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Ladder Rung vs. Siderail Hand Grip Strategies

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ABSTRACT

When climbers lose their foothold on fixed, straight or extension ladders, the incipient fall may be arrested by gripping either the ladder rungs or siderails. Grasping the rungs provides an interference or power grip; squeezing the siderails provides a friction grip which is the primary focus of this paper. The falling scenario begins with free fall that lasts for the duration of the simple reaction time. Free fall is then decelerated by contravening friction forces derived from hand grip forces rapidly applied to the siderails. Using hand grip/time histories for various individuals, their fall distances were calculated for bare and gloved hands on a vertical steel fixed ladder. Sometimes the candidates could not arrest their falls; often their fall distance was too great to prevent ground impact. Under some circumstances, the vertical motion was brought under timely control. Although a rich literature is available for characterizing grip strength, data reflecting grip/time profiles does not appear. Grip strength/time diagrams were measured for fourteen test subjects.

INTRODUCTION

When climbing a fixed, extension or straight ladder, the climber may elect to grasp either the siderails or the rungs. A review of the literature relative to "How to Climb a Ladder" reveals that one of the articles recommends holding onto the siderails [Ref: 1], two advocate holding onto the rungs [Refs: 2, 3] and the eleven remaining papers admonish the climbers to hold onto the ladder without specifying a handhold preference [Refs: 4-14]. None of the referenced articles attempt to technically establish which strategy, siderail support or rung support, is better. Such a comparison is the primary goal of this paper.

Under ordinary ladder climbing conditions, users are usually supported by three or four appendages. To prevent falling, the hands must supply a small horizontal resistance to prevent the user from rotating backward off the rungs. It is not necessary for the hands to grip either the rungs or the siderails; the fingers need only provide a "hook". When normal conditions prevail, the two climbing protocols provide equivalent safety. It is only when there is a complete loss of foothold that radical differences between the protocols may be distinguished. The siderail strategy cannot reestablish equilibrium without securing a tight grip on the siderails; the rung strategy need only maintain the hook-like geometry of the fingers to arrest the fall.

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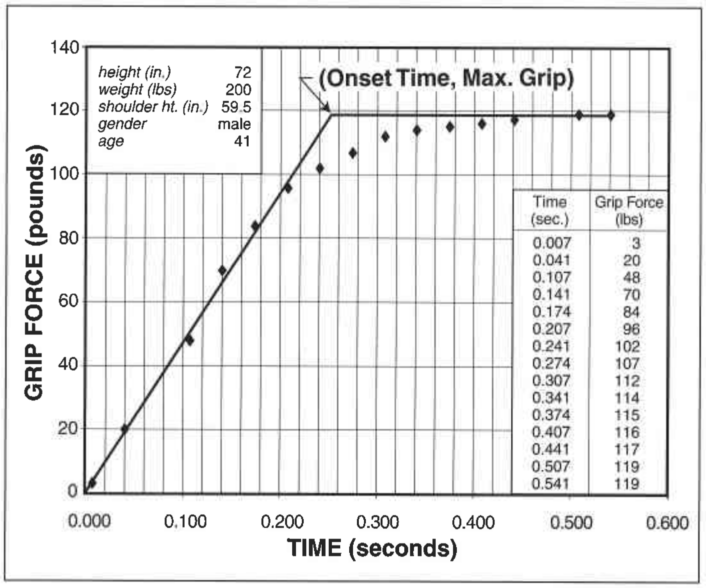
Two central concepts are used in this paper to analyze the "siderail" climbing strategy. First, classical equations of motion are formulated to provide fall height, H; i.e., the vertical fall distance from the instant foothold is lost until the motion is arrested. Second, a "best case scenario" is always assumed for the siderail climbing protocol. For example, the dominant hand grip strength will be taken for both hands. Assumptions of this kind always lead to predictions for H that are less than the actual fall heights.

Hand Grip/Time Relationship

The literature abounds with grip strength studies that reflect the following factors: gender, age and handedness [Refs: 15-18, 23, 30, 31, 45, 56]; time of day [Refs: 23, 24, 31, 38, 46, 56]; body position [Refs: 36, 56]; altitude [Ref: 49]; gloves [Refs: 20, 25, 43, 50, 52, 54]; arm support [Ref: 23]; grip size [Refs: 20, 24, 27, 42, 53] oxygen [Ref: 48]; temperature [Refs: 26, 40, 50, 58, 60]; fatigue [Refs: 19, 30, 31, 32, 55]; diet [Ref: 47]; training [Refs: 28, 31, 37, 44]; height and weight [Refs: 15, 22, 29, 33, 34, 35, 39, 41, 42]; wrist and forearm position [Refs: 21, 42, 57, 59]; and smoking [Ref: 51]. None of the studies consider the time history of the grip force application. The grip/time history directly effects the retarding force acting on a falling climber who is grasping the siderails.



height (in.)	72
weight (lbs)	200
shoulder ht. (in.)	59.5
gender	male
age	41

Time (sec.)	Grip Force (lbs)
0.007	3
0.041	20
0.107	48
0.141	70
0.174	84
0.207	96
0.241	102
0.274	107
0.307	112
0.341	114
0.374	115
0.407	116
0.441	117
0.507	119
0.541	119

Figure 1 - Grip/Time Diagram -Test Subject 1

Grip/time relationships were measured for fourteen candidates using the protocol outlined in Appendix A. Figure 1 is a typical grip/time diagram which is bounded by a bilinear curve; the initial portion is called the onset curve and the horizontal portion is the maximum grip strength curve. The intersection of the two curves defines the onset time for achieving the maximum grip strength. The fictitious bilinear curve underestimates the actual time for achieving maximum grip strength; it provides a constant maximum grip strength throughout a longer period than actually experienced in reality. Thus, the bilinear bounding curve overestimates a climber's ability to decelerate his or her body during a fall.

Friction

When a climber uses the siderails to arrest a fall on a vertical fixed ladder, each hand produces a gripping force G on two surfaces. If the coefficient of sliding friction between the siderail and the hand is represented by μ_s, the total drag resistance D resisting the fall is:

$$D = 4G\mu_s \qquad \text{Eq. 1}$$

Using the test setup depicted in Fig. 2, the room temperature sliding friction was measured for each of the fourteen test subjects in the grip strength testing program. Candidates rested their hands on a table with their palms facing upward; a Chatillon digital force gauge was fastened to a mild steel angle and the 5.71 pound assembly was dragged over their palms with a standard "slip meter" power winch. A tripod mounted camcorder recorded the drag resistance at each of seven stations one inch apart. These drag forces and their associated coefficients of sliding friction are tabulated in Tables B-1 through B-14 in Appendix B for the fourteen test candidates. The coefficient of sliding friction is defined as the Drag Force divided by the Normal Force acting on the hands, i.e., μ_s = Drag Force ÷ (5.71 lbs). Tables B-15 through B-23 reflect the results of drag tests conducted using various types of gloves.

