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

- Young, JG; Woolley, C; Ashton-Miller, JA; Armstrong, TJ. (2012). The effect of handhold orientation, size, and wearing gloves on hand-handhold breakaway strength. *Human Factors*, *54:3*, 316 – 333.
- Young, JG; Woolley, C; Armstrong, TJ; Ashton-Miller, JA. (2009). Hand/handhold coupling: effect of handle shape, orientation, and friction on breakaway strength. *Human Factors, 51:5*, 705-717.
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- 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.
- Ehrlich, P. F., Young, J. G., Ulin, S., Woolley, C., Armstrong, T. J., Galecki, A., ... & Ashton-Miller, J. A. (2013). Maximum Hand-Rung Coupling Forces in Children The Effects of Handhold Diameter. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, *55*(3), 545-556.

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)*

Ladder Orientation	**Vertical (0°)**	**10° forward tilt**	**5° right bank**
Treatments (3 repetitions each)	Climb w/rungs Climb w/rails Carry toolbox (rungs) Carry toolbox (rails)	Climb w/rungs Climb w/rails Carry toolbox (rungs) Carry toolbox (rails)	Climb w/rungs Climb w/rails

*not tested for 5° Lateral Bank

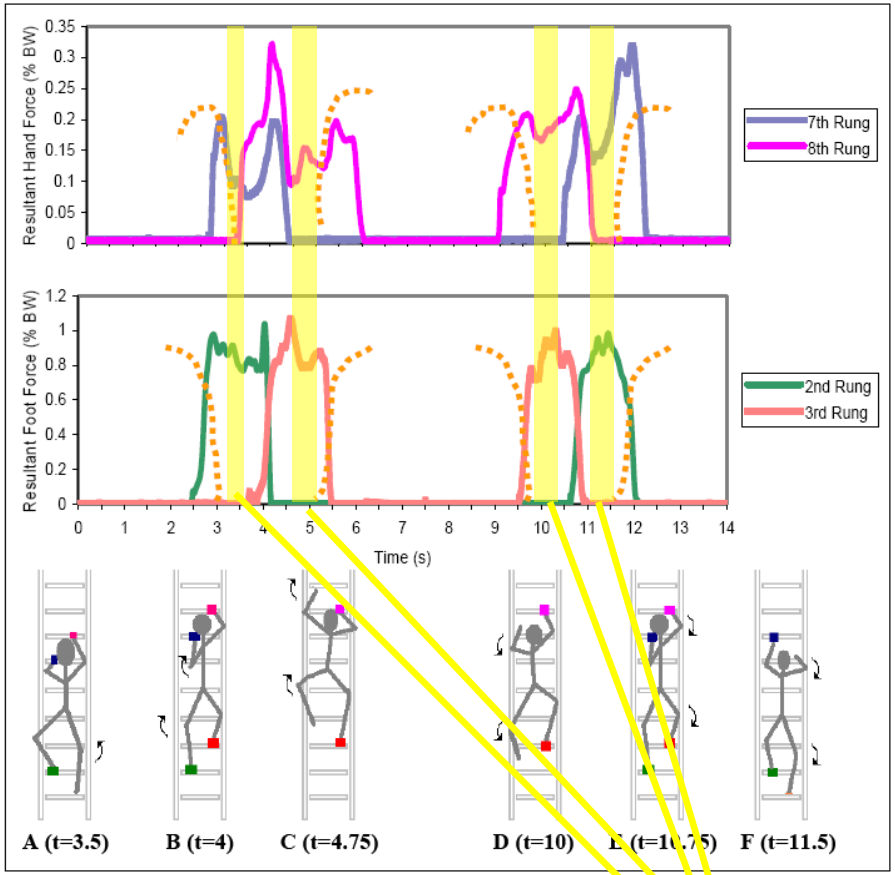
Total Trials

(2 Methods x 3 Orientations x 2 Carrying – 2) x 3 reps = 30

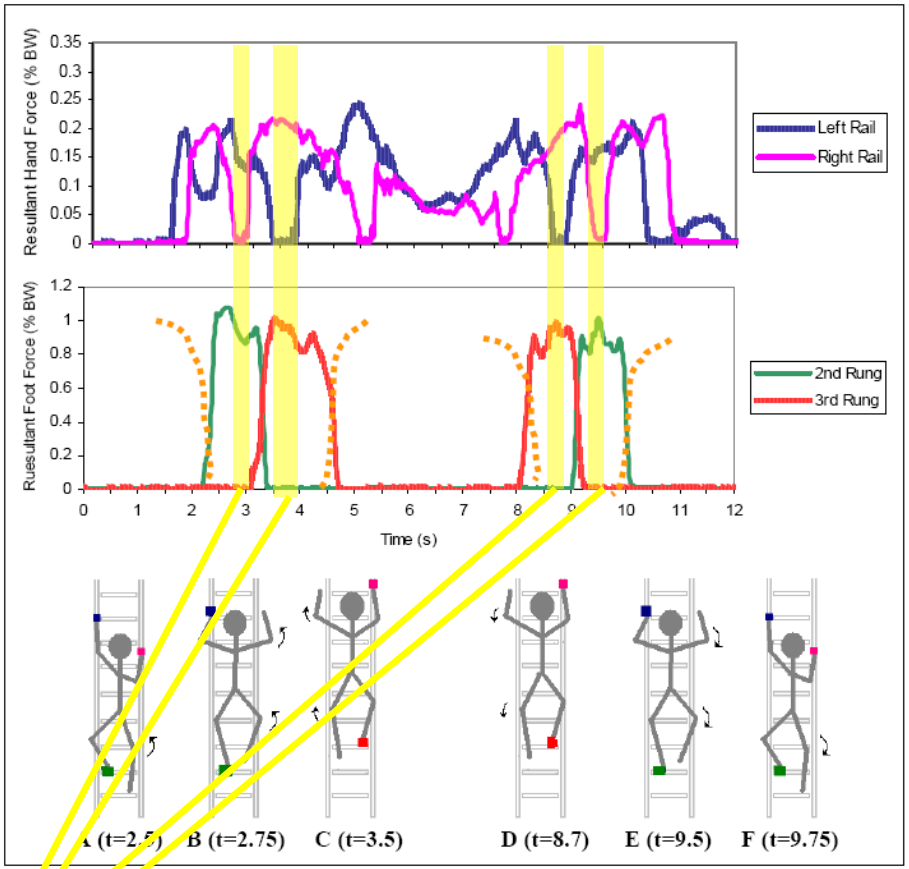
Results: the myth of "natural" 3-point control

-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)

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

*left rail forces only

Rails < Rungs

Carrying Toolbox increases force

Hand and foot forces for during loading profile

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

	Climb w/ Rungs		Climb w/ Side Rails	
	Ascent	**Descent**	**Ascent**	**Descent**
Vertical (0°)	34 ± 1	36 ± 12	29 ± 4	29 ± 5
Lateral Tilt (5° Bank)	32 ± 7	39 ± 16	31 ± 6	28 ± 6

