# Biomechanics of Human Gait – Slip and Fall Analysis

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## Glossary

**Friction demand ($m_d$)** Friction demand ($m_d$) is a ratio between horizontal and vertical ground reaction forces during the heel contact phase of the gait cycle. It represents the overall requirement for the foot to not slip significantly.

In order to analyze the principles of body stability and the mechanism of slips and falls, it is necessary to understand the dynamic principles of human locomotion. In this article, the biomechanics of human gait is presented to elaborate on the 'human' aspects of slip and fall accidents. This information may provide a comprehensive tool for forensic scientists to better understand the relationship between the 'biomechanics of human gait' and 'slip and fall accidents' and may assist in formulating cogent expert opinions.

## Biomechanics of Human Gait

The purpose of this section is to assist in the understanding of the gait mechanisms involved in walking, which reflect the dynamic principles of each body segment in locomotion that are relevant for investigating slip and fall accidents. The purpose is also to describe the motor control strategies associated with walking to reveal the complex aspects of initiating events leading to fall accidents and its relationship to posture and balance in human gait. Understanding the motor control strategies associated with walking may provide us with information relevant to decouple the system into identifiable pieces for the scientific reconstruction of accidents. Here, we begin with some basic concepts in human gait.

Locomotion, an inclusive characteristic of all animals, is defined as the process by which an animal moves itself from one location to another. Walking is characterized as a method of locomotion involving the alternate use of the two legs to provide both support and propulsion. Finally, 'gait' can be described as the mannerism or style of an individual's walking pattern. Human locomotion falls into a general category known as 'striding bipedalism,' a locomotion activity in which the center of gravity is carried alternately over the right and left foot. Normal walking depends on a series of reciprocal movements involving the alternation of the function of each leg between supporting the body and advancing into the next position. These complex tasks are governed by open- and closed-loop motor control systems.

The mechanical definition of human walking and especially the function of gait may help us to better understand human locomotor control. In essence, the main purpose of walking is to transport the body safely and efficiently across the terrain. In order to do so, five major functions of gait must be performed during each step: (1) maintaining upper and lower limb support (such as preventing collapse of the leg during stance phase of the gait cycle), (2) maintaining upright posture and balance of the body, (3) foot trajectory control (such as acquiring safe ground clearance and heel contact), (4) mechanical energy generation to maintain or increase forward body speed, and (5) mechanical energy absorption to decrease forward speed of the body. All of these major functions must be performed within the biomechanical constraints of the body and the physical constraints of the environment. Additionally, the central nervous system (CNS) must also integrate efferent feedback from sensory organs to generate the correct patterns of moments of force at each joint to compare and represent the internal model against the real-world interactions.

### Body Segments in Locomotion

Apart from the multiple variations that may occur between different individuals or within the same individual (for instance, as a result of changes in the speed of walking), there are certain observable events that are shared by all. This is because the mastering of the erect bipedal type of locomotion is a learned process and associated with certain personal peculiarities superimposed on the basic pattern of erect bipedal locomotion. In the following subsections, the process of walking in terms of body segments (i.e., lower and upper extremities) in locomotion is further reviewed.

Lower Extremities: Gait has been studied using the 'walking cycle,' which is the time interval between successive floor contacts of each foot. The activity of one leg can be divided into a short swing phase and a longer stance phase.

The stance phase occurs when the foot is in contact with the floor (starting at heel contact (passive) and ending at toe-off (propulsive)) and the swing phase occurs when the foot is advancing forward to take the next step (Figure 1). During each walking cycle, there are two periods of single-limb support and two brief periods of double-limb support (while one limb is about to begin the swing phase and while the other has just ended the swing phase).

Forward walking is achieved by pushing off the stance leg while swinging the other leg forward. At the time of the heel contact phase of the gait cycle, the forward-moving heel contacts the ground and as the limb is kept relatively straight, deceleration of the foot converts to acceleration of the hip. During this phase, the hip and knee extend. Continued forward motion of the body results in the forefoot coming to the ground, and the propulsive part of the support phase begins. At this phase (the muscles plantar flex the foot, flex the knee, and extend the hip), the heel is raised and pushes the foot

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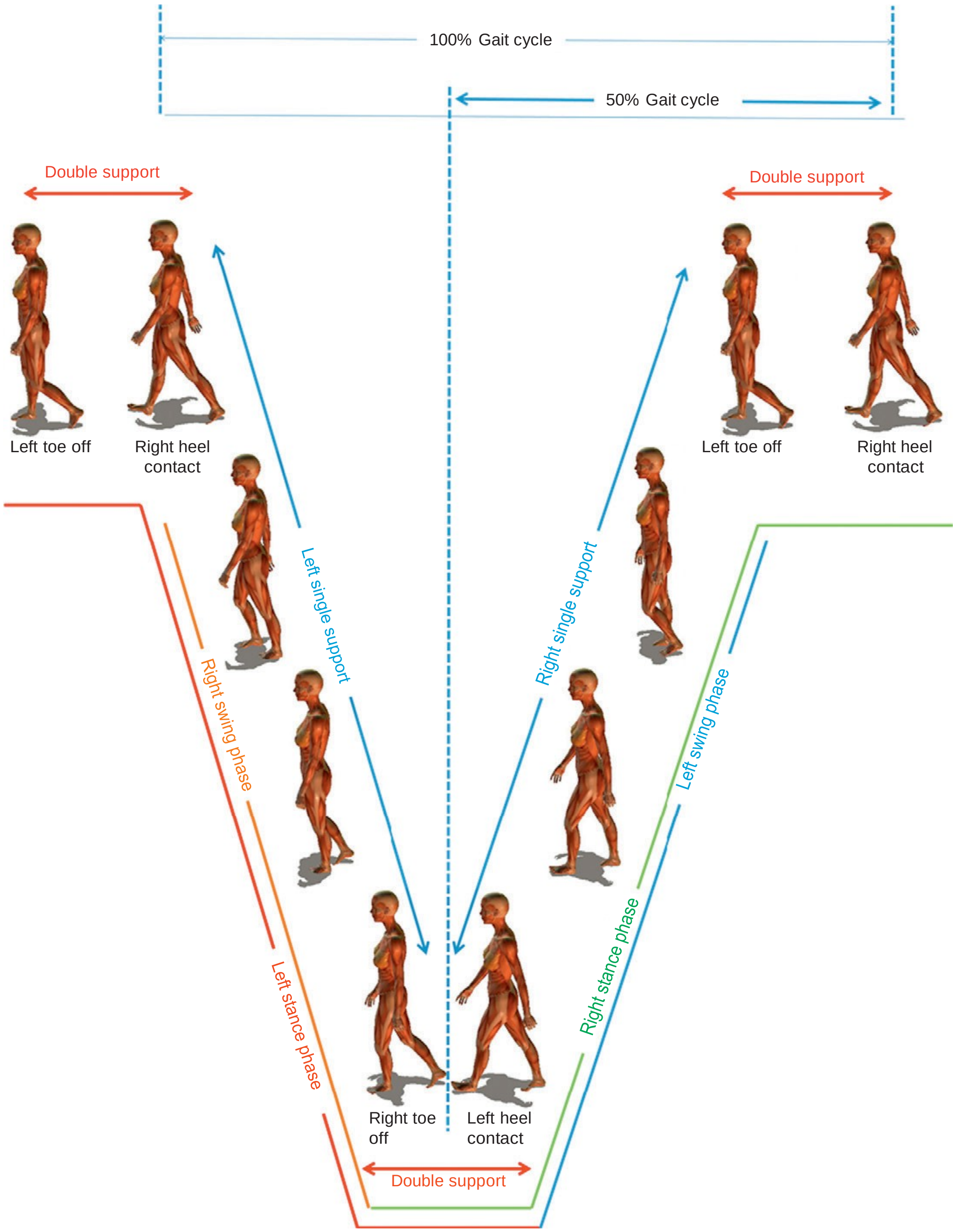