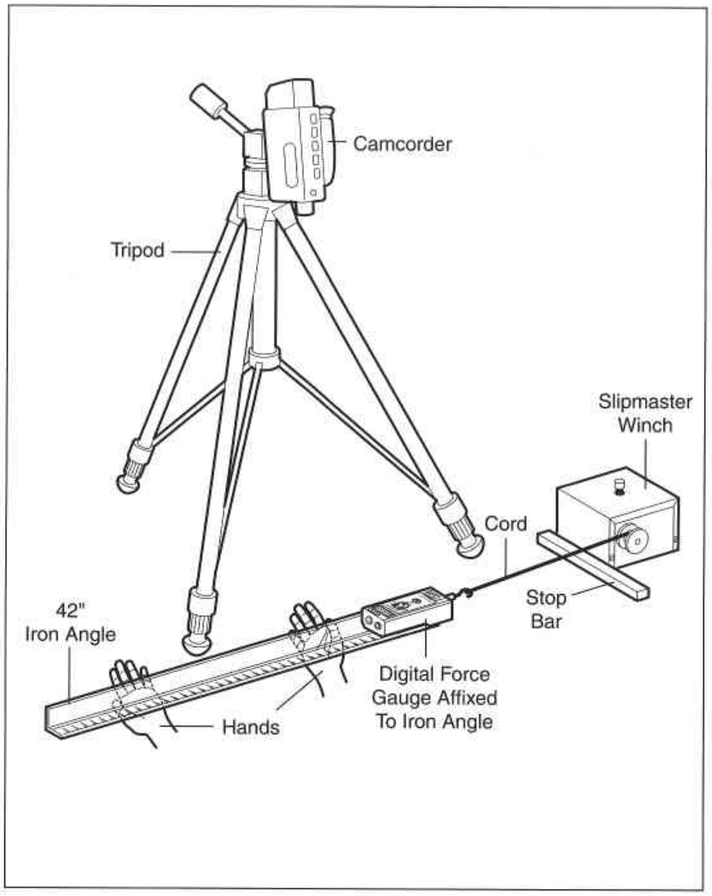


Figure 2 - Sliding Friction Test Setup

The following equipment was used in the test program:

a) Carbon Steel Angle
   Cross section: 1-1/2 x 1-1/2 x 1/8 inches
   Length: 42-1/4 inches

b) Power Winch
   Brand: Whiteley Industries
   Model: HPS-3
   Pull Speed: 3.5 inches/minute

c) Chatillon Digital Force Gauge
   Model: DRC 100
   Serial: M002027
   Capacity: 100 lbs
   Increments: 0.1 lbs

Fall Height - Siderail Strategy

Under the influence of gravity, a climber's loss of foothold results in a falling excursion that can be characterized using Newton's Second Law of Motion, i.e., a particle's acceleration is proportional to the impressed forces and inversely proportional to its mass. Using this law, there are three natural ranges where the downward motion may be studied; free fall, increasing grip resistance and maximum constant grip strength. At the beginning of each range, the clock will be set at zero and the symbol t will represent the time in that range. The overall time will be represented by the term T.

During the initial phase of a fall, sensory receptors are stimulated and after a time interval called the simple reaction time, t_r, [Ref: 61] the climber's hands will begin to counteract the fall by tightening their grip on the siderails. Referring to the free-body diagram shown in Fig. 3, the equation of motion and the boundary conditions become respectively,

$$\ddot{x} = g \quad 0 \le T \le t_r \qquad \text{Eq. 2}$$

$$At: \ t = 0, \ \ x = \dot{x} = 0 \qquad \text{Eq. 3}$$

where g is the acceleration due to gravity and $\dot{x} \equiv \frac{dx}{dt}$.

When these equations are solved we obtain the fall height H_1 and the velocity $\dot{x}_1$ at the time $t = t_r$; thus,

$$H_1 \equiv x(t_r) = \frac{1}{2} g t_r^2 \qquad \text{Eq. 4}$$

$$\dot{x}_1 \equiv \dot{x}(t_r) = g t_r \qquad \text{Eq. 5}$$

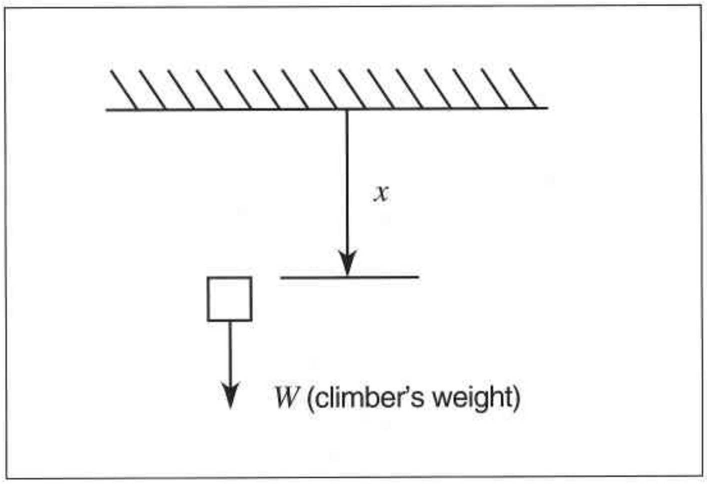


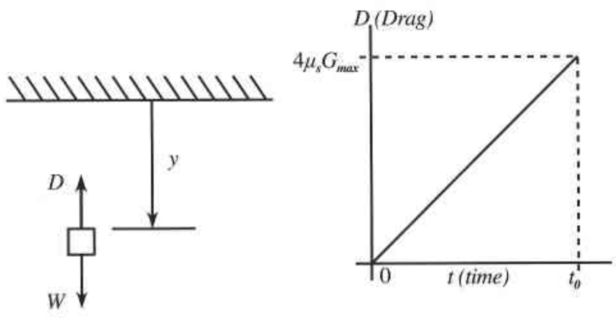
Figure 3 - Free-Body Diagram: $0 \le T \le t_r$

After a time t_r has elapsed, the hands begin to grasp the siderails with a linearly increasing intensity corresponding to the onset curve represented in Fig. 1. This linear portion of the grip/time diagram terminates at the onset time, t_0, which is shown as the abscissa of the intersection of the two bounding curves. It is convenient to study the second range of motion in the time interval $t_r \le T \le t_0$. A free-body diagram reflecting the prevailing conditions in the second range is depicted in Fig. 4a where the drag force D given by Eq. 1 has the time history shown in Fig. 4b. The maximum grip strength is represented by the term $G_{\max}$ and the climber's weight by W. Thus, the equation of motion and the boundary conditions at the beginning of phase two are:

$$\ddot{y} = -g\left[\frac{4\mu_s G_{\max}}{W}\left(\frac{t}{t_0}\right) - 1\right] \qquad \text{Eq. 6}$$

$$At: \ t = 0, \ y = 0 \qquad \text{Eq. 7a}$$

$$t = 0, \ \dot{y} = \dot{x}(t_r) = g t_r \qquad \text{Eq. 7b}$$



a) Free-Body Diagram

b) Drag/Time History

Figure 4 - Free-Body Diagram: $t_r \le T \le t_0$

Solving these equations we obtain the fall distance H_2 in the second range and the velocity $\dot{y}_2$ at the time t_0 at the end of the second range:

$$H_2 \equiv y(t_0) = \frac{1}{2} g t_0^2 - \frac{2\mu_s g G_{\max}}{3W} t_0^2 + g t_r t_0 \qquad \text{Eq. 8}$$

$$\dot{y}_2 \equiv \dot{y}(t_0) = g\left[t_r + t_0\left(1 - \frac{2\mu_s G_{\max}}{W}\right)\right] \qquad \text{Eq. 9}$$

In the third and final range of motion, the maximum grip strength of the climber has been achieved which produces a constant drag resistance of $4\mu_s G_{\max}$. This case is represented by the free-body diagram shown in Fig. 5. The equation of motion and the appropriate boundary conditions at the beginning of the range are:

$$\ddot{z} = -g\left[\frac{4\mu_s G_{\max}}{W} - 1\right] \qquad \text{Eq. 10}$$

$$At:\ t = 0,\ \ z = 0 \qquad \text{Eq. 11a}$$

$$t = 0,\ \dot{z} = \dot{y}(t_0) = g\left[t_r + t_0\left(1 - \frac{2\mu_s G_{\max}}{W}\right)\right] \qquad \text{Eq. 11b}$$

