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ABSTRACT

This paper summarizes research performed to evaluate the impact of handrail profile dimensions on graspability. It reports on research performed to determine the forces that stairway users exert on handrails when they fall, tests demonstrating the forces persons with various hand sizes can exert on handrails with different profiles, and comparisons of the probability of loss of grip by stairway users when they attempt to arrest a fall by grasping a handrail. The recommendations based on this work include specific definitions of the shapes of handrails that are deemed to be sufficiently graspable to constitute functional handrails.

Keywords: handrail graspability, stairway falls, handrail profiles, handrail research

INTRODUCTION

Falls on stairs constitute a major cause of accidental injury in the United States. While various stairway design parameters have significant influences on the number and severity of accidents, there is no available statistical information that establishes a correlation between the cross-sectional shape of stair handrails and the number or severity of accidents on the stairs.

Statistics aside, a stair handrail should be designed to serve at least four important functions. First, it should provide a guidance surface (i.e., a source of haptic sensory cues) for the user, along which the user can slide his/her hand while moving up or down the stair. Second, it should serve the user as an object against which forces may be applied as a means for enhancing his/her postural stability while using the stair. Third, the handrail must provide something to grab to arrest or mitigate a fall. Fourth, for individuals who experience difficulty ascending stairs, it should provide a means for the user to help pull himself/herself up the stairs.

The first of the above-named functions is relatively undemanding, requiring only a continuous, firm surface - preferably without interruptions such as balustrade or brackets - on which the user's hand can slide. The last three functions require, among other features, a handrail cross-section that will allow the user to pull, at various angles, with enough force ("graspability") to support a significant portion of his/her weight. The most demanding scenario is the third, for which the grasp on the handrail must be sufficient to mitigate the effects of a fall.

In addition to allowing users to develop adequate pulling forces, the grasping surface must be uninterrupted along the length of the handrail, be sufficiently distant from adjacent walls to allow for free grasping action, and be of appropriate height.

The research described herein addresses the performance of handrail shape as it relates to the last two of the four functions described above. The results also are applicable to the evaluation of the ability of handrails to aid in the maintenance of postural stability.

PAST HANDRAIL RESEARCH

For the handrail designer, there are various functional issues that need to be addressed. Intuitively, the greatest force demand on a handrail occurs during a fall. For users already grasping the handrail, how is the handrail used to arrest a fall? If the victim is not touching the handrail, what are the scenarios by which the victim reaches out, grabs the handrail, and arrests his/her fall? For what angles and magnitudes of pull relative to the axis of the handrail should the cross-section be designed? What cross-sectional shapes will enhance the ability of the user to utilize his/her maximum potential pull strength? What shapes will enhance the aesthetic or architectural qualities of the stairway while simultaneously satisfying the functional issues? The answers to these questions are not easy to obtain, and the difficulty is compounded by the consideration that they must be valid for almost the entire user population: whether young or old, small or large, weak or strong, infirm or healthy.

Several researchers have studied the hand and the influence of a number of factors on its ability to develop grasping forces. Wrist and arm position have been shown to influence peak grip forces (Hazelton, et al., 1975; Berme, et al., 1977; Pryce, 1980; Mathiowentz, et al., 1985; Amis, 1987; Savage, 1988; Chao, et al., 1989; Balogun, et al., 1991; Lee and Rim, 1991; O'Driscoll, et al., 1992; Su, et al., 1994; Lamoreaux and Hoffer, 1995; Halpern and Fernandez, 1996; Keng, et al., 1996; Richards, 1997; Werremeyer and Cole, 1997; De Smet, et al., 1998; LaStayo and Hartzel, 1999; Lee and Zhang, 2004). These references and others (Cochran and Riley, 1986; Cochran, et al., 2007) address the influence of aspects of the shape and size of the grasped object on grasping force.

In addition, age, gender, physical training, and infirmities have been shown to be determinants for grip strength (Mundale, 1970; Hall, 1981; Steinfeld, 1986; Desrosiers, et al., 1995; Gorski, 2005; Lever, 2006).

Stairway usage has been studied (Miller and Esmay, 1961; Chaffin, et al., 1976; Archea, et al., 1979; Hay and Barkow, 1985; Templer, 1985; Templer, et al., 1985; McFadyen and Winter, 1988; Pauls, 1991a; Pauls, 1991b; Templer, 1992; Cohen, 2000; Cohen and Cohen, 2001; Ellis, 2001; Di

Pilla, 2003; Gunatilaka, et al., 2005; Scott, 2005), with the findings leading to recommendations concerning stair geometry, including handrail position and cross-section. Elderly persons as a subgroup also have been studied (Hill, et al., 2000a; Hill, et al., 2000b; Startzell, 2000; Wolfinbarger and Shehab, 2000), including evaluation of the role of the handrail in the maintenance of stability (Ishihara, 2002; Whittlesey, 2003). The information presented in these papers primarily is observational.

Some researchers have considered the efficacy of the handrail grasping action and the visuospatial implications of grasping and stepping activities (Maki, et al., 1998; Winges, et al., 2003).

While these prior studies and others have contributed to the understanding of stairway usage and relevant matters related to effective grips on handrails, none has attempted to establish a relationship between the various dimensions of a milled handrail cross-sectional configuration and handrail effectiveness as a grasping surface for stairway use. The only relevant published data prior to the research reported herein was developed at the University of Toronto (Maki, et al., 1984, Maki, et al., 1985a, Maki, 1985b). That research considered handrail texture and user preference, among other factors. Regarding forces that test subjects could exert on stairway handrails, that research tested, for the stabilization function only, a variety of round, square, and rectangular shapes and one milled (decorative) handrail. Test subjects were asked to push or pull on handrails while braced, standing erect on a mock stair. Based on that study, Maki recommended oval handrails (one such shape, with height of 50 mm (2.0 in.) and width of 37 mm (1.5 in.) was tested) and circular handrails with 38 mm (1.5 in.) diameter for young subjects, and circular handrails with 38 mm (1.5 in.) or 44 mm (1.7 in.) diameter or square handrails with rounded corners with 29 mm (1.1 in.) height and width for elderly subjects.

The Maki 1985 research was not intended to determine the forces that people actually exert on handrails during a fall. Rather, the research tested the ability of the test subjects to push or pull on handrails while standing braced in an upright posture, as opposed to the forces that develop in typical stairway use or during the complex process of falls when inertial effects affect the applied forces, and subjects' posture tends to be crouched, off balance, and kinematic. Maki's tests did not consider body-handrail proximity, nor did they model the directions and magnitudes of the forces exerted on handrails during falls. Further, those tests were not designed to evaluate the variety of handrail shapes that are in common use.

RESEARCH DESCRIBED HEREIN

The studies described herein were conducted to study fall kinematics, the forces exerted by fall victims on handrails during falls, the nature of the grasp response, the effect of specific handrail characteristics on graspability, and the probability of defined user types in the population maintaining a grasp on specific handrail shapes during a fall.

To assess the function of handrails of various shapes when the applied forces are the largest, the authors replicated conditions during falls. Among the parameters investigated while developing test protocols were the actual forces exerted on handrails during falls and events involving loss of balance, and the position and posture of fall victims when they apply the maximum forces to the handrail.

To achieve fidelity in the graspability studies, these conditions were replicated to the greatest extent practicable. (As discussed below, fall victims do not exert the greatest forces on handrails when standing erect; the greatest forces occur when victims have fallen forward, rotated around an axis running between their foot on a step and hand on the handrail, with arm outstretched to their side. Hence, test subjects' arms were extended horizontally during grasp force tests to simulate this posture.).

Graspability studies were performed at Simpson Gumpertz & Heger Inc. (SGH); supporting research on fall kinematics and forces exerted on handrails during falls was performed for the authors at the Centre for Studies in Aging at the University of Toronto.

The ultimate objective of these engineering studies is to arrive at proposed specific language, for adoption by model codes, to define the requirements for functional handrail cross-sections. The various phases of this research have been summarized in papers presented by the authors (Dusenberry, et al., 1996 and Dusenberry, et al., 1999). In addition, Dr. Maki and his colleagues at the University of Toronto published an independent paper (Maki, et al., 1998) on the research that they performed as part of one of the research phases of this project.

CURRENT RESEARCH

The research reported herein includes the following studies:

- Tests of subjects induced to fall on stairs to study fall kinematics and to establish forces exerted on handrails during falls.
- Tests to establish the forces that subjects can exert in three principal directions on handrails of various shapes.
- Analyses to extend the data collected in tests to evaluate forces associated with falls by subjects of varying stature.
- Comparisons of forces generated in falls to forces that subjects can exert on handrails to determine the probability of loss of grip.
- Development of specific definitions of shapes that provide appropriate graspability.

This research does not study how stairway users employ available handrails in advance of a fall. For instance, the authors did not investigate the demographics or usage patterns of handrail users before they fall or whether they tend to use their dominant hands when they have a choice, test protocol, subject selection, and analyses were developed to represent the physical characteristics of the adult population with equal consideration to the use of dominant and nondominant hands.

Professor Emeritus Robert W. Mann, a biomechanics expert at the Massachusetts Institute of Technology, and Dr. Alan N. Ertel, an orthopedic surgeon, assisted with the development of the testing protocol at SGH.

Forces Induced on Handrails during Falls and Loss of Balance Events

A major goal of this research was to develop an improved understanding of the nature of the stairway fall and handrail grab response phenomena. This was achieved through a test program, conducted at the request of the authors by Dr. Maki at the University of Toronto, involving the recording of the motions and grab responses of subjects during falls and loss of balance on stairs. Test instrumentation and experimental protocol were developed to identify the influence and relative importance of perturbation magnitude, stance, proximity to the handrail, and initial hand position. The research summarized in this section has been presented in detail elsewhere (Maki, et al., 1996 and Maki, et al., 1998). It is summarized herein because it provides the basis for the author's analytical studies described later.

