the leading causes of occupational traumatic injuries among construction workers in the United States [31]. In 2008, the construction industry reported an estimated 24,720 falls and 21,310 overexertion injuries involving days away from work, which accounted for approximately 21% and 18% of total injuries, respectively [32]. Among fall injuries, 63% of cases were falls to a lower level [32]. One specialty of the construction industry—drywall installers—is also traditionally plagued with high frequencies of overexertion and fall injuries. In a study of injury characteristics of drywall installers, falls were found to be the second leading cause of injury (overexertion was the leading cause) accounting for 32% of total injuries [33,34]. In a workers' compensation study of North Carolina residential construction workers, drywall installers were among the specialties with the highest rate for falls from a different level resulting in medical costs or lost work time [35]. The analyses of administrative data revealed that the most common mechanisms of injury for drywall installers involved being struck by objects, overexertion, and falls [36]. Similarly, in a large cohort study of union carpenters and drywall installers, the major causes of injury were being struck by or against something, manual materials handling, and falls [37]. This high frequency of overexertion and fall injuries of drywall installers is likely due to the main job demands for this workforce—constant handling of heavy and bulky drywall sheets and working at elevations to perform tasks close to ceilings or on the upper half of walls.

FIGURE 25.15 Construction stilts with four reflective markers attached to each side for motion study.

Falls from heights may occur from a variety of surfaces for carpenters and drywall installers [37]. One unique item of elevating equipment that is commonly used for drywall tasks is stilts (Figure 25.15). In a study of Washington State Workers' compensation data for the period of 1996–2001, stilts-related injuries resulted in a median of 73 lost workdays compared to 24 lost workdays for all claims combined [38]. Like scaffolds, stilts are an elevating tool that raises workers above the ground level to allow them to perform tasks on the ceiling or upper half of a wall. Stilts are composed of more than 50 small parts, providing mobility for workers to move from one location to another without the burden of erecting scaffolds or repositioning ladders. A pair of common commercially available construction stilts weighs about 7.26 kg (16 lb) and the height is typically adjustable from 0.6 to 1.02 m (24–40 in.). When wearing stilts, a shoe plate is strapped onto the bottom of the workers' shoes with a strut tube running up the side of the leg and strapped right below the knee. Two lower strut tubes connect the shoe plate with a nylon floor plate. The lower tubes are spring loaded to provide forward and rearward stilt-walking actions (Figure 25.15). The construction activities commonly performed by workers on stilts include drywall finishing, taping, and sanding. Stilts can also be used for interior tasks such as painting, plastering, insulation installation, acoustical ceiling installation, and any other light-duty building maintenance.

Earlier studies addressing safety and health issues of drywall installation have focused on asbestos, dust, or silica exposure from drywall sanding [39–42]. A limited number of studies have been conducted to examine the overexertion and fall injury mechanisms that may be associated with the use of stilts. The potential hazards associated with stilts in construction have been well recognized nationally and internationally. The state of California, New York City, the provinces of Ontario, Canada, and Victoria, Australia, do not recommend, and/or have established legislation against, the use of stilts in construction as a preventive measure against occupational injuries. Several interested parties have made recommendations regarding the use of stilts; for example, one of the training guidelines of the International Union of Painters and Allied Trades recommend the maximum safe height for stilts be limited to 24 in. for painter apprentice training [43]. However, most of the guidelines and regulations were established based on experiences and perceptions of safe operating parameters. No quantitative and objective data demonstrated the injury mechanism associated with stilts until NIOSH embarked on a series of laboratory studies and computer simulations [44–47].

25.2.2 Musculoskeletal Injuries Associated with Stilts

Stilts add excessive weight to the mass moments of inertia to the lower limbs, requiring the stilt users to apply more efforts during walking. Consequently, workers may require excessive forces in their lower limbs when walking on stilts, which could contribute to cumulative trauma musculoskeletal disorders in the lower limbs for construction workers [48]. Increased musculoskeletal forces can increase the risk of injuries to tendon and muscle tissue [49–51], while increased joint loading converts to excessive contact pressure in articular cartilage. Numerous clinical studies indicated that excessive nontraumatic loading pressure on articular cartilage is the main cause of the initiation and development of osteoarthritis in old age [52–54]. The etiology of overexertion injuries can include the contribution of slip and fall injuries to tissue damage, leading to subsequent overexertion injury to soft body tissues. The mutual interaction of overexertion and slip-and-fall injury events in inducing further injury has been extensively reported [55–57].

25.2.2.1 Lower Extremity Joint Forces

Despite the need for further research articulated by Schneider and Susie [58], who hypothesized that the use of stilts may place workers at increased risk for knee injuries, the musculoskeletal loadings imposed on workers during stilts walking were not investigated until two stilt-walking models were developed by researchers at NIOSH [44,47]. This research was based on the emerging scientific techniques of multibody system dynamic modeling and simulation, which were increasingly found to be valuable techniques that could be used to evaluate joint loadings, fall scenarios, and gait-related issues. In 2002, using ADAMS and LifeMOD as a simulation platform, a human-stilts multibody system was first developed through a collaborative research project between NIOSH and Mechanical Dynamics Inc. Although computer simulations of human walking were well established [59–62], no published literature existed at that time on computer simulations of gait on stilts. After the stilt model was developed, it was further validated using kinematic and kinetic data of construction workers walking on stilts, collected using a motion-analysis system and force plates [44]. The validated model can be used to predict the mechanical stability, joint reaction forces, and trajectories of human center of mass for workers on stilts. Furthermore, it can be used to assess tripping hazards, struck by/against, sudden starts/stops, pivots while using stilts, and other traumatic injury scenarios.

The second stilt-walking model developed by NIOSH involved an inverse dynamic model to investigate musculoskeletal loadings in the lower limbs [47]. The model was established using musculoskeletal simulation software AnyBody (version 3.0, AnyBody Technology, Aalborg, Denmark) by modifying its existing three-dimensional gait model. Seventy muscles of the lower extremities, 35 muscles on each leg, were simulated to estimate the muscle forces. Eight muscle groups—soleus, gastrocnemius, gluteus maximus, vastii, rectus femoris, hamstring, posterior gluteus minimus/medius, and anterior gluteus minimus/medius—were compared for walking trials with or without stilts.