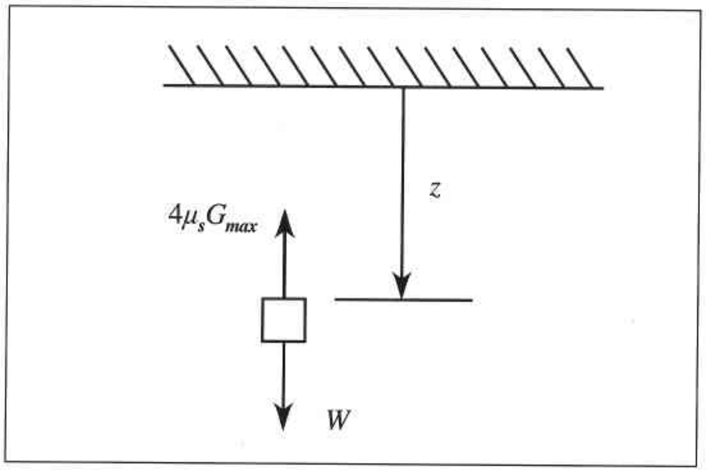


Figure 5 - Free-Body Diagram: $t_r + t_0 \leq T$

These equations define the following solutions:

$$z = \frac{1}{2} g t^2\left(1 - \frac{4\mu_s G_{\max}}{W}\right) + g t\left[t_r + t_0\left(1 - \frac{2\mu_s G_{\max}}{W}\right)\right] \qquad \text{Eq.12}$$

$$\dot{z} = g t\left(1 - \frac{4\mu_s G_{\max}}{W}\right) + g\left[t_r + t_0\left(1 - \frac{2\mu_s G_{\max}}{W}\right)\right] \qquad \text{Eq.13}$$

The maximum fall in the third range, H_3, occurs when the climber's velocity $\dot{z}$ becomes zero. The associated time, t_m, is found by setting Eq. 13 equal to zero; hence,

$$t_m = \frac{\left[t_r + t_0\left(1 - \frac{2\mu_s G_{\max}}{W}\right)\right]}{\left(\frac{4\mu_s G_{\max}}{W} - 1\right)} \qquad \text{Eq. 14}$$

Substituting Eq. 14 for t in Eq. 12 gives,

$$H_3 = z(t_m) = \frac{1}{2} g \frac{\left[t_r + t_0\left(1 - \frac{2\mu_s G_{\max}}{W}\right)\right]^2}{\left(\frac{4\mu_s G_{\max}}{W} - 1\right)} \qquad \text{Eq. 15}$$

The total fall height of the climber, H, is the sum of the fall heights in the three ranges; thus,

$$H = H_1 + H_2 + H_3 \qquad \text{Eq. 16}$$

$$H = \frac{1}{2} g t_r^2 + \left[\frac{1}{2} g t_0^2\left(1 - \frac{4\mu_s G_{\max}}{3W}\right) + g t_r t_0\right] + \frac{1}{2} g \frac{\left[t_r + t_0\left(1 - \frac{2\mu_s G_{\max}}{W}\right)\right]^2}{\left(\frac{4\mu_s G_{\max}}{W} - 1\right)} \qquad \text{Eq.17}$$

or

$$H = \frac{1}{2} g t_r^2 \left\{1 + \left(\frac{t_0}{t_r}\right)^2\left(1 - \frac{4\mu_s G_{\max}}{3W}\right) + 2\left(\frac{t_0}{t_r}\right) + \frac{\left[1 + \left(\frac{t_0}{t_r}\right)\left(1 - \frac{2\mu_s G_{\max}}{W}\right)\right]^2}{\left(\frac{4\mu_s G_{\max}}{W} - 1\right)}\right\} \qquad \text{Eq. 18}$$

Equation 18 is valid whenever the quantity within the square brackets is non-negative. A negative value indicates that the motion was arrested during the second phase while the climber was building up to his maximum grip $G_{\max}$. Clearly, if the maximum drag resistance $4\mu_s G_{\max}$ is less than the climber's weight, the fall will never be arrested. The velocity of the climber, given by Eq. 13, can never go to zero.

Using a simple reaction time $t_r = 0.2$ seconds, the fall height H of Test Subject 1 may be calculated using Eq. 18. From Fig. 1 we obtain his weight, W = 200 lbs, his maximum grip, $G_{\max}$ = 119 lbs, and his onset time, t_0 = 0.25 seconds. Table B-1 provides his coefficient of sliding friction, μ_s = 0.72. Thus,

$$H=\frac{1}{2}(32.2)(0.2)^2\left\{1+\left(\frac{0.25}{0.20}\right)^2\left(1-\frac{4(0.72)119}{3\cdot 200}\right)+\right.$$

$$\left.2\left(\frac{0.25}{0.20}\right)+\frac{\left[1+\left(\frac{0.25}{0.20}\right)\left(1-\frac{2(0.72)119}{200}\right)\right]^2}{\frac{4(0.72)119}{200}-1}\right\}=3.94\,ft. \quad \text{Eq.19}$$

Using the data provided in Appendixes A and B, the fall height was computed for each test subject and the results are tabulated in Table I. This table shows that four candidates cannot check their falls, two others fall 5 and 7 feet and the remainder fall less than 4 feet. The fall heights were also computed for each test subject when they wore nine different types of gloves. These findings are displayed in Table II where we observe that over 60% of the falls are critical (over seven feet).

There is an inverse relationship between the fall height H and the coefficient of sliding friction μ_s which is portrayed in Fig. 6 for test subject 2. This curve is asymptotic to the vertical line $\mu_s = W/(4G_{max})$. Friction coefficients to the right of this line will cause test subject 2 to stop falling; values to the left of the line lead to unchecked falling.

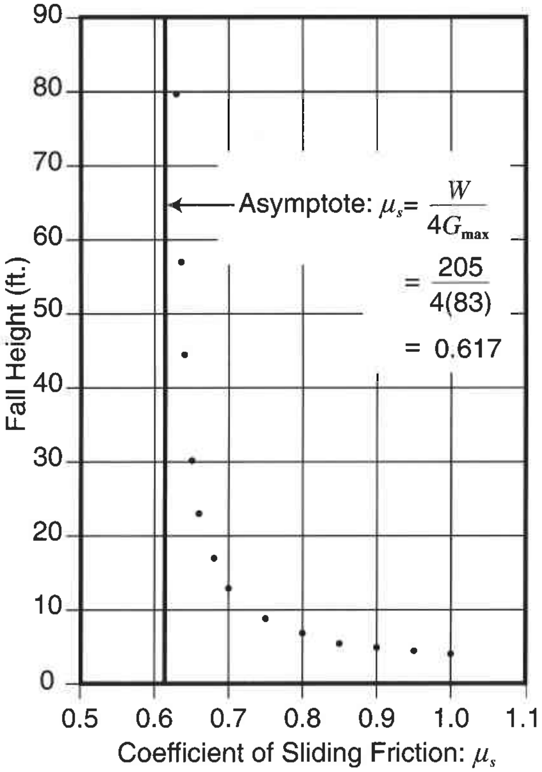


Figure 6 - H vs. μ_s: Test Subject 2

Table I - Fall Heights (t_r=0.2 seconds)

Test Subject	Onset Time t_0 (sec.)	Weight W (lbs)	Max.Grip G_{max} (lbs)	Sliding Friction μ_s	$\frac{4\mu_s G_{max}}{W}$	Fall Height H (ft.)
1(M)	0.25	200	119	0.72	1.71	3.94 ft.
2(M)	0.226	205	83	0.63	1.02	79.23 ft.
3(M)	0.142	157	83	0.86	1.82	2.58 ft.
4(M)	0.107	250	113	0.70	1.27	4.91 ft.
5(M)	0.120	155	84	0.83	1.80	2.42 ft.
6(M)	0.140	126	72	0.75	1.71	2.77 ft.
7(M)	0.119	195	110	0.73	1.65	2.73 ft.
8(M)	0.070	184	102	0.65	1.44	2.89 ft.
9(M)	0.142	250	49	0.59	0.46	∞
10(M)	0.162	180	85	0.80	1.51	3.71 ft.
11(F)	0.160	150	31	0.67	0.55	∞
12(F)	0.144	140	52	0.82	1.22	6.61 ft.
13(F)	0.171	110	39	0.67	0.95	∞
14(F)	0.122	190	71	1.02	1.52	3.16 ft.

