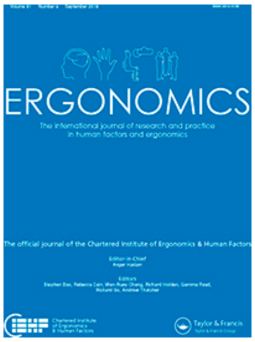

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Preventing falls from roofs: a critical review

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Keywords: Fall; balance control; roofer; visual cues; virtual reality.

Work-related falls from roofs remain a significant problem for workers in the construction industry. Knowledge about the main causative or initiating factors leading to fall incidents is desperately needed for fall prevention intervention. From biomechanical and psychophysiological perspectives the majority of occupational falls, including falls from roofs, can be regarded as loss-of-balance incidents. The primary objective of this paper is to summarize the current knowledge from multiple fields about factors that are related to the control of balance during roofing work. An extensive literature review identified a number of environmental, task-related and personal factors that degrade the control of balance and could be associated with the initiation of falls from roofs. These factors include visual exposure to elevation; unstable visual cues and inadequate visual information in the work environment; 'confined' and inclined support surfaces; unexpected changes in roof surface properties; load handling; physical exertion; fatigue; task complexity that diverts workers' attention; individual differences; work experience and training; and personal protective equipment. Current measures to reduce falls from roofs focus mainly on fall protection procedures, such as the use of covers, guardrails, safety nets, and personal fall-arrest systems, or the application of warning-line systems, safety monitoring systems, and fall protection plans. In many instances, these procedures are not practical for the industry and current regulations allow the use of alternative means of fall protection, such as slide guards. Future research on preventing falls from roofs should consider the main effects and interactions of the environmental, task-related and personal factors that affect the balance control of workers. Research-supported improvements in the visual and physical characteristics of the roof work environment, the construction materials and methods, and work procedures and practices may result in improved workers' balance control as well as overall safety performance, and would ultimately reduce incidents of falling from a roof.

1. Introduction

Falls from roofs constitute the leading cause for work-related fall fatalities, and they represent more than one-fifth of all occupational fatal falls (Bureau of Labor Statistics [BLS] 1997b). Analyses of occupational fatality data between 1994 and 1996 indicate an increasing trend in the number of fatal falls from roofs during construction (BLS 1996, 1997a, b). The occupation of roofers has been rated as one of the most dangerous occupations, with a fatality rate of 29 per 100 000 workers

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(Toscano 1997). Roofers are at about six times higher risk for fatal occupational injuries than the average worker, with falls being fatal events in 75% of cases (Ruser 1995). Additionally, falls from roofs are a serious cause of non-fatal injuries in the construction industry. In 1996, an estimated 2550 serious injuries (with days away from work) in the USA were due to construction-related falls from roofs (BLS 1998b). The injuries caused by falls from roofs are typically extremely severe, requiring long periods of treatment and recovery and resulting in substantial medical costs (Parsons and Pizatella 1985, Gillen *et al.* 1997).

Continuing improvement in work practices on roofs is needed to reduce roofer-fall incidents. This can be achieved first by identifying, understanding and controlling the fall-initiation factors during roofing work.

1.1. *Definition of roofers*

According to the Bureau of Labor Statistics the number of roofers (roofing workers) in the USA in 1995 was 205 000, which was approximately 2.8% of the workforce employed in the construction industry (BLS 1997b). Other construction workers such as construction labourers, carpenters, and general contractors are also involved in roofing work, especially in residential construction. Furthermore, special-trade contractors who perform siding, plumbing and heating/air conditioning, etc. may also work on roofs. This paper focuses on these professional occupational roofing workers; 'fixing your own roof' is not included in these cases. It is estimated that the number of construction workers who are at risk for falls from roofs is well over half a million.

1.2. *Characteristics of roofing work*

Roofing work includes roof construction, repair, renovation and maintenance. The complexity of the work depends on the construction method, roof style and geometry, and the roofing materials applied. Residential roofing work typically includes tasks such as cutting, aligning and attaching plywood sheets, asphalt felt, shingles, flashing, and accessories to the roof structure. Commercial and industrial roofing often involves some of these tasks. This work is characterized not only by constant exposure to elevation, but also by manual handling of heavy and bulky materials (sheets of plywood, rolls of felt, bundles of shingles, and others). In addition, walking, reaching, stooping, crouching, and kneeling on sloped roof surfaces, on narrow planks, or along the edge of the roof, are very common (Department of Labor [DOL] 1993).

1.3. *Current literature on the causes of occupational falls from roofs*

Although current literature on falls from roofs provides us with good knowledge of injury frequency and circumstances, for example falls from roof edge and falls through roof structure (National Bureau of Standards [NBS] 1975, Cloe 1979, O'Gara 1982, Parsons and Pizatella 1985, Culver and Connolly 1994, Suruda *et al.* 1995), information on risk factors of occupational falls from roofs is still very limited. Johnson and Pain (1987) discussed this problem in a review of research on occupational falls. They found that the majority of literature is anecdotal or 'advice-giving' and that there is little empirical information about the relative importance of the factors involved in fall incidents.

Attempts have been made by some authors to identify critical tasks and activities leading to falls from roofs. Hsiao and Stanevich (1996) discussed the most hazardous activities for roofers' work in construction and reviewed potential ergonomics concerns including fall prevention and protection. Cloe (1979) reported that 89% of falls from roofs occurred while the workers were performing their normal job activities, such as installing roofing material, walking from one work area to another, moving materials or equipment, working at the edge of the roof surface or an opening, and backing off the edge. Parsons and Pizatella (1985) reported that falls from roofs occurred while workers were walking forwards or backwards (36%), standing (18%), kneeling (21%), climbing (7%), and handling materials (14%).

While the exact triggering factors leading to fall incidents are rarely found in the literature, fatality investigation reports, or worker compensation descriptions, the most commonly mentioned initial reasons for falls were slips, trips and losses of balance. Workers either slipped while walking, or lost their balance while on the roofing surface, or lost their balance when surface materials slipped, for example roofing shingles lying on the roof slipped (Parsons *et al.* 1986). Stepping on loose materials on pitched roofs, resulting in slips off the roof edge (Suruda *et al.* 1995), steep roofs causing slip or imbalance (Parsons and Pizatella 1985), and inadequate workers' perceptions of the strength and load-bearing capacity of skylight elements (National Institute for Occupational Safety and Health [NIOSH] 1989, Bobick *et al.* 1994) were also reported as common incidents.