Results from the simulations revealed that the time-history patterns of the muscle forces for stilts walking were similar to those for no stilts. The use of stilts was found to induce force redistribution among the muscles. The forces in five out of eight muscle groups increased, whereas those in three muscle groups were decreased due to the stilts use. Injuries to the quadriceps group, which consists of the vastii and rectus femoris, are among the most common muscle injuries in sports [63] and also in some occupational activities. The loading levels increased substantially in the rectus femoris (180%) and slightly in vastus muscles (6%) due to the stilts use. The magnitudes of the muscle forces during stilts walking were lower than those that cause injuries [63]. However, the use of stilts may still have some effects on the muscle loading in the hamstring. The most common hamstring injuries occur after indirect trauma from excessive stretching or forceful contraction. Stilts may potentially cause an increase in loadings in five of eight major muscle groups in the lower extremities. The major increase was the force in the rectus femoris muscle, which was 1.8 times more than that of normal walking. The increase in muscle loadings during stilts walking may likely speed the muscle fatigue of the workers and increase the balance demand.

25.2.2.2 Lower Extremity Postures and Ranges of Motion

During normal walking, the hip flexes and extends, and the maximum extension is reached during the middle of the gait cycle with heel contact at 0% and the subsequent heel contact at 100%. The knee flexes in the loading response and the early part of the stance phase and fully extends before the initial foot contact of the next cycle. In comparison with normal gait, the hip and knee motion profiles are similar in curve shapes in general except for the smaller ranges of motion associated with gait on stilts (Figure 25.16). The ankle joint motions are quite different when walking on stilts. In particular, the angular changes of ankles during the weight acceptance and swing phases are largely reduced, with no plantar flexion observed (Figure 25.16). The ankles are dorsiflexed throughout the entire gait cycle to keep the feet on stilts and sustain the weight of stilts.

The major impact of stilts on joint motions is the restrictions of lower extremity joint movements during walking. Ankle, knee, and hip motions are restricted because of the 7.3 kg of extra weight of the stilts attached to the feet and the confinement of the straps around the feet and knees. The most restricted joint was the ankles, with 56% and 61% decrease in range of motion for 24 and 40 in. stilts, respectively. The reduction is 29%–41% for knees and 20%–30% for hips [45]. As the height of the stilts increases, the joint flexibility decreases, suggesting more muscle activities are needed to maintain

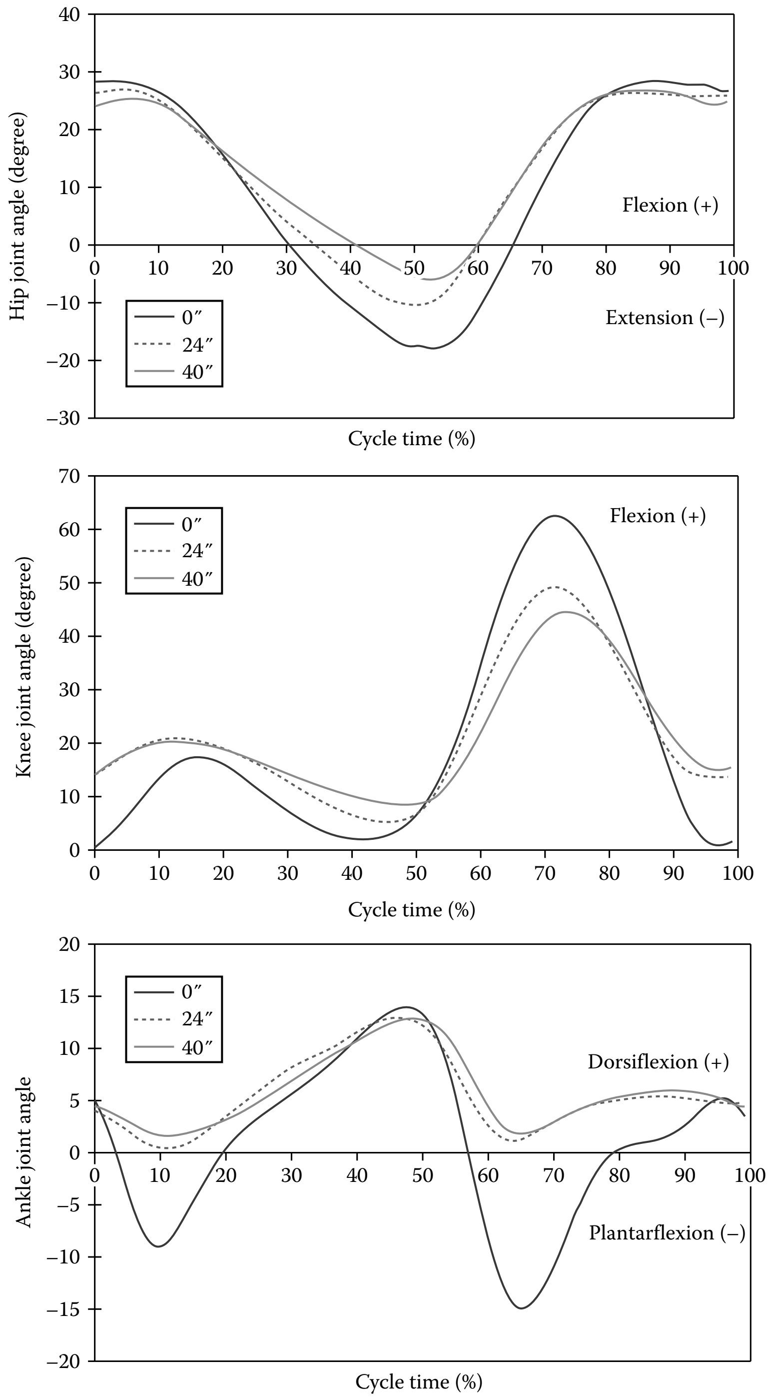


FIGURE 25.16 Hip, knee, and ankle joint angles for three stilt conditions averaged over all subjects. Joint angles were normalized to the gait cycle with the first foot contact at 0% and the second heel contact of the same foot at 100% of gait cycle.

stability on stilts and suggesting that this activity is more likely to result in accumulated muscle fatigue in the lower extremities.

25.2.3 Fall Injury Potential Associated with Stilts

When walking on stilts, construction workers are typically elevated 0.6–1.0 m above the ground. Due to the increased height, the postural stability of workers is likely to be influenced by visual or psychological perturbations at the construction work sites. A survey of carpenters and drywall installers indicated that workers perceived the greatest fall potential to be associated with the use of stilts, when compared to other common devices, such as scaffolds and ladders [64].