Table II - Fall Heights With Gloves (feet)

Test Subject	Glove Type								
	Felt Covered Rubber Gloves μ_s=0.43	Black Leather Gloves μ_s=0.45	Cotton Work Gloves With Leather Palms μ_s=0.54	All Cotton Gloves μ_s=0.60	Tan Leather Work Gloves μ_s=0.61	Excessively Worn Tan Leather Work Gloves μ_s=0.62	Canvas Gloves With Rubber Dotted Palms μ_s=0.66	Cloth Gardening Gloves With Rubber Dotted Palms μ_s=0.77	Knit Gloves With Rubber Cross Beaded Palms μ_s=0.89
1	74.29	25.56	7.56	5.55	5.34	5.15	4.55	3.59	3.04
2	∞	∞	∞	∞	∞	368.45	24.40	7.88	5.05
3	∞	∞	9.48	5.55	5.23	4.95	4.13	3.02	2.47
4	∞	∞	∞	13.22	11.07	9.57	6.37	3.65	2.71
5	∞	∞	7.45	4.68	4.44	4.23	3.59	2.68	2.22
6	∞	42.23	6.15	4.30	4.11	3.95	3.44	2.67	2.25
7	∞	71.54	6.02	4.12	3.94	3.78	3.27	2.52	2.12
8	∞	∞	5.39	3.57	3.40	3.25	2.80	2.13	1.79
9	∞	∞	∞	∞	∞	∞	∞	∞	∞
10	∞	∞	64.80	10.77	9.58	8.66	6.38	4.02	3.08
11	∞	∞	∞	∞	∞	∞	∞	∞	∞
12	∞	∞	∞	∞	∞	∞	∞	9.43	4.85
13	∞	∞	∞	∞	∞	∞	∞	15.53	6.27
14	∞	∞	∞	∞	∞	∞	∞	8.34	4.39

Rung Climbing Strategy

Climbing a fixed vertical ladder using a "rung grasping" strategy gives rise to a number of important observations:

1. A small horizontal inward acting force component must <u>always</u> be present to prevent a climber from rotating backward off of the ladder. This force is supplied by one or both hands.

2. To provide the required horizontal stabilization force, the climber's fingers need only maintain a "hook-like" geometry. No squeezing is necessary; however, it is acceptable.

3. Gravitational forces are resisted by the legs and by one or both hands. Force sharing among the appendages is constantly and abruptly changing which causes the climber to maintain a substantial "hook-like" grip but not a maximum power grip.

4. Loss of foothold causes a vertical downward translation of the climber without rotation away from the ladder. Both hands will always remain close to the plane containing the ladder rungs.

5. If there is a loss of foothold and the hands offer some counterforce to falling, the climber will fall a shorter distance than he would in free fall, i.e., less than 7.73 inches as calculated from Eq. 4 using t_r = 0.2 seconds.

6. At least one of the arms holding onto a rung will not be straightened out by a fall of only 7.73 inches. This implies that at least one hand will be protected by the shock attenuating property of a bent arm.

7. If the power grip used in the normal ascent or descent of a ladder is capable of supporting the weight of a climber for one second, the rung grasping strategy will protect the climber during a loss of foothold.

8. If the second hand is free at the time the foothold is lost, after the passage of 0.2 seconds it may be inserted four inches into the plane of the rungs in an attempt to grab a rung. Under ideal conditions, the hand can move inward at the hand speed constant, v_h= 63 inches/second [Refs: 62, 63, 64, 65, 66]. The time required to reach four inches is,

   t = distance ÷ v_h = 4/63 = 0.0635 seconds

   At that time, the climber would have been falling for t = 0.2 + 0.0635 = 0.2635 seconds. The downward speed and descent of the free hand at t = 0.2635 seconds is given by Eqs. 5 and 4, respectively, as 8.48 ft/sec and 13.41 inches. The impact speed between the hand and a rung may be greater than 8.48 ft/sec; it cannot be lower. It is possible for the second hand to aid in a fall arrest scenario, but it cannot be relied on given such high closure speeds and the uncertainty of the rung catching dynamics.

9. If a fall is checked by one hand, the other may easily reach four or five rungs when attempting to reestablish a normal equilibrium configuration.

CONCLUSION AND OBSERVATIONS

1. For the siderail climbing strategy, all of the fall height calculations underestimate the actual fall heights that will be experienced during a loss of foothold. Some of the conservative assumptions reflected in the calculations include:

   a. The grip strength of the non-dominant hand was assumed to be equal to that of the dominant hand.

   b. The gripping surfaces of the ladder siderails were assumed to be as efficient as the grip provided by the Smedley Dynamometer.

   c. The grip/time relationships were assumed to follow the bilinear bounding curves.

   d. The climbing hand strength was taken as the non-fatigued strength measured in the laboratory.

   e. It was assumed that the maximum grip strength would not decrease when the hand slid down the siderail.

2. The fall heights calculated for bare hands are tabulated in Table I. Twenty-nine percent of the test subjects experienced uncontrolled falls; 7% suffered a critical fall (7 to 14 feet) and the remaining 64% were able to limit their falls to less than five feet. Thus, under unattainable, ideal conditions, a full 36% of the climbers would be seriously injured during a loss of foothold. Furthermore, it seems likely that in real world excursions, another 21% of the falls would be critical.

3. Loss of foothold calculations using gloved hands are exhibited in Table II. Fifty-two percent of the entries show uncontrolled falls; another 10% are critical. In real fall scenarios, another 12% of the entries will probably become critical.

4. The maximum grip strength of a gloved hand is less than that of a corresponding bare hand [Refs: 20, 43, 50, 52, 54]. Cochran [Ref: 25] indicates a 7.3% decrease for cotton gloves and a 16.8% decrease for leather and cotton gloves. Accordingly, the fall heights displayed in Table II would be greater than shown since they were all calculated using grip tests conducted with bare hands.

5. The siderail grasping strategy does not deal effectively with a loss of foothold.

6. The rung grasping strategy will prevent climbers from falling after a loss of foothold if the power grip used in ordinary ascent and descent will resist their weight for about one second. The dangling arm and legs can reestablish a new purchase on the ladder in one second.

7. One bent arm will always be exerting an upward force on a rung during the onset of a fall. Downward motion is always restrained even during the simple reaction time; the power grip is always active; and the bent arm prevents impact loading of the hand.

8. It is assumed that the community of users of straight, extension and fixed ladders are capable of dangling from a rung with only one hand for one second.

9. The fourteen test subjects used in this study were arbitrarily selected; each could hang from a fixed ladder rung using one arm.

10. It should be noted that grip tests are never limited by fingers losing their grasp on the test device handle or trigger. The resistance of a "hook-like" finger geometry is always greater than the corresponding grip strength.

11. If a hand is not in contact with a rung at the onset of a fall, the ability to grab a rung is delayed by the time required to reach the rung and the simple reaction time. This delay time, in conjunction with a rung spacing of 12 inches, implies that the first rung encountered by a falling hand occurs after a drop of 13.41 to 25.41 inches. This corresponds to

a hand/rung closure speed of 8.49 to 11.35 ft/sec. These speeds are 62% to 116% greater than the hand speed constant; they are too fast to be relied upon for fall protection.

12. To achieve their actual maximum grip strength, the average time required by the fourteen test subjects was 0.349 seconds with a standard deviation of 0.093 seconds. Their times ranged from 0.209 to 0.541 seconds. It should be noted that the test protocol required the candidates to squeeze the dynamometer as quickly as they could.

APPENDIX A

Fourteen candidates, ten males and four females, were tested to establish their grip/time relationships. Their ages ranged from 20 to 60 years; their occupations included: technician, mechanics, secretaries, engineers, librarians and college students. The testing program reflected the following protocol:

1. A Smedley type adjustable spring dynamometer, as illustrated in Fig. A-1, was used to measure grip strength in pounds. The grip size setting was maintained at two inches.
2. The dynamometer was mounted on a column with its handle in a vertical orientation to reflect the attitude of a fixed ladder siderail.
3. The dynamometer was mounted at the shoulder height of each candidate as depicted in Fig. A-2.
4. A digital camcorder was focused on the dynamometer dial. Frames were recorded at a time interval of 1/30th second throughout the test duration.
5. Candidates were instructed to begin the test by lightly grasping the dynamometer handle.
6. Candidates were told that they could commence squeezing the dynamometer at their discretion.
7. Candidates were asked to squeeze the dynamometer as fast as they could, as if startled.
8. The video recording was terminated when the candidate achieved his or her maximum grip.
9. Several days prior to the testing program, candidates were instructed in the operation of the dynamometer and allowed to practice with the instrument.

