Center of Excellence

Triodyne Inc.
Consulting Engineers & Scientists – Safety Philosophy & Technology
666 Dundee Road, Suite 103, Northbrook, IL 60062-2702
(847) 677-4730 FAX: (847) 647-2047
e-mail: infoserv@triodyne.com
www.triodyne.com

SLIP, TRIP and FALL

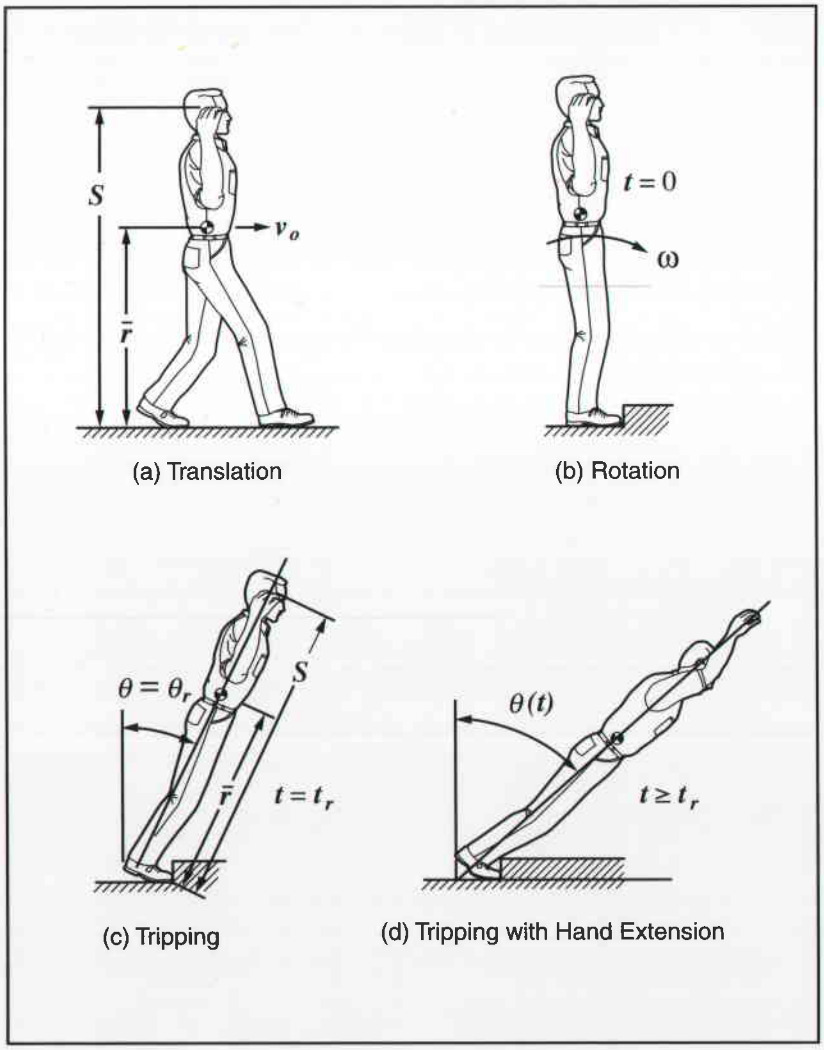

Figure 1 - Tripping Scenario

PROBLEM STATEMENT

With respect to traumatic accidents, every year "slip, trip and fall" accounts for the second largest number of deaths and the second largest number of disabling injuries in the world. Only the automobile kills and injures more people. For senior citizens, "slip, trip and fall" is the number one killer. In spite of this horror story, the legal profession treats this subject as they would a "fender bender."

The basic theory of slip began with Leonardo da Vinci in 1495. His work on friction provided the theoretical underpinning for a conventional slip and fall theory which established 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 criterion. This threshold friction is not selected by some rational protocol; it is often established by legislative fiat or consensus.

In 2002 Professor Ralph Barnett introduced a revolutionary new theory of slip and fall. He reformulated conventional slip theory to account for the statistical nature of friction. The new theory uses extreme value statistics to predict the number of walkers who will slip on a given floor. This paper, "Slip and Fall Theory - Extreme Order Statistics" won the Best Paper Award for the years 2000-2002 from the International Ergonomics Association/International Journal of Occupational Safety and Ergonomics. The complexity, sophistication, and challenges of slip and fall are staggering. The field is actively attended by scientists and laboratories around the world.

Tripping, railings, reaction times, and human push capability are topics that are closely related to human slip. These areas are included in the Triodyne Center of Excellence.

