Chapter 2
Pedestrian Fall Incidence and Slip Resistance Measurements

2.1 Brief Overview of Slip and Fall Incidences

As discussed in Chap. 1, slip and fall incidences are widely studied owing to their prevalence and associated costs in terms of human suffering and economic burden around the world. The incidents are categorized into falls from an elevation and same level falls. Falls from an elevation are those where the point of contact is below the level of the original supporting surface of the faller. Falls from the elevation are one of the leading causes of workplace fatalities and traumatic brain injuries on the job. These incidents create a substantial risk that an employee or worker will become momentarily or permanently disabled.

Whilst the same level falls are those where the point of contact is on the same level or above the original supporting surface of the faller. Falls from the elevation are considered more likely to lead to severe injuries but the same level falls occur far more frequently. In some cases, factors intrinsic to the pedestrians are solely responsible for the same level falls. But more often, these falls are at least partially induced by environmental factors. For example, trips occur during walking when the leading foot is arrested by an obstruction which interrupts the smooth movement of the body's centre of mass.

Slips are a more common cause of the same level falls, contributing to up to 85% of all fall-related occupational injuries (Courtney et al. 2013). They occur when the underfoot conditions induce a sudden loss of grip because the coefficient of friction (COF) between the shoe heel (or barefoot) and the floor surface is insufficient to resist the forces at the point of contact (Leamon 1992). Foot slips and trips are injurious when they result in harmful loading of body tissues as a result of a sudden release in energy (Grönqvist et al. 2001).

A number of gait studies from the literature have confirmed that slips typically occur either when the trailing foot is pushing off (toe-off) or when the leading foot contacts the ground (heel strike) (Perkins and Wilson 1983; Redfern et al. 2001).

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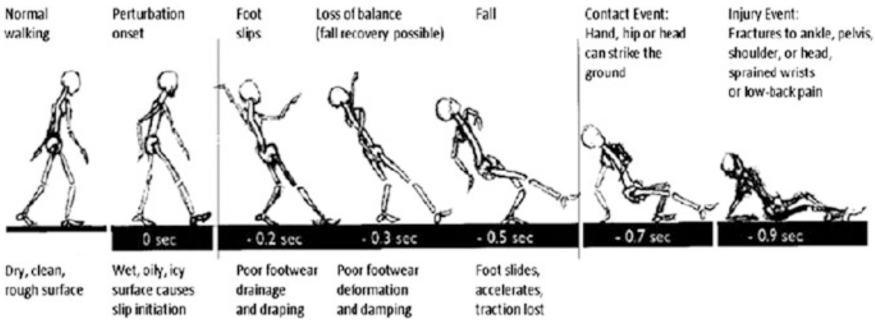


Fig. 2.1 Typical event sequences for slips and falls (Grönqvist et al. 2001)

At the phase of toe-off, the forces generated at the foot are used to propel the body's centre of mass forward after the majority of weight has already been transferred to the contralateral foot.

At the stage of heel strike, the vertical component of weight is transferred onto the leading foot. As weight is being transferred the body is inherently unstable, relying on safe planting of the striking foot for momentary stabilisation. Accelerations at the heel during heel strike can, therefore, lead to balance loss and potential falls. As such, slips at toe-off are less hazardous than those at heel strike (Leamon 1992).

Slip resistance is a term used to describe properties of underfoot surfaces and footwear that resist the tendency to slide relative to one another (Grönqvist et al. 2001; ASTM F1637 2013). The provision of adequate slip resistance is important in reducing the risk of slip and fall incidents. Figure 2.1 illustrates the typical sequence of normal walking followed by slip initiation at heel strike due to inadequate slip resistance. This then leads to balance loss, fall, and injury, accordingly.

2.2 Injuries Owing to Slips and Falls

Fall incidents from slips or trips are hazardous because they cause to injuries (Baker and Harvey 1985; Blake et al. 1988). Common injuries include sprains and fractures often affecting the wrists, pelvis and lower extremities. Hip fractures involving elderly people are of great concerns in falls. Whilst the same level fall incidents are hardly life-threatening, patients are at increased risk of premature death for several years following a hip fracture (Abrahamsen et al. 2009). Injuries resulting from falls have also been found to greatly affect the activity level and lifestyle of older people.

In the workplace, the injury frequencies from slips and falls also affect the older workers more than younger ones and can impact differently between men and women employees. Nenonen (2013) used data mining techniques to analyse occupational slips, trips and falls from the Finnish occupational accidents and diseases statistics database. This study found out that slip, trip, and fall incidents incurred 66% in the male workers and 34% in the female ones, respectively.

Layne and Landen (1997) studied hospital emergency department records of 136,985 work-related injuries involving workers over the age of 55 across the United States in 1993. Fall-related incidents accounted for 26.3% of all non-fatal injuries, of which same-level falls were the most common (55.9%). Women experienced more same-level falls (67.9%) than men. Falls were also the leading cause of hospitalization (43.9%) and fractures and dislocations sustained as a result of falls accounted for the greatest proportion of hospitalizations (36.1%).

2.3 Improvements of Fall Prevention

High traction or slip resistant floors and floor coverings and proper maintenance procedures have been found to reduce slips and falls. Specialized flooring materials for increased grip functioning including abrasive paints and tactile strips have been shown to be useful (Bell 1997). Cautious and immediate elimination of spills and other contaminants on floor surfaces as well as removal of any obstructions are also important for decreasing falls (Weisberger 1994). Other environmental changes that can reduce fall risks include the application of warning signs (Gadomski 1998) and improving lighting conditions (Maynard 2006).

Bentley (2009) described the importance of perception and cognition of hazards in the prevention of fall incidents. His study of construction workers in New Zealand found that in 75% of cases, workers did not notice the fall hazard prior to the incident. Typical reasons for having not perceived hazards a priori include distraction or divided attention or the hazard was obstructed from view.

In a review of the literature, Bell (1997) suggested that aside from improving slip resistance of floor surfaces, the other effective way to prevent slip and fall incidents in the workplace was through footwear. Targeting improvements in footwear for increasing slip resistance has the potential to impact falls on a large scale as evidenced by various cases in indoor industrial environments. Verma et al. (2011) showed that adopt of slip resistant shoes from 36 limited-service restaurants across the US reduced slipping rates by 54%. A further analysis of the slip resistant footwear in these restaurants showed that older workers and women were more likely to use the slip resistant footwear (Verma et al. 2011).

Courtney et al. (2013) studied the relationship between the subjective perception of slipperiness and the risk of slipping in the workplace. They found out that when the perception of slipperiness (rated on a 4-point scale) was assessed across restaurants, the awareness of slipperiness was strongly associated with rates of slipping. For every 1-point increase in the mean rating of slipperiness, there was a 2.71 times increase in the rate of slipping.

Staal et al. (2004) studied the effectiveness of positive-grip (or high traction) shoe covers in a hospital setting where the rates of slipping incidents had increased as a result of changing the hospital floors from carpet to porcelain tile. In the initial phases of this study, they found out that majority of the fall incidents had occurred whilst employees were helping patients to transfer from shower chairs on wet floors. From a small sample of shoes, they concluded that high traction shoe covers were effective in preventing fall incidents.

Many other studies from the literature have also indicated a need for specialised footwear and many researchers have suggested the use of spikes or studs for added traction on risky environments. However, there remains very little evidence to show how such anti-slip devices actually impact slip and fall risks. Pedestrians continue to experience high rates of slips and falls despite using them (Rolfsman et al. 2012). Similarly, whilst certain outsole materials and tread designs have been touted to potentially reduce falls, highly effective designs for shoe sole/heel treads have not been established. In order to find effective footwear solutions for preventing slips and falls, an understanding of the interacting factors between the human, the footwear, and the environment is necessary (Gao and Abeysekera 2004).

2.4 Factors Influencing Pedestrian Fall Incidence

Pedestrian slip and fall incidents are caused by a number of reasons. As briefly illustrated in Fig. 2.2, multi-factorial risk factors seem to, directly and indirectly, affect the incidence. These risk factors signify that fall safety assessment is a highly complex area to study, where the likelihood of a slip and fall is a function of a variety of elements such as surfaces (types, materials, and surface finishes), environmental conditions (dry or lubricated), and individual users (physical conditions and footwear).

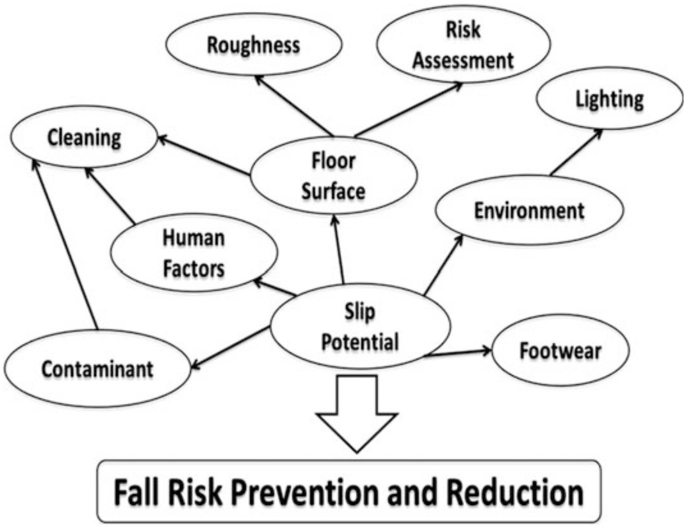


Fig. 2.2 A schematic diagram for contributing risk factors to fall incidents

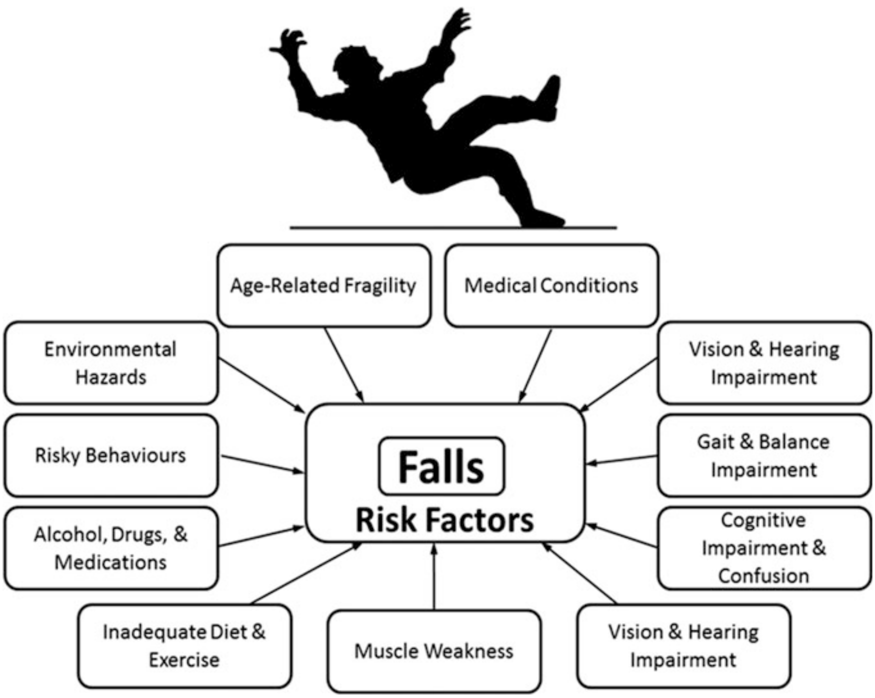


Fig. 2.3 A schematic diagram for Intrinsic and extrinsic fall risk factors

As shown in Fig. 2.3, slip and fall incidents are a continuing problem and frequently caused by a combination of risk factors that are specific to physiological (intrinsic factors) and environmental (extrinsic factors) conditions (Pearson and Coburn 2011; Titler et al. 2011).

