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Human-centred approaches in slipperiness measurement

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Abstract

A number of human-centred methodologies—subjective, objective, and combined—are used for slipperiness measurement. They comprise a variety of approaches from biomechanically-oriented experiments to psychophysical tests and subjective evaluations. The objective of this paper is to review some of the research done in the field, including such topics as awareness and perception of slipperiness, postural and balance control, rating scales for balance, adaptation to slippery conditions, measurement of unexpected movements, kinematics of slipping, and protective movements during falling. The role of human factors in slips and falls will be discussed. Strengths and weaknesses of human-centred approaches in relation to mechanical slip test methodologies are considered. Current friction-based criteria and thresholds for walking without slipping are reviewed for a number of work tasks. These include activities such as walking on a level or an inclined surface, running, stopping and jumping, as well as stair ascent and descent, manual exertion (pushing and pulling, load carrying, lifting) and particular concerns of the elderly and mobility disabled persons. Some future directions for slipperiness measurement and research in the field of slips and falls are outlined. Human-centred approaches for slipperiness measurement do have many applications. First, they are utilized to develop research hypotheses and models to predict workplace risks caused by slipping. Second, they are important alternatives to apparatus-based friction measurements and are used to validate such methodologies. Third, they are used as practical tools for evaluating and monitoring slip resistance properties of foot wear, anti-skid devices and floor surfaces.

Keywords

Slipperiness measurement; Human factors; Postural and balance control; Slip recovery; Fall avoidance; Safety criteria; Friction thresholds

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1. Introduction

Data on how to accurately measure risk exposures to slipping and falling hazards seem to be sparse. One of the underlying reasons is the complex nature of slip and fall avoidance strategies such as their dependence upon anticipation of hazards and adaptations of gait to slippery environments (Strandberg 1985, Llewellyn and Nevola 1992, Cham *et al*. 2000, Redfern *et al*. 2001). A number of human-centred approaches for the measurement of slipperiness have been utilized to estimate slipping and falling hazards and risks. These approaches have explored initial events from slip onset to foot slide, as well as subsequent events from loss of balance until falling. The output estimates have comprised, among others, perceived sense of slip and slip distance evaluations, slipperiness ratings, heel velocity measurements, heel and trunk acceleration and postural instability measurements, and falling frequency estimations (Strandberg *et al*. 1985, Leamon and Son 1989, Grönqvist *et al*. 1993, Myung *et al*. 1993, Cohen and Cohen 1994a, b, Hirvonen *et al*. 1994, Chiou *et al*. 2000). Other approaches have focused on kinematics (spatial movement of the body) and kinetics (ground reaction forces, utilized and required friction) of slipping and falling (Strandberg and Lanshammar 1981, Morach 1993, Redfern and Rhoades 1996, Hanson *et al*. 1999, Brady *et al*. 2000, You *et al*. 2001) or electromyographic (EMG) activity of compensatory muscle responses during simulated slipping (Tang *et al*. 1998).

Human-centred measurement methodologies form an important complementary to mechanical friction-based test methods which are discussed elsewhere (Chang *et al.* 2001a,b). The former add a further dimension—the human factor—to the measurement of slipperiness process, and have been widely used to validate mechanical test methods as well (Strandberg 1985, Jung and Fischer 1993, Grönqvist 1999, Leclercq 1999).

The following human-centred approaches to slipperiness measurement will be addressed (figure 1):

1. ‘subjective’ approaches such as rating scales, rankings and paired comparisons of floors and footwear, as well as direct observation of protective responses to slipping;
2. ‘objective’ biomechanically-oriented approaches such as measuring ground reaction forces, friction usage, body segment movements, joint angles and moments, slip distances and velocities, centre of mass and centre of pressure trajectories, or electromyography; and
3. ‘combined’ approaches that comprise subjective evaluations in combination with objective measurements.

The main objective of the present paper is to review the relevant literature on human-centred approaches for the measurement of slipperiness. The role of human factors in slips and falls is discussed, including topics such as awareness and perception of slipperiness, postural and balance control, and adaptation to slippery environments. An overview of friction-based criteria and thresholds for safe walking without slipping is presented, including criteria for some specific work tasks (pushing and pulling, lifting, load carrying) and some special risk groups (the elderly and mobility disabled).

2. The role of human factors in slipping

2.1. Primary and secondary risk factors

Injuries due to slips and falls are not purely random events, but rather predictable entities with known risk factors that may be extrinsic (environmental factors), intrinsic (human factors) or mixed (system factors). The primary risk factor for slipping is, by definition (cf. Grönqvist *et al*. 2001), poor grip or low friction between the footwear (foot) and the underfoot surface (floor, pavement, etc.). Static friction is assumed to be important for preventing the initiation of slipping, while dynamic friction would determine whether a foot slide might be recoverable and an injury avoidable, or whether the slip might lead to an injurious fall or any other type of injury, for instance, due to strenuous body movements for regaining balance.

Secondary risk factors ('predisposing factors') for slipping accidents are related to a variety of environmental and human factors, for instance, inadequate lighting, uneven surfaces, incomplete stairway design, non-use of handrails and vehicle exit aids, poor postural control, ageing, dizziness, vestibular disease, diabetes, alcohol intake, and the use of anti-anxiety drugs (Waller 1978, Honkanen 1983, Templer *et al*. 1985, Pyykkö *et al*. 1988, [1990], Sorock 1988, Alexander *et al*. 1992, Malmivaara *et al*. 1993, Nagata 1993, Fothergill *et al*. 1995, Fathallah *et al*. 2000). Merely the slipperiness of the shoe/floor interface may not be a sufficient explanation for falls and other slip-related injuries. The secondary risk factors tend to predispose persons to accidental injuries in slippery conditions and during sudden unexpected changes in slipperiness. The multitude of risk factors and their possible cumulative effects seem to further complicate both slipperiness measurements and the prevention of accidents and injuries due to slipping.

2.2. Postural and balance control

Maintaining postural balance and stability during locomotion is a complex process of position adjustments by muscles and bones acting over joints and controlled by several sensory systems, including vision, vestibular organ, proprioceptive receptors in joints and muscles (e.g. stretch reflexes), and cutaneous receptors with elements such as the pressor receptors of the feet and the velocity- and position-sensitive muscle spindles (Nashner 1983, Johansson and Magnusson 1991). These sensory systems are further controlled by the central nervous systems located in the spinal cord, the brainstem, basal ganglia, cerebellum and cerebral cortex (Horak 1997). Vestibular input governs typically 65% of the body sway during sudden perturbation in standing, while 35% is accounted for by visual, proprioceptive and other input (Pyykkö *et al*. 1990).

A balance perturbation due to a foot slide constitutes a risk situation, especially if a person's primary task is not maintaining balance. Some common dual-task situations in which locomotion is a secondary task, include walking while reading or talking (on a cellular phone), searching through aisles for a particular object (e.g. grocery shopping), or lifting, lowering and carrying loads while walking. The perseverance of performance in these dual-task situations is critically dependent upon control of the rhythm of locomotion (Danion *et al*. 1997) and the rhythm of the primary task being attended to (Jones 1976). An accident may occur as a result of a person not being focused on the locomotion, but on perceptual and cognitive processes related to primary task performance. It may also result from a breakdown in rhythm control. High accelerations or decelerations are frequently associated with balance loss, and may cause high inertial forces that have to be supported by the musculoskeletal system.

The way balance is maintained and which balance strategies are sought in a particular situation is dependent on the ability to anticipate postural demands in response to external perturbations, and to move and control the body's centre of mass (COM) back to a position over the base of support (BOS) and the centre of foot support/pressure (COP). A region of stability can be predicted based on the physical constraints of muscle strength, size of BOS, and floor surface contact forces within an environment (Pai and Patton 1997). The alignment of body segments over the BOS must be kept such that the projection of the body COM falls within the boundaries of stability. However, movement termination during a foot slide also depends on the presence of an external braking force that allows the stability region to extend beyond the anterior limit of the BOS in the direction of slipping (Pai and Iqbal 1999). It appears that an increasing friction force might provide such an external braking force, eventually enabling a recovery of stability.

Three strategies for co-ordinating legs and trunk to maintain the body in equilibrium with respect to gravity during standing have been presented (Nashner 1985, Winter 1995): the ankle and hip strategies, and the combined strategy (figure 2). For compensation of antero-posterior sway displacements, the head and the body COM moves in the same direction backwards or forwards during the ankle strategy. This strategy helps to correct small perturbations by using the ankle plantar- and dorsiflexors. During the hip strategy in more perturbed situations or when the ankle muscles cannot act, the body COM moves backwards or forwards opposite to the head movement by means of muscle responses that either flex or extend the hip (Winter 1995). Allum *et al*. (1998) questioned the major role of lower-leg proprioceptive control of posture, especially the dominant ankle strategy, and concluded that postural and gait movements are centrally organized at two levels. The first level involves the generation of a directionally-specific response pattern based primarily on hip or trunk proprioceptive input and secondarily on vestibular input. The second level is involved in the shaping of centrally set multi-sensorial activation patterns, so that movements can adapt to different task conditions.

A sufficient muscle tonus—high enough to maintain postural stability but low enough to facilitate movement—is another prerequisite for the co-ordination of posture and gait. The potential advantage of the stiffness control was recently discussed by Winter *et al*. (1998) during perturbed standing. Their inverted pendulum model assumed that muscles act as springs to cause the COP to move in phase with the COM as the body sways. The COM-COP difference, on the contrary, has been reported to be proportional to the horizontal component of the ground reaction force captured by plantar cutaneous receptors located in the foot sole (Morasso *et al*. 1999). Following latencies in muscle activation after tripping and slipping perturbations have been reported: 120 – 200 ms for visual control and 60 –140 ms for proprioceptive control (Pyykkö *et al*. 1990, Eng *et al*. 1994, Tang *et al*. 1998). However, other studies have claimed that a stiffness control may act almost immediately as the ankle joint angle is changed, causing the COP to move in the same direction as the COM (Winter *et al*. 1998, cf. Redfern *et al*. 2001).

