The Effect of Handhold Orientation, Size, and Wearing Gloves on Hand-Handhold Breakaway Strength

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Objective: The aim of this study was to quantify the effect of handhold orientation, size (diameter), and wearing a glove on the maximum breakaway strength between a hand and handhold.

Background: Manual breakaway strength is known to be greatly reduced for vertical compared with horizontal handholds, but oblique orientations have yet to be studied.

Method: For this study, 12 young adults (6 female) attempted to hold on to fixed overhead cylindrical handholds with one hand in low-speed simulated falls as forces on the handhold were recorded in two experimental designs. Breakaway strength was measured for (a) three different-sized cylinders in four orientations while the participants were using the dominant hand and (b) a single-sized cylinder in four orientations while the participants were bare-handed or wearing a glove on the nondominant hand.

Results: Handhold orientation ($p < .001$), handhold diameter ($p < .001$), and wearing gloves ($p < .001$) significantly affected breakaway strength. Breakaway strength increased 75% to 94% as the orientation of the handhold was moved from vertical to horizontal. Breakaway strength decreased 8% to 13% for large-diameter (51-mm) handholds as compared with smaller diameters (22 mm to 32 mm), depending on orientation. Gloves may increase or decrease the ability to hang on depending on interface friction; greater friction increased breakaway force.

Conclusion: Handles oriented perpendicular to the pull direction and high-friction gloves provide the greatest breakaway strength. Smaller handhold diameters than predicted by grip strength afford greater capability in these orientations.

Application: These insights can be used to design handholds that increase the ability to support one's body weight and reduce the effort needed to pull or lift heavy items.

Keywords: grip strength, friction, biomechanics, handle design, falls, climbing, ladders, grasp

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INTRODUCTION

Coupling between the hand and the handhold is important for many tasks, such as pulling, lifting, or climbing. Of particular importance are situations in which the hands are used to support the body, as a loss of hand-handhold coupling could result in a fall leading to injury or death. Fixed structures in the workplace, such as ladders, grab rails, and grab bars, are commonly employed as a means for workers to climb into, onto, or out of heavy equipment, truck cabins, and machinery. Grab rails and bars are also commonly employed as support structures for persons in bathrooms and on stairways and ramps. Despite the widespread use of fixed handholds for supporting the body, there is little knowledge of the capability of persons to hold onto and exert force on the various designs and types of existing handholds.

The purpose of the present study was to examine how generalized handhold properties (orientation, size) and how wearing common work gloves will affect the ability to hang on in a fall. This research will extend previous knowledge about hand-handhold coupling and will allow for development of biomechanical models that can be applied to the broad range of existing handholds. Results can be used to help establish design criteria and safety standards for handles and handholds on ladders, fixed equipment, stairwells, tools, and other safety-critical items.

Background and Hypotheses

Hand-handhold coupling comprises active components from finger flexion and passive components from friction between the grasped object and the hand (Woldstad, McMulkin, & Bussi, 1995; Young, Woolley, Armstrong, & Ashton-Miller, 2009). Friction between the handle and hand has been shown to increase the amount of force needed to pull an overhead

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handhold from the grasp of the hand ("breakaway strength") by 26% compared with a simulated zero-friction condition (Young et al., 2009). This finding means that breakaway strength and maximum isometric grip strength ("grip strength") are related, but neither alone is directly predictive of the other (Rajulu & Klute, 1993; Young et al., 2009). However, since grip strength is a measure of the ability of the finger flexor muscles to squeeze an object, it is reasonable to hypothesize that factors affecting grip strength, such as object size and wearing gloves, will also affect breakaway strength.

The effect of handle size or the span of grip on grip strength has been examined in many previous studies. These studies generally agree that grip strength is minimal at very small or very large finger spans and that a maximal value lies somewhere in between. Maximum grip strength occurs at cylinder diameters of approximately 31 mm to 38 mm (Amis, 1987; Edgren, Radwin, & Irwin, 2004; Lee & Rim, 1991) or at Position 2 or 3 (48 mm to 60 mm) on a Jamar-type dynamometer or similar device (Blackwell, Kornatz, & Heath, 1999; Dvir, 1997; Härkönen, Piirtomaa, & Alaranta, 1993; Lee, Kong, Lowe, & Song, 2009). However, the optimal cylinder diameter may be different for breakaway strength because the fingers resist an external load (e.g., a pull force) rather than squeeze the grasped handle into the palm.