If these risk features are identified, then it would be beneficial to develop appropriate prevention strategies for the fall incidence.

The following is a brief summary of the recent studies on intrinsic and extrinsic fall risk factors:

2.4.1 Intrinsic Fall Risk Factors

Intrinsic risk factors are mainly related to physiological issues such as

- Age-related changes (weakened vision, mobility, and gait issues) (von Schroeder et al., 1995; Evans et al. 2001; Hathaway et al. 2001; Krauss et al. 2005, 2007; Currie 2008; Carroll et al. 2010; Tinetti and Kumar 2010).
- Arthritis (Rubenstein and Josephson 2006; Peeters et al. 2009).
- Chronic illness (The Joint Commission 2007).

- Confusion and dizziness (Evans et al. 2001; Tzeng 2010b; Gray-Miceli et al. 2012).
- Depression (Huang et al. 2005; Yu et al. 2009).
- Length of hospital stay, fear of falling, and history of falls (Hitcho et al. 2004; The Joint Commission 2007; Dykes et al. 2009; Tzeng 2010a, b; Pearson and Coburn 2011; Titler et al. 2011; Boushon et al. 2012).
- Lower extremity weakness (Helbostad et al. 2010; Hatton et al. 2013).
- Polypharmacy (five or more medications) (Hartikainen et al. 2007; The Joint Commission 2007; Rhalimi et al. 2009; Titler et al. 2011).
- Status of activity of daily living (Zijlstra et al. 2007; Leung et al. 2010).
- Urinary incontinence (Hitcho et al. 2004; Dykes et al. 2009; Tzeng 2010a).

2.4.2 Extrinsic Fall Risk Factors

Extrinsic factors are mainly related to environmental issues such as

- Lack of grab bars, poor condition of floor surfaces, inadequate or improper use of assistive devices (Donald et al. 2000; Agostini et al. 2001; Pearson and Coburn 2011).
- Surface finishes and wear developments of the floors and shoes and their interactive effects on slip resistance performance (Kim 1996a, b, c, d, 2004a, b, 2006a, b, 2015a, b, c, d, 2016a, b; Kim and Smith 1998a, b, 1999, 2000, 2001a, b, c; Kim et al. 2001, 2003, 2013; Chang et al. 2003a, b; Kim and Nagata 2008a, b).
- These can be minimised through improved design and installation practices, better cleaning maintenance practices, safety audits, remedial policies, and mandatory legislation (Kim et al. 2013; Kim 2015b). Shoes may be considered as an extrinsic factor since inappropriate or excessively worn heels/soles may be the prime cause of an accident (Kim 2015a, c, 2016b).

Recognizing that widening the perspectives may better define the role of multi-factors in detection and prevention of fall incidence, but this book is mainly focused on exploring environmental (floorings and shoes) correlations for slip and fall incidents under a range of environmental conditions as a starting point. However, following sections from 2.2 to 2.5 briefly overview human walking, gait and its impacts on fall incidents, gait analysis and fall risk prediction, respectively.

2.4.3 Mechanics of Human Walking

Human walking (or gait) is a method of locomotion in which the body weight (or centre of gravity) is carried alternately by the right and left foot (Skoyles 2006). Interestingly, every individual has a unique gait pattern. Human's gait can be largely affected by injury or disease processes. By evaluating the gait patterns of an individual, a clinician, rehabilitation scientist, and/or physiotherapist can determine specific weaknesses and develop recovery programs to address detailed issues and problems.

Objective assessments of human gait parameters such as stride length, heel velocity, and slip distance during ambulation under normal and abnormal conditions have been conducted by many investigators (Herman et al. 1976; Crowinshield et al. 1978). These gait parameters also have been used to develop slip resistance measuring devices and apparatus for tribo-physical studies amongst the shoe heels, floor surfaces, and slip resistance properties. By studying human gait and gait-related parameters, more practical measurements and analyses for the pedestrian fall safety can be obtained (Perkins 1978; Strandberg and Lanshammar 1981).

2.5 Human Gait and Its Impacts on Fall Incidents

Human gait depends on several factors such as body weight, body shape, and age and is unique to an individual. The motion in which the foot contacts the floor is equally exclusive and can be both positive and negative with respect to the overall direction of motion (Whittle 1999).

The gait cycle is the term describing an ambulatory phase of walking or running. It is rather complex with each gait pattern being unique to each individual. There are many reasons that our gait patterns are different amongst us, but there are still core components that can be measured and evaluated by biomechanists, podiatrists, clinicians, or researchers.

There are four main phases of gait stages during foot-floor contact: namely, impact (initial contact), foot-flat, propulsion (midstance and heel lift), and toe-off. Figure 2.4 shows a gait cycle during normal walking.

As illustrated in Fig. 2.4, one leg is in the stance phase whilst the other is in the swing phase. Muscles must contract to counterbalance the forces of gravity, to offer acceleration or deceleration to momentum forces, and to overcome the resistance of walking surfaces.

Slips typically occur at the initial impact stage, known as a heel strike, where the foot generates a converging wedge and the contact area is small. In the case of fluid contaminants, this promotes the formation of fluid films and hydrodynamic lubrications. However, the small contact areas between the foot heel (or shoe heel) and the floor surface and relatively large sizes of contaminant particles (or pollutants) may significantly affect traction (or friction) properties and reduce slip resistance performance.

Redfern et al. (2001) suggest that the peak load (expressed as impact force per unit body weight) is approximately 10 N/kg (or roughly equal to body weight) occurring at 25% into the stance phase during walking on a horizontal surface. However, the foot reaches the 'foot-flat' (FF) position approximately 15% into the stance phase at which point the reaction force is around 8.5 N/kg (see, Fig. 2.5).

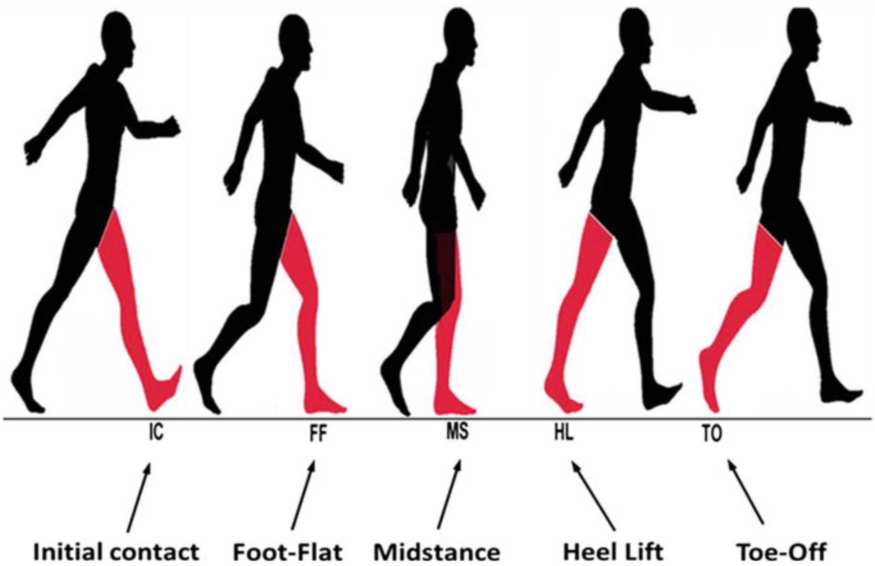


Fig. 2.4 Phases of gait cycle: impact (initial contact), foot-flat, propulsion (midstance and heel lift), and toe-off

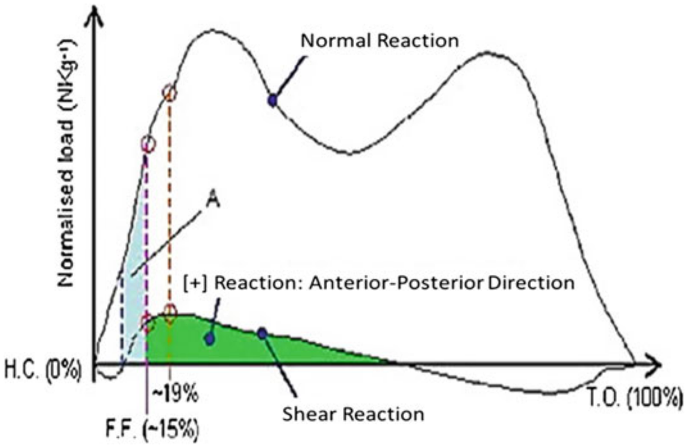


Fig. 2.5 Relative variation of normal and shear reactions over a single step (Whittle 1999)

The position of the highest fall risk is likely to be just prior to this point when the foot is still inclined to the floor. The pressure generated seems to depend upon the shoe contact area with the ground surface (highly shoe and gait dependent). Despite the importance of this contact mechanism during the gait phase, any detailed information on this issue is hardly found in the literature.

The maximum shear force of approximately 1.5 N/kg occurs at a position (19%) into the stance (Redfern et al. 2001), but the critical position in the stance where the shear to normal load ratio is the largest and contact area the smallest. is likely to occur within the shaded region (***A***) of Fig. 2.5 (before FF position), when the shear stress ranges from 0 to around 1.25 N/kg.

2.6 Observation of Human Gait

Walking is one of the most fundamental actions in our daily life. Regardless of its severity, gait injury can affect the overall quality of day-to-day living. Clinicians and researchers are interested in examining gait behaviours to characterise altered movement patterns due to gait impairment. Gait imperfection can be caused by musculoskeletal disorders and/or neurological diseases (Ashton-Miller 2005), but even healthy individuals can have difficulty in walking due to injury from an unforeseen accident. Many injured individuals can fully recover from trauma, surgery, or sudden pathology, but significant numbers of injured people also turn out with permanent damages in their walking after rehabilitation (Wade et al. 1987; Burdett et al. 1988; von Schroeder et al. 1995).

The main objective of human gait analysis is to identify and uncover underlying gait pathologies or impairment and develop rehabilitation programs (Park 2012). Hence, better understandings on gait patterns and movements may help clinicians and researchers to develop a strategy to prevent injury or long-term disability. In addition, observation of movement patterns from body segments and joints during walking can reveal important information on gait performance. Deviations from normative movement patterns can be an indicator of nerve damages, injuries, anatomical abnormalities, and other neurological or musculoskeletal problems (Park 2012).

Gait analysis is based on an assumption that gait abnormality is due to underlying neurological or musculoskeletal disorders. In addition, the environmental hazard can affect gait behaviour, resulting in abnormal gait patterns. Thus, quantitatively assessing deviations from normative gait patterns can indirectly provide insights into the mechanisms behind neurological and/or musculoskeletal illnesses and adaptations of a challenging environment that affects joint movements during walking or running.

