Injuries associated with slips and falls continue to be a significant burden to society, both in terms of human suffering and economic losses. Fall accidents are the second leading cause of accidental death in the United States (after motor vehicle accidents), resulting in more than 25,000 fatalities in 2009 and accounting for nearly 9 million visits to the emergency department (National Safety Council, 2011). Fall accidents also are prevalent in the occupational arena, where they are responsible for a significant proportion of worker absenteeism and disability leading to 1 or more days away from work. According to the U.S. Bureau of Labor Statistics, disabling work injuries in the entire nation totaled approximately 5.32 million, and more than 14% of injuries involved slips and falls (Yeoh, Lockhart, & Wu, 2013; for additional information, see http://www.bls.gov/iif/oshcdnew.htm). In European countries, slip and fall accidents also contribute significantly to serious injuries, causing hospitalization and days away from work (Sicre et al., 2008).

In this chapter, I elaborate several approaches used by ergonomics researchers to decouple the mechanisms associated with slips and falls, and I provide comprehensive guidelines for designing a safe living environment in which the risk of slips and falls is minimized.

Ergonomics researchers have applied several different methodologies stemming from tribology (surface dissipative forces and hydrodynamics of two surfaces), psychophysics, and classical biomechanics to better understand the interacting mechanisms associated with slips and falls so as to design a safe living environment. I begin by discussing the tribological aspects of fall accidents, including the characteristics of surface dissipative forces, the characteristics of hydrodynamic properties, and the various devices to measure the coefficient of friction (COF) of floor surfaces. I also discuss guidelines regarding safe COF levels.

Next, I discuss psychophysical characteristics, as the perception of the surrounding environments (e.g., slippery floor surfaces) also is important in fall safety. Psychophysical methods have been employed to investigate human judgments of slippery floor surfaces in an effort to provide input to comprehensive viscoelastic and hydrodynamic models of shoe–floor interactions. Researchers using the psychophysical methodology have asked research participants to subjectively assess the slipperiness of floors to obtain further insight into the parameters of vision and tactile sensation, which, in turn, is used to assess the discrepancy between a model (our perception of the floor surface) and reality (what we can currently measure).

Furthermore, in analyzing the principles of body stability and the mechanism of slips and falls, it is necessary to understand the dynamic principles of human locomotion. In this section, I present the biomechanics of human gait to elaborate on the “human” aspects of slip and fall accidents. This information may provide a better understanding of the relationship among the various factors involved in fall accidents and may also assist in formulating cogent requirements for optimal human systems integration.
TRIBOLOGY

A slip occurs when insufficient friction exists between a pedestrian’s shoe sole and a walking surface to prevent the foot from sliding (Bunternchit, Lockhart, Woldstad, & Smith, 1999; Lockhart, 1997, 2008). A fall occurs when the pedestrian cannot recover from a slip, resulting in loss of balance. Thus, the slip resistance of shoe soles and the surfaces that are underfoot is important for human locomotion and pedestrian safety; an adequate frictional force is required to prevent slipping. Slip resistance is defined as the “frictional force opposing the movement of an object across a surface” (American Society for Testing and Materials, 1975, p. XX). This includes forces opposing movement in both the static and dynamic phases of foot contact. The fundamental idea of slip resistance is that a slip will occur whenever the frictional force opposing the movement of an object is less than the shear force of the shoe in contact with the walking surface. The tribological approach to fall prevention concentrates on the static and dynamic COF between the shoe and the floor surface. In the following sections, I discuss friction (dynamic vs. static) and review slip resistance measurement devices.

Ground Reaction Force

The COF is a ratio of the horizontal shear force divided by the vertical normal force (Chaffin, Woldstad, & Trujillo, 1992). The forces applied by the foot to the floor when it touches the surface act in three directions: horizontally in the direction of body motion ($F_{H}$), horizontally transverse to the direction of body motion ($F_{T}$), and vertically ($F_{v}$). At the instant of heel contact, there is a forward thrust component of force on the swing foot against the floor. This results in anterior and posterior shearing forces ($F_{a}$) acting at the foot–floor interface. Walking speed, which is the product of cadence (step frequency) and step length, affects the magnitude of $F_{H}$. Although forward horizontal force ($F_{H}$) increases with increasing step length and cadence, the effects of cadence are more pronounced than those of step length.

Longitudinal transverse force ($F_{T}$) is the result of lateral momentum during walking. This lateral momentum exists because of an out-toeing walking pattern. Yet, this force component can be ignored in normal level walking due to the relatively small transverse forces compared to the other ground reaction force components, as observed in locomotion experiments (Gronqvist, Roine, Jarvinen, & Korhonen, 1989).