Range: maximum force 15% to 69% of bodyweight

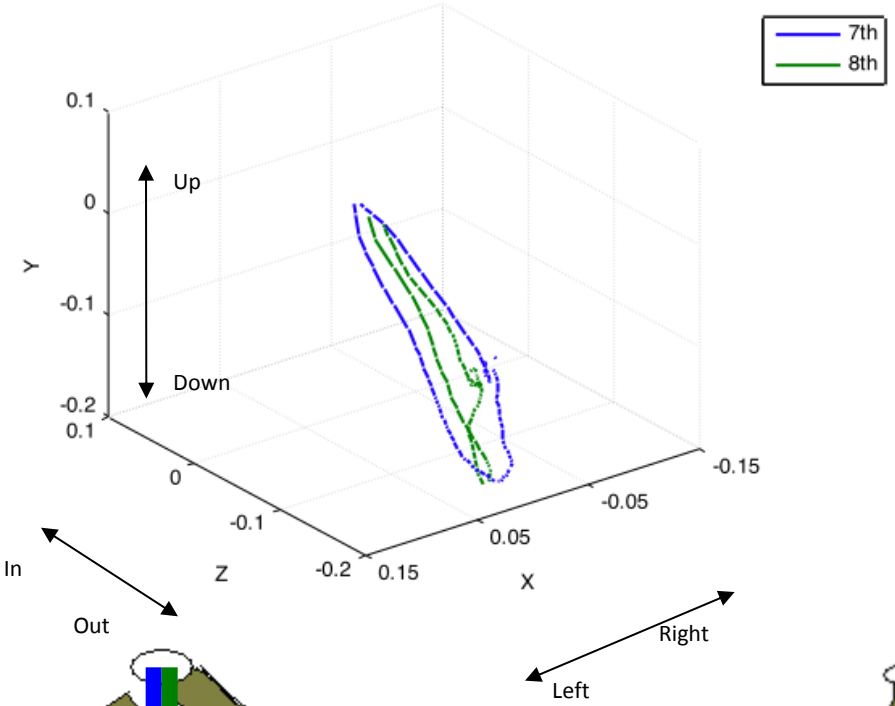
Average maximum resultant **foot** force (% bodyweight) during loading for data subset, n=6

	Climb w/ Rungs		Climb w/ Side Rails	
	Ascent	**Descent**	**Ascent**	**Descent**
Vertical (0°)	105 ± 15	97 ± 11	100 ± 11	96 ± 12
Lateral Tilt (5° Bank)	101 ± 13	95 ± 11	100 ± 14	94 ± 12

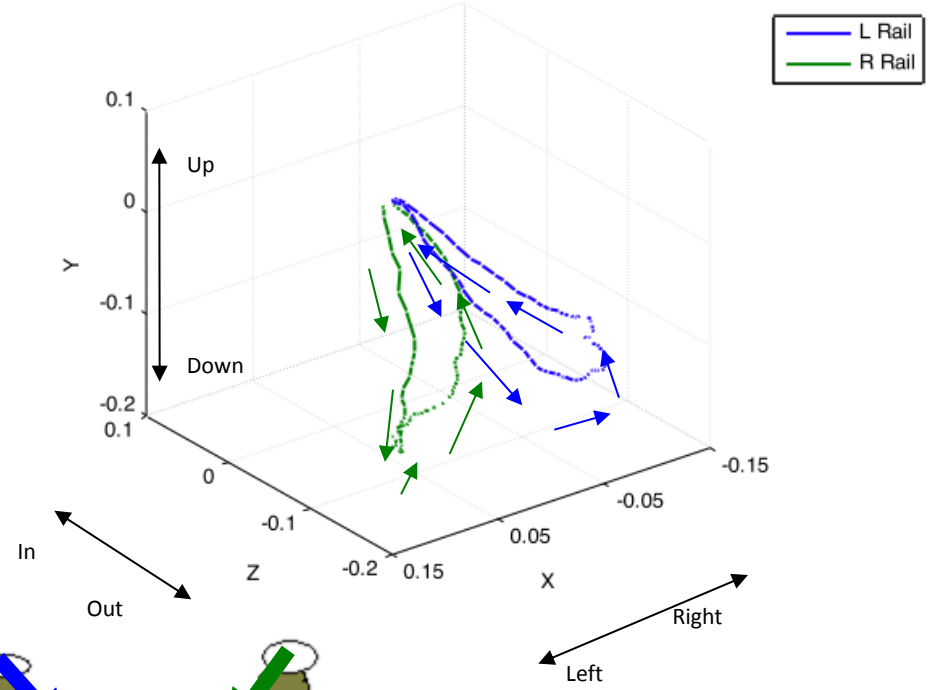
Range: maximum force 73% to 143% of bodyweight

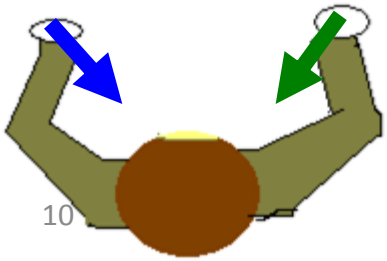
3D force profile for hands

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



Rungs





Rails

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

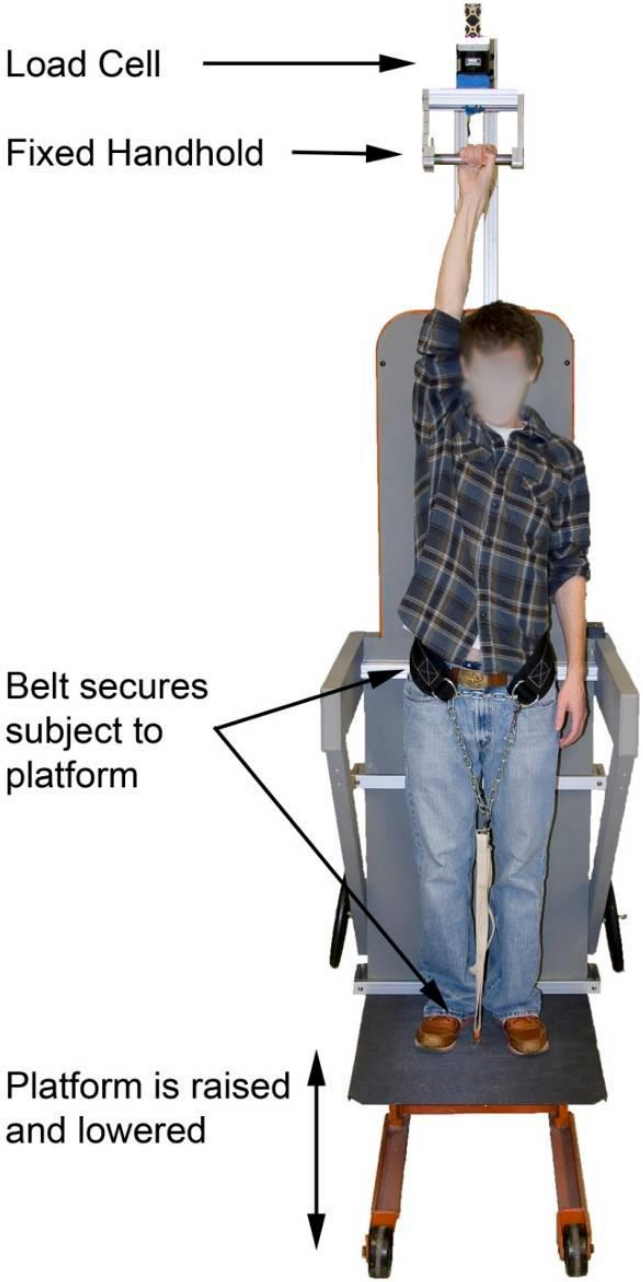
1. Typical ladder handholds and a zero-friction condition
2. Handhold cross-sectional shape
3. Orientation & size, and orientation & gloves (friction)

Each had 12 subjects (=m/f)

