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Influence of Personal Protective Equipment Use on Fall Risk

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CONTENTS

Personal protective equipment (PPE) is apparatus that is designed to prevent or limit the exposure of wearers to physical hazards as well as to chemical, biological, radiological, or nuclear (CBRN) hazards. The apparatus may include respirators, garments, head protection, hearing protection, eyewear, footwear, gloves, protective vests or ensembles, or other devices that provide a barrier between the wearer and the environment. PPE ranks last on the hierarchy of hazard controls, following elimination and substitution of hazards, engineering controls, and administrative measures. As such, it constitutes the final line of defense for worker exposure to hazardous substances, and it should be used in cases when other means of protecting the worker cannot be implemented.

According to Occupational Safety and Health Administration (OSHA) standards (29 CFR 1910.134), when effective engineering controls are not feasible or while they are being instituted, appropriate respirators shall be used. Approximately 20 million workers use PPE regularly in occupational settings to protect them from exposure to hazards [1]. Workers across all industry sectors, including agriculture, forestry, fishing, construction, health

care, manufacturing, services, transportation, the wholesale and retail trade, and mining, regularly use PPE [2]. Proper use of PPE can result in effective reduction in exposure to inhalation hazards and also to hazards to skin, hearing, and traumatic injury, which often correlates directly to reduced injury, disease, and fatality rates [3].

Since 2001, there has been growing concern about CBRN agents, because of the danger of both deliberate attacks and industrial accidents [4]. First responders (e.g., firefighters, law enforcement, HAZMAT workers, and emergency medical teams) are frequently the first personnel at the scenes of mass-casualty incidents, and they are required, as a condition of compliance with existing OSHA standards (OSHA 1910.95, 120, 132–138, 156; 1926.56–106), to wear significant amounts of PPE to protect them against a wide range of hazards [5].

The 2014 Ebola outbreak in West Africa highlighted the importance of PPE in protecting health-care workers from the deadly Ebola virus. It also emphasized the urgent need for improved protection of health-care workers so that they could respond safely and efficiently to infectious disease epidemics in adverse environments. It is known that the use of PPE may prevent the worker from direct contact with an environmental hazard, but it does impose additional hazards: reduced visibility, increased weight and bulk, increased propensity to fall as a function of gait and proprioception effects, and other human factors hazards [6–8]. All of these factors may affect the ability of the workers to function effectively and safely in performing designated tasks, and since these tasks frequently involve public safety and health, the design and manufacture of PPEs that are safe, comfortable, and designed with the task and user in mind are pressing concerns for researchers, government agencies that are concerned with public safety and health, hospital administrators, and first-responder incident commanders.

PPE has limitations in that it does not eliminate the hazard at its source and may result in employees being exposed to the hazard if the equipment fails; damage to PPE may subject workers to traumatic injuries, pulmonary diseases, dermal exposures, and, under extreme circumstances, may cause immediate danger to their lives and health. Since physical damage is known to occur in dynamic situations, the ability of PPE to resist damage and to impose minimal constraints while maintaining a barrier against exposure becomes significant.

The current chapter addresses the effects of additional constraining factors or limitations imposed by PPE in terms of additional weight, reduced visibility, confinement, and impacts on workers' postural balance. The National Institute for Occupational Safety and Health (NIOSH) has devoted considerable effort to understanding this issue and has conducted various research projects aimed at understanding the contribution of PPE to postural balance and subsequent fall-related injury risk. This chapter starts with a background review of motor control, balance control, and gait control as they are related to fall injuries. Intrinsic and extrinsic factors that are related to postural balance and that may increase the propensity to loss of balance are described herein. The chapter further discusses the effects of PPE on postural instability and the slip-trip-fall (STF) injury potential of two groups of first responders—firefighters and hospital first receivers who treat contaminated patients—while wearing PPE. A full complement of firefighting turnout gear conforming to National Fire Protection Association (NFPA) standards and a set of first-receiver PPE that met the requirements of OSHA are used as examples to examine fall risks associated with PPE.

This chapter identifies the restrictive nature of PPE and its relationship with fall risk and presents previous and current findings. It promotes the recognition of the fall injury hazards associated with PPE and the current leading research for injury prevention and hazard evaluation to better understand the stresses PPE may impose on workers and to

provide scientific information for future recommendations for improved work practices and PPE design.

6.1 Background

6.1.1 Slips, Trips, and Falls

A fall is an event that results in a person unintentionally coming to rest on the floor or on lower levels. Prior to the moment in which a fall incident occurs, a person first experiences postural instability or loss of balance. The duration between the sense of loss of balance and the event of fall is usually very short. When a person is not able to recover from loss of balance, a fall incident occurs. A slip is a type of fall causing loss of balance and commonly causing a subsequent fall; slips are often caused by environmental factors, such as contaminated floors. Falls are commonly categorized by the location where the incidents occur: falls on the same level, falls from elevation, and stair falls. Slips and trips are the main contributors to falls on the same level. Examples of falls from elevations are falls from roofs, scaffolds, or ladders. Stair falls may include slips or trips while descending or ascending.

Trips are also loss-of-balance events, frequently leading to a subsequent fall. OSHA defines trips as events involving loss of balance caused by striking an object with the foot or lower leg while the upper body continues its trajectory, or an event causing loss of balance involved with stepping down to a lower level [9].

In 2014, there were approximately 316,650 injuries attributable to work-related STF involving days away from work in private industry [10]. STF is one of the leading causes of workplace injuries in the United States with an estimated cost of $5.7 billion each year [11]. In many industries, falls are the key cause of injuries in the workplace. Falls frequently result in severe bodily injury, permanent disability, and even fatality. Take the health-care industry as an example; the Bureau of Labor Statistics (BLS) reported that health-care workers suffered a greater than average rate of injuries due to falls on the same level (BLS 2014). In 2014, the BLS incidence rate of lost-workday injuries from STF on the same level in hospitals was 31.3 per 10,000 FTEs [10], which was 52% greater than the average rate for all private industries combined. Epidemiological, biomechanical, psychological, and tribological studies have been conducted to reduce slips and falls, and it has been found that the causes of STF are complex and multidimensional [12–16]. Previous studies examined causes of STF in workplaces and have shown that STF can result from personal, environmental, and job-task factors [12]. Understanding the causes of STF enables the development of intervention strategies to reduce the incidence of STF. The three factors related to STF will be discussed further in later sections of the chapter.

