ISSN 1041-9489

SAFETY BRIEF

June, 2005 Volume 27, No. 4

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EXTREME VALUE FORMULATION OF HUMAN SLIP - A SUMMARY

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ABSTRACT

Conventional "slip and fall" theory establishes a go/no-go criterion that indicates whether or not a given floor has satisfactory slip resistance. Specifically, the theory states that no slip, and hence no fall, will occur whenever the average coefficient of friction between a floor and some "worst case standard footwear material," e.g. leather, is greater than a threshold friction coefficient. This threshold friction is not selected by some rational protocol; it is often established by legislative fiat or consensus. Using extreme value statistics, this paper reformulates classical "slip theory" to explicitly account for the stochastic nature of friction coefficients. By abandoning the traditional deterministic approach to slip in favor of a statistical formulation, fully integrated protocols are able to be developed which predict the number of pedestrians who will slip or, alternatively, who will violate a threshold slip criterion. A new theory emerges that embraces everything from a simple floor with a single walker to very complicated real floors traversed by a throng of pedestrians with multiple ambulation styles and wearing a variety of footwear. It must be emphasized that the new slip protocol merely provides a mathematical framework that enables walkway professionals to make quantitative estimates of slip propensity. Like conventional theory, it also suffers from the "garbage in-garbage out" syndrome. Accurate tribometers, for example, are still required for precise predictions. On the other hand, the concept of threshold criterion and worst case footwear surrogates are replaced by force-plate data obtained by gait laboratories using various communities of walkers. Reliability determination for real floors requires the introduction of floor duty cycles.

1. INTRODUCTION

Pedestrian locomotion involves acceleration during start-up, slowdown, steady movement and maneuvers. These accelerations are associated with tangential forces transferred from a walker's footwear to the walking surface. To accomplish desired ambulation without slipping, i.e., without relative motion between the floor and the footwear, the tangential forces must be equilibrated by ground reaction forces. Adopting

This paper was published in the XIX Annual International Society for Occupational Ergonomics and Safety Conference Proceedings in June 2005, Las Vegas NV, Pgs 490-500 and edited by TE Lockhart and JE Fernandez. It is reprinted here with permission from ISOES.

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the same friction model used in classical slip theory, this paper resists the ground reactions only by dry static friction and not by mechanical interference, hydrodynamic drag, surface tension, suction or adhesion.

Classic slip theory adopts the friction model developed by DaVinci and Amontons (1699) and Coulomb (1781). When applied to a body resting on an uncontaminated horizontal floor surface, the horizontal friction or shear resistance H developed in the contact area may be written,

$$H \leq \mu V \qquad \text{(Eq.1)}$$

where V is the normal force squeezing the bodies together, μ is a constant called the coefficient of friction (COF) and where the equality holds only at incipient sliding. In this model, μ is assumed to be independent of the area of contact, normal compressive stress, speed or sequence of loading, contact time between the surfaces, temperature, humidity and the measuring system. In short, it is assumed to be an intrinsic property of the floor/footwear couple in slip applications.

To provide a deterministic go/no-go protocol for determining whether or not a floor is slippery, traditional slip theory was developed along the following lines:

1. Assume the floor is homogeneous.

2. Select a surrogate material that represents a "worst case footwear material."

3. Characterize the floor/footwear surrogate by adopting the DaVinci-Amontons-Coulomb friction model to determine its COF.

4. Measure the COF at a small number of locations using any one of many dozens of tribometers. Following the tribometer's protocol, the arithmetic average of less than twenty-four readings determines $\overline{\mu}$.

5. Compare $\overline{\mu}$ to the prevailing threshold or critical COF, μ_C,

$$\overline{\mu} > \mu_C \; ...no\,slip \qquad \text{(Eq. 2)}$$

The shortcomings of this prediction system are outlined by Marpet (2002) and Barnett (2002). The present paper describes a reformulation of classical slip theory which eliminates the assumptions contained in items (1), (2) and (5). Furthermore, it explicitly accounts for the stochastic nature of friction and predicts the number of slips experienced in each pedestrian category using a given floor.