These tests used a 51-mm-diameter (2-in. diameter) round handrail made of painted aluminum, mounted 864 mm (34 in.) above the leading edge of the treads of a three-step mock stairway. Figure 1 illustrates the test configuration. The mock stairway was mounted on a moving platform. The subjects stood against a vertical backboard mounted to the stairway for support as the platform was accelerated forward to horizontal velocities corresponding to slow, average, and fast descent of stairs. Without warning, the activated stairway was decelerated suddenly to pitch the test subjects forward and down the stairs, which were padded to minimize the potential for injuries. A plastic domed tread cover was mounted on top of the next stair tread down, forcing the subject to bypass this step to regain footing.

The four test subjects were healthy males ranging in age from 20 to 37 years, in weight from 578 N to 890 N (130 lbs to 200 lbs), and in height from 1.7 m to 1.8 m (5 ft-6 in. to 6 ft). Subjects were tested for different standing locations on the stairs, foot positions, velocities, and rates of deceleration, among other variables. Peak platform speeds ranged from 0.25 m/sec to 0.75 m/sec, to represent speeds within two standard deviations of the mean speed that stairway users were observed (Maki, 1998) to traverse stairways. Table 1 summarizes the test program performed on each subject. Data collected included videotapes of the subjects during tests, measurements of human response characteristics, positions of grasp on the handrail, and forces exerted on the handrail.

The forces exerted on the handrail were determined using force plates mounted at the bases of the posts supporting the handrails. Force data were processed and resolved into component forces relative to the main axis of the handrail. To facilitate comparison between individuals of differing size, the force variables were normalized by dividing by body weight.

Stairway accident kinematics were determined from the video data, which also revealed the position of test subjects' bodies at critical times during the fall and loss of balance sequences.

Test results listed in Table 2 show the magnitudes of the average peak forces, expressed as a percentage of body weight, exerted on handrails in the three orthogonal primary directions – transverse (sideways), longitudinal (along the axis of the handrail), and normal (upward) direction. (Figure 2) While the standard deviations of the forces are somewhat large, the magnitudes of the average peak forces ranged between approximately 12% and 17% of the subjects' body weights for all directions and all cases tested.

Graspability Tests / Limits of Forces Imposed by Individuals on Handrail Sections

The test protocol, as reported in the previous section of this paper, to determine the forces exerted on handrails during falls was impractical to investigate the influence of handrail cross-sectional profile on graspability. Costs, time, and safety issues precluded fall-simulation testing for the numerous combinations of test subjects and handrail characteristics required to evaluate handrail performance by the general population. Therefore, to evaluate the impact of handrail shape on graspability, the authors developed apparatus and protocol for testing the forces that people could exert on handrails of various shapes.

Test data were acquired in four test programs, referred to as Phases I, II, III, and IV, using the test apparatus shown schematically in Figure 3. As discussed in greater detail below, testing phases were as follows:

- Phase I testing measured graspability in the transverse direction for the 51-mm (2 in.) diameter round and a milled profile commonly referred to in the U.S. handrail manufacturing industry as the “6010” milled handrail section for a total of 73 subjects, including males and females of various ages and with various hand sizes.
- Phase II testing measured graspability in the transverse direction for six additional milled rail sections for six subjects, three male and three female, selected from the Phase I subjects and representing the small, medium, and large hand sizes for each gender.
- Phase III testing measured graspability in the normal upward direction, for the same test subjects used in the Phase II testing and for five additional milled handrail sections. Handrail sections with a similar crown radius and side purchase but with different widths were not repeated. The round handrail was not retested because the grasped configuration for the transverse and normal upward directions is similar.

- Phase IV testing measured graspability in the longitudinal direction for the same test subjects used in the Phase II and Phase III testing, for the round section and five of the milled handrail sections. Some of the milled handrail sections were omitted from this testing due to budget and time limitations. The shapes of the omitted handrail sections were bracketed by the tested sections.
- The test apparatus included an adjustable, padded table against which the subjects braced themselves, a sliding platform on which the handrail specimen was mounted, an electric motor with speed control for moving the handrail away from the test subject, and a load cell and associated instrumentation for measuring the force exerted by the subject on the handrail.

Test subjects were in a seated position, with outstretched arms. A seated position was chosen for two reasons. First, it was apparent from the fall simulation tests at the University of Toronto that the maximum forces exerted on handrails occur while the person is falling, not while standing erect. In fact, loss of grip often occurred when the test subject's body had lowered enough that the grasping arm was extended essentially horizontally from the shoulder to the handrail, with elbow straight. Hence, tests with the arm outstretched at the elevation of the shoulder reasonably simulate the arm's orientation at the time of maximum applied force. Second, tests with subjects seated and braced enhanced repeatability.

A total of nine handrail cross sections were tested: eight milled sections and one 51-mm (2-in.) round section (Figure 4). In general, the milled sections were variants of the aforementioned "6010" milled handrail. Each cross section contained a variation in one of the critical dimensions: the width of cross section, the depth of finger purchase (or undersurfaces) on both sides, and the height of the crown. The purpose for using this set of handrail profiles was to isolate and investigate the influence of each of these critical dimensions on graspability.

Tests were performed for force directions that were pulls transversely, pulls upward in a direction normal to the axis of the handrail, and sliding longitudinally forward on the handrail. While the Toronto tests (Maki, et al. 1998) also showed that significant push forces are exerted on handrails during falls and loss of balance, the ability of handrail users to develop such forces is not likely to be significantly influenced by the shape variations studied in the research reported herein. Hence, these studies do not evaluate the ability of test subjects to push against handrails.

The initial test series (Phase I) obtained comparative graspability data for two handrail designs: the basic 6010 milled handrail (Figure 4 Section 7) and a 51-mm (2 in.) diameter round handrail. This test program measured the maximum pull in a transverse direction, applied by each subject to each handrail as the handrail was slowly moved away from the subject. Subjects were seated and the handrail positioned such that the arm was fully extended but the subject could freely grasp the handrail in a comfortable manner. With the subject grasping the rail, the padding was moved laterally to support the arm and contact the subject just below the arm pit and take up any slack between the rail section and the torso. The padding was locked into place. The handrail section was moved laterally using a variable speed motor driving a screw jack. The motor was connected to the worm drive of the screw jack using a drive belt and sheaves. The mechanical advantage of the connection was such that there was no noticeable difference between the translation of the unrestrained handrail compared to the translation during the graspability testing. The speed control on the motor was set to move the unrestrained handrail section approximately 4 inches per minute, resulting in a typical time to release of about one minute. The test speed used was a compromise between an appropriate test time to maximum force and in consideration of the safety of the test subject. Force was recorded with a Mecmesin AFG-2500N digital force gage set to hold the peak force. The unit has a specified accuracy of 0.1% of full scale (+/- 3 N) The electrical output of the force gage was connected to a computer-displayed bar graph, with no numerical scale, so that the subject could watch the scale rise as the exerted force increased. Verbal instructions provided to the test subjects included:

- Please sit on the adjustable chair at the end of the table with your right (left) arm extended over the pad. Turn sideways so that your shoulders and arm form a straight line.
- Let's adjust the extension of the table, the table height, and the chair height until your arm is fully extended when holding the handrail, your arm is horizontal, and the pad is firmly under your arm and against your side.
- Take a firm grip on the handrail.
- Put your legs together straight in front of you with your shins vertical.
- During the test, please to not move your feet or attempt to raise off of the chair.
- The computer screen on the table has a scale that looks like a thermometer. This scale will show how the force you exert is changing during the test. Please watch this screen.
- It is important for us to know differences in forces that you can develop with each hand and each handrail. Please try to make the scale go as high as you can, but please let go when and if you feel in danger of overstraining yourself. As soon as it appears you can't make the scale go any higher, you should let go.

A single "practice" trial was performed prior to the first test for new subjects, so that the subject could experience the test apparatus. No practice trials were performed for subsequent testing on the same subjects. Repetitive sessions of the various rail sections were performed in a random order.

In this phase of tests, 73 subjects, ranging in age from 10 years to 83 years, tested their ability to maintain a grasp on the selected shapes. The distribution of hand sizes for these test subjects closely represented the hand size distribution for the U.S. general population (SAE J833 May 1989). Hand size was determined by measuring the overall length of the open-palmed hand from the wrist crease to the tip of the middle finger. The subject group included persons with hands smaller than the 5th-percentile woman's hand (165 mm) and larger than the 95th-percentile man's hand (205 mm) as defined by SAE J833. Figure 5 shows age, hand size relative to the mean (185 mm), and gender distributions. Subjects were verbally provided scripted instructions for the test. The maximum grasp forces for one trial of each subject's left and right hands on each handrail section were recorded in a single sitting. A total of 292 tests were performed. The Phase I test data are presented in Figure 6 as the ratio of the grasp force of the milled section over the grasp force of the round section versus measured hand size.

Six subjects from the Phase I population were selected for the Phase II tests. One subject was selected to represent each group of small, medium, and large hand sizes for both men and women. These same six subjects also participated in the Phase III and Phase IV testing programs. All subjects were healthy with no known disabilities. Table 3 includes physical data for the selected subjects.

Phase II testing evaluated the influence of geometric parameters of the handrail shape on transverse graspability. Following the same test protocol used in Phase I, we tested six additional milled shapes (Figure 4 -Sections 1 through 6) with variations in the crown radius and depth of finger purchase.

Testing protocols for this and all subsequent phases were developed to minimize testing fatigue and virtually eliminate the influence of test sequence. Tests for a single subject were administered in two separate sessions. Each session consisted of one trial of each hand on each of three handrail sections, or six trials per session. The order in which the handrail sections were tested was determined randomly for each subject.