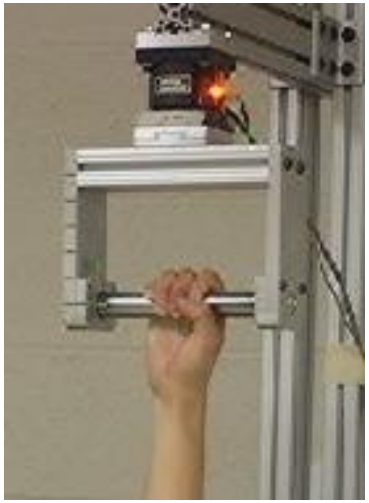
Apparatus

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



Horizontal Rung

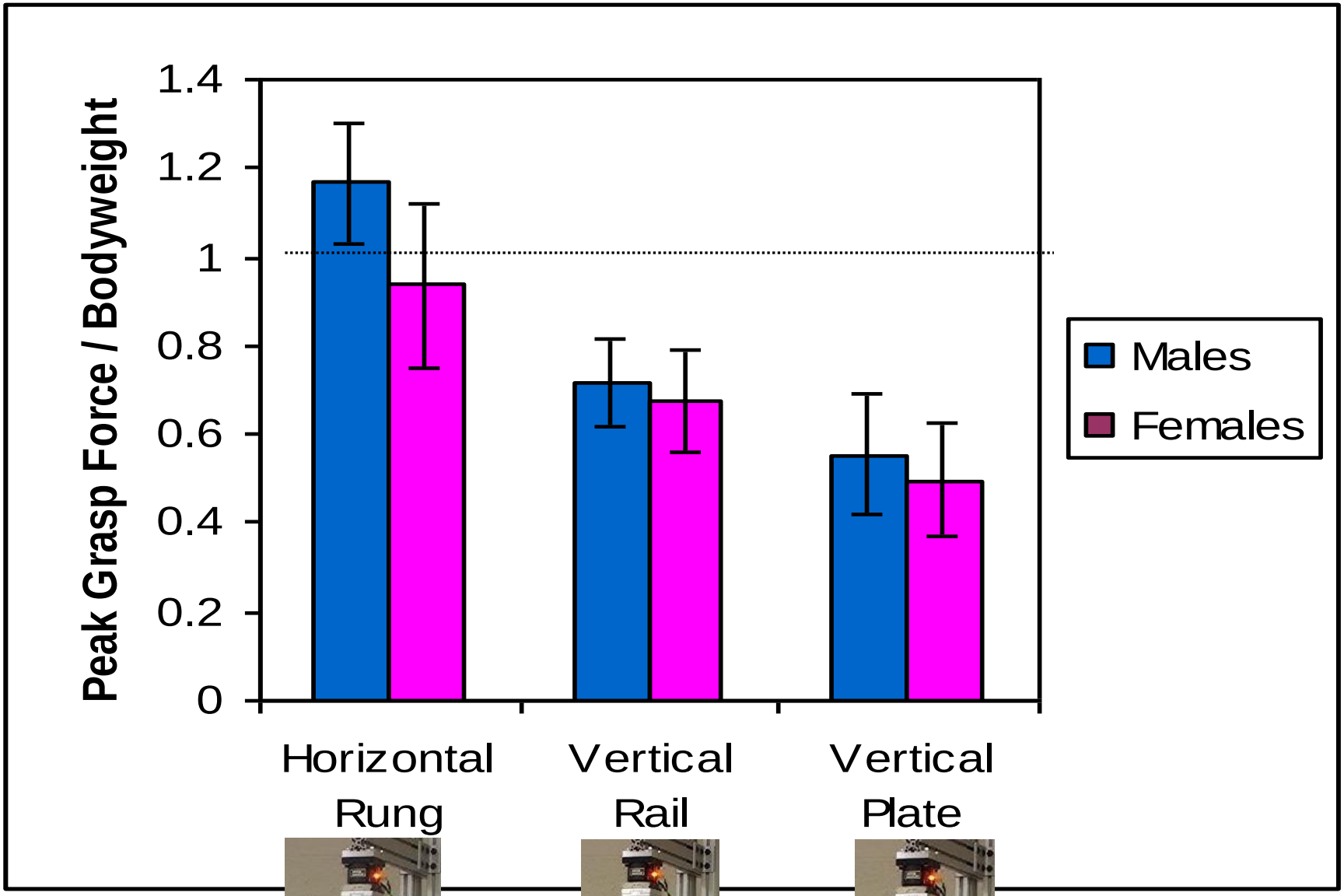
Vertical Rail

Vertical Plate

Subjects

6 males: age 21$\pm$2 years old, weight 152 $\pm$ 36 lbs

6 female: age 21 $\pm$ 2 years old, weight 120 $\pm$ 21 lbs


Peak Grasp Force / Bodyweight
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Horizontal Rung
Vertical Rail
Vertical Plate
Males
Females

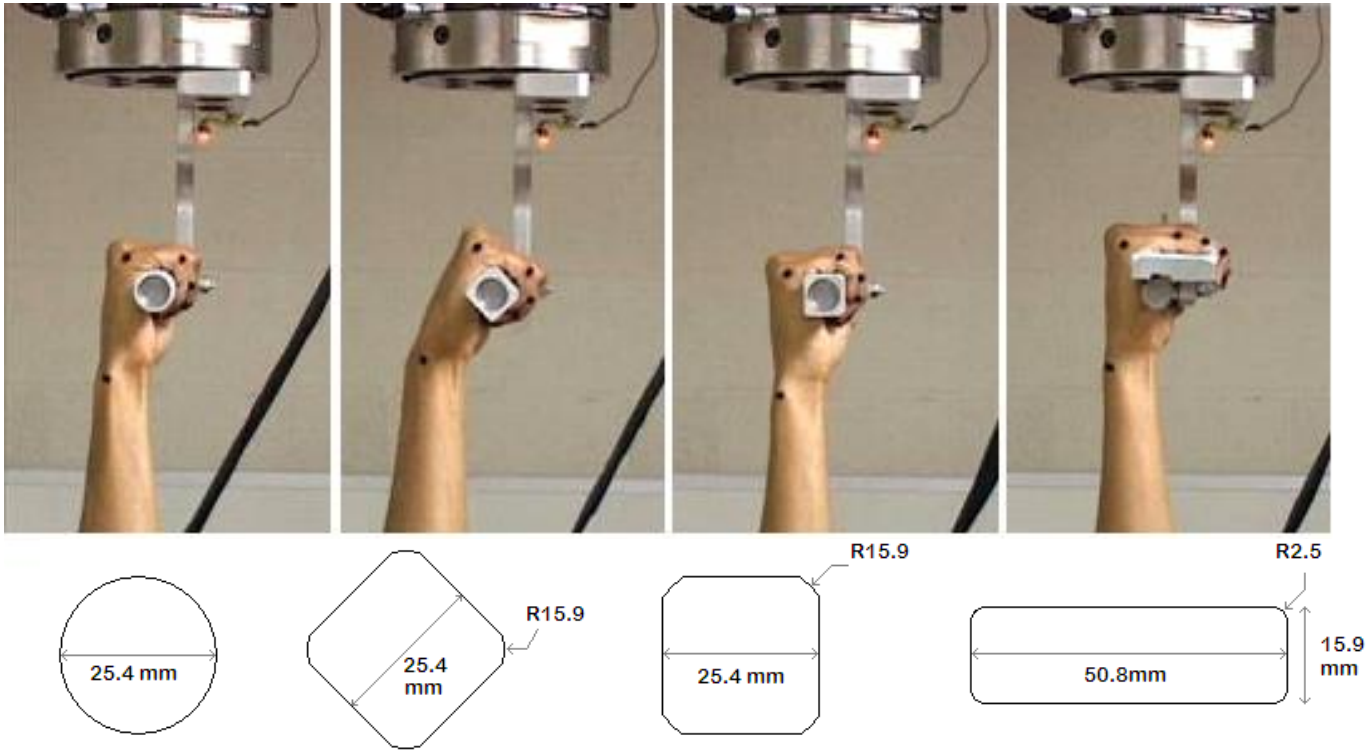
EXP 1a: Peak breakaway strength, normalized strength, and grip strength (mean ± SD), by handle and gender, for typical ladder handholds. Experiment with 6 males and 6 females, dominant hand measurement.*

Handle	Peak Force (lbs)		Peak Force / Bodyweight		Peak Force / Grip Strength	
	Males	Females	Males	Females	Males	Females
RUNG (cylinder)	189 ±	111 ±	1.17 ±	0.94 ±	1.52 ±	1.53 ±
1" diameter	47	21	0.13	0.18	0.26	0.2
RAIL (cylinder)	116 ±	80 ±	0.72 ±	0.68 ±	0.93 ±	1.10 ±
1" diameter	30	10	0.1	0.12	0.15	0.13
RAIL (plate)	92 ±	59 ±	0.55 ±	0.50 ±	0.73 ±	0.81 ±
2.5"x0.4"	37	16	0.14	0.13	0.23	0.19
Grip Strength	124 ±	72 ±	0.85 ±	0.61 ±	1	1
(Jamar 45mm)	13	8	0.2	0.08		