2.3. Unexpected changes in slipperiness

The question of whether the risk of slipping injuries is more related to a constantly poor shoe/ floor traction or an unexpected, sudden loss of grip due to frictional variation still remains unsolved. The latter case might be the more likely possibility. Precipitation, temperature and snowfall, and the presence of contaminants or lubricants on the contact surface are important risk factors for occupational and non-occupational slips and falls according to several studies (Honkanen 1982, Merrild and Bak 1983, Lund 1984, Strandberg 1985, Manning *et al*. 1988, Grönqvist and Roine 1993, Leclercq 1999). Slip-related injuries often seem to occur on wet, dirty, oily, greasy, snowy, icy, or other contaminated walking surfaces. Nevertheless, weak inverse relationships between, for example, seasonal effects (precipitation and cold temperatures) and occupational slips and falls injuries have been reported (Leamon and Murphy 1995).

The role of human factors in the measurement of slipperiness is significant. Strandberg (1985) presented some interesting results from psychophysical walking experiments performed on a continuously slippery triangular path (circumference 12 m). Twelve equally trained healthy male and female subjects were advised to walk as fast as possible over a smooth vinyl (PVC) floor wearing four different shoe types. Other shoe/floor conditions were assessed also, but will not be discussed here. Each test comprised five laps to be walked as fast as possible without slipping and falling. Since cornering was involved in these tests, a higher walking speed required greater friction utilization. The vinyl floor surface was contaminated and the viscosity of the lubricants was adjusted to either 0.001 N s m^{-2} (water and detergent), 0.01 N s m^{-2} (diluted glycerol) or 0.2 N s m^{-2} (concentrated glycerol). The falling frequencies during five laps were counted and compared to an average time-based friction utilization (TFU) value during the complete trial and an average force plate-based friction utilization (FFU) value over one step in the 90° corner of the triangular path (Lanshammar and Strandberg 1985, Strandberg *et al*. 1985). The results were surprising especially with two of the tested shoe types, Bovinide and Studded (table 1): the test condition with medium TFU (and FFU) caused the highest number of falls (20) while the high and the low TFU (and FFU) conditions caused less falls (6 falls each). The average friction utilization values showed, as expected, that slipperiness increased as the viscosity of the lubricant increased. However, the medium friction utilization values in the range 0.20 to 0.25, obtained with the lubricant of medium viscosity (0.01 N s m^{-2}), were surprisingly linked to the highest number of falls during these experiments. (Note: The 'Bovinide' sole was linked to a higher falling risk over the 'Studded' sole, which was associated with a greater variation in friction utilization within steps and over consecutive steps. Thus, the smooth, non-patterned and stiff surface of the 'Bovinide' sole may have reduced the effective contact area in comparison with the flexible and patterned 'Studded' sole.)

One possible explanation for this apparent discrepancy between friction utilization and frequency of falls might be that the subjects were not able to walk as fast during the slippery, low friction condition (TFU about 0.1) as during the medium friction condition (TFU about 0.2). By adopting a slower 'protective' gait strategy in the low friction condition (i.e. less risk-taking) the subjects were thus able to reduce the number of falls. Then the next question is 'why were the subjects not able to adapt their gait safely during the medium friction condition'? Perhaps because it was a borderline safe/unsafe and deceptive condition, and was hence more difficult to anticipate, which resulted in a greater number of falls. Then why did the high friction condition (TFU about 0.3) cause just as many falls as the low friction condition? This apparent contradiction might be explained by the fact that the subjects were able to walk more quickly over the high friction floor condition, thus challenging their balance more (i.e. taking a higher risk) than during the low friction condition.

2.4. Postural adjustments and adaptation to slipping risks

Under constant low-friction conditions, humans typically adopt a protective gait strategy, which involves the combined effect of force and postural changes of the early stance. The subjects take shorter steps and increase their knee flexion, which reduces the vertical acceleration and the forward velocity of the body (Llewellyn and Nevola 1992). As a consequence, the foot impact against the ground should reduce during early stance. Theoretically this strategy should, in the presence of lubricants, minimize the hydrodynamic pressure generation in the lubricant film and the load support between the interacting surfaces (Moore 1972). Hence, a better true contact between the shoe and the underfoot surface should be achieved, which can result in an increased grip and traction (a higher friction coefficient) and a lesser risk for slipping and falling.

A stepping response to a foot slide may have a unique importance in balance recovery and fall prevention (Maki and McIlroy 1997, McIlroy and Maki 1999, Pai and Iqbal 1999). However, it is still unclear what factors might determine the success rate of recovery during a stepping response after the onset of a slip perturbation. These responses can be volitional, involving conscious efforts and/or they can be automatic reflexive reactions. To deal with the risk of falling and injury, the body integrates voluntary movements with so-called 'associated postural adjustments'. These adjustments are involuntary and smoothly organized into the movement repertoire to ensure accurate and harmonious motion. Based on the timing relative to the event of perturbation, the adjustments can be arbitrarily classified into two postural control systems —adaptation and anticipation (Redfern *et al.* 2001)—which in turn may be linked to situation awareness, perception and comprehension of the environment and the ability to project future states. Endsley (1995) gives a thorough definition of situation awareness; one class is concerned with the physical capacity to avoid or accommodate the environmental (ecological) challenges; another class is concerned with the competence to recognize them. Adaptation is reactive in nature and involves the co-ordination of the neuromusculoskeletal system, while anticipation is proactive and entails navigating through complex and often cluttered environments by using multiple sensory inputs to assist in the control and adaptation of gait. The level of situation awareness persons can achieve in a particular environment may dictate whether they anticipate state changes potentially leading to loss of balance. A poor situation awareness may be indicative of adaptive postural adjustments due to perturbations.

Following the above discussion, one might anticipate that it is much easier to adapt one's gait properly when the slippery condition is steady than when rapid and unexpected variation in slipperiness occur. There may not be sufficient injury statistics to confirm this statement, but a study by Merrild and Bak (1983) showed that certain high-risk winter days characterized by drastic temperature changes, precipitation and snowfall, can cause an enormous increase in pedestrian injuries due to falls initiated by slipping. Merrild and Bak (1983) also reported that the proportion of fractures especially in the lower extremities, increased during the high-risk days, and led to a redistribution of injuries in the lower extremities towards their proximal ends. Fractures of the femoral neck and pelvis became more frequent and sprained ankles less frequent than during normal winter days. A recent fall-study made in Norway (Bulajic-Kopiar 2000) confirmed that season affects the incidence of all types of fractures in elderly people, and that slipping on ice or snow seems to be a causal mechanism behind this seasonal effect. In Finland, Honkanen (1982) concluded that the causative role of slippery weather conditions in falls was likely to be more important than any other single factor. He estimated that falls due to slipping during winter months, as compared to summer months, formed 25% 'excess' of all falls on the same level and 47% 'excess' of slip-related falls.

2.5. Protective movements during falling

A fall by definition is to descend freely by the force of gravity. A fall occurs when human balance is perturbed beyond a certain recoverable point. When examining forward falls on an outstretched hand from low heights, Chiu and Robinovitch (1998) predicted that fall heights greater than 0.6 m carry significant risk for wrist fractures to the distal radius (the most common type of fracture in the under-75 population). Robinovitch *et al*. (1996) and Hsiao and Robinovitch (1998) studied common protective movements that govern unexpected falls from standing height. They measured body segment movements when young subjects were standing on a mattress and attempted to prevent themselves from falling after the mattress was made to translate abruptly. The subjects were more than twice as likely to fall after anterior translations of the feet (posterior fall) when compared to lateral or posterior translations (anterior falls) of the feet. Since a posterior fall would most likely follow a foot slide during early stance, this study may give us some hints on possible fall mechanisms and protective movements due to slip-induced falls as well. The results by Hsiao and Robinovitch (1998) suggested that body segment movements during falls, rather than being random and unpredictable, involved a repeatable series of responses facilitating a safe landing. Posterior falls involved pelvic impact in more than 90% of their experiments, but only in 23% of the lateral falls and in none of the anterior falls. In the falls that resulted in impact to the pelvis, a complex sequence of upper extremity movements allowed subjects to impact their wrist at nearly the same instant as the pelvis, suggesting a sharing of contact energy between the two body parts. Hsiao and Robinovitch (1999) predicted—using experimental and mathematical models of balance recovery by stepping—that a successful recovery of falling perturbations was governed by a coupling between step length, step execution time, and leg length (cf. Redfern *et al*. 2001).

3. Measurement of slipperiness and falling risks

3.1. Perception of slipperiness

During walking one is often unaware of the fact that sliding or creep between the footwear and the floor occurs on contaminated surfaces and even on dry ‘non-slippery’ surfaces in the very beginning of the heel contact phase (Perkins 1978, Strandberg and Lanshammar 1981, Perkins and Wilson 1983). In fact, Lanshammar and Strandberg (1983) showed that there typically exists an initial spike in the fore-aft component of the ground reaction force immediately after heel strike. The existence of this spike was explained by a small but detectable non-zero backward horizontal motion of the rear edge of the shoe heel. Lanshammar and Strandberg (1983) concluded that since the foot must be strongly decelerated shortly before heel strike an overshoot reaction of the human locomotor system could explain this behaviour.

The lengths of such small slip incidents (also termed micro-slips) on dry, nonslippery surfaces were less than 1 cm, according to Leamon and Son (1989). The tendency of human subjects to such movement on a slippery surface was determined by Leamon and Li (1990), who redefined the term micro-slip to cover a range from zero to 3 cm. Their data indicated that any slip distance less than 3 cm would be detected in only 50% of the occasions, and that a slip distance in excess of 3 cm would be perceived as a slippery condition.

Vision seems to be the only sensory mode that proactively allows a person to identify a slippery floor surface before stepping over it. The other postural control systems may require that one already has walked over a slippery surface for getting the feedback to properly adapt one’s gait. Visual control of locomotion has been classified into both avoidance and accommodation strategies (Patla 1991). Avoidance strategies include, for instance, changing the foot placement, increasing ground clearance, changing the direction of gait, and controlling the velocity of the swing foot. Redfern and Schuman (1994) emphasized that temporal control is as critical as spatial control in placement of the foot to maintain balance during gait. Accommodation strategies involve longer term modifications, such as reducing step length on a slippery surface.