Gait assessments mainly consist of two areas: qualitative observation and quantitative approach. Qualitative measures include visual inspection of gait behaviours (Perry and Burnfield 2010). The Hoehn and Yahr scale described the severity of symptoms of Parkinson's disease (PD) (Hoehn and Yahr 1998), and the Berg Balance scale measured static and dynamic balance ability (Berg et al. 1992). However, the usage of qualitative measures is limited because this assessment approach cannot provide detailed information on gait behaviours.

Moreover, the qualitative measurements are based on observers' subjective opinions so they are often not consistent and unable to capture the .small deviations of specific gait patterns in comparison to healthy individuals' ones. Therefore, information and judgment based on a clinician's subjective observation may be insufficient to accurately diagnose a patient's gait condition.

To address the deficiencies of the qualitative assessment, quantitative gait analysis can be adopted with laboratory equipment and instruments such as computerised motion capture systems and force platforms. These quantitative measurements enable clinician and researchers to conduct very detailed gait analyses. Continuous movement patterns can reveal important and detailed information on the gait analysis for a subject through deviations from normal gait patterns.

In the quantitative analysis, conventional techniques to characterize human gait behaviours have mainly focused on examining discrete events during a specific task-related motion, such as heel strike and toe-off during walking, or on using univariate statistical measurements such as a stride and step length, and the durations of stance and swing phases of gait (Danion et al. 2003; Diop et al. 2004; Hausdorff 2004; Knoll et al. 2004; Owings and Grabiner 2004; Schwartz et al. 2008).

The quantitative gait analysis has the ability to capture complex motion patterns produced throughout the gait cycles. Human gait is a spatiotemporally complex movement that involves interactions between multiple body segments and couplings across multiple joints. It is, therefore, crucial to assess complex motion patterns and correlated movements across multiple joints in order to detect physiological and neurological constraints, limitations, and injuries.

2.7 Gait Analysis and Fall Risk Prediction

Gait analysis offers reasonable tools to detect various population groups prone to falling. Gait disturbances and instabilities can result in increased slip and fall risks for older adults, people with PD, and workers in a range of industries.

Previous studies proposed that asymmetry, variability, complexity, and joint couplings during walking can be used as markers of slip and fall hazards in a variety of populations (Tiberio 1987; Blin et al. 1990; Hausdorff et al. 1998; Hamill et al. 1999; Frenkel-Toledo et al. 2005). Despite the detailed studies on gait and balance controls in fallers and non-fallers, specific gait behaviours that are critically associated with falls and fall predictions still remain unclear. New tools for investigating joint variability, symmetry, and coupling in gait motion patterns may provide added insight to this association.

Slip and slip-related fall incidents are responsible for many musculoskeletal injuries (Strandberg and Lanshammar 1981; Manning et al. 1988) and occur when the level of friction available at the shoe/floor interface is less than expected (Tisserand 1985; Leamon and Son 1989). If a low friction level is expected, gait adjustments can reduce the likelihood of a slip (Cham and Redfern 2002) and increased readiness can improve the likelihood of balance recovery if a slip occurs (Marigold and Patla 2002). The obvious benefits of these gait adjustments and increased readiness are fewer slip-related injuries. However, many real-world slip and fall incidents occur unexpectedly (Leclercq 1999), whereas most laboratory-based slip and fall simulations happen with some level of prior knowledge (Cham and Redfern 2002; Marigold and Patla 2002; Andres et al. 1992; You et al. 2001; Marigold et al. 2003; Brady et al. 2000; Bunterngchit et al. 2000; Hanson et al. 1999; Lockhart et al. 2003; Oates et al. 2004; Pai et al. 2003; Pavol et al. 2004; Hirvonen et al. 1994).

Although the recent studies have attempted to quantify differences between laboratory-based gait trials and real world gait events (Cham and Redfern 2002; Marigold and Patla 2002; Andres et al. 1992), their results showed that subjects who knew the floor was potentially slippery approached heel strikes with a flatter foot and a more vertical shank, even if asked to walk normally (Cham and Redfern 2002; Marigold and Patla 2002; Andres et al. 1992). Subjects also reduced their vertical and horizontal ground reaction forces and impulses during heel contacts, and thus reduced the friction necessary to walk without slipping (Cham and Redfern 2002; Marigold and Patla 2002; Andres et al. 1992).

Such gait adaptations have been cited as limitations in many slip and fall experiments (Perkins 1978; Kulakowski et al. 1989; Leamon and Son 1989; Andres et al. 1992; Hirvonen et al. 1994; Fendley and Marpet 1996; Marpet 1996; Brady et al. 2000; Bunterngchit et al. 2000) and may affect the external validity of some slip and fall studies (Leclercq 1999).

Prior knowledge encompasses both awareness of potential future slips and experiences gained from the past slips. Multiple slips are used in some studies and the recent experience gained from prior slips can be integrated with awareness to refine the gait adjustments. Thus, it is important to understand the effect of awareness on both experienced and inexperienced subjects to determine whether awareness or experience has a dominant effect.

Andres et al. (1992) varied both awareness and experience simultaneously and showed that the independent effects of these variables could not be discerned from their study. Cham and Redfern (2002) observed awareness-related changes in normal gait but pooled data from subjects with and without slip experience.

Marigold and Patla (2002) observed that the combined awareness and prior slip experience produced a “normal” gait different from that of both experienced and inexperienced subjects who knew for certain they would not slip.

Again, the independent effects of awareness and experience, and in particular the effect of awareness on inexperienced subjects, could not be discerned from their data. Therefore, detailed understandings on how prior knowledge affects the genesis of a slip is needed to better analyse slip and fall assessment results.

2.8 Measuring Devices for Slip Resistance Properties

A range of apparatuses and devices have been fabricated and developed to quantify frictional behaviours between the shoe and floor. The earlier studies related to slip and fall incidents were focused exclusively on the measurements of a COF quantity.

For friction measurements, about 70 different types of slip measuring testers and instruments are recorded in the literature and they differ substantially in their designs (Chang et al. 2001; Expert Panel 2004). In general, most slip resistance measuring devices and instruments fall into four categories: articulated strut, drag/towed-sled, pendulum, and other types, respectively. Following sub-section is the summary of those apparatuses for the measurements of slip resistance properties.

2.8.1 Articulated Strut Devices

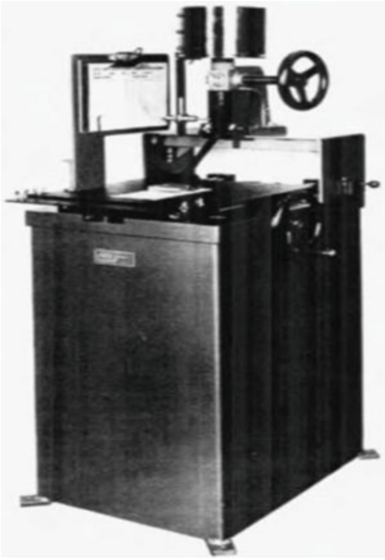
This device consists of a weight attached to a shaft articulated at an angle. The angle of articulation increases until a shoe sole sample slips. The tangent of the angle at which the shoe sole slips is related to a static COF. The James Machine developed by Sidney James of Underwriters Laboratories in 1951 is a good example of the articulated strut devices. The James Machine is a laboratory apparatus for dry testing only (Fig. 2.6a). As an articulated strut class of tribometer, the James Machine applies a known constant vertical to a test pad (i.e., a leather pad when testing flooring materials), and then applies an increasing lateral force until a slip occurs.

The two NBS (National Bureau of Standards) testers: Brungraber Portable Slip Resistance Tester (Mark I and II) and Ergodyne Slip Resistance Tester are examples of the articulated strut device as well. Figure 2.6 shows photographic images for the James Machine and Brungraber Portable Slip Resistance Testers: Mark I and II.

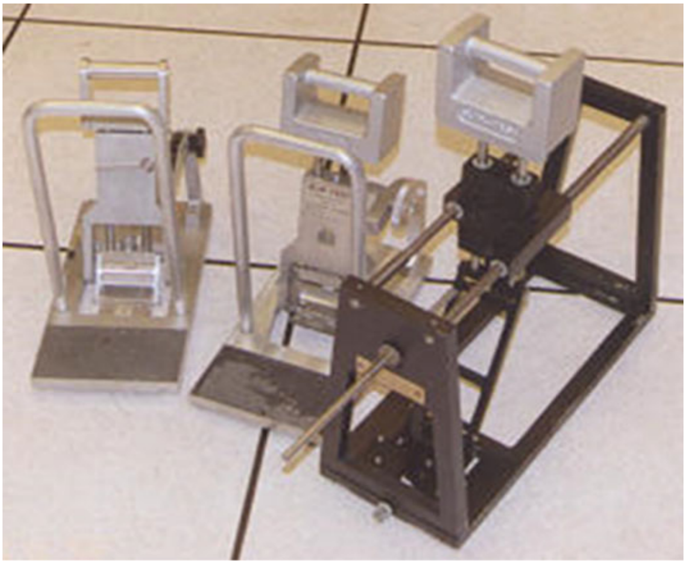
2.8.2 Drag and Towed-Sled Devices

This type of device slides a weighted scale mounted with a shoe sole sample across a test surface. Such a device is pulled either manually or by a motor at an adjustable speed. It is the most common type of a slip meter due to its simplicity, portability, and ease of use. The COF is derived by dividing the force required to cause slippage by the weight of the sled. Some models measure only static friction and others do both static and dynamic frictions.

Figure 2.7 shows photographic images for examples of the drag and towed-sled type devices: the Horizontal Pull Slipmeter (HPS) and the Tortus Floor Friction Tester designed by British Ceramic Research Limited, respectively.



(a) James Machine



(b) Brungraber Mark I and II

Fig. 2.6 Photographic images for **a** the James Machine and **b** Brungraber Portable Slip Resistance Tester, Mark I and II

(a) Horizontal Pull Slipmeter

(b) Tortus Floor Friction Tester

Fig. 2.7 Photographic images for **a** the horizontal pull slipmeter (HPS) and **b** the Tortus floor friction tester designed by British Ceramic Research Limited

The Horizontal Pull Slipmeter (HPS; ASTM F 6098-79), the Bigfoot designed by Safety Sciences, Inc. (Lockhart 1997), Dynamometer Pull-Meter (ASTM C 1028-84), CEPBT Skidmeter (Majcherczyk 1978), and the Tortus Floor Friction Tester designed by British Ceramic Research Limited (Ceram Research) are the drag type devices which are most frequently referenced in the literature.

2.8.3 Pendulum Type Devices

This type of device is represented by the Sigler Device, the British Portable Skid Test (TRRL Pendulum Tester), Wessex Universal Tester, Small Pendulum Impact Tester and measures only dynamic friction. A shoe sole material is attached to a mechanical foot that is impacted onto and swept over a floor surface at a relatively high speed. Dynamic friction is measured by the energy loss of the pendulum at the beginning and the end of a swing.

One of the earliest comprehensive studies on COF measurements was conducted by Sigler et al. (1948). They developed a pendulum type of device to measure the COF between a slider of leather and a type of rubber and 23 different underfoot surfaces against dry and wet conditions.