Figure 1 The time dimensions of walking cycle.

backward. This is associated with fixation and elevation of the pelvis by the abductors as well as tilting of the body toward the swing leg that allows it to land in a line anterior to the stance leg. The backward (propulsion) force is resisted by friction under the sole.

During the swing phase, the leg is flexed and slightly rotated externally at the hip, flexed at the knee, and dorsiflexed at the foot. Throughout the remainder of the swing phase, the limbs move under the influence of gravity alone, and finish in a position which allows direct entry into the next step.

Heel Velocity: An important lower extremity variable such as heel velocity during walking provides a linkage between motor control and slip severity as the control of the foot during swing is essentially a ballistic and positional task. Horizontal velocity builds up gradually after heel-off and reaches a maximum velocity late in the swing phase and drops rapidly to near zero just prior to heel contact.

The vertical trajectory during the mid- and late swing phases drops rapidly, but, just before the heel contact event (based upon the stride period), the vertical drop is arrested about 1 cm above the ground level. During the last 10% of swing, the heel is lowered very gently to the ground as horizontal velocity decreases rapidly to near zero. Figure 2 shows the body kinematics at HC for a typical trial. It can be seen that the forward velocity of the body's center of gravity was 1.6 m $s^{-1}$ and the heel velocity was reduced to 0.4 m $s^{-1}$ horizontally and a mere 0.05 m $s^{-1}$ vertically.

The significance of the heel velocity before the HC is that at the end of the swing phase, the heel velocity must be reduced sufficiently so that a dangerous slip will not occur. Walking speed influences heel contact velocity, that is, faster walking speed will increase the contact velocity. In order to reduce the forward velocity of the foot prior to heel contact, the foot is slowed through earlier and/or increased activation of the hamstring muscles. These muscles become active at the termination of swing phase by elongating as they act to decelerate the swinging leg (this is a very effective use of muscle). Decelerating the swinging leg at an appropriate time requires attentional resources via sensory modality.

Upper Extremities: Corrective postural movements are made by the upper body, arms, and shoulder. In walking, arm swing is used to offset some of the rhythmical acceleration and deceleration of the trunk by the leg movements, and also to damp out the rotational forces on the trunk. The arm swing varies considerably with variation in the speed of the walk. In the unladen state, the arm swings forward from the shoulder with the arms hanging more or less relaxed in a sagittal plane, but may move slightly toward medial plane. In the laden state, however, these dampening effects are not available. Load carrying (in front) also displaces the body center of mass (COM) anteriorly, placing it closer to the forward edge of the supporting base, thus requiring additional rotational torque at the foot–ground contact. Increasing the rotational torque during heel contact phase of the gait may increase the friction demand and increase slip severity. Additionally, blocking the visual path with a load may further influence the awareness of an impending slip perturbation.

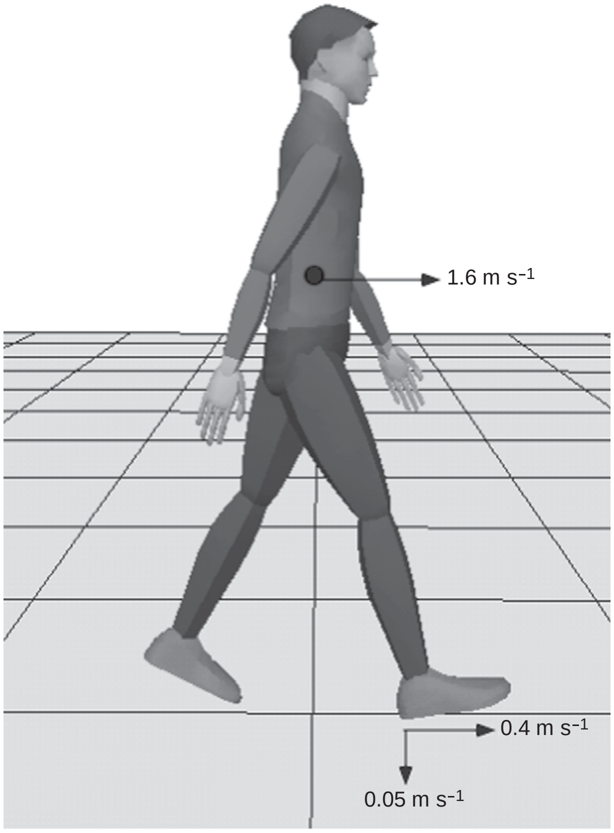


Figure 2 Body kinematics at HC for a typical walking trial. Adapted from Winter DA (1991) Biomechanics and Motor Control of Human Movement. New York, NY: John Wiley & Sons Inc.

