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Friction Lock – "Falling Flat on One's Face"

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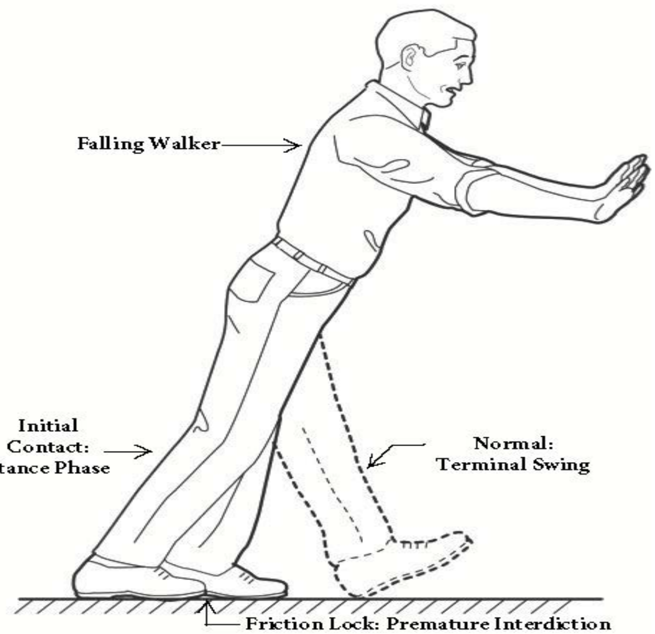
Figure 1: Friction Lock



Abstract

Normal ambulation and shuffling are both complex processes where a pedestrian is in a state of continuous forward falling. This is regularly interrupted when the walker's trailing leg is brought forward in a timely manner to prevent tumbling in the forward direction. Anything that blocks or sufficiently inhibits the swinging trailing leg leads to a subset of trip and fall onto one's face. In this paper, we call this unnamed phenomenon "Friction Lock." Here, premature interdiction of the trailing foot onto the walking surface at an arbitrary point in the gait cycle enables the walker to tumble onto a flat surface. Tripping proceeds without the usual "Change of Level" provided by visible asperities (stumbling blocks). In the shuffling mode where drag is present throughout the walking gait, premature transfer of the walker's full weight from the stationary forward leg onto the sliding rear leg gives rise to "Friction Lock" and its concomitant forward fall scenario. High levels of the coefficient of kinetic friction exacerbate the onset of "Friction Lock" which disproportionately affects senior citizens. Specialists in human ambulation are aware of the conundrum that low friction is counterproductive for slip and fall and high friction exacerbates the frequency of trip and fall; the problem is currently intractable.

Key words: Slip, Slip and Fall, Trip, Trip and Fall, Asperities, Change of Level

1. Introduction

Albert Einstein: "Make everything as simple as possible, but not simpler." This quote by Albert Einstein is apropos of the "Continuous Falling" model adopted in this paper to describe human ambulation. This model [1] is one of many that are evaluated in the classic book "Human Walking" edited by Jessica Rose and James G. Gamble in 2006 [2].

A. Conventional Forward Walking

Forward ambulation in a sagittal plane is a steady state process of continuous falling which is regularly interrupted by swinging the trailing leg and foot forward before the pedestrian tumbles to the surface. A person's sagittal plane is the medium plane from front to back. Human locomotion involves acceleration during startup, slowdown, steady movement, and maneuvers. Such accelerations give rise to tangential forces transferred from a walker's footwear to the walking surface. To accomplish desired ambulation, the tangential forces must be resisted by ground reaction forces. On uncontaminated dry floors, ground reaction forces are developed through friction.

The time-history of contact forces impressed by walking candidates during steady state straight level walking exercises is displayed in Figure 2 which was generated from two sources by Grönqvist, Roine, Jarvinen, and Kohjonen [3]. The top of the figure shows gait phases developed by Murphy [4] during normal level walking for one step with the right foot. What is not indicated is the fact that there is no slipping taking place between the footwear and the walking surface.

