9

Fall Risk Associated with Restricted and Elevated Support Surfaces

Peter Simeonov

CONTENTS

ABSTRACT This chapter addresses the effects of restricted and elevated support surfaces on balance control as related to the risk of occupational falls from elevation. The chapter presents a summary of the pioneering research studies conducted at the National Institute for Occupational Safety and Health (NIOSH) to evaluate and apply virtual reality technology for fall prevention research. The described research outcomes include practical strategies and solutions to improve workers' balance control in challenging construction work environments. Also included is a brief review of related research on balance control, in which exposures to restricted and elevated surfaces are used to understand and prevent

falls in the elderly. The chapter concludes with a brief summary of suggested measures to control falls from restricted and elevated surfaces.

9.1 Problem of Falls from Elevation

Falls remain a leading cause of fatal injury in the workplace. In 2012, there were approximately 704 fatal work-related falls in the United States. More than 80% (570) of these fatal fall injuries were due to falls from elevation, and nearly 50% (279) of the falls from elevation occurred in the construction industry (BLS, 2013). In addition, in 2012, there were 56,890 nonfatal injuries with days away from work due to falls from elevation in the United States (BLS, 2014). According to the 2013 Liberty Mutual Workplace Safety Index, the cost of injury resulting in falls from elevation in 2011 in the United States was $4.9 billion (Liberty Mutual, 2013). These staggering statistics reveal the persistent nature of fall hazards in the workplace and, specifically, the fall prevention challenges that remain within the construction industry.

Work at elevation, especially in construction, is associated with frequent standing and walking on restricted surfaces, such as temporary work platforms (scaffolding planks), structural components and elements (trusses, rafters, and steel beams in metal construction), and unfinished work surfaces (wall top plates), which are not designed for but are frequently used as support surfaces. Temporary support surfaces at elevation are frequently compliant (they can bend, yield, and move when loaded). Restricted and elevated surfaces can also be sloped (e.g., in residential roofing).

Developing a good understanding of the fall risks associated with exposure to restricted and elevated surfaces may help in selecting effective fall prevention strategies. An important first step in this process is the adequate characterization of the components of this exposure.

9.2 Restricted and Elevated Support Surfaces

Restricted and elevated support surfaces are characterized by open unprotected edges and are therefore associated with a fall-from-height hazard; they may be characterized by visual exposure to elevation (open space with distant visual references) and therefore associated with reduced visual feedback for balance control and increased risk of losing balance; and they also may be limited in at least one dimension that can reduce the base of support (BOS) during standing or restrict stepping control strategies during walking, and therefore they may be associated with an increased risk of losing balance.

How high must a support surface be to be considered elevated? For practical purposes, the Occupational Safety and Health Association (OSHA) General Industry Standard (29 CFR 1910) "Walking-working surfaces"—1910.23(c)(1) has defined a lower limit of dangerous surface height by requiring guarding of open-sided floors or platforms 1.22 m (4 ft) or more above adjacent floor or ground level (OSHA, 1984), while the OSHA Safety and Health Regulations for Construction (29 CFR 1926) Subpart M "Fall Protection"—1926.501(b)(1) sets the height limit for fall protection at 1.83 m (6 ft) (OSHA, 1995). However, in steel erection

(OSHA Safety Standards for Steel Erection)—1926.760(a)(1), fall protection is required for all work above 4.5 m (15 ft) and, for some tasks, above 9 m (30 ft) (OSHA, 2001). An increase in fall height has been positively correlated with higher injury severity (Lau et al. 1998) and increased risk of fatal injury (Warner and Demling, 1986); however, even falls from very low heights can be fatal.

What are the dimensions that define a support surface as restricted? There is practically no lower limit for the width of a surface used as support while standing and performing tasks at elevation—examples include the rungs or steps of a ladder, scaffolding frames, roof trusses, and other structural components. However, balance on such narrow support surfaces is usually maintained by using the hands or body for extra support. Walking and balancing tasks for short distances are frequently performed by construction workers without any protection on elevated surfaces as narrow as 10–15 cm (4–6 in.), such as wall top plates, rafters, and beams.

Some practical determinations for the dimensions of restricted support surfaces can be found in the safety standards and regulations. For example, the OSHA Safety and Health Regulations for Construction (29 CFR 1926) Subpart L "Scaffolds" sets the minimum width for a scaffolding plank at 30 cm (12 in.); however, this requirement is not enforced for roofing planks (1926.451(b)(2)(i)), and the common roofing practice is to use 25 cm (10 in.) and even 15 cm (6 in.)-wide planks (OSHA, 1996). The OSHA General Industry Standard (29 CFR 1910) Subpart D "Walking-working surfaces"—1910.23(c)(2) sets a minimum width requirement of 46 cm (18 in.) for a runway that is unguarded on one side (OSHA, 1984). The OSHA Safety and Health Regulations for Construction (29 CFR 1926) Subpart M "Fall Protection"—1926.502(g)(1)(i) defines the distance of 183 cm (6 ft) from an unprotected edge as critical for workers' safety in setting the requirements for controlled access zones (OSHA, 1995).

9.3 Fall Risk Associated with Restricted and Elevated Support Surfaces

9.3.1 Theoretical Considerations for Fall Causation

From the perspective of mechanics, biomechanics, and human factors, a fall can be defined as uncontrolled descent under the influence of gravity, and the causes of falls can be regarded as failures or disruptions in the control of dynamic postural stability during human interaction with the environment. Control of balance is a complex process in which the central nervous system integrates sensory information from visual, vestibular, and somatosensory inputs and uses knowledge acquired through past experience to select and implement postural control strategies (Horak, 2006). The postural control goal is to maintain the body's center of mass (COM) within its stability limits, considering the instant position and velocity of the COM with relation to its BOS defined by the position of the feet.