Figure 2.8 shows photographic images for the Horizontal Pull Slipmeter, Sigler Pendulum Tester, and English XL Tribometer, respectively.

2.8.4 Other Type Devices

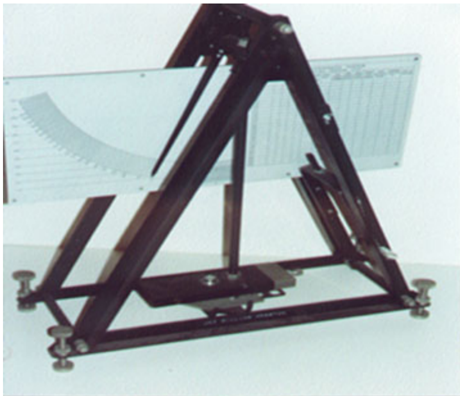
Braun and Roemer (1974) developed a device to determine static and dynamic friction properties between a shoe heel/sole material and floor surface. The objective of this development was to investigate the effect of polishes on COFs. Five different flooring materials and eight commercially available polishes were used with their device. The friction measurements were conducted before and after the treatments of polishing. It was interesting to note that the COFs increased in almost every case after the surfaces were treated with polishes. The average of static COFs on the untreated floor surfaces was 0.32, and the average COF was increased to 0.45 against the treated floor ones. For the case of dynamic COFs, the average dynamic COF was increased from 0.28 to 0.42. Therefore, the polishing process increased slip resistance performance by an average of over 30%.

Reed (1975) designed and constructed a portable type friction measuring device to test industrial working surfaces and named this device as “Universal Friction Testing Machine (UFTM)” (see, Fig. 2.9). This device was used to determine the values of COF between two shoe materials: leather and rubber and three-floor surfaces: vinyl (asbestos reinforced), oak (across the grain), and oak (with the grain).

Each floor material was tested against the leather and rubber specimens under dry conditions at different velocities from static to dynamic of 152 cm/s. A table of

Fig. 2.8 Photographic images for **a** the horizontal pull slipmeter, **b** Sigler pendulum tester, and **c** English XL Tribometer, respectively

(a) Horizontal Pull Slipmeter



(b) Sigler Pendulum Tester

(c) English XL Tribometer

Fig. 2.9 A photographic image for the universal friction testing machine which was designed expressly to enable the National Institute for Occupational Safety and Health to measure COFs

COFs was produced at various slip speeds. However, it should be pointed out that the vertical forÎ applied to this device could not provide a good simulation of human walking and suffered from serious reliability problems. As a result, this device was never commercially produced.

Other types of slip resistance measuring devices also include the Multicomponent Quartz Force Plate (FP) manufactured by Kistler Instrument, Switzerland. The Quartz FP device measures the magnitude and direction of the ground to foot reaction force in three component forces (mediolateral, anterior-posterior, and vertical), static and dynamic COFs as well as the point of force application or centre of pressure during foot contact. The force is recorded when the subject walks over the floor sample mounted on the plate top. Detailed descriptions of the mechanisms of the FP can be found in the literature (Schieb et al. 1990). Figure 2.10 shows a photographic image of the Multicomponent Quartz Force Plate. Further information on the above four categories of slip resistance measuring devices are found in the recent literature (Brungraber 1977; Grönqvist et al. 1999; Chang et al. 2003b).

Pedestrian walkways and footpaths should be tested using a tribometer (floor slip resistance tester) to discover if there is a high propensity for slip and fall accidents on it, either dry and/or when polluted with water or lubricated with other contaminants such as kitchen grease, hydraulic oil, etc. As discussed in the above, there are numerous slip resistance testing apparatuses either in a laboratory (before or after installation) or on floors in situ produced around the world to measure both

Fig. 2.10 A photographic image for the multicomponent quartz force plate (FP) manufactured by Kistler Instrument, Switzerland. Frictional and ground reaction forces are measured by the FP

static and dynamic COFs, but presently there are only a few that have been proven to be reliable for obtaining useful safety results and that have current official test methods. Table 2.1 summarizes laboratory based slip resistance tests with their usage and brief descriptions.

2.8.5 Slip Measuring Testers Used in This Book

Slip resistance measurements in this book were carried out by two pendulum-type dynamic friction testing machines that were designed and built to meet the International Standard Organization (ISO) requirements (ISO 1992; Stevenson 1997). Figures 2.11 and 2.12 show the dynamic friction testing machines developed by Stevensn et al. (1989) and Stevenson (1997), respectively.

As shown in Fig. 2.11, this testing machine consists of two hydraulic systems with an attached artificial foot, a force component transducer (Kistler 3-Component Dynamometer, Type 9257A), a desktop computer and an angular displacement transducer (Kim et al. 2013). This tester was designed to simulate the movement and loading of the foot during heel strike and initial slip and to quantitatively determine the slip requirement as DFC. The tester set up values could be adjusted to cover various parameters taken from biomechanical studies (human walking trials) such as heel contact angle, vertical load and its rate of increase and sliding speed.

To adjust the heel contact angle, tapered shims were inserted between the base of the pendulum and the last on which the shoe was mounted. The vertical load was set by the length of the pendulum adjusted by two nuts. Some fine adjustment to the vertical load was also possible by a pressure control on the oil fed to the vertical hydraulic cylinder. The sliding speed was set by a flow control valve.

Table 2.1 A summary of the laboratory based slip resistance tests

Floor slip resistance lab test	COF[a] assess	Procedure	Statement
ANSI[b] A137.1 (aka 'AcuTest'[c])	DCOF[d]	Specified in 2012 International Building Code for indoor wet areas	Like ANSI B101.3, but needs a higher minimum "passing" value and more stringent sensor prep
ANSI B101.1	SCOF[e]	Not a valid test for pedestrian safety, because it's a static test	Outdated by ANSI B101.3, a dynamic test
ANSI B101.3	DCOF	Using the BOT-3000E digital tribometer and for mostly indoors	Pendulum is more appropriate for outdoor surfaces due to its higher speed
ASTM C 1028-07	SCOF	Some specifiers still require it	An outdated and misleading test removed by ASTM in 2014
ASTM E 303 road skid test	DCOF	An American skid test for road surfaces	A simplified pendulum test with soft TRL rubber
Pendulum (CTIOA[f], HB 198/AS 4663-2013, or EN 13036-4)	DCOF	Dry and wet slip resistance appropriate to various conditions (pool deck, lobby, rest room, etc.)	The most widely used slip resistance tests worldwide. Endorsed by CTIOA since 2001
SlipAlert	DCOF	Qualitative demo mimics pendulum readings	A simple and durable machine is used that requires minimal training
Sustainable slip resistance pendulum	DCOF	Test whether slip resistance persists after significant abrasive wear by pedestrians	High pedestrian traffic areas must remain slip resistant
Tortus digital tribometer	DCOF	Dry and wet slip resistance up to high COF values with hard or soft rubber	Endorsed by CTIOA since 2001

[a]COF: coefficient of friction
[b]ANSI: American National Standards Institute
[c]DCOF AcuTest is an evaluation of the COF of a tile surface under known conditions using a standardized sensor prepared according to a specific protocol. Measurements are made with the BOT-3000, an automated and portable device that measures DCOF. The ANSI standard A137.1-2012 also allows the use of other equivalent tribometers
[d]DCOF: dynamic coefficient of friction
[e]SCOF: static coefficient of friction
[f]CTIOA: ceramic Tile Institute of America

In this tester, the test shoe was firmly attached to a last and mounted at the end of the pendulum mechanism. To minimise any movement, the shoe was nailed to the last. The floor surface specimen was glued to a steel plate that was bolted onto the force component transducer.

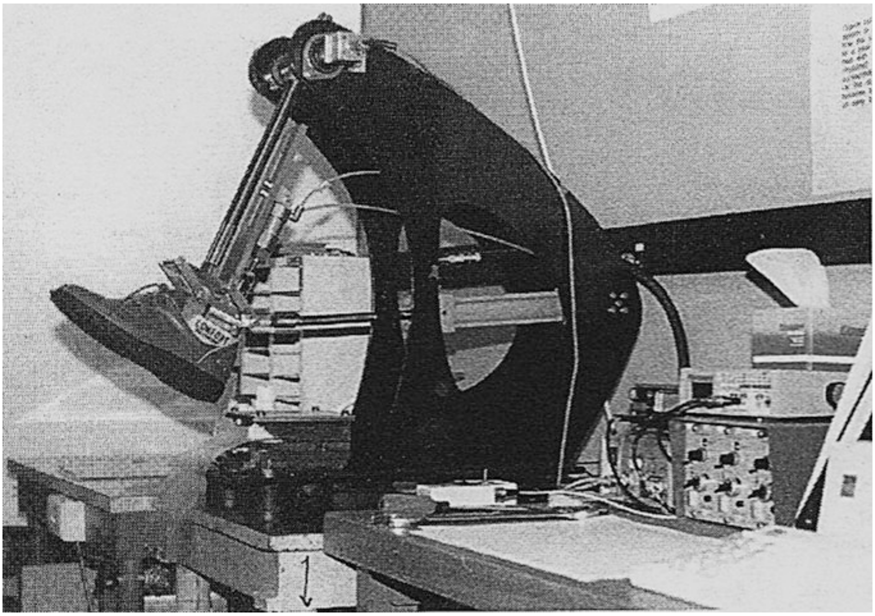


Fig. 2.11 A photographic image for a pendulum-type dynamic friction tester (Stevenson et al. 1989)

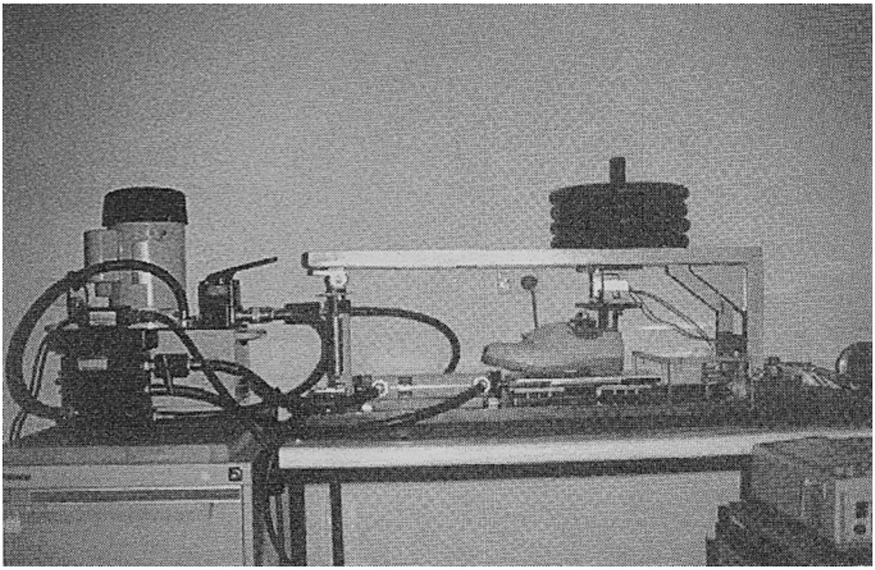


Fig. 2.12 A photographic image for a dynamic friction tester (Stevenson 1997)

In a test, the shoe was driven forward by the horizontal hydraulic cylinder to contact the floor sample surface at the heel edge. Another hydraulic cylinder was mounted at the end of the pendulum to simulate the body weight portion supported by the leading foot at heel strike. The two hydraulic cylinders were in a common circuit supplied by a pump which was driven by an electric motor.