Orientation of overhead handholds will also affect the amount of active force and passive force that resists hand-handhold breakaway. Overhead breakaway strength for a 25-mm diameter cylinder was 54% greater when oriented horizontally rather than vertically (Young et al., 2009). The specific orientation of a handhold can be defined as the angle between the direction of applied pull force and the long axis of the handhold. In the case of overhead handholds, the pull force direction is vertically downward (the direction of gravity) and acts in the same direction as the forearm. For horizontal handholds, the pull direction and the long axis of the handhold are perpendicular (orientation = 90°), meaning that for the grasped handhold to break free from the grasp of the hand, the finger joints must be extended against the action of the flexor muscles (eccentric contraction). Concurrently, as the wrist translates downward with respect to the handhold, the fingers will slide over the handhold surface (active and passive forces directly resist breakaway). For vertical handholds, the pull direction and the long axis of the handhold are parallel (orientation = 0°), meaning that the pull force does not act against the flexion of the fingers. As the pull force is increased and the hand begins to slide, only friction between the hand and the handhold resists the downward pull of body weight (only passive forces directly resist breakaway). These coupling situations exhibit the two different ways that the hand-handhold couple may be broken: by forced extension of the fingers so that grasp is relinquished (Figure 1a) or by sliding off the end of a handhold while maintaining grasp without extension of the fingers (Figure 1b).

Although the type of breakaway that occurs for handholds oriented either parallel or perpendicular to the pull direction is clear, at what orientation the transition occurs between these two types of breakaway is unknown. This transition is dependent on the coefficient of friction, μ, between the hand and the handhold surface. A simple passive model of hand-handhold coupling on an obliquely oriented handle is presented in Figure 2, in which the hand is approximated by a block of weight (BW) and the handle as an inclined plane at angle θ. The normal reaction force at the handle surface can be thought of as flexion force from the fingers resisting the weight of the block or the body. Frictional force keeps the block from sliding down the plane. The resultant vertical force from the normal and frictional components must be greater than body weight to keep the block from moving. By simple calculation, static equilibrium can be maintained for a given μ only if the handhold angle is greater than $\text{cotangent}^{-1}(\mu)$. This angle is independent of the weight of the block.

One way in which friction at the handhold surface is altered is by wearing a glove. Since glove use will affect the friction between the hand and the handhold surface, wearing gloves will affect the passive component of hand-handhold coupling and, consequently, breakaway strength. It is

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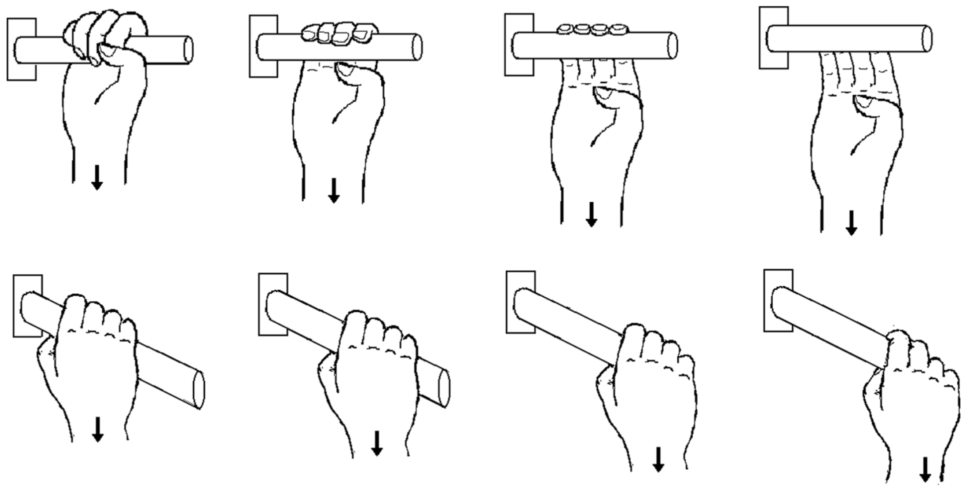

