Factors Affecting the Capacity to Hang On:
Research and Implications for Ladders

by
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Introduction

• The following is a summary of ladder climbing and handhold design research done over the last decade
• The results show that humans are not particularly suited to climbing; specifically that the hands do not have much capacity to support our own bodies in a fall situations
  – If one finds themselves in that situation, certain handhold designs will provide a much better chance of hanging on than others
References


• Dissertation: [http://deepblue.lib.umich.edu/handle/2027.42/84452](http://deepblue.lib.umich.edu/handle/2027.42/84452)

• Hur, P., Motawar, B., & Seo, N. J. (2012). Hand breakaway strength model—Effects of glove use and handle shapes on a person's hand strength to hold onto handles to prevent fall from elevation. *Journal of biomechanics, 45*(6), 958-964.

Part 1: ladder climbing

• We performed a study for the CPWR in 2007-2008, examining climbing when using the rungs or the rails
  – Which is better?
• We tested
  – rail versus rung use
  – ladder pitch and bank
  – carrying objects
Methods

• Subjects were instructed to climb a fixed ladder at a comfortable speed
• From a bipedal stance on the ground, subjects ascended 5 rungs, paused, and then descended to the ground
• No other instruction was given as to climbing style
Design

Independent Variables

• Ladder Orientation (3), Climbing Method (2), Carrying (2)*

<table>
<thead>
<tr>
<th>Ladder Orientation</th>
<th>Vertical (0°)</th>
<th>10° forward tilt</th>
<th>5° right bank</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatments (3 repetitions each)</td>
<td>Climb w/rungs Climb w/rails Carry toolbox (rungs) Carry toolbox (rails)</td>
<td>Climb w/rungs Climb w/rails Carry toolbox (rungs) Carry toolbox (rails)</td>
<td>Climb w/rungs Climb w/rails</td>
</tr>
</tbody>
</table>

*not tested for 5° Lateral Bank

Total Trials

(2 Methods x 3 Orientations x 2 Carrying – 2) x 3 reps = 30
Results: the myth of “natural” 3-point control
-training and concerted effort required to overcome natural climbing gait

Climbing with the Rungs

Climbing with the Rails

Two-point contact
# Peak Hand Forces

Mean peak resultant hand force (% bodyweight) exerted by either hand during the climbing task for all subjects (n=12)

<table>
<thead>
<tr>
<th></th>
<th>Vertical (0°)</th>
<th>10° Forward Pitch</th>
<th>Lateral Tilt (5° Bank)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climb Rungs</td>
<td>0.424 ± 0.084</td>
<td>0.437 ± 0.110</td>
<td>0.468 ± 0.103</td>
</tr>
<tr>
<td>Climb Rails</td>
<td>0.322 ± 0.040</td>
<td>0.284 ± 0.056*</td>
<td>0.338 ± 0.044</td>
</tr>
<tr>
<td>Toolbox Rungs</td>
<td>0.445 ± 0.071</td>
<td>0.433 ± 0.089</td>
<td>--</td>
</tr>
<tr>
<td>Toolbox Rails</td>
<td>0.453 ± 0.104</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

Rails < Rungs  

Carrying Toolbox increases force

*left rail forces only
Hand and foot forces for during loading profile

Average maximum resultant **hand** force (% bodyweight) during loading for data subset, n=6

<table>
<thead>
<tr>
<th></th>
<th>Climb w/ Rungs</th>
<th>Climb w/ Side Rails</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ascent</td>
<td>Descent</td>
</tr>
<tr>
<td>Vertical (0°)</td>
<td>34 ± 1</td>
<td>36 ± 12</td>
</tr>
<tr>
<td>Lateral Tilt (5° Bank)</td>
<td>32 ± 7</td>
<td>39 ± 16</td>
</tr>
</tbody>
</table>

Range: maximum force 15% to 69% of bodyweight

Average maximum resultant **foot** force (% bodyweight) during loading for data subset, n=6

<table>
<thead>
<tr>
<th></th>
<th>Climb w/ Rungs</th>
<th>Climb w/ Side Rails</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ascent</td>
<td>Descent</td>
</tr>
<tr>
<td>Vertical (0°)</td>
<td>105 ± 15</td>
<td>97 ± 11</td>
</tr>
<tr>
<td>Lateral Tilt (5° Bank)</td>
<td>101 ± 13</td>
<td>95 ± 11</td>
</tr>
</tbody>
</table>

Range: maximum force 73% to 143% of bodyweight
3D force profile for hands

Orthogonal hand forces acting over the course of the load/unload cycle on the vertical ladder. Forces (% BW) are average values at each normalized time point from data subset (n=6).
Hand forces

• Average resultant peak hand force on the rungs for climbing vertical ladders was 34-36% of bodyweight
  – Bloswick and Chaffin (1990) reported 30% peak hand force; Ayoub and Bakken (1978) reported 36%.