## Ground Reaction Force

The mechanics and the forces involved in slipping are important in understanding fall accidents. The forces applied by the foot to the floor at the point of foot–floor contact act in three directions: vertical ($F_v$), horizontal ($F_H$) in the direction of body motion, and horizontal transverse ($F_T$) to the direction of body motion. Note that by Newton's third law, the ground reaction forces exerted by the floor on the foot are equal and opposite to the forces exerted by the foot on the floor. During heel contact, there is a resultant forward thrust component of force on the swing foot against the floor. This results in anterior/posterior shearing forces ($F_H$) acting at the foot–floor interface. Walking speed, which is the product of cadence and step length, affects the magnitude of forward horizontal force ($F_H$). Forward horizontal force ($F_H$) increases with increasing step length and cadence; however, the effects of cadence are more pronounced than those of the step length.

Lateral-transverse force ($F_T$) is the result of the lateral momentum during the gait. This lateral momentum exists due to an out-toeing walking pattern. However, the force component $F_T$ can be ignored in normal level walking due to the relatively small transverse forces compared to the other ground reaction force components observed in locomotion experiments.

Vertical force ($F_v$) is the result of the body weight and the downward momentum of the swing leg against the ground during heel contact. Vertical force ($F_v$) is affected by walking speed and cadence, which, as previously stated, has a more pronounced effect than step length.

Required coefficient of friction (RCOF): The required dynamic coefficient of friction (DCOF) represents the minimum (dynamic) coefficient of friction (COF) that must be available at the shoe–floor interface to prevent forward slipping at heel contact. Perkins used a force platform to measure the horizontal ($F_H$) and vertical ($F_v$) components of the force exerted between the shoe and the ground during normal walking. An analog divider calculated the ratio of horizontal to vertical forces ($F_H/F_v$) and displayed this on an oscillograph as a function of time (Figure 3).

Perkins found six peak forces in the normal gait cycle. The first four peaks occurred during the landing phase and the remaining two peaks occurred during the takeoff phase. Peaks 1, 3, and 4 are caused by a forward force, whereas peaks 2, 5, and 6 are caused by a backward force on the force platform.

Peak 1 is caused by the force of impact of the heel tip against the force platform and has a forward direction as a result of the approach angle of the heel to the ground.

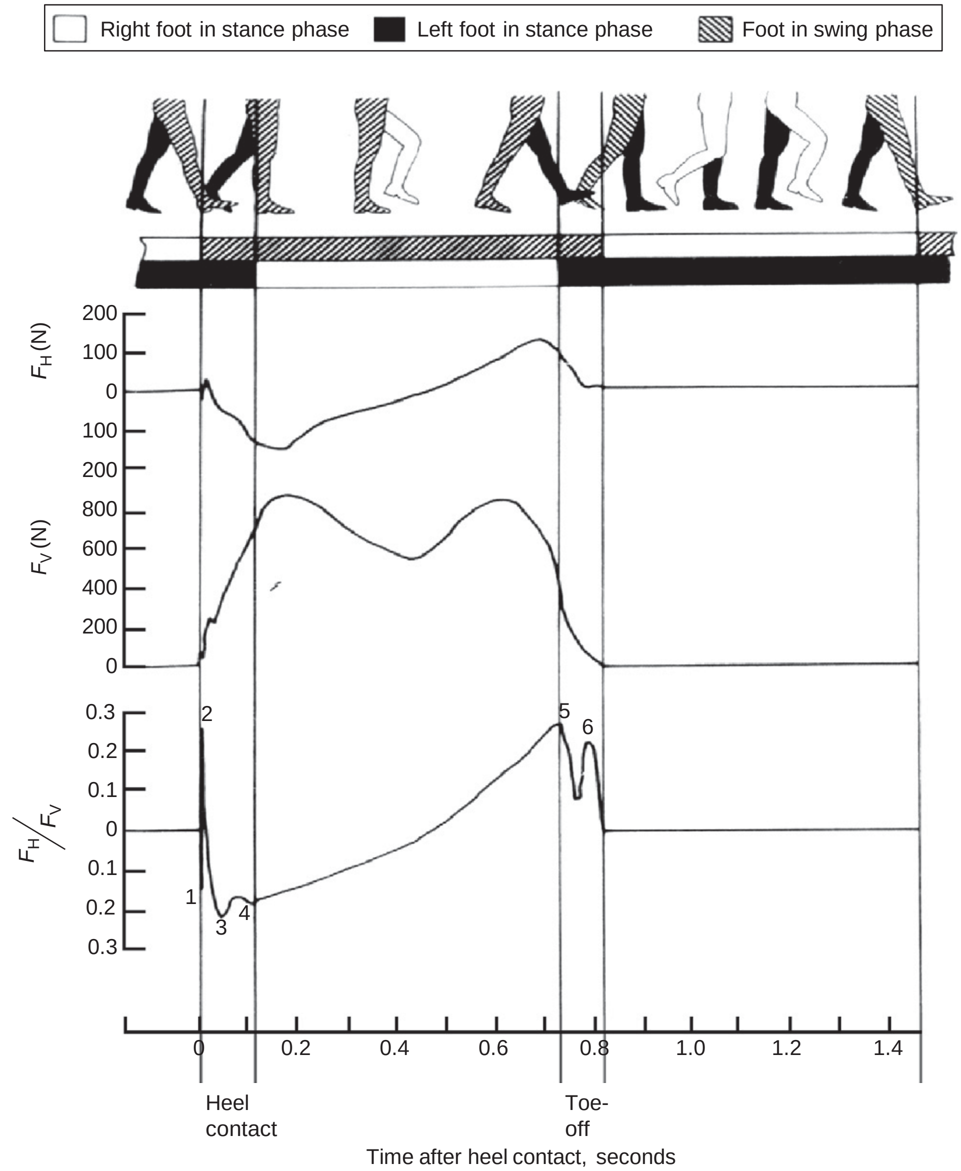


Figure 3 Gait phases in normal level walking with typical horizontal, vertical, and their ratio for one step. Reproduced from Gronqvist R, Roine J, Jarvinen E, and Korhonen E (1989) An apparatus and a method for determining the slip resistance of shoes and floors by simulation of human foot motions. Ergonomics 32(8): 979–995.