6.1.2 Control of Postural Balance

Control and maintenance of postural balance is essential in daily life as well as in the workplace. Postural control is the ability of the body to maintain its center of gravity over the base of support during standing or dynamic movement. The maintenance of postural balance is a complex process involving the coordination among musculoskeletal, sensory, motor, and CNSs. In daily life or in an occupational setting, postural balance is constantly challenged by perturbations arising from environmental changes, sudden movement of body segments,

or task demands, such as working at heights or the use of PPE. These perturbations could be visual, vestibular, or proprioceptive input changes resulting in conditions that challenge the body's equilibrium. Functionally, postural control can be divided into different activities, including maintenance of posture during standing or sitting, controlling the movement of the body's center of mass, and response to external perturbations [13].

Several physiological systems provide afferent information for maintaining postural balance. Afferents—that is, vision, proprioception, the vestibular system, and the cutaneous apparatus—elicit postural reflexes when they are individually or collectively challenged. Visual inputs are essential in the maintenance of postural equilibrium, and the characteristics of the base of support determine the extent to which the vestibular system is involved [14]. The role of the proprioceptive system and the vestibular system becomes critical when the base of support on which the subject stands becomes uneven and the visual input is excluded. Despite the availability of multiple sensory inputs for healthy adults, the preferred sensory input for balance control is the proprioceptors at the feet [15]. Although the CNS generally relies on one sense at a time for balance, when one source is reduced, alternative sensory inputs are used for balance [16]. Postural balance is widely used as an indicator of susceptibility to loss of balance or fall. The control of postural stability plays an important role in fall prevention among the elderly as well as among individuals performing workplace activities.

When the body's center of mass is shifted near the outer perimeter of the basal support due to perturbations, the instability is detected via afferent inputs from muscles, joints, the vestibular system, and vision. Subsequently, motor processes coordinate the muscle actions into discrete synergies to minimize postural sway and keep the body's center of mass within the base of support [17,18]. This entire process is controlled by the central nervous system (CNS). If static balance cannot be maintained, a rapid step or additional external support such as holding onto a guard rail is needed to reestablish the base of support. Motor control is a dynamic process that coordinates human movements and regulates the ability of the human body to move, to carry out daily activities, and to perform industrial tasks. It is a continuous and complex process that involves processing sensory information including body segment (e.g., position, force magnitude and directions) and environmental changes (e.g., floor slipperiness and lighting) and initiates the commands to regulate the movement of the human body.

6.1.3 Control and Maintenance of Dynamic Balance

A variety of tasks performed in a standing position can place the human body's ability to maintain balance at risk; however, task performance during walking places even more demands on the body's ability to maintain balance. In human gait, the body's equilibrium is lost and gained from one step to another. During gait, the center of gravity of the body ventures out of the basal support momentarily. An unexpected perturbation or an external loading may be enough to cause the center of gravity to travel outside the basal support area and cause a fall. Gait requires an integration of a complex neuromuscular–skeletal system as well as the coordination of muscles acting across many joints. This dynamic balance could be disturbed by traumatic injury, neurological damage and deterioration, and even fatigue [19]. It can also be challenged by perturbations arising from environmental changes, that is, floor slipperiness and clutter, or job-task requirements, such as working at heights and/or the use of PPE [20–23].

Previous studies have indicated that, to achieve safe and efficient locomotion, major motor functional requirements needed to be met. Upright posture and total body balance

must be maintained [24], and the upper body should be fully supported against the force of gravity during locomotion. Foot trajectory needs to be well controlled to achieve safe ground clearance [25]. In addition, sufficient mechanical energy needs to be generated by the body to maintain forward velocity during progression [26]. Moreover, the motor patterns at the hips, knees, and ankles have the major function of absorbing and generating energy [26], and the CNS must integrate and coordinate efferent commands with proprioceptive feedback and vestibular and visual inputs to generate the correct patterns of moment of force at each joint.

Previous studies on gait [21,27,28] have documented that people changed their gait as they approached and encountered slippery surfaces. Humans can adjust their gait to perceived changes indicated by sensory feedback and can safely negotiate many different friction-surface levels. The typical protective gait strategy adopted in response to increased slipperiness includes shorter steps and increased knee flexion to reduce vertical acceleration and forward velocity [29]. Gait changes are also observed in poorly lit environments. Subjects experiencing these conditions walked significantly more slowly and exhibited decreased incoming velocity and heel contact angle [21]. It is the sudden and unanticipated changes in surface slipperiness or other environmental factors (e.g., changes in floor/surface pitch and elevation) that often cause most slips and falls [30].

6.1.4 Factors Affecting Postural Stability

6.1.4.1 Personal Factors

There are many personal risk factors that are related to STF, such as gender, age, fatigue, obesity, physical inactivity, poor muscle strength, and poor fitness levels [31–38]. Other personal factors associated with an increased risk of falls include vision impairment, hearing problems, functional limitations, history of falls, and one's ability to perceive an impending fall [31–41].

Postural stability undergoes maturation from birth to about 10 years of age. After 25–30 years of age, body balance begins to deteriorate gradually [31]. A major determinant of postural instability in old age is the reduced attentional capacity and inability in the allocation of available resources to dampen sway. Reduced sensation, muscle weakness in the legs, and increased reaction time are important factors associated with aging and postural instability. The effects of age on postural control have been studied by previous researchers, and postural stability during upright standing has been shown to decrease with age [31]. When compared with younger adults (20–35 years old), older adults (60–75 years old) showed greater postural sway regardless of conditions, that is, with or without visual inputs [32]. No gender differences were found in several studies of postural stability during standing or mild perturbations [19,20]; however, when more challenging tasks are involved—such as those with visual and somatosensory inputs that are reduced or eliminated—the results indicated that elderly women showed greater impairments compared with elderly men [31]. Healthy elderly adults with no musculoskeletal or neurological disorders differ from healthy young adults in their responses to modest perturbations of upright stance; they tend to be unable to reduce small random perturbations as easily [34].