Figures A-3 through A-15 record the grip/time relationships of candidates 2 through 14. The height, weight, shoulder height, gender and age of test subjects appear in their grip/time diagrams.

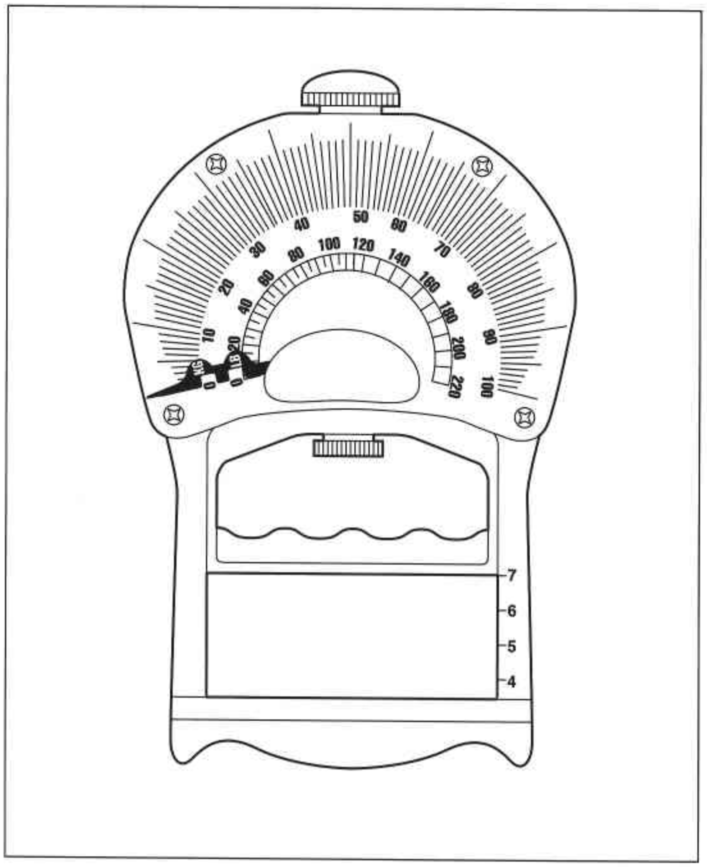


Figure A-1 - Smedley Type Adjustable Spring Dynamometer

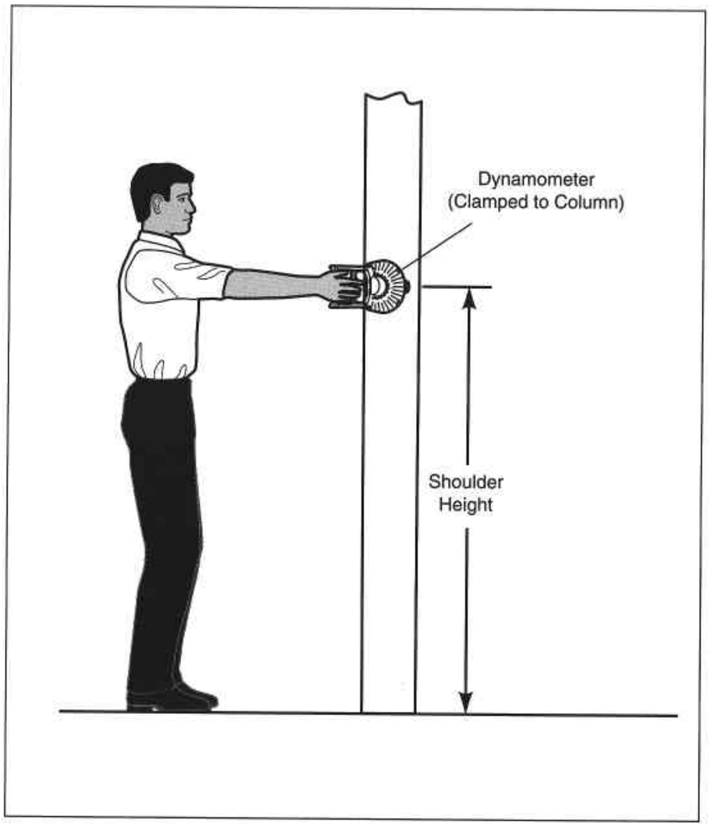
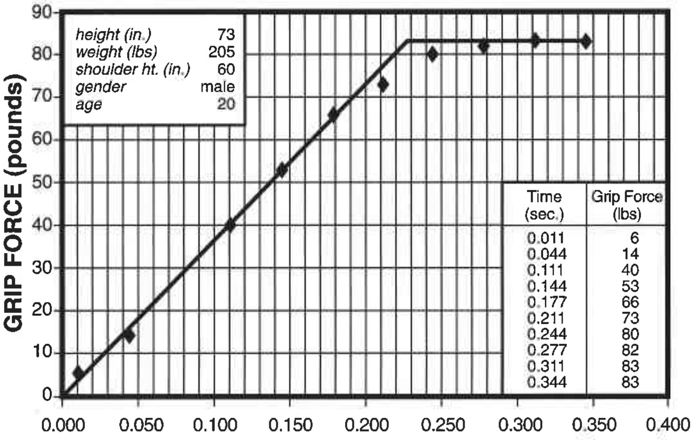


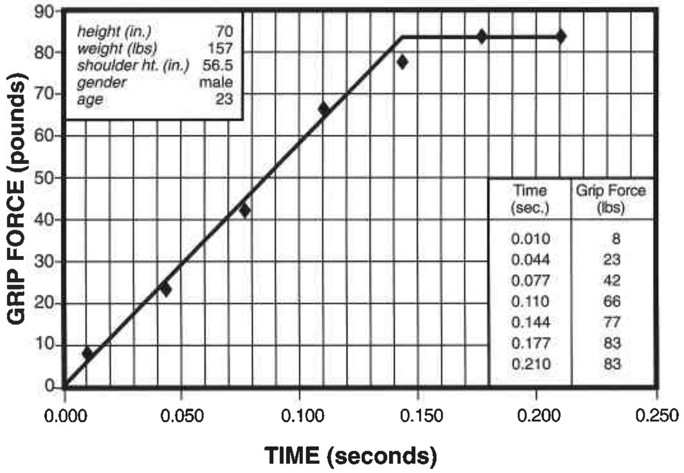
Figure A-2 - Grip/Time Test Setup



height (in.)	73
weight (lbs)	205
shoulder ht. (in.)	60
gender	male
age	20

Time (sec.)	Grip Force (lbs)
0.011	6
0.044	14
0.111	40
0.144	53
0.177	66
0.211	73
0.244	80
0.277	82
0.311	83
0.344	83

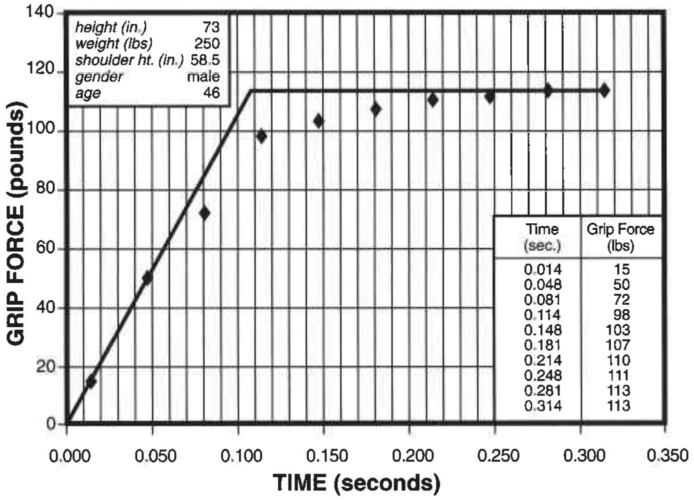
Figure A-3: Grip/Time Diagram (Test Subject 2)



height (in.)	70
weight (lbs)	157
shoulder ht. (in.)	56.5
gender	male
age	23

Time (sec.)	Grip Force (lbs)
0.010	8
0.044	23
0.077	42
0.110	66
0.144	77
0.177	83
0.210	83