25.2.3.1 Gait Characteristics

In a study of recreational wood stilts, stilt walking was found to be generally faster than normal gait due to an increased stride length, in spite of a decrease in cadence [65]. Such recreational stilts weigh approximately 2 kg each. In contrast, the construction stilts are much heavier, with a weight of 3.64 kg each. Experienced workers were able to adapt to the added weight on their feet; however, they walked significantly slower on stilts [45]. Table 25.2 shows general gait parameters for different stilt heights in a gait study of construction workers. Gait on construction stilts is characterized by a decrease in speed and increases in stride length, step width, and double stance period (i.e., the percentage of the time when both feet are in contact with the floor during a gait cycle). Workers walk significantly slower on stilts, with the mean stride period increased from 1.24 s of no stilts to 1.59 and 1.69 s for 0.6 m (24 in.) and 1.02 m (40 in.) stilts, respectively. The mean step width for gait on stilts can be significantly increased to as much as 25 cm on stilts compared to 15 cm of normal gait. The stride length is significantly increased to 1.75 m on stilts compared to 1.55 m for normal gait; however, it is still within the normal gait limits (1.25–1.85 m) [66]. When negotiating a curved path, the walking speed on stilts is slower with the mean speed of 1.03 m/s compared to a straight path (1.25 m/s).

Figure 25.17 illustrates the position of the right heel marker in the mediolateral direction as a function of gait cycle. The position of heel for no-stilts conditions remained essentially the same mediolateral position—around 0.23 m. For gait on stilts, the stilt was at 0.23 m in the beginning of the gait cycle but swung 8 cm outward during the swing phase. The functional gait changes reflect the adaptations adopted by workers to maintain

TABLE 25.2 Means and Standard Errors for Gait Parameters

		Stilt Height	
Gait Cycle Parameters	**Safety Shoes**	**0.6 m**	**1.02 m**
Average speed (m/s)	1.25 (0.16)	1.08 (0.15)	1.03 (0.16)
Stride period (s)	1.24 (0.08)	1.59 (0.15)	1.69 (0.17)
Double stance period (%)	20.0 (2.1)	21.6 (3.5)	22.6 (3.3)
Step width (m)	0.15 (0.05)	0.24 (0.08)	0.25 (0.10)

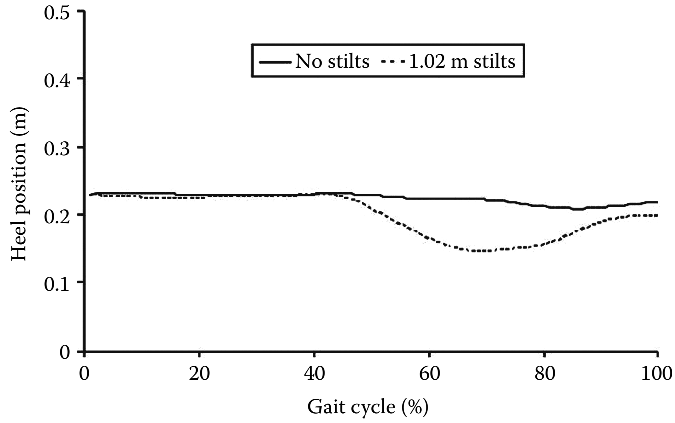


FIGURE 25.17 Mediolateral position of the left heel as a function of the gait cycle.

dynamic balance. The increase in balance demand is evident in the increases in step width and double stance period. The 67% increase in step width suggests a wider base of support was needed to improve stability on stilts. The lengthened double stance period indicates a longer period of time was required for the body to reestablish stability from one step to another. The trajectory of heel markers for gait on stilts suggests a "lurching style" walking pattern with the foot swung out laterally, providing a wider base of support.

25.2.3.2 Postural Stability for Various Foot Placements on Stilts

Walking on stilts may result in accumulated muscle fatigue in the lower extremities [47] and eventually produce postural instability while holding a prolonged standing position [58,64]. Other research findings have determined that postural stability and motor control mechanism were highly associated with various foot placements [67–69]. Independent research has attempted to identify and quantify issues related to standing and balance performance while conducting manual material handling, and various additional research efforts have attempted to determine and evaluate fall hazards associated with foot placement [67,70,71]. Workers' foot placements are known to influence whole-body postural stability and lower-extremity joint force [72–75]. As a result, alternative arrangements of foot placement are suggested as one of the main biomechanical implications from these studies, and the alternative foot placements are believed to increase postural stability and to reduce the incidence of fall-related injuries [67,74,76].

In a study of postural stability associated with stilts, a set of two by three stance conditions were investigated to determine the optimal foot placement for postural stability in a stationary standing position [43]. The six conditions include two levels of asymmetric foot placement direction (parallel versus forward) and three levels of foot placement width as scaled against shoulder width (SW) (0.5, 1, 1.5 SW) as shown in Figure 25.18. Findings from this study suggested stilt height, foot placement width, and foot placement direction all had significant effects on postural stability. Postural instabilities were increased with increasing stilt height and forward foot placement direction. Also, half-shoulder-width foot placement was the most hazardous condition in terms of fall-risk factors. A parallel foot

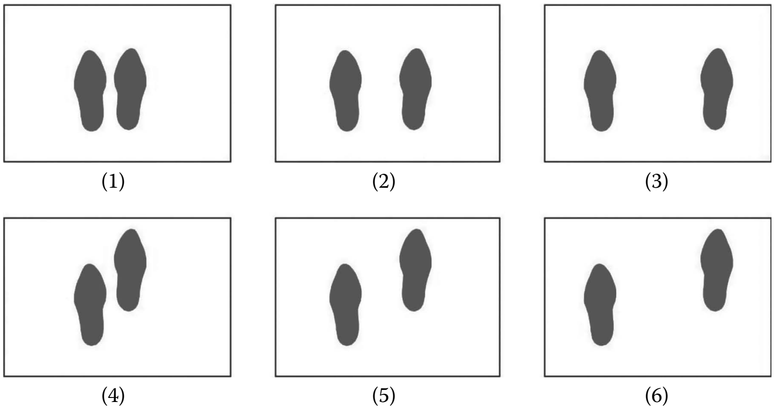


FIGURE 25.18 Six foot placements: (1), (2), and (3) are 2 ft parallel direction; (4), (5), and (6) are 1 ft forward direction. (1) Standing, with feet at half of the individual's shoulder width and directly beneath the body; (2) standing, with feet placed at participants' shoulder width and directly beneath the body; (3) standing, with feet placed at 1½ times shoulder width and directly beneath the body; (4) standing, with feet at half of the individual's shoulder width and with the left foot beneath the body and the right foot placed forward a distance of half the individual's foot length; (5) standing, with feet placed at participants' shoulder width and with the left foot beneath the body and the right foot placed forward a distance of half the individual's foot length; and (6) standing, with feet placed at 1½ times the participants' shoulder width and with the left foot beneath the body and the right foot placed forward a distance of half the individual's foot length.