1.4. *Association of roofing work and balance control*

The above mentioned slips, trips and imbalance episodes can all be regarded as loss of balance incidents. They occur when one or several modes of the proactive and reactive mechanisms of worker balance control are disrupted during worker-environment interactions (Patla 1997b, Woollacott and Tang 1997). The proactive mechanism of balance control, modulated mainly by visual information, 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 activation of postural adjustments *after* an external disturbance is encountered, thus enacting balance recovery (Patla 1993).

Balance control on roofs is important not only for standing or walking but also for other activities. Handling heavy and bulky materials as well as operating equipment on 'confined' surfaces make the control of balance challenging. Temporary work environments, more specifically the incomplete support surfaces on roofs, require workers' careful attention. Working on inclined, compliant and sometimes slippery surfaces demands intensive controls to maintain a posture and avoid balance disturbances. Walking on narrow beams and planks as well as working close to edges and around openings also requires constant and precise controls of balance.

1.5. *Objective*

This paper summarizes the current knowledge from multiple fields about environmental, task-related and personal factors that can be applied to the control of balance during roofing work. Current measures to reduce the potential for loss of balance during roofing work are discussed. New ideas for future research are suggested.

2. Methods

A list of papers on the topic of falls among roof workers was obtained using searches of computerized literature databases. The search used *Ergonomics* Abstracts, NIOSHTIC, MEDLINE, PSYCINFO, and COMPENEX. The strategy was to find papers concerned with falls or balance control during roofing work. Since literature on balance control during roofing work is somewhat limited, the search was extended to include human balance control studies in other industries that may be applicable to roof work. Manual reviews of the journals where studies on this topic have typically been published were also performed. These papers identified in the initial search were screened using three criteria: (1) they presented new data or a synthesis of a selected group of studies; (2) they concerned falls or balance control; and (3) they dealt specifically with roofing workers, or the study results were applicable to roofing work. Only those reviews with substantial documentation were included; papers that were mainly based on the authors' opinion, and simplistic 'how to' papers were excluded. Original papers, as opposed to abstracts, were reviewed. Attention was given to three main topics: findings about suspected risk factors; findings about measures for reducing fall risk; and research gaps about roofer-fall prevention.

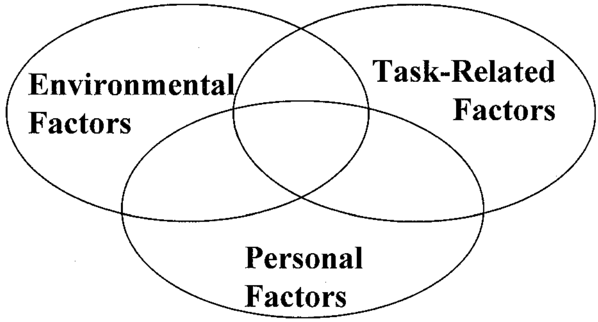
3. Results: factors involved in the control of balance during roofing work

The results are organized into three categories: environmental factors; task-related factors; and personal factors involved in the control of balance that are associated with falls from roofs (figure 1). The environmental factors concern the information available from visual and physical interactions. The task-related factors include load handling, physical exertion and fatigue, and complexity of tasks. The personal factors include individual differences, work experience, and interaction with personal protective equipment (PPE).

3.1. *Environmental factors*

During daily work, workers maintain their balance through visual and physical interactions with work environments. The visual information affects the mechanisms of balance control (Owen 1985, Wade and Jones 1997) and is especially important for the proactive control of balance (Patla 1997a). The physical interaction with work environments, which is mediated by the somatosensory and the vestibular systems, can affect the modes of the reactive control of balance (Woollacott and Tang 1997).

3.1.1. *Visual interactions with the environment*: The visually perceived information from work environments is used in a feedback mode to control human body sway during standing or walking, or in a feed-forward fashion for guiding locomotion and avoiding obstacles (Patla 1997a). Many factors in a visual environment, such as structure and illumination of the visible surroundings, the distance between eye and the closest object in the visual field, the distance between eye and the object stared at (visual target), visual target size and contrast, and retinal location of the visual scene, affect these balance controls (Paulus *et al.* 1984). The task that is performed (Warren *et al.* 1996) and personal characteristics of the worker, such as visual acuity (Paulus *et al.* 1984) also significantly alter the posture control of a worker in responding to visual environments. For roofing work these visual information effects can be



Environmental Factors

Visual interactions
- elevation
- moving visual scenes
- depth perception and visual ambiguity
- visual detection of obstacles and property changes

Physical interactions
- restricted support surfaces
- inclined support surfaces
- material properties of the surface of support (friction, contaminants, evenness, firmness)

Task-Related Factors

- load handling
- physical exertion and fatigue
- complexity of task and attention

Personal Factors

- individual differences
- work-job experience and training
- personal protective equipment

Figure 1. Factors involved in the control of balance during work on roofs.

organized into four categories: elevation effect; moving-visual scenes effect; depth-perception effect; and obstacle-detection effect.

3.1.1.1. *Elevation*: The literature reviewed provides evidence that exposure to elevation affects balance; the effect is associated with deficit of close visual contrasts and fear of falling. Workers involved in roof construction are constantly exposed to visual environments of elevation. A visual environment of elevation is characterized by a lack of close visual contrasts (cues), 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 double layers of foam rubber). 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 contracts (provided by peripheral vision) prevent the instigating sensory mismatch (Brandt *et al.* 1980). Citing Bles's work, Paulus *et al.* (1984) reported that postural instability due to height effect begins at 3 to 4 m eye height.