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

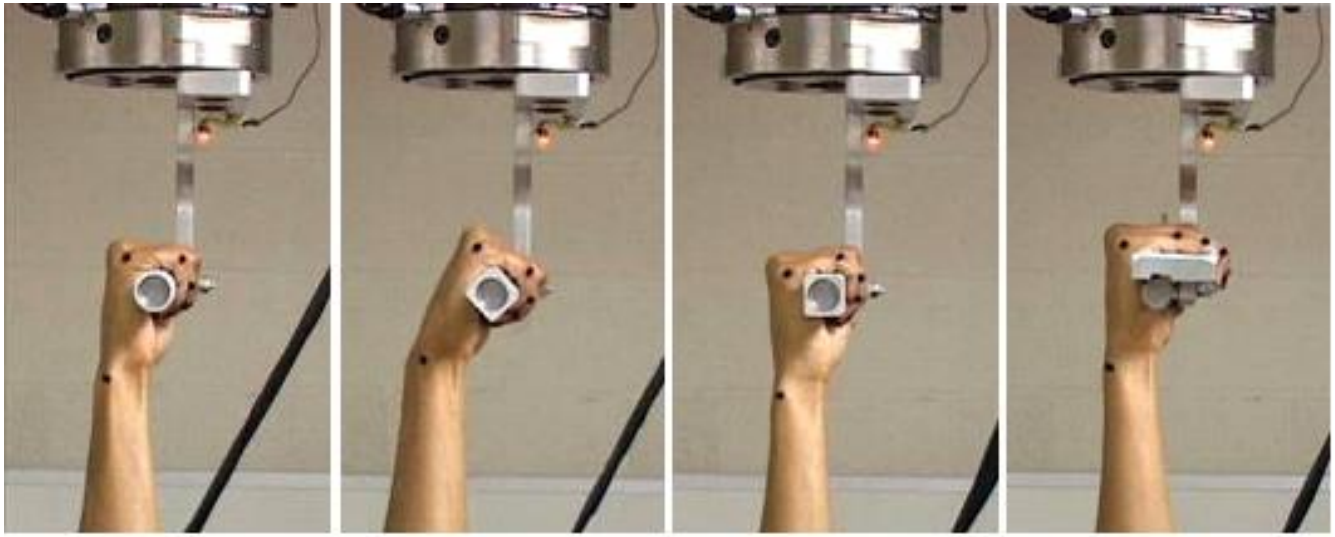
½ Fail

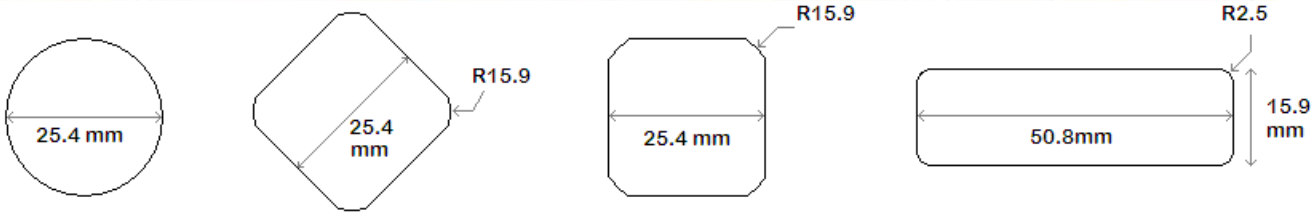
Experiment 2



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

Experiment 2





150 lbs	**127 lbs**	**116 lbs**	**102 lbs**
94% BW	**79% BW**	**73% BW**	**64% BW**

Δ 48 lbs

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.*

	Breakaway Force (lbs)			Breakaway Force / Bodyweight		
	Males	Females	All	Males	Females	All
RUNG[a] (cylinder)	188 ±	113 ±	150 ±	1.07 ±	0.83 ±	0.94 ±
1" diameter	43	24	51	0.33	0.21	0.30
RUNG[a] (diamond)	168 ±	86 ±	127 ±	0.96 ±	0.62 ±	0.79 ±
1"x1"	34	16	49	0.28	0.11	0.27
RUNG[a] (square)	146 ±	86 ±	116 ±	0.83 ±	0.63 ±	0.73 ±
1"x1"	28	29	41	0.21	0.25	0.20
RUNG[a] (plate)	131 ±	73 ±	102 ±	0.75 ±	0.54 ±	0.64 ±
2"x5/8"	27	18	37	0.21	0.15	0.21
Grip dynamometer[a]	123 ±	68 ±	95 ±	0.70 ±	0.50 ±	0.60 ±
(Jamar 45mm)	10	11	30	0.15	0.11	0.19
RAIL[b] (cylinder)	85 ±	67 ±	--	--	--	--
7/8" diameter	19	12				
RAIL[b] (cylinder)	96 ±	69 ±	--	--	--	--
1.25" diameter	18	12				
RAIL[b] (tapered cylinder)	105 ±	83 ±	--	--	--	--
7/8" to 1.25"	26	19				
Grip dynamometer[b]	114 ±	64 ±	--	--	--	--
(Jamar 45mm)	14	12				