Figure 1. Types of breakaway or "coupling failures." When the handhold is oriented perpendicular to the pull direction (top row), the pull force causes the fingers to extend against the action of the finger flexors. The fingers slide over the circumference of the cylinder as grasp is broken. When the handhold is not oriented perpendicularly to the pull direction (bottom row), the fingers may not extend, grasp may remain closed, and the pull force causes the hand to slide down the long axis of the handle and off the end.

hypothesized that increased friction will increase breakaway strength in any orientation. However, wearing gloves has also been shown to decrease grip strength (Bishu & Klute, 1995; Chang & Shih, 2007; Hallbeck & McMullin, 1993; Tsaousidis & Freivalds, 1998; Wimer et al., 2010). Therefore, wearing a high-friction glove may increase the passive component of coupling but decrease the active component.

Given this background, the specific aims of this experiment were to test the hypotheses that breakaway strength for overhead handholds would be (a) reduced as handhold orientation changes from horizontal to vertical, (b) increased for handhold sizes that correspond to maximal grip strength, and (c) increased by wearing of gloves having high-frictional surfaces. In addition to quantifying specific effects of orientation, size, and wearing gloves on the ability to hold on, implications of the results on underlying biomechanics of hand-handhold coupling are discussed.

METHOD

To achieve the proposed aims, two overhead breakaway strength experiments were performed on a single set of healthy young adult volunteers. The first experiment tested the effects of handhold orientation and size (diameter) for only the dominant hand of the participants, and the second experiment tested the effects of handhold orientation and glove use for only the nondominant hand of the participants. The breakaway strength measurement apparatus and test procedures are similar to those described in Young et al. (2009), so they are described briefly here with any differences noted.

Breakaway strength was measured as the maximum vertical force participants could exert on overhead handholds during a simulated vertical fall. Participants stood while wearing a belt that secured them to a weighted platform and held onto an instrumented handle mounted overhead with one hand. The platform was then lowered slowly (14 cm/s) while the participants held onto the cylindrical handle as long as they could until either they let go or the handle slipped from their grasp. The maximum resultant vertical force exerted in the duration of lowering was considered breakaway strength for that specific trial.

Each participant wore a fall harness attached to a fall arrestor for additional safety; this harness did not interfere with the participant's

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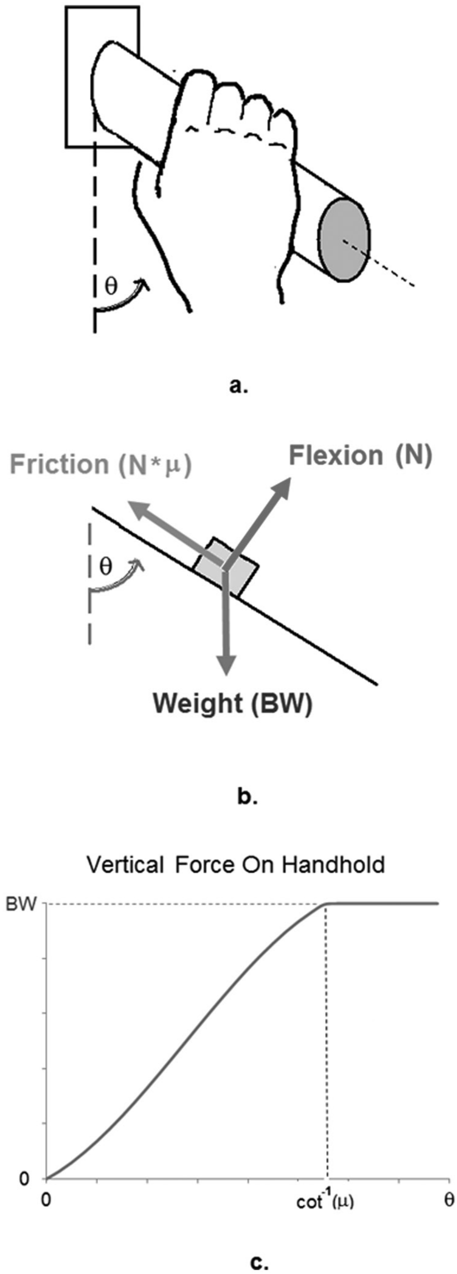