Visual exposure to close-by unguarded edges on elevated support surfaces can affect workers' balance through fear-related behavioural 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. It has been associated with enforced tight control over centre of mass (COM) kinematics (Brown and Frank 1997), selection of a wider base of support (BOS; Maki *et al.* 1994), reduced stride length and velocity (Maki 1997), and enhanced gain of the vestibular-ocular reflex (Yardley *et al.* 1995). The level of anxiety experienced 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 fall from elevation may include worker's task and posture, distance to the edge of the elevated support surface, availability of fall protective devices and barriers, and stability of the structure (Cloe 1979, Suruda *et al.* 1995, Janicak 1998). The perceived factors that determine the severity of injury from a free-fall are 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).

3.1.1.2. *Moving visual scenes*: 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 (four times, with amplitude almost three times greater than the stimulus) and caused occasional falls in their test subjects. While on the roof, the 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 workers' balance.

3.1.1.3. *Depth perception and visual ambiguity*: The perception of depth is a complex process involving the unconscious integration of multiple visual cues. Some of the sources of information for perception of depth include binocular cues (e.g. stereopsis, convergence and accommodation) and monocular cues (interposition, linear perspective, familiar size, relative size and motion parallax; Clark *et al.* 1996). The depth perception is accomplished by interaction of some of these cues in a process called fusion. Conflicts between cues are resolved by 'vetoing' in which the strong cue overrides the weak cues. Misperception in depth may cause loss of balance and may precipitate falls; many fall incidents are commonly caused by misjudgement of distance (Clark *et al.* 1996). Lasley *et al.* (1991) demonstrated that stereo-ambiguous visual stimuli such as caused by an escalator tread may give rise to false fusion (an inappropriate angle of visual convergence), and cause postural instability and disorientation, which may result in a fall. They also suggested that visual ambiguity may be caused by periodicity in the visual targets, e.g. stairs, steps, carpets and tiles. Visual environments on roofs involve various periodical patterns, e.g. layers of shingles, which may cause visual ambiguity and deterioration in the normal control of balance.

The process of human locomotion does not require constant visual control (Patla 1997a), and often is regulated by the short-term memory of visual perceptions. Rieser *et al*. (1990) demonstrated that the accuracy of walking without vision to previously seen targets is closely calibrated to visually perceived distance. Recently, Sinai *et al*. (1998) reported that the terrain influences the accurate judgement of distance; gaps in the ground or distinct texture regions may impair distance judgements. The visual environment of unfinished roof surfaces includes gaps and distinct texture regions, which may cause erroneous perception of distance and precipitate falls by disrupting the proactive control of balance.

3.1.1.4. *Visual detection of obstacles and property changes*: Visual detection of obstacles and changes in the properties of the surfaces used as support on the roof is critical for the proactive control of balance. Obstacles are defined as objects in the 3D environment which are in the trajectory of anticipated movement (e.g. piles of materials, power cords, tools and instruments, roof elements, etc.). Changes in the properties of the roof surfaces may include changes in their geometry (e.g. extent, incline, openings, and edges) or changes in their material properties (e.g. friction, firmness) caused by weather conditions or worker activities. Successful proactive detection of these potential hazards is possible only if they are associated with significant change in optical properties (visual cues), which distinguish them from their surroundings. Furthermore, detection depends on worker visual attention and the parameters that define worker visual field (e.g. gaze direction, focal distance, etc.) in relation to a task. Zohar (1978) reported that the probability of bumping into an object is a function of the optical angle between the object and the axis of the person's effective visual field. Manipulating the walker's line of sight by environmental factors should radically reduce stumbling and falling incidents (Owen 1985).

Successful recognition of potential hazards in the visual environment (e.g. fragile roofing materials and elements or slippery areas) also depends on personal factors, such as the prior experience and knowledge of the worker. Knowledge acquired through past experience plays an integral role in interpreting visual information, therefore both visually observable and visually inferred properties of the environment influence the avoidance or accommodation-strategy selection and implementation (Patla 1997a).

3.1.2. *Physical interactions with the environment*: Successful task performance on roofs would not be possible if the work environment does not afford an adequate support surface. To provide support for the worker, a surface must have adequate extent, inclination (orientation to the force vector defined by the gravitational and the inertial forces acting on the worker's body), friction, firmness (resistance to deformation), and flatness (Stoffregen and Riccio 1988). This section describes the impact of restricted support surfaces, inclination of surfaces, and properties of the surfaces on balance control during roof work.

3.1.2.1. *Restricted support surfaces*: In roof construction, workers frequently stand or walk on narrow planks, beams, and rafters, and may work close to unguarded edges and openings in the roof surface. Narrow surfaces, supporting only part of the foot, may diminish or eliminate the somatosensory input, subserving the normal mode of postural control. In such conditions, the human posture control system relies heavily on visual inputs (Amblard *et al.* 1985); where there is a lack of close visual cues or a fixation on moving structures, there is a high potential for imbalance and fall. In addition, perturbation studies in standing (Maki *et al.* 1996) have shown that a sudden displacement of the base of support 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.

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 peoples' behaviour in the vicinity of elevated edges, Davis (1983) defined a 'bio-mechanically 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. Referring to a study conducted at the University of Michigan in the 1970s and to his own experiments, Ellis (1994) stated that workers can fall from a standing position over an edge within 183 cm by tripping, slipping, stubbing their toes, or other loss of balance. The distance of 183 cm from unprotected edges of flat roofs and rake edges of gable roofs was considered to be critical for workers' safety and is used in the current standard for fall protection in construction (US Department of Labor [DOL] 1999a) and in the Interim fall protection compliance guidelines for residential construction (Occupational Safety and Health Administration [OSHA] 1995).

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 over. However, the dose-response relation between the sizes of support and levels of balance-control degradation is not well studied yet.