To account for variability in each individual subject, this series was repeated at a later date with the same subjects, except that three trials were recorded for each hand for each of the tested cross sections. Tests were conducted in multiple sessions, limiting the total trials to 12 (six for each hand) for each sitting, to minimize potential fatigue effects. All trials for each handrail section and each subject were combined for a total of eight test values for each condition.

Phase III measured the maximum pull applied by each subject in a normal upward direction on milled sections. We observed that, for the purpose of this research, the grasp on a round handrail was similar for the transverse and the normal upward directions. While the extension of the wrist would likely affect forces that test subjects could exert, our analytical studies herein used results for transverse tests on round handrails to predict forces in a normal upward direction on round handrails. (This likely overestimates the capacity of the round handrail in the upward direction.) Hence Phase III tests evaluated milled handrail sections only, by positioning the test specimens in the apparatus with the handrails rotated 90^{o} around their longitudinal axes, such that they were oriented in the test apparatus, with its top surface facing the subject. Five handrail sections, (Figure 4 – Sections 1 through 4, and 7a) with varying depth of finger purchase and overall width, were tested in this series. To prevent subjects from developing unrealistically high capacities by grasping milled handrails beyond the intended grasping surfaces (i.e., on the underside of the handrails), a wooden barrier was affixed to the bottom of the milled handrails to force test subjects to grasp the handrail using only its top surfaces. We conducted three trials of each hand for each tested handrail section. One trial of each handrail section was performed per session for a maximum of 10 tests per session. Handrail sections were tested in a random order.

Phase IV testing measured the ability to grasp handrails for forces in the direction parallel to the longitudinal axis of the handrail section and perpendicular to the subject's outstretched arm. The test apparatus was modified as shown in Figure 3. An anchored sling was added to restrain horizontal movement of the arm during testing. Following protocol similar to those of previous tests, subjects were tested on six handrail sections. We conducted three trials of the dominant hand for each tested handrail crossection. All tested subjects were right-handed. Tests were performed over three, days with one test of each handrail section per day. Handrail sections were tested in a random order at each session.

TEST RESULTS AND COMMENTS

Stairway Fall Tests

The results of the tests performed at the University of Toronto for the forces on the handrail required to arrest a fall and restore postural stability are presented in Table 2.

With respect to the test variables, review of the test results reveals the following:

- As perturbation magnitude increased, so did the measured forces in all directions.
- The initial stance (left or right foot) had little effect on any of the analyzed variables.
- Proximity to the handrail had a significant effect on measured values, probably because as the subject was positioned closer to the handrail, the grasp became more vertical.
- Test data indicate that for tests in which the subject was instructed to grip the handrail prior to perturbation, the transverse force on the handrail was about one-half of, and the normal upward force was significantly higher than, the values obtained when the subject did not initially grasp the handrail.

Graspability Tests

Graspability data for the primary directions and all tested handrail sections are summarized in Table 3. The presented data for the upward direction include transverse data for the round handrail from the Phase I tests. Transverse pull and normal upward pull test results should be similar on round handrails provided the grip is not compromised by balustrades or other supports.

Results for Phase I transverse pull tests are plotted in Figure 6, which shows, for each hand size, the mean ratio of milled handrail grasp strength to round handrail grasp strength. The shaded zone in the figure shows that most of the ratios are between 0.8 and 1.2, suggesting that the most commonly installed milled handrail and the 51-mm-diameter (2-in. diameter) round handrail provide similar support potential in the transverse direction. More definitive demonstration of the relative graspability of these handrails follows from later phases of the study.

Based on the Phase I tests, women as a group and men with small hands tend to be able to develop larger forces when grasping the tested milled handrail than when grasping the round handrail.

Video of test subjects in the fall tests demonstrate that as the subject falls and is pulled away from the handrail, his thumb necessarily pulls away from the handrail, thereby voiding any “power grip” or “span grip” initially achieved. (A “power grip” is defined as the closed hand encircling and clenching the handrail. A “span grip” is essentially the same as “power grip,” except that the clenched hand does not close around the profile.)

In all cases, finger purchases on the sides of handrails enhanced the test subjects’ ability to obtain a firm grip on the handrail for both transverse and normal upward pulls. For transverse pull, the finger purchases allowed the subject to place his/her finger tips below a protrusion, thus facilitating a firm, hook grip that is not possible without a protrusion. For normal upward pull, the finger purchases created lips for the fingers and thumb to engage. The influence of the finger purchase was not as marked for longitudinal pull tests.

The height of the handrail crown had little influence on the forces generated by the test subjects. Also, the effects of handrail width, within the range tested, were minimal.

As discussed above, six subjects from the Phase I study, one male and one female subject representing small, medium, and large hand sizes of the adult population, were selected for additional testing. Graspability values were measured in the three principal directions relative to the handrail section for a variety of shapes. Average maximum measured values ("capacities") expressed as a percentage of body weight are summarized in Table 3.

THEORETICAL STUDIES

It is impractical to physically test all combinations of test subjects and handrail shapes in fall and loss of balance studies. Also, limits imposed by subject safety and testing feasibility constrain test protocols. These constraints led the authors to develop and validate an analytical approach to extend the applicability of the results obtained by the University of Toronto tests. The subjects of the Toronto tests were all young males of similar stature. Also, limitations imposed by the test apparatus forced each test to start with the test subject standing erect with straight legs, creating a somewhat unnaturally upright posture for someone modeled to be descending stairs.

The objective of the analytical modeling study was to evaluate the effects that subject height and posture have on the forces exerted on the handrail, and to extrapolate the experimental results to classes of individuals not represented in the experimental program. Furthermore, by combining the results of the experimental program and analytical studies and by using statistical analysis, the probability that individuals within the general population would lose grip during a fall could be determined.

The kinematics of a stairway fall are complex. Victims who stumble on stairs and try to arrest their fall reach for an object to grab, step forward if they can, and generally try to lower themselves toward the stair. The path of travel of the victim's body is affected by its mass, gravity, initial speed and trajectory of motion, and any forces that the victim exerts on the stairs, handrails, or any other objects with which he/she makes contact while in motion.

Fall kinematics developed by studying videotapes of test subjects and films of actual stairway accidents (Archea, 1979) allowed development of an analytical kinematic model to represent the process of the subject falling down the stairs. This model, which captures the essence of the motion in the most critical time period – while there is still hope that a falling victim might successfully arrest a fall, concentrates the body weight at the sternum and treats the victim as standing on one foot on a tread and gripping the handrail with one hand. Essentially, the person is assumed to be set in motion with an initial velocity and trajectory that represent his/her movement after a stumble, and the movements and forces are calculated as the victim pivots and falls around the contact points with the tread and handrail.

The analytical model engages an axis of rotation from the foot on the stair tread to the hand grasping the handrail. The model uses rigid links to connect these two points through the sternum. The initial velocity corresponds to the perturbation speeds used in the Toronto tests. The ends of the rigid links are fixed against translation at the foot and hand points, but rotation about the axis is freely permitted as reaction forces are developed. For illustration, the analytical model is shown superimposed on a photo of a person on stairs in Figure 7.

In this model, the centrifugal force created by the moving mass is:

$$F_c = m \cdot r \cdot \left(\dot{\phi}\right)^2$$

where F_c = centrifugal force

$m =$ moving mass

$r =$ perpendicular distance between the axis of rotation and the centroid of the mass

$\dot{\phi} =$ angular velocity, equal to the initial translational velocity divided by r.

The force on the handrail is:

$$F_h = F_c \cdot \frac{L_f}{L_a}$$

where $F_h =$ force on the handrail

$L_f =$ distance along the axis of rotation from the support provided by the foot to the point on the axis where a normal to the axis passes through the centroid of the mass

$L_a =$ length of the axis from the support provided by the foot to the support provided by the hand.

The direction of the force on the handrail is parallel to the time-varying direction of the normal connecting the axis of rotation to the centroid of the mass.

The algorithm was tested for conformance with test data by determining the angle of rotation at which the algorithm produced peak forces that correlated with test data for a subject of the stairway fall tests. This angle of rotation was used to investigate theoretical forces exerted on the handrail by persons of various statures and with knees slightly bent to represent subjects walking on stairs. This was considered to validate the analytical model for the evaluation of the effects of victim height and posture on handrail forces.

Using published data (SAE, 1989) of adult height distribution, analyses were performed using input parameters representing large (95th-percentile male), medium (50th-percentile male or female), and small (5th-percentile female) subjects to envelope the force demands for the general population. Solutions were determined for the three perturbation speeds used in the Toronto tests. These analyses show that the upward pull exerted by the subject during the fall decreases as the height of the victim's concentrated body weight is lowered (representing either shorter victims or victims with bent knees at initiation of a fall), but that the forces transverse to the handrail and along the axis of the handrail are not influenced strongly by height.

Based on the results for the kinematic analytical model, a relationship between height and upward pull on the handrail was established and used for extending fall test data to the general population.

Probability of Failure (inability to arrest a fall)

The fall tests, combined with the results of the kinematic analytical modeling, provided the statistical distribution of forces generated on the handrail by individuals of various heights. The graspability tests provided the statistical distribution of the grasping capacity that individuals can achieve before the grip fails. Using these demands and capacities, we calculated the probability of loss of grip as a function of victim stature. These results, when combined with the probabilistic distribution of the hand size and height of the adult population, yielded the overall probability that fall victims in the general adult population will lose grip after they stumble on stairs and reach for handrails of various configurations. We performed the statistical analysis for the various handrail shapes used for the graspability tests and for each of the three directions along which loss of grip is likely to occur-longitudinal, normal upward, transverse. For example, Figure 8 is a graphical representation of the probability of loss of grip for an average male and handrail section 7 (A30/8.0) in the normal direction. Figure 9 shows comparisons of the probabilities of loss of grip as a function of depth of finger purchase recess, crown height, and width.