2. VIRTUAL SLIP-SOLITARY WALKER

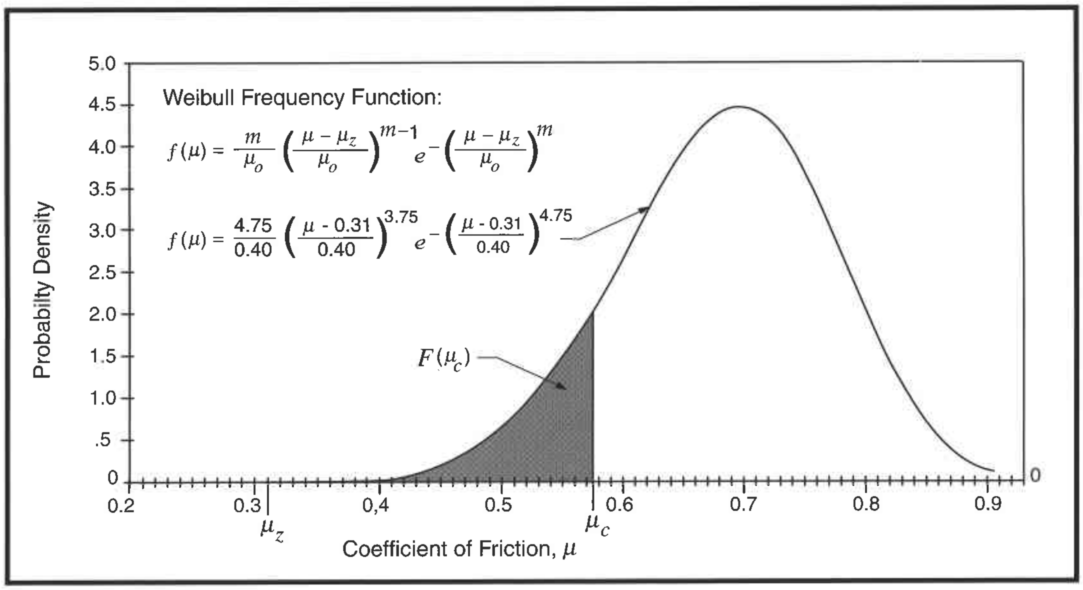
Slip of a solitary walker can be studied by making a single departure from conventional slip theory. Specifically, the assumption of a homogeneous floor is replaced by a statistically homogenous floor. This assumption recognizes that a simple floor represents an infinite array of COF's for every footwear material. If these COF's belong to the same statistical population, the floor is statistically homogeneous. This implies, for example, that every region of the floor will produce the identical "bell shaped" curve of COF's if an infinite number of tribometry readings were obtained for each region. On the other hand, the arbitrary oil spill, discarded banana peel or the presence of a drinking fountain all lead to a non-homogeneous floor.

Both the conventional and the proposed slip theory discussed in this paper assume that a floor is isotropic. A statistically isotropic floor has the same statistical distribution of COF's in every direction measured.

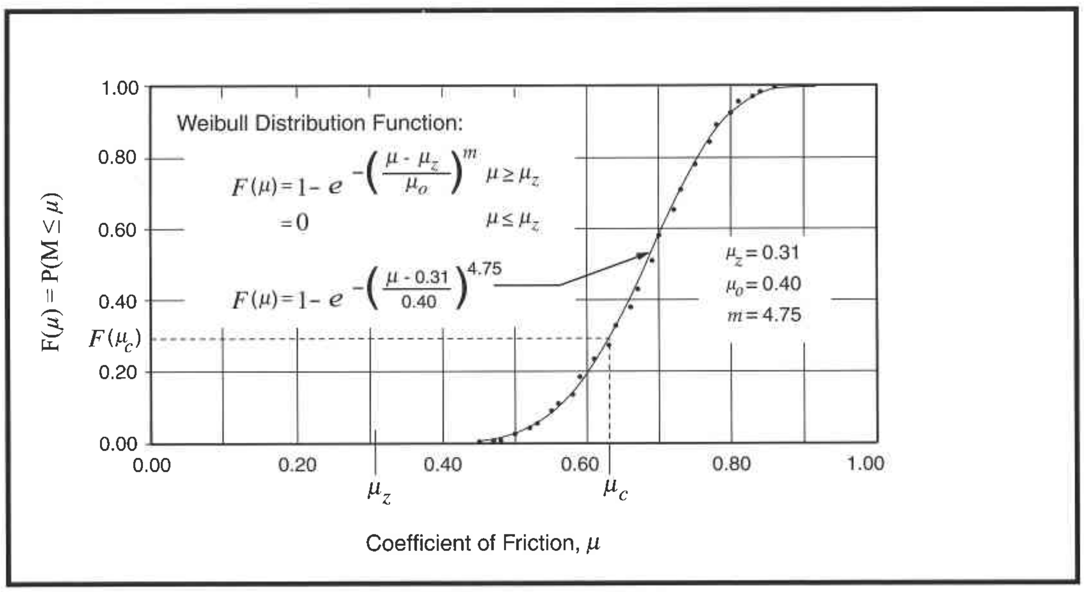
The existence of the classical threshold or critical COF, μ_C, is assumed in our study of the solitary walker. In addition to Marpet (2002) and Barnett (2002), the veracity of a single value numeric threshold has been challenged by Sotter (2002) who displays the situational character of slip criteria in his Tables 5-1 and 5-2. Nevertheless, a threshold COF may be legally imposed on a walkway professional as indicated by Sotter (2002) in his Table 3-1. Because an arbitrary threshold COF is unrelated to real slip, the term virtual slip is used whenever