Vertical force ($F_{v}$) is result of body weight and the downward momentum of the swing leg against the ground during heel contact. Vertical force is affected by walking speed and cadence, which have a more pronounced effect than step length.

Required coefficient of friction (RCOF). The RCOF represents the minimum COF that must be available at the shoe–floor interface to prevent forward slipping during the heel contact phase of the walking cycle. Perkins (1978) utilized a force platform to measure the horizontal $F_{H}$ and vertical $F_{v}$ components of the force exerted between the shoe and ground during normal walking.

Static versus dynamic COF. In the early 19th century, Morin (1835) introduced the concepts of static friction and kinetic friction. In most engineering applications, the static COF is greater than the dynamic COF. The static COF varies regularly as a function of the static application time (adhesion of the two component forces), and the dynamic COF drops off as the sliding velocity increases.

Whether the static COF or the dynamic COF provides a better estimate of the degree of slipperiness has been studied in depth in various experiments. Many studies in the field of kinesiology have indicated that under normal walking conditions, there is little or no relative movement between the foot and the floor (James, 1983). Perkins (1978) suggested that no movement between the shoe and ground occurs when both the heel and sole of the shoe are in contact with the ground. Therefore, many researchers initially suggested that the static COF should be incorporated into studies of slips and falls. Because the static COF is related to normal walking conditions, dynamic friction would only be valid after the foot has started to slip.

Friction Measurement

To protect people from slipping and falling, various groups have proposed that minimum values be set
for the COF under standardized test conditions. In other words, by standardizing the shoe and floor conditions, applying a normal load, and measuring the resulting frictional force, the COF could be measured. In turn, these standardized COF values could be used to establish the slip hazard level for a given shoe or floor.

Unfortunately, the methods for determining the COF value for a particular shoe or floor material have not yet been standardized, primarily because of the many factors involved in establishing what may be considered a safe COF to prevent slips and falls. These factors can be divided into four categories. First are factors related to the floor surface, such as the nature of the surface, the roughness or smoothness of the surface, and its exposure to exterior environmental conditions (temperature and humidity). Second are biomechanical and psychological factors, such as various foot force distributions for individual movement patterns (walking velocity, slipping velocity, and contact area of sole), the physical and neurophysiological capacity of the walker (response of the individual to a sudden change in floor characteristics), and judgments and evaluations made by the walker (slipperiness of the floor). Third are task factors, such as the types and frequency of static and dynamic manual tasks, any required changes in elevation, and the direction of movement. Finally, there are characteristics of the shoe, such as the nature of the sole, the surface relief and the shape of sole, its wear and tear, and its static and dynamic mechanical characteristics.

In essence, designing an effective and accurate mechanical device to measure COF (slip resistance) of shoe sole means fixing values for each of the variables associated with the first three factors and arriving at an overall value for characteristics of the shoe (Tisserand, 1985). However, the variables are so numerous that the resulting combination of factors would give rise to an infinite number of slip COF values. Noting this enigma, Tisserand (1985) suggested a need for a scientific approach to the problem and, in particular, an experimental rather than theoretical approach to obtain a meaningful COF measurement. In particular, the following factors have been recognized as affecting COF values during the last decade (psychophysical factors are explained in next section).

**Inclined support surface.** Walking down a ramp poses a significant hazard to pedestrians due to the generation of higher shear forces when ambulating over an inclined surface as opposed to a level surface (McVay & Redfern, 1994). Bentley and Haslam (2001) indicated that 30% of roofers and postal workers walking on downward slopes had slip and fall accidents. To prevent slips and falls when working on ramped surfaces, high slip-resistance characteristics are required for the shoe-floor interface; above a certain slope, the slip resistance required for safe walking cannot be achieved.

**Velocity of contacting surface.** When the heel contacts the ground during walking, the heel–floor closing velocities may exceed 0.5 to 1 m/s. Under some combinations of shoe or floor materials, contaminants, and surface geometry, the static and dynamic COF values change due to this velocity. The basic underlying assumption in computing the COF is that the friction value increases proportionally to the normal force holding the contacting surfaces together. Due to adhesion and deformation forces, however, under some circumstances this may not be true (Chaffin et al., 1992). One way to look at the process that creates the frictional force is to decompose it into two separate but additive components: contacting surface and contact time. Adhesion depends on the time the two materials are in contact. Contact time appears to increase the static COF (a sticking effect), although under most walking conditions (due to very fast shoe–floor contact time) this is not a major factor, compared to when one stands in one place for several minutes.