TRIODYNE PUBLICATIONS

- The Drunk, the Child and the Soldier – My, How They Fall by Ralph L. Barnett, *Safety Bulletin*, Vol. 2, No. 2, September 1995.
- Slip and Fall Theory – Extreme Order Statistics by Ralph L. Barnett, *International Journal of Occupational Safety & Ergonomics*, Vol. 8, No. 2, June 2002. Reprinted as *Safety Brief* Vol. 21, No. 3, September 2002.
- Hand Motion During Trip and Fall by Ralph L. Barnett and Suzanne A. Glowiak, *Safety Engineering and Risk Analysis*, SERA-Vol. 7, American Society of Mechanical Engineers, 1997.
- Hand Trajectories Under Free Fall by Ralph L. Barnett and Suzanne A. Glowiak, *Safety Brief*, Vol. 12, No. 2, January 1997.
- Stochastic Theory of Human Slipping by Ralph L. Barnett, Suzanne A. Glowiak and Peter J. Poczynok, *Safety Engineering and Risk Analysis*, SERA-Vol. 12, American Society of Mechanical Engineers, November 2002. Reprinted as *Safety Brief*, Vol. 22, No. 4, February 2003.
- Floor Reliability With Respect to Slip and Fall by Ralph L. Barnett and Peter J. Poczynok, *Safety Brief*, Vol. 24, No. 3, November 2003.
- Friction Sled by Claudine Giebs, Ralph L. Barnett and Peter J. Poczynok, *Safety Bulletin,* Vol. 2 No. 1, September 1995.
- Falling: The Cook County Illinois Experience by Claudine P. Giebs-Myers and Peter J. Poczynok, *Safety Bulletin*, Vol. 7, No. 1, June 1998.
- Above-Ground Pool Safety - Mechanical Solution by Ralph L. Barnett and Peter J. Poczynok, *Triodyne Safety Brief*, Vol. 23, No. 1, March, 2003.
- Human Push Capability by Ralph L. Barnett and Theodore Liber, *Triodyne Safety Brief*, Vol. 22, No. 1, November, 2002.
- Tautliner Vans, Case Study: Safety Philosophy by Ralph L. Barnett and Christopher Ferrone, *Triodyne Safety Bulletin*, Vol. 10, No. 1, January 2002.
- Friction-Related Aspects of Human Pushing by Ralph L. Barnett and Cheryl A. Pattin, *Safety Engineering and Risk Analysis*, SERA - Vol. 11, New York, American Society of Mechanical Engineers, November 2001.
- Case Study: The Safety of Wood Railings by Ralph L. Barnett and William G. Switalski, *Triodyne Safety Brief*, Vol. 18, No. 1, March 2001.
- Safety Potpourri by Ralph L. Barnett, *Triodyne Safety Brief*, Vol. 17, No. 4, January 2001.
- Swing Gates: The Weak Link in the Chain Link by Ralph L. Barnett and Patrick M. Brinckerhoff, *Triodyne Safety Alert*, Vol. 1, No. 2, July 1998.

Figure 2 - Beth Hamilton Safety Library - Expert Transcript Center (ETC) Collection

- *Fall Protection: Minimum Weight Lanyards for Bowhunters* by Ralph L. Barnett, *Triodyne Safety Bulletin*, Vol 4, No. 1, August 1996.
- *Extreme Value Formulation of Human Slip - A Summary* by Ralph L. Barnett and Suzanne A. Glowiak, *Triodyne Safety Brief*, Vol. 27, No. 4, June, 2005
- *Slip and Fall Characterization of Floors* by Ralph L. Barnett, and Peter J. Poczynok, *Triodyne Safety Brief*, Vol. 26, No. 2, June, 2004.

TRIODYNE BIBLIOGRAPHIES

Triodyne's Beth Hamilton Safety Library has comprehensive collections of books, articles, papers, codes and standards on hundreds of safety topics.

Triodyne Bibliographies include the full text of standards, codes, regulations, technical papers and journal articles that are useful to educators, safety professionals, government agencies, manufacturers, and plaintiff and defense attorneys. For more information, to purchase a Bibliography, or to receive a copy of *Bibcat 2500*, the catalog of all available Bibliographies, please call Library Services (847) 677-4730.

Accident Investigation and Reconstruction Bibliographies

- *Bathtub Falls*, No. 1301 [30 references]

Sample references:

1. Bathtub and Shower Injuries, *CPSC*, 1977.
2. Home Hazards and Falls in the Elderly: The Role of Health and Functional Status, *American Journal of Public Health*, 1995.
3. Household Falls: Keep Your Feet on the Ground, *Family Safety & Health*, 1993.
4. Standard Consumer Safety Specification for Slip-Resistant Bathing Facilities, *ASTM*, 1994.