However, this peak has been found to be inconsistent due to low vertical force during this phase (peak 1).

Peak 2 is caused by a backward force exerted on the heel of the shoe shortly after contact. This force has been noted by several investigators but no reason for its existence has been suggested.

Peaks 3 and 4 are caused by the main forward force which retards the motion of the body and leg. During peaks 3 and 4, the vertical force has risen and a significant proportion of the body weight is being applied through the heel tip (less than 0.1 s after heel contact). Therefore, the error in $F_H/F_v$ ratio is relatively small. As more of the body weight is progressively transferred to the contacting foot, the center of gravity of the body moves over the now stationary foot and the forward force causing peak 4 decreases. During the takeoff phase, the $F_H/F_v$ (again) increases due to the force (peaks 5 and 6) exerted by the foot propelling the body forward. The significance of the ratio ($F_H/F_v$) is that it indicates where in the walking step a slip is most likely to occur. If the magnitude of $F_H/F_v$ exceeds the COF between the two surfaces at a particular moment in time, a slip will occur. In this view, there are two critical gait phases in normal level walking from the viewpoint of slipping: (1) shortly after the heel contact, when only the back edge of the heel is in contact with the ground (peaks 3 and 4 in Figure 3). Peaks 1 and 2 are not considered hazardous because $F_v$ is quite small at peak 1 and because $F_H$ is directed backward at peak 2. (2) At the moment of toe-off, when only the forepart of the shoe is in contact with the ground (peaks 5 and 6 in Figure 3) – here, the required static COF demand is important to thrust the body forward. Theoretically, forward slip at peaks

3 and 4 during landing is more hazardous since the forward momentum of the body will continue to apply the body weight on the slipping foot. Conversely, backward slip at peaks 5 and 6 is less likely to be hazardous, as most of the body weight has been transferred forward from the slipping foot to the opposite leading foot. Backward slip at peak 2 shortly after landing appears to be hazardous, but the likelihood of slip continuing in a backward direction is less as the force rapidly changes direction.

## Static Versus Dynamic COF (Tactile)

Tisserand found that rank-order correlation with subjective judgments of slip resistance was negligible for static COF measurements and very high for dynamic COF measurements. Additionally, Harris and Shaw found a high correlation between (walker's) opinions of slipperiness and the kinetic friction of wet floors. Their results are in close agreement with Strandberg and Lanshammar's walking experiments demonstrating that kinetic friction values, measured with sufficient sliding velocity, correlated better with the actual risk of falling than low-speed kinetic friction values or static friction values. Another study by Swensen et al. compared the perceived slipperiness of steel beams by both professional ironworkers and students. They were asked to rate and rank the slipperiness of each beam that was either uncoated or coated with contaminants (water, clay, and oil) after walking across the beams. The results of this study indicated that there is a strong correlation between dynamic COF values and subjective ratings of floor slipperiness. Figure 4 shows the result of a series of experiments using ten subjects and five different shoes. The mean subjective ranking and the ranking using the dynamic COF are very similar.

## Visual Versus Tactile Sensation

Cohen and Cohen further explored the perceptual and cognitive factors involved in the perception of floor tile surface slipperiness. The results of this study also demonstrated that tactile cues are most sensitive to physical measurement of dynamic COF. A follow-up field study of the psychophysical assessment of the perceived slipperiness of floor tile surfaces concluded that people tended to make predictions about the slipperiness of walking surfaces and verified these expectations as they crossed them. The results suggest that visual cues to slipperiness are inferior to tactile sensation. They also suggested that in real-world conditions, the perception of walking surface slipperiness is probably the result of tactile cues, with visual impressions being confirmatory. Thus, in unfamiliar conditions, people may rely on the primary but inferior visual information about a surface's traction until they actually walk on it. The potential for an accident can be created due to misjudgment of slipperiness based on initial visual sensing and the limited time available to make immediate adjustments in gait to accommodate for the hazardous condition.

## Slip Resistance Measuring Devices

Many devices have been developed by individuals, organizations, and federal agencies (e.g., OSHA, NIOSH, and NBS) to quantify the slip resistance of floor surfaces (i.e., COF). At least 70 different meters have been cited in the literature; however, none of these devices are universally accepted. In general, most devices fall into three categories: drag/towed-sled, pendulum, and articulated strut types.

There are two approaches to measuring friction. In the direct approach, the test device measures or indicates the horizontal and vertical forces. These include drag-type meters and articulated strut devices. The indirect approach calculates the frictional force by observing an energy loss in the test device. The most common example of the indirect approach is a pendulum-type device. These devices are limited in their ability to simulate biomechanical factors for an accurate DCOF measurement.

Strandberg and Lanshammar stated that on the basis of tribology and biomechanical analysis of slips and falls, the slip-resistance meter should reproduce the following operating variables from crucial gait phases: (a) contact time and normal

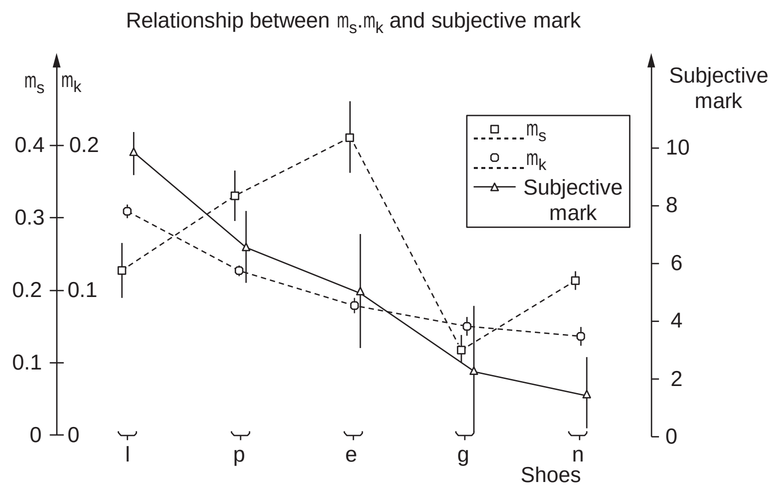


Figure 4 Comparison of mean subjective ranking by ten subjects and ranking using static and dynamic COF for five shoes. Subjective binary choice test. Reproduced from Tisserand M (1985) Progress in the prevention of falls caused by slipping. Ergonomics 28(7): 1027–1042.

force time derivative, for the influence of surface patterning and its drainage capability; (b) foot angle, for testing the most critical part of the shoe; (c) contact force application point at the shoe; (d) vertical force, for correct pressure in the contact area; and (e) sliding velocity, for correct dynamic friction forces.