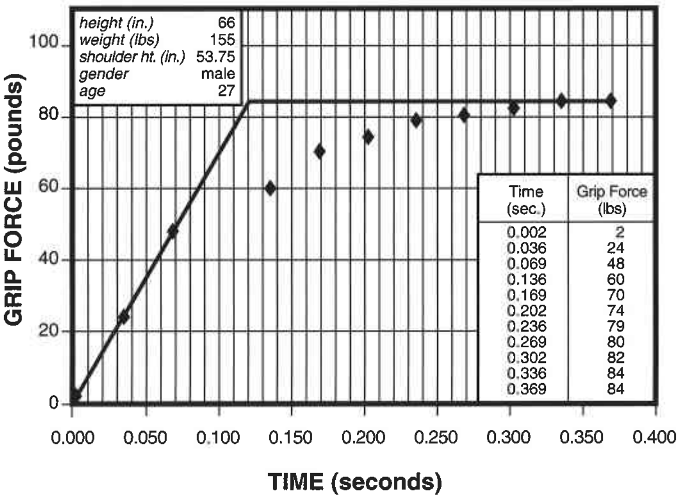
Figure A-4: Grip/Time Diagram (Test Subject 3)



height (in.)	73
weight (lbs)	250
shoulder ht. (in.)	58.5
gender	male
age	46

Time (sec.)	Grip Force (lbs)
0.014	15
0.048	50
0.081	72
0.114	98
0.148	103
0.181	107
0.214	110
0.248	111
0.281	113
0.314	113

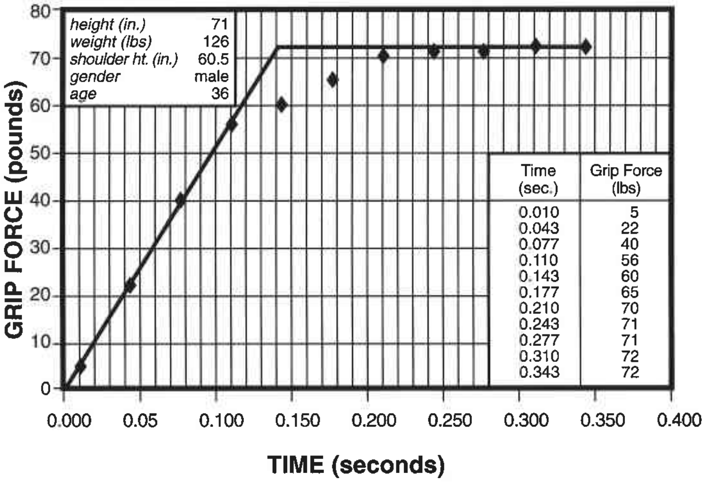
Figure A-5: Grip/Time Diagram (Test Subject 4)



height (in.)	66
weight (lbs)	155
shoulder ht. (in.)	53.75
gender	male
age	27

Time (sec.)	Grip Force (lbs)
0.002	2
0.036	24
0.069	48
0.136	60
0.169	70
0.202	74
0.236	79
0.269	80
0.302	82
0.336	84
0.369	84

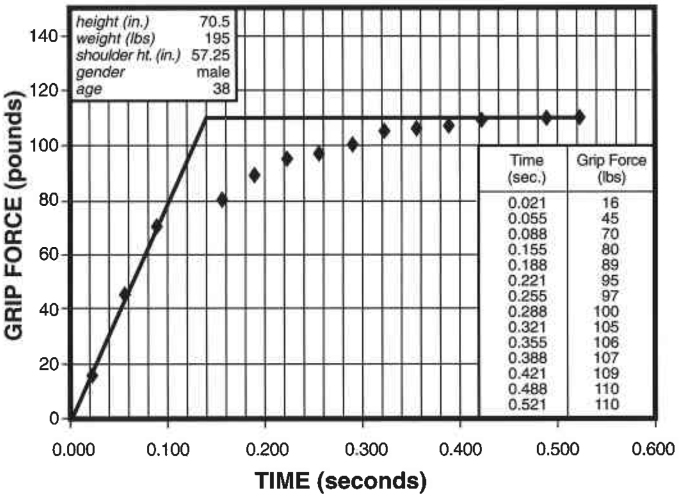
Figure A-6: Grip/Time Diagram (Test Subject 5)



height (in.)	71
weight (lbs)	126
shoulder ht. (in.)	60.5
gender	male
age	36

Time (sec.)	Grip Force (lbs)
0.010	5
0.043	22
0.077	40
0.110	56
0.143	60
0.177	65
0.210	70
0.243	71
0.277	71
0.310	72
0.343	72

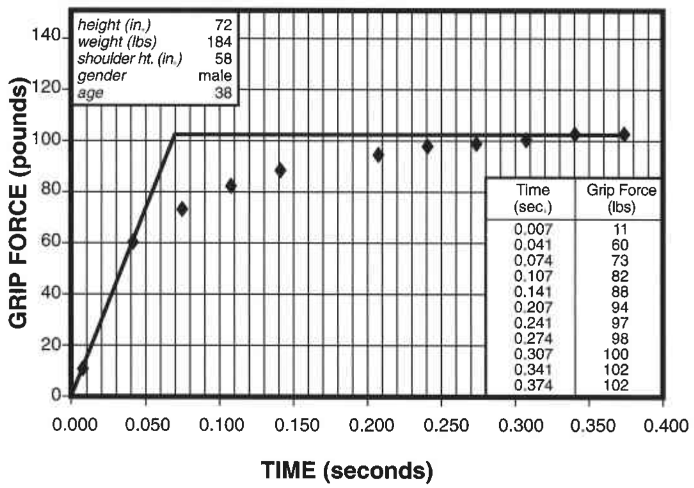
Figure A-7: Grip/Time Diagram (Test Subject 6)



height (in.)	70.5
weight (lbs)	195
shoulder ht. (in.)	57.25
gender	male
age	38

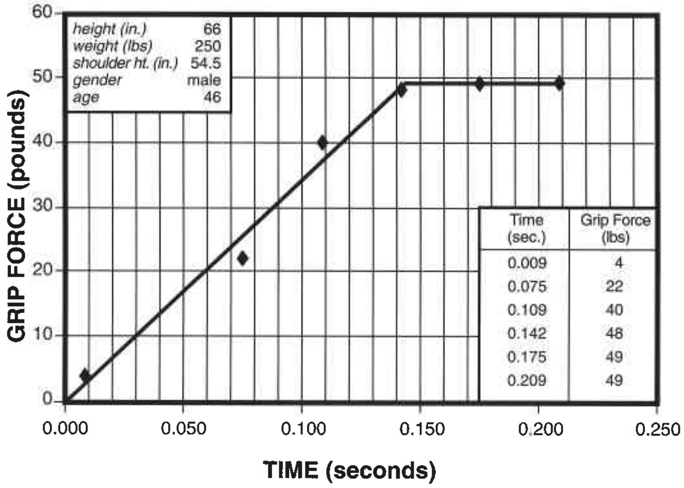
Time (sec.)	Grip Force (lbs)
0.021	16
0.055	45
0.088	70
0.155	80
0.188	89
0.221	95
0.255	97
0.288	100
0.321	105
0.355	106
0.388	107
0.421	109
0.488	110
0.521	110

Figure A-8: Grip/Time Diagram (Test Subject 7)