- *Biomechanics of Human Gait*, No. 1284 [80 references]

Sample references:

1. Analytical Method for the Analysis and Simulation of Human Locomotion, *Journal of Biomechanical Engineering*, 1990.
2. Mechanical Analysis of the Landing Phase in Heel-Toe Running, *Journal of Biomechanics*, 1992.
3. The Mechanics of Walking, *Research Applied in Industry*, 1962.
4. A Method for Studying Walking on Different Surfaces, *Ergonomics*, 1962.

- *Coefficients of Friction Measurement Methods*, No. 0710 [80 references]

  Sample references:

  1. Coefficient of Friction and Subjective Assessment of Slippery Work Surfaces, *Human Factors*, 1992.
  2. Evaluation of the Effect of Contact-Time When Measuring Floor Slip Resistance, *Journal of Testing and Evaluation*, 1986.
  3. Slip Resistance of Floor Surface Materials, *ASTM*, 1992.
  4. Slip-Resistance Testing of Shoes, *Ergonomics*, 1983.

- *Floor Mats, Runners & Gratings as Factors in Slip & Fall*, No. 0351 [40 references]
- *Floor Surfaces & Measurement of Slipperiness*, No. 0073 [70 references]
- *Handrails & Guardrails as a Factor in Slip & Fall*, No. 0302 [55 references]
- *Housekeeping Issues as a Factor in Slip & Fall Cases*, No. 0050 [55 references]
- *Measuring Friction Coefficients of Footwear and Walking/ Working Surfaces*, No. 1444 [55 references]
- *Preventing Pedestrian Falls on Snow or Ice*, No. 1438 [30 references]
- *Prevention of Worker Falls From Roofs,* No. 1283 [40 references]
- *Regulations & Code Requirements for Stairways*, No. 0377 [55 references]
- *Shoes & Shoe Soles as a Factor in Slip & Fall*, No. 0610 [45 references]
- *Sidewalk Design and Maintenance for Fall Prevention*, No. 1391 [15 references]
- *Slip & Fall – General References*, No. 0609 [165 references]
- *Slip & Fall on Stairs and Stairway Design*, No. 0046 [75 references]
- *Slip & Fall Outdoors*, No. 0608 [25 references]
- *Slipperiness of Terrazzo Floors*, No. 0067 [25 references]

FACILITIES

- Tribometers: Measuring friction resistance (Figs. 3, 6 & 7)
- Force Plates: Measuring required friction/Gait Studies
- Working Model™: Walking simulations
- Anthropomorphic Models: Falling studies
- Safety Belts/Hardware: Laboratory simulations
- Forklifts/Manlifts: Laboratory aids
- Wood Shop - 3,000 ft^2 (Fig. 4)
- Metal Shop - 2,000 ft^2 (Fig. 5)
- Laboratory - 10,000 ft^2

Triodyne staff has given seminars on slip and fall at the Amusement Industry Manufacturers and Suppliers International Safety Seminar; the American Society of Mechanical Engineers International Mechanical Engineering Conference; and the International Society for Occupational Ergonomics and Safety Conference.

ACCIDENT INVESTIGATIONS

Triodyne has conducted over 400 slip and fall accident investigations involving falls on a variety of floor surfaces, stairs, scaffolding, decks, docks, airplanes, bridges, fire escapes, roofs, bleachers, in bathtubs, parking lots, by swimming pools, and many other places. This number also includes investigations of fall prevention systems like railings, ramparts, guards, gates and harnesses.

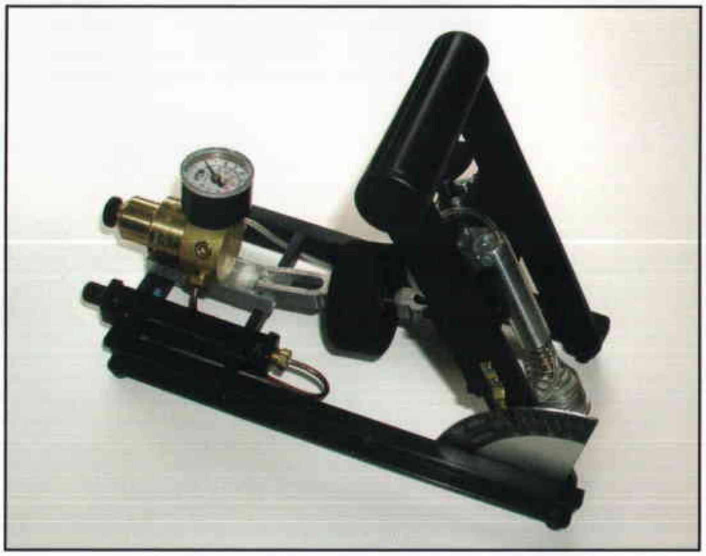

Figure 3 - Variable Incidence Tribometer

Figure 4 - Wood Shop (3,000 ft²)

Figure 5 - Metal Shop (2,000 ft²)

Figure 6 - Friction Sled

TRIP, SLIP AND FALL RESEARCH

Slip Resistance

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. Slip resistance arises from ground reaction forces acting in concert with the coefficient of friction between the floor material and a walker's footwear.