3.2. Biomechanically-oriented approaches

Ground reaction forces and sagittal plane body movements have been investigated in slippery conditions (as well as in non-slippery baseline conditions) during walking on level and inclined surfaces as well as during load carrying (Perkins 1978, Strandberg and Lanshammar 1981, Morach 1993, Hirvonen *et al.* 1994, McVay and Redfern 1994, Redfern and Rhoades 1996, Myung and Smith 1997, Redfern and DiPasqale 1997). In these studies, researchers especially focused on measuring *leg and heel kinematics*, *normal and shear forces* in the shoe/floor contact surface, and *friction usage* (or required friction) as well as joint angles for the ankle, knee and hip. The effects of *ramp angle* to *forces* at the shoe/floor interface were measured while walking up and down ramps (McVay and Redfern 1994, Redfern and DiPasqale 1997). Also *protective responses* and hand/arm or trunk movements for restoring balance after slipping, *falling frequencies*, and/or *slip/fall probabilities* were examined (Strandberg and Lanshammar 1981, Strandberg 1985, Hanson *et al.* 1999). Some investigators focused on measuring *slip distances* and *micro-slipping* during walking as indicators for slipping and falling hazards (Leamon and Son 1989, Leamon and Li 1990).

Strandberg and Lanshammar (1981) simulated unexpected heel slips when approaching a force platform which was lubricated with water and detergent in 76 trials (61%) out of 124. The trials were categorized into two main groups, grips (85 trials) and skids (39 trials). The skids were split into two categories, slip-sticks (16 trials) and falls (23 trials), while the slip-sticks were finally differentiated into mini-, midi- and maxi-slips. The subjects were unaware of the sliding motion in the mini-slips, in the midi-slips no apparent gait disturbances were observed, but in the maxi-slips compensatory swing-leg and arm motions occurred. The peak sliding velocity was above walking speed (1 – 2 m s^{-1}) in the skids that resulted in a fall, but did not normally exceed 0.5 m s^{-1} in the remaining skids called slip-sticks, where the subjects were able to regain balance. These slipping experiments indicated that a slip was likely to result in a fall if the sliding exceeded 0.1 m in distance or 0.5 m s^{-1} in velocity. A recent study by Brady *et al*. (2000) suggested that foot displacement rather than the velocity of the slipping foot would predict the outcome of a slip, and that the threshold values for fall avoidance may be higher than previously thought. Roughly 75% of the subjects in these bare foot slipping experiments over an oily vinyl surface were able to recover balance, when the slip distance was 0.2 m and the slipping foot velocity was 1.1 m s^{-1} (cf. Redfern *et al*. 2001).

Morach (1993) performed slipping experiments on contaminated floors (oil, glycerol, and water) and found that the *horizontal foot velocity* in forward direction immediately (i.e. during 10 ms prior to heel contact) varied between 0.3 and 2.75 m s^{-1} (the average walking speed was 1.5 m s^{-1}) depending on the type of slip, i.e. slip start after a short (more than 26 ms) static position (106 trials), immediate (during less than 6 ms) slip start (300 trials), and unclear (6 to 26 ms) slip start (112 trials). The highest foot velocities occurred on a steel floor with oil as lubricant, when there was an immediate slip start after heel landing.

Winter (1991) and Lockhart (1997) reported a higher heel contact velocity in the horizontal direction for *older subjects* compared with *younger subjects* on dry floor surfaces, even though the walking velocity of the older subjects was slower. On a slippery floor surface (oily vinyl tile), a higher heel contact velocity (figure 3) coupled with a slower transition of whole body centre-of-mass velocity of older individuals significantly affected sliding heel velocity and dynamic friction demand. Consequently, the result was longer slip distances and increased falling frequencies for the older compared to younger individuals (Lockhart *et al*. 2000a, b).

Lockhart *et al*. (2002) conducted a laboratory study to determine how *sensory changes* in elderly people affected subjective assessments of floor slipperiness and how these were associated with friction demand characteristics and slip distance. The results indicated that sensory changes in the elderly increased the likelihood of slips and falls more than in their younger counterparts due to incorrect perceptions of floor slipperiness and uncompensated slip parameters, such as slip distance and adjusted friction utilization (cf. section 5.4).

Redfern and Rhoades (1996) reported experimental results concerning heel dynamics of subjects during *load carrying* (boxes of varying weights up to 13.5 kg) at three different walking cadences (70, 90 and 100 steps per minute). The surface condition studied was probably dry, but some micro-slipping occurred during the experiments after heel contact. The horizontal (forward) heel velocity decreased from a pre-heel contact maximum of 4.5 m s^{-1} at the end of the swing phase to between 0.14 and 0.24 m s^{-1} at heel contact in the beginning of the stance phase. The heel pitch angle at heel landing was between 20 and 25° and decreased to foot flat within about 100 ms after initial contact. The heel came to a complete stop during micro-slip conditions about 100 ms after the impact. Carrying loads showed, according to Redfern and Rhoades (1996), the same dynamic qualities as normal walking. They concluded that load carrying had only minor effects on the heel movement parameters. Recently, Myung and Smith (1997) argued that this was true only for dry conditions while oily floors significantly affected those parameters. They recorded for oily vinyl and plywood floors horizontal heel landing velocities of at least 0.6 to 1.4 m s^{-1} during load carrying experiments with ten young male subjects. Myung and Smith (1997) also found that stride length was reduced as floor slipperiness and load carrying levels increased (cf. Redfern *et al*. 2001).

3.3. Psychophysical and subjective approaches

Human-centred approaches for the measurement of slipperiness may be psychophysical in nature. A perceived magnitude of ‘slipperiness’ can be quantified on a psychophysical scale using ‘foot movement’ or ‘postural instability’ as the physical stimulus. The stimulus can be measured subjectively using opinions and preferences but can be measured objectively too. Objective measures are, for instance, video filming or high-speed imaging of gait and may also include ground reaction forces obtained with force platforms. Human-centred approaches may involve simultaneous acquisition of objective biomechanical data and subjectively perceived data (Strandberg 1985, Grönqvist *et al.* 1993). Subjective opinion data is quantitatively treated on an ordinal (category) scale, while a nominal scale can be used for analysing motion and force data (slip distance, slip velocity, friction usage, joint angles, etc.). Engström and Burns (2000) spoke for *psychophysical scaling* (continuous ratio scales) as an alternative to common category scaling of opinions and preferences.

A number of ‘purely’ subjective approaches (e.g. paired comparisons) have been applied to measure slipperiness. Human subjects seem to be capable of differentiating the slipperiness of *floors* (Yoshioka *et al.* 1978, 1979, Swensen *et al.* 1992, Myung *et al.* 1993, Chiou *et al.* 1996) and *footwear* (Strandberg *et al.* 1985, Tisserand 1985, Nagata 1989, Grönqvist *et al.* 1993) in dry, wet, or contaminated conditions. Cohen and Cohen (1994a, b) pointed out that tactile sliding resistance cues are the most sensitive predictors of the coefficient of friction under various experimental conditions but particularly on wet surfaces. Leamon and Son (1989) and Myung *et al.* (1992) suggested that measuring micro-slip length or slip distance during slipping incidents might be a better means to estimate slipperiness than the apparatus-based friction measurement techniques. Recently Chiou *et al.* (2000) reported findings of workers’ perceived sense of slip during standing task performance (e.g. a lateral reach task) and further related their sensory slipperiness scale to subjects’ postural sway and instability. They found that workers who were cautious in assessing surface slipperiness had less postural instability during task performance.

Skiba *et al.* (1986), Jung and Schenk (1989, 1990) and Jung and Rütten (1992) evaluated walking test methods used for measuring the slipperiness of floor coverings and safety footwear on an *inclined plane* on dry, wet and oily surfaces in the laboratory. The inclination angle at a point when walking down the ramp became unsafe gave the subjective estimate for slip resistance by transforming it geometrically to a friction value. These papers also discussed the validity and reliability of such tests, use of standard reference materials and separation characteristics for choosing a limited number of test subjects for standardized slipperiness measurements.

Subjective and combined human-centred approaches have been utilized to assess footwear *friction on ice*. At least two test rigs have been developed by Bruce *et al.* (1986) and Manning *et al.* (1991): the first test rig consists of a tubular metal frame with four legs, fitted with large castor action wheels. A test subject, standing on both feet on an icy surface, is dragged across the substrate. Bruce *et al.* (1986) conducted tests at an ice skating rink and the horizontal (frictional) force in the shoe/ice interface was measured by a load cell (spring balance) at a low sliding velocity. The frame of the rig prevented the subject from falling. The second technique, by Manning *et al.* (1991), can be applied to measure the slipperiness of a footwear/ice interface as well as a footwear/floor interface. In this method, a subject is walking (backward steps) on a surface to be assessed while pulling against a spring and supported by a fall-arrest harness. The subject is also protected by two handles suspended from a pulley that moved freely on an overhead rail. The load cell is positioned between the harness belt of the subject and a rigid base (e.g. a wall). Manning and Jones (1993) modified this walking traction rig for mobile field use as well. Since the resisting force is not measured in the shoe/floor interface, the load cell measures indirectly the maximum frictional force before feet will slip. Scheil and Windhövel

(1994), who criticized the validity and precision of this method, evaluated the latter mobile version of the above method on various floor surfaces attached to a force platform. The walking action was abnormal and the friction readings were biased by inertial forces that increased the load cell reading (horizontal force) compared to the measured friction force in the shoe/floor interface.

3.4. Rating scales for balance and walking safety

3.4.1.Balance and functional abilities—Rating scales, for example Bohannon's ordinal scale for standing balance (Bohannon and Leary 1997) and the 'Timed Up and Go' test (Podsiadlo and Richardsson 1991) have been used to assess balance capabilities of the individuals, but no perfect standard exists among these methods. An objective test often used today is the Berg balance test (Berg 1989, Berg *et al*. 1992a). Combined with a test of walking speed the Berg balance test shows a high sensitivity and specificity as a screening method (Berg *et al*. 1992a). Berg's balance scale is an instrument for quantitative evaluation of balance, a scale with 14 moments, testing static and dynamic balance with increasing difficulty. All moments are described in a manual with grades from 0 to 4 with a maximum of 56 points. The test takes 20 min to perform. The Berg balance scale has good concurrent validity with many other methods used in this area; the Bartel Index for activities of daily life, Tinetti's sub-scale for balance (Tinetti *et al*. 1986), the Fugl-Meyer scale for isolated movements and balance (Fugl-Meyer *et al*. 1975), the `Get-up and Go' test (Mathias *et al*. 1986), the 'Timed Up and Go' test (Podsiadlo and Richardson 1991) and a test of functional mobility (Berg *et al*. 1992b).