Table 4 shows the probability of failure for the three principal force directions, for each of the subjects by height, and for each of the tested handrail sections. Female graspability subjects with small and large hands had the same height, so data were combined.

The results of the statistical analysis are summarized in Table 5. The results show that the most likely failure mode is slip along the longitudinal direction. The probability of loss of grip in this direction ranges between 33.7% and 47.8%, with higher probabilities of failure for the round shape and the shape with no side recess.

As the depth of the finger purchase increases, the probability of loss of grip in the normal upward direction decreases; the loss of grip in the other directions is unaffected. The probabilities of loss of grip (i.e., the likelihoods that the force required to be exerted on a handrail to abort a fall exceeds the ability of the test subject) in the transverse direction for all shapes are relatively small and, therefore, capabilities in this direction are unlikely to control whether a person is able to retain a grip during a fall. The height of the crown and the width of the handrail, within the limits tested, do not have significant correlation with the probability of loss of grip.

DISCUSSION

The fall scenario evaluated in this study, e.g., a forward fall while descending stairs, is only one way – but perhaps the most hazardous way – that victims fall on stairs. Films of actual falls (Archea, 1979) reveal that some victims fall to a sitting position instead of forward when they stumble. This scenario creates less critical demand on handrails when compared to the scenario we analyzed. Victims who fall while ascending stairs normally would fall to their knees on the steps in front of them without using the handrail.

It is likely that many victims of serious falls never achieve firm grip on the handrail. They might be too far away from the handrail when they stumble, their hands might be occupied carrying an object, or they might simply miss when they lunge for support. In these cases, it is unlikely that the shape of the handrail has significant impact on the outcome of the accident.

Considering the factors mentioned above, it is apparent that the fall scenarios studied here represent hazardous events in which the shape of the handrail may have a significant impact on the outcome. For other fall scenarios, both more serious and less serious and representing the majority of stairway accidents, the influence of handrail shape is probably far less significant. The calculated probabilities of loss of grip appear to offer a reasonable basis for judging the relative performance of handrail shapes under certain fall scenarios which are considered to be the most demanding.

Kinematic modeling and statistical analysis determine the probability that the forces required to arrest a fall by a random sampling of the adult population will exceed the ability of individuals in the population to maintain a grip on a handrail of a given shape. The higher the probability of loss of grip, the less effective is the handrail shape.

The results show (Figure 9) that it is important for handrails to have a finger purchase for firm grip in the normal upward direction. Even the relatively small radius (when compared to the tested round handrail radius) associated with the top surface of most tested milled shapes allowed all subjects, and especially subjects with small hands, to maintain a firm grip in the transverse direction even after the thumb pulled away from the handrail at the time of maximum force generation. Height of crown and width of the handrail, within the limits tested, have minimal influence on handrail safety.

The testing and analyses also show that the peak forces generated on a handrail by a user during a fall are through a grasp that involves the fingers in contact with the outside surface of the handrail, but with the thumb drawn away from the inside surface. Therefore, the peak forces resisting a fall do not occur through the action of a power grip or a span grip.

CONCLUSIONS

Much is yet to be learned about handrail graspability, stairway fall scenarios and statistics, and how handrails are used to arrest a fall. However, the tests and analyses conducted during this study reveal the relative importance of critical geometric characteristics of handrail shapes. Specifically, the following are demonstrated by this research.

- Tests and analyses show that depth of the finger purchase in the sides of handrails is an important factor affecting handrail performance. Within limits, the deeper the finger purchase, the lower the probability that a fall victim will lose grip (Figure 9). Also within limits, the height of the handrail crown (up to 32 mm, or 1-1/4 in) and the width of the handrail (up to 70 mm, or 2-3/4 in) are relatively unimportant for handrail performance. The 51-mm (2-in.) round handrail tested in this study consistently performed well.
- Tests and analyses show that it is in the longitudinal direction that fall victims are most likely to lose grip (Figure 9). In this direction, the variation among in the probabilities of loss of grip for the shapes tested is relatively small: the probability of loss of grip is in the range of approximately 34% to 48% for all shapes, with the round shape and the shape with no finger purchase having the highest probability of loss of grip and shapes with relatively deep finger purchases having the lowest probability of loss of grip.
- For the most severe fall scenarios in which handrail shape is likely to influence outcome (victims falling forward and attaining grip on the handrail), round handrails of the size tested in this study and handrails with relatively deep finger purchases on the sides are

likely to perform better than handrails with relatively shallow finger purchases or no finger purchases. To maximize the probability that victims will arrest falls, handrails should have either an “under surface” or a finger purchase at least as deep as that found on the 6010 shape (approximately 8 mm or 5/16 in) (Figure 9).

HANDRAIL PROVISIONS IN BUILDING CODES

In recent years, the community of code-writing bodies has debated many stairway safety issues. One such debate has centered on the effectiveness of handrail sizes and profiles in the development of sufficient grasping force to arrest a stairway fall and enhance safety for the stairway user. Intuitive arguments have been presented to support a variety of opinions about the suitability of some profiles for arresting an actual fall or loss of balance, but there has been little scientific justification. In the United States, these arguments have led to increased restrictions on handrail shapes.

The purpose of the research presented herein is to systematically evaluate the influence of key profile dimensions on graspability by testing dynamically under controlled fall scenarios the actual forces victims exert on handrails when they fall. The body of data collected during the research reported herein provides a substantial base for definitive conclusions about the effectiveness of handrails of various shapes. From these conclusions, specific prescriptive language can be developed for adoption as mandatory requirements by code-writing bodies.

Perhaps the most important feature essential for functional handrail profiles are protrusions, or lips, that create finger purchases into which users can place fingers and thumb when grasping both sides of handrails. These protrusions allow users to develop a firm grip and, therefore, sufficient upward and transverse forces to achieve secure grasp. Protrusions also enhance the longitudinal force capability.

Of course, properly mounted round handrails of limited diameter provide the effect of such protrusions. The current research confirms what has been commonly accepted by building codes for some time: round handrails that are 51 mm (2 in) in diameter are functional.

The current research shows that handrails need not be round to be functional. An entire family of shapes, with certain widths, heights, and depths of finger purchases on the sides, provides surfaces that can be grasped adequately to arrest a fall. Within this family are profiles of width and height such that small hands can encircle the grasping surface while large hands can achieve a functional grip without digit/thumb overlap interference or obstructions from support brackets or balustrade.

The essential recesses that create the finger purchases must be located within a prescribed distance below the crown and below the widest portion of the gripping surface to provide proper locations for the finger and thumb lands. With these parameters properly controlled, the handrail profile below the finger purchases – below the grasping surface – can have an arbitrary shape, thereby allowing for variety and artistic expression.

Based on our test results, we conclude that symmetric handrail shapes that are at least 32 mm (1-1/4 in) and not more than 70 mm (2-3/4 in) wide, with a height above the widest portion of the profile not exceeding 19 mm (3/4 in) are sufficiently graspable as long as there is a recess on both sides at least 8 mm (5/16 in) deep. Each recess should achieve this minimum depth no farther than 22 mm (7/8 in) below the widest portion of the handrail, and extend down at least 51 mm (2 in) from the top of the handrail. Additionally, the portion of the height of each recess that is at least as deep as 8 mm (5/16 in) should be at least 9.5 mm (3/8 in). In all aspects tested, the probability of loss of grip on a handrail with this shape is essentially the same as or better than for a 51-mm (2 in.) diameter round shape.

Depending on the details for mounting handrails, shapes that are not round have one advantage: round shapes mounted on balusters could have their undersurfaces, and therefore their graspability, interrupted at each connection to the balusters. The grasping surfaces of shapes conforming to the limitations stated above are not interrupted.

Data and analyses presented herein have been considered by the International Code Council in the United States during its deliberations, leading to its reversal of prior restrictions and adoption of the "Type II" handrail for residential applications.

RECOMMENDATIONS FOR FUTURE STUDIES

The research reported herein provides guidance on the adequacy of a family of symmetric handrail shapes that have a top grasping surface with finger purchases on both sides. Additional areas of study that could advance the knowledge about functional handrail shapes could include the following.

- The effectiveness of handrails that are wider or narrower than those studied herein.
- Graspability of asymmetric handrails, having different depth finger purchases on opposite sides.
- The efficacy of the grasp of handrails of various shapes when grasped rapidly.
- The influence of specific grasp-related infirmities on the ability to grasp handrails of various shapes.
- Forces generated on handrails during uses that are less demanding than fall arrest scenarios, including stabilization during normal stairway use and as a pull bar to assist while ascending stairs.

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Table 1 – Summary of Tests for Forces Induced on Handrails during Falls

Main Test Parameter	Variable Test Parameter	Number of Conditions	Total Number of Trials
Familiarization Trials [1]			3
Main Tests [2]			36
	Speed [a]	3	
	Leg Stance [b]	2	
	Lateral Displacement [c]	2	
Feet Obstructed [3]			6
	Speed [a]	3	
	Lateral Displacement [c]	2	
Hand on Handrails [4]			6
	Speed [a]	3	
	Leg Stance [b]	2	
No Handrail [5]			6
	Speed [a]	3	
	Leg Stance [b]	2	

Total Number of Trials Per Subject: 57

Main Test Parameters:
[1] Familiarization Trials – Preliminary tests for subject to understand how test apparatus works.
[2] Main Test Program – Three trials of each set of conditions.
[3] Tests conducted with both feet down and “restrained” with a piece of foam over the top. One trial of each condition.
[4] Tests conducted with the subject’s hand on the handrail prior to the start. One trial of each condition.
[5] Tests conducted with handrail removed from staircase. One trial of each condition.