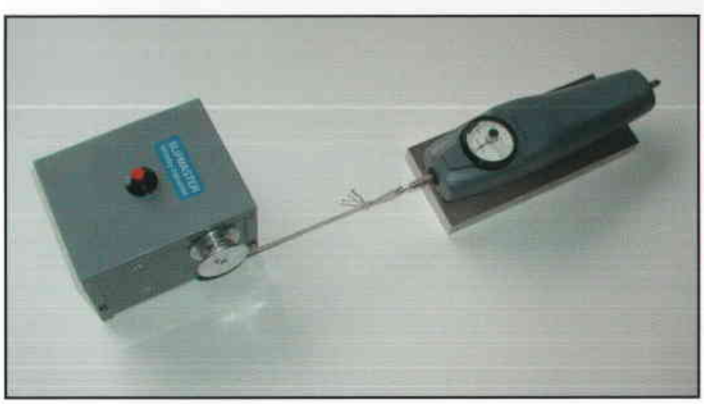

Figure 7 - Horizontal Pull Slipmeter

Conventional Theory

$$\bar{\mu} > \mu_c \text{ ....} \textit{no slip} \qquad \text{(Eq.1)}$$

where $\bar{\mu}$ is the average coefficient of friction for a floor/footwear surrogate and μ_c is a threshold or critical friction coefficient.

Extreme Value Slip Theory

$$\begin{aligned} F_w(\mu_c) &= 1 - e^{-n\left(\frac{\mu_c - \mu_z}{\mu_e}\right)^m} & \ldots \mu_c \geq \mu_z \\ &= 0 & \ldots \mu_c \leq \mu_z \end{aligned} \qquad \text{(Eq.2)}$$

This simple elegant formula, which reflects the Weibull form, provides a relationship among the probability $F_w(\mu_c)$ 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).

Duty Cycle

It is established that a real floor cannot be quantitatively evaluated without considering the actual floor usage, i.e., its duty cycle (see Fig. 8).

Floor Reliability

It turns out that the 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.

Using $f_\beta(\mu_a)$ defined by force-plate studies and $f_k(\mu_r)$ defined by Eq. 2, the floor reliability becomes,

$$R_{\beta kj} = \int_{-\infty}^{Z_k} \tilde{f}_\beta(\mu_a) d\mu_a + \int_{Z_k}^{\infty} \tilde{f}_\beta(\mu_a) e^{-n_j\left(\frac{\mu_A - Z_k}{S_k}\right)^{m_k}} d\mu_a \qquad \text{(Eq. 3)}$$

where $(1 - R_{\beta kj})$ is the probability of slipping for the community of walkers exposed to the k^{th} floor/footwear couple while traveling through n_j steps. The first term in Eq. 3, 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.

Real Floors - Real Slip

The new Triodyne slip theory 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 (see Fig. 9).

Hand Motion During Slip, Trip and Fall Scenarios

The location of workplace hazards, the design of fall intervention systems, the development of climbing and walking strategies, and the forensic analysis of slip and fall accidents all benefit from a knowledge of hand motion under combined effects of gravity and human response.

These problems are studied analytically and through simulation programs such as Working Model™. The hand trajectories associated with Fig. 1 are shown in Fig. 10.