The test 'Get-up and Go' measures a person's risk of falling according to a 5-grade scale; normal, very slightly abnormal, mildly abnormal, moderately abnormal and severely abnormal (Mathias *et al*. 1986). A person is observed while raising from a chair with armrests, walking 3 m and then returning to the chair. The test focuses on many basic functional aspects and is easy to perform. The `Timed Up and Go' (Podsiadlo and Richardsson 1991) is a balance test focusing on walking speed and functional ability. The time to perform the test from leaving the chair until sitting on the chair again is measured by a stop-watch.

A functional perspective is important when dealing with balance problems in a test situation. Basic functional abilities for people of all ages are the ability to go and rise from bed, sit down and rise from a chair or toilet, and to walk a few steps (Isaacs 1985). These abilities are prerequisites for elderly people to live independently in their own home or in open home care without assistance. Functional abilities are important for the evaluation of rehabilitation effects in patient groups. For that purpose, an index of muscle function and a battery of functional performance tests for the lower extremities have been developed. The total index can be divided into four separate areas: pre-tests of general functioning; muscle strength; muscular endurance; and balance and co-ordination (Ekdahl *et al*. 1989).

3.4.2. Evaluation of icy surfaces and anti-skid devices—Methods to describe functional problems in walking on different slippery surfaces during winter conditions have been developed by Gard and Lundborg (2000) as rating scales for evaluating walking safety and balance, and as observation scales to observe posture and movements during walking. The methods were then used to investigate functional problems when wearing different anti-skid devices (attached to shoes) for slip and fall protection. First, rating scales for perceived walking safety and balance were developed and tested for reliability. Inter-reliability tests of these scales were done from video-recordings of walking with different anti-skid devices on a number of surfaces in experiments done by two experienced physical therapists. The percentage of agreement between the physical therapists was 86% (walking safety) and 88% (walking balance). Second, four rating scales for evaluation of observed walking movements were developed by a physical therapist, trained in movement analysis. The dimensions evaluated were:(1) walking posture and movements including normal muscle function in the hip and knee; (2) walking posture and movements in the rest of the body (head, shoulders and arms); (3) heel strike; and (4) toe-off. All four dimensions were evaluated by observation scales ranging from 0 to 3. The inter-reliability of these four observation scales were measured as the percentage of agreement between the physical therapists and was 85, 80, 86 and 85%, respectively (Gard and Lundborg 2000).

Abeysekera and Gao (2001) performed practical walk tests using a 5-point rating scale to evaluate slipping risks on a number of icy and snowy surfaces when wearing different types of footwear. Such walk tests may be used to assess the performance of footwear, or anti-skid devices, but also to study the human responses involved in slipping accidents. Gard and Lundborg (2001) carried out practical tests of 25 different anti-skid devices on the Swedish market, on different icy surfaces with gravel, sand, salt or snow on ice, and with pure ice. The anti-skid devices were described according to each subject’s perception of walking safety, walking balance and priority for own use. The posture and movements during walking were analysed by an expert physical therapist. One of the tested anti-skid devices was judged to be good regarding walking safety and balance and was chosen by subjects for their own preferred use (Gard and Lundborg 2001).

3.5. Measurement of sudden movements

Slipping may involve rapid movements resulting from a person’s effort to regain balance. A method has been developed to detect such movements by measuring trunk acceleration during walking (Hirvonen *et al*. 1994). By attenuating normal movement signals by band-pass filtering, it became possible to discriminate signals caused by unexpected movements. The portable equipment consisted of a small acceleration transducer, a pre-amplifier and a pocket computer (Hirvonen *et al*. 1994). Unexpected trunk movements during slipping of 20 male volunteers who walked at two speeds, normal and race walking, along a horizontal track were monitored. The peak acceleration levels of the trunk increased significantly in slipping incidents compared to normal or race walking without slipping, both in the antero-posterior and medio-lateral directions. The peak accelerations varied from 0.5 to 4.5 g (1 g = 9.81 m s^{-2}) during slipping, while the accelerations were less than 0.5 g during walking without slipping. The mean peak accelerations of the trunk during slipping incidents were of the order 1.3 g for the antero-posterior and 1.0 g for the medio-lateral directions, respectively. The levels were significantly higher than during reference non-slipping conditions. The seriousness of these slip incidents was observed using video filming: no observable slip; controlled slip; vigorous slip; extremely vigorous slip. Most experiments resulted in either controlled or vigorous slips.

Questionnaires can be used to study the risk of accidents and the role of sudden movements at work (Hirvonen *et al*. 1996). Workers were asked to subjectively rate the risk of accidents in their work tasks associated with walking on slippery or untidy surfaces, on uneven surfaces, and on stairs. For each question four alternatives of the risk were given: not at all (score 1); a little (score 2); moderately (score 3); much (score 4). Based on these four questions, a sum score of the risk of accident was calculated and classified into three categories: low (score 4 – 8); moderate (score 9 – 12); high (score 13 – 16). In a follow-up intervention at the workplace, a total of 297 unexpected incidents occurred during which the trunk acceleration level exceeded 1.0 g. The number of alarms (i.e. acceleration levels exceeding 1.0 g) was significantly greater for the high risk compared to the low risk category. However, the intensity of sudden movements, measured as the peak acceleration of the trunk, did not differ between the three self-assessed categories of accident risk.

3.6. Comparative evaluations of test methods

At least two studies have reported comparative evaluations of test procedures involving human subjects (Jung and Fischer 1993, deLange and Grönqvist 1997). The objective of the first study was to investigate the validity of mechanical laboratory-based test methods for measuring slip resistance of safety footwear when the same test protocol and procedure was applied in each participating laboratory. The second study aimed at bridging the gap between human-centred test procedures and mechanical slip test methods.

Ten subjective and combined human-centred test procedures were compared in the first study (Jung and Fischer 1993). Male subjects (4 to 8 depending on the test) wore five different types of safety footwear and walked over a smooth stainless steel surface contaminated with viscous glycerol or a mixture of water and wetting agent. The walking tests were performed on a straight level surface (3 paired comparison methods) or an inclined surface (7 walk-test methods down or up a ramp). The paired comparison methods yielded either a subjective scoring, a friction usage value, or a slip and fall frequency as the outcome (footwear rating). The outcomes of the ramp tests were either an average maximum inclination angle for safe walking (6 methods) or a paired comparison scoring using two fixed inclination angles (1 method). The rank correlation coefficients between the footwear ratings obtained with these seven human-centred test methods varied from 0.90 to −0.70. Of all the 44 comparisons only six correlation coefficients (14%) between test methods were statistically significant at the 95% probability level. Only two of these significant results were obtained between different types of walking tests, one level surface test and two similar ramp tests. A major limitation of this inter-laboratory experiment was that the assessed footwear did not exhibit large differences in terms of their slip resistance. The validity of the mechanical slip tests could not be confirmed in this study.

Three subjective and combined test procedures were compared in the second study (deLange and Grönqvist 1997). All three tests were also involved in the first study by Jung and Fischer (1993): an inclined surface (walking down a ramp) applying ramp angle as safety criterion (Jung and Schenk 1990) and two level surface test procedures applying subjective scorings based on paired comparisons of footwear as safety criteria. The level surface test methods used two different approaches. The first method was based on human action while walking, stopping and accelerating on a slippery surface (Tisserand 1985) and the second method was based on the heel landing phase when the subject stepped from a slip-resistant surface onto a slippery surface (Grönqvist *et al.* 1993). Male subjects (2 to 7 depending on the test) were wearing six different types of footwear for professional use and walked over a smooth stainless steel surface or a rough vinyl flooring contaminated with viscous glycerol or a mixture of water and detergent. The water and detergent conditions were assessed only with the ramp test method, so that no comparative data between the methods was available for this condition. The results of the two level surface test methods differed significantly for test condition steel/ glycerol, probably due to differences in performing the tasks (walking at a constant pace vs. accelerating, etc.). However, the ratings for two test conditions (steel/ glycerol, PVC/glycerol) between the second level surface method and the ramp test method were similar despite the two different approaches (walking on a level vs. inclined surface).

4. Modelling slip recovery and fall avoidance

4.1. Difference between static and kinetic friction

Tisserand (1985) suggested using a simple biomechanical model (considering a mechanical equilibrium of forces at the moment the foot strikes the ground) that the slipping velocity (v) is a function of the difference between the static (F_s) and kinetic (F_k) friction forces:

$$v \approx \frac{1}{M}(F_s - F_k) \cdot t$$

where M is the mass of the body parts in motion and t is the time.

Hence, Tisserand (1985) concluded that for a given coefficient of kinetic friction the seriousness of the fall would be directly proportional to the coefficient of static friction. Tisserand also presented experimental subjective evaluation data in support of his reasoning. In fact, Tisserand went even further in his analysis allowing him to assume that this relationship is valid even if there is no initial static phase as the heel strikes the ground. Tisserand (1985: 1030) completed the analysis with the following statement that 'preventing initial slipping of the foot requires a high or sufficient static friction force, while limiting slip velocity to avoid loss of balance requires a small difference between static and kinetic friction forces and that the latter is always required to prevent falling and injury'.

4.2. Critical slip distance

Strandberg and Lanshammar (1981) estimated that the critical sliding velocity leading to falling after a heel slip was about 0.5 m s^{-1}, and that the required minimum kinetic friction coefficient was about 0.2 during normal level walking. If the above figures are accepted as critical for a hazardous slip and fall, then the boundary slip distance s between an avoidable and an unavoidable fall would be about 6 cm (Grönqvist *et al.* 1999), since:

$$s = \frac{v^2}{2g\mu}$$

The above equation, where g is the acceleration of gravity, v is the velocity of sliding, and μ is the coefficient of friction, is derived from the work done by the frictional force. This equation, which governs the distance required to bring a moving object to a stop by friction, is based on the assumption of a constant initial sliding velocity. Nevertheless, it indicates that if the coefficient of friction increases for example to 0.4, then the boundary slip distance would be reduced to 3 cm, which would be perceived to be slippery by only 50% of the subjects in a slipping experiment (cf. section 3.1). Obviously, an increasingly safer situation from the point of view of balance recovery would follow. On the contrary, if the critical values ($s = 0.2$ m and $v = 1.1$ m s^{-1}) for slip distance and velocity suggested by Brady *et al.* (2000) would be applied in this equation, then the minimum coefficient of friction in the interface would need to be about 0.3 for a fall recovery.