As the shoe heel passed across the floor sample surface, the frictional (horizontal: ***H(F)***) and normal (vertical: ***V(F)***) components of the resultant force were measured by the force component transducer. The speed of the test was measured by a rotary potentiometer driven by the pendulum shaft. The force component signals and potentiometer voltage were recorded on a personal computer which continually calculated the ***H/V*** force ratio. During the tests, the normal force was kept around 350 N and the sliding speed was controlled at 40 cm/s based on gait studies (Redfern and Bidanda 1994; Jones et al. 1995). A heel contact angle of 9° was chosen by the result of previous biomechanical studies (Hoang et al. 1985, 1987).

Figure 2.12 presents the basic components of the test rig. It consists of two hydraulic systems to which the artificial foot is attached. The test shoe was filled with a polyester resin permitting a rigid connection to the machine. Then, the shoe heel is mounted to a last bolted to the base of a pair of load cells which monitor the vertical force on the shoe heel. A wedge between the shoe and the load cell is used to set the shoe heel angle.

The vertical load of 50 kg was applied partly by a share of the weight of the frame itself, but mainly by a set of weights resulting on top of the frame. The floor sample was screwed to a carriage which could move horizontally on low friction linear bearings. The movement of this carriage was controlled by a horizontal hydraulic cylinder. A vertical hydraulic cylinder was used to raise one end of the frame, thus lifting the shoe off the test surface. In order to measure the exact position from the shoe heel strike to heel off against the floor surface, a potentiometer was newly installed near the horizontal hydraulic cylinder.

In a test, the pressure of the vertical cylinder was released, allowing it to lower at a rate controlled by a flow valve. When the vertical force was fully applied, the horizontal cylinder was actuated, causing the carriage with the floor specimen to move at a controlled speed of 25 cm/s as the DCOF was measured. Other variables which were controlled in the tests were the heel contact angle (9°) and the rate of vertical loading on heel strike (5 kN/s). These values gave a reasonable simulation of heel strike conditions. The vertical and horizontal load cells were calibrated by dead weights of known mass.

2.8.6 Comparisons of Slip Measuring Devices

The versatilities of various devices and apparatus for assessing slip resistance properties have been compared and commented by several studies (National Research Council 1961; Bring 1964, 1982; Brungraber 1976; Braun and Brungraber 1978; Cohen and Compton 1982; Andres and Chaffin 1985; English 1990; Grönqvist et al. 1989, 1999).

Despite many years of investigations and fabrication of numerous testing machines, none of them is internationally adopted as a standard model yet, because each of them has some advantages and disadvantages in their designs and testing performance (Kim 2006b). In fact, because each testing instrument has different concepts, systemic parameters, and mechanical principles, it seems unreasonable to adopt a reference value without any citation to the instrument used for the slip resistance measurements (Kim 2006b; Kim and Smith 2003).

In the case of pendulum type devices, they require frequent calibrations and record only dynamic friction quantities which are not particularly critical in the initiation of a slip. The James Machine can only be used in a controlled laboratory condition for testing floor materials, not the actual floor surfaces due to the machine's heavy weight and bulkiness. On the other hand, the NBS—Brungraber Tester is easier to handle and can be considered as a portable James Machine. Tortus provides a permanent trace record when connected to a chart recorder, whereas most devices offer only a visual recording of the peak COF via an analogue meter or gauge.

The majority of slip meters require a number of replications in order to obtain a desirable level of statistical confidence in the measured quantities of COF and in measuring less than ideal surface conditions. This means that slip measurements need to be repeated as the floor surface is not being horizontal (inclined or ramp) or uniform status over the complete section rubbed by the shoe sole materials. For example, the small size of shoe samples on the UFTM, HPS, and British TRRL Pendulum Tester tends to interlock with less than uniform surfaces such as textured tiles or carpeted surfaces.

Additional problems include lack of movabilities and calibrations. The use of some other devices is also limited in certain locations such as steps due to the requirements of space on the horizontal plane for slip resistance measurements.

It seems to be more difficult to choose specific test conditions such as a test speed, heel strike angle (contact angle), and normal force. In the case of the test speed, it is controversial to choose an appropriate slip speed at which to drive the shoe heel across the floor surface. Normal walking speed varies from 1 to 2 m/s, but the forward speed of the shoe heel edge seems to be less than this speed just before the heel strike.

Strandberg (1983) reported that walking speed was varied from 0.06 to 0.32 m/s in his experimental results with different subjects. After sliding started, however, the shoe heel accelerated to a value above the walking speed. He concluded that the speed of a dynamic test should be in the range between 0 and 0.5 m/s. Perkins and Wilson (1983) also concluded from their experiments that

> Probably the ideal speed for high-speed measurements is 0.5–1.0 m/s since the foot and shoe can be travelling at this speed when the shoe heel tip touches the floor surface. Even if slip starts from a static situation, such is the acceleration that the speed of slip is about 0.5 m/s after only 0.01 m slip distance.

The strike angle at which the shoe heel first contacts the floor surface is an important factor in slipping (Kim and Smith 2003). This contact angle has proved to be an important variable because of its influence on the nominal contact area between the shoe heel and floor surface (Kim 2002a, b). Specifically, the contact area between the shoe heel and floor surface seems to play a dominant role in the sliding process when walking under lubricated environmental conditions (Moore 1972; Kim 2003a, b). Hence, observing the heel strike angle at a "correct angle" seems to be one of the most vital parts for the shoe heel during walking.

Hoang et al. (1987) conducted biomechanical studies to measure foot angles of 32 male subjects (height ranges: 155–180 cm) walking on a force platform. They found that the heel strike angle varied with walking speeds, step sizes, and subject's heights. On a horizontal surface, the strike angle laid with the range of 6°–10° measured from the floor surface.

In the case of the normal force, Strandberg and Lanshammar (1981) found that the leading foot was born up to 60% of the body weights, acting at the heel edge during the shoe heel contacted the floor surface.

Most of the testing devices for slip resistance are, however, not mechanically capable of simulating human gait parameters which are considered to crucial during actual slippage. Such gait parameters include horizontal and vertical shoe motions, normal and frictional forces, the normal force applying time, and sliding velocity. As indicated by Strandberg back in 1983, an ideal device should meet all the required demands and be reasonable to provide users' perspective in terms of cost/benefit ratios (Strandberg 1983).

Because such a device is obviously non-exist until at least now, Andres and Chaffin (1985) suggested that selecting a proper tester or technique would be a viable starting point for measuring slip resistance properties. They recommended that users should decide which characteristics of slip resistance needed to be investigated before the most appropriate technique(s) could be selected.

They also reminded that the requirement of static and dynamic COFs was only one aspect of a global assessment of slip and fall hazards. Therefore, extra efforts are urgently required to measure realistic COF readings that represent actual kinematics during critical gait phases when foot slippage starts (Grönqvist et al. 1993) and develop new concepts and theory models that allow to measuring, analysing, interpreting, and predicting slip resistance properties under a range of walking environments (Kim 2015a, b, 2016a).

2.9 Testing Standards and Safety Criteria for Slip Resistance Performance

2.9.1 Slip Resistance Test Methods and Safety Criteria

The essentials to assessing slip-related fall safety need an accurately measuring slip resistance test method, and a minimum numerical safety criterion such as 0.42, 0.50, and 0.60 to apply for the slip test results. It is generally recognised that there is no single device and standard for reproducing and quantifying the slipperiness of a floor surface yet. However, five methods currently co-operate internationally.

2.9.1.1 The Pendulum Slip Resistance Tester

The ASTM E303-93 (US), BS EN 13036-4:2011 (UK), and AS 4663:2013 and AS 4586:2013 (Australia) define the pendulum tester that is now a national standard for pedestrian slip resistance in 49 nations on five continents and has been endorsed by the CTIOA since 2001 (Sotter 2000; CTIOA 2001a; ASTM 2008; BSI 2011). It is the most widely used pedestrian slip resistance test method worldwide.

The pendulum uses a standardized piece of rubber (Four S rubber also known as Slider 96), which is set up to travel across the flooring sample for 123–125 mm, mounted onto the pendulum foot (see, Fig. 2.13). When the arm of the pendulum is set up to miss the flooring completely, the arm swings up to parallel from where it started, and the pointer (brought along by the arm holding the rubber slider) reads zero. Slippery flooring produces readings close to zero, and flooring which shows higher resistance to slipping give results further from zero—high numbers (such as those 36 and above) indicating suitable slip resistant flooring (UKSRG 2016).

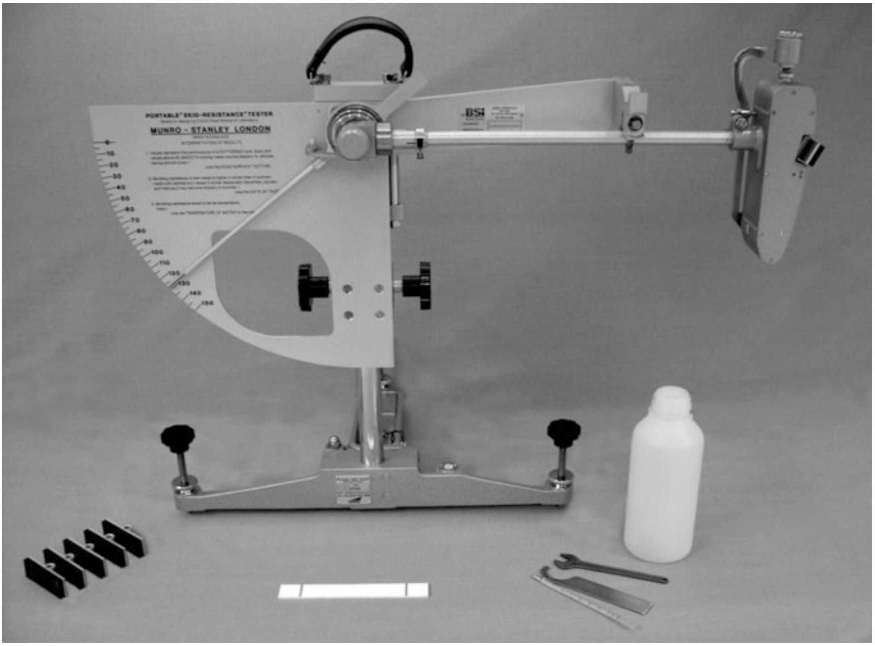


Fig. 2.13 A photographic image of a Munro British Pendulum Tester

Since 1971, the UK has established slip resistance standards based on the pendulum slip resistance tester. This test was developed for pedestrian traction by the US National Bureau of Standards in the 1940s and further refined in the UK (Giles et al. 1964). It was validated for pedestrian traction in 1971, together with its safety standards, in the UK over a period of 25 years by testing 3,500 real-world public walking areas (GLC 1971, 1985).