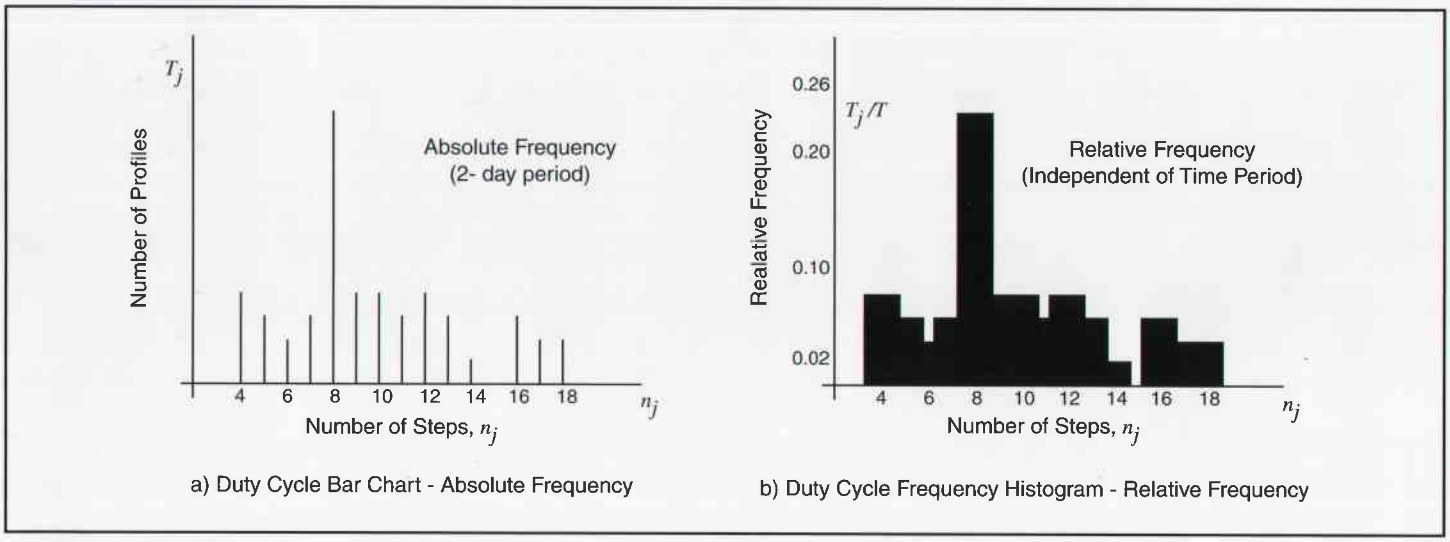

Figure 8 - Duty Cycle

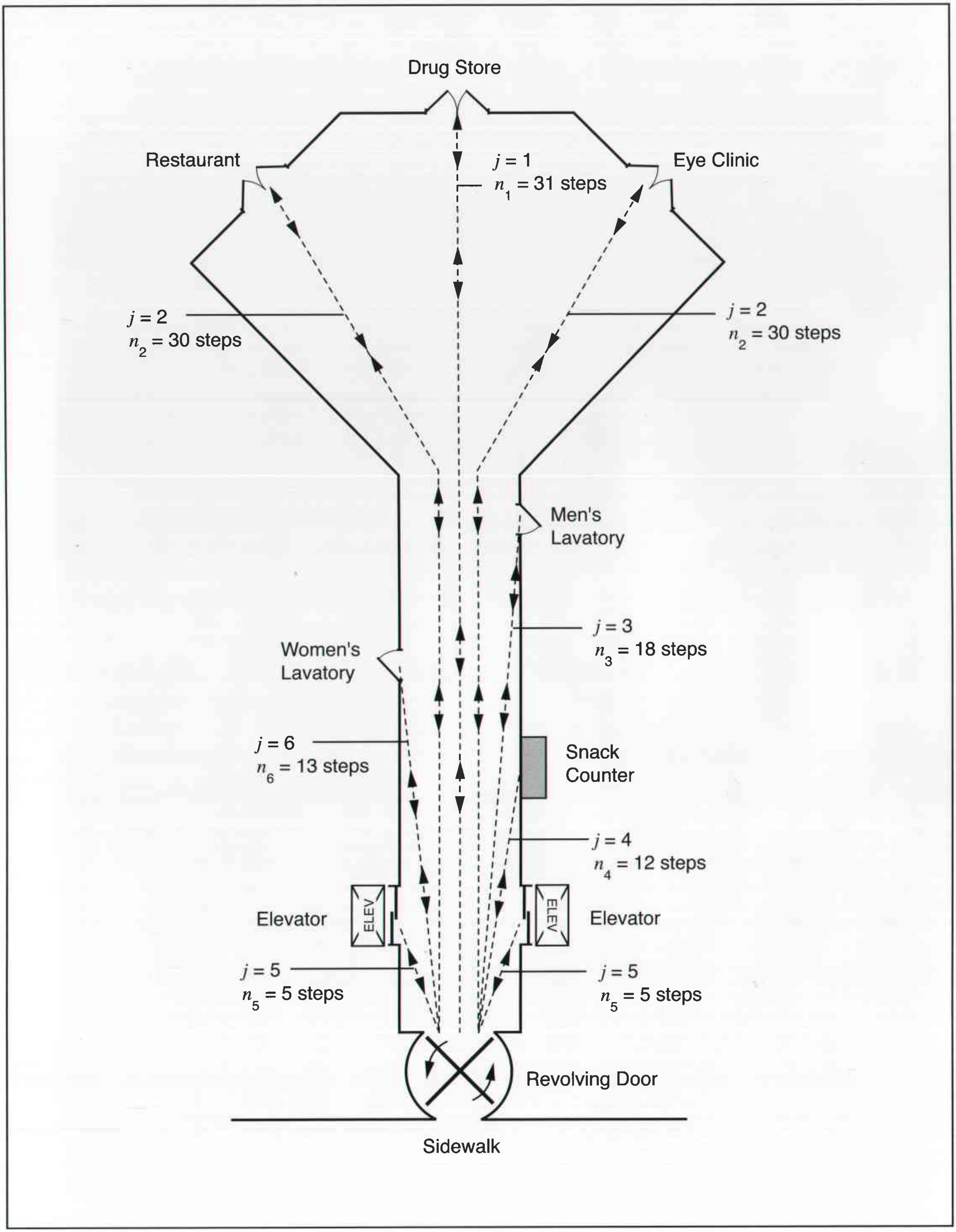

Figure 9 - Commercial Floor Plan - Traffic Patterns, j

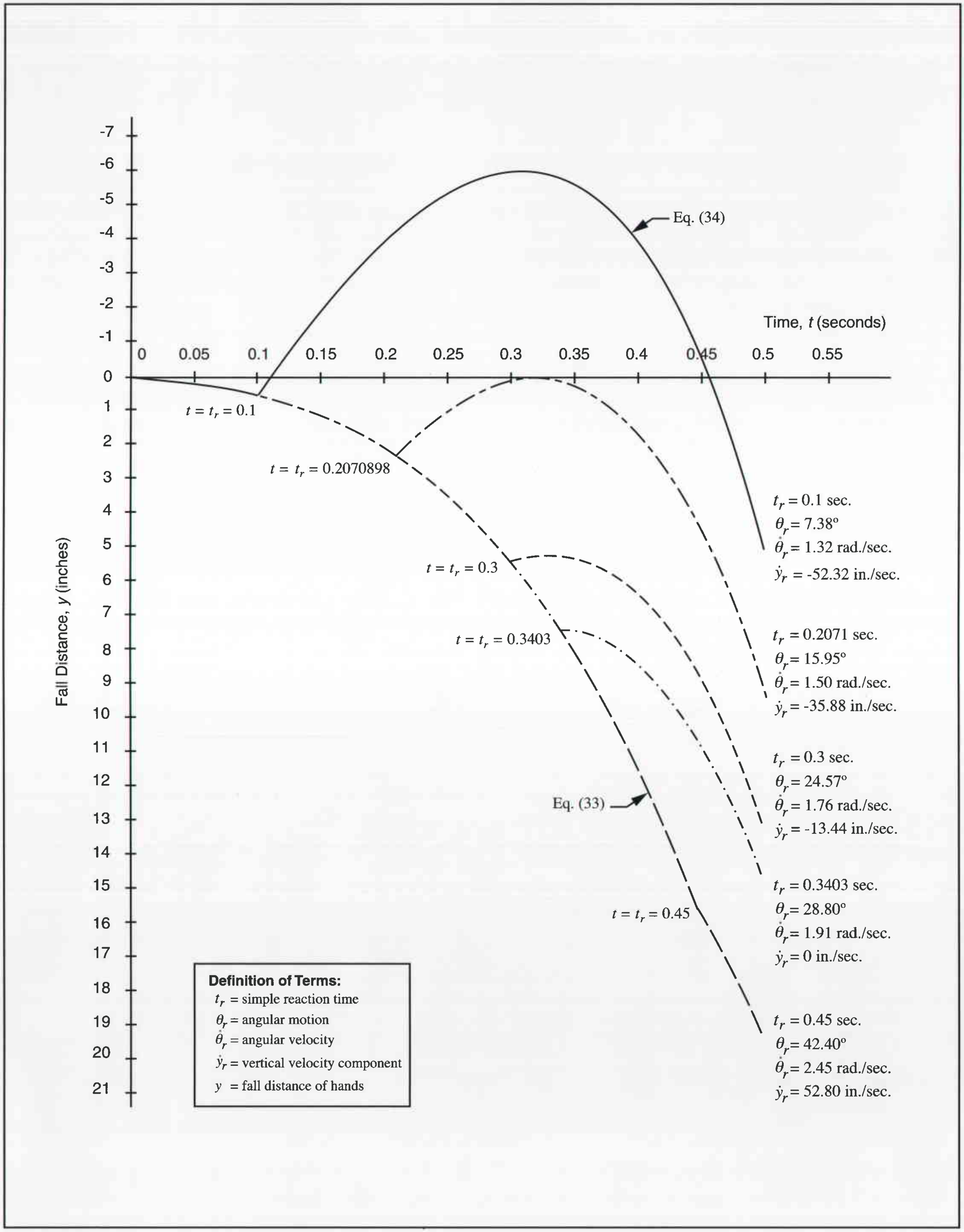

Figure 10 - Hand Trajectories Under Tripping Conditions

Human Push Capability

Use of unassisted human push capability arises from time to time in the areas of crowd and animal control, the security of locked doors, the integrity of railings, the removal of tree stumps and entrenched vehicles, the maneuvering of furniture, and athletic pursuits such as football or wrestling. Depending on the scenario, human push capability involves strength, weight, weight distribution, push angle, footwear/ floor friction, and the friction between the upper body and the pushed object. Ultimately, maximum push capability is limited by slip resistance (see Fig. 11).

Railings

Railings are used to protect floor openings, enhance stability on stairs, intercede in slipping scenarios, prevent tumbling from elevated structures, and prevent diving and jumping into pools. Triodyne maintains an active research program on railing heights, anti-climbing properties, structural integrity and deployment characteristics (see Fig. 12).