$$\mu \leq \mu_C \; ...virtual\,slip \qquad \text{(Eq. 3)}$$

For a specific floor/footwear couple, such as asphalt/leather, one of the tribometer devices may be used to measure the COF's at various locations on a statistically homogeneous floor. The resulting set of data is called a statistical sample, which, in the usual way, may be presented as a probability density curve (bell-shaped curve) or as a cumulative distribution curve such as shown in Fig. 1 for the asphalt tile/leather couple.



a) Probability Density Curve



b) Cumulative Distribution Curve

Figure 1 - Distribution of Friction Coefficients: Asphalt Tile / Leather Couple

To execute an n-step perambulation across the surface without slipping requires that a walker survive the step with the lowest friction. This observation has led to the development of a new theory of "slip and fall" based on extreme value statistics (Barnett, 2002). This theory provides that the "bell shaped" curve of friction coefficients must be of the Weibull form and that the probability that a solitary walker will experience a virtual slip is given by $F_W\,(\mu_C)$,

$$F_W(\mu_C) = 1 - e^{-n\left(\frac{\mu_C - \mu_Z}{\mu_O}\right)^m} \quad \ldots\mu_C \geq \mu_Z$$
$$= 0 \quad \ldots\mu_C \leq \mu_Z \qquad \text{(Eq. 4)}$$

This simple elegant formula, which also reflects the Weibull form, provides a relationship among the probability that a solitary walker will experience a virtual slip while executing a walk of n steps, the critical (threshold) friction criterion μ_C and three statistical parameters that characterize the floor/footwear couple (μ_Z, μ_O, m). These three Weibull parameters describe the entire distribution of COF's including their average, their spread and their asymmetry; however, only the zero probability friction μ_Z has an explicit physical meaning. There is zero probability that any COF will fall below μ_Z. Recall that classic slip theory uses only the central measure, the average friction $\overline{\mu}$.

In keeping with the dictates of the extreme value statistics formulation, the data in Fig. 1 have been fitted with Weibull functions which are shown together with their parameters. The parameters were established using the method of moments (Gregory, Spruill, 1962). It may be observed in Fig. 1a that the bell-shaped curve is not symmetrical. This implies that the highest point on the curve, the mode, will not represent the mean or average coefficient of friction. Because the mean does not represent the most probable value of μ, it has no physical significance, only a mathematical one.

3. VIRTUAL SLIP - GENERIC PEDESTRIANS

Using the same virtual slip criterion given by Eq. (3) for a statistically homogeneous and statistically isotropic floor, the findings for solitary walkers can be extended to more realistic situations involving multiple generic pedestrians. These folks are assumed to have the same footwear and ambulation styles; however, they will undertake different length walks and may repeat some of their trajectories.

One of the significant departures from conventional slip theory is the presence of the term n in Eq. (4) reflecting the number of steps in a preset journey. Physically it represents the fact that longer walks have a greater probability of encountering lower COF's. This raises the question, "Can Eq. (4) predict the slip probability of the group of pedestrians by simply inserting into n the total number of steps walked by the whole group?" Unfortunately, this simplification is not available. A single long walk of n-steps leads to no more than one slip since this terminates the journey. On the other hand, dividing the n steps into k different sub-journeys makes it possible to experience as many as k slips. It is proven in Barnett (2002) that a long walk is more reliable than equivalent length short walks. This implies that the entire collection of walking profiles must be evaluated.

Following the protocol described by Barnett, Glowiak and Poczynok (2002), let T_j be the total number of walk profiles consisting of exactly n_j steps. The duty cycle for the floor may then be defined as the entire collection of walk profiles undertaken by pedestrians during a specified time period. It may be designated as

$$(n_j, T_j) \; where \; j = 1,2,...,\beta \qquad \text{(Eq. 5)}$$

and where β is the total number of different walk profiles.