Loss of balance incidents (falls) occur when one or several modes of the proactive and reactive mechanisms of balance control are disrupted during human–environment interactions (Patla, 1997b; Woollacott and Tang, 1997). The proactive mechanism of balance control, modulated mainly by visual information (Patla, 1997a), involves the activation of postural adjustments prior to the occurrence of destabilizing forces and acts to minimize balance disturbances. The reactive mechanism of balance control, triggered by somatosensory and vestibular inputs, involves the activation of postural adjustments after an external disturbance is encountered, thus enacting balance recovery (Patla, 1993). Restricted and elevated support surfaces can affect the control-of-balance process, and thus the risk of falls, by one or more of the following mechanisms: inducing fearful perceptions and triggering protective behavior; reducing and modifying the adequate sensory information; and restricting the performance of some of the available balance-control strategies.

9.3.2 Psychophysiological Effects of Exposure to Elevation

Exposure to close-by unguarded edges on elevated support surfaces can affect workers' balance through fear-related behavioral and physiological responses (Brown and Frank, 1997). The feeling of anxiety or fear of falling in some cases can lead to overreaction in controlling posture and cause instability. Increased postural threat has been associated with enforced tight control over COM kinematics (Brown and Frank, 1997), selection of a wider BOS (Maki et al., 1994), reduced stride length and velocity (Maki, 1997), and enhanced gain of the vestibular–ocular reflex (Yardley et al., 1995). Furthermore, the increased postural threat does not have to be directly visually induced—any awareness of an existing immediate danger is sufficient to trigger protective responses (Tersteeg et al., 2012).

The level of anxiety experienced from a perceived postural threat is associated with the worker's perceptions of danger, which are a function of the perceived risk for fall and the perceived severity of the expected injury (Menzies and Clarke, 1995). The risk parameters for a fall from elevation may include the worker's task and posture, distance to the edge of the restricted and elevated support surface, availability of fall protective devices and barriers, and stability of the structure (Cloe, 1979; Suruda et al., 1995; Janicak, 1998). The physical factors that determine the severity of injury from a free fall are the height of the fall, properties of the surface of impact, body orientation at impact, and body mass (Warner and Demling, 1986). On the other hand, habituation to a specific dangerous environment can significantly diminish workers' danger perceptions—experienced roofers have been found to underestimate the risk associated with their job (Zimolong, 1985).

9.3.3 Physiological Effects of Exposure to Elevation

A visual environment of elevation is characterized by a lack of close visual references, which can influence balance control through the mechanism of visual stabilization (Bles et al., 1980; Brandt et al., 1980). Bles et al. (1980) reported that when at elevation, human body sway gradually increases both in lateral and fore–aft directions with increasing distance between the eye and the closest object within a person' s visual field. This correlation is stronger when a higher proprioceptive interference is involved (e.g., standing on unstable surface). The sway reaches its maximum at eye–object distances of 5 m and over. Postural instability associated with eye–object distance is not significant at ground level because cues from nearby stationary contrasts (provided by peripheral vision) prevent the instigating sensory mismatch (Brandt et al., 1980). Paulus et al. (1984) reported that postural instability due to height effect begins at 3–4 m eye height.

While on an elevated and restricted surface, workers may direct their eyes to a tree moving in the wind or look at swinging objects such as materials moved by a crane. Given the absence of other stable visual references, these actions might degrade a worker's balance. Research has demonstrated that exposure to moving visual scenes can affect a person's postural stability (Lee and Lishman, 1975; Berthoz et al., 1979; Stoffregen, 1985). Peterka and Benolken (1995) found that, in conditions with inaccurate somatosensory cues, the visually induced postural sway increased significantly (with amplitude almost three times greater than the stimulus) and caused occasional falls in their test subjects.

9.3.4 Biomechanical Effects of Restricted Support Surfaces

Depending on the level of restriction, a support surface can affect balance control in several ways: by directly reducing the BOS determined by feet/shoes dimensions and position; by limiting the availability of a stepping control strategy for balance recovery; and by limiting the affordance of some of the walking balance-control strategies.

Narrow surfaces, supporting only part of the foot, may diminish or eliminate the somatosensory input, subserving the normal mode of postural control, and they may also reduce the effectiveness of the "ankle" postural control strategy (Horak and Nashner, 1986). Perturbation studies in standing (Maki et al., 1996) have shown that a sudden displacement of the BOS is frequently compensated for with stepping responses within a radius of 60 cm, and sometimes several steps are required to restore equilibrium. Restricted support surfaces reduce the potential for effective emergency-reactive control; the worker has a reduced ability to use stepping strategies to recover from occasional instability.

Lateral stability during walking on unrestricted surfaces is most efficiently controlled by the "mediolateral foot placement" (MacKinnon and Winter, 1993; Bauby and Kuo, 2000; Patla, 2003). On narrow walking surfaces (e.g., 15 cm), which enforce suboptimal step width (Donelan et al., 2001), the "mediolateral foot placement" strategy is not available, and the only remaining effective way to control balance in the frontal plane is the individual or combined use of "ankle" and "hip" strategies, applied by lateral tilting movements at the foot and the trunk. During walking, a tripping perturbation is usually compensated for with an increase in the subsequent step length or with several small steps. The magnitude of the movement responses and the distance required for recovery of balance depend on many factors, including the walking velocity, perturbation characteristics, timing, and perceived threat of the task (Eng et al., 1994). If the reactive control fails after a perturbation, and a fall occurs, a restricted support surface may not afford the possibility of arresting the falling body, and a fall to a lower level will follow.

The standing/walking distance from the edge of elevated surfaces has been reported to be associated with the risk of fall incidents. Based on his own observations of people's behavior in the vicinity of elevated edges, Davis (1983) defined a "biomechanically safe distance." It is equal to the subject's own height (at the eyes), which, for the average male, was a little less than 183 cm. He related this distance to the fear of falling and defined a "45° rule." People stopped approaching elevated edges when the edge was seen as being 45° below the horizontal at a distance equal to their eyes' height, a distance they perceived to be biomechanically safe. Workers can fall from a standing position over an edge within 183 cm by tripping, slipping, stubbing their toes, or experiencing other loss-of-balance events (Ellis, 2001).