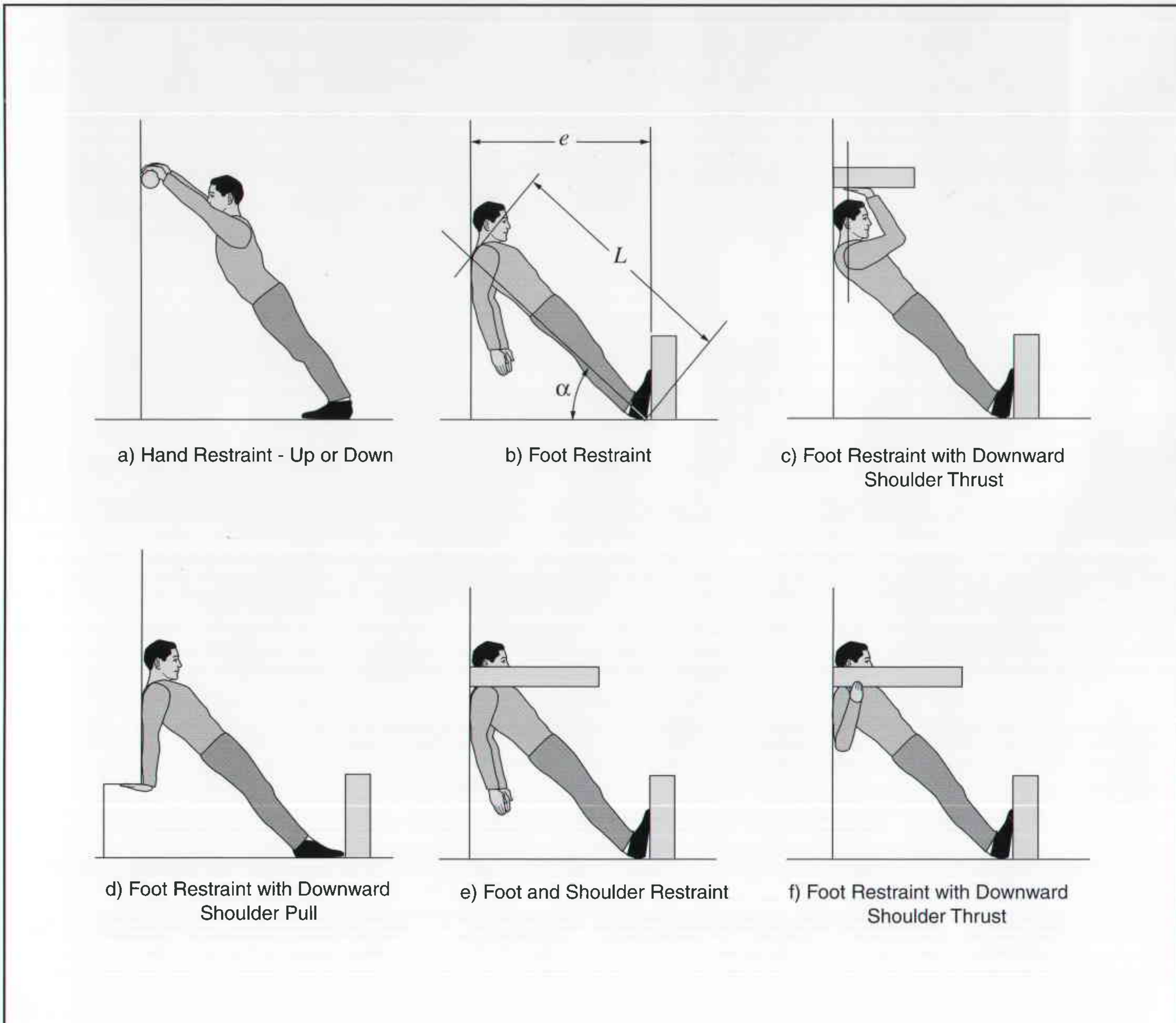

Figure 11 - Slip Inhibitors