Variable Test Parameters:
[a] Speed: Maximum speed of platform at deceleration = 0.25, 0.5, and 0.75 m/sec (0.82, 1.64, and 2.46 ft/s).
[b] Leg Stance: Test started with either right or left foot extended.
[c] Lateral Displacement: Subject positioned with the center of the body to the center of thehandrail at 32 cm or 61 cm (1.05 ft or 2.00 ft).

Table

Table 2 – Summary of Results of Tests for Forces Induced on Handrails during Falls

Direction	Force (% of Body Weight)	
	Mean	Standard Deviation
Transverse direction – perpendicular to handrail, horizontal direction	16.3	8.4
Longitudinal direction – parallel to main axis of handrail section	17.3	7.9
Upward direction – perpendicular to handrail, vertical direction	11.6	7.1

Table

Table 3 – Summary of Graspability Testing

Gender / Handsize	Female Small	Female Average	Female Large	Male Small	Male Average	Male Large
Weight (N)	579	530	690	712	734	1,291
Height (mm)	1,626	1,626	1,829	1,778	1,803	2,032
Age, years	31	23	47	35	29	40
Size, mm Dominant hand	167	173	194	181	193	213
Size, mm Non-Dominant hand	166	176	195	183	189	220
Average hand size, mm	167	175	195	182	191	217
Handrail Shape	Average Capacity Transverse Direction, (% of Body Weight) Phase II Testing					
(1) A00/8.0	34.6	40.0	34.4	46.9	61.5	46.1
# of Tests/Std. Dev.	8/4.6	8/5.4	8/5.4	8/10.6	8/3.9	8/3.6
(2) A15/8.0	41.6	44.7	39.6	55.3	66.9	46.8
# of Tests/Std. Dev.	8/5.7	8/8.2	8/3.1	8/8.1	8/4.1	8/2.6
(3) A45/8.0	40.3	48.1	38.3	57.3	73.0	52.4
# of Tests/Std. Dev.	8/3.4	8/6.6	8/2.4	8/7.1	8/5.6	8/5.1
(4) A30/2.0	40.9	42.9	39.7	55.7	67.1	50.2
# of Tests/Std. Dev.	8/9.2	8/5.5	8/3.2	8/3.0	8/2.6	8/5.1
(5) A30/1.5	36.3	48.1	41.5	53.0	70.8	50.7
# of Tests/Std. Dev.	8/3.9	8/5.5	8/6.2	8/3.7	8/5.4	8/5.1
(6) A30/1.25	36.1	43.5	38.2	57.8	67.1	46.1
# of Tests/Std. Dev.	8/3.1	8/5.3	8/4.8	8/3.2	8/7.0	8/6.2
(7) A30/8.0	28.5	53.0	26.9	64.1	61.3	55.9
# of Tests/Std. Dev.	2/2.6	2/1.0	2/0.3	2/6.0	2/2.6	2/0.4
Round	32.6	53.7	37.8	65.9	71.5	58.2
# of Tests/Std. Dev.	2/0.5	2/1.6	2/11.8	2/2.6	2/1.9	2/2.1
Handrail Shape	Average Capacity Longitudinal Direction, (% of Body Weight) Phase IV Testing					
(1) A00/8.0	14.4	16.7	11.4	19.8	30.2	19.6
# of Tests/Std. Dev.	3/3.2	3/1.1	3/1.7	3/0.8	3/7.1	3/6.5
(3) A45/8.0	19.2	18.2	13.2	23.0	36.5	21.3
# of Tests/Std. Dev.	3/2.5	3/1.6	3/2.7	3/0.8	3/1.8	3/4.7
(6) A30/1.25	17.4	20.8	14.3	23.0	33.3	21.0
# of Tests/Std. Dev.	3/0.8	3/4.1	3/0.8	3/2.2	3/5.4	3/4.9
(7) A30/8.0	18.1	19.4	12.6	22.5	30.1	21.1
# of Tests/Std. Dev.	3/1.3	3/2.5	3/1.2	3/2.8	3/6.2	3/4.1
(7a) A30/8.0	21.2	20.5	13.6	22.3	37.4	18.2
# of Tests/Std. Dev.	3/0.9	3/5.0	3/0.2	3/1.3	3/4.9	3/0.6
Round, D	15.9	15.5	12.5	20.9	30.6	24.6
# of Tests/Std. Dev.	3/3.7	3/1.6	3/0.6	3/0.8	3/3.3	3/1.8
Handrail Shape	Average Capacity Normal Upward Direction, (% of Body Weight) Phase III Testing					
(1) A00/8.0	10.2	13.6	9.5	11.4	13.3	9.5
# of Tests/Std. Dev.	6/2.9	6/1.8	6/0.7	6/1.6	6/1.5	6/0.6
(2) A15/8.0	13.5	17.9	12.4	16.5	18.4	12.9
# of Tests/Std. Dev.	6/0.9	6/2.7	6/1.1	6/3.5	6/2.1	6/1.3

(3) A45/8.0	20.3	24.9	17.3	26.5	29.2	23.3
# of Tests/Std. Dev.	6/3.5	6/2.8	6/1.6	6/3.5	6/3.5	6/3.2
(4) A30/2.0	16.9	22.3	15.1	22.1	24.5	18.2
# of Tests/Std. Dev.	6/3.9	6/1.9	6/0.6	6/3.2	6/4.2	6/2.5
(7a) A30/8.0	17.5	22.2	15.9	23.1	21.6	18.7
# of Tests/Std. Dev.	6/3.8	6/1.3	6/1.1	6/3.2	6/3.2	6/1.4
Round	32.6	53.7	37.8	65.9	71.5	58.2
# of Tests/Std. Dev.	2/0.5	2/1.6	2/11.8	2/2.6	2/1.9	2/2.1

Table

Table 4 – Summary of Probability of Failure

Gender / Handsize	Female Combined Small and Average	Female Large	Male Small	Male Average	Male Large
Height (mm)	1,626	1,829	1,778	1,803	2,032
Handrail Shape	Probability of Failure – Transverse Direction Phase II Testing				
(1) A00/8.0	3%	1%	0%	5%	1%
(2) A15/8.0	1%	0%	0%	2%	1%
(3) A45/8.0	1%	0%	0%	3%	0%
(4) A30/2.0	2%	0%	0%	2%	0%
(5) A30/1.5	1%	0%	0%	2%	0%
(6) A30/1.25	2%	0%	0%	3%	1%
(7) A30/8.0	2%	0%	0%	14%	0%
Round	1%	0%	0%	3%	0%
Handrail Shape	Probability of Failure – Longitudinal Direction Phase IV Testing				
(1) A00/8.0, D	58%	76%	39%	10%	40%
(3) A45/8.0, D	44%	69%	27%	4%	33%
(6) A30/1.25, D	42%	64%	27%	6%	34%
(7) A30/8.0	43%	71%	28%	10%	33%
(7a) A30/8.0	35%	67%	29%	3%	46%
Round, D	58%	72%	34%	9%	22%
Handrail Shape	Probability of Failure – Upward Direction Phase III Testing				
(1) A00/8.0	29%	61%	46%	39%	79%
(2) A15/8.0	15%	46%	22%	18%	63%
(3) A45/8.0	4%	23%	4%	2%	18%
(4) A30/2.0	7%	32%	8%	6%	36%
(7a) A30/8.0	7%	29%	7%	10%	34%
(8) Round	0%	1%	0%	0%	0%

Table

Table 5 – Combined Probability of Failure

Handrail Shape	Transverse Direction	Longitudinal Direction	Upward Direction
(1) A00/8.0	2.2%	**47.8%**	38.8%
(2) A15/8.0	0.9%	Not tested	**22.0%**
(3) A45/8.0	0.9%	**36.6%**	6.4%
(4) A30/2.0	1.0%	Not tested	**11.1%**
(5) A30/1.5	**0.9%**	Not tested	Not tested
(6) A30/1.25	1.3%	**35.3%**	Not tested
(7) (Ph I) A30/8.0	2.8%	**37.8%**	Not tested
(7a) (Ph I) A30/8.0	Not tested	**33.7%**	10.3%
Round	0.9%	**45.3%**	0.1%

Bold values indicated the greatest combined probability of failure for the handrail section

Figure

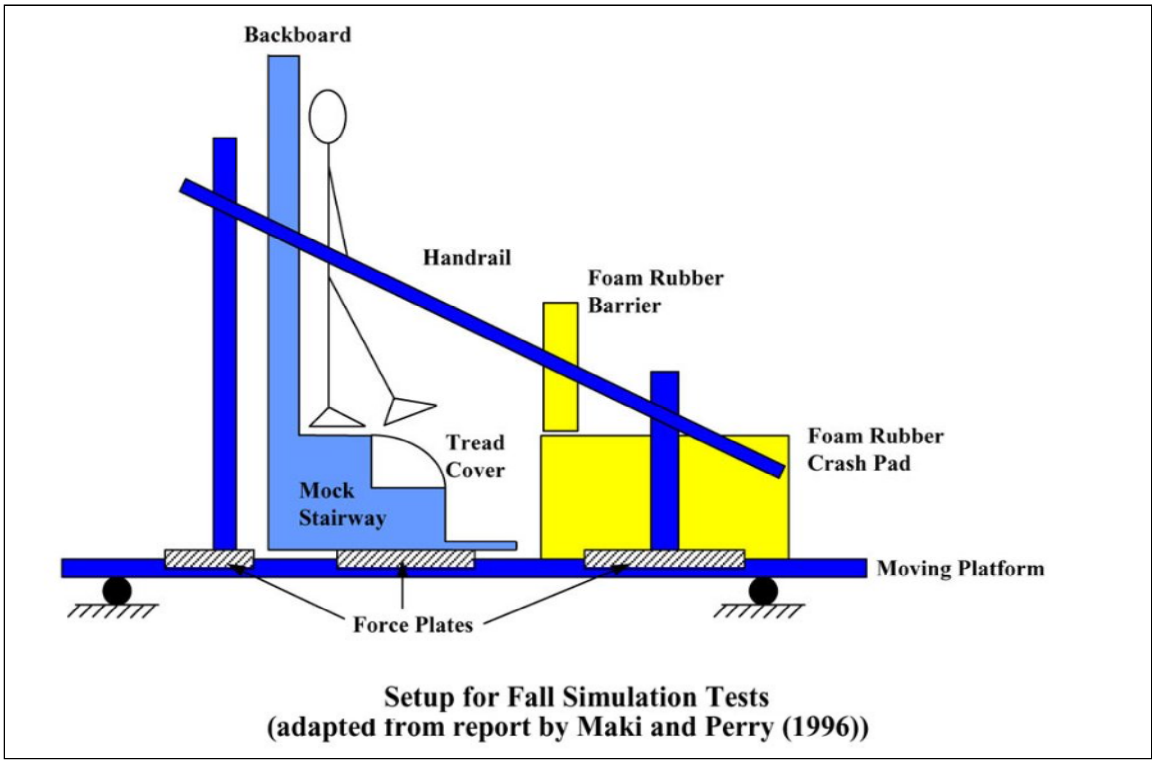


Figure 1– Schematic Test Configuration for Forces Induced on Handrails During Falls and Loss of Balance Events.