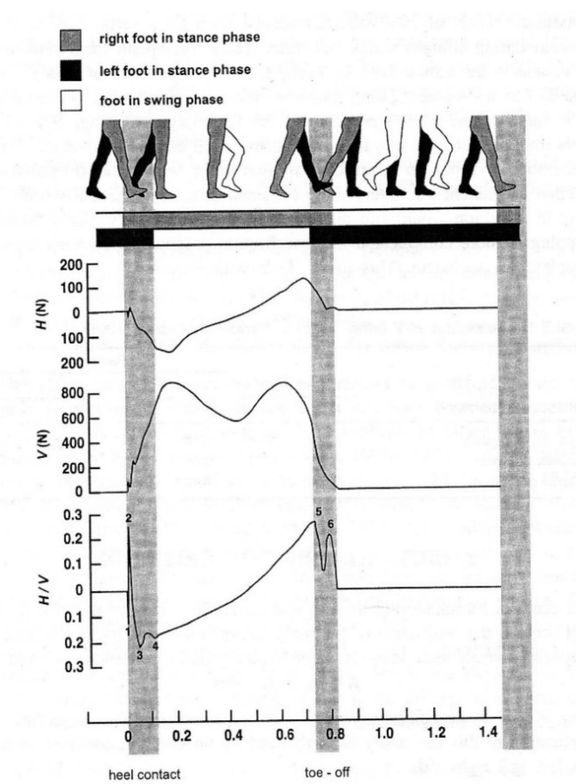


Figure 2. Time (sec.) After Heel Contact(s) [6]

The force-time diagrams depicted in Figure 2 were obtained by Perkins [5]. Curves are shown for the horizontal component of force H, the vertical force component V, and their ratio H/V. The horizontal component of force applied by the foot to the floor is opposed by the static coefficient of friction between the two, μ_S. At the point of incipient slipping H = μ_SV. Thus, if the ratio H/V is not as great as μ_S, slipping will not occur. The development of a modern stochastic slip and fall theory has been based on Figure 2 by Barnett [6], "Slip and Fall" Theory – Extreme Order Statistics.

B. Conventional Forward Shuffling

A pure shuffling gait requires that both feet constantly contact the support surface. Forward ambulation involves continuous falling regularly interrupted by shuffling the trailing leg forward before the pedestrian topples onto the surface. Locomotion proceeds by sliding one's footwear from one static position to another static position. When the trailing leg begins to slide forward to interrupt the falling motion of the pedestrian, only a small frictional resistance must be overcome because the bulk of the walker's weight is supported by the leading leg. To stop the swinging rear leg, the walker's autonomous nervous system transfers most of the walker's weight to the sliding leg and shoe which abruptly terminates the sliding. The body selects a static position for the trailing leg that both prevents falling and allows the ambulation process to continue. The body's muscle memory provides different static positions that depend on the step length and cadence (number of steps per unit time).

2. "Change of Level"

A. Background

A perfect walking surface is normally depicted as a horizontal plane. Convex protrusions from such a surface are characterized as <u>trip and fall</u> hazards because they have the potential of blocking or impeding the motion of a pedestrian's swinging leg which may cause a stumble, a trip, and perhaps a fall. To minimize the effect of these obstructions, safety practitioners have embraced two general strategies. The first is to eliminate stumbling blocks when this is possible, to demarcate them with movable barriers, or to warn about their existence. The second strategy is to modify the pedestrian's footwear, reconfigure the leading-edge geometry of protrusions, or adopt safer walking strategies.

With respect to footwear, one can lower the coefficient of friction of the soles and provide a ski-nose geometry (toe spring) at the front of the shoes [7-11]. The standards referenced in this section of the paper offer suggestions for constraining the height and streamlining the profiles of all visible stumbling blocks. Safe walking strategies are studied extensively under the appellations "ground clearance" and "toe clearance" [12, 13].

Tripping mitigation presents an interesting trade-off in cases involving floor mats, runners, and carpets. These items are often specified for the control of "slip and fall" excursions which are generally more dangerous than "trip and fall" accidents which occur less frequently. High friction mitigates "slip and fall," low friction favors "trip and fall."