The tester has adopted as an ASTM standard (E 303) with slightly modifications for pedestrian traction measurement. The usual safety standard for a level floor is a minimum Pendulum Test Value (PTV) of 36. The pendulum is also the instrument used in the Sustainable Slip Resistance (SSR) test method, which measures the possible impact of years of use on potential flooring's slip resistance performance. The pendulum is also used elsewhere for determining the slipperiness of roads and airport runways.

Standards Australia HB 197:1999 as well as Standards Australia HB 198:2014 give detailed recommendations and guidelines of minimum wet Pendulum Test Slip Resistance Values (PTSRVs) for many different situations, such as external ramps, external walkways, pedestrian crossings, shopping center food courts, and elevator lobbies (Standards Australia 1999). There are also barefoot area recommendations based on the pendulum tests with a soft rubber slider (TRL rubber and also known as Slider 55). The Australian recommendations are presently the world's most detailed standards for the pedestrian wet slip resistance.

2.9.1.2 Tortus Digital Tribometer

The Tortus digital tribometer slip resistance test method is based on a proprietary or patented device, which is produced in the UK, and is in a category of slip resistance tester devices known as "drag-sled meters". Figure 2.14 shows a photographic image for the Tortus device sitting on a tile floor.

It travels across flooring under its own power at a constant speed with a piece of standardized rubber dragging on the flooring (Munro Instruments 2013). The amount of friction created by this piece of rubber as it is dragged across the flooring (dry or wet) is recorded and calculated by the machine as it travels a predetermined path length. An average number of DCOF is calculated by the machine after its run across the flooring has been completed. This is recorded as the "DCOF", or the amount of friction necessary to drag the standardized rubber across the flooring. High numbers (>0.50) indicate that it is difficult for the machine to drag the rubber across the flooring because it is anti-slip. Whilst low numbers (<0.50) means that the rubber easily slides across the flooring and is therefore slippery.

The Tortus becomes a primary instrument for assessing dry slip resistance in the latest Australian slip test standard—AS4586-2013 (SAI Global 2013). It also has been endorsed as a secondary standard by the CTIOA since 2001, with the pendulum being the primary standard. As compared to the pendulum tester, the Tortus tribometer can perform many slip tests in a short period of time under dry and wet environments, using both hard and soft rubbers. Unlike some tribometers, test

Fig. 2.14 A photographic image for the Tortus floor slip resistance tester

results from the Tortus tribometer are less influenced by an operator because an electronic button is pushed and then the test is run without any further help from the operator. The CTIOA has endorsed a minimum DCOF for level floors of 0.50 using the Tortus slip resistance test method (CTIOA 2001a).

2.9.1.3 BOT 3000 Slip Tester

The BOT 3000 is manufactured by Regan Scientific Instruments, Southlake, TX (Regan Scientific Instruments 2015). Figure 2.15 shows a photographic image of the BOT slip tester. It is self-propelled at 20 cm/s (7.9 in/s) and measures the SCOF and the DCOF against both wet and dry surface conditions with very little operator input. It is similar in operation to the Tortus tribometer except that the test pad is not spring loaded and applies a normal force of 21.3 N (4.8 lbs.) only after an operator activates the test which tends to lessen the effects of sticktion.

The machine pushes itself along the floor and the horizontal force applied to the pad is digitally measured and logged by the means of strain gauges. As the machine moves, the COF is calculated internally and both static and dynamic COFs are logged and displayed in real-time. Since this data is stored in onboard memory, it can be graphed and the minimum and maximum readings are easily available.

The BOT 3000 is the only machine approved and recognized to perform material testing according to ANSI B101.1 "Test Method for Measuring Wet SCOF of Common Hard-Surfaced Floor Materials Standard" and ANSI B101.3 "Test Method for Measuring Dry SCOF of Common Hard-Surfaced Floor Materials

Fig. 2.15 A photographic image for the BOT 3000 slip tester

Standard" (American National Standards Institute (ANSI) 2012). The BOT 3000 is the only device approved for use by the Tile Council of North America (TCNA) for assessing and measuring the COF of tile (ANSI 2009). The TCNA had been using ASTM C1028 "Standard Test Method for Determining the Static Coefficient of Friction of Ceramic Tile and Other Like Surfaces by the Horizontal Dynamometer Pull-Meter Method" as the method for measuring the SCOF of tiles. In April 2012, an updated version of ANSI A137.1 "Specifications for Ceramic Tile" incorporates a DCOF testing method using the BOT3000.

The safety standards ANSI specifies for a level floor using the B101.3 dynamic test method is that a floor having a minimum DCOF of 0.43 has "high slip resistance". If the DCOF falls within the 0.30–0.42 range, then the test method states that the flooring is "acceptable, with an increased probability of slipping," and values below 0.30 are categorized as "low slip resistance" and a "higher probability of slipping" (ANSI 2012). The standard also states a minimum DCOF of 0.46 for ramps.

The BOT-3000 slip tester has passed the ASTM F2508-13 standard published in 2013 called the "Standard Practice for Validation, Calibration, and Certification of Walkway Tribometers Using Reference Surfaces" (ASTM 2013). Although this ASTM test method was created with good intentions, the test is often conducted and interpreted by operators who have conferred interests in their tribometer having passed the test. This means that a tribometer having passed this test should not be solely relied upon deciding whether a certain tribometer is trustworthy or not. A reliable tribometer also should be able to provide a reasonable precision statement as required by every test standard-publishing agency, such as the ASTM, ANSI, Standards Australia, and British Standards.

2.9.1.4 Variable Angle Ramp

The Variable Angle Ramp is a German developed method for obtaining pedestrian slip resistance values. Figure 2.16 shows a photographic image of the Variable Angle Ramp system. Flooring samples are mounted horizontally on the ramp tester and an operator clad in safety boots or bare feet performs a standardized walk up and down the sample while wearing a harness to stop the operator from being injured. The sample is slowly inclined until the operator slips on the surface. The angle at which the subject slips is then recorded. Two operators repeat this test three times and then an average is calculated (HSE 2009). The repeatability of this test method was extensively documented (Jung and Schenk 1988).

Tests can be performed under dry, wet with soapy water, and wet with oil environments. Over 150 safety criteria have been adopted in Germany and Australia for specific situations such as swimming pool decks, commercial kitchens, and restrooms which are based on the variable-angle ramp. But, the ramp itself is not readily portable, so this instrument is only for lab testing and is therefore quite limited in its effectiveness (Sotter 2000; CTIOA 2001b).

This signifies that you can't test your specific floor tiles using this method without ripping part of your floor up and putting it into the ramp tester. However,

Fig. 2.16 A photographic image for the variable angle ramp

since it is measuring human ambulation, it is considered by many to be the most realistic test method in existence, and the results of pendulum and drag-sled meter tests are sometimes compared with results from variable angle ramp tests to see if the results have a strong correlation. A good correlation with ramp test results can help a slip resistance test device become more widely used and accepted.

2.9.1.5 SlipAlert Slip Tester

SlipAlert is a new British slip tester. Figure 2.17 shows a photographic image of the SlipAlert slip tester. It is a roller-coaster type tribometer that is designed to mimic the readings of the modern pendulum. It measures the slipperiness of a floor in order to assess whether it is safe. SlipAlert has been specifically designed to simulate a real slip and to correlate with the TRL Pendulum. It has been used for field testing, but is of limited utility in laboratory testing because it requires a long path length of flooring to conduct slip tests (SlipAlert 2011). As the SlipAlert is an exclusive device, it does not have an official American standard test method, but it now has an official British standard for its use in the field: BS 8204-6:2008 (Standards Centre 2010).

The SlipAlert "car" has a rubber slider on its bottom, which slides across the flooring after running down a fixed ramp. If the SlipAlert stops short, then the flooring is slip resistant, but if it slides a long distance then the floor is considered slippery. There is a digital readout on the device that records the maximum distance the SlipAlert has traveled across the flooring, and a safety criterion graph which

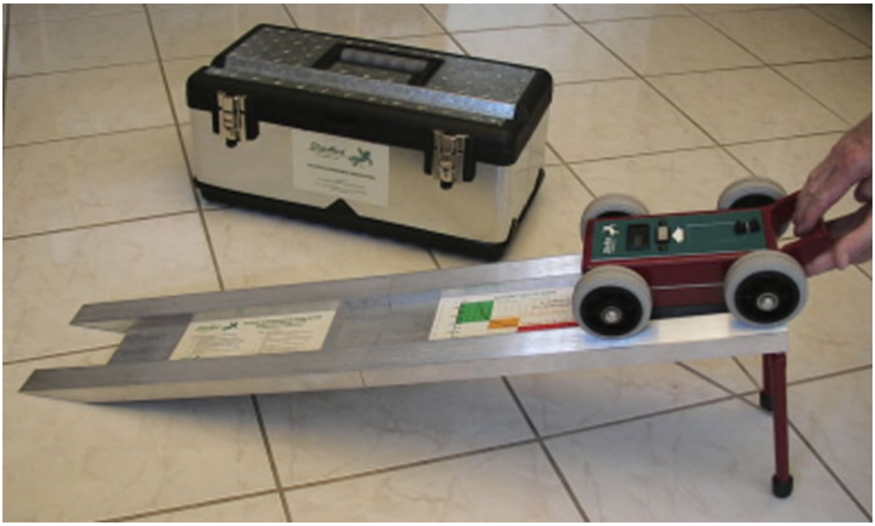


Fig. 2.17 A photographic image for the SlipAlert slip tester

interprets the results. Tests can be done under dry and wet environments, and extensive research by U.K. and Australian government agencies have resulted in several endorsements of this test device for in situ testing.

2.9.2 Undependable Test Methods and Removed Standards

2.9.2.1 ASTM C1028-07

This test method covers the measurement of static coefficient of friction (SCOF) of ceramic tile or other surfaces under both wet and dry conditions whilst utilizing Neolite heel assemblies. This test method can be used in the laboratory or in the field so often has operated in the US for assessing walkway safety (ASTM 2014).

Formerly under the jurisdiction of Committee C21 on Ceramic Whitewares and Related Products, however, this test method was withdrawn in February 2014. This standard is being withdrawn without replacement due to its limited use by industry (ASTM 2014). Safety criteria based solely on the SCOF are too often misleading where floors get wet or otherwise lubricated in use (CTIOA 2001b; ASTM 2005; Astrachan 2007; Powers et al. 2007). For example, static friction tests can be conducted before and after a fresh coat of wax is applied to a floor surface to validate whether the SCOF has not changed noticeably with a new wax, or the SCOF readings can be taken at different times during a day to make sure that any dirt and dust is not making the slip resistance condition of floorings worse throughout the day.

Monitoring changes in dry SCOFs can be a useful practice. However, SCOF tests should never be used to determine if a floor surface is wet or polluted. The Occupational Safety and Health Administration (OSHA) in the USA has recommended an SCOF of 0.50 for workplace environments, but often floorings having a rating of 0.60 or greater is proven by reliable test devices (and multiple slip and fall accident victims) to be very slippery when wet using this test method. As a result, this ASTM test standard has expired, and there are no plans to renew it as it has caused more confusion than anything else. Therefore, the ASTM C1028 test method was officially withdrawn with no replacement in 2014 (ASTM 2014).