Figure 2. (a) Simple model of breakaway strength for a hand holding onto a fixed handhold resisting a vertical load. (b) The hand is modeled as a block of weight (BW) on a ramp with coefficient of friction μ. Normal force can be thought of as flexion of the fingers and has a corresponding orthogonal friction force. (c) Plot of vertical calculated force applied to the handhold by the block versus handhold angle. The angle at which the block will slide is independent of the weight of the block and is related to μ.

range of motion. A custom-made handle attachment structure was mounted to the load cell (ATI® Theta) that allowed for cylindrical handles of varying diameter to be easily interchanged and oriented at increments of 15° between horizontal and vertical (Figure 3). When grasping the handle in horizontal orientation, the participant's forearm posture was pronated. The participant grasped the handle so that his or her thumb was on the side of the handle closest to the pivot. This position resulted in an ulnar deviation of the wrist when the handle was at an angle other than horizontal (90°) because the thenar side of the hand was higher than the hypothenar side. Forearm rotation was not constrained for the vertical handle orientation, which resulted in pronated to neutral postures. A video camera recorded hand motion during all breakaway trials.

Participants

Participants for both experiments were recruited from the University of Michigan community and were paid for their involvement. A total of 12 healthy young participants (6 females) participated in the study. No participants reported previous injuries or surgeries that would affect upper limb performance. The protocol for the experiments was approved by the University of Michigan Institutional Review Board, and participants gave written informed consent prior to testing.

Mean (± *SD*) age, height, and body weight for the 12 participants were 22 ± 2 years, 1.70 ± 0.11 m, and 65.3 ± 14.7 kg (640 ± 145 N), respectively. On average, males were 20.2 kg (198 N) heavier and 0.16 m taller than females. Average hand lengths (measured according to the method of Garrett, 1971) were 189 ± 19 mm for males and 173 ± 7 mm for females. Of the participants, 11 were right hand dominant, and 1 was left hand dominant.

Design

For this study, the participants performed a different experiment using each hand (dominant and nondominant; Table 1). This method was chosen because it is assumed that each upper limb is independent of the other and differences in overall strength between the dominant and nondominant hand will affect only total breakaway strength and not the effects of treatment

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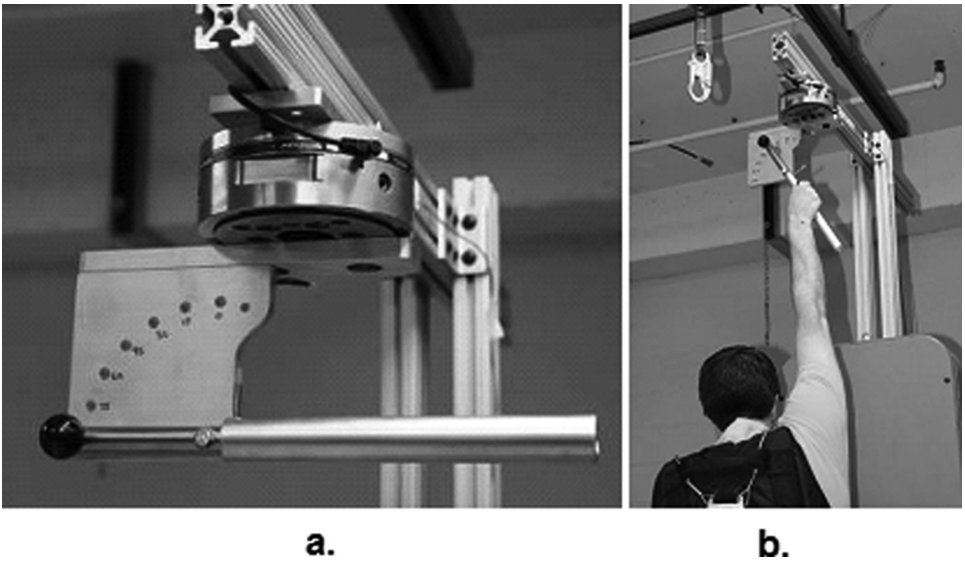

Figure 3. Experimental apparatus. (a) An adjustable handle was attached to a six-axis load cell. The handle could be adjusted to be oriented in 15° increments between horizontal and vertical. Different diameter metal cylinders can be easily interchanged. (b) Participant position during breakaway trials.

variables. Also, because of the required rest period between trials, both experiments could be performed in half the time of doing each separately by testing one hand while the other was resting.