3.1.2.2. *Inclined support surfaces*: Work on roofs is frequently performed on inclined support surfaces. Inclined support surfaces are associated with increased risk for mechanical perturbations of the BOS (slipping) during task performance due to potentially large shear forces at the shoe/floor interface. As the angle of inclination increases, shear forces along the surface have an increasing gravitational component (Harper *et al.* 1967). In a static case, shear forces would increase as a function of the cosine of the angle (Grieve 1979a, b, 1983). The required coefficient of friction (RCOF) is estimated by dividing the shear forces by the normal forces and is expected to increase as the tangent of the angle of inclination increases (James 1983). Peak RCOF has been used to determine the risk of slipping incidents on inclined surfaces (McVay and Redfern 1994). Redfern and McVay (1993) observed a linear increase of the maximum RCOF with increase in the angle of inclination. Peak RCOF increases from 0.15 for a flat surface to over 0.6 for a 20° incline and is consistently higher for walking upwards than for walking downwards. However, slips are more likely to occur in downhill walking, and at heel contact when the weight is being transferred from the back foot to the front foot. McVay and Redfern (1994) reported an increase in the shear forces not only during the initial contact but also through longer portions of the step as the ramp angle increased. These long periods of elevated shear force may be an important contributing factor to falls on inclined surfaces at greater angles. Working on steep roof surfaces may require extremely high slip-resistance characteristics for the shoe/floor interface to prevent slips-and-falls, and above certain slope angles, slip-resistance required will not be possible to achieve.

Human subjects appear to be able to perceive the slipperiness of a floor surface, and to modify their gait to mitigate the effects of slippery surfaces (Myung *et al.* 1993). In addition, people perceive the increased friction demand at sloped support surfaces and adjust their behaviour to reduce the risk of a slip when they step on sloped surfaces. Sun *et al.* (1996) observed that in uphill walking, people reduce the walking speed, the cadence and the step length in order to decrease their power demand associated with the increase in their potential energy and to reduce the risk of slips at the toe-off phase. In downhill walking, people reduce their step length in proportion to the slope angle to counteract the increased friction demand and reduce the risk of a slip at the heel-strike phase. Standing or walking on inclined surfaces is achieved very often with only a small reserve in the available COF relative to the RCOF; failure to detect small changes in the frictional properties of an inclined support surface or to control the velocity of the foot (and the applied tangential force) in a safe range may result in perturbation of the BOS (slip). Such perturbations are generally associated with disruptions of the proactive control of balance, and a fall will occur if the reactive control of balance cannot restore the equilibrium.

If a fall occurs the inclined support surface may not afford termination of the fall within the vicinity of the landing sites on the surface. Currently, there is no research specifying a critical inclination, for walking/working surfaces, that will afford secure landing (with or without sliding or rolling) in case of a fall. The installation of slide guards, described in the Interim fall protection compliance guidelines for residential construction (OSHA 1995) is a general practice to stop incidental sliding/rolling down.

For standing activities, postural balance is deteriorated with increased inclination of the support surface (Bagchee *et al.* 1997). Emerich *et al.* (1993) measured postural sway on sloped surfaces using a strain-gauge force platform to assess individuals' posture stability in simulated roofing tasks — forward and side-to-side lifting and standing, facing both up and down the slope. They reported that increase of the slope (from 0 to 14° and 26°) resulted in increased instability. The extent of subjects' instability is also associated with the task performed and the orientation of the body to the slope.

In summary, there is overwhelming theoretical and experimental evidence in the literature that inclined support surfaces increase the risk of slipping and thus fall incidents. However, the threshold level of the angle of roof inclination for workers to safely perform various roofing tasks has not been scientifically defined yet.

3.1.2.3. *Material properties of the surface of support (friction, contaminants, evenness and firmness)*: During task performance on roofs significant static and dynamic tangential forces are applied to the surface of support by the soles of the worker's shoes. To afford the safe transfer of these forces the interface between the surface of support and the shoe sole must have adequate slip resistance under various conditions. The slip resistance is defined by the material properties of both the surface of support and the shoe sole, and is also related to the dynamics of movement between the two surfaces. The measure of coefficient of friction (COF) is commonly used to describe the degree of traction between the sole and the surface of support. Both static and dynamic COFs have been used to determine slipperiness, but currently there is no universally accepted method or apparatus for slip-resistance measurements (Lin *et al.* 1995). Biomechanical analyses may be used to calculate required COF (RCOF) for adequate control of balance during task performance. The role of friction and slip resistance in the occurrence of falls has been extensively studied and reviewed in the scientific literature (Leamon 1992, Lin *et al.* 1995). While a safety threshold of COF is usually associated with a measurement method (Leclercq 1999), by consensus in the USA a safety threshold of 0.5 for the static COF (tested with the James Machine, Underwriters Laboratories, Inc., Northbrook, IL) is recommended to prevent a slip on a level walking surface (Redfern and Bidanda 1994, Lin *et al.* 1995).

Some of the currently used roofing materials, such as asphalt shingles and roofing rolls, may result in unstable surfaces due to the loosely attached sand particles. The frictional properties of these materials are not well defined and may change significantly with changes in environmental conditions (e.g. increased temperature), which may have an adverse effect on the control of balance. In addition, moisture from precipitation and condensation, snow and ice, mud from workers' shoes, wind-borne dust and dust from workers' activities may significantly alter conditions in the interface between the shoe and the surface of support. These altered support-surface conditions increase the risk of mechanical perturbation to the BOS (slipping). It may not be possible for shoe or material manufacturers to protect completely against slipping incidents on these type of surfaces (James 1983).

Uneven support and walking surfaces increase the risk for mechanical perturbations (e.g. slipping and tripping). Schieb (1995) reported that walkway unevenness causing a step up higher than 2.5 cm or a step down lower than 1.5 cm may contribute to initiating a trip, stumble, or fall, since the ground reaction forces (GRF) are significantly altered with these conditions. Unexpected and undetected change in the surface evenness will further increase the risk for falls. In a study on the critical kinematics of foot trajectory, Winter (1991) pointed out that at the time of minimum toe clearance (when the forward foot velocity is at its maximum, 4.5 m/s) an obstacle as little as 5 mm in height has the potential to cause a trip.

Material and structural characteristics of the working and walking surfaces on the roof define surface firmness and worker stability. Compliant support surfaces degrade a worker's normal reactive control over balance by distorting the proprioceptive information from the foot and ankle. It contributes to sensory conflict and thus increases a person's postural sway (Bles *et al.* 1980, Redfern *et al.* 1997). Asphalt roofing materials, especially in hot weather, become highly plastic.

Arranged in several layers, the materials may reduce the somatosensory inputs or provide misleading proprioceptive cues to the postural control system. Unexpected and unperceived changes in the firmness of the support surface may further affect the proactive and reactive control of balance and increase the risk of perturbations of the base of support (tripping). Furthermore, unstable support surfaces on the roof, such as poorly secured planks or rafters, may rotate or translate the forces being applied by the foot to an unexpected direction, and thus cause perturbations of the base of support.