Deformation of the contacting materials is affected by the stiffness of the materials, the contact area, and the normal loads applied. Grönqvist, Roine, Korhonen, and Rahikainen (1990) stated that the reason floor surface roughness measures correlate with dynamic COF values is deformation forces (i.e., the rougher the floor, the higher the COF). Heel contact area does not significantly affect deformation forces because the actual heel contact area is small during the heel strike (Chaffin et al., 1992).
The effect of the normal load applied varies with the shoe sole and floor materials; for example, when a soft material such as crepe is loaded heavily on a rough surface, the deformation force effect on friction will be larger than when using a smooth surface or harder sole materials.

**Slip Resistance Measuring Devices**

Many apparatuses have been developed by individuals, organizations, and federal agencies (e.g., Occupational Safety and Health Administration, National Institute for Occupational Safety and Health, National Bureau of Standards) to quantify slip resistance (i.e., the COF). In general, most devices fall into three categories: dragged or towed sled, articulated strut, and pendulum. There are two approaches to measuring friction. In the direct approach, the test device measures or indicates the horizontal and vertical forces. These include drag-type meters and articulated strut devices. The indirect approach calculates the frictional force by observing an energy loss in the test device. The most common example of the indirect approach is the use of pendulum-type devices.

**Drag-type meters.** This type of device slides a weight of known value mounted on a footwear sole sample across the test surface. The device is pulled either manually or by a motor at an adjustable speed. It is the most common type of slipmeter due to its simplicity, portability, and ease of use. The COF is derived by dividing the force required to start motion or maintain motion by the weight of the sled (normal force). Among the most frequently cited drag-type devices are the Horizontal Pull Slipmeter (ASTM F 6098-79), the Dynamometer Pull Meter (ASTM C 1028-84), and the Tortus Floor Friction Tester developed in Europe.

**Articulated strut devices.** These devices consist of a weight attached to a shaft that is articulated at an angle. A known vertical force is applied to a shoe affixed with sole or heel materials. An increasing lateral force is then applied until slip occurs. The ratio of lateral force at slip to the known vertical force is the COF. There are three ways of going from the initial position to the position at the instant of slip: (1) the shoe can be pushed or pulled until slip occurs (dynamic friction; Hunter Machines), (2) the floor surface can be moved until the shoe slips (static friction; James Machines), and (3) the weight can moved until the shoe slips (static friction; NBS Brungraber Tester).

**Pendulum-type testers.** In a pendulum-type tester, a pendulum attached to a shoe sole or heel material sweeps a path across a flooring surface. The potential energy of the pendulum at the beginning of a swing and its residual energy at the end of a swing can be determined from the known weight and position of the pendulum's center of gravity. The difference, or loss in energy, is equal to the work done in sliding the contact material over the walkway surface, which is the average contact friction force times the distance of contact. By definition, the average frictional force is equal to the COF times the average force normal to the plane of contact. From these relationships, an equation can be established for the COF in which all factors except the scale reading at the end of the swing are known constants of the instrument.

Generally, drag-type devices are used most often and have the greatest acceptance among both researchers and practitioners. The BOT 3000 digital tribometer can also provide both static and dynamic COF measures.

**PSYCHOPHYSICS**

The working environment should include salient features that are relevant to safe locomotion. For example, a slip and fall event could occur as a person steps onto the floor in a dimly lighted environment without being aware of some contaminant. In this section, I elaborate the psychophysics of slips and falls to provide a better understanding of the linkages between our sensory integration, behavior, and safe ambulation.

Many investigators have documented the kinematics of shoe-floor interactions. These models, however, are strictly mechanical and do not take into account the neurological mechanisms of the humans inside the shoes. Many investigators confirm that there is a relationship between kinematic change and behavioral change (e.g., when walking...
onto a slippery surface; Lockhart, 2008). Modifications in muscle activity patterns when walking on different surfaces with varied friction are further proof that the person wearing the shoes can affect the outcome of exposure to slippery situations (Parijat & Lockhart, 2012). Also, research into postural responses to transient perturbations has demonstrated that the walking human can adapt rapidly to many types of balance challenges. In the following sections, I describe factors affecting the perception of slipperiness, such as visual and tactile sensations.

**Perception of Slipperiness**

Attempts have been made to determine factors that influence people when they are walking. In earlier years, Carlsson (1962) investigated human gait to assess whether different floor hardnesses can influence different patterns of walking with different muscle coordination and muscle load. The results suggested that differences in muscle activities did exist for floors of different hardness. Additionally, when potentially hazardous conditions are perceived through visual or tactile sensations, or are expected to exist in walking, one adjusts gait accordingly. The length of stride is shortened, which consequently produces lower foot velocities and smaller foot shear forces, as the body’s center of gravity is better maintained (Lockhart, Woldstad, & Smith, 2003). The ground reaction force during the heel contact and the toe-off phases is also significantly reduced to diminish the likelihood of slipping.