4.3. Walking speed and step length

Gait and anthropometric parameters such as length of stride may, however, affect the above critical sliding velocity of the heel. In fact, Strandberg (1985) presented a falling criterion based on the biomechanical skidding data by Strandberg and Lanshammar (1981), using a simple biomechanical inverted pendulum model of the human body during a single stance phase. The model predicted that the maximum permissible (without falling) sliding velocity (v_s) increases with walking speed (v_w) and decreases with step length (L).

The model's falling criterion is:

$$v_s > \mathrm{k}v_w - 0.5\mathrm{c}L\sqrt{\frac{Mgh}{J}}$$

where k and c are constants and M is the mass of the inverted pendulum, centred the distance h above the heel/floor contact point, and with J the mass moment of inertia about this contact point.

A higher walking speed (v_w) may be favourable, if the step length (L) is kept constant and if no cornering forces are required. The horizontal velocity of the body COM must be sufficiently greater than the sliding velocity of the BOS. Otherwise, the COM velocity relative to the BOS velocity will become negative before COM has reached a position above the BOS, and a backwards falling motion will begin. This gait pattern with short steps in comparison to the walking speed will also result in a reduction of the body's COM vertical acceleration, whether it is the primary aim or not. The relationship between walking speed, step length and friction demand has been investigated by Lindberg and Stalhandske (1981). Recently, You *et al.* (2001) confirmed that the displacement and velocity of the COM with respect to the BOS can be used to discriminate slip/non-slip incidents of the heel in barefoot walking over a slippery soap patch. During the critical double-support period from heel strike to contra-lateral toe-off, a smaller displacement and a faster velocity of the COM were important for regaining balance.

5. Criteria for safe friction

This section will bring some insight to basic safety criteria, frictional demands, and minimum friction thresholds proposed for a number of activities and work tasks including walking, running, and manual exertion. The criteria for some special risk groups (mobility disabled and the elderly) are also discussed. Frictional demands are related to either a baseline non-slip 'required friction' or a more global 'friction usage' (i.e. 'utilized friction') criterion, which is independent of whether a slip occurs or not (cf. Grönqvist *et al.* 2001a).

5.1. Level walking

The frictional demand, based on human experiments during normal level walking, has been found to vary between 0.15 and 0.30 (Perkins 1978, James 1980, Strandberg and Lanshammar 1981, Bring 1982, Skiba *et al.* 1983). See also Redfern *et al.* (2001) who discusses the role of safety criteria based on ground reaction forces during locomotion without slipping and during slips. The significance of the horizontal (shear) to vertical ground reaction force ratio (F_H/F_V) is that it indicates where in the step cycle a slip would most probably start (figure 4). However, if a foot slide starts, the evolution of frictional shear forces in the shoe/floor interface would determine whether the slip can be retarded or stopped and balance recovered. Hence, the measured friction coefficient should always be greater than the utilized or the required friction coefficient (cf. Grönqvist *et al.* 2001a, Redfern *et al.* 2001). Hanson *et al.* (1999) applied the difference between measured and required friction as safety criterion instead of the friction ratio, which was proposed by Carlsöö (1962).

Grönqvist *et al.* (2001b) found that the contact time related variation in utilized friction in the presence of a slippery contaminant was large (possibly due to gait adaptations) in response to the reduced available (measured) friction between the interacting surfaces. In this case, a single safety limit for the friction coefficient, such as the maximum peak value after heel contact, may not be an appropriate discriminator between safe and dangerous conditions. The evolution of the friction coefficient over contact time seems to be at least equally important.

Perkins (1978) reported both 'maximum' and 'average' peak values for the frictional demand. Strandberg and Lanshammar (1981) measured the friction usage peak, F_H/F_V, approximately 0.1 s after heel strike. The peak value in their experiments was on the average 0.17 when there was no skidding (grip), 0.13 when the subject was unaware of the sliding motion or regained balance (slip-stick), and 0.07 when the skid resulted in a fall. Kinetic friction properties appeared to be more important than static ones, because in most of their walking experiments the heel slid upon first contact even without a lubricant. On the other hand, Strandberg *et al*. (1985) and Grönqvist *et al*. (1993) also reported stance time-averaged friction usage values for estimating frictional demands during walking over continuously and unexpectedly slippery surfaces, respectively. The values reported by Strandberg *et al*. (1985) were based on the mean stance time for one step (approximately 0.5 – 0.7 s). These values were of the order 0.25 for the safest experiments on a smooth steel surface with glycerol as contaminant. In comparison, the mean F_H/F_V ratios during time-interval 100 – 150 ms after heel contact, for the safest experiments without falling, reported by Grönqvist *et al*. (1993) were much lower (between 0.11 and 0.13) in the same test condition (steel/ glycerol).

Strandberg (1983) favoured 0.20 as a safe limit for the coefficient of kinetic friction in level walking, indicating that he added a safety margin to the measured frictional demand (cf. peak ratios of the ‘grip’ and ‘slip-stick’ trials above). Nevertheless, he pointed out that the adequate value was depending greatly on anthropometric and gait characteristics as well as the method of measurement. He found that friction properties were most important for preventing falls at sliding velocities below 0.5 m s^{-1}. In contrast, static friction values proposed in the USA in the mid-1970s used 0.40 to 0.50 as lower limits for safe walking (Brungraber 1976). These values are not in line with the actual frictional demands based on human walking on level surfaces, and thus may be more an indication of practical eligibility for the test methods in question.

5.2.Other modes of locomotion

In general, minimum coefficient of friction limit values should be correlated to normal variability of human gait, since walking speed, stride length and anthropometric parameters may greatly affect the frictional demands during locomotion (Carlsöö 1962, James 1983, Andres *et al*. 1992, Myung *et al*. 1992). McVay and Redfern (1994) found that the mean across subjects of the peak required friction increased from about 0.25 to 0.50 as ramp angle increased from 0° in level walking to 20° on an *inclined surface*. Their study indicated that geometric predictions based on ramp inclination angles did not fully explain the actual changes in frictional demands and resulted in excessively high values for the required friction limit. Walking up the ramp produced greater frictional demands than walking down the ramp. Ground reaction forces on inclined surfaces are discussed extensively by Redfern *et al*. (2001).

Depending on the type of movement (walking on a *ramp* or on *stairs*) James (1980) referred to limit values between 0.15 and 0.40. Harper *et al*. (1967) and Skiba *et al*. (1983) referred to limit values between 0.30 and 0.60 during *stopping* of motion, *curving* and walking on a *slope*. Later Skiba (1988) defined that the safety limit for the kinetic friction coefficient, based on the forces measured during human walking and the social acceptance of the risk of slipping, would be 0.43 at sliding speeds of at least 0.25 m s^{-1}. At heel strike in *running* gait the peak F_H/F_V is typically slightly greater (about 0.30) compared to walking, and this difference is even greater at toe-off when the force ratio peak is about 0.45 (Vaughan 1984). *Jumping* during exiting commercial tractors, trailers and trucks can produce large impact forces in the shoe/ ground interface (Fathallah and Cotnam 2000) and may increase the friction demand as well as the risk of slipping (Fathallah *et al*. 2000). The average peak required friction range was from 0.13 to 0.33 depending on the vehicle type, jumping height, and the use of safety aids such as steps and grab-rails.

Skiba *et al*. (1985) reported that the peak friction usage at foot contact during *stair ascent* was lower than during normal level walking (0.17 versus 0.21). During *stair descent*, the peak friction usage at foot strike was lower than during normal level walking (0.12 versus 0.21) but higher during the push-off phase (0.34 versus 0.20) according to the same study. Christina *et al*. (2000) found that the peak frictional demand at foot strike during stair descent was remarkably similar to level walking (i.e. between 0.30 and 0.32) but that the required friction was lower during the push-off (0.26). Note that the reported friction usage values were contradictory in these two studies. Redfern *et al.* (2001) also discusses ground reaction forces during stair ambulation.

5.3. Manual exertion

Kroemer (1974) measured horizontal *push and pull forces* when subjects were standing in working positions on various surfaces. Forces exerted while braced against a footrest or wall were compared against the forces exerted while standing on high, medium and low traction surfaces. The mean push and pull forces exerted were reduced considerably depending on the slipperiness of the surfaces: the forces exerted were roughly 500 – 750 N for the braced situation, 300 N for the high traction surface (static friction coefficient μ>0.9), 200 N for the medium traction surface (μ~0.6), and 100 N for the low traction surface ($0.2<\mu<0.3$). Ciriello *et al.* (2001) investigated maximum acceptable horizontal and vertical forces of *dynamic pushing* on high and low friction floors. They found that the 'required' friction coefficient (i.e. the horizontal to vertical shoe/floor force ratio required to sustain a push-cart movement) was 0.32 for the high friction floor but only 0.19 for the low friction floor. However, push duration on the low friction floor was significantly longer and slip potential greater than on the high friction floor.

Grieve (1979, 1983) examined limitations of performance due to friction and static friction limits for avoiding slipping during manual exertion (*lifting, pushing and pulling*). Grieve found that static manual exertion can create unavoidable slips due to high frictional requirements (even >1) in some conditions, and concluded that more efforts should be concentrated on the events that follow the foot slide. Zhao *et al.* (1987) showed that the determination of slipping risks associated with *lifting on inclined surfaces* should not be based solely on the slope angle. Dynamic lifting increases the ratio of tangential (shear) to normal forces compared to the static condition. Consequently, Zhao *et al.* (1987) suggested that slope angle must be smaller than the friction angle of the shoe/ground interface. For example, for a slope angle α of 15° the peak force ratio of shear to normal forces would be 0.27 (= tan α) for the static case but in the range of 0.30 to 0.36 for dynamic lifting.

Kinoshita (1985) examined the effects of light and heavy loads on certain gait parameters and found that the shear and normal components of the ground reaction force significantly increased compared to habitual walking. However, the frictional requirements in terms of their ratio did not seem to change due to *different loads* and *carrying systems* (double-pack and back-pack). Analysis of spatial and temporal parameters of the gait patterns revealed that only the double and single support periods of stance were affected by the changes in load. The double support period, expressed as a percentage of the total support period, lengthened and the single support period shortened significantly as the load increased.

5.4. Mobility disabled and the elderly

Buczek *et al.* (1990) emphasized that the slip resistance needs for *mobility disabled* may be greater than for able-bodied persons. Their study indicated that the required coefficient of friction near touch-down for the unaffected side of the mobility disabled person was significantly higher (average 0.64) than for the able-bodied (average 0.31) regardless of the speed (slow or fast) of walking, whereas no difference was observed for the push-off phase.