3.2. *Task-related factors*

Workers on roofs perform multiple tasks, which typically require constant transitions in their postural and perceptual states. Some task-related factors that may affect the control of balance on roofs include load handling, physical exertion leading to fatigue, and attention-biasing associated with task complexity.

3.2.1. *Load handling*: Roof work typically involves frequent lifting, holding and carrying loads while standing and walking on inclined and restricted surfaces. Holding and carrying loads may affect all modes and mechanisms of balance control of a person. Loads change the configuration of masses and the location of the total COM that have to be controlled and thus directly affect the normal (reactive) and the predictive (proactive) control of balance.

In a normal lifting task, picking up a load induces a forward shift of the COM position. To preserve the equilibrium a proactive control of balance generates anticipatory postural adjustments to counteract the expected perturbation. This involves prospective control processes using memory of relevant object characteristics for scaling response specifications (Gordon *et al.* 1993). The preparatory actions are programmed according to the expected load, and not according to the actual (unknown) load (Toussaint *et al.* 1997a, b). Absence of load knowledge or overestimation of the load to be lifted leads to an increased risk of losing balance in lifting tasks (Commissaris and Toussaint 1997).

Holding and carrying loads can affect the avoidance and accommodation modes of proactive control by interfering with (blocking part of) the visual field of the worker. It can deteriorate important visual exproprioceptive inputs about the limb when a worker is going over an obstacle, which in turn increases the variability in toe clearance and the probability of a trip (Patla 1997b). In addition, holding a heavy load results in increased sway magnitude, especially when the centre of gravity of the body and the load system is raised. The additional task of controlling an external load appears to make balance recovery more difficult (Holbein and Redfern 1993). Based on theoretical considerations, Davis (1983) found that loads decrease the postural stability when held at and above the waist level, and the greater the load the smaller is the stability. When the upper limbs are used to carry a load they cannot be used to damp out the rotatory torques on the trunk, and greater forces are required at foot-ground contact (Davis 1983). Asymmetric carrying was found to be more unstable than symmetric carrying (Holbein and Redfern 1994). It is also important to know that load carrying would increase the RCOF in the foot-support interface. In a study that required subjects to carry a load close to the chest or to the back, Leamon and Li (1991) reported a significant increase of the length of a slip while the subject walked on a low friction surface.

In summary, there is sufficient experimental evidence that load handling (due to weight, size, and handling method) affects the control of balance through different mechanisms. However, the threshold conditions that result in falls and the safety limits for load weight, dimensions, and handling techniques to improve balance control during load handling, have not been established.

3.2.2. *Physical exertion during work and fatigue*: Fatigue resulting from prolonged physical exertion may suppress the ability of the nervous system to regulate balance efficiently. Under conditions of fatigue, the latency of a response may be increased, which may have a degrading effect on both the normal and the emergency reactive control of balance. Workers on roofs often perform physically demanding tasks, which may compromise their ability to control balance and lead to a fall. Seliga *et al.* (1991) reported that fatigue from increased work load significantly increased the length of sway. Nardone *et al.* (1997, 1998) found that body sway was significantly increased after strenuous physical exercise. Fatigued individuals are at increased risk of injury due to loss of balance (Sparto *et al.* 1997, Johnston *et al.* 1998).

3.2.3. *Complexity of task and attention*: In the hazardous roof environments attention is crucial for successful proactive control of balance. Complex tasks that divide a person's full attention can reduce his/her ability to execute proactive control of balance. Zohar (1978) demonstrated that biasing attention can increase the probability of tripping. Chen *et al.* (1996) found that divided attention significantly increased the risk of obstacle contact while negotiating obstacles. Generally speaking, the attention demand for walking is significantly higher than that for standing, which is higher than that for sitting (Lajoie *et al.* 1993). Roofing tasks are frequently performed near the vicinity of edges and openings in the surface of support, which require increased visual attention for effective proactive postural control. Many roofing tasks may involve stepping in lateral and backward directions. Since the visual information for control of movement is used in a feed-forward manner (Patla 1997a), very often the performance of such movements is done without on-line visual inputs, and is based only on visual memory or assumptions about the extent of the surface of support. In such cases, incorrect or insufficient visual information or lapses in the visual memory of the worker can result in a fall with fatal consequences. Such incidents can occur even when the worker is aware of a close-by fall hazard but his/her attention is diverted by tasks or unexpected events.

3.3. *Personal factors*

Personal (intrinsic) factors that degrade balance control and precipitate falls are most frequently discussed in literature related to the elderly (Tinetti and Speechley 1989, Black *et al.* 1993). Some of these factors were reported in both prospective and retrospective studies (Maki *et al.* 1994, Maki 1997, Shumway-Cook *et al.* 1997). Occupational fatality data also showed a correlation between falls and age (Bell *et al.* 1990, Stout *et al.* 1996). Three major issues are discussed in this section: individual differences; work experience and training; and sensory interfaces with personal protective equipment.

3.3.1. *Individual differences*: Gender and age are known to be associated with postural stability, and should be considered when analysing workers' risk for a fall.

Ageing is associated with gradual degradation of the sensory systems, which may lead to instability and may precipitate falls. Decline in visual performance with increasing age is also a well-recognized phenomenon. Visual acuity, adaptation to dark, peripheral vision, contrast sensitivity, and accommodation ability, all of which are related to stability, may be affected by age-related changes (Tinetti and Speechley 1989). Other age-related changes that may affect the control of balance include reduced vestibular function, proprioception, and cutaneous sensation, reduced general muscle strength, slowing of muscle contraction, increased joint stiffness, reduced range of motion, slowing of nerve conduction and information processing (Tinetti and Speechley 1989, Black *et al*. 1993). Some of these changes, however, may also occasionally be observed in younger workers due to a health condition or to the use of medications and other substances (e.g. drugs, alcohol).