An analysis of the percentage increases in sway under conditions where visual and peripheral sensation systems are removed or diminished, compared with sway under optimal conditions, indicated that peripheral sensation is the most important sensory system in the maintenance of static postural stability [42]. A thorough understanding of falls

requires the study of personal factors—such as the effect of age on a person's ability to maintain balance, postural adjustment capability due to sudden movement of body segments, and the perception of an impending fall—under various workloads, surface conditions, environmental lighting, and lack of availability of peripheral vision. Previous studies have shown an association between blocked peripheral vision and fall potential [32].

6.1.4.2 Environmental Factors

Loss of balance can also arise from various environmental hazards. Major environmental factors associated with an increased risk of workplace STF are those related to lighting, walking surface conditions [30], and the shoe–floor interfaces [21,27,29]. Examples of environmental factors are surface evenness, surface firmness, contaminants and/or obstacles on the floor, type of floor, shoe-sole material and tread, and shoe wear conditions.

Previous studies have shown that poor lighting along with obstruction of peripheral vision, which can be due to poor workplace layout, oversized material, or the use of PPE, can place the worker at the risk of a fall incident [35]. A clear view of the walkway and of any potential hazard is a necessity. Any lack of visual acuity due to poor lighting or poor contrast can lead to slips and falls [43]. Poor lighting detrimentally influences postural balance, especially in more demanding tasks, such as tasks involving reaching or bending [22].

Visual cues play an important role in postural stabilization. They are used in a feedback mode to control balance during standing and walking, or in an anticipatory mode to guide locomotion [44]. When working at heights without close visual references, the destabilizing effect is similar to that of eyes closed at ground level [13]. Other environmental factors are exposure to noise and organic solvents [45] and the surface conditions. Tasks being performed on conformable, narrow, sloped, or slippery surfaces challenge workers' balance control system, and workers often need to adopt different strategies to maintain postural balance [27]. An increase in the slope and height of the working surface increases postural sway synergistically [46].

6.1.4.3 Job-Task Factors

Job-task factors related to falls are those that involve tasks placing the human body's ability to maintain upright balance at risk. Examples are tasks that are physically demanding and tasks requiring the use of elevated devices such as ladders, scaffolds, or aerial lifts. Additional tasks/activities that may place workers at risk for falls include lifting a load, bending down to pick up an object from floor level, excessive arm reach, handling sudden loadings, and the use of PPE.

Physically demanding tasks cause perturbations to the body and trigger anticipatory postural adjustments [47] that actively initiate muscle adjustments when possible disturbances of balance are anticipated by the CNS [48]. When there is a discrepancy between the anticipation and perturbation, such as an overestimation of the weight to be lifted or the handling of sudden loadings, an unnecessarily high momentum of the body may disturb balance and lead to a fall [49]. Tasks performed on ladders are extremely challenging as the workers standing on the rung of a ladder have a limited base of support. Any perturbations may easily shift the body's center of mass outside the base of support, thus causing a fall incident. Manual material lifting such as lifting a sheet of drywall places great demands on the workers' postural control, especially when the drywall is lifted vertically [50]. Tasks involving excessive arm reach shift the body's center of mass forward

and may require the body to take a step to reestablish balance. When the center of mass moves outside the base of support and workers are not able to take a step, such as on a ladder, a fall will occur. The use of bulky tools and PPE increases the demand for highly developed and flexible balance skills [12]. Specific items of protective equipment, such as footwear, clothing, eyewear, and respirators, can affect workers' postural balance [12].

6.1.5 Effect of PPE on Postural Stability and Dynamic Balance

6.1.5.1 Full-Face Respirator and Eyewear

While protective eyewear, respirators, masks, and head protectors can function as protective devices, they can affect workers' postural stability due to the restrictions they place on the wearers' peripheral vision. More importantly, the limitation in vision may further interact with other work conditions, such as workload and shift work. In a study of effects of respirators and workload, subjects wearing a respirator showed increases in postural sway length during demanding physical work, which were attributable to the work load-induced proprioceptive fatigue effect [51]. Self-contained breathing apparatus (SCBA) is the most significant piece of PPE negatively affecting functional balance [52].

Protective eyewear can cause deleterious effects on sensory input from the visual system, and compensatory strategies are usually enacted to maintain or regain postural stability [53]. Full-face respirators affected human cognitive performance negatively in an experiment conducted to compare three respirators—dust, mist, fume respirators, powered air-purifying respirators, and full-face respirators [53]. There is a potential for full-face, negative-pressure respirators to negatively affect jobs demanding high cognitive skills such as problem-solving and decision-making [54]. Workers who employ respirators, protective eyewear, and other face/head protection on a daily basis need to be aware of the effect of altered visual input resulting from PPE use on their postural stability, especially during sensory-challenging tasks, such as navigating ladders, roofs, uneven surfaces, scaffolding, and the elevated surfaces found in most construction work.

6.1.5.2 Protective Clothing and Ensemble

It has been well documented that personal protective clothing affects mobility in terms of the range of body motions defined by the maximum angular changes available at joints [55,56]. Such negative effects often impede work performance and may prolong the time required to perform hazardous tasks [55]. Furthermore, the reduction in lower extremity range of motions, such as knee and hip flexion/extension, may affect workers' abilities to negotiate obstacles or handle an impending fall/slip [57].

A previous study on military load carriage indicated that load bearing increased the stance time and step width used to provide stability to the body [58]. The impact of PPE weight on body movement is an issue that may affect workers' efficiency and create detrimental impacts on postural balance. In a study investigating the impact of body armor on lower body mobility, wearing an 18 lb ballistic outer tactical vest significantly increased knee flexion, foot plantar flexion, anterior pelvic tilt, stance phase, and the time required to establish stability during gait [59]. These changes reflect the increased demand of postural balance and energy expenditure, which can negatively affect soldiers' performance and increase injury risk. Subjects who wore heavier protective equipment contacted tall floor obstacles more frequently during locomotion, suggesting a greater risk of tripping [59]. Heavier equipment also resulted in greater forces by the trailing leg in both the anterior–posterior and vertical directions, suggesting greater risk of slipping [59].