As an example, a floor's duty cycle may be determined using a security camera which monitors the walking activities on a single floor during a two-day period. Counting the number of steps for each pedestrian during this surveillance, a set of walking profiles may be recorded as shown in the sample displayed in the first two columns of Table I. There are possible walk profiles which give rise to a total number of pedestrian ambulations T where

$$T = \sum_{j=1}^{\beta} T_j, \quad j = 1,2,...,\beta \qquad \text{(Eq. 6)}$$

in a specified time period. The fraction T_j / T provides the proportion of pedestrians who walk exactly n_j steps. Since T_j and T represent the same time period, the relative frequency T_j / T is independent of any specified surveillance period. The veracity of the duty cycle characterized by $(n_j, T_j / T)$ depends on how well the surveillance period represents the floor usage. Alternatively, the total number of pedestrians studied, T, must be sufficiently large to accurately represent the floor usage pattern.

A floor is characterized by establishing the number or percentage of pedestrians who will slip while negotiating a given duty cycle. The probability of slipping during a walk of n_j steps, $F_W(n_j)$, is given by Eq. (4) for a particular floor/footwear couple and critical slip criterion μ_C. If T_j pedestrians undertake such a walk, the number of slips is given by $T_j F_W(n_j)$. The total number of walkers who will slip during the floor's duty cycle is found by adding the slips associated with each of the β walk profiles, i.e.,

$$\text{Total Number of Slips} = \sum_{j=1}^{\beta} T_j F_W(n_j) \qquad \text{(Eq. 7)}$$

The fraction of pedestrians who will slip during a duty cycle is found by dividing both sides of Eq. (7) by the total number of pedestrians T ; thus,

Percentage of slips =

$$100\left[\left(\frac{T_1}{T}\right)F_W(n_1)+\ldots+\left(\frac{T_\beta}{T}\right)F_W(n_\beta)\right]$$

$$=100\sum_{j=1}^{\beta}\left(\frac{T_j}{T}\right)F_W(n_j) \qquad \text{(Eq.8)}$$

Table I displays all the calculations relative to the evaluation of the asphalt floor characterized in Fig. 1 with a critical friction criterion $\mu_C = 0.5$. We observe that twelve of the fifty pedestrians who traversed the asphalt floor in the two-day surveillance period slipped or, more accurately, encountered a friction coefficient smaller than μ_C. The last column of Table I indicated that the floor's slip rate is 24.29% for its duty cycle, i.e., 243 people out of a thousand will slip or engage a friction coefficient below the critical friction μ_C.

4. REAL SLIP- GENERIC PEDESTRIANS

It turns out that the annoying notion of a mystical critical friction criterion can be replaced by the body of data obtained by gait laboratories which use force-plates to measure the required friction for stable locomotion. For a given community of walkers and a specific type of ambulation, force-plate studies provide a statistical description of floor loading. The stochastic resistance previously developed is combined with the stochastic floor loading using techniques borrowed from reliability theory. This makes it possible, using numerical integration, to calculate the number or percentage of walkers that actually slip during a given exercise.

4.1 Force-Plate Studies

Gait laboratories use an instrumented walking surface called a force-plate to record the time history of both the horizontal force component $\mathrm{H(t)}$ and the corresponding vertical force component $\mathrm{V(t)}$ impressed on the surface by walking candidates. Throughout a typical step, the horizontal applied loading $\mathrm{H(t)}$ must be resisted if no slip

Table I - Duty Cycle Slip Calculations - Asphalt Tile / Leather Couple

Duty Cycle (two-days)		Slip Probability	Number of Slips (2-day period)	Slip Proportion
Number of Steps	Number of Pedestrians			
n_j	T_j	$F_w(n_j) = 1-e^{-n_j\left(\frac{0.5-0.31}{0.40}\right)^{4.75}}$	$T_j F_w(n_j)$	$(T_j / T)\, F_w(n_j)$
4	4	0.10998	0.43991	8.798×10^{-3}
5	3	0.13553	0.40658	8.132×10^{-3}
6	2	0.16034	0.32069	6.414×10^{-3}
7	3	0.18445	0.55334	11.067×10^{-3}
8	12	0.20786	2.49430	49.886×10^{-3}
9	4	0.23060	0.92239	18.448×10^{-3}
10	4	0.25269	1.01074	20.215×10^{-3}
11	3	0.27414	0.82242	16.448×10^{-3}
12	4	0.29498	1.17990	23.598×10^{-3}
13	3	0.31521	0.94564	18.913×10^{-3}
14	1	0.33487	0.33487	6.697×10^{-3}
15	0	0.35397	0	0
16	3	0.37251	1.11754	22.351×10^{-3}
17	2	0.39053	0.78105	15.621×10^{-3}
18	2	0.40802	0.81604	16.321×10^{-3}
	Total 50	Critical Friction Criterion $\mu_c = 0.5$	Total 12.145	Total 242.9×10^{-3}