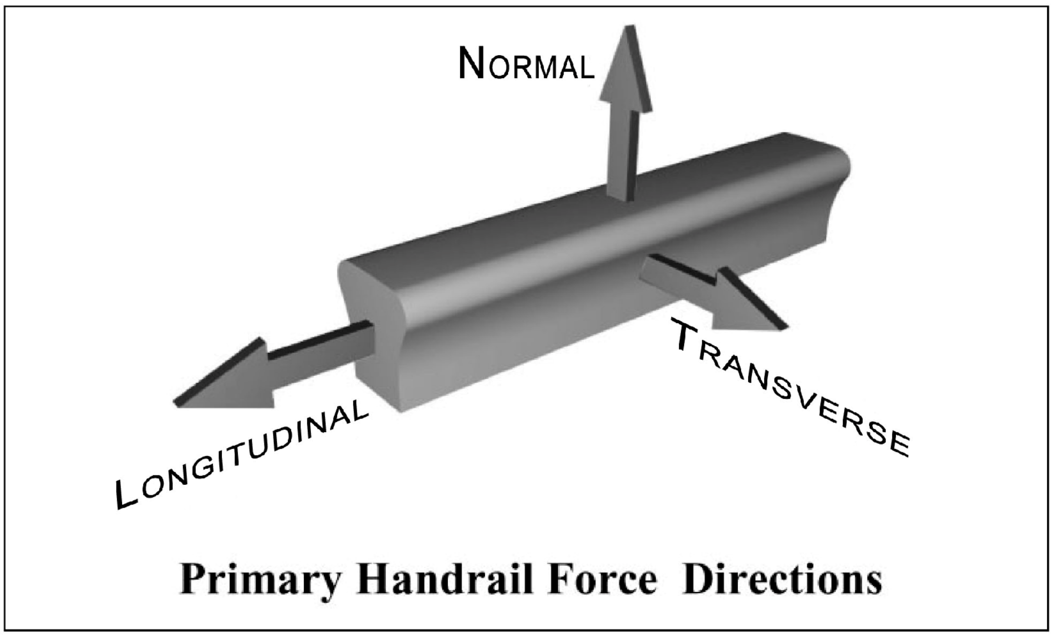


Figure 2– Primary Handrail Directions

Figure

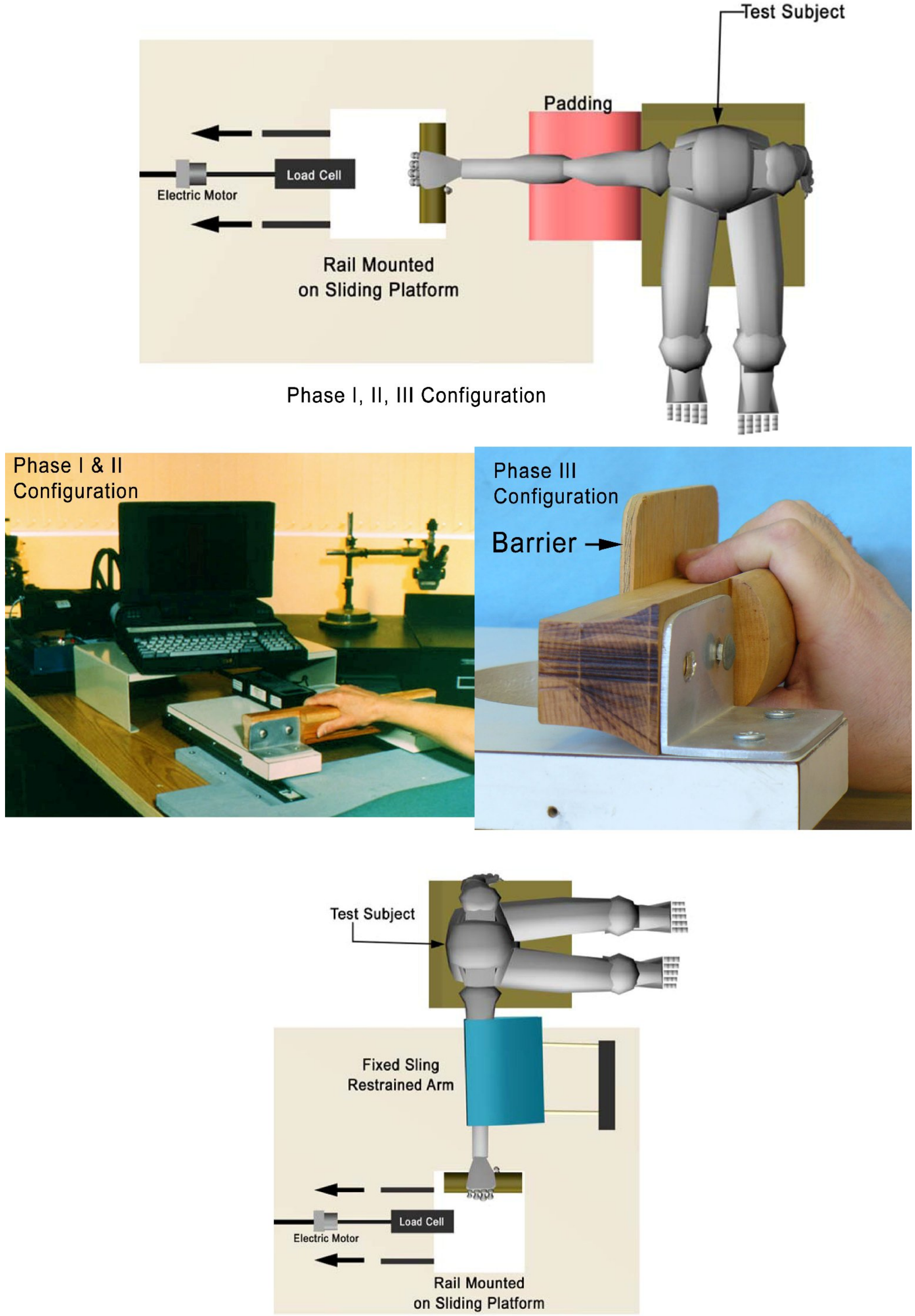


Figure 3 – Schematic Test Configuration Graspability Tests / Limits of Forces Imposed by Individuals on Handrail Sections