Besides the reduction in mobility and increase in load bearing, the effect of PPE may interact with other task, environmental, or personal factors to create additional adverse impact on users. In a study of firefighters' postural stability, it was shown that prolonged work shifts may be an important contributor to the high prevalence of slips and falls among firefighters [60]. Postural sway variables showed negative/impaired differences in postural stability in workers wearing different levels of PPE required by the U.S. Environmental Protection Agency (EPA) while having fatigued muscle [35]. Level A protection is required when the greatest potential for exposure to hazards exists and when the greatest level of skin, respiratory, and eye protection is necessary [61]. Level B protection is required under circumstances demanding the highest level of respiratory protection, with a lesser level of skin protection [61]. The PPE Level B produced greater instability than PPE Level A when subjects were tested with eyes closed and standing on a four-inch foam. This result indicated that postural stability may be altered with PPE use and with fatigued postural muscles [35]. Wearing PPE negatively affects postural and functional balance, and the effects were more pronounced among older subjects (43–56 years old) than younger subjects (33–38 years old) [52].

6.1.5.3 Protective Footwear

Footwear can affect postural stability from many perspectives. Shoes act as a sensory interface between the foot and surface of support, and the modification of this interface may affect postural stability [62,63]. A number of shoe-design aspects have been shown to impact balance, including heel height, heel-collar height, sole hardness, heel, and the midsole geometry and slip resistance of the outer sole [64,65]. Studies have shown that shoes with thin hard soles provided better stability for men, while shoes with thick soft midsoles destabilized walking stability due to a decreased awareness of foot position [66,67]. An evaluation of midsole hardness on dynamic balance control during response to gait termination suggested that variations in midsole material impaired the dynamic balance control system [66]. Enhancing rear foot motion control and improving ankle proprioception were identified as two major shoe-design pathways for improving walking ability at elevations in a study of roofer footwear [62]. For public and outdoor workers, such as construction and service workers, studies have shown that slip-resistance properties were the top requirements by the users [68].

There have been numerous studies conducted to examine the impact of sports shoes on joint loadings, postures, performance, balance, and slip resistance [69–71]. A few articles on biomechanical evaluation of military boots were found [72,73]. Most of them emphasized the climatic comfort, flexibility, and energy absorption quality of shoes. Research specifically focused on protective footwear, especially properties or designs that are related to slips and trips, were scarce. Studies on sports footwear may not be generalizable to protective footwear for workers due to the inherent differences in the activities the wearers were involved in and the different design characteristics of protective footwear. A few studies were found to have examined the biomechanical and physiological effects of firefighter boots specifically [74,75]. The heavy weight of firefighter boots has been shown to significantly increase the physiological stresses of firefighters [76]. Significant differences were found in sway velocity between the pre- and posttest measures and among two different firefighter boots, suggesting that rubber firefighter boots elicit greater postural instability [77]. The slip resistance of firefighter boots for the different boot–surface interfaces firefighters may be exposed to, however, have not been studied in detail.

6.2 NIOSH Case Studies

6.2.1 Firefighter PPE

Firefighting is one of the most dangerous jobs in the United States, with the work-related injury rate exceeding those of most occupations [78]. In 2007, an estimated 80,100 firefighter injuries occurred in the line of duty, and fall-related injuries were the leading cause, accounting for 27.3% of total fire ground injuries [79]. In firefighting and rescuing operations, firefighters are exposed to varied, complex, and unpredictable conditions as well as a rapidly changing environment. They are constantly exposed to chemical and physical hazards, such as carbon monoxide, heat, and noise. They also frequently work on roofs, stairs, and ladders, and the walking surfaces are often cluttered or slippery due to the existence of debris, building materials, or contaminants.

6.2.1.1 Effect of Firefighter PPE on Risk of Tripping

In 2010, NIOSH conducted a study to evaluate the effect of firefighters' ensemble on their physiological and biomechanical responses during simulated firefighting tasks. One important objective for the study was to examine workers' mobility and their ability to negotiate obstacles while wearing a full turnout gear and different types of fire boots. Firefighters have traditionally worn heavily insulated rubberized boots as protective footwear, which can add 10 lb (4.4 kg) of extra weight to the body, significantly increasing energy expenditure and biomechanical stress such as joint loadings. There are two general types of certified (UL/SEI) structural firefighting boots in use today: 13″–16″ rubber bunker boots and 8″–16″ leather boots. Rubber boots are generally approximately 3lb (1.7 kg) heavier than leather boots, while leather boots are lighter but generally are more expensive than rubber boots. A 5%–12% increase in oxygen consumption per kilogram of weight added to the foot has been observed [80,81]; however, the increase may depend on gender, task, ankle-fit, and whether or not subjects are wearing additional protective clothing or equipment.

The objective of the NIOSH study was to investigate the effect of firefighter boot weight on firefighters' gait characteristics and risk of fall injuries while negotiating obstacles. Twelve healthy men (28.9 ± 5.0 years) and nine healthy women (35.3 ± 3.1 years), employed as professional firefighters and aged between 23 and 39 years, participated in the study. Four models of firefighter boots conforming to NFPA 1971 Standards for structural firefighting were selected for the study [82]. These boots were pull-up bunker boots that were commercially available. The four models of boots represented two models of leather boots, one model of leather/fabric hybrid boots, and one model of rubber boots. The boot characteristics are shown in Table 6.1. The sole flexibility was determined by the longitudinal stiffness of footwear testing based on the TM 194 procedures of the UK SATRA Technology Center [83].

The test protocol involved subjects walking along a 6.3m path and stepping over two 15 cm and two 30 cm obstacles. The participants, while wearing full turnout gear and randomly assigned boots, walked from one end of the walkway, stepping over four obstacles to travel to the other end. They then turned around and continued walking and crossing obstacles for five minutes at a mean speed of 0.57 m/s. The walking speed was paced using a metronome. A six-camera motion analysis system (Peak Motion Analysis System™, Vicon Inc., Centennial, CO) was used to collect 3-D marker trajectory data at 60 Hz and was low-pass filtered using a fourth-order Butterworth filter with a cutoff frequency of 6 Hz. Two 10 s sequences of kinematic data were collected during the 5-min walk, one in the beginning after 30 s of walking and the other during the last 30 s of walking. Each

TABLE 6.1

Boot Characteristics by Model

Boot Model	A	B	C	D
Upper material	Leather	Leather	Leather/fabric	Rubber
Sole flexibility[a]	More flexible	Less flexible	Less flexible	More flexible
Boot weight (men)	3.1 (0.1)	2.9 (0.1)	2.5 (0.1)	3.8 (0.1)
Boot weight (women)	2.5 (0.1)	2.4 (0.1)	2.0 (0.1)	3.3 (0.04)
Boot length (men)	31.2 (0.9)	31.2 (0.8)	30.9 (0.9)	30.7 (1.0)
Boot length (women)	27.1 (0.9)	27.0 (0.8)	26.5 (1.0)	26.8 (0.6)
Boot width (men)	10.8 (0.2)	10.1 (0.2)	10.6 (0.2)	11.1 (0.3)
Boot width (women)	9.6 (0.2)	9.0 (0.2)	9.6 (0.2)	10.1 (0.2)

Note: Standard deviations are shown in parenthesis. Boot weights are in kilograms and boot length and width are in centimeters.