Christina *et al.* (2000) found in *stair descent* that the frictional demand at foot touch-down was lower for the *elderly* (0.27 – 0.28) than for the younger subjects (0.30 – 0.32), indicating a safer stair descent strategy chosen by the elderly (cf. section 5.2).

On a dry *level-walking surface* (outdoor carpet), Lockhart *et al*. (2000a), found no statistically significant differences in required coefficient of friction characteristics between *young* (0.176), *middle-aged* (0.188), and *elderly* (0.192) adults. Lockhart *et al*. (2000b) also reported dynamic frictional demand characteristics between these three age groups on a slippery floor surface (oily vinyl tile) during slip-grip responses (i.e. slip recovery) by measuring adjusted friction utilization (AFU). A typical kinetic and kinematic profile of a slip-grip response starting from heel contact point on the oily vinyl tile floor surface is shown in figure 5. Heel contact was defined as the point where vertical foot force exceeded 10 N. Initially, as indicated by the horizontal heel position (figure 5(c)), the heel does not slip forward. The horizontal heel velocity decreases (figure 5(b)) as the heel quickly decelerates (figure 5(a)), and both the vertical downward force (figure 5(d)) and the horizontal forward force (figure 5(e)) increase. Shortly after heel contact (approx. 60 ms), the heel begins to slip forward (SD1, figure 5(c)). Afterwards, the sliding heel reaches Peak Sliding Heel Velocity (PSHV, figure 5(b)). During this slipping period, the heel accelerates reaching the maximum (figure 5(a)) near the mid-point of the sliding heel velocity profile (figure 5(b)). At this time, both the vertical and the horizontal foot forces decrease. After reaching the maximum heel velocity (approx. 180 ms after heel contact), the sliding heel velocity decreases to a minimum, halting further slipping (figure 5 (b)).

AFU is the measured ratio of the horizontal to vertical foot force at the peak sliding heel velocity point (figure 5(f)) and represents the subject's ability to adjust to dynamic frictional requirements during slipping. The significance of this ratio is that it indicates where in the gait profile compensation for a slip is most likely to occur. The AFU of younger individuals (0.074) was adjusted within the dynamic friction requirements (0.08) of the oily vinyl tile floor surface. However, the AFU of middle age (0.10) and older individuals (0.12) was not adjusted within the dynamic friction requirements. Consequently, the result was longer slip distances and increased frequency of falls for these groups.

6. Conclusions

Why do we need to measure slipperiness? Do not current theories on friction mechanisms and biomechanical slip and fall models satisfactorily predict the risks associated with slipperiness? In fact, the underlying mechanisms of slips and falls are not yet fully understood and, therefore, we are not capable of measuring the risks properly. Nevertheless, human-centred approaches for slipperiness measurement do already have many applications. In particular, they are utilized to develop research hypotheses and models to predict workplace risks due to slipping and falling. They are equally important as alternatives to and as means to validate apparatus-based friction measurements, and as practical tools for routine control of slip resistance properties of footwear, anti-skid devices, and floor surfaces.

6.1. Strengths and weaknesses of human-centred approaches

- Strengths of human-centred approaches over mechanical measurement methodologies are given below:
- the methods are inherently valid for the situation being examined, because human subjects are involved in the experiment, while individual behaviour affects the outcome measures;
- the human factor aspect is included in the analysis and can be partly controlled (e.g. walking speed and cadence, anticipation versus unexpectedly slippery surfaces);
- they allow combining biomechanical measurement data with observations of performance and/or subjective ratings (Strandberg 1985, Strandberg *et al*. 1985, Jung and Schenk 1989, 1990, Hanson *et al*. 1999).

One major concern is that the results obtained with different human-centred methodologies may vary to a great extent, and although it may be a true effect it is sometimes caused by experimental bias; Jung and Fischer (1993) reported in an inter-laboratory study that the outcome of two similar ramp test methods was significantly different for the same test conditions. A possible underlying reason may have been the design of the experimental protocol. Obviously one must strictly control all relevant measurement parameters—such as walking speed and cadence, anticipation of slipperiness, use of safety harness, test environment, sample properties and pre-treatment—in human-centred trials as one needs to do during mechanical friction tests.

Weaknesses of human-centred approaches compared to mechanical slipperiness measurements include the following:

- human-centred experiments are time-consuming and expensive;
- they are mostly suitable for the laboratory environment (field applications are rare, cf. Manning and Jones 1993, Hirvonen *et al*. 1996);
- inter- and intra-individual variation in gait due to anticipation and adaptation to hazards may limit their use (Grönqvist *et al*. 1993);
- learning can affect the measured outcomes, such as magnitude of friction usage and ramp inclination angle or EMG activity changes over repeated trials (Skiba *et al*. 1986, Tang *et al*. 1998);
- a safety harness used to protect subjects from falling can be a confounding factor in many experimental set-ups and may affect the measured outcomes, such as ground reaction forces, required friction, slip velocity and/or distance (Lockhart *et al*. 2000a, b).

6.2. differentiation between slipping and falling

Various definitions of slipping and falling have been used in published studies (cf. Strandberg and Lanshammar 1981, Grönqvist *et al*. 1993, Hirvonen *et al*. 1994, Hanson *et al*. 1999). More precise definitions are needed to discriminate between different outcomes of a slip, for instance, when does a controlled slip (that can be terminated) turn into an uncontrolled slip and fall? The sliding distance of the foot was applied as discriminator between recoverable slips and likely falls by Grönqvist *et al*. (1993). Hanson *et al*. (1999) defined a slip or fall based on each subject's perception; the subjects were asked after each trial whether they subjectively felt 'no slip', 'slip and recovery' or 'slip and fall'. The subjects were also instructed to define a trial as a 'slip and fall' if they required support from a safety harness used to protect them against falling, or if they slid to the end of the force platform that measured the ground reaction force.

Novel experiments are needed to model effective slip recovery and fall avoidance strategies. Pai and Patton (1997) and Pai and Iqbal (1999) used an inverted pendulum model with a foot segment to simulate centre of mass velocity-position constraints and movement termination for balance recovery. In fact, recent studies suggest that in addition to foot displacement during slipping (Brady *et al*. 2000), the movement of the body's centre of mass over the base of support plays a significant role in slip recovery and fall termination (Pai and Patton 1997, Pai and Iqbal 1999, You *et al*. 2001).

6.3. Safety criteria and thresholds

Since frictional demands and thresholds for safe friction have been defined differently in different studies, the implications for discriminating safe conditions from potentially hazardous conditions do vary owing to methodological reasons. However, the requirements do also vary by task, subject and gait characteristics as well as by criterion for safe friction such as maximum peak or time-averaged utilized or required friction coefficient. Rarely have suggested frictional demands been related to duration of friction force during stance, which is surprising, since any contact-time-related variation of the utilized or required friction will be omitted, if a maximum peak value is used as the only safety criterion. Consequently, this may lead to misinterpretation of frictional demands that do vary as a function of contact time, particularly in the presence of contaminants between shoes and floor surfaces (Strandberg 1985, Grönqvist *et al.* 2001).

Current criteria and thresholds for safe friction are still incomplete. Frictional demands and their relation to availability of friction need to be better understood. Environmental consistency (i.e. sufficiently high and steady friction conditions) might be one key factor for improved slip and fall prevention. Perhaps much less can be done to improve human performance or to change work tasks for reducing the frictional demands in the workplace.

7. Future directions of research

For improving the validity and reliability of current risk assessment methods for slips and falls, one must better understand how foot/floor interactions are involved during the events leading to occupational injury and how slip and fall incidents should be simulated. Future directions of research must deal with modelling of basic tribophysical, biomechanical and postural control processes involved in slipping and falling. Slip/fall mechanisms need to be studied for a number of usual and high-risk tasks from walking to manual materials handling, and for different age groups. Events that trigger foot slides and subsequent events during which balance recovery is feasible should be examined in particular. Hypothetical injury mechanisms of falls on the same level and from a higher to a lower level should be tested. The role of slipperiness in the onset and causation of unexpected loading on the musculoskeletal system (especially the low back) is an area of research that has not received sufficient attention.

Objectives for future slips, trips and falls research are detailed below.

1. To document how anticipated postural controls develop—when does a person predict a potential slipping or tripping condition based on *a priori* knowledge about themselves and the environment, such as proprioceptive and kinesthetic cues, internal situation models characterizing spatial relationships of objects, changes in lighting, shadows, floor arrangement, etc? For example, psychophysically, what magnitude of change in lighting intensity constitutes a slip-and-fall warning?
2. To develop an understanding of how dual-task situations may impede anticipation and adaptation controls—in particular, we want to explain how a person's situation model may influence judgements on temporal and spatial perturbations.
3. To document how adaptive postural controls develop—what kind of sensory feedback is used in the adaptation—visual, vestibular and proprioceptive feedback? (How do people process information in fall situations?) What kind of feedback makes a person decide to co-activate certain muscles to, for example, gain more leg joint stiffness and maintain an upright torso (i.e. to fight a fall)? What makes a person decide to lower his body for a better fall position to counteract the potential negative consequences of an impending impact?
4. To understand how postural adjustments associated with voluntary movements are organized for various dual-task situations—how do harmonious motions develop to support primary task performance and balance of gait simultaneously? (This has been labelled physical mode-locking.)
5. To test the hypothesis that mode-locking between the primary task and gait control facilitates better anticipation and adaptation—if postural adjustments can be made that satisfy both primary and secondary task performance naturally, are cognitive

resources off-loaded for improving sensory perception and situation model development to better avoid or address fall events?

6. To explore mode-locking ability in a younger and an elderly population of healthy subjects and its influence on locomotion under perturbations.

For further exploration of the aetiology of slip and fall accidents on icy surfaces, in particular, and for providing the basis for their prevention, Abeysekera and Gao (2001) presented a systems model, which focuses on an improved understanding of the roles of contributing factors to slip and fall accidents.

The following systems factors were identified.