**Vision**

The visual field is an important psychophysiological parameter involved in gait regulation. Studies of the human visual mechanism have indicated that the visual field of a walking person changes dynamically and only a small part of the effective visual field is attended to. In other words, attention is divided in such a way that priority is given to objects within the effective visual field. Therefore, if a slippery condition is not detected within one’s effective visual field (usually 10–15 ft ahead), the likelihood of falling increases significantly (Zohar, 1978).

The *optic flow field effect* (Lishman, 1981) may explain how an individual’s judgment of velocity and displacement of surrounding objects (during walking) can influence perception of tripping hazards. For example, if one is trying to catch a thrown ball, the apparent diameter of the ball increases as it comes nearer, because the size of the retinal image also increases, and the brain seems to calculate the time of arrival of the ball from the rate of change in size of the retinal image. Thus, judgment of the velocity and distance of approaching objects are effectively managed by utilizing the optic flow field effect.

Yet, judgment will be altered if a finite object is not in view; consider an infinitely long corridor that has uniformly painted walls and ceiling and an unpatterned carpet on the floor. In such a situation, if there is a tripping hazard, such as a step in the corridor or an object someone has dropped, then judgment of its (tripping hazard) distance can be hampered, potentially resulting in tripping and falling accidents.

**Visual Versus Tactile Sensation**

Tisserand (1985) suggested that people estimate and unconsciously memorize frictional values from preceding steps (i.e., creating one’s own model of slipperiness) and that this information is updated whenever individuals feel the floor conditions differ from what is expected (reality). Therefore, if a discrepancy exists between the model and reality (a failure of the evaluation system), a slip and fall might result. Cohen and Cohen (1994b) explored the perceptual and cognitive factors involved in the perception of floor tile surface slipperiness, finding that tactile cues are most sensitive to the physical measurement of dynamic COF. A follow-up field study (Cohen & Cohen, 1994a) of the psychophysical assessment of the perceived slipperiness of floor tile surfaces concluded that people tended to make predictions about the slipperiness of walking surfaces and then verified these expectations as they crossed the surfaces.

Such results suggest that visual cues to slipperiness are inferior to tactile sensation. They also suggest that in real-world conditions, the perception of walking surface slipperiness is probably the result of tactile cues, with visual impressions being confirmatory. Thus, in unfamiliar conditions, people may rely on the primary but inferior visual information...
about a surface’s traction until they actually walk on it, creating the potential for an accident due to misjudgment of slipperiness based on initial visual sensing and the limited time available to make immediate adjustments in gait to accommodate for the hazardous condition. Although implicated, vision remains the only sensory cue that may be used to avoid an adverse walking condition.

BIOMECHANICS

The body’s center of gravity is a key factor in human gait analysis as it reflects the motion of the whole body. The center of gravity is the theoretical point about which body mass is evenly distributed. Reduction of the partial body masses into a common center of gravity or mass simplifies the movement dynamics to a point at which the effect of the moving forces on the mechanism of gait as a whole can be deduced. In the human body, the location of this theoretical point depends on several factors, including the distribution of segmental masses and the location of those segments.

Shimba (1984) and MacKinnon (1990) reported that the lateral path of the center of gravity passes forward along the medial border of the foot (sometimes slightly outside that border: ±2 cm). These lateral movements represent automatic postural adjustments, shifting the line of gravity alternately toward the eccentrically placed bases of support in keeping with the demands of stability.

The balance of the human body or its parts requires that all gravitational forces be completely neutralized by counterforces. These counterforces are supplied by the resistance of the supporting surface of the body. When gravitational forces fall outside of the supporting surfaces, however, the translatory force of gravity is not neutralized. To neutralize the rotatory forces, the line of one’s center of gravity must also fall in the supporting surface. In the human body, the constant mass is supported in standing on a small base. Additionally, the area of the base and the position of the center of gravity are subject to constant rapid changes, therefore requiring a complex reflex system involving the integration of sensory nerves and the motor nerves controlling the muscles to maintain balance in any given posture of the body. The deviation of the center of gravity is constantly monitored by the following (Nashner, 1983; Stelmach & Worringham, 1985):

- sensory mechanoreceptors in the capsules and ligaments of joints, which provide information about their position and rate of movement;
- stretch receptors in muscles (muscle spindles), which give information on the amount and rate of muscle stretching;
- pressure receptors (exteroceptors) in the skin, which provide information about the amount of pressure on the skin of the soles of the feet;
- the vestibular apparatus, including the semicircular canals found in the inner ear within the temporal bone of the skull, which provides information about the motion of the head in all planes; and
- the visual system, which provides information about the position of the body in relation to objects and surfaces that can be seen.