*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

Rails << Rungs

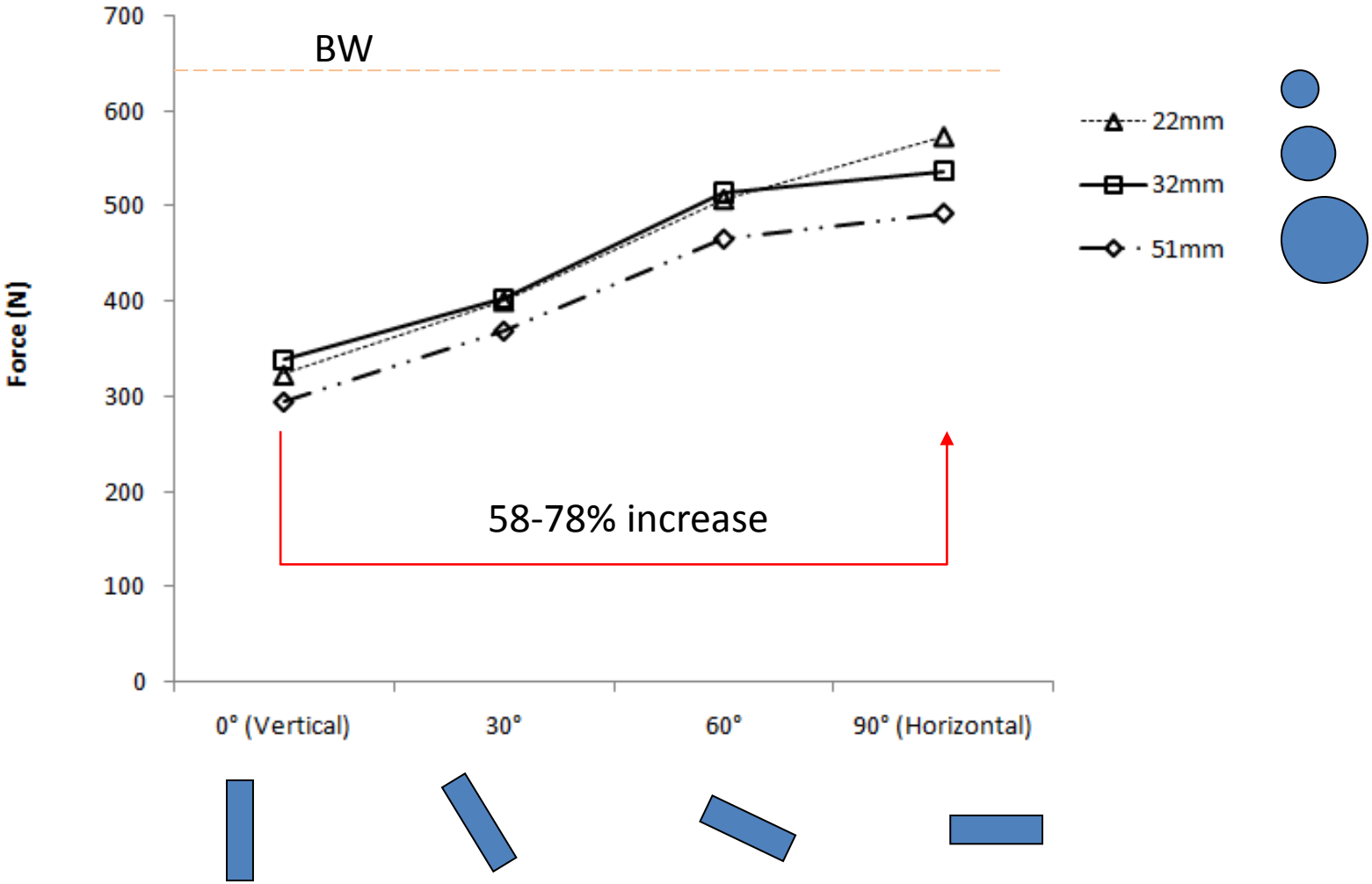
½ Fail

Experiment 3

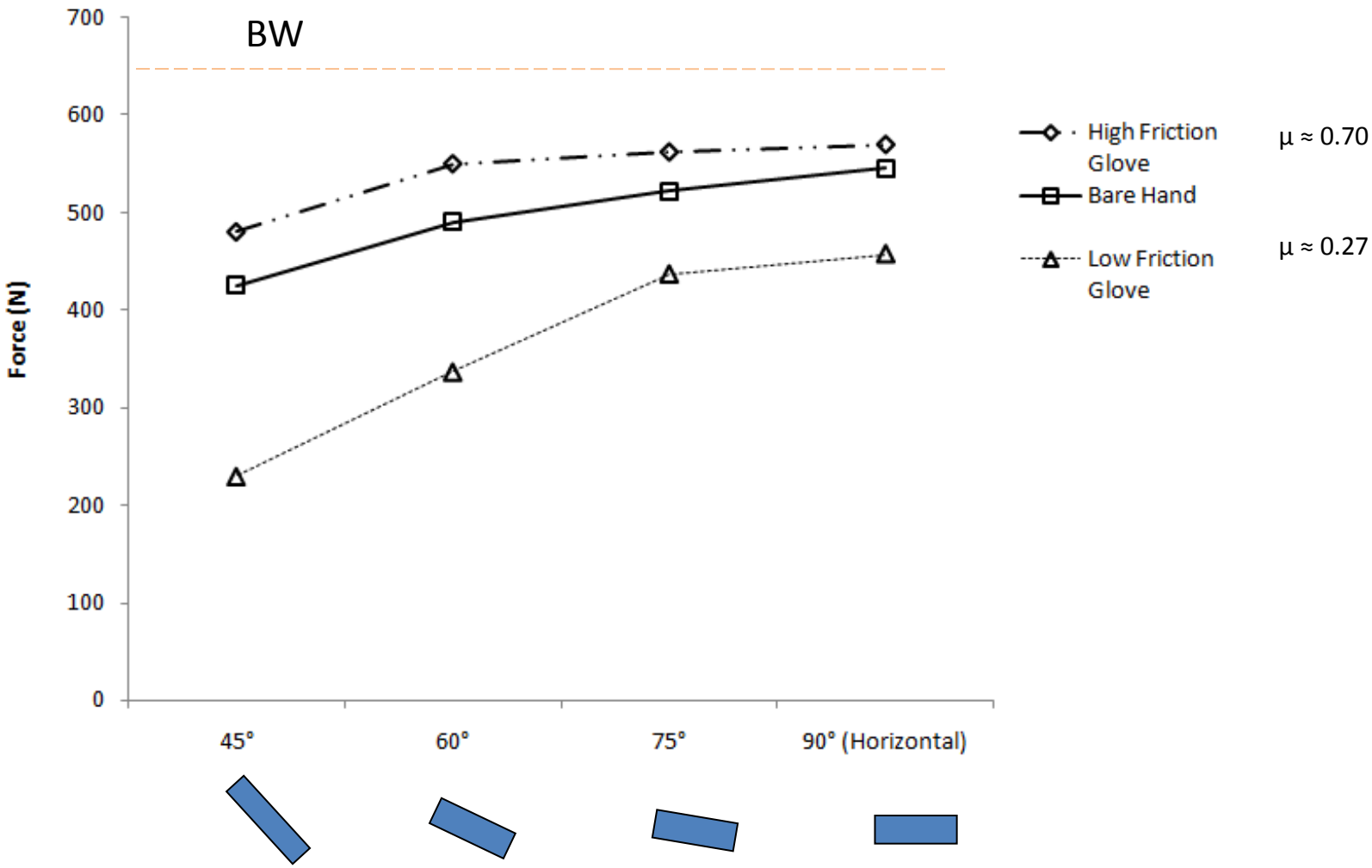
- This experiment varied:
  - The size of cylindrical handholds
  - The orientation at several angles between rungs (90°) and rails (0°)
  - Changing friction with gloves