Floor hardware such as thresholds, caps, and ADA compliant ramps are products that present rigid obstructions to a pedestrian by a "Change of Level" in a horizontal walkway. The technical term, "Change of Level" also applies to adjacent sidewalk slabs that are set at different elevations. The early '90s saw the introduction of consensus standards covering "Change of Level" that were uniformly adopted by the leading US safety organizations, e.g.,

1. ADA…Department of Justice
2. ICC…International Code Council
3. ASTM…ASTM International (American Society for Testing and Materials)
4. NFPA…National Fire Protection Association
5. ANSI…American National Standards Institute

Each of these organizations have endorsed the identical safety specifications in spite of fundamental differences in their scope and point of view. The ADA, which is administered by the US Department of Justice is focused on the rights of disabled citizens to accessible ambulatory facilities. Practical safety solutions for the construction of accessible and usable buildings and facilities are the thrust of building code standards developed and administered by the International Code Council. Fundamental research on slip, trip, misstep, and fall technology is a principal preoccupation of ASTM. The NFPA is concerned with rapid egress of personnel during a fire emergency. Finally, ANSI is the largest developer of safety consensus standards in the US.

A typical presentation of the "Change in Level" rules may be taken from the ICC/ANSI A117.1-1998 [14],

303 Changes in Level

303.1 General. Changes in level in floor or ground surfaces shall comply with Section 303.

303.2 Vertical. Changes in level of 1/4 inch (6 mm) high maximum shall be permitted to be vertical.

Fig. 303.2
Vertical Changes in Level

303.3 Beveled. Changes in level between 1/4 inch (6 mm) high minimum and ½ inch (13 mm) high maximum shall be beveled with a slope not steeper than 1:2.

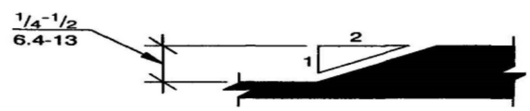


Fig. 303.3
Beveled Changes In Level

Violations of these rules have been judged by the technical community to create an unreasonably dangerous trip hazard. Note the use of the important "shall" language which makes code compliance mandatory.

B. Size of Asperities

All stumbling blocks that can be visually inspected are capable of tripping a pedestrian. The "Change of Level" specified by the standards represent the maximum allowable heights in the sense that smaller or equal levels are not unreasonably dangerous even though they remain a trip hazard. On the other hand, heights greater than those specified by the standard are technically judged as unreasonably dangerous. Consensus only tells you whether or not a visible protrusion is unreasonably dangerous.

The surface of all solids present asperities that are not visible without magnification. The field of tribology addresses the resistance developed between solid uncontaminated surfaces such as a walker's footwear and the walking surface. A reference to the first chapter of the ASM Handbook, Volume 18, "Friction, Lubrication, and Wear Technology," [15] indicates the role that asperities contribute to frictional resistance. This paper posits that invisible asperities may give rise to trip and fall hazards in addition to well-known slip and fall hazards. A brief introduction to the first-order theory of friction is essential to our analysis.

In 1495, Leonardo da Vinci deduced two basic laws of friction:

1. The friction force is dependent on the force pressing bodies together.
2. The friction force is independent of the apparent area of contact.

He found that the friction force was a fraction of the normal force, that is

$$F = \mu N$$

where F is the tangential friction force, μ is the coefficient of friction (constant), and N is the Normal component of the contact force between the contacting bodies.

Leonard Euler, in 1725, established that the coefficient of friction was different for static conditions, μ_S, and for dynamic or kinetic conditions, μ_K. He found that usually,

$$\mu_S > \mu_K$$

The static coefficient of friction is the ratio of horizontal force to normal force required to initiate sliding between two solid bodies. In 1875, Charles A. Coulomb discovered that the kinetic friction, μ_K, is nearly independent of the sliding speed; this is often referred to as the third law of friction. These historical facts have been carefully chronicled by Duncan Dowson [16] in his History of Tribology.