All of this information is processed in the central nervous system (CNS)—principally in the cerebellum and the brain stem—and signals are sent to skeletal muscles to contract appropriately to adjust the position of the body to maintain the center of gravity over the base. This process involves unconscious prediction of body motion so that the adjustments are not merely responding to the existing body position but instead are arranging for the relationship of the center of gravity to base to be appropriate for subsequent movements (i.e., the next step in walking).

Human bipedal locomotion (walking) is a challenging balance task for the CNS, one that appears to be completely different than the balance task during standing. During standing, the CNS is challenged to keep the body’s center of gravity safely within the borders of the two feet (or a single foot if balancing on one foot). Studies of balance and posture during quiet or perturbed standing have identified the ankle muscles (plantarflexors and dorsiflexors, invertors and evertors) as dominant (Winter, 1991). During locomotion, however, ankle muscles are no longer important because the balance task has changed. As explained previously, the lateral path of the center of gravity is monitored by the CNS to ensure that it remains within the supporting surface.
gravity passes forward along the medial border of the foot (or even slightly outside that border). Thus, during single support, the body is in a continuous state of falling down because the body’s center of gravity is outside the foot. The only way that recovery is achieved is to position the swing limb so that during double support the CNS can make any rebalancing adjustments.

This recovery is a challenging balance task that requires a complex interplay of neural and motor control mechanisms. Motor control is directly linked to the CNS’s processing of sensory inputs from the visual, vestibular, and proprioceptive systems. The brain constructs internal representations of the world by integrating information from the different sensory systems. In other words, the transformation from sensory signals to motor commands is processed within the CNS. The motor system transforms neural information into physical energy via commands transmitted from the brain stem and spinal cord to skeletal muscles.

**Gait Models**

A system model that mimics the behavior of a natural process is known as an internal model, and it includes two main components: an inverse model and a forward model (Wolpert, Ghahramani, & Jordan, 1995). An inverse model functions as a motor command computation to calculate the desired states. A forward model acts as a predictor to estimate the next state (e.g., future position and velocity). The sensory systems send inputs to an online control to make an adjustment in real time. The commands from the inverse model and a real-time controller are then sent to a neuromechanical apparatus as well as to the forward model as an efferent copy to control the location of the whole-body center of mass. Afterward, the forward model predicts the trajectory of postures to adjust the center of mass in slight future time. The sensory feedback resulting from self-generated movement is sent back to correct the next motor command. In essence, we use the online controller to modify our walking behavior: For example, walking off the sidewalk to cross the street and stepping back onto the curb requires the online controller. Additionally, the internal model is used to predict and adapt to the next step, thereby enabling us to feel momentum changes, such as when walking onto a broken escalator.

Understanding the gait model above is important to obtaining a better understanding of the processes associated with slips and falls. Here, it is clear that expectancy is required to walk—that is, during walking we expect the ground to be stable, and, in turn, we modify our gait to traverse the terrain with the appropriate force and speed to ambulate safely. If the ground is not stable, however, there will be a motion perturbation (i.e., expectation and reality did not match). If not controlled, this perturbation could grow into slips and falls.

**Gait Characteristics Influencing Slip Initiation, Detection, and Recovery**

The process of slipping and falling can be categorized into four levels, as shown in Figure 14.1. The environmental phase considers the effects of contamination. As noted by (Chaffin et al., 1992), “any fluid contaminant between two sliding surfaces will provide lubrication and thereby lower the dynamic coefficient of friction (DCOF) values” (p. XX). Therefore, the presence of contamination (oil, water, etc.) will reduce the available COF of the floor surfaces. In terms of slip-induced falls, friction demand characteristics between the shoe sole surface and the floor surface have been implicated as an important predictor variable related to severity of falls. Slip is initiated by the combination of lower available COF (of the floor surface) and higher friction demand (i.e., RCOF). A static COF of 0.5 on a level walking surface commonly has been recommended for preventing slips by standards organizations and by individual authors (Lin, Chiou, & Cohen, 1995). Dangerous forward slips that lead to falls are most likely to occur 70–120 ms after the heel contacts the ground (Grönqvist et al., 1989; Perkins, 1978).