- 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

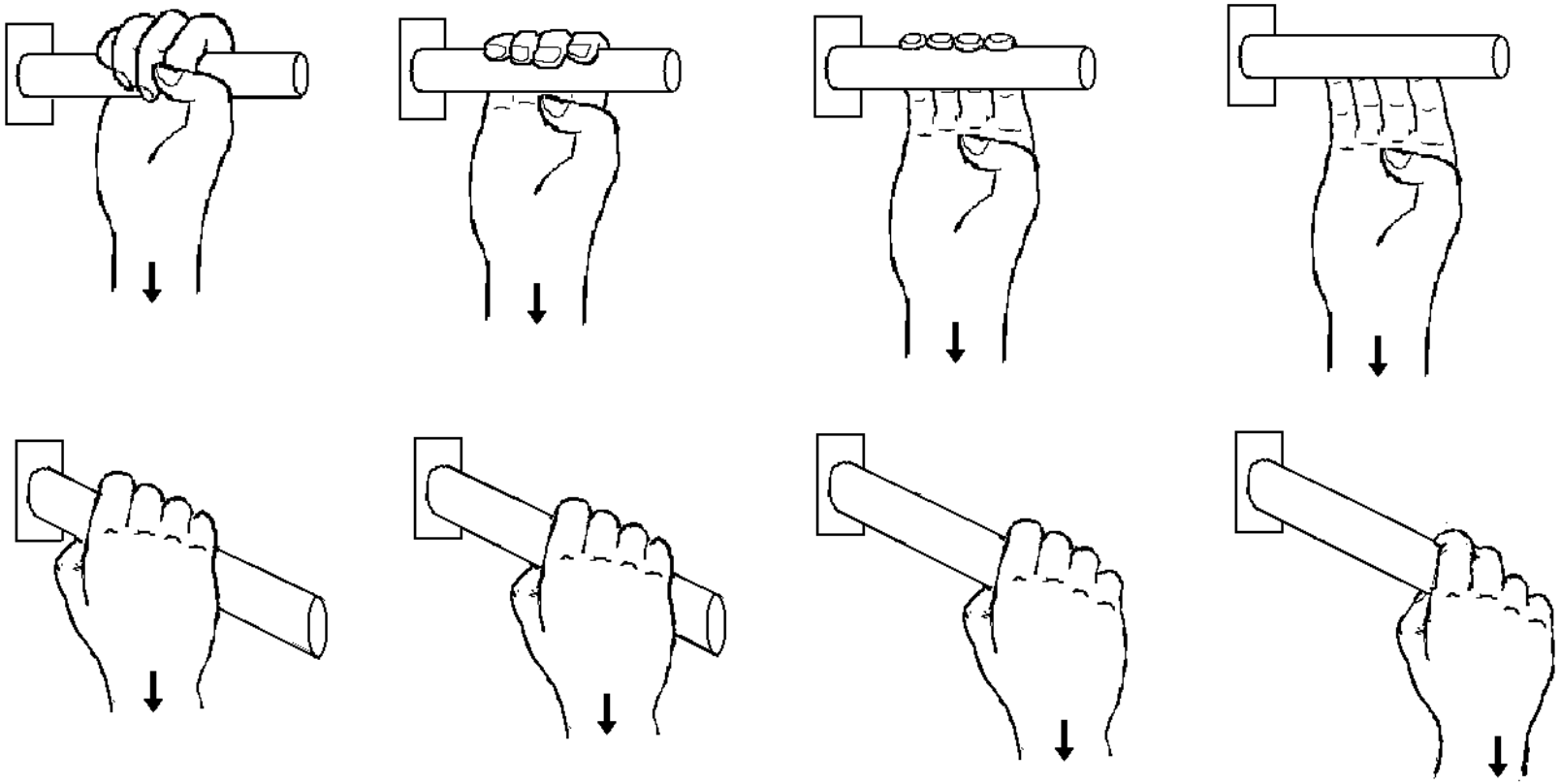


Orientation vs. Friction

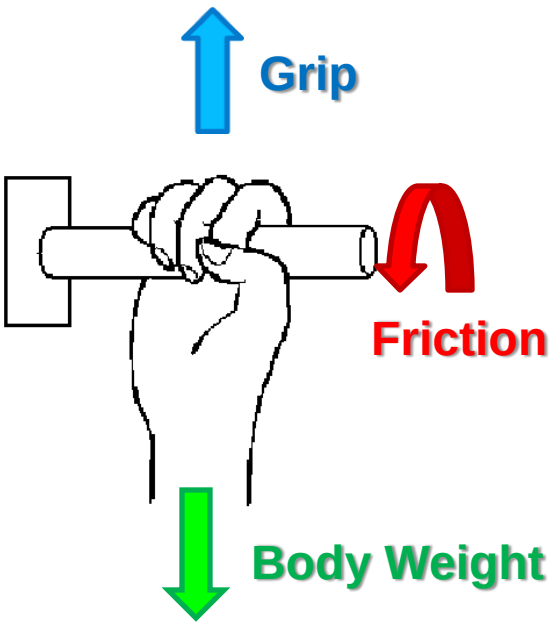


Types of Breakaway

(Fingers forced open)

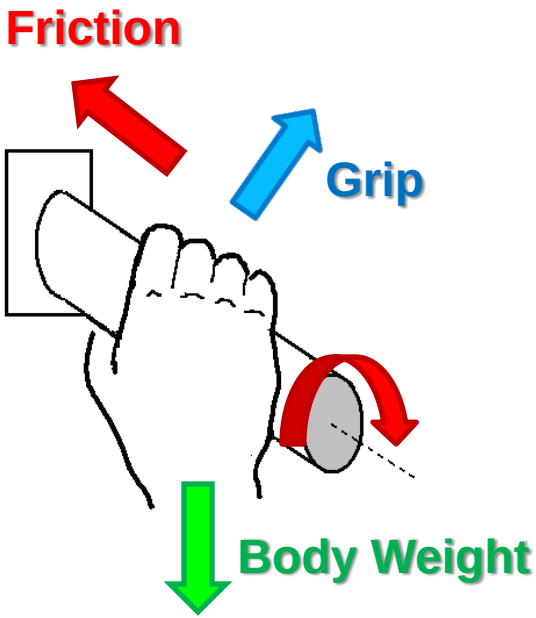


(Hand slides off of the handle)