Generally speaking, there is sufficient experimental evidence in the literature that standing or walking on narrow supports degrades the control of balance. Furthermore, the standing/walking distance to an edge of a restricted surface is recognized as a factor associated with the risk of falling. However, studying the dose-response relations between the parameters of the restricted and elevated support surfaces and their effects on balance control, and the risk of fall remains a challenging research area.

9.4 Fall Prevention Research with Virtual Reality Simulations of Height

In contrast to the considerable number of experimental studies on the causes and prevention of slips and falls on the same level (Grönqvist et al., 2001), very little experimental research has been conducted to systematically investigate the contributing factors leading to falls from elevation. A serious barrier to such research is the high risk of injury, for both human participants and researchers, associated with the unprotected exposure to elevation, for example, in an experimental setup such as a roof or a scaffold.

The virtual reality (VR) technology that emerged and was developed during the last two decades provided an opportunity for conducting research at simulated elevated workplaces without the risk of injury. However, a systematic preliminary research project was needed to develop and validate this approach before it could be used for practical applications. The efforts to develop and use the VR technology for fall prevention research included the following logically interconnected activities: preliminary studies at real height and development of the VR laboratory; validation studies of virtual models of height and elevated workplaces; and evaluation studies of new fall prevention strategies with the application of virtual models of elevated workplaces.

9.4.1 Efforts to Develop Adequate Models of Elevation

9.4.1.1 Preliminary Studies at Real Height

The development of adequate models of elevation and elevated workplaces could benefit from preliminary information on workers' perceptions and performance at height. Since an adequate balance control at elevation was critical to avoid a fall, a study was initiated to evaluate the effects of height exposure on workers' balance performance and perceptions under various support conditions. Earlier research had suggested that the open space at elevation may lead to postural instability and height vertigo (Bles et al., 1980). The height exposure was per se exposure to distant visual scenes in conditions deficient in close visual references (Lee and Lishman, 1975). One of the study hypotheses was that a close visual structure may serve as a frame of reference and act as a countermeasure to the height-induced instability.

The first stage of the study investigated the effects of deformable/unstable work surfaces, height, and visual references—two vertical bars and the balcony edges in the visual field periphery—on the standing balance of construction workers. The participants were tested in a laboratory setting under two surface conditions (firm and deformable), at three heights (0, 3, and 9 m), and under two visual conditions (with and without visual references). The second stage of the study investigated the effects of the roof work environment characteristics of surface slope, height, and visual reference on standing balance in construction workers. The participants were tested in a laboratory setting at four slopes (0°, 18°, 26°, and 34°), at two heights (0, 3 m), and under two visual conditions (with and without visual references). Postural sway characteristics were calculated using center-of-pressure recordings from a force platform. Workers' perceptions of postural sway and instability were also evaluated.

The results of the study indicated that height exposure without close visual references significantly increased all sway parameters. The destabilizing effects of height increased dramatically on deformable surfaces, while the presence of close visual references resulted in improved postural stability (Simeonov and Hsiao, 2001). Slope surface and height synergistically increased workers' standing postural instability. While workers recognized the individual destabilizing effects of slope and height, they did not recognize the synergistic effect of the two. Visual references significantly reduced the destabilizing effects of height and slope (Simeonov et al., 2003).

This preliminary study had two main implications. First, it provided supporting evidence for the effectiveness of some simple practical measures and strategies for improving workers' balance at elevation, such as the use of temporary level work surfaces and the proximal vertical reference structures as postural instability control measures during roofing work. Second, it provided a basis for the comparative evaluation of virtual models of elevated workplaces. In this respect, one limitation of this study was that it addressed only the physiological effects of height on balance during protected exposure to elevation. Conducting experiments with unprotected exposure to simulate existing work practices in a construction workplace would be ethically acceptable only in a model of elevation within a VR system.

9.4.1.2 The NIOSH Virtual Reality Laboratory

The NIOSH fully immersive VR laboratory was designed and built in 1996 and was upgraded to a digital format in 2010—it is among the largest in scale of its kind and is one of very few being utilized for occupational safety research applications in the country. At present, this laboratory, measuring 8.5 m (28 ft) × 10.7 m (35 ft) × 4.3 m (14 ft), is being utilized to better understand human behavior, physical responses, and decision-making skills under simulated conditions of elevated work, such as scaffolding, roofing, and ladder-use tasks.

The VR laboratory is equipped with a projection-based CAVE-type surround-screen virtual reality (SSVR) system (MechDyne Corporation, Marshalltown, Iowa), with three 4.0 (13 ft)×3.0 m (10 ft) rear-projection screens for the walls and a 4.0 (13 ft)×4.0 m (13 ft) front-projection screen for the floor (Figure 9.1). The projected images are generated and controlled by a PC with four graphic cards. The participants wear a pair of liquid-crystal shutter glasses that separate the left- and right-eye images that are being projected, making the images appear three-dimensional. A position tracking system tracks the head

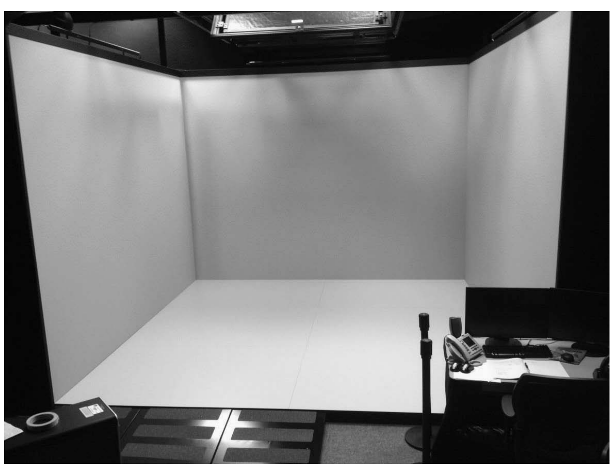


FIGURE 9.1
The NIOSH surround-screen virtual reality (SSVR) system.