[a] SATRA TM 194 Testing performed.

subject was allowed to select his or her preferred limb for leading over the obstacle. A total of eight reflective markers were placed on the subjects at the toe, heel, fifth metatarsal joint, and the ankle to monitor gait patterns and rear foot motions for both leading and trailing feet. Two markers were placed on the two ends of each obstacle to define its position in 3-D space. The obstacles were made of lightweight PVC pipes measuring 3.5 cm in diameter and one meter in length. They posed little to no risks of falls if contacted.

The motion data were analyzed from the toe-off of the trailing foot before stepping over the first obstacle to the heel strike of the trailing foot after crossing the second obstacle. Swing foot trajectories were assessed through the examination of crossing step length, toe–obstacle clearance, lead foot heel-strike distance, and trail foot approach distance. The cross step length was the distance from the trailing toe-off to the leading heel contact. Toe–obstacle clearance was defined as the vertical distance between the toe and the top of the obstacle at the instant when the toe was directly above the obstacle. The heel-strike distance was the distance from the lead heel to the obstacle, while the trailing foot approach distance was the distance from the trailing toe to the obstacle. During testing, it was observed that subjects tended to displace their crossing limb laterally when clearing the obstacle. Therefore, the lateral position of the lead foot was quantified, which is the horizontal position of the lead toe from the stance foot at the time it crossed over the obstacle.

Data from successful trials for which the subjects stepped over the obstacle without contacting the obstacle was included in the analysis. Of all 168 trials collected, 19 (11.3%) tripping incidents occurred. All tripping over obstacles occurred with the trailing foot. Repeated-measure analyses of variance (ANOVAs) were performed to test the effect of gender, boot weight, boot-sole flexibility, and time period (beginning vs. end of 5-min walk) on the temporal–distance variables. The effect of boot weight and time period was found to be significant on trailing foot toe–obstacle clearances for both high and low obstacles ($p < .02$). As the boot weight increased, the toe–obstacle clearances decreased. For each 1 kg increase in boot weight, there was a 2.8 cm decrease in toe–obstacle clearance for the taller obstacle. Subjects were able to maintain a toe–obstacle clearance of 23.5 cm in the beginning of the walk (Figure 6.1); however, the clearance was decreased to 21.9 cm near the end of the 5-min walk over the high obstacle ($p < .05$). In addition, significant differences were observed for lateral toe position by gender ($p < .01$) and time period ($p < .03$). On average, the lead toe was initially 42 cm to the right of the stance foot when crossing the high obstacle, but it was increased to 46 cm near the end of the walk. Women firefighters were found to displace the toe farther away from the stance foot than the men firefighters (Figure 6.1).

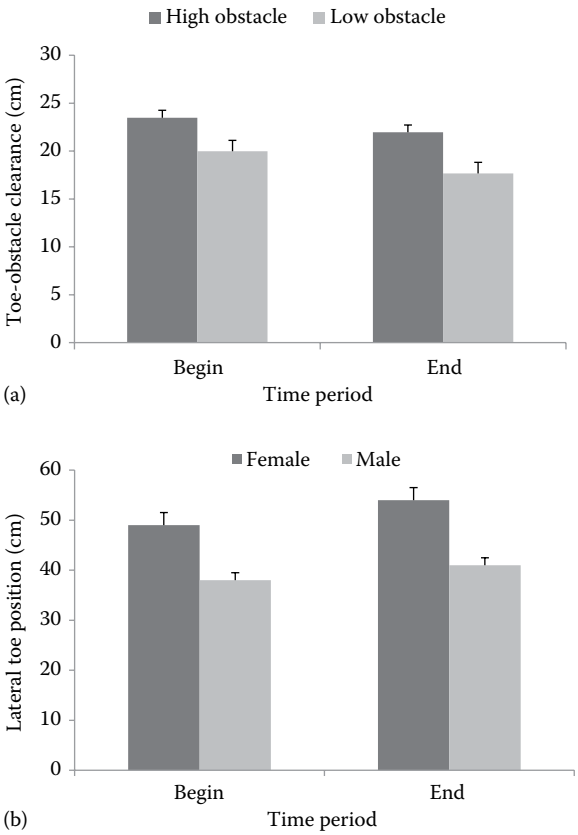

FIGURE 6.1
(a) Mean toe-obstacle clearance for two obstacles by time period and (b) mean lateral toe position by gender and time period.

In summary, successful navigation through the fire ground necessitates the effective avoidance of obstacles and securing adequate footing. In this study, the toe–obstacle clearances significantly decreased as boot weight and task time period increased. Insufficient toe–obstacle clearances often result in unsuccessful obstacle avoidance at the job site and may lead to tripping [84]. Results from this study indicated that boot weight and task time period affected firefighters' gait characteristics in negotiating obstacles. Subjects were more likely to trip over obstacles when wearing heavier boots and after walking for a period of time. Men and women firefighters adopted different kinematic strategies in negotiating obstacles. By swinging the foot outward, female subjects increased the toe height to help maintain toe clearance above the obstacle. Findings from this study may provide scientific evidence for firefighters and manufacturers in boot selection and design for preventing falls on the fire ground.

6.2.1.2 Slip Resistance Properties of Firefighter Boots

Previous studies have documented the evidence on the effect of PPE on firefighters' postural balance [85]. Firefighters are at an increased risk for STF injuries since they are exposed to extreme conditions such as high temperatures, wet surfaces, and strenuous tasks. Their working conditions are often varied and fast-changing. In many firefighting

FIGURE 6.2
Four types of firefighter boots (B1–B4) and one type of safety shoe (S) tested in the study.

tasks, they are required to hastily ingress and egress from the fire truck while they are on the fire ground. Footwear plays an important in role in slip-and-fall prevention. Loss of foot traction between footwear and the work surface is considered as a major source of slip injuries [30]. In addition to the slip-resistant properties of the shoe sole itself, characteristics of shoe wear and tear can also affect the available coefficient of friction (COF) of the shoes [86].