1. Footwear (sole) properties including sole material, hardness, roughness, worn/unworn, tread (geometry) design, centre of gravity, anti-slip devices, wearability (weight, height, flexibility, ease of walking, comfort).
2. Road surface characteristics, covered with ice, snow, contaminants, anti-slip materials, uneven, ascending/descending slope.
3. Footwear (sole)/road surface interface—the tribological aspect and friction (static, transitional and dynamic friction coefficients).
4. Human gait biomechanics: muscle strength, postural control, musculoskeletal function, postural reflex and sway, balance capability, acceleration, deceleration, stride length, step length, heel velocity, vertical and horizontal forces.
5. Human physiological and psychological aspects, i.e. the so-called intrinsic factors, including declines in visual, vestibular, and proprioceptive systems, ageing, perception of slipperiness, information processing, experience, training, diabetes,drug and alcohol usage, unsafe behaviour (rush, reading while walking).
6. Environment (extrinsic factors): temperature, humidity, snowfall, warm stream, lighting condition, warning and road signs.

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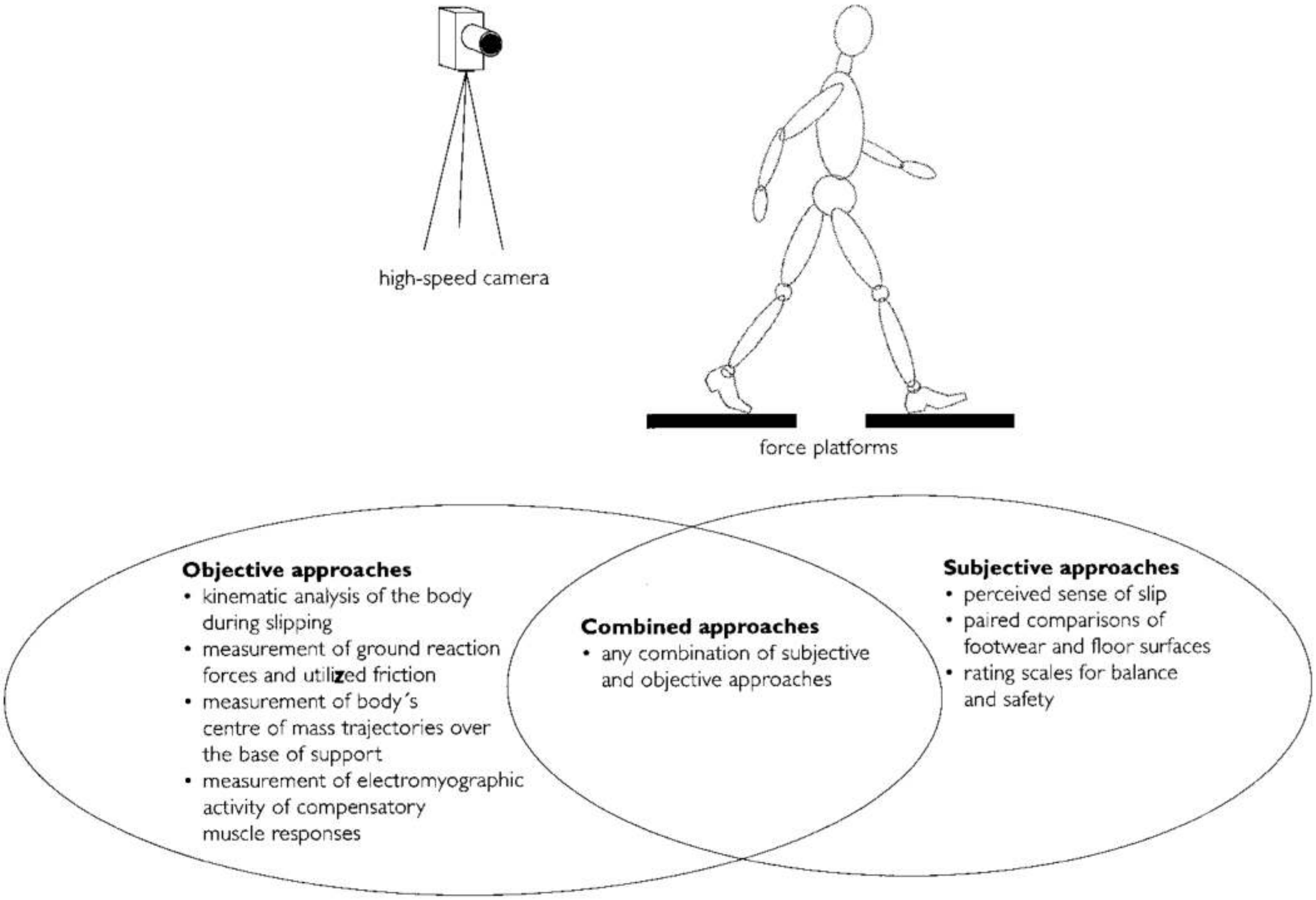

Figure 1.

Objective, combined and subjective human-centred approaches for the measurement of slipperiness.

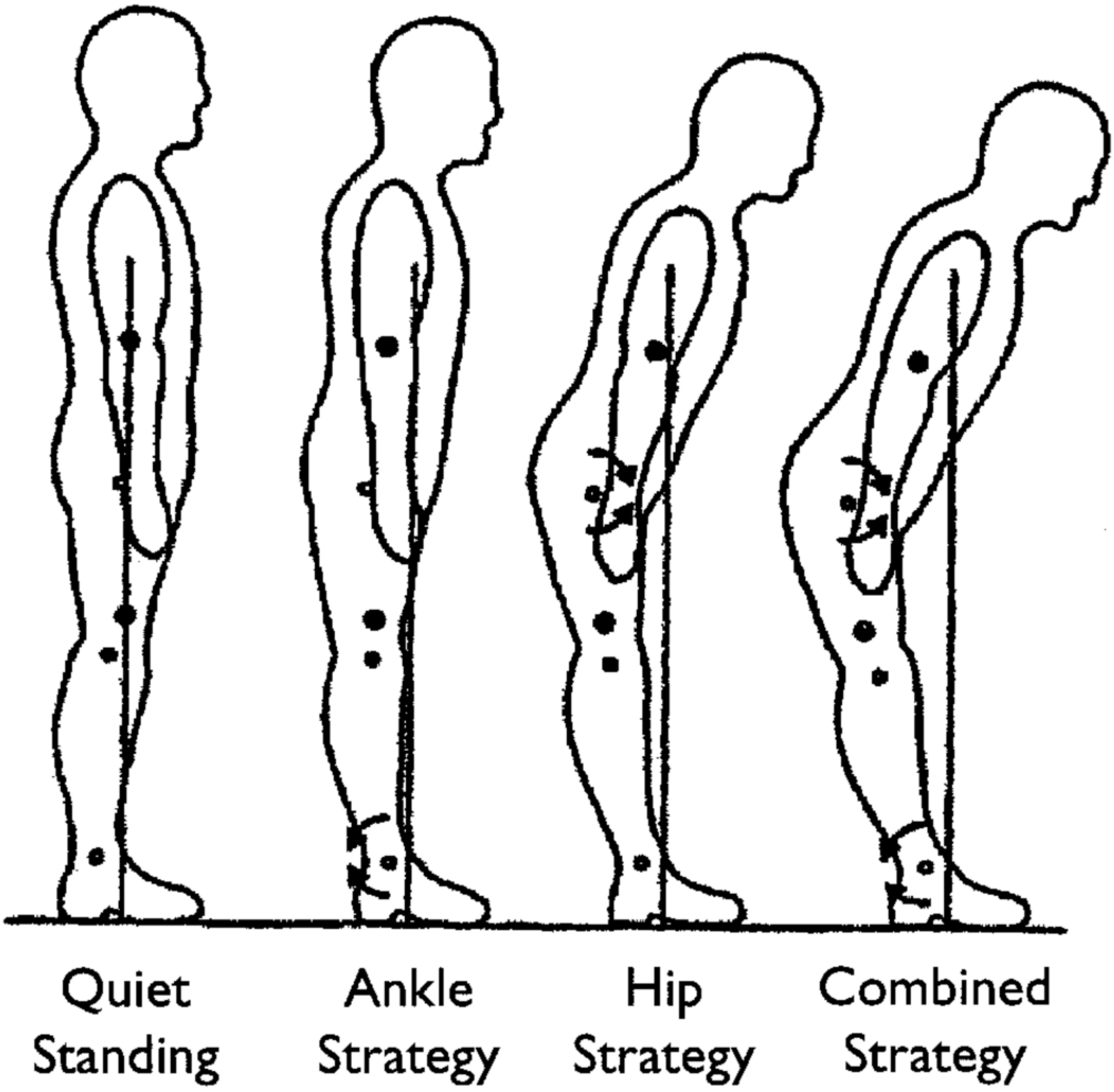

Figure 2.
Strategies for co-ordinating legs and trunk to maintain body in equilibrium with respect to gravity during standing (adapted from Winter 1995, figure 2.15).