• This level of force is significant especially in situations where friction is low, such as during inclement weather
Rungs vs. Rails?

• Peak resultant hand forces are significantly less for rail climbing than rung climbing

• Hand forces for the rails were more affected by ladder pitch than for the rungs

• Hand foot distance is constrained by rung location. Climbing with rails enables climbers to easily increase the distance between the hands and the feet, which may explain the reduced and forces

• The hand-rail forces involve a large lateral component that must be counter acted through static foot and dynamic body forces, which may be destabilizing
• The feet do most of the work to elevate or lower the body, while the hand stabilizes the body

• A rung that is optimized for hand force will not necessarily be optimal for foot force and visa versa.

Conclusion: Rungs or rails, its hard to say...but can we even hang on in a fall?
Part 2: Hand/handhold coupling

Three breakaway strength experiments were performed

1. Typical ladder handholds and a zero-friction condition
2. Handhold cross-sectional shape
3. Orientation & size, and orientation & gloves (friction)

Each had 12 subjects (=m/f)
Apparatus

Perform simulated fall:

• Platform and subject are lowered slowly, no impulse (14.5 cm/sec)

• Posture passively stabilizes upper-limb joints

• Body weight provides external load
Experiment 1

Subjects

6 males: age 21±2 years old, weight 152 ± 36 lbs
6 female: age 21 ± 2 years old, weight 120 ± 21 lbs
The graph illustrates the peak grasp force in multiples of bodyweight for males and females across different grasp configurations: horizontal rung, vertical rail, and vertical plate. The data shows that males generally exert a higher peak grasp force compared to females, especially in the horizontal rung. The graphs for vertical rail and plate also indicate a difference in grasp force between males and females, with males generally maintaining a higher force level.
EXP 1a: Peak breakaway strength, normalized strength, and grip strength (mean ± SD), by handle and gender, for typical ladder handholds. Experiment with 6 males and 6 females, dominant hand measurement.*

<table>
<thead>
<tr>
<th>Handle</th>
<th>Peak Force (lbs)</th>
<th>Peak Force / Bodyweight</th>
<th>Peak Force / Grip Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Males</td>
<td>Females</td>
<td>Males</td>
</tr>
<tr>
<td>RUNG (cylinder)</td>
<td>189 ± 111</td>
<td>1.17 ± 0.94</td>
<td>1.52 ± 1.53</td>
</tr>
<tr>
<td>1&quot; diameter</td>
<td>47</td>
<td>21</td>
<td>0.13</td>
</tr>
<tr>
<td>RAIL (cylinder)</td>
<td>116 ± 80</td>
<td>0.72 ± 0.68</td>
<td>0.93 ± 1.10</td>
</tr>
<tr>
<td>1&quot; diameter</td>
<td>30</td>
<td>10</td>
<td>0.1</td>
</tr>
<tr>
<td>RAIL (plate)</td>
<td>92 ± 59</td>
<td>0.55 ± 0.50</td>
<td>0.73 ± 0.81</td>
</tr>
<tr>
<td>2.5&quot; x 0.4&quot;</td>
<td>37</td>
<td>16</td>
<td>0.14</td>
</tr>
<tr>
<td>Grip Strength</td>
<td>124 ± 72</td>
<td>0.85 ± 0.61</td>
<td>1</td>
</tr>
<tr>
<td>(Jamar 45mm)</td>
<td>13</td>
<td>8</td>
<td>0.2</td>
</tr>
</tbody>
</table>

*Table adapted from Young et al. 2009 (Table 2) also in Young, JG. Dissertation (Table 2.3.1)
Experiment 2