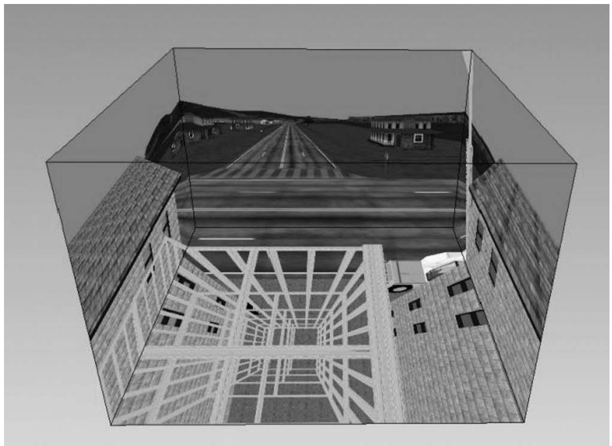


FIGURE 9.2
A SSVR model of a construction environment featuring restricted and elevated surfaces.

movements of the participants, and the image generator continuously updates the VR environment to give the subjects the right perspective. The fully immersive SSVR system, which has an active floor-projection screen and head-tracking functionality, is an excellent tool for the simulation of construction environments featuring restricted and elevated support surfaces (Figure 9.2).

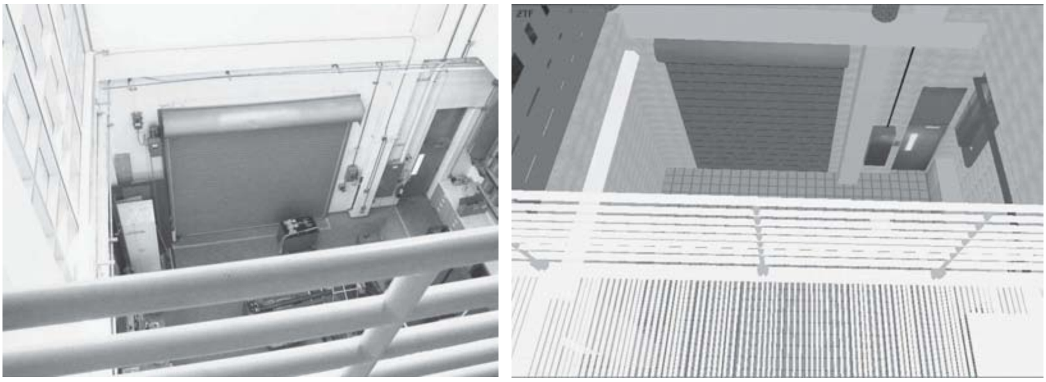
Other equipment used in the VR laboratory include a portable force platform (Accusway, Advanced Mechanical Technologies, Inc., Watertown, MA), an Optotrak-3020 motion measurement system (Northern Digital Inc., Waterloo, Ontario), and since 2010, a six-camera VICON motion measurement system (VICON, Oxford Metrics Group, Oxford, United Kingdom), as well as a Biolog Data Recorder (Biolog 3992, UFI, Morro Bay, CA) capturing users' physiological responses.

9.4.2 Validation Studies of Virtual Models of Elevated Workplaces

9.4.2.1 Comparative Evaluation of Real and Virtual Height Effects

Humans detect and recognize elevation and exposure to elevation exclusively by the available visual information. Elevation in the environment is perceived by the observer as a vertical distance from the surface of support to a lower surface, in other words, height perception is a special case of depth perception (Gibson and Walk, 1960). Exposure to elevation may induce a psychological effect of fear of falling, leading to physiological and behavioral protective responses, and it can also affect human balance control due to degraded visual stabilization. The visual nature of the height effects suggested that they could be successfully induced by computer-generated models in a VR system.

To test this idea, a study was designed to compare the human responses with height exposure in real and similar virtual environments of elevation. The NIOSH high-bay laboratory, with the 3 m and 9 m high balconies, used in the preliminary studies was selected as the real height environment, and a virtual model of the laboratory was created with reasonable detail in the NIOSH VR laboratory. The study 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 study hypothesis



(a) (b)

FIGURE 9.3
Exposure to elevation effects—validation study. View over the railing of a 9 m-high balcony: (a) Real height environment in the High-bay laboratory. (b) Virtual height environment in the SSVR system.

was that virtual and real height can induce similar perceptions, physiological responses, and postural instability effects.

The participants performed "lean-over-the-railing" and standing tasks on real and comparable virtual balconies, using the SSVR system (Figure 9.3). The results indicated that the virtual display of elevation provided realistic perceptual experience and induced some physiological responses and postural instability effects comparable with those found in a real environment (Simeonov et al., 2005). The study demonstrated that the simulation of elevated work environment in a SSVR system, although with reduced visual fidelity, is a valid tool for safety research. A direct follow-up from this study was the design of virtual models of scaffolding and a roof on a construction site for the safe evaluation of human performance and the assessment of new fall prevention strategies.

9.4.2.2 Augmenting Virtual Scaffolding Models with Real Planks

A scaffolding structure on a construction site is one of the most challenging work environments, involving the use of narrow and deformable or unstable planks as walking and working surfaces at height. Designing an adequate virtual model of a scaffold required careful consideration and representation of the properties of the supporting surfaces. A key question was whether a visual representation of a plank on the floor of the SSVR system was sufficiently realistic. The strong interactions between the destabilizing visual conditions at elevation and the properties of the support surface in the preliminary studies suggested that including a real plank in the virtual scaffolding model may provide a more realistic experience and improve the overall fidelity of the model.

To test this hypothesis, a study was designed to investigate the effect of adding real planks to virtual scaffolding models of elevation on human performance in the SSVR system. Construction workers and inexperienced controls performed walking tasks on real and virtual planks at three virtual heights (0, 6, 12 m) and under two scaffolding platform–width conditions (30 and 60 cm) (Figure 9.4). Gait patterns, walking instability measurements, and cardiovascular reactivity were assessed. The results showed differences in human responses to real and virtual planks in walking patterns, instability score, and heart rate interbeat intervals, and they supported the hypothesis that real planks in the virtual scaffolding models enhanced its realism (Hsiao et al., 2005).