In an NIOSH study of the slip resistant properties of firefighter boots, four pairs of NFPA certified firefighter boots and one pair of safety shoes (Figure 6.2) were tested using a Brungraber Mark II Slip Meter. The shoe soles were conditioned with fresh P400-grit abrasive paper prior to slip testing. The characteristics of the firefighter boots and safety shoes are provided in Table 6.2.

The slip resistance of firefighter boots as indicated by COF values on a wet surface ranged from 0.15 to 0.53. Boot model B1 was a pair of rubber boots with the lowest COF values. Boot model B3 exhibits the best slip resistance of all. The shoe sole samples were maintained in a controlled environment with a constant temperature of 21°C and relative humidity of 17% RH.

Figure 6.3 shows the COF results between each heel sample of footwear and stainless-steel plate abraded with 36-grit abrasive paper as a function of the number of trials. In general, the COF values of all tested footwear decreased as more trials were performed. This trend was consistent for both testing days. The decrease in COF values can be attributed to wear and tear due to repeated trials and/or a possible hydration phenomenon, in that shoe-sole material gradually saturated with fluid under wet conditions. Since firefighters consistently walk on wet surfaces, further research is needed to examine the changes in slip resistance due to wear and tear and surface contaminations.

TABLE 6.2

Shoe Sole Properties and Tread Characteristics

			Tread Configuration (mm)				
Model	**Hardness[a]**	**Surface[b] Roughness (Rz)**	**Max. Width**	**Min. Width**	**Max. Depth**	**Min. Depth**	**COF[c]**
S	76.17	14.650	9.8	0.9	5.5	0.6	0.42
	(1.47)	(1.470)					
B1	69.25	15.795	8.6	3.4	5.7	2.2	0.15
	(0.97)	(2.885)					
B2	83.83	11.718	27.6	1.4	9	1.2	0.36
	(1.11)	(2.217)					
B3	75.58	19.270	10.1	3.3	7.1	1.6	0.53
	(2.78)	(3.374)					
B4	68.75	40.192	4.1	0.8	5.3	0.8	0.40
	(1.48)	(3.798)					

[a] Mean and (SD) of Shore A hardness measured by HPSA-M durometer (mm).

[b] Mean and (SD) of Surface Roughness Parameter Rz (μm) measured by Mitutoyo Surftest SJ301P.

[c] COF (Coefficient of Friction) measured by Brungraber Mark II on a wet stainless steel plate.

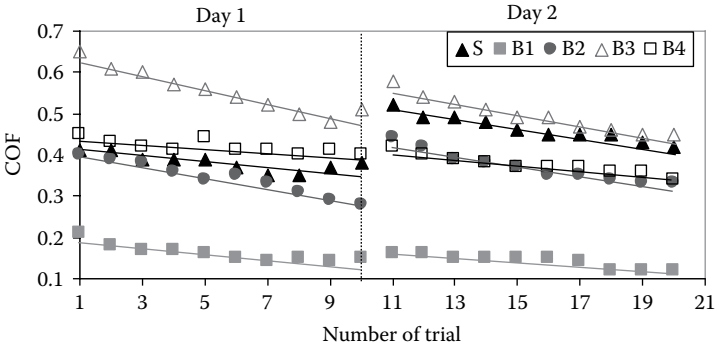

FIGURE 6.3
COF values between footwear sole samples and a wet stainless steel plate abraded with 36-grit abrasive paper measured on two different days.

6.3 First-Receiver PPE

According to OSHA's best-practices document for hospital-based first receivers, the minimum PPE needed to provide protection from a wide range of unknown hazards includes a powered air-purifying respirator (PAPR) (Figure 6.4), a double layer of protective gloves, chemical-protective boots, and a chemical-resistant suit (e.g., Tychem® or Tyvek®) with its openings sealed with tape [87]. A PAPR is a respirator composed of a headpiece or hood, breathing tube, filter, and battery-powered blower. The user wears the battery and the pump while it draws ambient air in through a filter and supplies it to the loose-fitting hood. The design of protective ensembles often focuses on the physical and mechanical properties of protective materials, with few considerations of usability [88]. The weight, the

FIGURE 6.4
Example of first-receiver PAPR system.

bulk, and the corrugated breathing tube of the PAPR and the restrictive nature of the protective suit and gloves may immobilize first receivers to some extent, thus encumbering dexterity and limiting first receivers' effective emergency response. In addition, especially under mass-emergency conditions, triage, decontamination, and treatment operations could take place at outdoor facilities or outside hospitals in order to handle a large patient volume and to keep contaminated patients away from emergency departments [89]. Under those conditions, there is an ongoing concern about inclement weather, especially the thermal environment, which can affect operational tasks as well as affecting the ensemble conditions itself; physiological constraints can be magnified under these circumstances.

To date, quantified data on biomechanical, ergonomic, and physiological stresses imposed by the first-receiver ensemble have been limited. Performance criteria and test methods specific to the biomechanical and ergonomic stresses of wearing first-receiver gear have not been established. Little to no research has been conducted to evaluate the injury potential for overexertion and slips/trips/falls associated with the first-receiver protective ensemble among health-care workers performing job-specific tasks. Furthermore, scientific data for the effects of first-receiver PPE on performance for both male and female workers in a hot environment remains lacking.

Beginning in 2014, NIOSH undertook a study to evaluate the ergonomic and physiologic burden imposed on first receivers, wearing OSHA-recommended PPE, performing simulated decontamination and treatment tasks in the environmentally controlled Human Factors Laboratory. The test ensemble included a 3M Breathe Easy PAPR system, Ansell Sol-Vex gloves, Bata Hazmax boots, and a DuPont Tychem® CPF3 suit (model C3125T). The 3M Breathe Easy PAPR system is a motorized unit powered by a battery pack, which filters air surrounding the wearer through cartridges to provide respiratory protection. This system consists of a loose-fitting butyl rubber hood, a blower, a battery pack, a breathing tube, and cartridges. The system weighs approximately 4.0 kg, and it protects the wearer against CBRN hazards. The DuPont Tychem® CPF3 protective garment is composed of a multilayer barrier that protects against a broad range of chemicals. The Bata Hazmax boots are 16in high with steel toes and slip-resistant soles; to assure an air-tight seal, boots are taped to the suit legs. The Ansell Sol-Vex gloves are made of chemical-resistant nitrile compound. They are worn over vinyl exam gloves and are taped to the Tychem® suit sleeves.