placement directly beneath the body reduced postural instability more than a placement with the right foot placed forward to the left foot. These findings are especially important for those construction tasks involving confined work spaces, within which drywall carpenters or painters frequently perform tasks within shoulder-width range (e.g., in closets and bathrooms).

Construction workers wearing stilts had significantly higher postural sway and instability than those with no stilts. This instability increased substantially with increasing stilt height regardless of the foot placement (i.e., width and direction). This finding supports the views of the painter's union [43] that 24 in.—the lowest setting—is a safe height setting for occupational stilt use. Thus, it is suggested that users keep stilts at the lower height settings whenever possible and adopt proper standing posture with stilts, that is, keep feet parallel and directly beneath the body and place them one shoulder-width apart.

25.2.3.3 Dynamic Stability and Fall Hazards Associated with Gait on Stilts

Human gait requires an integration of a complex neuromuscular-skeletal system and the coordination of many muscles and joints. In most gait studies, joint moments are quantified to better understand how the work is distributed among joints; to determine the net muscular, ligament, and friction forces acting on the joints; and to obtain a clear picture of the balance mechanism during locomotion [77–79]. For gait on stilts, the general patterns of lower extremity joint moment are similar to those of normal gait with safety shoes; however, the peak joint moments are significantly greater on stilts. Findings from published and definitive studies [45,47] indicate that the peak joint moments for stilt walking are significantly greater in the weight acceptance and preswing phases of the gait cycle. There is no significant dependency on stilt condition in general when comparing the joint moments during the swing phase between 60% and 100% of gait cycle. In contrast, during the stance phase (0%–60% of gait cycle) when the foot is in contact with the floor, differences are observed in the hip, knee, and ankle joint moments due to stilt wearing. Immediately after initial foot contact, sudden and quick increases occur in hip extension, knee extension, and ankle dorsiflexion moments. Approximately 19%, 30%, and 110% increases are observed in peak joint moments at the hips, knees, and ankles, respectively. As the foot progressed to 50% of gait cycle in the preswing phase, 56% and 28% increases occur in peak hip and knee flexion moments, respectively [45,47].

The most pronounced differences in joint moments observed during stilt walking are the high magnitudes of ankle dorsiflexion moments and hip flexion moments. Ankle and hip muscles appear to play dominant roles in modulating the joint loadings to compensate for the weight of stilts and the increase in demand for balance. The high ankle dorsiflexion moments in the early gait cycle are needed to ensure a successful landing, while the high hip flexion moments in late stance are needed for propulsion of the body forward and upward. The increases in lower extremity joint moments could be interpreted as signs that gait on stilts is a particularly challenging task for the neuromuscular system [77]. Moreover, if any additional unexpected perturbations arise from environmental changes or job task demand—for example, slippery surfaces, excessive arm reach, and negotiating a sharp turn—the dynamic balance of the workers could be further challenged.

Walking on stilts, like normal gait, requires sufficient foot clearance of the swing limb as well as the stability of the body supported primarily by the stance limb. Previous gait studies have documented the minimum foot clearance of the midswing phase [80–83] as an indicator for examining the potential of tripping. When walking on stilts, workers' minimum foot clearances during midswing phase were found to be distinctly related to the stilt condition [45]. In general, the foot clearances for stilt conditions were consistently lower than those of no stilts during the entire gait cycle. An approximate 1-cm reduction was observed during midswing when the stilt swings directly beneath the body. The small foot clearance on stilts could come from insufficient knee flexion during swing phase, excessive knee flexion during stance phase, or the mechanism of the stilt floor plate. Due to the restricted joint motions and the weight of the stilts, workers may not pick up their feet as high as they would for a normal gait. Thus, workers are more likely to trip on any objects that might be on the ground at the job site when wearing stilts. The risks of tripping may be even greater since workers on 40-in. stilts may not visibly detect obstacles on the floor. Workers should inspect the work environment before putting on stilts, to ensure the floors are free of obstacles.

25.2.4 Future Direction for Stilts

Stilts appear to place greater demands on lower extremities to compensate for the limited joint motions caused from restriction by the binding straps as well as by the weight of the stilts abnormally loading the limbs. The computer simulations presented in this chapter suggested that the use of stilts may potentially cause increased musculoskeletal loadings in five of eight major muscle groups in the lower extremities, with the greatest increase suggested for the rectus femoris. Workers may need to limit the prolonged use of stilts, especially at high elevation, to alleviate the burdens on the joints and reduce muscle fatigue arising from increased muscle activities required to maintain balance. However, the theoretical analysis of muscle fatigue as well as energy expenditure is yet to be investigated by further clinical and experimental studies.

25.3 SCAFFOLDS

Scaffolds are defined by OSHA as any temporary platform, either suspended or supported, and its supporting structure, including its anchorage system, used for supporting materials or employees or both [84]. The definition is broad enough to include different types of scaffolding used in various industries; while it is common to think of scaffolds as construction-related devices, they are found in numerous industry groups and industrial applications. Across all industrial sectors, surveillance findings indicate that falls from scaffolds represent a serious occupational hazard; falls from scaffolds are one of the leading causes of work-related fall fatalities and injuries [85]. In 2006, approximately 14.2% (809 of 5703) of fatal occupational injuries were due to falls; of those, 10.9% (88) involved scaffolds or staging [86].