is to occur. This resistance is developed by the normal surface loading $V(t)$ acting in conjunction with the COF between the surface and the walker's footwear which shall be designated μ_r to indicate resistance. At any time t, the non-slip criterion may be written as $H(t) < \mu_r V(t)$. If the maximum ratio of H/V, $(H/V)_{max}$, obtained during one entire step is designated as μ_a, the non-slip criterion for an entire step becomes $\mu_r - \mu_a > 0$. The COF μ_a is the required or applied COF; μ_r is the available or resisting COF.

The collection of force-plate data for $\mu_a = (H/V)_{max}$ can be characterized by a probability density function $\tilde{f}_\beta(\mu_a)$ where the subscript β designates a particular community or population of walkers distinguished perhaps by gender, age, health, walking speed or locomotion style. If this applied floor loading is represented by a normal or Gaussian distribution,

$$\tilde{f}_\beta(\mu_a) = \frac{1}{\sigma_\beta \sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\mu_a - \bar{\mu}_\beta}{\sigma_\beta}\right)^2} \qquad \text{(Eq. 9)}$$

where $\bar{\mu}_\beta = \overline{(H_\beta / V_\beta)}_{max}$ is the mean value of the $(H_\beta / V_\beta)_{max}$ distribution and σ_β is its standard deviation.

4.2 Slip Resistance

If an infinite number of n-step walks are taken, each has a lowest COF μ_r. When the applied friction μ_a exceeds this resisting COF μ_r, slipping occurs. The "bell-shaped" distribution of these μ_r's is given by the probability density curve associated with Eq. (4) when μ_C is replaced by, μ_r i.e.,

$$\bar{f}_k(\mu_r) = \frac{nm_k}{s_k}\left(\frac{\mu_r - z_k}{s_k}\right)^{m_k - 1} e^{-n\left(\frac{\mu_r - z_k}{s_k}\right)^{m_k}} \quad \ldots \mu_r \geq z_k$$

$$= 0 \quad \ldots \mu_r \leq z_k$$

(Eq.10)

where μ_r is the resisting coefficient of friction for a particular floor/footwear couple delineated by the subscript k; n is the number of steps taken during a given walk; and z_k, s_k, and m_k are the Weibull parameters obtained from the friction data for the k^{th} floor/footwear couple.

4.3 Reliability Theory

Combining stochastic floor loading and stochastic friction resistance was first undertaken by Barnett and Poczynok in (2003). This was done for a single community of walkers using a specific type of ambulation and footwear on a given statistically homogeneous and statistically isotropic floor surface.

The probability that a walker will not slip, and hence not fall, is called reliability and it will be designated by R. When the applied floor loading μ_a and the friction resistance of a floor/footwear couple μ_r are both stochastic, the floor reliability R may be determined by well established techniques developed in reliability theory. These techniques are all predicated on the observation that failure (slip) will not occur if the loading (stress) does not exceed the resistance (strength); for non-slip this implies that $\mu_a \leq \mu_r$. Using $\tilde{f}_\beta(\mu_a)$ defined by force-plate studies and $\bar{f}_k(\mu_r)$ defined by Eq. (10), the floor reliability becomes,

$$R_{\beta kj} = \int_{-\infty}^{z_k} \tilde{f}_\beta(\mu_a)\,d\mu_a + \int_{z_k}^{\infty} \tilde{f}_\beta(\mu_a)\,e^{-n_j\left(\frac{\mu_a - z_k}{s_k}\right)^{m_k}} d\mu_a$$

(Eq. 11)

where $(1 - R_{\beta kj})$ is the probability of slipping for the β community of walkers exposed to the k^{th} floor/footwear couple while traveling through n_j steps. The first term in Eq. (11), depending on the distribution function, may be expressed in closed form, may require numerical integration, or may be a tabulated function as in the case of the normal distribution. The second term always requires numerical integration or some equivalent evaluation.