The sensorimotor degradation in older adults often leads to altered gait characteristics that affect the slip-initiation process. Lockhart et al. (2003) reported that older adults’ heel velocity was faster than their younger counterparts at the heel contact phase of gait cycle. Increases in heel velocity during critical weight transfer may increase the potential of a slip-induced fall if the floor is slippery. In addition,
the friction demand of older adults was found to be higher than their younger counterparts (Lockhart, Smith, & Woldstad, 2005). It also has been suggested that the center of mass velocity relative to the base of support may be a factor related to RCOF (Lockhart et al., 2003; Pai & Patton, 1997). Slower whole-body center of mass velocity and center of mass transitional acceleration (velocity changes from heel contact to shortly after heel contact) were reported in older adults (Lockhart et al., 2003). Alterations in these factors can increase the risk of a slip initiation.

During the detection and recovery phases of the slip and fall process, CNS control plays an important role. The CNS must undertake certain processing activities (detection phase) if a fall is to be avoided or compensated for (recovery phase; Lockhart et al., 2005). During the detection phase, a trigger must be sent through the sensory feedback to the motor control regions of the CNS. This process may be initiated by one or more of the following sensory inputs: somatosensors, vision, and vestibular function. At the input stage, any disruption in the quality of the input signal may increase the likelihood of slips and falls. The somatosensors are responsible for proprioception—the sensing of joint and limb motion (Winter, 1991). The vestibular organs located at the inner ear (semicircular canals and otoliths) detect angular velocity of the head and act as linear accelerometers (Horak & Macpherson, 2010). Visual cues provide information about the position and motion of the head with respect to surroundings. In the case of posture control, the relevant signals are processed by motion detection circuitry in the retina as well as in the visual cortex. These sensory signals are fed back to a series of hierarchical feedback loops to generate motor commands.

The reactive recovery phase involves quickly bringing the body center of mass within stability limits after a slip has begun. This is achieved through changes in various kinematic, kinetic, and muscle coactivity mechanisms. One of the important mechanisms during reactive recovery is to reduce the displacement of the slipping foot through increased coactivity of the muscles of the lower extremity (Brady, Pavol, Owings, & Grabiner, 2000; Kim, Lockhart, & Yoon, 2005). Numerous studies have linked slower muscle activation rates in older adults to an increased risk of slip-induced falls (Kim et al., 2005; Winter, 1991). Kim et al. (2005) found a decreased hamstring activation rate in older adults and related it to higher risks of slip-induced falls. The postural activity from bilateral leg and thigh muscles and the coordination between the two lower extremities were found to be the keys to reactive recovery balance control (Tang, Woollacott, & Chong, 1998).

FALL RISK FACTORS

In general, fall risk factors can be categorized into extrinsic (environment) and intrinsic (individual) factors. Typical extrinsic factors include slippery or uneven floor surfaces, ill-designed stairways, and poor lighting (Gill, Williams, & Tinetti, 2000; Nevitt, Cummings, & Hudes, 1991). Most of these
hazards can be controlled using engineering measures. Major intrinsic factors include musculoskeletal degradations, sensory or cognitive impairments, and inappropriate medications (Cesari et al., 2002; Stalenhoef, Crebolder, Knoottnerus, & VanderHorst, 1997). Certain intrinsic risk factors can be controlled by walking aids, gait and balance training, physical therapy, or medical treatment (Cesari et al., 2002; Close, 2005).

Age
Many studies have shown that with advancing age there is an increasing incidence of fatal slip and fall injuries (Campbell, Reinken, Allan, & Martinez, 1981; Rubenstein et al., 1988). Falls occur in one of every three older adults, and their frequency increases with aging. Falls are the leading cause for admissions to nursing homes, and the mean cost of injuries caused by falls ranges from $3,476 to $10,749 per faller (J. C. Davis, 2010). Approximately 2.2 million older adults underwent treatment in emergency departments in 2009 for nonfatal fall injuries, and around 581,000 were later hospitalized (National Center for Injury Prevention and Control, 2010). About 82% of fall-related fatalities in 2008 were in the age group of 65 years and older (Ste- vens & Rudd, 2013). The direct medical costs alone for falls was around $19 billion in 2000 and is projected to be about $54.9 billion by the year 2020 (National Center for Injury Prevention and Control, 2010). These demographics clearly suggest that risks and prevention of falls must be evaluated in high-risk groups, such as the aging population in the United States. Although young people fall more frequently than older individuals, the injury rate, particularly for serious fall-related injuries, is higher among older adults (Layne & Pollack, 2004).