Agnew and Suruda (1993) found that in the work environment there is an increased risk of a fatal fall after the age of 45 years. They suggested that the increased fatality rates may be associated with being age-related, increased likelihood of falling and corresponding increased vulnerability to physical trauma. It is unclear whether the roofing industry follows the trend or not. Very limited literature provided age-specific rates for fatal or non-fatal falls from roofs. The age distribution of the non-fatal falls from roofs in 1995 and 1996 (Bureau of Labor Statistics [BLS] 1998a, b) shows a higher percentage of incidents for younger age groups. It is likely that the information reflects a roof-related job-specific age distribution.

Suruda *et al*. (1995) reported that male workers accounted for all but one in an analysis of 288 fatal occupational falls from roofs. In addition, the BLS survey for 1995 reported that all 3839 non-fatal falls from roofs involving days away from work were experienced by men (BLS 1998a). The traditionally male-dominated construction industry (Kisner and Fosbroke 1994) and the high-risk tasks performed on roofs, requiring physical strength and endurance, most likely determine the exclusively male exposure to the fall hazards on roof work environments.

According to the BLS, the construction industry accounted for 82.4% of the fatal and 81% of the non-fatal falls from roofs in 1995 (BLS 1997b, 1998a). Special trade contractors (Standard Industrial Code #17 [SIC 17]) accounted for the largest share (60%; Suruda *et al*. 1995).

Chronic diseases that impair sensory, cognitive, neurologic or musculoskeletal functions increase the risk of falling (Tinetti and Speechley 1989). Acute illnesses and conditions (e.g. postural hypotension) as well as medications (e.g. sedatives, antidepressants and antihypertensives) may contribute to instability and falls through various mechanisms (Tinetti and Speechley 1989). Alcohol is also known to cause deterioration of equilibrium control and may cause falling incidents (Woollacott 1983). Furthermore, psychological and behavioural factors may also affect the normal performance of balance control (Yardley *et al*. 1995, Brown and Frank 1997, Maki 1997).

There is an excessive amount of evidence in the literature that multiple personal factors such as age, gender, visual performance, muscle strength, general health, medical condition, use of alcohol, drugs and medications, may all affect the control of balance and increase the risk of falls. The role and the effects of these primary and well-recognized factors must always be considered in the analysis of causes of falls and for development of fall-prevention strategies.

3.3.2. *Work/job experience and training*: Job experience is reported to be correlated to the occurrence of fall incidents in the roofing industry (Prater *et al*. 1975). BLS injury statistics for 1995 (BLS 1998a) show that workers who had less than 3 months' service with their employer accounted for 15% of all non-fatal occupational falls, but were victims of 48% of incidents of non-fatal falls from roofs. It is likely that the roof environment with its unique characteristics and specific fall hazards is a substantial challenge to inexperienced workers as well as to the roof workers who are unfamiliar with the new roof environment, and might adversely affect their ability to control their balance and to avoid hazards during task performance. Experienced roofers seem to achieve good balance with insensitivity to height (Brandt *et al.* 1980).

Both physical and visual training can improve postural stability by enhancing the mechanisms of balance control (Robertson *et al.* 1994, Hoffman and Payne 1995, Perrin *et al.* 1998). Perrin *et al.* (1998) reported that training improves adaptive posture control. Hoffman and Payne (1995) demonstrated that proprioceptive ankle training significantly decreased postural sway in healthy subjects. Training also can result in a shift from visual to proprioceptive dominance in the regulation of postural control (Mesure *et al.* 1997). Studying gymnasts balancing on a beam, Robertson *et al.* (1994) suggested that part of becoming skilled involves developing the ability to rapidly detect and efficiently correct movement errors. They noticed that as practice progresses, feedback adjustments become more continuous. In a similar study, Robertson and Elliott (1996) concluded that skill development involves learning how to use the available sensory information (including visual feedback) rapidly and efficiently.

3.3.3. *Personal protective equipment (PPE)—sensory interfaces*: Workers have to use personal protective equipment in some conditions in roof-work environments. The sensitivity of a worker's sensory system and posture control ability can be affected by various 'sensory interfaces' (e.g. footwear, clothing, eyeglasses, respirators, and ear plugs/protectors). This section describes the potential impact of two most frequently used PPE: footwear and eyewear.

Shoes act as a sensory interface between the foot and the surface of support. The properties of the shoes affect the functional limits of the BOS, the slip resistance of the BOS, and the sensitivity of the foot to surface extent, friction, firmness and incline. The footwear property parameters may include shoe type, fastening type and proper fit, sole and heel height, and shoe material and condition (Cohen and Compton 1982). The frictional resistance in the BOS is defined by multiple parameters including the material, hardness and the thread of the sole and the heel of the shoe, the material and surface roughness of the surface of support, and the contaminants at the interface. Sole and surface of support need to have complementary properties to optimize slip resistance (Wilson 1996). Shoe sole considerably affects the frictional properties of the shoe (Gronqvist 1995). It may also affect the worker's ability to correctly perceive the true slipperiness of a surface (Chiou *et al.* 1996).

The compliance of the shoe sole can affect the normal mode of the reactive control of balance and degrade postural stability. It has been demonstrated that shoes with thick, soft soles, similar to modern athletic footwear and 'walking shoes', reduce foot position awareness and destabilize men of all ages while walking, and shoes with thin hard soles provide superior walking stability (Robbins *et al.* 1994, 1997, Waked *et al.* 1997).

The properties of the shoes also affect the mobility of the ankle. Ankle taping, used in sports, improves the proprioception and foot position awareness (perception of slope; Robbins *et al.* 1995). Careful selection and inspection of the shoes used for work on roofs may provide better postural stability for the worker.

Eyewear can be a sensory interface to the visual system. Protective eyewear and other face/head-protection devices may restrict the visual field and thus may create adverse effects on posture stability. Reduced visual acuity increases postural instability (Paulus *et al.* 1984). Bifocal lenses may lead to errors in depth perception, particularly when descending stairs or steps (Black *et al.* 1993). In addition, a full-face respirator was found to increase the postural sway in conditions of increased workload (Seliga *et al.* 1991).

The literature provides evidence that some PPE (e.g. shoes and eyewear), act as sensory interfaces and may affect the control of balance. This warrants further research to determine the extent of such effects and their role in the occurrence of falls.