Consider a generic group of pedestrians consisting of men walking straight on a level surface. Data taken from Harper, Warlow and Clarke (1961) indicated that for these walkers their distribution of $(H/V)_{max}$ is Gaussian with mean $\bar{\mu}_{\beta=1} = 0.17$ and standard deviation $\sigma_{\beta=1} = 0.04$. If all of the men are wearing leather footwear and the floor is asphalt tile, the associated Weibull parameters from Fig. 1 are $z_{k=1} = 0.31$, $s_{k=1} = 0.40$ and $m_{k=1} = 4.75$. Using these five constants in Eq. (11), one obtains the reliabilities tabulated in Table II for five different length walks (n_j = 1, 10, 100, 1000, 10000). It should be noted that Eq. (11) must be numerically integrated which is both accurate and very rapid.

Table II - Floor Reliability:
Asphalt Tile / Leather Footwear / Men / Straight Walking

Number of Steps n_j	Reliabilty R	Probability of Slipping $1 - R$	Slips Per Million Walkers
1	0.999 999 999	3.11×10^{-10}	zero
10	0.999 999 997	3.07×10^{-9}	zero
100	0.999 999 969	3.05×10^{-8}	zero
1000	0.999 999 707	2.93×10^{-7}	0.293
10,000	0.999 997 681	2.32×10^{-6}	2.32

5 REAL SLIP - REAL PEDESTRIANS

With the exception of marching soldiers, the concept of generic pedestrians is not realistic despite the fact that conventional slip theory adopts this idealization. If duty cycles and some additional bookkeeping notions are included in the analysis developed in the previous section, the general theory can be extended to real floors traversed by pedestrians with multiple ambulation styles and wearing a variety of footwear (Barnett & Poczynok, 2004).

5.1 Duty Cycles (Real Floors)

Assume that a surveillance/counting system is available with the following capability:

a. It will identify all traffic patterns or pedestrian pathways (designated by the subscript j) and their lengths, n_j steps.
b. It will indicate multiple classes of walkers (designated by the subscript β).
c. It will identify every floor surface/footwear couple (designated by the subscript k).
d. It will record the number of ambulations, $T_{\beta kj}$, along each pathway for every walking profile $P_{\beta kj}$ defined as the combination of a walker type (β), footwear style (k), and walking distance in steps .

5.2 Example

As an example, consider the six traffic patterns or pedestrian pathways ($j = 1,2,...6$) that are illustrated in Fig. 2 for a simple commercial floor plan. Next to each pathway, its length n_j steps, is indicated. Observe that there are two branches for pathways $j = 2$ and $j = 5$. Assume that the floor is comprised of ceramic tiles and that men and women wearing leather and rubber soled shoes traverse each pathway in either direction. This gives rise to 24 walking profiles with the parameters tabulated in Table III.

Note that the total number of walking profiles is given by the product of $\beta_{\max}$, $k_{\max}$, and $j_{\max}$; i.e., 2 x 2 x 6 = 24. Assume that a surveillance system has recorded the number of ambulations $T_{\beta kj}$ for each walking profile $P_{\beta kj}$ as tabulated in the top of each box displayed in Table IV for a 14 day period.

The reliability $R_{\beta kj}$ for a walk profile $P_{\beta kj}$ is the probability that no slipping will occur during an ambulation along the j^{th} pathway by walkers of type β wearing footwear style k. Using the data displayed in Table III, the reliability may be calculated from Eq. (11) when Eq. (9) has been subsumed. These results are shown in the middle of the boxes in Table IV.

The probability of slipping for a profile $P_{\beta kj}$ is $(1 - R_{\beta kj})$. The number of slips for a fixed time period (14 days in the example) associated with a given profile is the product of the slip probability and the number of ambulations undertaken in the time frame; thus,

$$\text{Slips} = \left(1 - R_{\beta kj}\right) T_{\beta kj} \qquad \text{(Eq. 12)}$$

The number of slips predicted for the 14-day time period is tabulated in the bottom of the boxes in Table IV.

The following formulas are helpful in presenting the floor analysis:

Total Ambulations - Fixed Time Period: T

$$T = \sum_{\beta} \sum_{k} \sum_{j} T_{\beta kj}$$

Total Slips - Fixed Time Period:

$$\text{Total Slips} = \sum_{\beta} \sum_{k} \sum_{j} \left(1 - R_{\beta kj}\right) T_{\beta kj}$$