The versatility of different meters has been compared and commented on by many investigators. Due to its heavy weight and bulkiness, the James Machine can be used only in a controlled laboratory situation for testing sample floor material, not the actual floor. The NBS-Brungraber Tester, on the other hand, is easier to handle and can be considered as a portable James Machine. The Tortus provides a permanent trace record when connected to a chart recorder, whereas most devices provide only a visual reading of the peak COF (analogy meter or gauge). However, drag-type devices have overcome most limitations and generally met with the greatest acceptance among both researchers and practitioners. The BOT 3000 digital tribometer can also provide both static and dynamic COF measures.

## Trajectory of the Total Body Center of Gravity

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

In the standing position, the center of gravity is situated centrally in the pelvis, approximately at the level of the second sacral vertebra. However, during forward walking, the equilibrium is lost with the takeoff of the propelling foot when the body's center of gravity momentarily lies beyond the anterior border of the supporting surface, and regained as soon as the swinging leg is extended forward and the heel touches the ground. Additionally, the legs move forward and backward relative to the trunk (torso), the arms swing, and the trunk moves up and down and from side to side during locomotion. Consequently, the center of gravity progresses forward and at the same time moves up and down and from side to side.

In normal level walking, the center of gravity describes a smooth sinusoidal curve when projected on the plane of progression (Figure 4). The path curve of the common center of gravity in the sagittal plane moves up and down. This motion is sinusoidal, with a period of approximately 50 mm in extent for adult males at normal walking speed. The summits occur at the middle of the stance phase of each side and the lowest points occur during double support when both feet are on the ground (Figure 5). At the peak of vertical movement, the horizontal velocity reaches a minimum (maximum acceleration). Conversely, the reverse is true at the time of lowest trajectory. The magnitude of the vertical excursion during free-cadence walking correlated significantly with the length of the stride and the peak-to-peak vertical oscillation increased as cadence increased.

In the frontal plane, the common center of gravity moves from left to right as each leg alternately becomes weight bearing. It follows a smooth sinusoidal curve, but with only one oscillation per stride as opposed to the two vertical oscillations in the sagittal plane (Figure 6). The center of gravity attains its greatest distance from the midline shortly after the support of the standing leg is shifted to the whole sole. At this point, there is an inversion of motion (the velocity is zero and the acceleration is maximal). Afterward, the center of gravity follows the period of double support and the velocity increases as the center of gravity again approaches the midline.

Shimba and MacKinnon reported that the lateral path of the center of gravity passes forward along the medial border of the foot (sometimes slightly outside that border: ±2 cm; Figure 7). The lateral movements represent automatic postural adjustments, shifting the line of gravity alternately toward the eccentrically placed bases of support in keeping with the demands of stability.

In the transverse plane, the center of gravity carries out forward and backward movements (U shape). In this plane,

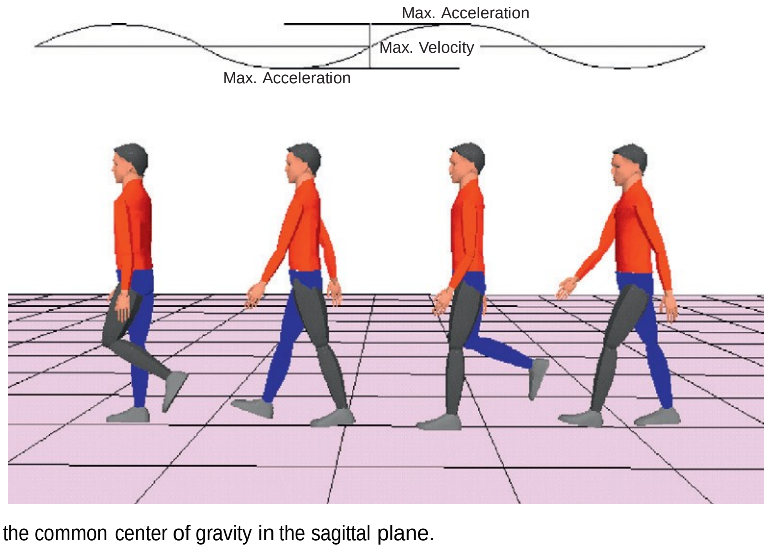


Figure 5 The path curve of the common center of gravity in the sagittal plane.

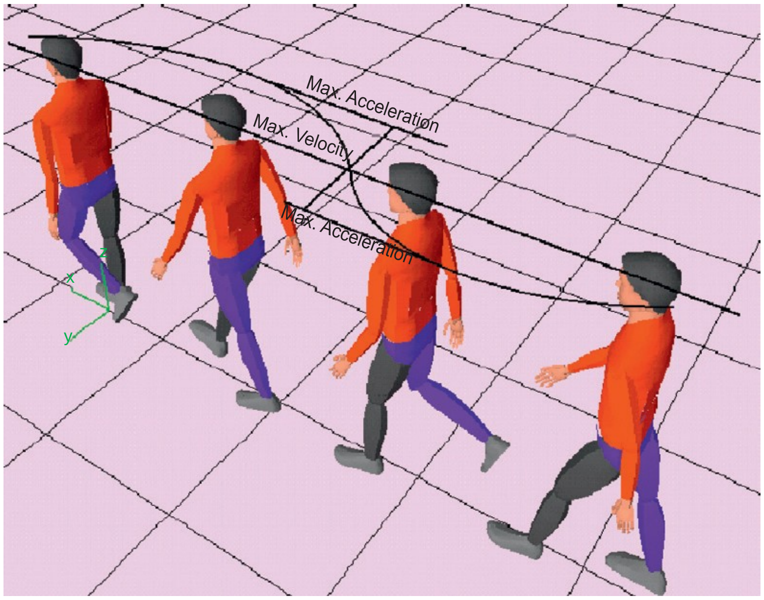


Figure 6 The path of the common center of gravity in the frontal plane.