6 males: age 23±4 years old, weight 180 ± 31 lbs
6 female: age 23±3 years old, weight 139 ± 18 lbs
Experiment 2

Δ 48 lbs

150 lbs  94% BW
127 lbs  79% BW
116 lbs  73% BW
102 lbs  64% BW
EXP 2a&b: Peak breakaway strength and normalized strength (mean ± SD), by handle and gender, for typical ladder handholds. Experiment with 6 males and 6 females, both hands.*

<table>
<thead>
<tr>
<th></th>
<th>Breakaway Force (lbs)</th>
<th>Breakaway Force / Bodyweight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Males</td>
<td>Females</td>
</tr>
<tr>
<td>RUNG(^a) (cylinder)</td>
<td>188 ± 43</td>
<td>113 ± 24</td>
</tr>
<tr>
<td>1&quot; diameter</td>
<td>168 ± 34</td>
<td>86 ± 16</td>
</tr>
<tr>
<td>RUNG(^a) (diamond)</td>
<td>146 ± 34</td>
<td>86 ± 16</td>
</tr>
<tr>
<td>1&quot;x1&quot;</td>
<td>131 ± 28</td>
<td>73 ± 16</td>
</tr>
<tr>
<td>Grip dynamometer(^a) (Jamar 45mm)</td>
<td>123 ± 27</td>
<td>68 ± 18</td>
</tr>
<tr>
<td>RAIL(^b) (cylinder)</td>
<td>85 ± 10</td>
<td>67 ± 11</td>
</tr>
<tr>
<td>7/8&quot; diameter</td>
<td>96 ± 19</td>
<td>69 ± 12</td>
</tr>
<tr>
<td>RAIL(^b) (cylinder)</td>
<td>105 ± 26</td>
<td>83 ± 19</td>
</tr>
<tr>
<td>7/8&quot; to 1.25&quot;</td>
<td>18 ± 14</td>
<td>12 ± 12</td>
</tr>
<tr>
<td>Grip dynamometer(^b) (Jamar 45mm)</td>
<td>114 ± 18</td>
<td>64 ± 12</td>
</tr>
</tbody>
</table>

*Table adapted from Young & Armstrong 2009 (Table 9) and Young, JG. Dissertation (Table 3.3.1)

\(^a\) dominant hand measurement

\(^b\) non-dominant hand measurement

½ Fail

Rails << Rungs
Experiment 3

• This experiment varied:
  – The size of cylindrical handholds
  – The orientation at several angles between rungs (90°) and rails (0°)
  – Changing friction with gloves

• 12 subjects over three sessions
  – 6 males: age 22±2 years old, weight 166 ± 43 lbs
  – 6 female: age 21±1 years old, weight 122 ± 17 lbs
Orientation vs. Size

58-78% increase

*From Chapter 4
Orientation vs. Friction

BW

- High Friction Glove: $\mu \approx 0.70$
- Bare Hand: $\mu \approx 0.27$
- Low Friction Glove

*From Chapter 4*
Types of Breakaway

(Fingers forced open)

(Hand slides off of the handle)
Friction

Grip

Body Weight

$\alpha = 90^\circ$

Fingers forced open

Friction

Grip

Body Weight

$\alpha \approx 45^\circ$

Fingers forced open
-or-
Hand slides off

Friction

Grip

Body Weight

$\alpha = 0^\circ$

Hand slides off
Types of breakaway: friction

High Friction Gloves

Low Friction Gloves

Breakaway Force = 542 N

Breakaway Force = 426 N

Overall, high friction gloves or bare hands increase force 25-118% compared to low friction gloves.
Orientation

\[ \mu \approx 0.70 \]

\[ \mu \approx 0.27 \]

*From Chapter 4*
Size (cylinder diameter)

From Chapter 4
**EXP 3a:** Peak breakaway strength and normalized strength (mean ± SD), by handle and gender, for typical ladder handholds. Experiment with 6 males and 6 females, dominant hand measurement.*