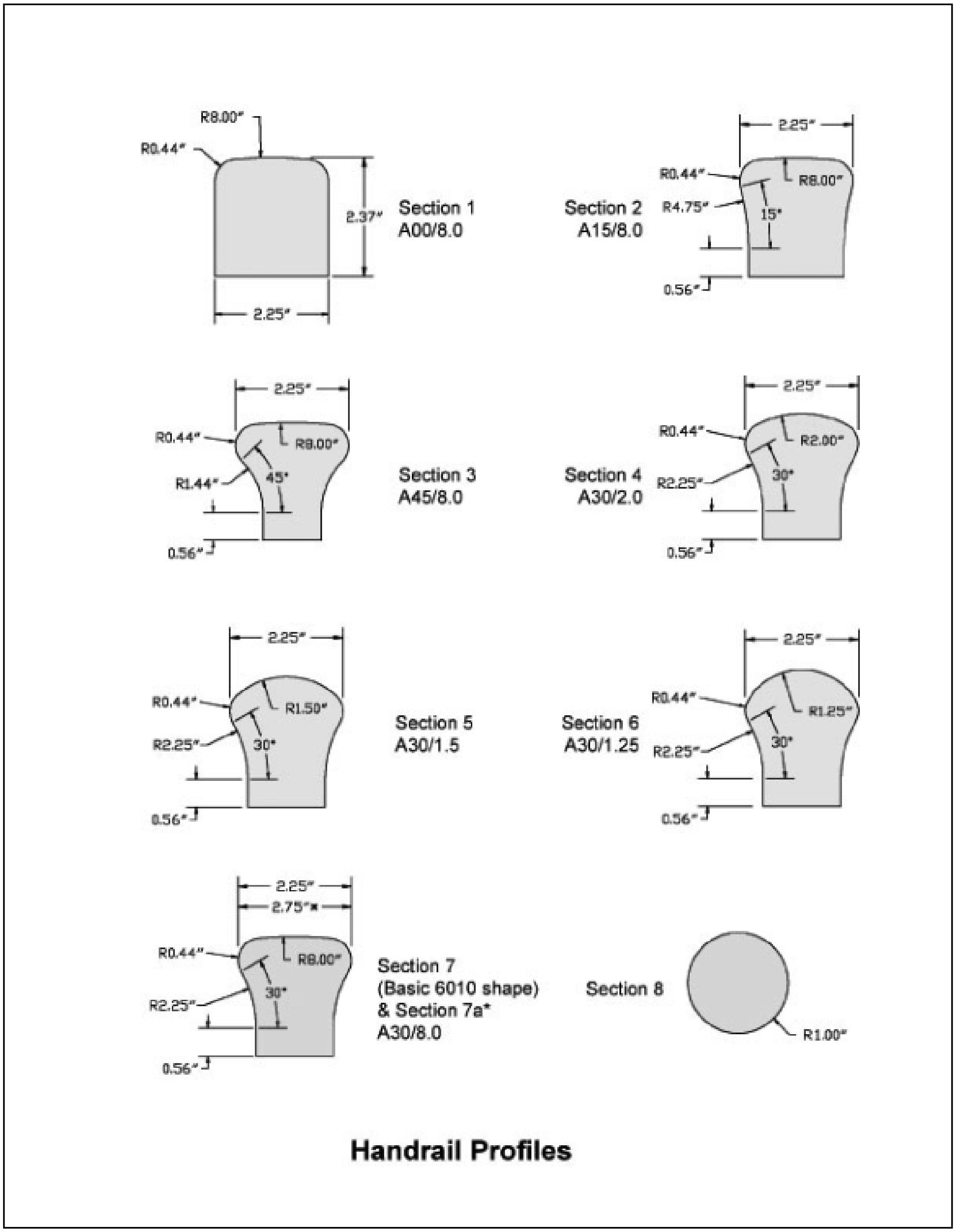


Figure 4– Handrail Shapes Tested for Graspability

Figure

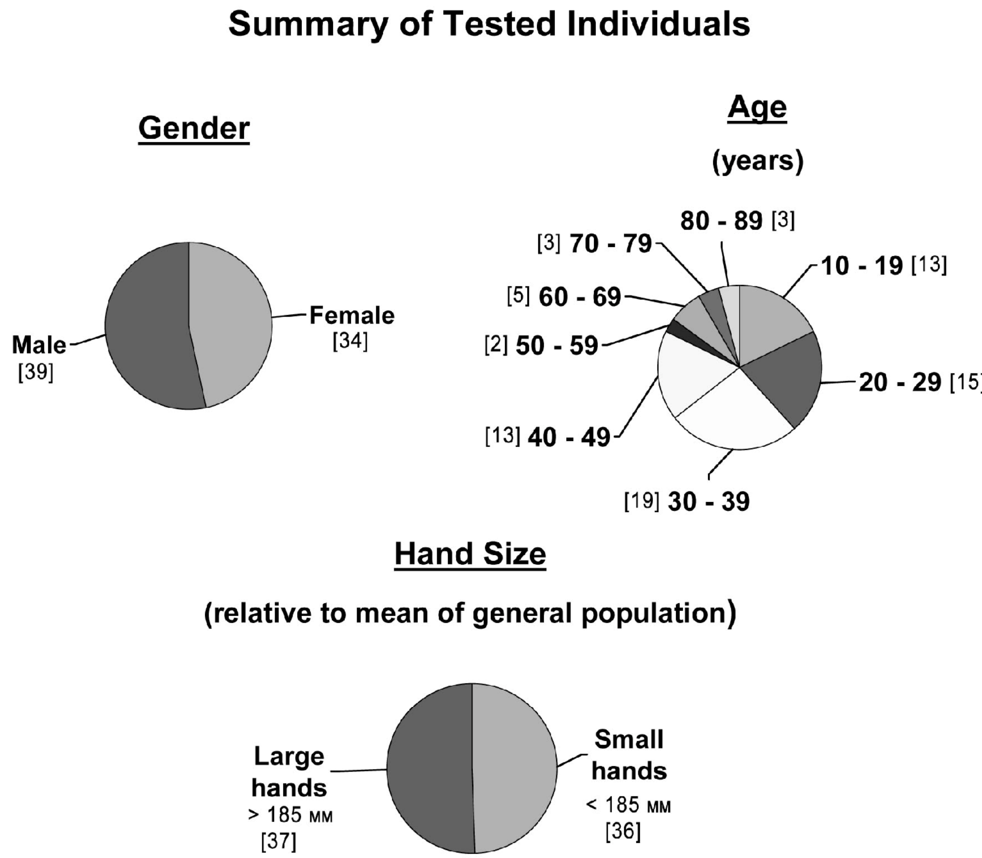


Figure 5– Distribution of Graspability Test Subjects
[ ] - Number of Subjects Per Group

Figure

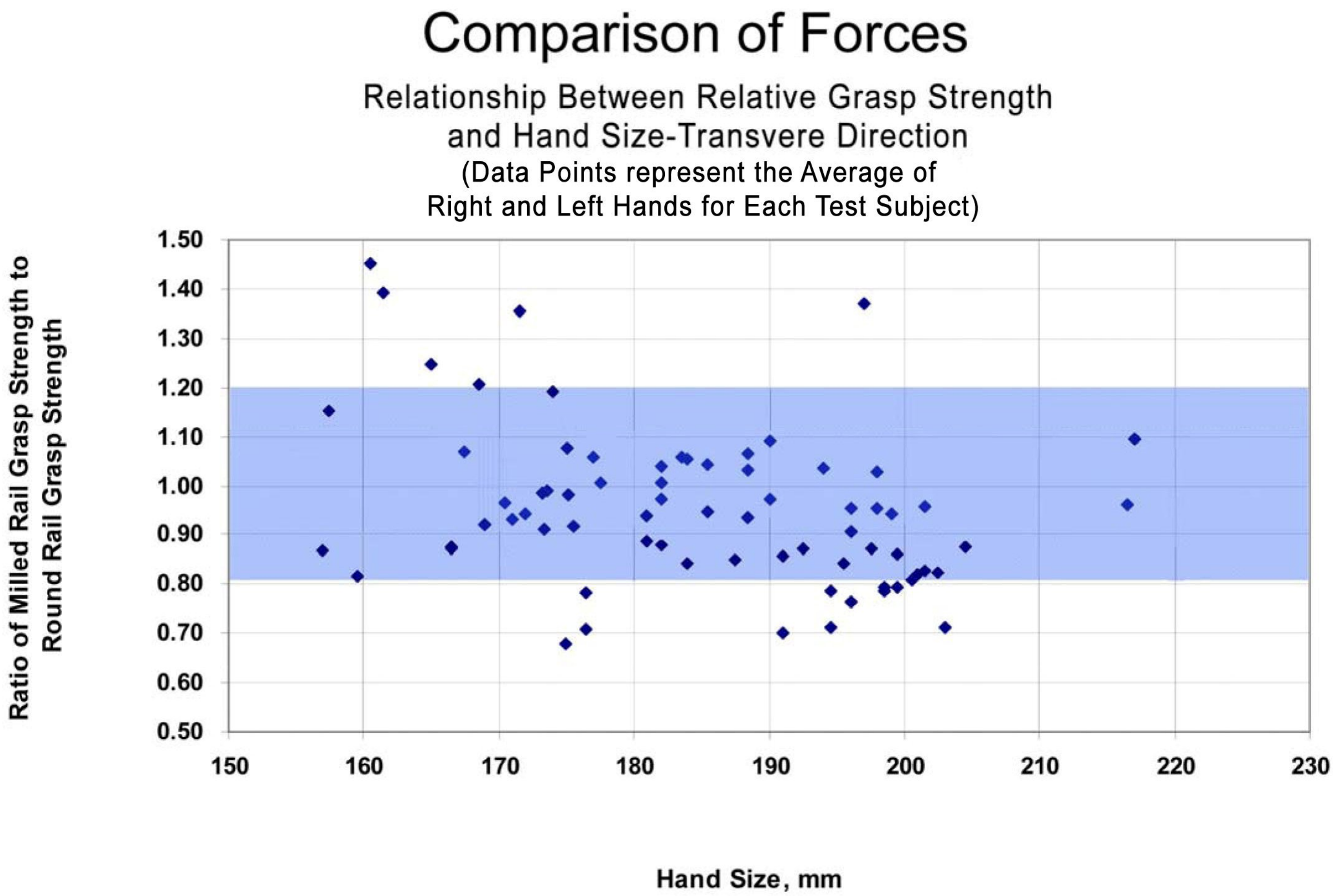


Figure 6- Phase I Graspability Test Results - Comparison of 51-mm Diameter Round Rail and Basic 6010 Milled Shape.