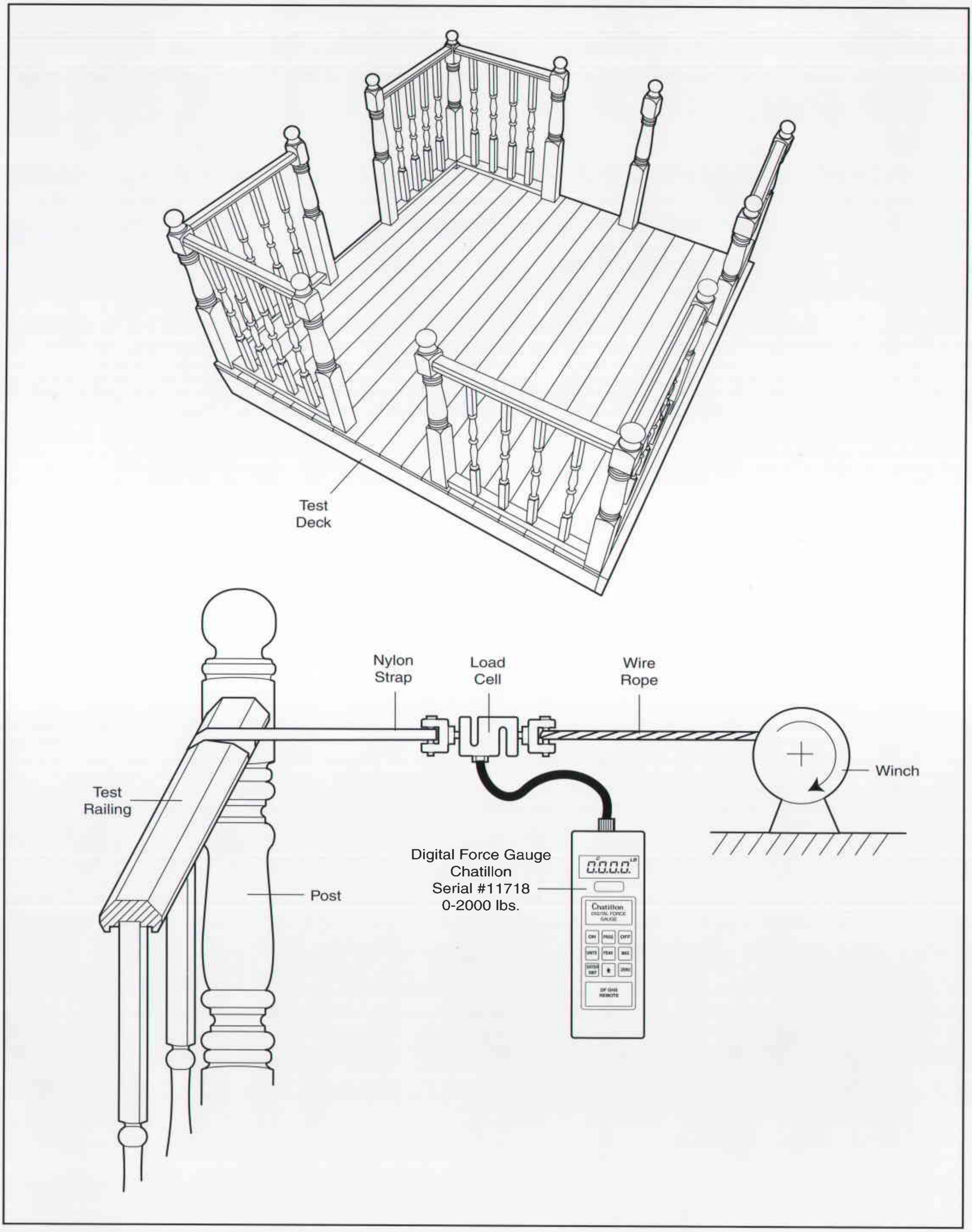

Figure 12 - Test Deck and Instrumentation