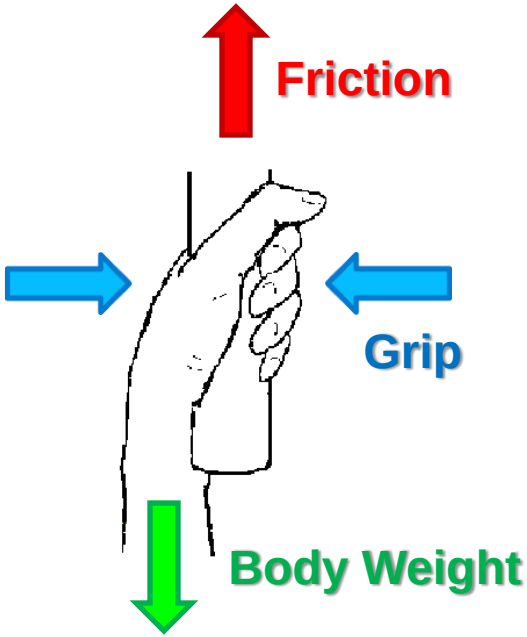
$\alpha = 90^\circ$

Fingers forced open



$\alpha \approx 45^\circ$

Fingers forced open
-or-
Hand slides off



$\alpha = 0^\circ$

Hand slides off

Types of breakaway: friction

High Friction Gloves

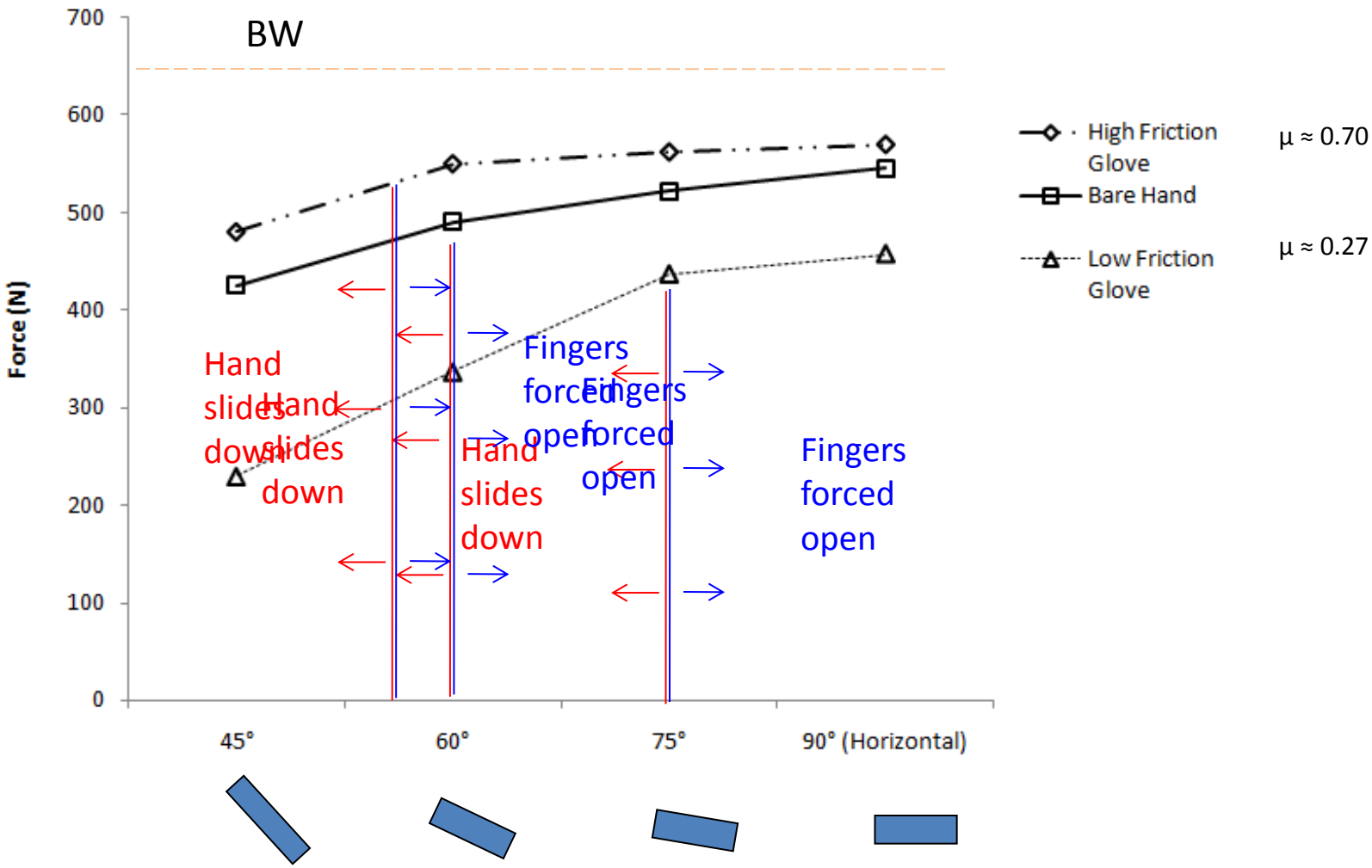
Breakaway Force = 542 N

Low Friction Gloves

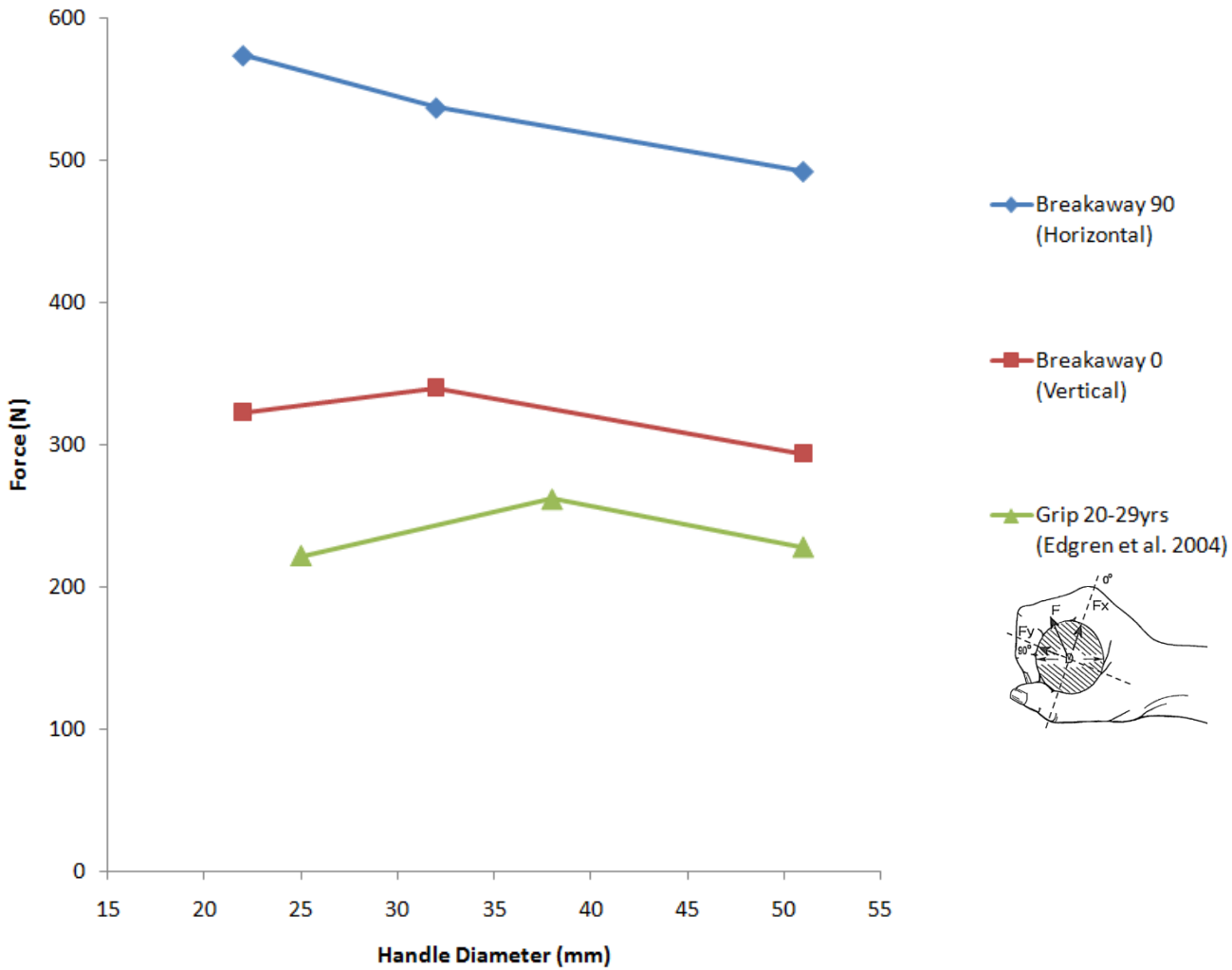
Breakaway Force = 426 N

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

Orientation



Size (cylinder diameter)



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.*

	Breakaway Force (lbs)			Breakaway/ Bodyweight		
RUNGS (cylinders)	Males	Females	All	Males	Females	All
2" diameter	147 ± 32	75 ± 26	111 ± 46	0.90 ± 0.24	0.61 ± 0.16	0.76 ± 0.25
1.25" diameter	157 ± 34	84 ± 24	121 ± 47	0.98 ± 0.30	0.71 ± 0.17	0.84 ± 0.28
0.875" diameter	169 ± 38	90 ± 25	129 ± 51	1.04 ± 0.28	0.78 ± 0.27	0.91 ± 0.30
All Diameters Pooled	157 ± 35	83 ± 25	120 ± 48	0.97 ± 0.28	0.70 ± 0.21	0.84 ± 0.28
RAILS (cylinders)	Males	Females	All	Males	Females	All
2" diameter	84 ± 20	48 ± 18	66 ± 26	0.52 ± 0.15	0.39 ± 0.13	0.46 ± 0.15
1.25" diameter	93 ± 16	60 ± 19	76 ± 24	0.57 ± 0.14	0.49 ± 0.12	0.53 ± 0.14
0.875" diameter	87 ± 22	58 ± 21	73 ± 26	0.54 ± 0.19	0.48 ± 0.14	0.51 ± 0.17
All Diameters Pooled	88 ± 20	55 ± 20	72 ± 26	0.54 ± 0.16	0.45 ± 0.13	0.50 ± 0.15

<½!!!

*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).