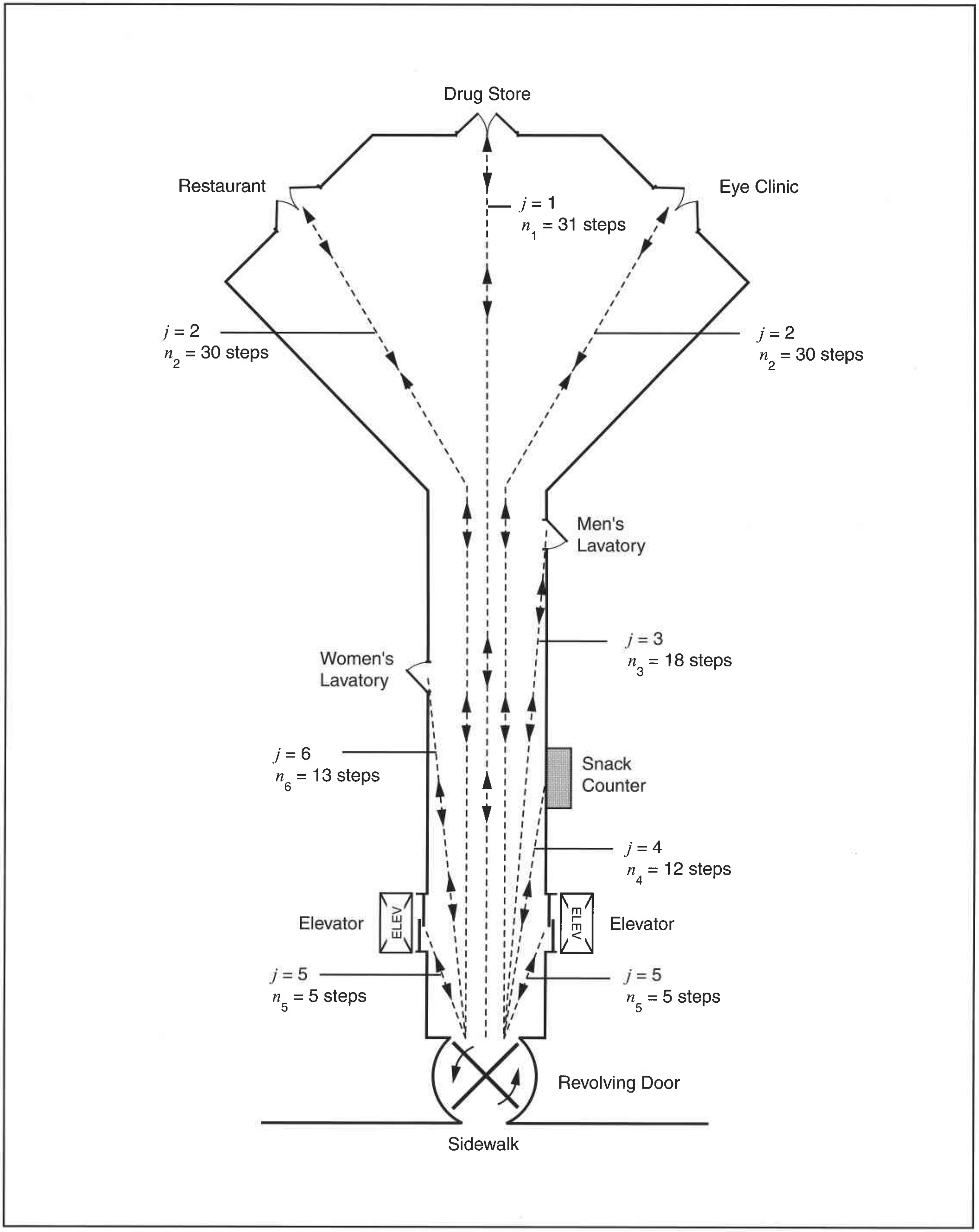


Figure 2 - Commercial Floor Plan - Traffic Patterns, j

Table III - Ceramic Floor:
Characterization of Walking Profiles $P_{\beta kj}$

$\beta = 1$ ... men, straight walking (Barnett 2002) $\bar{\mu}_1 = 0.17$; $\sigma_1 = 0.04$
$\beta = 2$ ... women, straight walking (Barnett 2002) $\bar{\mu}_2 = 0.16$; $\sigma_2 = 0.03$
$k = 1$ ... ceramic / leather couple (Barnett 2004) $z_1 = 0.10$, $s_1 = 0.51$, $m_1 = 5.5$
$k = 2$ ... ceramic / rubber couple (Barnett 2004) $z_2 = 0.25$, $s_2 = 0.28$, $m_2 = 1.9$
$n_1 = 31, n_2 = 30, n_3 = 18, n_4 = 12, n_5 = 5, n_6 = 13$ steps