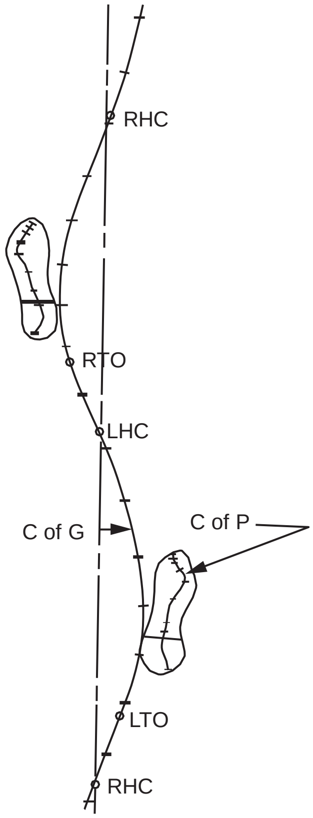


Figure 7 Lateral pathway of center of gravity passing forward along the medial border of the foot. Reproduced from MacKinnon CM (1990) Control of Whole Body Balance and Posture in the Frontal Plane During Human Walking. University of Waterloo.

the center of gravity moves forward commensurably with the movements of the pelvis. The maximum forward point is reached as the heel is set to the ground and the maximum backward movement occurs at the takeoff phase of the gait. The amplitude of these backward and forward oscillations is about 12 mm.

## Balancing the Center of Gravity of the Human Body

Achievement of even sinusoidal displacements depends on smoothly coordinated angular displacements of the various segments of the lower limb. Various investigators used a series of simple models to illustrate how this smooth sinusoidal displacement pathway is achieved in bipedal locomotion. They show that this type of locomotion requires that the center of gravity be elevated to a height equal to the center of gravity in the standing position. Thus, it will result in a severe jolt at the point of interaction of each two arcs where there is an abrupt change in the direction of movement of the center of gravity. As such, decreasing the total elevation, depressing the center of gravity, and smoothing the series of interrupted arcs require coordinated movements involving all the joints of the lower extremities.

The balance of the human body or its parts requires that all gravitational forces be completely neutralized by counter-forces. These counter-forces are supplied by the resistance of the supporting surface of the body. However, when gravitational forces fall outside of the supporting surfaces, the translatory force of gravity is not neutralized. In order to neutralize the rotatory forces, the line of COG must also fall in the supporting surface. In general, two factors influence stability: (1) the broader the supporting area (area over which one object is supported by another; in the standing position, the base of support of the human body is the area bounded by the contact points of the feet with the floor) the greater is the force necessary to destroy the balance by throwing the line of COG beyond the supporting surface and (2) the lower the center of gravity is located, the greater is the arc that an unbalancing force must describe before it can bring the center to fall outside the supporting area (i.e., more stable). In the human body, the constant mass is supported in standing on a small base.

Additionally, the area of the base and the position of the center of gravity are subject to constant and rapid changes and, therefore, require a complex reflex system involving the integration of sensory nerves and the motor nerves controlling the muscles to maintain balance in any given posture of the body. The deviation of the center of gravity is constantly monitored by

1. Sensory mechanoreceptors in the capsules and ligaments of joints, which provide information about their position and rate of movement.
2. Stretch receptors in muscles (muscle spindles), which give information on the amount and rate of muscle stretching.
3. Pressure receptors (exteroceptors) in the skin, which provide information about the amount of pressure on the skin of the soles of the feet.
4. The vestibular apparatus, including the semicircular canals found in the inner ear within the temporal bone of the skull, gives information of the motion of the head in all planes.
5. The visual system giving information about the position of the body in relation to objects and surfaces that can be seen.

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

Balance Task of Walking versus Standing: Human bipedal locomotion (walking) provides a challenging balance task to the CNS and appears to be completely different from the balance task during standing. During standing, the CNS is challenged to keep the body's center of gravity safely within the borders of the two feet (or one foot if balancing on one foot). Studies of balance and posture during quiet or perturbed standing have identified the ankle muscles (plantarflexors/dorsiflexors and invertors/evertors) as dominant. However, during locomotion, ankle muscles are no longer important because the balance task has changed. As explained in the last section (Lateral Oscillations of the COG), the lateral path of the center of gravity passes forward along the medial border of the foot (even slightly outside that border). Thus, during single support, the body is in a continuous state of falling down because the its center of gravity is outside the foot. The only way that recovery is achieved is to position the swing limb so that during double support the CNS can make any rebalancing adjustments.

Gait Model: This recovery is a challenging balance task that requires a complex interplay of neural and motor control mechanisms. Motor control is directly linked to the CNS's processing of sensory inputs (vision, vestibular, and proprioceptive systems). The brain constructs internal representations of the world by integrating information from the different sensory systems. In other words, the transformation from sensory signals to motor commands is processed within the CNS. The motor system transforms neural information into physical energy by transmitted commands from the brain stem and spinal cord to skeletal muscles. A system model that mimics the behavior of a natural process is known as an internal model, an important theoretical concept in motor control. The internal models include two main components: inverse model and forward model. An inverse model functions as a motor command computation to calculate the desired states. A forward model acts as a predictor to estimate the next state (e.g., future position and velocity). The sensory systems send inputs to an online controller to make an adjustment in real time. In essence, we use the inverse model to modify our walking behavior; that is, walking off the sidewalk to cross the street and stepping back onto the curb requires online controller. Additionally, the internal model is used to predict, and adapt to, the next step (i.e., forward model); thus, we are able feel momentum changes, for example, when walking onto a broken escalator. The importance of understanding the gait model above is to provide a better understanding of the processes associated with slips and falls. Here, it is clear that 'EXPECTANCY' is required to walk – that is, during walking, we expect the ground to be stable and, as such, we modify our gait to traverse the terrain with appropriate force and speed to safely ambulate; however, if the ground is not stable, there will be a motion perturbation (i.e., expectancy and reality did not match). This perturbation, if not controlled, could lead to slips and falls.