Major physiologic changes affecting the potential for slip and fall accidents begin to appear in the mid-20s. In general, isometric muscle strength peaks in the mid-20s and then decreases slowly until after 50 years of age when there is an accelerated decline (Åstrand & Rodahl, 1986; Larsson, 1982; Rice & Cunningham, 2001). These declines in strength development appear to stem from changes in muscle contraction mechanisms (Theilen, Schultz, Alexander, & Ashton-Miller, 1996), mitochondrial enzyme activity (Houmard et al., 1998), and the proportion of fast-twitch to slow-twitch muscle fibers (Lexell, 1995). Studies suggest that age-related changes in muscle strength have an important effect on recovery from slip and fall accidents (Larsson, Grimby, & Karlsson, 1979; Lockhart et al., 2005; Whipple, Wolfson, & Amerman, 1987; Wolfson, Judge, Whipple, & King, 1995; Wolfson, Whipple, Amer- man, Kaplan, & Kleinberg, 1985). This effect can be further aggravated by fatigue, which increases the risk of falls among older individuals.

A number of studies have documented the decline of postural control (keeping the body’s center of mass over its base of support during quiet stance and active movement) due to sensory degradation among older adults (Nashner & Peters, 1990; Sheldon, 1963). This decline of postural control is believed to be an integrative process associated with a greater risk of falling (Isaacs, 1985; Maki, Mcl- roy, & Perry, 1996). Sensory inputs important for balance include vision, proprioception, and vestibular sensations (Lacour, Vidal, & Xerri, 1983; Nash- ner, 1980). Vision plays a major role in maintaining stability, both in quiet stance and while undergoing movement such as walking (Tinetti & Speechley, 1989). Visual acuity, adaptation to the dark, peripheral vision, contrast sensitivity, and accommodation are all related to stability and may be affected by age-related changes (Cohn & Lasley, 1985; Gold- man, 1986; Kornzweig, 1977). For example, age-related decrements in peripheral vision may impair an older individual’s use of visual reference information. Narrowing the visual field may deprive the older person of that part of the visual field most sensitive to movement (Stelmach & Worringham, 1985), and, as a result, postural control may be compromised.

Studies indicate that proprioceptive deficits also are significantly higher in older individuals (Rab- bitt & Rogers, 1965; Skinner, Wyatt, Hodgdon, Conard, & Barrack, 1986). The proprioceptive system contributes to stability, particularly during changes of position. Woollacott, Shumway-Cook, and Nashner (1986) demonstrated the significance of ankle proprioception for balance retention in older adults by utilizing a moveable platform that permitted either stabilization of the visual field or of
the support surface. Comparing postural sway, they found that older adults had large increases in postural sway when ankle proprioception was eliminated (via the platform). Proprioceptive information also plays a vital role in the modification of internal models using feedforward control mechanisms (Bard, Fleury, Teasdale, Paillard, & Nougier, 1995; Ghez & Sainburg, 1995). During a slip perturbation, motor programs have to be modified to maintain dynamic stability. Modification of the motor program is closely associated with visual input as well as with proprioceptive input. In a situation when visual cues conflict with the environment, however, proprioceptive input may be the quickest and most accurate modality associated with balance maintenance (Ghez & Sainburg, 1995). As a result, older adults' proprioceptive deficits may hinder optimum balance recovery during slip-induced perturbations and increase the likelihood of falls, especially in a fatigued state.

Furthermore, increasing age also can affect gait due to postural and balance changes. Older adults tend to have a shorter step length and a broader walking base, which increases stance time and double support time (Gillis, Gilroy, Lawley, Mott, & Wall, 1986; Imms & Edholm, 1979; Murray, Kory, & Clarkson, 1969; Winter, 1990). Many researchers have observed that on slippery floor surfaces, older individuals tend to shorten their step length to reduce foot velocities and foot shear forces so as to reduce the likelihood of slipping (Cooper & Glassow, 1963; Ekkubus & Killey, 1973). The shorter step length and the broader walking base of older adults are thought to result in a more stable, safer gait pattern. Yet, these gait adaptations may have some important implications for the initiation of slip-induced falls. General gait instability among older individuals, and specifically higher horizontal heel velocity during the critical phase of the gait cycle, may increase the friction demand, thereby increasing the likelihood of slip-induced fall accidents. This effect can be further aggravated by fatigue (Saggini, Pizzigallo, Vecchiet, Macellari, & Giacomozzi, 1998) and increase the risk of falls among older adults.

In summary, gait instability, sensory degradation, and diminished rapid torque development capacities of older workers imply that age must be considered as a factor in the identification of risk of occupational falls.