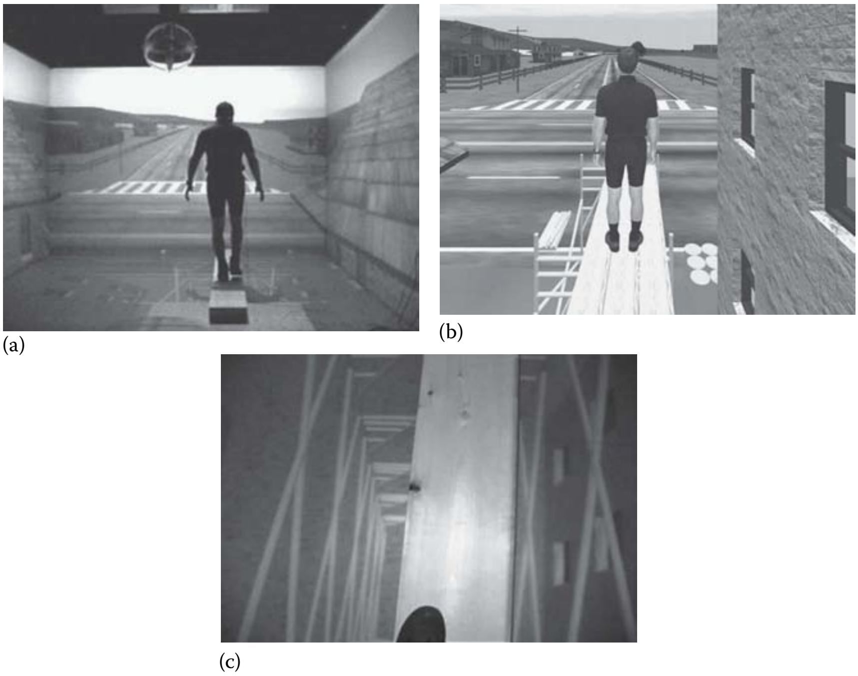


FIGURE 9.4
Virtual model of elevated and restricted surface (scaffolding)—validation study. (a) A participant on a virtual scaffold with a real wood plank. (b) A participant on a virtual scaffold with virtual planks. (c) A view over the edge of a real scaffolding plank at virtual height.

This study had two main implications: First, it suggested a new element of a comprehensive fall prevention strategy—the significant differences in performance between construction workers and the control group implied that inexperienced construction workers may benefit from a program of balance-control training in simulated environments before entering a construction job at elevation; second, it provided supporting experimental evidence for the adoption of augmented virtual models of elevated construction environments for the purpose of injury-prevention research.

9.4.3 Evaluation Studies Using Virtual Models of Elevated Workplace

9.4.3.1 Footwear Effects on Balance at Restricted and Elevated Surfaces

Simple measures to improve workers' balance at elevation can serve as efficient interventions for the reduction of fall incidents and injuries. As already mentioned, appropriate use of visual references is one of the very effective strategies for balance control at elevation. Although inexpensive, such an approach still requires some environment and behavioral modifications and thus the involvement of the worker. A strategy of using passive controls, which minimize worker involvement, is more promising since it guarantees automatic compliance. For example, appropriate design modification of personal protective equipment, including work apparel and shoes, may improve balance control by enhancing critical aspects of the available sensory information (Hsiao and Simeonov, 2001).

Due to the visually induced instability at elevation, a worker's postural control system relies heavily on proprioceptive inputs from the feet. Shoes act as a sensory interface between the worker's feet and the support surface, and their design can modify balance control (Menz and Lord, 1999). To evaluate the importance of shoe type and style as a potential balance-control intervention in an elevated construction environment, a study was designed using a virtual model of a sloped residential roof in the SSVR system (Figure 9.5). To enhance the realism of the simulation, the virtual model was augmented with real roofing planks (15 and 25 cm wide), which were used as walking surfaces. The study hypothesis was that shoe design may be essential for adequate control of balance on a narrow walking surface at elevation.

Construction workers were tested while walking on the narrow planks at a virtual residential roof in the SSVR system (Figure 9.6). Dependent variables included three athletic and three work shoe styles (Figure 9.7) and walking surfaces with different widths and lateral slopes. The angular velocities of the trunk and the foot in the medial–lateral direction

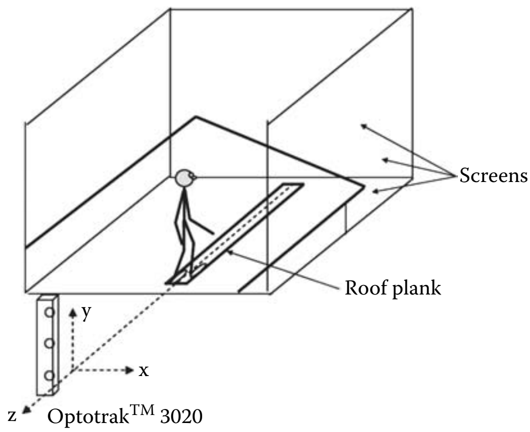


FIGURE 9.5
Footwear effects on walking stability at restricted and elevated surface—evaluation study. Schematic diagram of the virtual roof setup with a real wood roofing plank in the SSVR system.

FIGURE 9.6
Footwear effects on walking stability at restricted and elevated surface—evaluation study. Virtual roof environment with a participant on a roofing plank.

(a)

(b)

FIGURE 9.7
Footwear effects on walking stability at restricted and elevated surface—evaluation study. The test shoes: (a) work shoe styles, from left to right: low-cut work shoe; work boot; safety boot; (b) athletic shoe styles, from left to right: running shoe; tennis shoe; basketball shoe.

were calculated from data recorded with a motion measurement system. Workers' perceptions of instability were assessed with a computerized visual analogue scales.