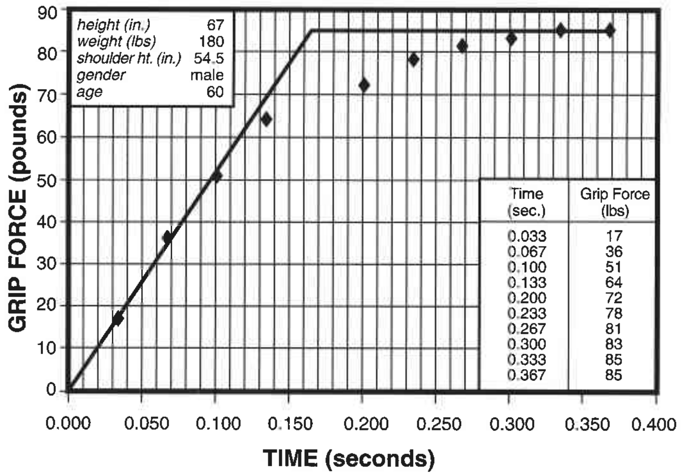
Time (sec.)	Grip Force (lbs)
0.007	11
0.041	60
0.074	73
0.107	82
0.141	88
0.207	94
0.241	97
0.274	98
0.307	100
0.341	102
0.374	102

Figure A-9: Grip/Time Diagram (Test Subject 8)



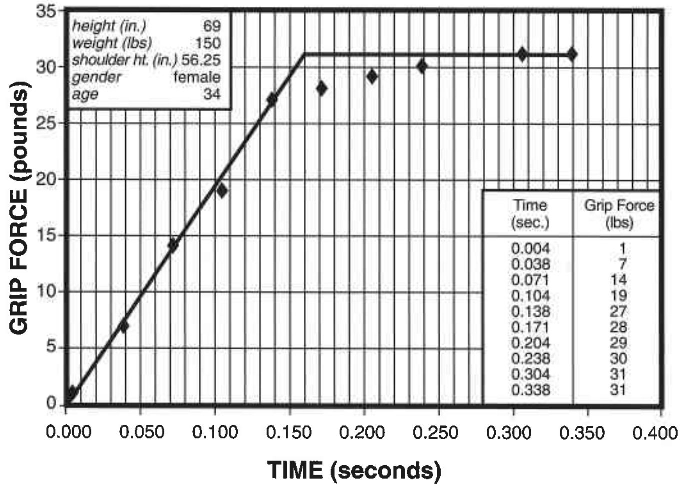
Time (sec.)	Grip Force (lbs)
0.009	4
0.075	22
0.109	40
0.142	48
0.175	49
0.209	49

Figure A-10: Grip/Time Diagram (Test Subject 9)



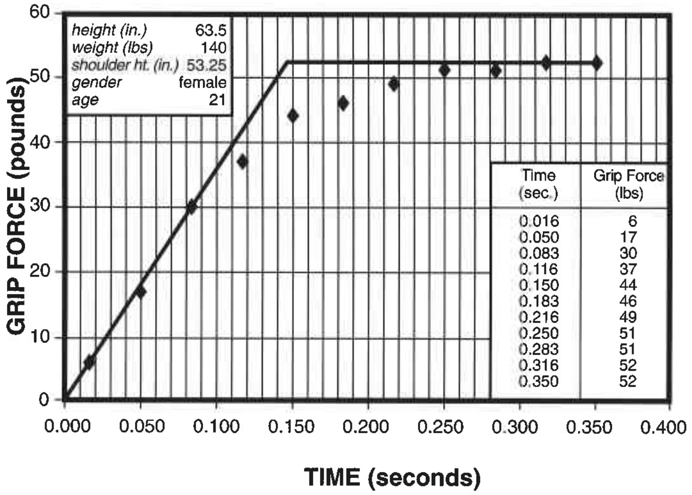
Time (sec.)	Grip Force (lbs)
0.033	17
0.067	36
0.100	51
0.133	64
0.200	72
0.233	78
0.267	81
0.300	83
0.333	85
0.367	85

Figure A-11: Grip/Time Diagram (Test Subject 10)



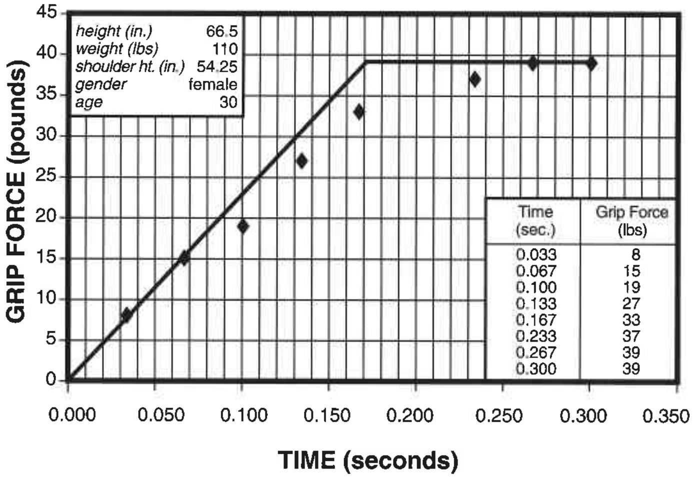
Time (sec.)	Grip Force (lbs)
0.004	1
0.038	7
0.071	14
0.104	19
0.138	27
0.171	28
0.204	29
0.238	30
0.304	31
0.338	31

Figure A-12: Grip/Time Diagram (Test Subject 11)



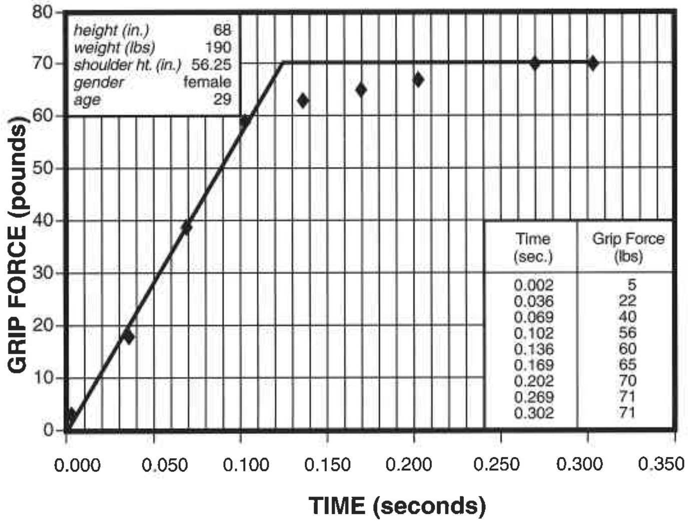
Time (sec.)	Grip Force (lbs)
0.016	6
0.050	17
0.083	30
0.116	37
0.150	44
0.183	46
0.216	49
0.250	51
0.283	51
0.316	52
0.350	52

Figure A-13: Grip/Time Diagram (Test Subject 12)



Time (sec.)	Grip Force (lbs)
0.033	8
0.067	15
0.100	19
0.133	27
0.167	33
0.233	37
0.267	39
0.300	39

Figure A-14: Grip/Time Diagram (Test Subject 13)



height (in.)	68
weight (lbs)	190
shoulder ht. (in.)	56.25
gender	female
age	29

Time (sec.)	Grip Force (lbs)
0.002	5
0.036	22
0.069	40
0.102	56
0.136	60
0.169	65
0.202	70
0.269	71
0.302	71

Figure A-15: Grip/Time Diagram (Test Subject 14)

APPENDIX B

This appendix displays tabulations of the sliding coefficient of friction between various surfaces and a carbon steel bar that is typical of the type of siderail material used in most fixed vertical ladders. The surfaces include the palms of fourteen men and women and nine pairs of work gloves.