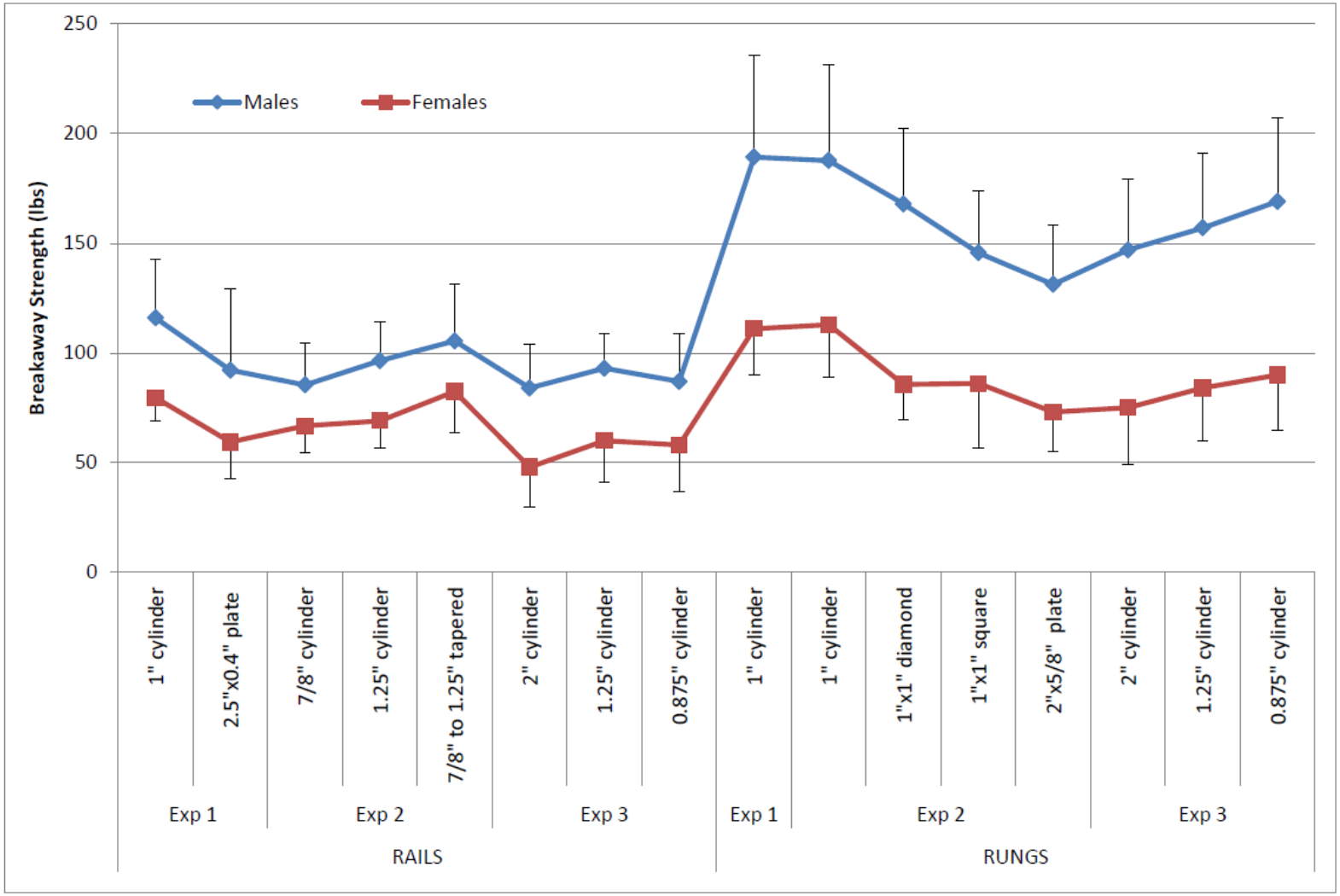


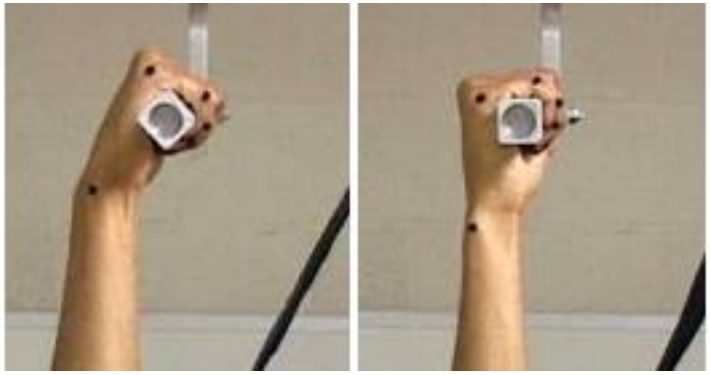
Figure 1. RAILS vs. RUNGS for all 3 experiments. For males, mean strength is greater for any of the rung designs compared to any of the rail designs tested. For females, only the 1" cylinder rail and the tapered cylinder rail afford greater strength than the 2" cylinder rung or the plate rung, otherwise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

Generalizations

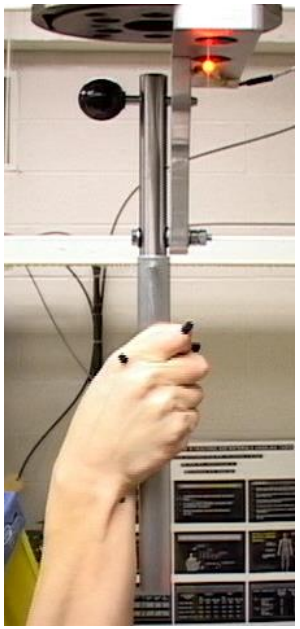
- Breakaway strength can be much greater than grip strength, even without friction
  - 21-32% increase due to eccentric contraction (internal friction or eccentric motor control)
- Friction responsible for 22-29% of breakaway strength for bare hands
- As handhold orientation moves toward vertical, friction 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

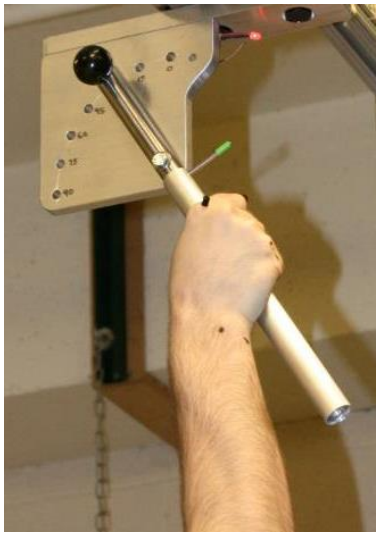
- Difference between square and diamond shapes not significant
  - Difference in joint location w.r.t. external loading



- 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

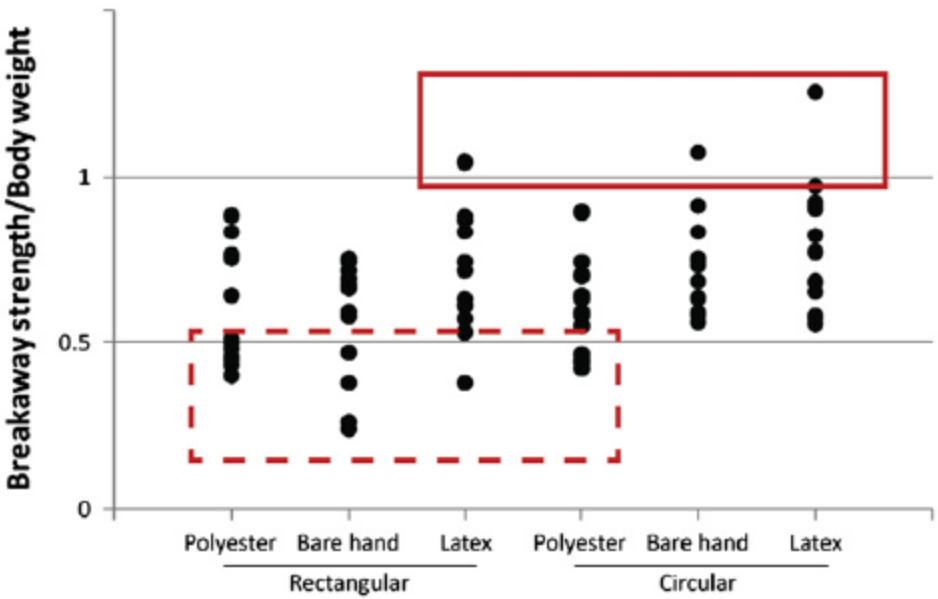
- Optimal climbing handhold size is dependent on orientation
  - Smaller handholds than predicted by grip strength biomechanics afforded more strength for horizontal handholds
  - For vertical handholds, optimal handhold size is likely similar to grip
- Gloves:
  - Despite reducing isometric grip strength 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



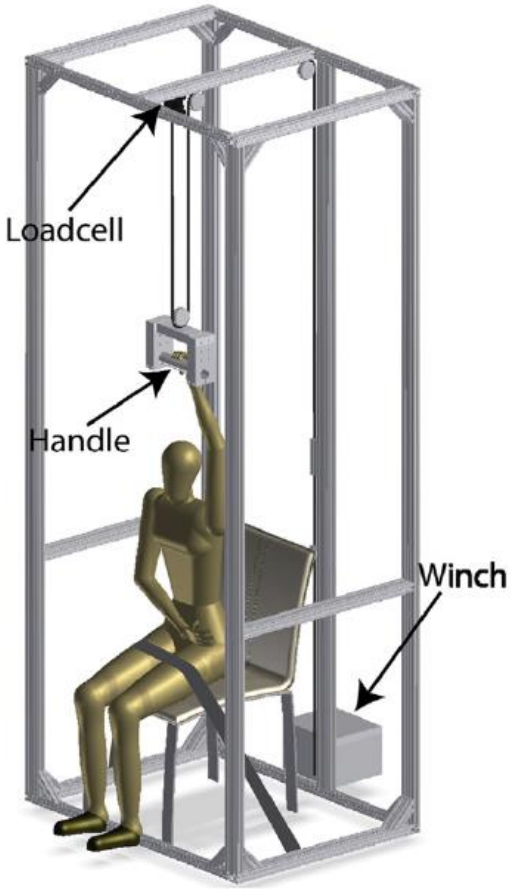


Fig. 3. Experimental setup. The handle moved up via a winch. Breakawa
was measured by the load cell connected to the handle.

Discussion & Questions

THANK YOU!