3. "Friction Lock"

A. The Normal Gait Cycle

One gait cycle is defined as a "Stride." A single stride is illustrated at the top of Figure 2. With respect to a single leg, two phases can be identified, a stance phase when the foot is on the floor, and the swing phase when the foot is in the air. There is a period that occurs midstride where both feet are simultaneously on the floor called the "Double Support" [17]. Here, the total weight of the walker is autonomously transferred from one leg to the other. Normally, this transfer plants the former trailing leg in a position that interrupts the walker's fall and allows the stride to continue without tumbling.

B. Premature Interdiction

If we assume that the normal gait cycle is somehow compromised in a way that prematurely transfers the pedestrian's weight to the swinging leg before it completes the "Double Support" period, the swinging foot will be locked onto the surface with a friction force resistance $W\,\mu_S$ where W is the walker's total weight. This very large tangential force cannot be overcome by a walker. Under "Friction Lock," the rear leg does not advance far enough to counteract the falling moment; this results in forward tumbling. In summary, if the walker's weight has been transferred prematurely to the swinging leg, a "Friction Lock" occurs that binds the foot in a stationary position before it extends enough to prevent upsetting.

A pedestrian's response in transferring weight from one leg to another in a timely fashion determines whether the specter of "Friction Lock" will cause the walker to trip on a flat walking surface. This premature interdiction is exacerbated by high coefficients of static friction which increase the magnitude of the "Friction Lock."

When premature interdiction occurs in the conventional shuffling mode, most of a pedestrian's weight is transferred to the trailing foot while it's moving forward. This sliding foot immediately decelerates under the influence of the dynamic coefficient of friction μ_k. When it becomes stationary, the static coefficient of friction μ_S locks the foot to the walking surface at an unstable location. Once again, the pedestrian trips and falls forward on a completely flat surface.

4. Observations

A. Be afraid of tripping, be very afraid. The head impact speed of a stationary toppling pedestrian against a walkway may be as great as v_O,

$$v_O = \sqrt{3\,gh}$$

where g is the acceleration due to gravity and h is the walker's height [18]. This is 22.5% greater than the freefall speed. For a 6-foot pedestrian, the head contact speed is 16.4 mph. It is even greater when a pedestrian is moving.

B. The height of visible asperities is called "Change of Level." All of the major consensus and administrative standards uniformly define the allowable magnitudes of reasonably safe "Change of Levels." Nevertheless, every visible "Change of Level" remains a trip hazard.

C. Invisible asperities are reflected in the <u>coefficients of friction</u> that characterize floor/footwear couples.

D. "Friction Lock" is a phenomenon that arises from a premature transfer of weight from a foot in the stance phase to the other foot in a swing phase. This locks the swinging foot into a position where it cannot intercede to prevent toppling of the walker. Premature transfer may arise from autonomous misbehavior of the nervous system, walkway irregularities, and lateral jostling the pedestrian.

E. Sensitivity to "Friction Lock" is increased in the face of high friction levels in floor/footwear couples. This is especially true for walking modes that involve shuffling which acts like a hair trigger. Old age compromises all of the physical factors that mitigate "Friction Lock."

F. The floor mats and runners represent safety systems that are widely specified for the control of <u>slip and fall</u> hazards that require elevated coefficients of friction. Unfortunately, lower friction levels mitigate the occurrence of <u>trip and fall</u> hazards associated with "Friction Lock." Too much friction in floor/footwear couples is currently an intractable safety problem.

G. "Friction Lock" gives rise to tripping and falling forward on a perfectly flat surface. It is often mischaracterized forensically as <u>slip and fall</u> behavior.

H. The frequency of "Friction Lock" is not palliated by commonplace anti-trip strategies, e.g., elimination of trip hazards, isolation of trip hazards, ski-nose footwear, adopting walking gaits that accentuate toe lift, optimizing the profile of obstructions, and minimizing "Change of Level."

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