Localized Muscle Fatigue
Modern technology has contributed greatly to the reduction of heavy work in industrialized countries, but intense, labor-demanding physical work is still necessary in some occupations, such as construction, forestry, health care, and many service occupations. It has been estimated that one third of the U.S. workforce must exert significant strength as part of their jobs and, in turn, experience fatigue at workplaces (Swan, Van Amelsvoort, Buhrman, & Kant, 2003). Localized muscle fatigue has been defined as the inability of the muscles to maintain expected force output or as a reduction in the force-generating capacity of the total neuromuscular system. A recent review on occupational falls (Hsiao & Simeonov, 2001) identified localized muscle fatigue as influencing risk of injury due to loss of balance, especially fatigue of the distal lower extremity muscles (ankle plantar flexors and knee extensors; Sparto, Parmianpour, Reinsel, & Simon, 1997) and proximal muscles (hip and low back; Davidson, Madigan, & Nussbaum, 2004; Tang et al., 1998).

The literature suggests that localized muscle fatigue adversely affects proprioception (Skinner et al., 1986), movement coordination (Sparto et al., 1997), and muscle reaction times (Häkkinen & Komi, 1986), all of which may degrade the reactive recovery control of balance during slip perturbation. Possible contributions of muscle fatigue to perturbations in joint positioning sense also have been attributed to decreases in motor neuron output (Kernell & Monster, 1982; Macfield, Hagbarth, Gorman, Gandevia, & Burke, 1991). Furthermore, Lattanzio, Petrella, Sproule, and Fowler (1997) observed an impaired ability to reproduce lower extremity joint angles after fatiguing exercise. Consequently, an increase in postural sway, which is associated with a greater risk of falling (Isaacs, 1985), was observed after fatigue was induced by increasing the workload (Seliga et al., 1991).

Work Pace (Walking Speed)
Natural or free cadence is defined as the steps per minute of a person walking at a self-selected speed; it
ranges from 101 to 122 steps per minute for adults less than 65 years of age (Winter, 1991). Rushing typical industrial tasks requires workers to perform at a greater work pace than their normal walking pace. When an individual walks with a faster cadence (e.g., is rushed), he or she must override his or her natural frequency and consciously force cadence to a faster rate to increase the walking speed. Walking speed directly affects the magnitude of shear force ($F_H$), therefore directly affecting the friction demand (RCOF; Kim et al., 2005). An increase in walking velocity usually increases the friction demand and risk of slip initiation (Soames & Richardson, 1985).

Dynamic stability of walking also is influenced by walking velocity. Dingwell, Cusumano, Cavanagh, and Sernad (2001) observed that increased walking speed reduces dynamic walking stability. Thus, faster work pace or walking speed during rushed industrial activities may adversely affect slip initiation and fall recovery processes. Although theoretical and experimental evidence provide support for an increased risk of slipping and falling while walking at faster pace, the relationship between muscle fatigue, walking speed, and risk of falls has not been scientifically determined.

**Load Carrying**

In normal walking, corrective postural movements are made by the upper body, arms, and shoulders. Arm swing is used to offset the rhythmical acceleration and deceleration of the trunk by the leg movements, and also to damp-out the rotational forces of the trunk arising from the same causes (Haywood, 1986). These dampening effects, however, are modified during the laden state (P. R. Davis, 1983) and by altered gait and posture, and they may influence risk of slip initiation (Liu & Lockhart, 2006). Load carrying (in front) also displaces the whole-body center of mass anteriorly, placing it closer to the forward edge of the supporting base, requiring additional rotational torque at the foot–ground contact.

**CONCLUSIONS**

In summary, controlling the risk of slips and falls in the living environment may require several different approaches—namely, engineering control, administrative control, and personal protective equipment. In terms of engineering control, maintaining a safe COF level of floor surfaces may increase pedestrian safety. Using appropriate tribological relationships, an effective shoe–floor interface can be determined. Additionally, administrative control can be used to enhance fall safety by utilizing a radio-communication system to schedule a clean-up immediately after a spill (Bell et al., 2008). In some situations (e.g., working at height), personal protective equipment should be used to protect individuals from a fall.

In terms of designing future living environments, several approaches presented in this chapter should be applied to the interaction between the environment and pedestrians. Using the epidemiological approach, key variables related to occupational fall safety in particular organizations can be ascertained to better control these accidents—understanding these characteristics may help in identifying the human–environment requirements for future living environments. Perceptual requirements also should be carefully planned, as discussed in the Psychophysics section. Because visual requirements exceed all other sensory requirements, careful assessment of the needs of the visual system may improve the safety of pedestrians (e.g., avoid single-step walkway and transitional floor surfaces). Finally, as indicated in the Biomechanics section, human attributes related to fall accidents should be carefully considered in the design phase of living environments.

**References**


Slips and Falls