Three out of every four fatal and nonfatal injuries associated with scaffold use [87] occur in just one of the three major categories of scaffolds: supported scaffolds. Supported scaffolds are defined as platforms supported by outrigger beams, poles, frames, or similar rigid support systems [88]. Since the magnitude of injury events is much smaller within the other two categories of scaffolds—suspended and other categories—NIOSH summary research has focused on supported scaffolds, and the incidence of injury in supported scaffolds is what is reported herein. Emerging technology represents a significant component of the "other" category of scaffolds, and this emerging technology is chiefly represented in one category of scaffold, the aerial lift; research in aerial lifts chiefly represents original research and is reported separately in this document.

Given the high magnitude, incidence, and personal consequences of supported-scaffold, fall-related injuries, NIOSH has directed significant resources to determining the cause and characteristics of falls related to the use of scaffolds and to identifying risk factors and common scenarios related to the deployment and use of scaffolds at work sites. This research has encompassed numerous avenues to determine the state of the art: consultation with experts, extensive review of the state of knowledge published in peer-reviewed literature and user-oriented publications focused on industrial applications, as well as original NIOSH-directed research studies addressing under-researched areas directly related to scaffold safety. Areas in which original research has been conducted at NIOSH addressed issues related to the lack of published biomechanical results and findings related to common postures in scaffold disassembly, handling methods, body postures, and optimal hand placement. Basic research on the use of virtual reality techniques in simulating fall-hazard exposure for scaffolds also represents NIOSH contribution to the body of knowledge in this area.

NIOSH has reviewed various summary research findings and presented them before the ergonomics society, a leading research institute addressing the ergonomic component of occupational safety. The extensive findings constitute an overview of the current (2008) state of knowledge of scaffold safety; these findings have been published as a succinct review of the knowledge gaps, opportunities for directing research, and current knowledge of safety related to scaffolds. This summary, published as a chapter in *Contemporary Ergonomics 2008: Proceedings of the International Conference on Contemporary Ergonomics*, remains a valuable and still current summary of the research direction for much ongoing scaffold-safety research [89].

The strategies and recommendations from this research summary provides valuable information on (1) key fall-injury risk factors related to supported scaffold use, including OSHA's performance-based criteria to protect employees from scaffold-related hazards; (2) technologies for supported scaffold safety; (3) the state of knowledge about fall safety; and (4) remaining unanswered questions pertaining to supported scaffold safety and existing knowledge gaps. In addition to OSHA criteria, which can be accessed separately, two main summaries were presented and are reported here: current measures and technologies to control falls from scaffolds and knowledge gaps remaining to be answered.

The NIOSH review on the leading risk factors associated with falls from scaffolds found that the most common causes of falls could be organized into five major categories: (1) scaffold tipping or structure failure [90,91]; (2) planks breaking, slipping, and gapping [87,92]; (3) unguarded scaffolds [92,93]; (4) difficult access or transition onto or off a scaffold [93]; and (5) problems with erection and dismantling of scaffolds [90,93].

Scaffold tipping or structure failure was attributable to various factors, such as inadequate anchoring into the walls, improper scaffold assembly, improperly secured bracing, loading beyond designed capacity, and failure of scaffold components under stress [86,90,94]. Plank breaking, slipping, and gapping may result from a heavy load, physical damage to a plank, misinformation about the type of plank or its rating, inadequate overhang over the supporting bearers, unsecured planks (no cleat), sideways movement of planks, and missing planks [88,95,96]. Conditions of unguarded scaffolds include missing guardrail and inadequate cross bracing [92,93]. A variety of factors may influence safe access to the working level of the scaffold: the width of a run of integral ladders in scaffold end frames, the distance between two runs, and the difficulty transiting onto or off a scaffold platform to integral ladders due to the required plank overhang [92]. Problems with erection and dismantling of scaffold may result from environmental conditions, the weight of scaffold units, and the availability of handholds [95]. OSHA regulations addressing scaffold use were reviewed in this document; further information in this area is available from review of the original document or, because of the evolving nature of knowledge related to this risk exposure, preferably by reference to the current OSHA website (http://www.osha.gov/SLTC/scaffolding/index.html).

The current measures and control technologies were presented as follows. OSHA requires an anchorage to control scaffold tipping or failure when the scaffold reaches four times its width at the base [96]. Halperin and McCann (2004) [97] reported that properly erected scaffolds were correlated with supervision by a competent person.

Modern modular scaffold systems, which are simpler to erect, were reported to be safer because they reduced the possibilities for errors in construction [98]. The use of metal catwalks or platforms is also a solution to the problem. Plank locks are available in the market to prevent scaffold planks of solid sawn lumber from slipping [99]. Fabricated steel planks in 15- and 23-cm widths are also commercially available, thereby making it possible to arrange the planking to reflect the constraints of work situations involving irregular surface contact. Because of this fact, the maximum room between planks and the uprights of the scaffold frame can be lessened to below 7.5 cm, instead of the allowed 24 cm, to provide better slippage control [100].

Essentially all scaffold manufacturers currently provide guardrail components that can be used to ensure compliance with current OSHA requirements; some frame scaffold systems use a modular guardrail and midrail system that does not rely on cross bracing to provide fall protection. As to the control of difficult access or transition onto or off a scaffold, engineered scaffold planks that hook onto the horizontal scaffold member and do not extend beyond the end frame (as compared to the required 15-cm overhang to the supporting member for sawn lumbers) provide increased ease of access to the working surface from a ladder built into the end frame. Finally, lightweight scaffold components are available to ease the problem of falls during scaffold erection and dismantling [95]. Fabricated scaffold planks are also available that are lighter than wood planks and thus decrease the risk of imbalance-related falls during the erection and dismantling phase.

A current study based on the findings of OSHA fatality investigations may help improve our understanding of the extent to which scaffolds tip when they are not anchored or are improperly anchored. Industry literature generally suggests that fabricated planking or decking appears to offer certain advantages over sawn lumber planks; it may be useful to conduct a series of experiments to validate these putative safety differences and the life-cycle costs. In addition, if one considers exposure to scaffold falls as a function of time, then the initial access phase during which the worker accesses or steps onto the scaffold may be the most dangerous part of scaffold work. The challenges in negotiating overhanging planks or guardrail components bear serious consideration. Evaluations were also needed on whether certain scaffolding designs are safer to erect and safer to use, given current advances in scaffold technology and work practices. Moreover, what opportunities are there for scaffold erectors to use PFAS? How can technology be used to reduce fall exposures for this group? The development of a comprehensive set of “best scaffold safety practices” is suggested. Finally, the most recent detailed BLS survey on scaffold use and injuries dates to 1978 [86] and is now over three decades old; this survey may not be fully representative of the conditions under which workers perform tasks on scaffolding today. At the date of this publication an enhanced national survey on scaffold use and injuries remains long overdue.