The results demonstrated that shoe style significantly affected workers' walking instability at elevated work environments and highlighted two major shoe-design pathways for improving walking balance at elevation: enhancing rear foot motion control; and improving ankle proprioception (Simeonov et al., 2008). The study adds to the knowledge in the area of balance control by emphasizing the role of footwear as a critical human–support surface interface during work on narrow surfaces at height. The results can be used for footwear selection and footwear design improvements to reduce the risk of falls from elevation.

9.4.3.2 Vibration Effects on Balance at Restricted and Elevated Surfaces

The risk of falls from height on a construction site increases under conditions that degrade workers' postural control. At elevation, workers depend heavily on sensory information from their feet to maintain balance. Prior research suggested that imperceptible random vibrations applied to the feet can improve the feedback from the pressure receptors and lead to a more stable posture, especially in conditions with reduced visual input (Priplata et al., 2003). A study was designed to test the "sensory enhancement" hypothesis that subsensory (undetectable) random mechanical vibrations at the plantar surface of the feet can improve a worker's balance at elevation; and an alternative "sensory suppression" hypothesis that suprasensory (detectable) random mechanical vibrations can have a degrading effect on balance in the same experimental settings.

Workers were tested while standing in standard and semitandem postures on instrumented gel insoles, which applied sub- or suprasensory levels of random mechanical vibrations to the feet (Figure 9.8). The tests were conducted in a SSVR system, which

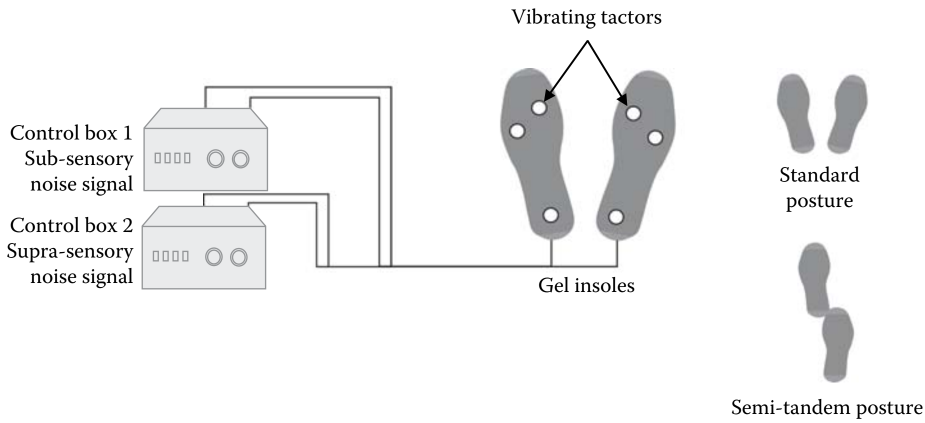


FIGURE 9.8
Vibration effects on balance at restricted and elevated surface—evaluation study. The instrumented gel insoles experimental setup.

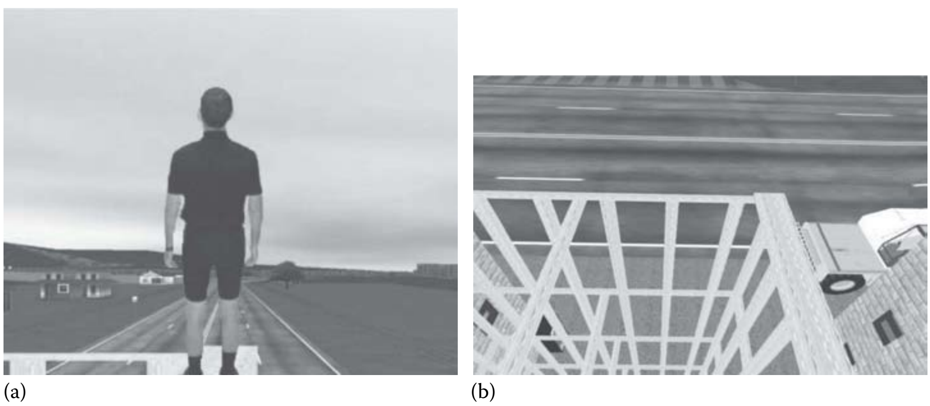


FIGURE 9.9
Vibration effects on balance at restricted and elevated surface—evaluation study. Experimental setup in the SSVR system. (a) A participant on a restricted surface at simulated elevation. (b) A view over the edge of a restricted surface at virtual height.

simulated a narrow plank at elevation on a construction site (Figure 9.9). Upper-body kinematics was assessed with a motion measurement system. Postural stability effects were evaluated by conventional and statistical mechanics sway measures as well as trunk angular displacement parameters. The results did not confirm the "sensory enhancement" hypothesis but provided evidence for the "sensory suppression" hypothesis. The suprasensory vibration had a destabilizing effect, which was considerably stronger in the semitandem posture and affected most of the sway variables (Simeonov et al., 2011).

There are several practical implications from this study. Sensory suppression associated with vibration in a supporting structure at a construction site may increase the risk of losing balance. Construction workers at height might be at elevated risk of falling if they can detect vibrations under their feet. This risk may be significantly increased when they are in a more unstable posture (on a beam or narrow plank). To reduce the possibility of losing balance, mechanical vibration to the supporting structures used as walking/working surfaces should be minimized when performing tasks at elevation.

9.4.4 Methodological Limitations and Future Research

The reviewed VR validation research addressed the following major issues related to the virtual modeling of elevated workplaces: postural stability and fearful responses during elevation exposure, and responses to tactile augmentation with real walking surfaces. The level of understanding of these key aspects and the associated limitations in virtual modeling development and evaluation will determine, to a great extent, the validity of any future research applications.

The similarly increased postural instability at both real and virtual elevation as compared with that at ground level is related to deficient visual information; however, the underlying causation mechanisms in both environments are different. While postural instability at real heights is the result of exposure to distant visual scenes and references, instability in the virtual height simulation is related to a different set of visual information deficiencies in addition to the distant references, including image resolution, contrast, and refresh rate or, in other words, reduced visual fidelity. In this respect, for certain tasks, the destabilizing effects of a virtual height model may be overrepresented. Overall, virtual elevation modeling still remains a very safe and efficient research methodology for the evaluation of instability control measures in dangerous workplaces. The fast progress in digital technology and the constant improvements in the visual fidelity of digital imaging will improve this aspect of the virtual height models.