4. Current measures to control balance and to prevent falls from roofs during roof work

Many government agencies, academic institutes, public and private research organizations, labour organizations and professional societies are concerned with the prevention of occupational falls, including falls from roofs. As a result, multiple sources of safety information have been developed, including regulations, codes and standards, industry practices, training courses, written procedures and instruction manuals. Most of the sources describe *fall protection* procedures with less information on *fall prevention*. A primary source of information for protection of work-related falls from roofs in the USA is the current OSHA (1995) standard for fall protection in construction.

4.1. *Current regulations*

The continuous efforts of government, industries, and workers to reduce injuries in the workplace have resulted in the development of performance-oriented regulations for fall protection (US DOL 1999a). The current OSHA construction standard — on fall protection — provides specific requirements for fall protection during work on roofs. Related rules may also be found in the OSHA General Industry Standard — Walking-Working Surfaces (US DOL 1999b). In addition, the National Institute for Occupational Safety and Health (NIOSH) issued an alert providing specific recommendations on how to prevent falls from skylights (NIOSH 1989). The OSHA standard sets a uniform threshold height of 6 ft (1.8 m) as a hazardous condition requiring fall protection and identifies the employer as the responsible party to provide and require fall protection for employees.

Conventional fall protection includes the use of covers, guardrail systems, safety net systems, and personal fall-arrest systems. Warning-line systems and safety-monitoring systems may also be used in certain conditions and are mainly used in combination with conventional fall-protection systems. In cases where the use of these systems is not feasible, a specific fall-protection plan describing alternative measures for fall protection may be applied. According to Haddon's countermeasure strategies classification (Haddon 1973), conventional fall-protection systems are directed to separate the hazard from the workers by physical barriers (covers, guardrail systems) or modify the rate of release of the hazard (personal fall-arrest systems, safety net systems). Smith and Veazie (1998) define the measures of fall protection in construction as an example of an event-phase strategy that does not prevent an incident from occurring, but reduces the severity of injury after the incident has been initiated. Nevertheless, where work conditions allow their applications without creating additional risk, conventional fall protection systems are considered to be the primary approaches available to reduce fall fatalities. For work conditions on roofs and more specifically in residential roof construction, some of the described protective systems are not necessarily practical (NBS 1975, OSHA 1995). The use of alternative methods of fall protection (e.g. appropriate footwear, roofing slide guards, restricted storage in the rake edge zone, etc.) is acceptable according to the OSHA interim policy for residential construction roofing work (OSHA 1995).

4.2. *From protection to prevention*

Although current safe work practices on roofs are helpful in reducing the severity of injuries due to falling, more efforts in preventing workers' falls from roofs are needed. The injury statistics demonstrate that current measures are not enough to prevent falling incidents. There is a serious need for research to prevent falls from roofs—both by improving the existing work practices and by developing new approaches, methods and systems for fall prevention and protection. Studying the role and the effect of the main factors that may lead to disruption in the control of balance on roofs may provide a scientific basis for new fall-prevention strategies.

5. Summary and directions for future research

Loss-of-balance incidents resulting in falls from roofs might be associated with one or several of the factors discussed in this paper. Analysing the individual and combined effects of these factors will help to determine, modify, or avoid certain environments, tasks and personal conditions that would lead to falls from roofs. The following are some ideas for improving our understanding of balance control during roofing work and for developing strategies to prevent falls from roofs. These subjects are proposed based on the above-mentioned literature review. The list is not intended to be inclusive. Rather, it is to inspire more ideas from readers.

5.1. *Visual references*

Visual exposure to elevation and dynamic visual scenes can affect the normal mode of human reactive control of balance and cause instability. Further research is needed to determine whether, and if so to what extent, aspects of vision other than monitoring of the walking surface and obstacle detection actually contributed to falls in the roof work environment. For example, close structures appearing in the worker's visual field might serve as visual anchors at heights. This simple concept can be tested and validated under laboratory conditions.

5.2. *Depth perception*

Inadequate depth perception may affect the proactive control of balance and lead to mechanical perturbations. In roof environments workers should avoid conditions with insufficient lighting and should allow themselves adaptation time in areas of lighting changes (e.g. sun to shade). In addition, to improve depth perception at locations that may cause perturbations, appropriate visual cues must be provided to signal changes in surface extent, slope, COF, evenness, firmness, etc. An effective approach may be to implement specific colour cues in the design of roofing materials, elements and equipment. Furthermore, safe work procedures should include and require the proper and timely use of visual cues during the construction process.

Light-intensity safe-threshold level and in particular its interaction effects with visual cues for adequate depth perception on roofs remains undetermined. Experimental studies can be designed to establish dose-response relations of lighting conditions, adaptation time, optical properties and location of visual cues with depth perception, human stability and fall propensity. The relations may then be used to develop criteria for defining safe performance ranges and improved visual cues during roof work.

5.3. *Visual ambiguity*

Stereo-ambiguous visual stimuli can cause postural instability and disorientation. Visual environments on roofs involve various periodical patterns (e.g. the layers of shingles), which might result in visual ambiguity and thus deterioration in the normal control of human balance. Research should be done to evaluate the effects of typical roof-cover layouts on human stability. Should any periodic visual structure lead to significant visual ambiguity, alternative work procedures (e.g. colour coding for certain areas or sequence of shingle layouts) need to be developed to avoid the periodicity of visual contrasts.

5.4. *Visual detection of obstacles and changes*

Successful detection of obstacles and surface changes that may introduce a fall hazard is possible only if they are associated with a significant difference in optical properties (visual cues) that distinguish them from their surroundings. It also depends on worker visual attention and the parameters that define worker visual field (e.g. gaze direction, focal distance, etc.) in relation to a task.

Many environmental modifications could prove to be reasonable and practical for workers' safety. Materials and elements that may become potential obstacles on the roof should be redesigned for safety (easy detection) with bright-coloured edges. During the construction process the existing and newly created changes in the working/walking surfaces (e.g. edges, holes, openings, contamination, unevenness, compliance, instability, etc.) should be eliminated, or, if this is not possible, marked immediately with signal/reflective tape. Laboratory studies using eye-tracking methods within simulated roof environments can be performed to evaluate/verify the effect of these modifications.