In addition to the summary measures presented in the preceding study, various original analytic studies were conducted by NIOSH to address under-researched areas related to supported scaffold safety. NIOSH sponsored original research studies on pressing safety issues related to scaffolds: (1) biomechanical evaluation of scaffolding tasks, (2) a comparison of different postures for scaffold end frame disassembly, (3) optimal hand locations for safe scaffold end frame erection and dismantling, and (4) carrying strategies for scaffolds. In addition, various NIOSH research activities were undertaken to determine the value of virtual reality applications in relation to scaffold safety. This constituted a novel and emerging research area, with potential application to all areas of safety under elevated conditions.

A primary research component of NIOSH activity related to scaffold safety was that of a biomechanical assessment of erection and dismantling tasks [101]. This comprised a field study to identify tasks and activities that specifically increased the risk of overexertion injury associated with the erection and dismantling of frame scaffolds and to determine strategies that would prevent or reduce the worker's risk of injury. Twelve construction sites were visited involving a total of 29 workers. The investigation identified activities that increase the risk of overexertion injuries during task performance: lifting scaffold end frames, carrying end frames, handling scaffold planks, removing cross braces, and removing guardrails. This chapter focuses on end frame handling problems. Although the techniques used to handle end frames varied among the construction sites and subjects, six lifting and five carrying strategies were commonly used. Computer simulations of these work techniques show that considerable biomechanical stress occurs to most of the workers at their shoulders, elbows, and hips. To reduce overexertion injuries during erection and dismantling of frame scaffolds, design of an assistive device to lift scaffold end frames and modifications to the end frame fixtures are suggested. Future research areas for the prevention of injury during scaffolding work are also proposed. The relevance to industry is also discussed: The construction industry is characterized by high frequencies of musculoskeletal injuries. This chapter analyzes scaffolding, a common activity in construction; evaluates stresses associated with different methods used; and develops recommendations on changes in scaffold design, training, and accessory equipment necessary to reduce accidents and injuries.

A second study was conducted related to scaffold end frame erection and disassembly while adopting postural variations [102]. This study attempted to identify the most favorable scaffold end frame disassembly techniques and evaluate the associated slip potential by measuring whole-body isometric strength capability (Figure 25.19) and required coefficient of friction (RCOF) to reduce the incidence of injury. Forty-six male construction workers were used to study seven typical postures associated with scaffold end frame

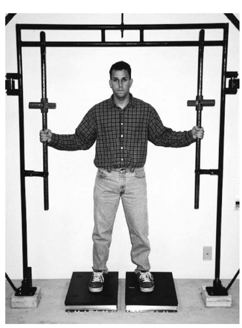
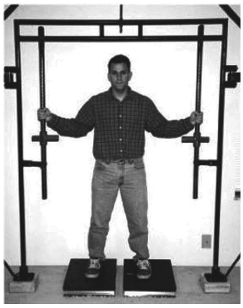


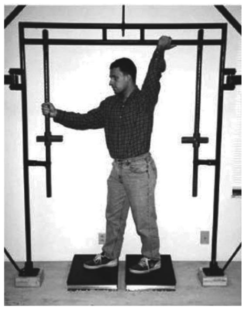
FIGURE 25.19 Isometric strength-testing apparatus.

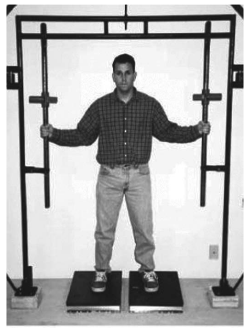
Posture 1
symmetric front
lifting (chest ht)



Posture 5
symmetric front
lifting (acromial ht)

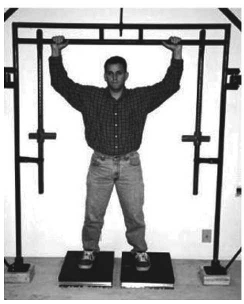
Posture 2
asymmetric
overhead lifting

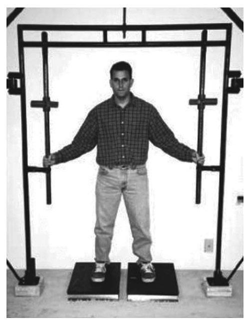




Posture 6
symmetric front
lifting (elbow ht)

Posture 3
symmetric
overhead lifting





Posture 7
symmetric front
lifting (knuckle ht)

Posture 4
asymmetric
twist lifting

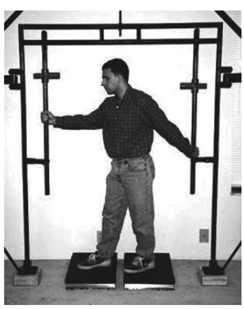


FIGURE 25.20 Scaffold disassembly postures.

disassembly (Figure 25.20). An analysis of variance showed that the isometric forces resulting from the seven postures were significantly different. Three of the disassembly postures resulted in considerable biomechanical stress to workers. The symmetric front-lift method with hand locations at knuckle height would be the most favorable posture; at least 93% of the male construction worker population could handle the end frame with minimum overexertion risk. The static RCOF value resulting from this posture during the disassembly phase was less than 0.2; thus, the likelihood of a slip should be low.

A third NIOSH study was conducted related to the potential for musculoskeletal injury from scaffold carrying, specifically focusing on hand location and isometric force generation [103]. Based on the location of scaffold end frame center of mass and the isometric strength data collected in this study, a hand separation of 46 cm between the elbow and chest heights would be an optimal hand location for an assistive lifting device for scaffold disassembly. This 46-cm separation would mitigate the likelihood of postural imbalance while allowing for the generation of a mean maximum isometric force of about twice the weight of a scaffold end frame. At least 95% of the construction population would have isometric forces in excess of the weight of a scaffold end frame. An alternative method without an assistive device would be a hand location slightly higher than the elbow height with a hand separation of 116.8 cm. This is a compromised situation that yields 2.4 times isometric strength of the scaffold weight with little risk of postural imbalance.