PPE enables workers to perform tasks in environments that are potentially hazardous, but it can negatively affect work productivity and expose those working in hazardous environments for a long period of time to hazardous substances. The bulky PPE ensemble can restrict mobility, limit effective emergency response, and increase risks for overexertion and STF injuries. The objective of this study was to quantify the barriers to the use of first-receiver ensembles by evaluating ergonomic and biomechanical stresses imposed on the wearers.

The restriction of body motions caused by the use of PPE may affect workers' ability to respond to perturbations arising from the work environment or job tasks. It may also affect workers' ability to react to an impending fall. Range of motion (ROM) is an important measure for workers wearing PPE as it is a way to assess worker mobility. In the NIOSH study of first receivers, ROM measurements were collected from 24 health-care workers (mean age: 31.2 ± 8.1 years) with at least 12 months of experience wearing surgical masks or N-95 (particulate-filtering facepiece) respirators. Measurements of ROM at the shoulders, elbows, trunks, hips, and knees in both sagittal and frontal planes were taken for each subject while wearing PPE or regular clothing (T-shirt and shorts) using a universal goniometer (Model 01135, Lafayette Instrument, Lafayette, IN). All measurements were taken using a universal goniometer by the same researcher to avoid any possible intertester reliability concerns.

Repeated-measure ANOVAs were performed to determine the effects of PPE and gender on 14 ROM variables. The effects of PPE and gender were significant on all ROM variables ($p < .01$) except for hip abduction and elbow flexion.

Figure 6.5 shows the percentage decrease in ROM due to the effect of PPE. The use of PPE had a significant effect on all movements. Subjects' ROM capabilities decreased consistently across all joints with PPE use. The most restricted areas were shoulders with more than 30% reduction in extension and 40% reduction in adduction. Frontal plane motions were more restricted than sagittal plane motions as indicated by more than 20% ROM reduction in hip abduction and trunk lateral flexion and more than 40% reduction in shoulder adduction.

To assess first receivers' dynamic stability, gait tests were conducted, which include normal walking and obstacle negotiation. The normal walking task required subjects to walk across a 12 m (40 ft) walkway with two embedded force plates. The subjects walked at a self-selected speed (e.g., natural cadence). They were required to step on the first force plate with their right foot (right foot heel strike), and take the subsequent step (left foot heel strike) on the second force plate. The gait starting position from the force plate was adjusted for each subject to achieve a right heel strike approximately at the center of the first force platform.

For obstacle negotiation trials, subjects walked at a self-selected pace along the same walkway used for the normal walk task, also stepping over an obstacle. The obstacle was placed in the middle of the walkway between two force plates. Prior to the experiment, the participants were given time to familiarize themselves with the walkway and the obstacle. A total of eight reflective markers were placed on the boots at the toe, heel, fifth metatarsal joint, and ankle for the monitoring of foot trajectories. The obstacle was either 15 cm or 30 cm in height. The obstacles were made of PVC pipes measuring 2.5 cm diameter and 1 m in length. The pipes were rigid but light, posing little to no risks of falls if contacted.

Of all 96 obstacle-crossing trials for which data was collected, 18 (18.8%) involved contacting or knocking down the obstacle, which were considered to constitute tripping incidents. Of all 18 tripping incidents, 16 (89%) occurred while negotiating a high obstacle, and 83% occurred when subjects were wearing PPE, possibly due to reduced

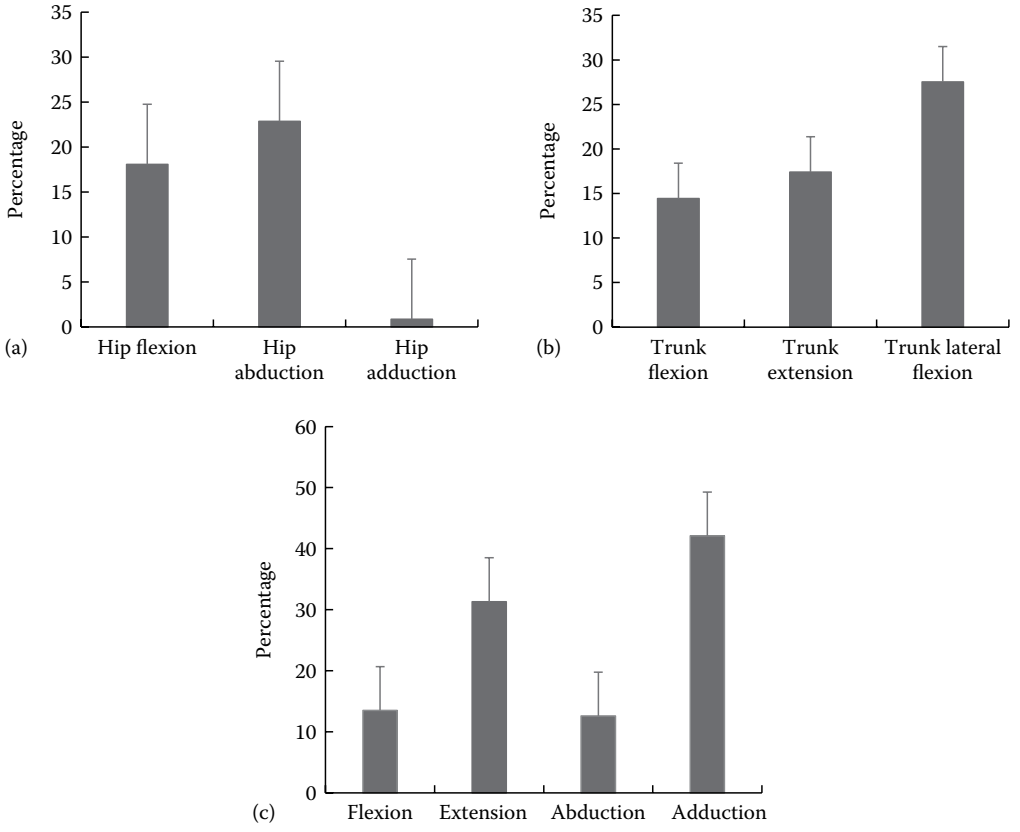

FIGURE 6.5
Percentage decrease in range of motion due to PPE at (a) hip, (b) trunk, and (c) shoulder joints.

hip and knee range of motion. All tripping over obstacles occurred with the trailing foot. This phenomenon can be attributed to the fact that neither the trailing foot nor the obstacle was within the subject's field of vision when the trailing foot was clearing the obstacle. In addition, the trailing foot was one step length closer to the obstacle than the toe of the leading limb. Thus, workers need to be advised that their trailing foot is more likely to trip on obstacles when wearing PPE. Subjects were able to negotiate a 6″ obstacle, but it was shown that they may trip over a 12″ obstacle while wearing first-receiver PPE.