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

The process of slips and falls can be categorized into four levels as shown in Figure 8. The environmental phase considers the effects of contamination. As noted by Chaffin et al., 'any fluid

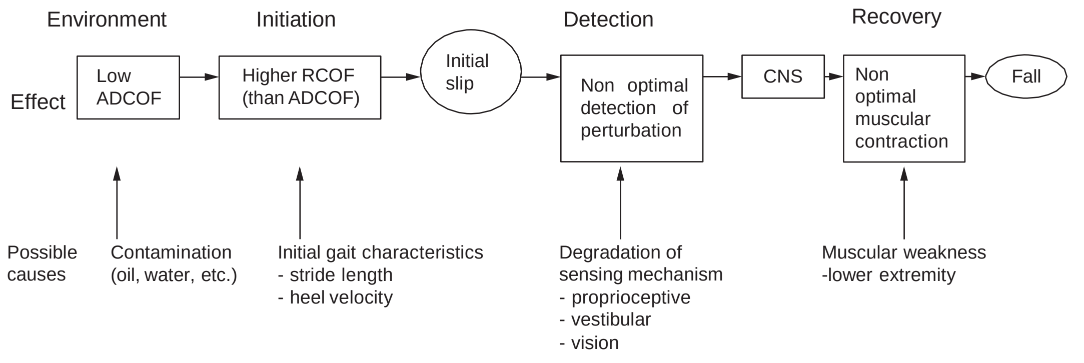


Figure 8 The process of initiation, detection, and recovery of inadvertent slips and falls with possible causes and effects. Reproduced from Lockhart TE, Woldstad J, and Smith J (2003) Effects of age-related gait changes on the biomechanics of slips and falls. Ergonomics 46(12): 1136–1160.

contaminant between two sliding surfaces will provide lubrication and thereby lower the DCOF values.' Therefore, the presence of contamination (oil, water, etc.) will reduce the available DCOF of the floor surfaces. In terms of slip-induced falls, friction demand characteristics between the shoe sole surface and the floor surface has been implicated as an important predictor variable related to severity of falls. It was stated that most of slip-induced falls occurred when the frictional force ($F_m$) opposing the direction of foot movement is less than the horizontal shear force ($F_h$) of the foot immediately after the heel contact on the floor. The RCOF is defined as the ratio of horizontal ground reaction force to vertical ground reaction force. It represents the minimum RCOF between the shoe and floor interface to prevent slipping. Consequently, slip is initiated by the combination of lower DCOF and higher RCOF. A static COF of 0.5 on a level walking surface has been commonly recommended by standard organizations and by individual authors. Dangerous forward slips that lead to falls are most likely to occur 70–120 ms after the heel contacts the ground.

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

During the detection and recovery phases of the slip and fall process, the CNS control plays an important role. The CNS must undertake certain processing stages (detection phase) if a fall is to be avoided or compensated for (recovery phase). During the detection phase, a trigger must be sent through the sensory feedback to the motor control regions of the CNS. This process may be initiated by one or more of the following sensory inputs: somatosensors, vision, and vestibular function. At the input stage, any disruption in the quality of the input signal may increase the likelihood of slips and falls. The somatosensors are responsible for proprioception, the sensing of joint and limb motion. The vestibular organs located at the inner ear (semicircular canals and otoliths) detect angular velocity of the head and act as linear accelerometers. Visual cues provide information about the position and motion of the head with respect to surroundings. In the case of posture control, the relevant signals are processed by motion detection circuitry not only in the retina but also in the visual cortex. These sensory signals are fed back to a series of hierarchical feedback loops to generate motor commands.

The reactive recovery phase involves bringing the body COM within stability limits quickly after a slip is initiated. This is achieved through changes in various kinematic, kinetic, and muscle coactivity mechanisms. One of the important mechanisms during reactive recovery is to reduce the displacement of the slipping foot through increased coactivity of the muscles of the lower extremity. Electromyography (EMG) recorded from the lower extremity showed an increased coactivation of the rectus femoris and hamstrings, along with the tibialis anterior and gastrocnemius muscles, while recovering from a slip. The postural responses generated by distal perturbed leg muscles are of short latencies (65–110 ms), significant magnitude (2–3 times higher than normal walking), and long duration (�150 ms). Numerous studies have linked slower muscle activation rates in older adults as an indicator of increased risk to slip-induced falls. Kim et al. found a decreased hamstring activation rate in older adults and related it to higher risks of slip-induced falls. The postural activity of bilateral leg and thigh muscles and the coordination between the two lower extremities were found to be key to reactive recovery balance control.

## An Example of an Expert Witness Report

In this section, opinions and basis for expert opinions will be further described using an example of a case involving a slip and fall accident. First, a general description of the accident is presented – usually, gathered information at this time is in the form of 'depositions' from various individuals involved either directly or indirectly in the accident. In addition to witness statements and/or discussions with the potential client, experts also inspect the area (either via photograph, video, or a visit to the accident site) in question and make measurements (e.g., COF, slope, and illumination).

Afterward, the opinion of the expert is presented using a variety of supporting materials linking human locomotor control and fall accidents. Here, we start with a general understanding of the accident at the time of a group's arrival at a restaurant.

### General understanding of the accident

On the afternoon of 26 October 2012, Mrs. AC visited the C's restaurant in Parkins, Texas, for a lunch after a salon visit with a church group. Mrs. AC and the church group members arrived at the restaurant in a van. It was raining steadily and heavily at the time of their arrival (to the restaurant). As such, the van was parked close to the entrance to accommodate for the rain. Mr. Priggs (Assistant Manager of the C's at that time) held the front door open as they were entering the restaurant. The first group of ladies entered the restaurant. When Cynthia (a member of the group who witnessed Mrs. AC's fall from the posterior view) and Mrs. AC entered the restaurant, they were among the last of the group to enter the restaurant.