A final study examined commonly used methods of carrying scaffold end frames [95]. This study determined the most favorable strategy for carrying scaffold end frames while minimizing the risk of injuries from being struck by an object, falling, and overexertion. An experimentally validated method of isolating the effect of scaffolding-carrying methods established that the effects of carrying method on postural instability and task difficulty were significant for handling a commonly used 22-kg end frame. Response time, postural instability, and perceived task difficulty rating were significantly reduced when a 9-kg end frame was used as compared with the 22-kg frame. The conclusion drawn from this research was that the symmetric side-carrying method was the best option for handling 22-kg scaffold end frames. A 9-kg end frame (e.g., made of reinforced lightweight materials) had the potential to reduce injury risk among scaffold handlers during their scaffold erection and dismantling jobs. The NIOSH recommendation was that scaffold erectors may want to adopt the symmetric side-carrying method as the primary technique for handling the 22-kg scaffold end frame, which is currently the one most used in the industry.

NIOSH additionally performed significant research in establishing basic understanding of the validity and application of virtual reality techniques in modeling and simulating fall-safety exposures from scaffolding. NIOSH acquired a surround-screen virtual reality (SSVR) system in 1996 (Figure 25.21) to examine exposure conditions that could not be studied using human subjects, given safety concerns. This system employs projected computer-generated imagery to develop a visual sense of immersion on the part of the subject; participants wear goggles that integrate visual cues to give the impression that they are immersed within a simulated environment. Various published and unpublished methodological and applied research studies examined critical issues with the application of this simulation technology to elevated-use tasks involving scaffolds. A pioneering study by Hsiao et al. [104] investigated the effect of adding real planks, in virtual scaffolding models of elevation, on human performance in an SSVR system. Twenty-four construction workers and 24 inexperienced participants (controls) performed walking tasks on real and virtual planks at three virtual heights (0, 6, and 12 m) and two scaffolding platform width conditions (30 and 60 cm). Gait patterns, walking instability measurements, and cardiovascular

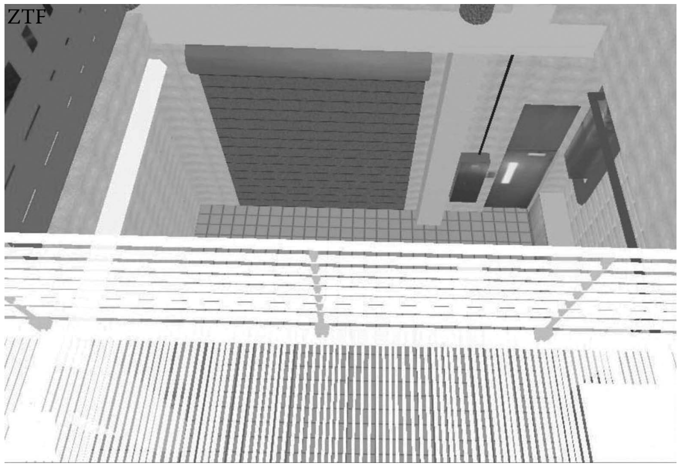


FIGURE 25.21 Simulated scene within SSVR.

reactivity were assessed. The results showed differences in human responses to real versus virtual planks in walking patterns, instability scores, and heart rate interbeat intervals; it appeared that adding real planks in the SSVR virtual scaffolding model enhanced the quality of SSVR as a human–environment interface research tool. In addition, significant differences were observed in performance between construction workers and the control group. The inexperienced participants were more unstable as compared to construction workers. Both groups increased their stride length with repetitions of the task, indicating a possibly confidence- or habit-related learning effect. The practical implications of this study are in the adoption of augmented virtual models of elevated construction environments for injury prevention research and the development of a program for balance-control training to reduce the risk of falls at elevation before workers enter a construction job.

A further study by Simeonov et al. [105] compared human perceptions of height, danger, and anxiety, as well as skin conductance and heart rate responses and postural instability effects, in real and virtual height environments. The 24 participants performed "lean-over-the-railing" and standing tasks on real and comparable virtual balconies, using the SSVR system. The results indicate that the virtual display of elevation provided realistic perceptual experience and induced some physiological responses and postural instability effects comparable to those found in a real environment. It appears that a simulation of elevated work environment in a SSVR system, although with reduced visual fidelity, is a valid tool for safety research. Potential applications of this study include the design of virtual environments for safe evaluation of human performance at elevation, identification of risk factors leading to fall incidents, and assessment of new fall prevention strategies.

This area of research remains ongoing within NIOSH, and future studies will assess exposure conditions under a variety of elevated conditions and for a variety of tasks within construction and other industrial conditions.

In summary, NIOSH research on supported scaffolds has consisted of original studies to address under-researched areas related to exposures from scaffold-related tasks, original research on the application of virtual reality to scaffold-related safety, as well as summary research on the most current and well-researched areas related to scaffold safety. NIOSH summary reviews on scaffolding safety, published in 2008, still constitute a valuable resource for determining the state of knowledge and the research gaps obtained from safety studies related to scaffolding. NIOSH research is part of an ongoing effort to reduce injury exposures from construction and other industrial tasks using this common elevating device.

25.4 MAST CLIMBING WORK PLATFORM

A NIOSH study initiated in April 2010 focuses on mast climbing work platforms (MCWP), an emerging form of scaffolding increasingly used throughout the construction industry. Originating in Europe in the 1970s, MCWPs have become more popular in North America in recent years. For this system, a platform is elevated and lowered along a mast by the use of an elevating unit. While the early units were powered by electric motors, gasoline engines have become standard for MCWPs used in North America. The mast can be used in a freestanding condition for heights up to 100 ft or in an anchored condition at greater heights. MCWPs have many advantages over other forms of scaffolding. One major advantage is its ability to elevate workers to working heights up to 1000 ft when anchored to a building. Also, the platforms can travel at speeds up to 40 ft/min, providing great advantage for the movement of materials. The platforms are able to support large loads (25,000 lb) and provide adequate work area. For wide facades, multiple platforms can be connected by bridges. This allows workers free access to the entire span of a wall, which reduces setup time. However, as MCWPs have increased in popularity, nonfatal and fatal incidents involving MCWPs have occurred.

In 2008, Ayub, Susi, and O'Shea individually presented data on these fatal and nonfatal injury incidents to the advisory committee on construction safety and health and identified the following potential hazards [106–108].