2.9.2.2 Brungraber Mark II (PIAST) and English XL (VIT) Tribometers

The former ASTM F1677 was the test method for the Brungraber Mark II (also known as Portable Inclinable Articulated Strut Tribometer or PIAST) slip resistance tester, and the former ASTM F1679 test method was written for the English XL Variable Incidence Tribometer (VIT), respectively. Shortly after being published in 2004, ASTM withdrew these two standards in 2006, with no replacement.

Regarding ASTM 1677, ASTM provides the following similar “Withdrawn Rationale”:

> Formerly under the jurisdiction of Committee F13 on Pedestrian/Walkway Safety and Footwear, this test method was withdrawn as an active ASTM standard by action of the Committee of Standards (COS) on September 30, 2006 for failure to include an approved precision statement (violating Section A21 of the Form and Style for ASTM Standards), and for including reference to proprietary apparatus where alternatives exist (violating Section 15 of the Regulations Governing ASTM Technical Committees) (ASTM 2006a).

ASTM also offers the following similar “Withdrawn Rationale” for F1679:

> Formerly under the jurisdiction of Committee F13 on Pedestrian/Walkway Safety and Footwear, this test method was withdrawn as an active ASTM standard by action of the Committee of Standards (COS) on September 30, 2006 for failure to include an approved precision statement (violating Section A21 of the Form and Style for ASTM Standards), and for including reference to proprietary apparatus where alternatives exist (violating Section 15 of the Regulations Governing ASTM Technical Committees) (ASTM 2006b).

Using these two instruments, different test labs showed very different answers on identical tiles amongst interlaboratory studies. These findings suggested that both test methods (or tribometers) were unreliable and unable to provide “reasonable precision statements” for slip resistance evaluations. However, the English XL Variable Incidence Tribometer (VIT) is still used commonly in the US and worldwide, mostly by professional experts, who have discovered that the test results can be considerably influenced by how the actuating button is pressed by the user.

2.9.3 *Clean and Dry and Wet Slip Resistance Measurements*

2.9.3.1 Importance of Dry Slip Resistance Measurement

Dry slip resistance measurements can provide valuable information with or without wet testing. There are several reasons for the importance of dry slip resistance measurements:

(1) Clearly, the laws for wet (or lubricated) surfaces are different to those for dry friction, because of the effect of lubricant films between the shoe heel and floor surface. In the case of the shoe-floor traction system, the types of contact surfaces are largely changed by different walking environment such as dry, dusty, fibrous, granular, organic and wet, moist or contaminated. As a result, the friction force for the shoe outsoles and heels moving over walkway surfaces increases with increase in contact area. This aspect is in violation of the ‘classical’ laws of friction (Bonstingl et al. 1975). However, for the dry friction, the friction force is independent of the contact area (Jenson and Chenoweth 1990), which is contrary to the above findings. This aspect indicates that dry friction behaviours attribute to a complex molecular-mechanical interaction that occurs between the contacting surfaces of shoe heel and floor surface. This

complex mechanism of the contact interface between them is mainly caused by the combined effects of asperity deformation, ploughing by hard surface asperities and wear particles, and adhesion between flat surfaces (Suh and Sin 1981; Czichos 1986; Kim 2015a, c, 2016a, b). As a result, wear developments of the floor surfaces seem to be occurred and can substantially affect slip resistance properties (Leclercq and Saulnier 2002; Kim and Nagata 2008b; Kim et al. 2013; Kim and Alduhishy 2013; Kim 2015c, d). Even though the significance of flooring wear issue, understandings of flooring wear behaviours, accompanying tribo-physical mechanisms, and their resultant consequences against slip resistance performance have remained as an unexplored area. Therefore, analytical investigations for the dry sliding friction behaviours should be thoroughly investigated and analysed for slip resistance measurements.

(2) Dry slip resistance measurements followed immediately by wet (or lubricated) tests on the same floor can help to demonstrate that the slip resistance test method is capable of measuring both high and low values on the targeted flooring.
(3) A floor surface may be dry and/or appear clean, but be slippery due to a thin film of contaminant, for instance grease in or near a restaurant kitchen or parking structure.
(4) Dry environment data can also help to diagnose problems such as furniture polish overspray, inadequate maintenance, airborne cooking fat or oil that settles to the floor overnight.
(5) A rare small spill on a normally dry floor may have occurred too after cleaning.
(6) Many claims of slips and falls are made that involve dry floors.

The actual causes of the slip and fall incidence may also include footwear, substance abuse, illness, or many other factors unrelated to the floor surface itself. Dry slip resistance testing—particularly before the alleged accident and on a periodic monitoring basis (such as traction auditing)—can help to establish that the floor is safe (or anti-slip) when dry.

2.9.3.2 The Sine Qua Non for Slip Safety Assessments

Although a number of different types of slip resistance measuring devices and testers have been developed, there is no universally accepted test apparatus or measuring method. The recent literature has shown wide disagreements on the results of these devices, even using the same test conditions and environments (Harris and Shaw 1988; McElvaney 1993; Dutruel and Degas 1997; Grönqvist et al. 1998, 1999; Ricotti et al. 2009). These discrepancies may stem from design principles, kinematic and kinetic characteristics of measuring devices, mechanical and physical properties of sliding materials, and test and operation conditions.

The US OSHA has long recommended a minimum COF quantity of 0.50 for the workplace safety without any detailing information such as how the COF is to be determined. Because different slip resistance test methods and measuring devices produce different results, particularly under wet environmental conditions, this makes a great deal of confusions and mistakes for objective assessments of fall safety. As a result, the same floor could show quite different COF readings such as 0.4, 0.5, 0.6, or 0.7 (or anywhere in between) depending entirely up on what test method and tool is used. The OSHA recommendation is, therefore, meaningless, but has caused misperceptions for many years. However, the following three slip testers are frequently adopted as valid ones for the appropriate purposes (Sotter Engineering Corp. 2017):

(1) BOT-3000E slip tester:

This tester is cost-effective, rapid and automatically documented dry and wet testing, both static and dynamic, with various available test foot materials.

(2) Pendulum Slip Resistance Tester:

This tester is for dynamic COF testing under wet and dry environments with hard and/or soft rubber sliders. This is for testing outdoor and barefoot areas. This tester provides sustainable slip resistance testing results and application of long-established detailed situation-specific standards for swimming pool deck and outdoor ramp.

(3) Tortus Tribometer:

This tester is for testing where pedestrians are not likely to be running, and where numerous wet and dry tests are needed with hard and/or soft rubber sliders.

As discussed in the above, however, none of these slip resistance testers is capable of doing all the tasks for measuring slip resistance performance. Above all, overall performance of the above three slip testers is significantly affected by many factors such as floor material types, texture characteristics, and presence of contaminants on the floor surface.

In summary, although slip resistance measurement results from different testers may not be necessarily compatible with each other against any targeted flooring material and encountered environmental condition, it needs to be advised that comparing the measured slip resistance data from a field investigation with different types of slip meters can be ineffective. Therefore, to evaluate slipperiness in the real-world walking situations, the performance of slip meters operated still require a great deal of research challenges to improve their accuracy, reliability, validity.

2.10 Relationships Between Human Gait and Slip Resistance Properties

The issues of slip resistance related to human gait were extensively investigated in the literature (Leamon and Li 1990; Myung et al. 1992a, b; Burnfield and Powers 2006; Powers et al. 2007). Leamon and Li (1990) demonstrated that there was usually a sliding between the shoes and floor surfaces, immediately followed heel strikes. If human subjects regain control, then sliding was stopped and subjects regained their balance. The sliding distance can change from an undetected micro-slip (<3 mm) that requires no corrective actions to an uncontrollable slide (>10 cm) that eventually results in a fall if the relative velocity or sliding distance between the shoe heel and floor surface exceeds 50 cm/s or 10 cm, respectively.

Myung et al. (1992a, b) also reported that the slip distance immediately following heel strikes was inversely proportional to the static COF (SCOF) of the floor surface, although their results were not statistically significant. However, a high level of friction could be beneficial to reduce the slip distance so it seemed to improve slip resistance.

Burnfield and Powers (2006) investigated the relationship between measures of floor surface slip resistance and an individual's peak utilised coefficient of friction (UCOF) on the probability of a slip occurring during level walking. Powers et al. (2007) assessed the viability of using slip risks (as quantified during human subject walking trials) to create a reference standard against which tribometer readings could be compared. Their study reported that only two of the nine tribometers tested (Tortus II and Mark III) met our compliance criteria by both correctly ranking all six conditions and differentiating between surfaces of differing degrees of slipperiness. This finding reinforces the need for developing objective criteria to ascertain which tribometers effectively evaluate floor slipperiness and pedestrians' risks from slipping and falling.

Whether static or dynamic friction is more relevant to the contact-sliding mechanism between the shoe and floor is still debatable. Ekkubus and Killey (1973) suggested that static friction was more applicable than dynamic friction because the foot (or the shoe heel) was static relative to the floor surface when walking. They also suggested that dynamic friction would be valid only after the foot started to slip so could not be related to normal walking conditions. However, Lanshammar and Strandberg (1983) showed that the horizontal velocity of the heel edge relative to the floor surface had small but "non-zero velocities" at the heel strikes in contrast to the assumption of "zero velocity" by the majority of studies.

Tisserand (1985) investigated the significance of static versus dynamic friction by an experiment in which subjects wore shoes of different material types on either foot. He reported that the subjective ranking of the slipperiness of particular shoes correlated highly with the measured DFCs. Based on this evidence, he concluded that dynamic friction is more applicable to simulate human walking than a static one.

Other studies also suggested that the DFC measurements for standards were more relevant to the biomechanics of slips and falls than SCOF (Perkins 1978;

Strandberg and Lanshammar 1981; Hoang et al. 1987; Redfern and Bidanda 1994). Another reason for favouring dynamic friction tests was that they seem to more realistically assess the effects of contaminants on the floor surface because this could not be duplicated in static friction tests (Hoang et al. 1987).

Perkins (1978) and Strandberg and Lanshammar (1983) introduced an $\frac{H}{V}$ (horizontal force/vertical force) diagram to study the characteristics of walking and slipping. The diagram trace suggested by Perkins and Wison (1983) is reproduced in Fig. 2.18.

The Point 1 in Fig. 2.18 indicates a forward force on the initial heel contact that must be resisted by friction if the step is to remain under control. The Point 2 shows a brief backwards force, whilst the Point 3 results from the further force in the forward direction requiring friction to prevent slipping. This means that the point at which slipping is most likely to occur is the Peak 3.

Perkins (1978) also analysed both horizontal and vertical components of forces exerted between the shoe and floor surface during normal walking. He drew the following conclusions:

(1) During normal walking, falls could result as the foot slid forward at the moment that the shoe heel contacted the floor surface. At this instant, the average value of the $\frac{H}{V}$ ratio was approximately 0.2 for eight subjects, and the maximum values were about 0.33 and 0.25, respectively.
(2) If the length of slip exceeded 10–15 cm, a loss of balance occurred.