The comparable anxiety and skin conductance responses to height exposures at real and virtual environments demonstrate the viability of the modeling approach. The reduced danger perceptions at virtual height, however, and especially the lack of heart rate response, indicated some deficiencies in the models. A defining factor is the lower level of visual fidelity of the simulation, which is also reflected in the reduced height/distance perceptions in the virtual model. The low danger levels of the simulated protected exposure in the validation study may have also contributed to the absence of heart rate response. Another powerful factor in VR is the associated level of presence—awareness of the laboratory setup and the simulated exposure can significantly reduce danger perceptions. Overall, it is reasonable to consider that the levels of induced postural threat and the corresponding fearful responses from exposure to virtual height models will be generally underrepresented. Further improvements in VR technology will lead to an increased sense of presence and ultimately more realistic danger perceptions.

The augmented virtual models with real walking surfaces enhanced both the visual and the somatosensory feedback and thus improved the overall sensory fidelity of the virtual model. However, the presence of a real object in the virtual world could be a distraction and thus reduce the sense of presence in the participants. The cost/benefit balance between distraction and enhancement effects from adding a real object in a virtual environment depends exclusively on the specific application. For the walking tasks during height exposure on a scaffold, the presence of real planks with visible edges and unstable/deformable walking surfaces provided improved fidelity both for walking instability and fearful responses.

The success and validity of future studies using VR models of elevated workplaces will depend on many factors, defined by the specific research goals and objectives of the investigation. Careful consideration of the benefits and limitations of this methodology is needed to design a study with optimal outcomes. Some of the future projects at virtual height may address ladder design modification effects on transitioning tasks at elevation; work–rest cycles and task-related fatigue interactions with height; and specially designed exercise programs as potential balance control enhancing interventions. Other potential research applications may include the development and evaluation of balance control screening procedures to detect and warn of dangerous personal conditions before work at elevation is initiated.

9.5 Other Related Research Using Real Models of Height

In recent years, exposure to height has become a well-established research paradigm for inducing postural threat. A growing number of research studies have used experimental setups of restricted and elevated surfaces to study postural behavior under conditions of increased postural threat (Adkin et al., 2000, 2002; Brown et al., 2002; Caetano et al., 2009; Carpenter et al., 1999, 2001; Davis et al., 2009; Delbaere et al., 2009; Sibley et al., 2007; Tersteeg et al., 2012). Most of these studies have been directed to identify postural control mechanisms, aiming toward an understanding how fear of falling, especially among the elderly, might influence postural control. Overall, the studies have suggested that postural control is modulated according to the degree of the impending postural threat and that the postural accommodations that occur would serve well to reduce the risk of falling (Brown et al., 2002).

The experimental methods in these studies have included setups with relatively low threat levels, for example, standing 50 cm away from the edge of a 160 cm-high platform (Adkin et al., 2000); or walking on restricted surfaces at elevations of less than 60 cm (Caetano et al., 2009; Delbaere et al., 2009; Brown et al., 2002). In setups with higher threat levels, such as standing at the edge of a platform with heights of up to 3.2 m (Davis et al., 2009) or walking on a 22 cm-wide surface at height of 3.5 m (Tersteeg et al., 2012), the participants have been protected by fall-arrest equipment. Along with young and healthy individuals (Adkin et al., 2000; Davis et al., 2009; Brown et al., 2002; Tersteeg et al., 2012), the test participants have included elderly subjects (Brown et al., 2002; Caetano et al., 2009; Delbaere et al., 2009), height-fearful subjects (Delbaere et al., 2009), and participants with pathological conditions (Caetano et al., 2009).

The findings of these studies indicate that postural threat triggers protective responses. Such responses for standing trials have been characterized with tighter postural control, described by smaller amplitude and higher frequency of COP displacements as compared with standing on the ground (Adkin et al., 2000). In walking trials, responses include an increase in the double-support phase, reduced velocity, reduced step length, and reduced cadence (Brown et al., 2002; Caetano et al., 2009; Delbaere et al., 2009). Overall, the reviewed research suggests that the postural control responses and the mechanisms associated with danger perceptions serve as a very powerful and effective fall prevention strategy. However, the direct applicability of the results from these studies for the prevention of falls from elevation may be limited—it is known that experienced workers in construction are well adapted to working at elevation, and as a consequence their danger perceptions are generally low.

Some of the limitations of the studies with real height models are that they use either conditions with low danger exposure or conditions with protected exposures. Exposing participants to lower heights may not be sufficiently dangerous and thus may induce some anxiety but not real fearful perceptions—it has been suggested that fear and anxiety are associated with two different postural behaviors (Davis et al., 2009). Harnessing the participants in studies with exposure to higher elevations affects their knowledge of the consequences of a potential fall and therefore reduces their danger perceptions and consequently affects their postural behavior. Furthermore, the full body harness and the attached lanyard might also affect their movement strategies to some extent.

Another limitation of the real height models is that, in laboratory conditions, they cannot recreate the visual exposure of an elevated workplace, characterized by open space and distant visual references, and therefore they cannot account well for some of the visual effects of height. Since these studies were not directed to understand and prevent falls from elevation, their experimental setups did not try to simulate all aspects of a dangerous workplace at elevation, include the use of experienced construction workers as test subjects, or to test appropriate fall prevention strategies.

9.6 Measures to Control Falls from Restricted and Elevated Surfaces

9.6.1 Fall Protection Measures

Applying fall protection measures remains the required practice for controlling the risk of fall injury during construction work on restricted and elevated surfaces (OSHA, 1995). However, short-term construction work on restricted and elevated surfaces usually associated with temporary and unfinished structures, presents a number of challenges for the effective application of fall protection systems. Some of these challenges and the available solutions are discussed in the OSHA's Fall Protection Directive STD 03-11-002 "Compliance Guidance for Residential Construction" (OSHA, 2011) and the related preceding documents.