<table>
<thead>
<tr>
<th>RUNGS (cylinders)</th>
<th>Breakaway Force (lbs)</th>
<th>Breakaway/Bodyweight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Males</td>
<td>Females</td>
</tr>
<tr>
<td>2&quot; diameter</td>
<td>147 ± 32</td>
<td>75 ± 26</td>
</tr>
<tr>
<td>1.25&quot; diameter</td>
<td>157 ± 34</td>
<td>84 ± 24</td>
</tr>
<tr>
<td>0.875&quot; diameter</td>
<td>169 ± 38</td>
<td>90 ± 25</td>
</tr>
<tr>
<td>All Diameters Pooled</td>
<td>157 ± 35</td>
<td>83 ± 25</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>RAILS (cylinders)</th>
<th>Breakaway Force (lbs)</th>
<th>Breakaway/Bodyweight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Males</td>
<td>Females</td>
</tr>
<tr>
<td>2&quot; diameter</td>
<td>84 ± 20</td>
<td>48 ± 18</td>
</tr>
<tr>
<td>1.25&quot; diameter</td>
<td>93 ± 16</td>
<td>60 ± 19</td>
</tr>
<tr>
<td>0.875&quot; diameter</td>
<td>87 ± 22</td>
<td>58 ± 21</td>
</tr>
<tr>
<td>All Diameters Pooled</td>
<td>88 ± 20</td>
<td>55 ± 20</td>
</tr>
</tbody>
</table>

*Table adapted from Young et al. 2012 (Table 3) also in Young, JG. Dissertation (Table 4.4.2)

**RUNGS outperform RAILS!** May not be able to support bodyweight with RAILS even with both hands!
In all three experiments, rungs significantly outperformed rails. Some rung designs performed poorly (plates, corners, large cylinders).

Figure 1. RAILS vs. RUNGS for all 3 experiments. For males, mean strength is greater for any of the rung designs compared to any of the rail designs tested. For females, only the 1” cylinder rail and the tapered cylinder rail afford greater strength than the 2” cylinder rung or the plate rung, otherwise rungs afford greater strength than rails on average.
Generalizations

- Breakaway strength can be much greater than grip strength, even without friction
  - 21-32% increase due to eccentric contraction (internal friction or eccentric motor control)

- Friction responsible for 22-29% of breakaway strength for bare hands

- As handhold orientation moves toward vertical, friction keeps hand from sliding
• Cylinders easier to hold than shapes with corners (>18% increase)
  – Only cylinder supported BW (only for males)
  – Contact area, locations of high pressure

• Difference between square and diamond shapes not significant
  – Difference in joint location w.r.t. external loading
• As handle long axis becomes parallel to the applied load, friction becomes increasingly responsible for breakaway strength

• For steeper handhold orientations, wrist becomes deviated
  – Decreased ability to squeeze (active component)
Summary

• Breakaway strength can be significantly greater (181%) or significantly less (65%) than grip strength for similar grasped objects

• Relative influence of significant factors:
  – Orientation (↓ 81lbs horizontal to vertical)
  – Friction (↓ 73lbs from high- to low-friction gloves, 45°)
  – Shape (↓ 56lbs From cylinder to rectangle)
  – Size (↓ 22lbs from 51mm to 22mm)

• Interactions between factors are important
Gender

• For the subjects tested in these studies, only male subjects could support their bodyweight with one hand on average
  – Females are at greater risk

• The only handholds on which average males are capable of supporting their own bodyweight with one hand:
  – Fixed horizontal cylinders of 22-25mm diameter
  – Fixed 32mm cylinders while wearing high-friction gloves in the horizontal and 75° orientations
Recommendations

• Orient handholds horizontally to increase the chances of arresting a fall caused by the unexpected loss of foot support
  – Other orientations are highly dependent on friction
  – Even in very low friction situations, horizontal handholds ensure that the fingers must be forced open to break coupling

• Cylindrical shapes or those without corners should be used for handholds
• Optimal climbing handhold size is dependent on orientation
  – Smaller handholds than predicted by grip strength biomechanics afforded more strength for horizontal handholds
  – For vertical handholds, optimal handhold size is likely similar to grip

• Gloves:
  – Despite reducing isometric grip strength slightly, high-friction gloves will increase breakaway strength
  – Gloves which reduce friction between the hand and the handle will reduce the ability to hang on
Other studies:

• We tested breakaway strength for 397 children for different sized handholds
• Age 5-11
• Large handholds reduced strength
  – Females could not hold own BW with one hand
Hur et al., 2012

- Another research group (UW-Milwaukee)
- 13 subjects
Discussion & Questions

THANK YOU!