Mrs. AC entered the restaurant and walked toward the end of the mat to look for the group. She located the group by identifying the 'backs of their heads.' She walked from the end of the last mat onto the exposed tile floor, where she slipped and fell to the left side of her body fracturing her pelvis. Mrs. AC was assisted by the restaurant employees until the ambulance transported her to the hospital.

### Opinion

The exposed tile floor surface between the 'mat' and the carpeted surface of the dining area at the C's restaurant at Parkins, TX, created an unreasonable hazard and risk of harm to pedestrians.

In order to maintain dynamic balance during locomotor activities and to help avoid slip-induced falls, gait parameters are adjusted to correct for contaminated or slippery conditions. In other words, when confronted with impending slip and fall situations, our walking style (i.e., the gait parameters) is adjusted accordingly to avoid slipping (note: online controller at work). Persons who have a prior knowledge of a contaminated walkway adjust their gait by reducing friction demand characteristics – for example, reducing heel contact velocity and step length by modifying the support leg's muscle stiffness. For younger individuals, this adaptation is quicker (within one step) than for older adults (at least two steps) – that is, it will take them at least one to two steps to adjust their gait to traverse even readily recognizable slippery floor surfaces. Mrs. AC is an older adult.

As indicated, the support leg is modified in muscle stiffness according to the walking conditions to progress the whole body smoothly without abrupt transition of friction demand. The ability to modify the muscle stiffness characteristic of our supporting leg (i.e., make rapid and adaptive adjustment of gait from walking on a nonslippery floor surface to a slippery floor surface) depends upon the quality of the user's perception of the surrounding environment. Hale and Glendon and Tisserand supported that a cognitive process occurs prior to action (locomotor activities) in order to safely traverse over slippery floor surfaces (i.e., online controller). The process starts with expectation – expecting the contaminant (i.e., water, grease, etc.) on the walkway, the area is surveyed (scanned) visually with appropriate thoroughness related to one's expectations. As such, the lack of obvious visual cues to elicit expectation can influence detection of slippery floor surfaces and modification of adaptive locomotor responses.

Furthermore, tactile cues to elicit expectation can also be important. Tisserand suggested that frictional values are estimated and memorized unconsciously from preceding steps (one's own model of slipperiness) and this information is updated whenever the subject feels the floor conditions are different from expected (reality) (note: adaptive controller). In the author's opinion, the cues necessary to correctly detect the prevailing slippery condition were neither obvious nor effective and resulted in a slip and fall accident. In other words, there were no obvious and effective cues to inform Mrs. AC that the exposed tile floor surface between the 'mat' and the carpeted surface was dangerously slippery and as a result Mrs. AC did not adjust her gait to compensate for the slippery floor surface.

Mrs. AC's expectation was influenced by several factors. Any visual cue that may distract a pedestrian's attention away from the slippery floor surface could be potentially dangerous. In this case, visual cues to distinguish the slippery floor surface were not available.

Furthermore, the assumption that the floor will be dry in the area where the fall occurred is lacking support. For example, in the case of heavy pedestrian traffic and heavy rain, water will accumulate on the mat and proceeding steps can track moisture onto the exposed tile floor surface making the floor surface very slippery. (Using a slip meter, the available (relevant) COF can be measured.) This statement is further supported by one of the witnesses to the accident – "The way I looked at it, the way that it even looked like this, I could see the skid [moisture trail] on the floor like her heel had hit instead of like the flatness of her foot." This statement further corroborates that not only was the tile floor surface wet, but Mrs. AC's gait was also not adjusted accordingly to walk on the slippery floor surface – that is, the usual gait characteristic associated with walking on a slippery floor surface is toe–heel gait to modify friction demand (more vertical ground reaction force than horizontal ground reaction force – as in walking on icy surfaces). In the author's opinion, effective tactile cues necessary for gait adjustment were also lacking.

As indicated above, tactile cues are import in eliciting protective response (i.e., gait adjustments) to walk on slippery floor surfaces. Frictional values are estimated, evaluated unconsciously from preceding steps, and updated readily to traverse the area safely. Walking on a slip-resistant mat first and then stepping onto a slippery surface may create a misperception leading to fall accidents. In other words, the slip-resistant mats provided a secure surface condition for normal walking with no need to modify gait (i.e., heel–toe gait) to traverse safely for Mrs. AC; however, when walking on a slippery surface with secure gait, her heel slipped, and she fell.

In summary, visual and tactile cues necessary to correctly detect the prevailing slippery condition (at the exposed tile floor surface between the 'mat' and the carpeted dining area) were not obvious and created an unreasonable hazard and risk of harm to Mrs. AC. In the author's opinion, the cues necessary to correctly detect the prevailing slippery condition were neither obvious nor effective and resulted in a slip and fall accident.

There are a number of measures that the C's restaurant could have taken to increase pedestrian expectation of slippery floor surfaces and/or reduce the likelihood of falls. One solution would have been to extend the mats covering the tile floor surface all the way to the carpeted area. This would have permitted Mrs. AC to get to the dining area without walking on the slippery tile floor surface. Warning signs such as 'Watch Your Step' and 'Caution – Wet Floor,' which are industry standards for hazardous floors, could have been posted (although warnings can be important, proper mats are the preferred safety measure). More probably than not, these measures would have prevented Mrs. AC's fall and injuries.

C's restaurant failed to institute reasonable measures to reduce the likelihood of falls and breached its duty to maintain its premises in a reasonably safe condition for patrons such as Mrs. AC.

In summary, although biomechanical aspects of gait and posture have been discussed in detail in this chapter, applicable codes and standards should also be referenced. As in all forensic investigations, careful and thorough investigations and analyses must be performed before scientifically credible expert opinions can be rendered.

See also: Engineering: Forensic Engineering/Accident Reconstruction/Biomechanics of Injury/Philosophy, Basic Theory, and Fundamentals; Human Factors Investigation and Analysis of Accidents and Incidents.

## Further Reading


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