Fall protection measures are directed and designed to reduce the dangerous consequences of a fall after it has initiated, to reduce the risk of impact injury by controlled transfer of the kinetic energy of the falling body to a supporting structure. A broader view is to recognize that a fall event can be characterized by three phases: initiation, descent, and landing (Hayes et al., 1993). With this classification, the initiation phase uses protective barriers and fall restraint systems. The descent phase uses fall-arrest systems, catch platforms, and safety nets; and the impact phase uses soft landing systems.

Fall protection systems have also been classified as collective and individual, passive and active by their protective range and the need for user action in achieving their protective function (Sulowski, 1993). Collective fall protection systems (protective barriers, catch platforms, nets, and soft landing systems) are generally passive, while individual fall protection systems (fall-arrest and restraint systems) are mostly active. From a design perspective, collective fall protection systems can also be described as environment-oriented interfaces, while individual fall protection systems can be considered as human-oriented interfaces. The environment-oriented interfaces are engineering control systems designed to guard or modify the hazard, while the human-oriented interfaces are personal protective equipment systems guarding the human.

All these classes of fall protection system have their advantages and disadvantages and their optimal application areas as related to controlling the fall injury risk on restricted and elevated surfaces. Furthermore, numerous products are available and new products are continuously being introduced to the market, providing flexibility in the selection and implementation of an effective fall protection approach. Collective and passive systems controlling the fall initiation are preferred but are not always practical for use on restricted and elevated surfaces. Simplicity of operation, reliability, cost-effectiveness, efficiency, requiring minimal time for installation and removal, and having minimal interference with the work task, would be among the desired features of an optimal fall protection system.

The most common fall protection measure used to control the fall risk on restricted and elevated surfaces remains the fall-arrest system. The fall-arrest system is an active, individual fall protection system consisting of a full body harness, a lanyard, and an anchor point. The anchor point remains the most critical element in the system because its installation has to be customized for the specific environment. Selecting or designing an appropriate anchor point is not a trivial task, and usually requires careful work-task analysis and environment-specific engineering design solutions. Adequate preplanning is a key requirement for the proper selection and installation of anchor points and the safe application of a fall-arrest system (NAHB, 2007). Many light temporary structures may not be sufficiently strong and stable to support a fall-arrest anchor—in such cases a structure-independent fall-arrest anchoring system may be needed.

An effective alternative solution to the use of fall protection for controlling the fall risk on restricted and elevated surfaces is the application of strategies to reduce or eliminate the fall hazard by using equipment for work at elevation and by modifying the construction work process.

9.6.2 Hazard Elimination Measures

Aerial lifts have become the equipment of choice for work at elevation in construction, maintenance, and repair jobs. Aerial lifts eliminate the need for work on restricted and elevated surfaces by providing convenient and flexible access to elevated locations with a controllable and protected platform. Scissor lifts, telescoping and articulating boom lifts, and a variety of other personnel aerial lifts have been suggested as a safer alternative measure to working at elevation (OSHA, 2011). Aerial lifts are designed for safe operation; however, proper training is an important safety requirement for lift operators. One limitation of the aerial lifts is that they are heavy equipment that requires road access around a structure, which may not always be available on small construction sites with light structures. In addition, some contractors may not be able to afford such equipment, and renting it for small construction projects may be economically infeasible (OSHA, 2011).

The best fall risk control solution would be to reduce or eliminate the need to work at elevation altogether by preplanning the construction process and applying constructability and safety-in-design principles. Constructability analyses can be applied to identify tasks that can be finished on the ground. Furthermore, implementing safety-in-design principles may reduce the need for work at elevation both in the short term during the construction process and in the long term during maintenance (Toole and Gambatese, 2008). For example, roof truss assembly on the ground has been suggested as a construction practice that can eliminate or reduce the need for standing and working on restricted and elevated surfaces such as wall top plates and trusses (NHAB, 2007).

9.7 Conclusions

Falls from elevation remain a persistent occupational injury problem, mainly associated with construction activities. On construction projects, workers are frequently exposed to restricted and elevated surfaces without any protection. Furthermore, these conditions present a considerable challenge for the workers' postural control systems and therefore increase their risk of falls. Conducting research on falls from elevation to identify risk factors and test fall prevention strategies remains a challenging research area due to the associated injury risk for both researchers and test participants.

The NIOSH fall prevention research program established a cornerstone in VR technology applications. The reviewed research studies provide a theoretical and methodological background for using VR as an adequate tool for simulating elevated construction workplaces. Furthermore, the studies deliver direct results of practical significance in fall prevention. Future VR applications will benefit from the enhanced fidelity of the subsequent generations of displays, improved computer graphics, and increased computing power.

Workers do not always correctly perceive the increased instability associated with height exposure on restricted and unstable support surfaces, which may increase their risk of loss-of-balance and fall incidents. Taking advantage of existing or enhanced visual references may be an effective approach to improving workers' balance at elevation. Other effective strategies to improve workers' balance at elevation may be the adequate selection of shoes, which act as sensory interfaces between the foot and the support surface; and avoiding or eliminating conditions such as detectable vibration in the support surface, which can degrade sensory inputs.

Fall protection remains the required practice for controlling the risk of fall injury during construction work on restricted and elevated surfaces; however, the short-term work on temporary or unfinished structures presents a number of challenges for the effective application of these systems. The best strategy to control falls from restricted and elevated surfaces is to modify and reduce the hazard by using safer equipment for work at elevation, or to completely eliminate the hazard by preplanning the construction process and applying constructability and safety-in-design principles.

9.8 Disclaimers

The findings and conclusions in this report are those of the author and do not necessarily represent the views of the National Institute for Occupational Safety and Health (NIOSH). Mention of any company or product does not constitute endorsement by NIOSH. In addition, citations to websites external to NIOSH do not constitute NIOSH endorsement of the sponsoring organizations or their programs or products. Furthermore, NIOSH is not responsible for the content of these websites. All web addresses referenced in this document were accessible as of the publication date.

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