5.5. *Surface extent*

There is sufficient evidence in the literature that standing or walking on narrow supports degrades the control of balance and constrains a person's emergency reactive ability. While protective rails, fall-catch platforms, or other physical barriers can be used as passive protective measures, research needs to be done to define optimal support conditions (i.e. plank width and compliance level) as well as minimum distance from edges for safe standing and walking, and for stopping a worker from falling over.

5.6. *Surface inclination*

There is evidence in the literature that inclined support surfaces increase the risk of slip-and-fall incidents. Using devices that provide a level surface (e.g. roof jacks and planks), slide guards, and additional supports for the hands are some general practices that reduce fall incidents from roofs. Research is needed to define the threshold level of the angle of roof inclination for workers to safely perform various roofing tasks. In addition, research is needed to specify a critical inclination, for walking/working surfaces, that will afford secure landing (with and without sliding or rolling) in the case of a fall. Finally, safe body-movement strategies (e.g. velocities, load carrying methods, work postures) for various roof tasks should be studied.

5.7. *Surface frictional properties*

Some of the currently used roofing materials, such as asphalt shingles and roofing rolls, may produce unstable surfaces due to the loosely attached particles. The frictional properties of these materials are not well defined and may change significantly with changes in environmental conditions (e.g. increased temperature), which may have an adverse effect on the control of balance. Research is needed to determine the available COF for different pairs of roof construction materials and shoe soles under various environmental conditions (temperature, moisture, contamination) and identify optimal shoe-sole materials. Furthermore, biomechanical studies of roofing tasks at different roof inclinations will help to determine maximum RCOF and define critical ranges for safe work on roofs. In addition, for materials used as walking/working surfaces, colour coding may be developed to visually enhance changes in frictional properties, to provide easy recognition by workers.

5.8. *Surface evenness, firmness and stability*

Unexpected changes in surface evenness, firmness, or stability may cause perturbation of the base of support and trigger human emergency reactive control of balance. While some hazards can be minimized by covering uneven surfaces, avoiding the use of compliant materials for support surfaces, fixing unsecured surfaces, and removing loose materials, at least two issues in this area need to be studied further. First, research is needed to define critical/acceptable surface evenness, compliance and stability. Second, research is needed on how to make workers quickly recognize these property changes in different work areas through visual cues.

5.9. *Physical interaction with obstacles*

Physical interaction with obstacles during roofing work may result in loss of balance and cause fall incidents. General guidelines to reduce trip-over hazards are to maintain good housekeeping, remove potential obstacles/debris, and cover cables (or use cordless power tools). It would also be highly desirable to identify optimal/protective body-movement strategies for negotiating obstacles, while still permitting a person to perform regular movement functions without slipping. A person's ability to terminate movement and to restore standing balance during an impending fall is largely based on how the person negotiates various physical forces, subject to physiological, anatomical and environmental constraints. The parameters to be studied would include velocity and mass of the body, obstacle size and mass, walking surface conditions and load handling.

5.10. *Large-size materials handling*

Roof workers frequently handle large-size materials such as plywood, planks and rolls. These materials are not only heavy, which can affect postural control, but also awkward to handle, and can block a person's visual field. Studies need to be done to increase our knowledge of relationships between materials handling methods/techniques and human balance control during roof work.

5.11. *Fatigue*

The literature provides convincing evidence that physical exertion and fatigue may affect the control of balance. Further studies on developing simple balance-control tests to detect the onset of fatigue, and to set up work-rest cycles, can help to minimize the problem.

5.12. *Attention*

It is well known that distracted attention can lead to perturbations and cause falls. It is not uncommon to find that roofers are performing measuring, unrolling, nailing, etc. while moving backwards on roofs, which will distract their attention from hazard avoidance. The demands of roofing-task complexity on attention, and thus on proactive mechanisms of balance control, have not been explored. Studies of the issue may help to develop task sequence, work strategies, or other protective measures for prevention of falls due to disruptions in workers' attention and proactive control of balance during roofing work.

5.13. *Individual differences*

Many individual factors affect a person's balance-control ability. Simple tests may be developed to warn workers of their balance conditions and problems immediately before getting on the roof. This would require studies to define individual balance threshold levels for performing various tasks.

5.14. *Work experience and training*

It is clear that training and experience can affect the mechanisms of balance control and reduce the risk of falling. Further studies on job-, environment- and task-specific training procedures and methods for roofing workers should be considered for improving their balance control and fall-prevention ability.

5.15. *Personal protective equipment*

In some conditions during roofing work, workers have to use personal protective equipment. Literature has indicated that some PPEs (e.g. shoes, eyewear, respirators), acting as sensory interfaces, may affect the human control of balance (e.g. through thick compliant soles, obstructed visual field). Studies can be done to determine the extent of such effects and their role in the occurrence of falls and to improve the design of PPEs.

5.16. *Dose-response relationships and synergistic effects*

The literature shows that visual exposure to elevation, moving visual scenes at heights, inadequate visual contrasts, narrow support surfaces, inclined support surfaces, compliant surfaces, load handing, task complexity, age, the state of general muscle strength, use of medications, work experience, and other factors can affect human stability or lead to loss-of-balance incidents. However, the safe threshold levels of postural instability during roof work, and the contribution of each of the factors that result in loss of balance control and cause human falls, remain undetermined. Experimental studies can be designed to establish dose-response relationships and identify synergistic effects of these factors with human stability and fall propensity. The relationships may then be used to develop criteria for defining safe performance ranges.

5.17. *Virtual reality technology for fall prevention studies*
It is evident that working at elevated surfaces is dangerous. However, very little research has been done to understand and analyse the fall hazards associated with specific tasks performed in elevated workplaces such as roofs. A serious barrier for conducting experimental research on human subjects under elevated environments is the associated high risk for injury. Current virtual reality technology provides an opportunity for conducting such research at simulated heights in computer-generated elevated work environments without placing human subjects at risk. Virtual reality technology has been used successfully to simulate exposure to elevations for treatment of acrophobia (Rothbaum *et al.* 1995) and fear of flying (Rothbaum *et al.* 1996). It may prove to be a highly effective approach for studying the causes of work-related falls from roofs and other elevated workplaces.

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