Figure

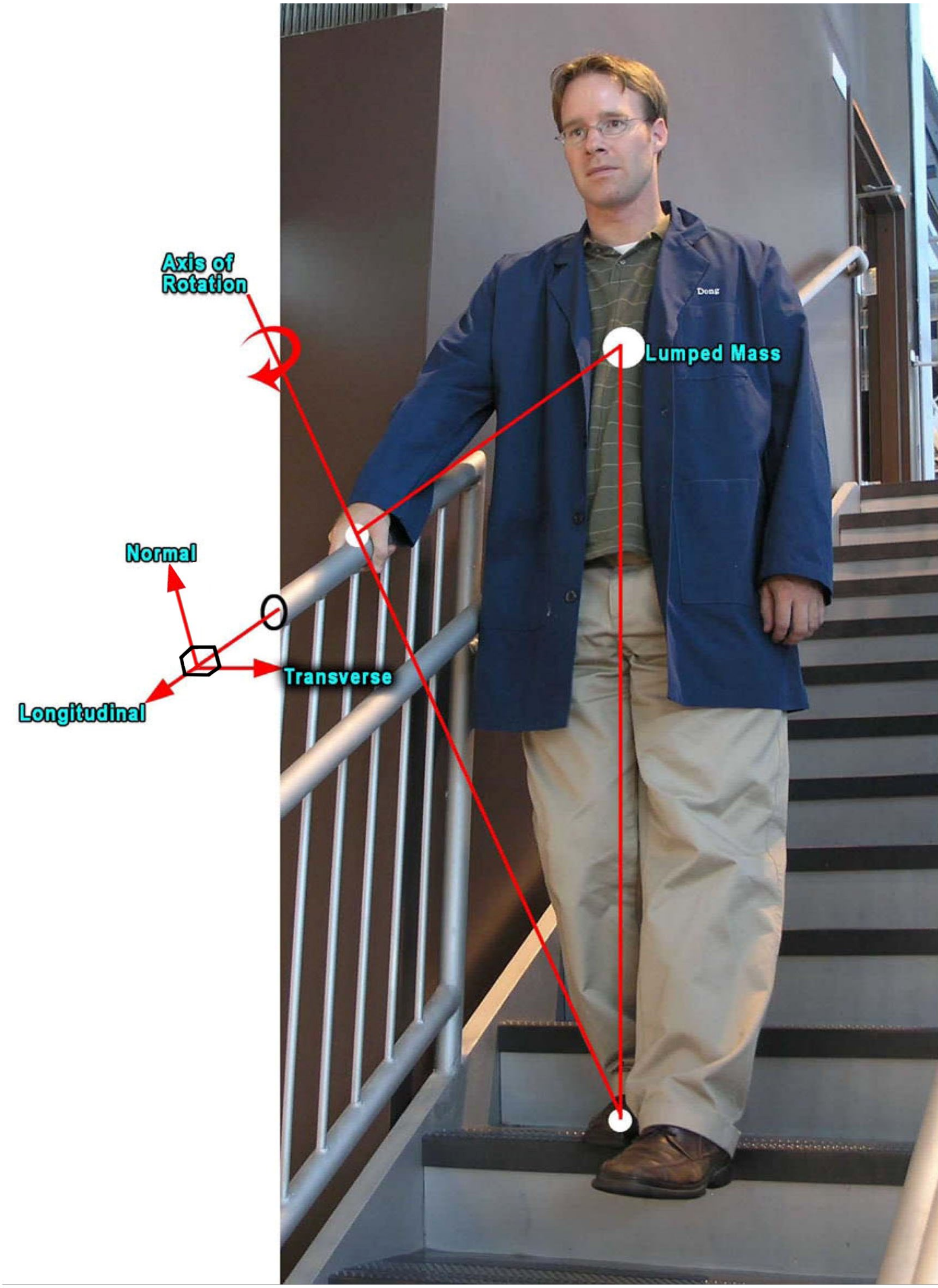
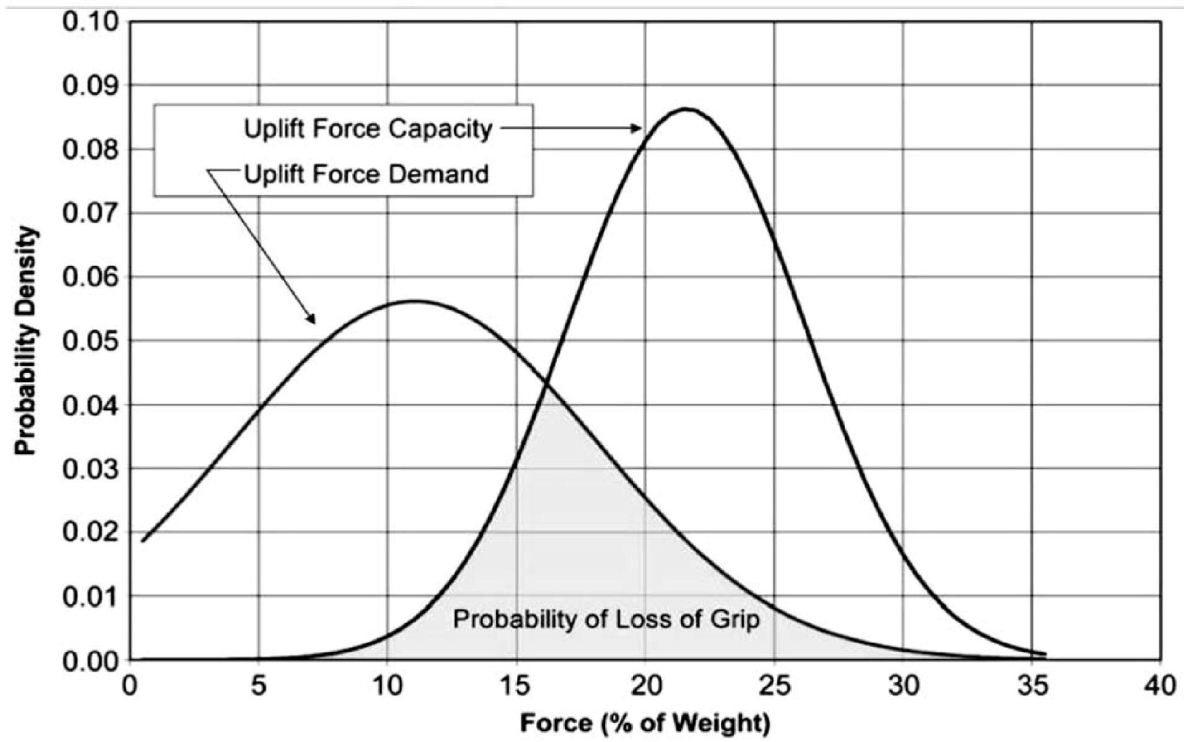


Figure 7– Configuration of Analytical Computer Model of a Person on a Stairway

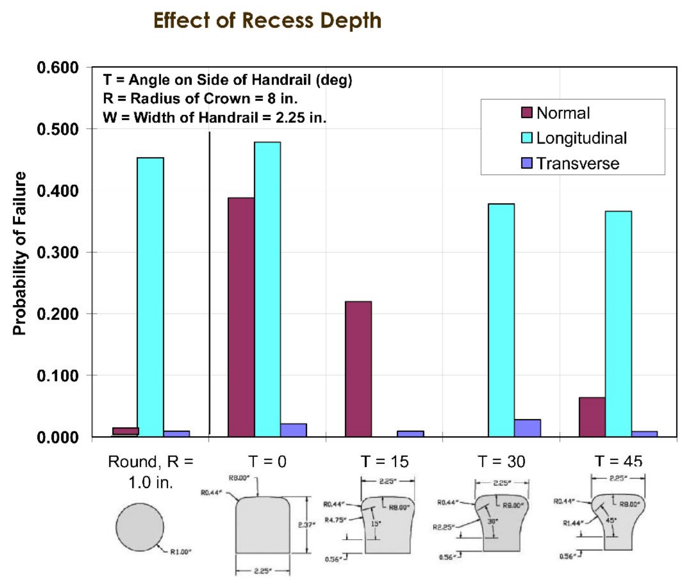
Probalility Density for Distribution of Resistance and Applied load for A30/8.0 for Average Male - Upward force

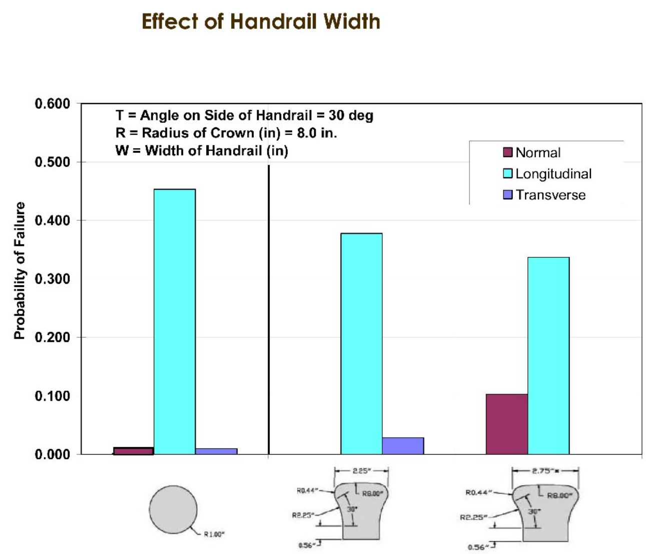


Probability Distribution Curves for Demand and Capacity

Figure 8- Combination of Uplift Force Demand Probability from Fall and Loss of Balance Testing with Upward Force Capacity Probability from Graspability Testing yields the Probability of Loss of Grip of Handrail Section

Figure





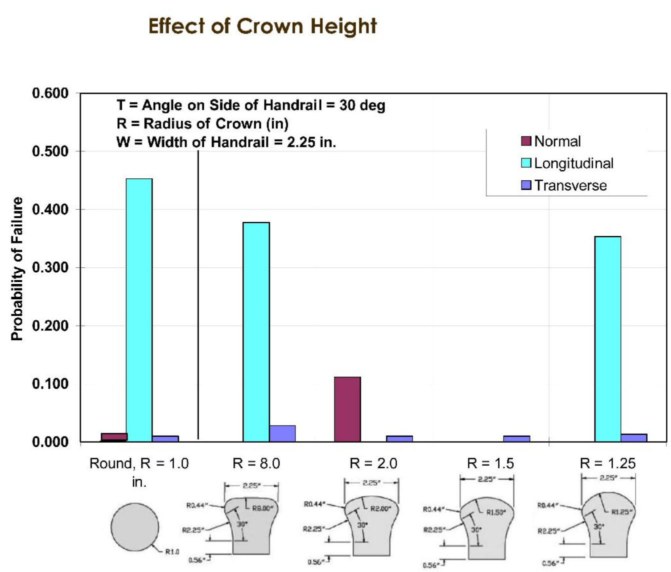


Figure 9 - Comparative Probabilities of Loss of Grip as a Function of Handrail Attributes