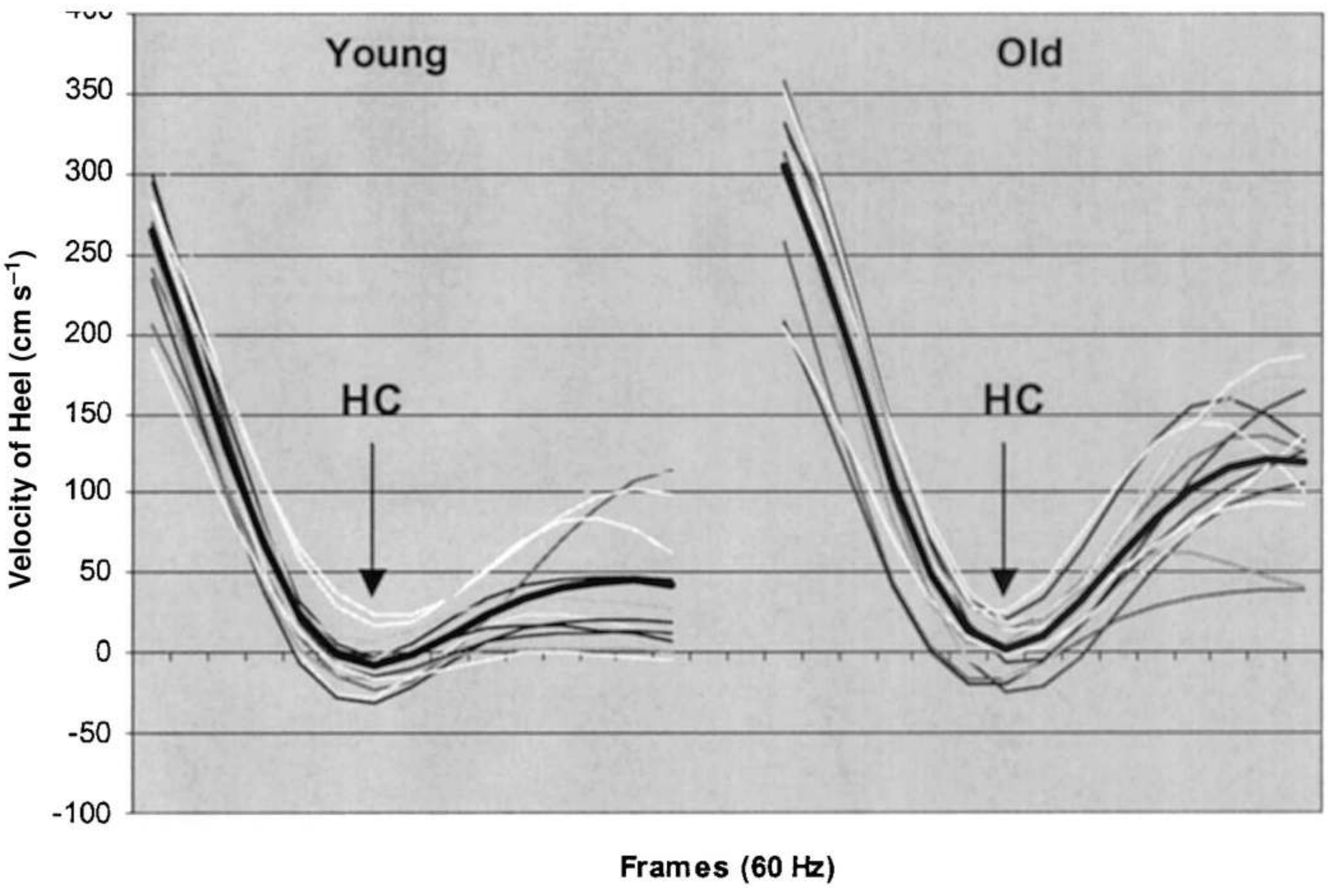

Figure 3.

Composite pattern of young and older individual's heel velocity 117 ms before heel contact (HV = heel velocity) and 117 ms after heel contact (SHV = sliding heel velocity) on an oily vinyl floor surface; heel contact (HC) was defined as the time when the vertical ground reaction force exceeded 10 N; the darker line expresses the average pattern of the heel velocities (Lockhart 1997).

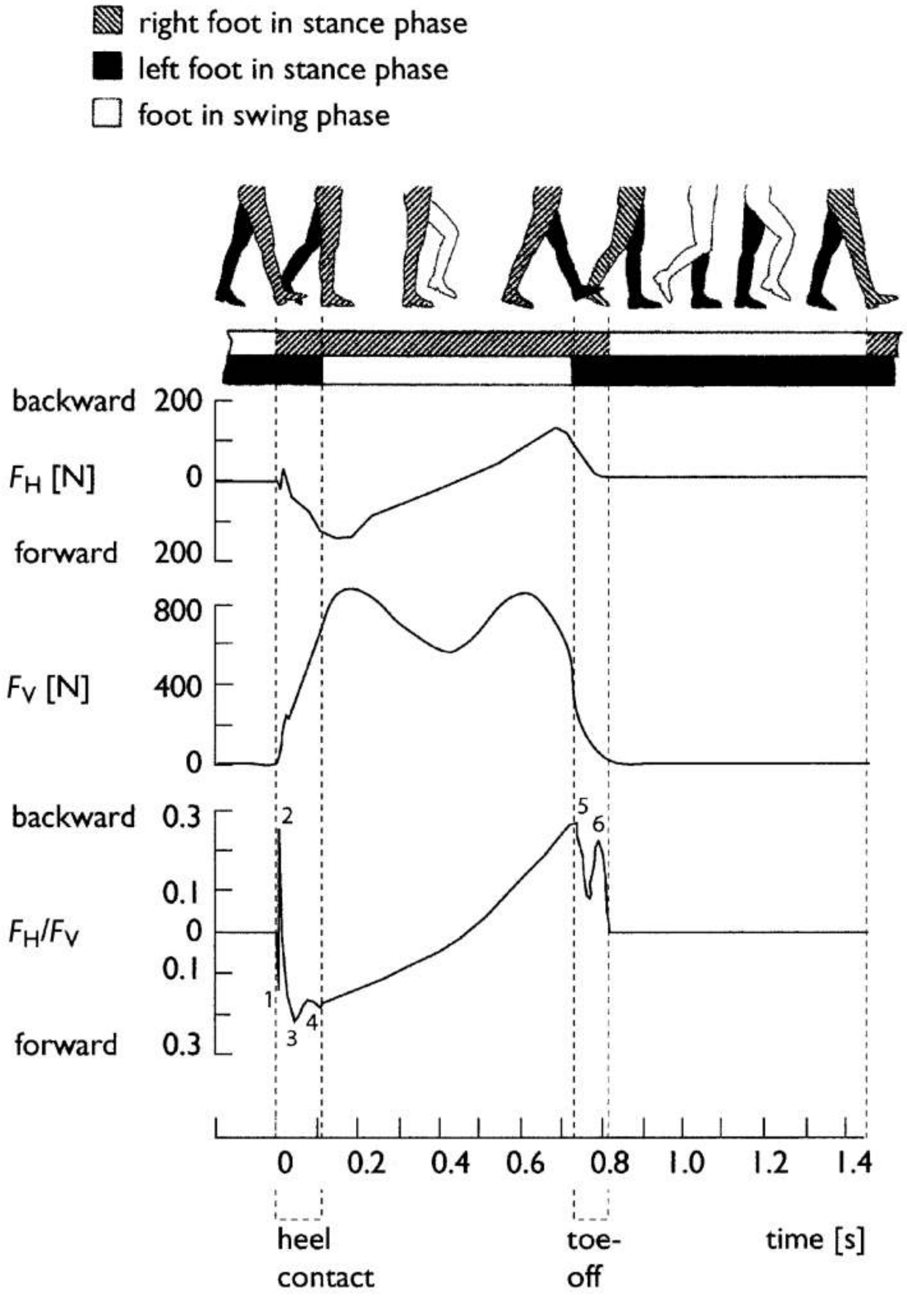

Figure 4.

Gait phases in normal level walking with typical horizontal (F_H) and vertical force (F_V) ground reaction components and their ratio, F_H/F_V, for one step (right foot). Critical from the slipping point of view are the heel contact (peaks 3 and 4) and the toe-off (peaks 5 and 6) phases (Grönqvist et al. 1989).

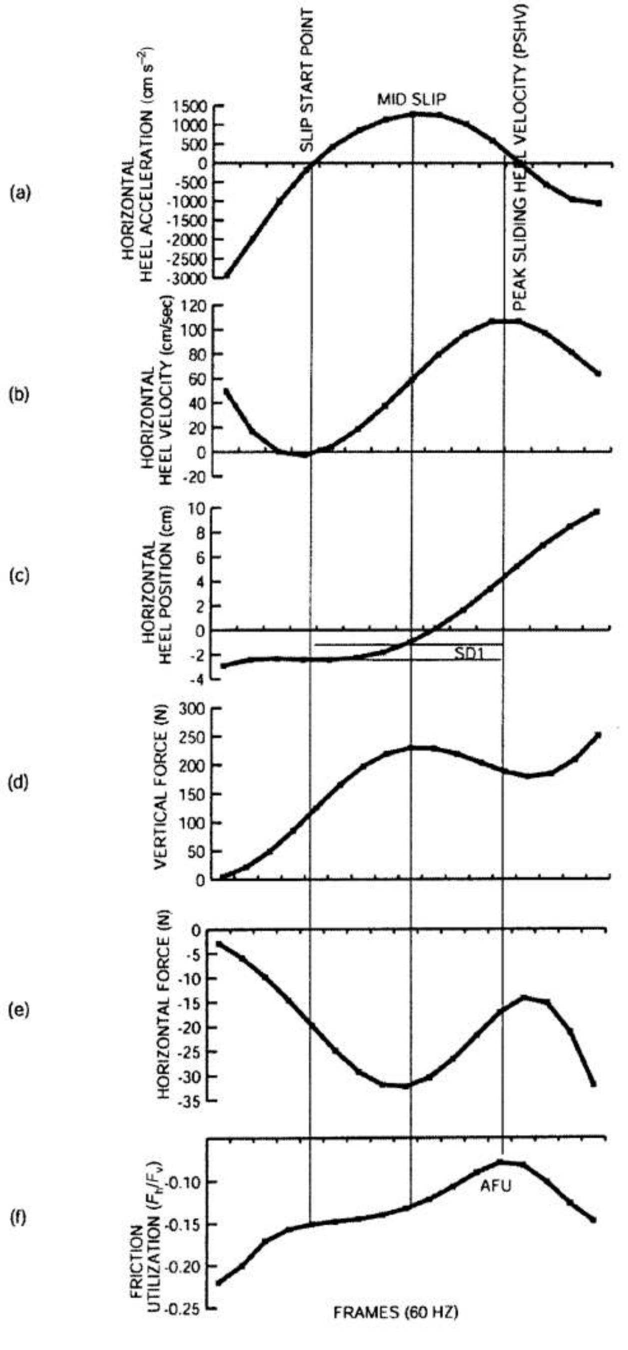

Figure 5.

Composite view of the heel dynamics (kinetics and kinematics) during a typical slip-grip response, including adjusted friction utilization (AFU) on an oily vinyl tile floor surface (Lockhart et al. 2000b).

Table 1

Viscosity of lubricant, average TFU and FFU, and falling frequency in psychophysical walking experiments on a continuously slippery triangular path covered with a smooth PVC floor (adpated from Strandberg 1985).

	Shoe types				
Parameters	**Bovinide & Studded**	**Bovinide & Studded**	**Astral & Bovinide & Studded**	**Bovinide & Studded**	**Astral & Bovinide & Studded**
Viscosity N s m^{-2}	0.001	0.01	0.01	0.2	0.2
Average TFU	0.300	0.205	0.203	0.093	0.078
Average FFU	0.331	0.250	0.248	0.099	0.087
Falling frequency	6	20	26	6	12

Average TFU=average time-based friction utilization during five laps of the triangular path;

Average FFU=average force plate-based friction utilization during one step in the 90° corner of the triangular path.