Table IV - Example Problem
Duty Cycle, Profile Reliability, and Slips

Number of Walks in 14 Days: $T_{\beta kj}$ or $R_{\beta kj}$ or Slips = $(1 - R_{\beta kj})T_{\beta kj}$					
j	n_j	$\beta = 1$ ... men $k = 1$ ... leather	$\beta = 1$ ... men $k = 2$ ... rubber	$\beta = 2$ ... women $k = 1$ ... leather	$\beta = 2$ ... women $k = 2$ ... rubber
1	31	$T_{\beta kj}$: 10 214	5282	1770	5454
		$R_{\beta kj}$: 0.99559 45028	0.99579 25174	0.99860 79365	0.99987 52145
		Slips: 45	22	2	1
2	30	$T_{\beta kj}$: 2178	1364	2034	1126
		$R_{\beta kj}$: 0.99573 41371	0.99589 36610	0.99865 26108	0.99987 87338
		Slips: 9	6	3	0
3	18	$T_{\beta kj}$: 6306	4006	—	—
		$R_{\beta kj}$: 0.99742 35929	0.99724 92296	—	—
		Slips: 16	11	—	—
4	12	$T_{\beta kj}$: 1522	572	1514	598
		$R_{\beta kj}$: 0.99827 81270	0.99804 81835	0.99945 93718	0.99994 74092
		Slips: 3	1	1	0
5	5	$T_{\beta kj}$: 8414	4818	6422	3236
		$R_{\beta kj}$: 0.99928 36039	0.99911 83541	0.99977 44654	0.99997 72869
		Slips: 6	4	1	0
6	13	$T_{\beta kj}$: —	7	5628	2562
		$R_{\beta kj}$: —	0.99790 82251	0.99941 44206	0.99994 33009
		Slips: —	0	3	0

Probability of Slipping:

$$\text{Slip Probability} = \frac{\sum_{\beta}\sum_{k}\sum_{j}\left(1 - R_{\beta kj}\right)T_{\beta kj}}{T}$$

where the explicit effect of the time frame disappears because of the ratio $\left(T_{\beta kj}/T\right)$.

Floor Reliability:

The floor reliability is (1-Slip Probability); thus,

$$\text{Floor Reliability} = \frac{\sum_{\beta}\sum_{k}\sum_{j} R_{\beta kj}T_{\beta kj}}{\mathrm{T}}$$

For our example, the reliability of the ceramic tile floor is 0.998214. The average coefficient of friction for the ceramic/leather couple ($z = 0.10$, $s = 0.51$, and $m = 5.5$) is $\bar{\mu} = 0.571$. Based on conventional standards, $\bar{\mu} > 0.5$, the ceramic floor used in our example of a commercial setting, is fully acceptable. Unfortunately, its reliability is remarkably low and leads to approximately 3500 slips/year.

6. CONCLUSIONS

Moving from the simplest case of a solitary walker and virtual slip, this paper ultimately determines the number of walkers who will actually slip within a given time period on a real floor traversed by walkers with multiple ambulation styles and wearing a variety of footwear. The calculation protocol embraces five "slip and fall" disciplines: force-plate studies, floor duty-cycles, tribometry, extreme value theory of slipperiness and floor reliability theory. Thus, for statistically homogenous and statistically isotropic floors the methodology predicts the number of walkers who actually slip (not fall) or the percentage who slip per unit time, or the floor reliability. These walkers may be men or women, young or old, healthy or infirmed; they may wear gym shoes, boots, leather-soled shoes, or sandals; they may walk straight, make turns, or jog; and finally, they may take combinations of long or short walks. The proposed approach to the prediction of slips does not supplant any existing floor technology, it merely adds additional mathematical tools for manipulating classical notions. However, these new tools reveal insights into the structure of slips in a way that introduces completely new concepts: the go/no go nature of classical slip predictions is replaced by a probability of slipping; low friction floor/footwear couples may lead to fewer slips than high friction ones; slipping will occur in every case where conventional theory predicts "no slip"; and the number of slips depends on the distance traveled by a pedestrian. Furthermore, the methodology embraces the idea that the slipperiness of real floors must be evaluated for a duty-cycle. There are many important areas that are not illuminated by the new theory, e.g., the relationship between slips and falls, the injury potential of slips that do not result in falls, slip behavior that cannot be described using dry friction concepts, and slips on randomly distributed contaminants such as water puddles or banana peels. On the other hand, it appears that the theory may be extended to include non-homogenous and anisotropic floors.

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June, 2005 – Volume 27, No. 4

Editor: Paula L. Barnett
Illustrated and Produced by
Triodyne Graphic Communications