With regard to gait characteristics, the effect of PPE was significant on step width ($p < .002$) and double stance time ($p < .001$) (Figure 6.6). First-receiver PPE affected health-care workers' gait stability as reflected in significant increases in step width and double stance time. While wearing PPE, the demand on postural stability was increased; therefore, workers needed to maintain a wider step width to increase their base of support. In addition, their foot contacted the ground for a longer period of time in each gait cycle to maintain balance from one step to another. Wearing first-receiver PPE significantly changed subjects' walking patterns and reduced ROMs at trunk, hips, and shoulders, which can negatively affect the free movement of the lower body, introduce more rapid fatigue, increase ankle injuries, and limit workers' ability to negotiate obstacles [90].

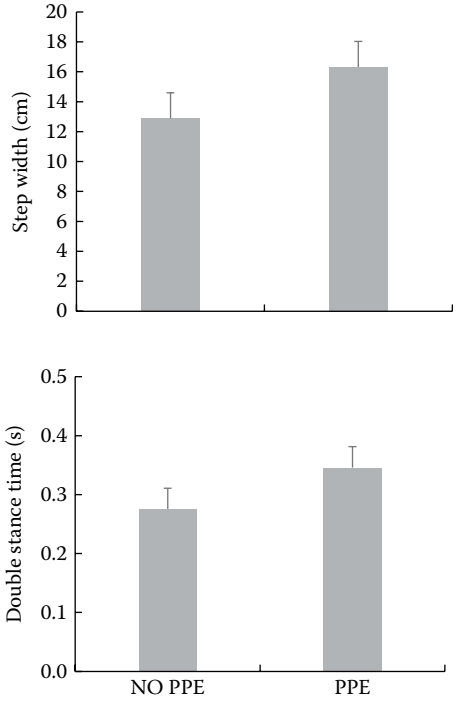

FIGURE 6.6
Effect of PPE on double stance time and step width.

6.4 Future Directions

In this chapter, basic aspects of PPE, postural stability, and motor control were presented, along with more comprehensive discussions of factors affecting postural balance and how PPE affects postural stability and dynamic balance. There are many directions in which research on effects of PPE on postural instability and fall risks described in the chapter could be extended.

A primary concern is the wide range in COF among the acceptable boots worn for firefighting tasks, as observed in the NIOSH case study. Research should focus on standardization of a slip tester and establish minimum required footwear COF criteria, so that firefighters are able to don firefighter boots with well-established characteristics and an acceptable safety profile. Firefighters may be required to adjust gait and stance according to environmental conditions on the fire ground, but footwear friction criteria would eliminate or reduce an additional variable. At a minimum, the establishment of a minimum COF and a standardized slip tester should be pursued, so that available boots should be roughly comparable in terms of the ability of footwear to produce comparable performance.

Similarly, safety-boot manufacturers should focus on weight reduction of their products, in the context of research that indicates a decrement in firefighters' ability to negotiate obstacles as a function of increases in time on the fire ground and the overall weight of boots.

It should also be recognized that heat stress and physiologic stress of various kinds can be increased among users of PPE. This is especially the case with first receivers within hospitals, who may be forced to perform critical tasks while subject to environmental stresses; and firefighters, who face increased dynamic, orientation, and communication tasks while on the fire ground.

Further, it should be recognized that the use of respirators carries a performance decrement, and this can be significant for certain types of industrial tasks. Currently, respirator use and selection is guided by NIOSH and OSHA requirements; however, it is not widely recognized that the use of certain items of protective equipment reduces the ability of the user to perform specific tasks, and further research could be undertaken to determine the manner in which ROM and limitations in perceptual ability and cognitive function, as well as related variables, can function to decrement task-specific performance. Future research should focus on performance speed and efficiency and the effect of time wearing PPE, time to complete tasks, or other measures on the performance decrement that is to be expected when a respirator is required.

Future research should also explore the impact of PPE bulkiness, peripheral field of view, weight, and weight distribution on both upper and lower extremity mobility and task performance. This is especially important for firefighters and first receivers who heavily reply on PPE for protection against hazards in unpredictable outdoor environments. Depending on the results of such studies, criteria and recommendations could be developed to improve the design of PPE. Evaluation of the slip resistance of protective footwear with the considerations of the walking surfaces for occupation-specific environments and tasks would provide important information for preventing falls due to loss of foot traction.

Causes of slips and falls are multidimensional, involving personal, environmental, and job-task factors. The prevention of fall injury due to PPE requires the evaluation of the contribution of individual PPE components (e.g., google, respirator, gown, footwear) to postural instability, as well as the impact of the ensemble as a whole. The contribution of PPE individually or collectively to common injury risks for traumatic injuries is intuitively apparent but not substantiated by sufficient research efforts. Efforts to incorporate biomechanical, tribological, anthropometric, and psychological findings into a systematic approach should be pursued to establish a better understanding of the pathways of fall injury and the resultant preventive strategies. Testing methods and performance criteria for various classes of protection defined by OSHA, ranging from maximal protection, Level A, to minimal protection, Level D, are needed. Further in-depth understanding in these areas will provide insights to improve PPE design and to develop intervention strategies to reduce STF.

6.5 Disclaimer

The findings and conclusions presented in the report are those of the authors and do not necessarily represent the views of National Institute for Occupational Safety and Health (NIOSH). Mention of any company names or products does not constitute endorsement by NIOSH.

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