- One area of concern is the erection/dismantling of the mast. During the erection of the mast, sections can be added by the use of a crane located on the work platform or lifted in place by workers. Alternatively, several sections of mast can be assembled on the ground and positioned by a crane. If the worker is not properly restrained, manual placement of the sections of mast could result in a worker falling to the platform or to the ground. Also, the platform could rise above the highest section and fall to the ground. The top mast section is equipped with a limit switch and/or physical stop, but it is the only protection for the fully erected mast. A removable stop could be designed to prevent the platform from climbing over the mast during erection. Another potential hazard is when the mast is unsupported after the last anchor has been removed. Even when the unsupported mast height is less than the freestanding height, tipover could occur from overloading the platform with removed mast sections.
- Due to the low velocities of a MCWP, stability is mainly a static issue. However, studying the effects of wind and platform loading on stability would be of importance. For example, tipover could occur when a fully loaded platform, while being used in high winds, is subjected to a force at the guardrail. This could be especially dangerous

when dealing with an unsupported or freestanding mast. Dynamic analysis performed with software such as ADAMS could lead to a better understanding of MCWP stability. Overhead protection and winter weather enclosures need to be addressed by manufacturers during use and especially during erection and disassembly.

- The anchoring of the mast to the building is also a process that should be evaluated. Due to various wall materials, the proper fastener may vary from one job to the next. Also, some wall materials may not be suitable for anchoring the mast. Although the manufacturer may specify the fastener to be used for a certain condition, workers may substitute other fasteners. This could become more complicated when using MCWPs supplied by rental companies. Tie-in to the building structure should be reviewed and approved by the engineer of record for the building.
- In general, lifting of the platform is accomplished by two types of systems. Rack and pinion systems perform climbing/descending by a motor-driven pinion traveling along a rack that is connected to the mast. For this system, the rack and gears should be inspected for corrosion and wear. Also, the use of duplicate drives could provide safety from failure of a single mechanical component. Some North American manufactures use hydraulic cylinders to climb/descend. Fraco's system consists of a hydraulic cylinder that actuates a hook (Fraco is the largest mast scaffold manufacturer and NIOSH's research partner for this proposed study). The hook climbs a tower rung that is fixed to the mast. The elevating unit is also equipped with a safety hook that prevents the platform from lowering in case of main hook failure.
- In order to move the worker closer to the building, extension outriggers can be used. A few potential hazards could occur from their use. First, the worker is exposed to an unprotected edge of the platform when extending the outriggers and installing the planks. The use of a safety harness could protect the worker while installing the planks. Also, if the planks used on the outriggers are not fastened properly, the dynamic motion created by the workers could cause the planks to move off the outriggers. Lastly, the planks must be able to support the applied loads. Rather than using wood planks from the jobsite, engineered planks with load ratings could be used. These planks could also have an antislip surface for wet conditions.
- Some systems allow multiple platforms to operate on the same mast. Work can then be performed simultaneously at different levels of the building façade. This configuration could create several safety issues. Tools, materials, and debris could fall from the upper platform to the lower platform. Also, the platforms could collide during raising/lowering if proper safety controls are not implemented.

In conclusion, MCWPs are an efficient means of elevating workers and materials to extreme heights. In order to prevent incidents, regulation specific to MCWPs must be developed and implemented. Proper training is essential in providing workers with the knowledge to safely use MCWPs. Lastly, structural analysis of various components and dynamic simulations of different operating conditions could lead to safer design (Figure 25.22).

(A)

(B)

(C)

(D)

(E)

FIGURE 25.22 Types of MCWPs (Reprinted with permission of Fraco Products Ltd., St-Mathias-sur-Richelieu, Quebec, Canada.) (A) and (B) are Fraco Model ACT8; (C–E) are Fraco Model FRSM-20 K.

25.5 FUTURE DIRECTIONS/RECOMMENDATIONS IN ELEVATED DEVICE RESEARCH

NIOSH is committed to supporting continuing research into elevating device safety, in a way that will support the need for advanced research into the most salient, anticipated conditions. While the continued use of frame scaffolding will surely continue for the foreseeable future, it is anticipated that increasing the use of mechanized scaffolds will transform the range of tasks associated with construction activities, as well as tasks in various industries requiring elevating equipment. The reasons for this are varied, but the combination of increased productivity factors, accessibility to mechanized scaffolds through rental agencies, increased familiarity with operational demands and requirements for skilled laborers at work sites, as well as other factors, supports a clear trend for the use of mechanized scaffolding, such as scissor lifts and mast scaffolds, in construction and related industries.

While NIOSH will continue to support pertinent research for frame scaffolding, an increasing awareness has emerged for issues related to mechanized scaffolding. Issues related to frame scaffolding include assembly, carrying, ingress and egress, disassembly, and task completion at heights. Certain issues remain under-researched for frame scaffolding, and NIOSH remains aware of the continued need for further research in these areas, but research into issues related to the emerging technology represented by mechanized scaffolding will call for increasing focus and attention.

The mechanized systems used to elevate workers in construction and other industries are more complex, subject to a wider range of mechanical issues and problems, and in general, involve more multifactorial exposures than frame scaffolds. This can be for multiple reasons: Mechanized elevating equipment can routinely reach greater heights than frame scaffolding and is subject to propulsion-related failures, hydraulic-system failures, anchorage issues, ingress–egress issues, stability-related failures, a range of fall-from-height issues, fall-arrest-induced destabilization and tipover, and other issues. A significant under-researched component is environmental conditions. The contribution of environmental conditions is largely unknown and can range from extreme and unanticipated weather conditions to catastrophic system failure. The contribution of misuse of equipment is similarly unknown, but it is known that fall-from-elevation injuries have occurred from equipment misuse in either a deliberate or unintended fashion. Other issues, such as location of self-arrest anchorage points, unsecured elevation of equipment, and task-destabilization-related issues (such as destabilization of scaffolds from drilling, cable pulling and similar tasks), call for continued and in-depth research.

Because of the complex and multifactorial nature of hazard exposures related to mechanized elevating equipment, it is unlikely that the research expertise necessary to conduct pertinent research on this wide range of issues will be found in private enterprises. The need for NIOSH to direct resources to this emerging issue is evident; however, NIOSH will not be able to address these issues singly. NIOSH will increasingly turn to stakeholders and interested parties in private enterprise, other research agencies with a national scope, consensus standard-development agencies and regulatory agencies, labor and manufacturing groups, and other interested parties to address the emerging hazards related to mechanized elevating equipment.

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Disclaimer

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

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