Table B-1 Coefficient of Sliding Friction - Test Subject 1

Station	Drag Force (lbs)	Coeff. Sliding Friction
1	4.0	0.70
2	4.0	0.70
3	4.2	0.74
4	3.9	0.68
5	4.1	0.72
6	4.3	0.75
7	4.2	0.74
	Average Coefficient:	0.72

Table B-2 Coefficient of Sliding Friction - Test Subject 2

Station	Drag Force (lbs)	Coeff. Sliding Friction
1	3.6	0.63
2	3.7	0.65
3	3.7	0.65
4	3.6	0.63
5	3.6	0.63
6	3.6	0.63
7	3.5	0.61
	Average Coefficient:	0.63

Table B-3 Coefficient of Sliding Friction - Test Subject 3

Station	Drag Force (lbs)	Coeff. Sliding Friction
1	4.8	0.84
2	5.2	0.91
3	5.0	0.88
4	4.9	0.86
5	5.1	0.89
6	4.7	0.82
7	4.8	0.84
	Average Coefficient:	0.86

Table B-4 Coefficient of Sliding Friction - Test Subject 4

Station	Drag Force (lbs)	Coeff. Sliding Friction
1	4.3	0.75
2	3.9	0.68
3	4.0	0.70
4	4.1	0.72
5	3.9	0.68
6	4.0	0.70
7	3.8	0.67
	Average Coefficient:	0.70

Table B-5 Coefficient of Sliding Friction - Test Subject 5

Station	Drag Force (lbs)	Coeff. Sliding Friction
1	4.8	0.84
2	4.7	0.82
3	4.8	0.84
4	4.7	0.82
5	4.8	0.84
6	4.8	0.84
7	4.7	0.82
	Average Coefficient:	0.83

Table B-6 Coefficient of Sliding Friction - Test Subject 6

Station	Drag Force (lbs)	Coeff. Sliding Friction
1	4.2	0.74
2	4.7	0.82
3	4.4	0.77
4	4.2	0.74
5	4.7	0.82
6	4.0	0.70
7	3.9	0.68
	Average Coefficient:	0.75

Table B-7 Coefficient of Sliding Friction - Test Subject 7

Station	Drag Force (lbs)	Coeff. Sliding Friction
1	4.2	0.74
2	4.3	0.75
3	3.7	0.65
4	4.3	0.75
5	4.3	0.75
6	4.2	0.74
7	4.2	0.74
	Average Coefficient:	0.73

Table B-8 Coefficient of Sliding Friction - Test Subject 8

Station	Drag Force (lbs)	Coeff. Sliding Friction
1	3.7	0.65
2	4.0	0.70
3	3.5	0.61
4	3.8	0.67
5	3.8	0.67
6	3.5	0.61
7	3.8	0.67
	Average Coefficient:	0.65

Table B-9 Coefficient of Sliding Friction - Test Subject 9

Station	Drag Force (lbs)	Coeff. Sliding Friction
1	3.4	0.60
2	3.5	0.61
3	3.9	0.68
4	3.1	0.54
5	3.5	0.61
6	3.3	0.58
7	2.9	0.51
	Average Coefficient:	0.59

Table B-10 Coefficient of Sliding Friction - Test Subject 10

Station	Drag Force (lbs)	Coeff. Sliding Friction
1	4.3	0.75
2	4.5	0.79
3	4.6	0.81
4	4.5	0.79
5	4.6	0.81
6	4.6	0.81
7	4.6	0.81
	Average Coefficient:	0.80

Table B-11 Coefficient of Sliding Friction - Test Subject 11

Station	Drag Force (lbs)	Coeff. Sliding Friction
1	4.0	0.70
2	3.8	0.67
3	3.8	0.67
4	3.7	0.65
5	3.8	0.67
6	3.7	0.65
7	3.7	0.65
	Average Coefficient:	0.67

Table B-12 Coefficient of Sliding Friction - Test Subject 12

Station	Drag Force (lbs)	Coeff. Sliding Friction
1	4.7	0.82
2	5.3	0.93
3	4.6	0.81
4	4.2	0.74
5	5.1	0.89
6	4.1	0.72
7	4.9	0.86
	Average Coefficient:	0.82

Table B-13 Coefficient of Sliding Friction - Test Subject 13

Station	Drag Force (lbs)	Coeff. Sliding Friction
1	3.8	0.67
2	3.8	0.67
3	3.7	0.65
4	4.0	0.70
5	3.8	0.67
6	3.6	0.63
7	3.9	0.68
	Average Coefficient:	0.67

Table B-14 Coefficient of Sliding Friction - Test Subject 14

Station	Drag Force (lbs)	Coeff. Sliding Friction
1	6.0	1.05
2	5.9	1.04
3	6.0	1.05
4	6.0	1.05
5	5.7	1.00
6	5.5	0.96
7	5.5	0.96
	Average Coefficient:	1.02

Table B-15 Coefficient of Sliding Friction - All Cotton Gloves

Station	Drag Force (lbs)	Coeff. Sliding Friction
1	3.7	0.65
2	3.6	0.63
3	3.5	0.61
4	3.4	0.60
5	3.3	0.58
6	3.2	0.56
7	3.2	0.56
	Average Coefficient:	0.60

Table B-16 Coefficient of Sliding Friction- Tan Leather Work Gloves

Station	Drag Force (lbs)	Coeff. Sliding Friction
1	3.8	0.67
2	3.7	0.65
3	3.6	0.63
4	3.5	0.61
5	3.4	0.60
6	3.3	0.58
7	3.1	0.54
	Average Coefficient:	0.61

Table B-17 Coefficient of Sliding Friction- Knit Gloves With Rubber Cross Beaded Palm

Station	Drag Force (lbs)	Coeff. Sliding Friction
1	5.8	1.02
2	5.1	0.89
3	5.0	0.88
4	5.1	0.89
5	5.0	0.88
6	4.9	0.86
7	4.7	0.82
	Average Coefficient:	0.89

Table B-18 Coefficient of Sliding Friction- Canvas Gloves With Rubber Dotted Palm

Station	Drag Force (lbs)	Coeff. Sliding Friction
1	3.8	0.67
2	3.9	0.68
3	3.8	0.67
4	3.7	0.65
5	3.7	0.65
6	3.7	0.65
7	3.6	0.63
	Average Coefficient:	0.66

Table B-19 Coefficient of Sliding Friction- Black Leather Gloves

Station	Drag Force (lbs)	Coeff. Sliding Friction
1	2.6	0.46
2	2.6	0.46
3	2.5	0.44
4	2.5	0.44
5	2.5	0.44
6	2.5	0.44
7	2.5	0.44
	Average Coefficient:	0.45

Table B-20 Coefficient of Sliding Friction- Excessively Worn Tan Leather Work Gloves

Station	Drag Force (lbs)	Coeff. Sliding Friction
1	3.8	0.67
2	3.7	0.65
3	3.6	0.63
4	3.6	0.63
5	3.4	0.60
6	3.3	0.58
7	3.3	0.58
	Average Coefficient:	0.62

Table B-21 Coefficient of Sliding Friction- Cloth Gardening Gloves With Rubber Dotted Palm

Station	Drag Force (lbs)	Coeff. Sliding Friction
1	4.6	0.81
2	4.5	0.79
3	4.4	0.77
4	4.5	0.79
5	4.3	0.75
6	4.3	0.75
7	4.2	0.74
	Average Coefficient:	0.77

Table B-22 Coefficient of Sliding Friction- Felt Covered Rubber Gloves

Station	Drag Force (lbs)	Coeff. Sliding Friction
1	3.2	0.56
2	2.3	0.40
3	2.5	0.44
4	2.5	0.44
5	2.3	0.40
6	2.3	0.40
7	2.3	0.40
	Average Coefficient:	0.43

Table B-23 Coefficient of Sliding Friction-
Cotton Work Gloves With Leather Palms

Station	Drag Force (lbs)	Coeff. Sliding Friction
1	3.2	0.56
2	3.2	0.56
3	3.1	0.54
4	3.1	0.54
5	3.1	0.54
6	3.0	0.53
7	3.0	0.53
	Average Coefficient:	0.54

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