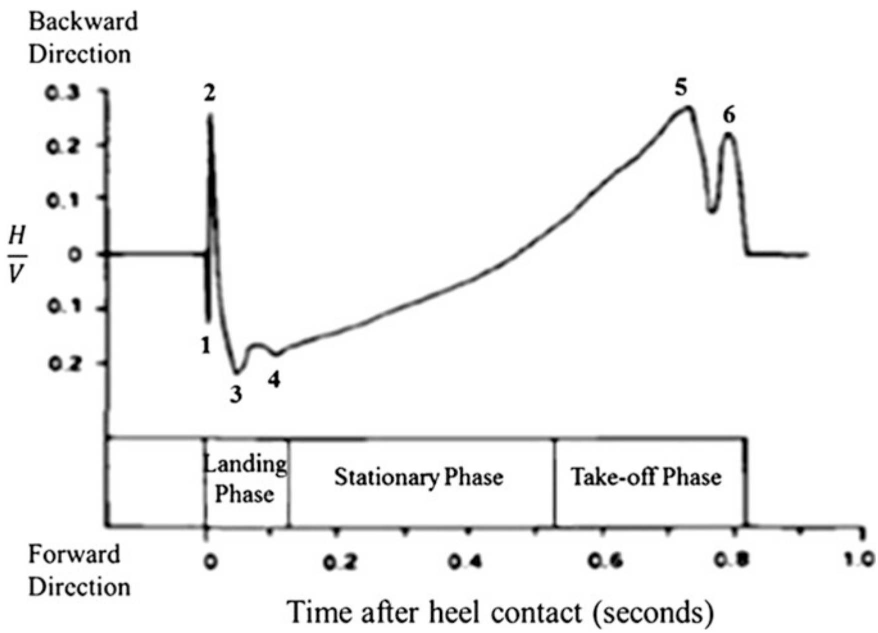


Fig. 2.18 The Perkins' H/V diagram for normal walking step (Perkins and Wilson 1983)

(3) In certain cases, the subject regained balance after slipping a short distance. This was explained by the fact that the entire shoe rapidly came into contact with the floor surface after the onset of slips and thus increased the level of friction.

The study results of Strandberg (1983) also showed a brief peak such as the Point 1 in Fig. 2.18. He further stated that "in most of the recorded experiments the shoe heel was sliding upon heel strike". Strandberg and Lanshammar (1981) conducted a biomechanical study with four subjects and concluded that

(1) A slipping of the shoe heel on the floor surface at the contact moment was observed during most of the tests. This movement was generally not noticed by the subject and occurred even if there was no lubricant on the floor surface.
(2) On average, the critical slipping movement occurred at 0.05 s after the shoe heel touched down. At this instant, the vertical force was equivalent to approximately 60% of the body weight and was applied to the sliding interface between the shoe heel (which made an approximately 5° angle) and the floor surface.
(3) Once initiated, a slip would progress if the $\frac{H}{V}$ ratio continued to increase after it begun.
(4) When the slip speed exceeded 0.5 m/s, or when the length of slip exceeded 10 cm, the slip generally led to falls.
(5) When there were no dangerous slips, the maximum value of the $\frac{H}{V}$ ratio at the beginning of the rolling action of the foot, was equal to 0.17 on average and was detected 90 ms. after the shoe heel contacted.
(6) When a slip did not lead to a fall, the $\frac{H}{V}$ ratio changed between 0.1 and 0.2 during the time that the feet sled forward.
(7) Sliding movements to the rear that occurred just before the toes were lifted from the floor surface never led to a loss of balance, or to a fall.

For the measurement of DFCs, Strandberg and Lanshammar (1981) suggested that slip resistance testers utilised certain variables from the crucial gait phase. Of many important parameters related to the crucial gait phase, Redfern and Bidanda (1994) classified the vertical force, shoe heel velocity, and shoe contact angle as the most significant biomechanical parameters. Shoe materials, floor types, and contaminants were classified as important environmental factors.

Strandberg and Lanshammar (1981) also mentioned that the vertical force was one of the particularly important variables that slip resistance meters should reproduce based on tribological and practical experiences. Grönqvist et al. (1989) and Wilson (1990) recommended that the range of vertical force in the testers varied from almost a whole-body weight to 50% of body weight. However, Chaffin et al. (1992) argued that although the basic assumption in computing the COF was that the friction force increased proportionally to the normal force holding the contacting surfaces together under some circumstances, this might not be true.

The effect of the normal load magnitude is not simple to predict. When a soft material such as crepe is loaded heavily on a rough surface, the effect of deformation forces on friction would be larger than when using a smooth surface or a harder shoe material (Chaffin et al. 1992). That is, an interaction mechanism between the shoe heel and floor surface exists so that this tribo-physical system makes to complicate generalising the interpretations and predictions of COF results under light and heavy loads. This fact is particularly troublesome for selecting a proper tester because some COF testing procedures use very light normal load (<10 N), but others advocate quite a high normal load (about 1000 N).

The other important issue to consider is to understand where the pedestrians place their foot to make contact with the walking surface. There are the requirements of adequate friction to resist slips (Perkins 1978; Strandberg and Lanshammar 1981) and the avoidance of excessive friction to cause trips (Grönqvist et al. 1989). This means that the use of roughened walking surface has a beneficial effect of raising the COFs significantly under both dry and lubricated surface conditions. However, the effect of walking on such high traction surfaces is problematic when walkers must continually rotate their feet.

If the shoe cannot be easily rotated in such floors, then additional torsional stress is placed on the knees and lower back areas. This "trade-off" effect between the surface roughness and walking comforts seems to be an important issue to investigate but it is scarce to find any detailed information explored in the current literature so definitely requires further studies (Kim et al. 2013). In this sense, the underfoot surfaces should be efficiently designed and built with optimal surface finishes that allow such topographic structures and comfort walking so that pedestrians would not require any adjustment to their gait.

The velocity of shoe heels at a striking moment is critically related to the occurrence of slips and falls (Strandberg and Lanshammar 1981; Perkins and Wilson 1983; Strandberg 1983; Rhoades and Miller 1988; Chambers et al. 2003; Lockhart et al. 2005).

Strandberg (1983) demonstrated that the shoe heel speed from different subjects varied from 0.06 to 1.7 m/s. He also found that the heel speed at skid started changed from 0.08 to 0.32 m/s. After skid started, the shoe heel accelerated to a value above that of walking speed. He accordingly concluded that the speed of a dynamic test should be in the range of 0–0.5 m/s.

Perkind and Wilson (Perkins and Wilson 1983) stated from their study that "probably the ideal speed for high-speed measurements is 0.5–1.0 m/s since the foot and shoe can be travelling at this speed when the shoe heel contacts the ground. Even if slip starts from a static situation, such is the acceleration that the speed of slip is about 0.5 m/s after only 0.01 m slip distance". Considering the slip speed issue as a controlling variable would add tremendous amounts of test volumes to assess the merits of shoe and floor materials. Therefore, it is necessary to identify a shoe test speed which represents real slip risks and keeps the speed during the planned tests.

The shoe strike angle is also an important factor in detecting any slip potential. Any change of the heel strike angle can affect the formation of a contact area between the shoe heel and floor surface so this result plays a dominant role in the sliding friction process under lubricated environments in particular (Moore 1972).

This means that the surface topographies of both shoes and floors also can be modified by the change of contact area and consequently slip resistance properties (Kim 1996a, b, c, d, 2004a, b, 2006a, b, 2015a, 2016a, b; Kim and Smith 1998a, b, 1999, 2000, 2001a, b, c, 2003; Kim et al. 2001, 2013; Kim and Nagata 2008a, b; Kim and Alduhishy 2013). Hence, striking at a "correct angle" seems to be one of the most important parts of the shoe in walking trials (Hoang et al. 1987).

Several studies suggested that the heel strike angle found to be around 5° (Strandberg and Lanshammar 1981; Grönqvist et al. 1989; Wilson 1990). However, Redfern and Bidanda (1994) reported that the heel strike angles between 5° and 15° were not practically significant.

By measuring COFs using different types of slip resistance testers, significant amounts of attempts have been made to develop a standard for the pedestrian safety. However, the earlier works clearly demonstrate the recognition of complex array of factors that affect the risks of slip and fall on walkway surfaces (Adler and Pierman 1979).

For example, Leclercq et al. (1995) reported that the measurement results of slip resistance were not identical to the new shoes with the same model. They stated that different manufacturing and storage conditions could explain those variations. Skiba et al. (1985) underlined the fact that the composition of shoe soles and the manufacturing process certainly influenced on slip resistance properties.

There seems to be growing consensus that friction measurement between the shoe heel/sole and floor surface is only one of many factors that relate to pedestrian fall incidence (Marosszeky 1985; Kim 1996a, b, c, d, 2004a, b, 2006a, b, 2015a, b, c, d, 2016a, b; Kim and Smith 1998a, b, 1999, 2000, 2001a, b, c, 2003; Kim et al. 2001, 2013; Kim and Nagata 2008a, b; Kim and Alduhishy 2013).

This finding clearly addresses that a single COF index or quantity can not accurately reflect slip resistance performance between the shoe and floor. Therefore, a thorough understanding of such complex mechanisms of slip resistance properties is urgently required to fully explore their multifaceted characteristics.

2.11 Chapter Summary

Pedestrian fall incidents resulting from slips or trips are major concerns. There have thus been prolonged efforts to understand the main causes of such incidence in order to reduce its severity and fatalities. However, pedestrian fall incidents are caused by multifactorial risk factors. These risk factors signify that fall safety assessment is a highly complex area to study, where the likelihood of a slip and fall is a function of a variety of elements such as surfaces, environmental conditions, and individual users.

Recognising that widening the perspectives may better define the role of multi-factors in detection and prevention of fall incidence, but this book is mainly focused on exploring environmental (floorings and shoes) correlations for slip and fall incidents under a range of environmental conditions as a starting point.

It has been found that the most common precipitating event leading to a fall is a loss traction or slip resistance between a shoe heel/sole and floor surface, followed by trips, misstep, loss of support, and postural overextension (Cohen and Compton 1982). Slip resistance property between the footwear and underfoot surface is of great importance for preventing slip and fall incidence and has been measured as a form of a COF. In this context, knowledge about friction demand and the friction available has been recognised as a main key factor to fall assessment.

A range of apparatuses and devices have been fabricated and developed to quantify frictional behaviours between the shoes and floors. Despite many years of investigations and constructions of numerous testing machines, none of them is internationally adopted as a standard model yet, because each of them has some advantages and disadvantages in their designs and testing performance (Kim 2006b). In fact, because each testing instrument has different concepts, operating parameters, and mechanical principles, it seems unreasonable to adopt a reference value without any citation to the instrument used for the slip resistance measurements (Kim 2006b).

There seems to be growing consensus that friction measurement between the shoe heel/sole and floor surface is only one of many factors that relate to pedestrian fall incidence (Marosszeky 1985; Kim 1996a, b, c, d, 2004a, b, 2006a, b, 2015a, b, c, d, 2016a, b; Kim and Smith 1998a, b, 1999, 2000, 2001a, b, c, 2003; Kim et al. 2001, 2013; Kim and Nagata 2008a, b; Kim and Alduhishy 2013). This finding clearly addresses that a single COF index or quantity cannot accurately reflect slip resistance performance between the shoe and floor. Therefore, thorough understandings of such complex mechanisms on slip resistance properties are urgently required to fully explore their multifaceted characteristics.

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