Because each breakaway trial involved a maximum voluntary eccentric exertion, the total number of trials for each hand needed to be minimized. To control for fatigue, a minimum of 2 min rest was given between trials, and each participant performed the experiment in three sessions, each at least 5 days apart. In each session, one repetition of all treatment conditions was performed in a randomized order. The three experimental sessions therefore correspond to the three repetitions of treatments.

TABLE 1: Experimental Design

	Experiment 1 (Participant's Dominant Hand)	Experiment 2 (Participant's Nondominant Hand)
Independent variables (for breakaway testing)	Gender (2): male, female Handle diameter (3): 22 mm (0.875"), 32 mm (1.25"), 51 mm (2") Handle orientation (4): 90° (horizontal), 60°, 30°, 0° (vertical)	Gender (2): male, female Glove type (3): low-friction glove, bare hand, high-friction glove Handle orientation (4): 90° (horizontal), 75°, 60°, 45°
Independent variable (for grip testing)	Gender (2): male, female Jamar span (2): Position 1 (36 mm), Position 2 (48 mm)	Gender (2): male, female Glove type (3): low-friction glove, bare hand, high-friction glove
Dependent variables	Breakaway strength (peak vertical force), grip strength (Jamar in two spans)	Breakaway strength (peak vertical force), Grip strength (Jamar in three glove conditions)
Total exertions per participant	(3 sizes × 4 orientations + 2 grip strengths) × 3 repetitions[a] = 42	(3 glove types × 4 orientations + 3 grip strengths) × 3 repetitions[a] = 45

[a]Repetitions of treatments performed in three experimental sessions.

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Experiment 1 (dominant hand). For the dominant hand, breakaway strength was measured for three aluminum cylinders (22-mm, 32-mm, 51-mm diameter) at four handle orientations (0° vertical, 30°, 60°, 90° horizontal). A Jamar grip dynamometer was used to measure isometric grip strength in two grip spans as a comparison with breakaway strength. Grip strength was measured overhead with the forearm pronated in a posture similar to that of breakaway strength testing. Grip strength and breakaway strength trials were interspersed and trial order randomized.

A mixed-model repeated-measures ANOVA was performed to determine whether breakaway force was significantly affected by the fixed effects of gender, handle size, handle orientation, and session (rep), with participant treated as a random effect nested within gender. Post hoc pairwise comparisons (with Bonferroni correction) were performed on significant main effects to compare breakaway strength between treatment levels. A similar analysis was performed to determine whether grip strength was affected by fixed effects of gender and span. An alpha level of .05 was considered significant. Statistical analysis was performed using SPSS Version 17 (Chicago, IL, USA) linear mixed-model module software.

Experiment 2 (nondominant hand). For the nondominant hand, breakaway strength was measured for a single cylinder while the participant was bare-handed or wearing one of two common work gloves at four handle orientations (45°, 60°, 75°, 90° horizontal). For this experiment, handle orientation angle resolution was increased and measured for near-horizontal orientations to better examine the transition between the two types of breakaway that can occur. The two gloves that were tested were The Home Depot brand All-Purpose Brown Jersey Gloves (70% polyester, 30% cotton) and The Home Depot brand Jersey Mini-Dotted Gloves (70% polyester, 30% cotton, with PVC dots on the surface). Frictional characteristics of the gloves were estimated by measuring the force at onset of movement required to pull a 1-kg aluminum plate over a gloved hand with fingers flat and palm supine. The PVC-dotted ("high-friction") glove had coefficient of friction of approximately $\mu \approx 0.70$, and the plain jersey cotton ("low-friction") glove had coefficient of friction of approximately $\mu \approx 0.27$. Each participant was given a new set of gloves at the beginning of the experiment and used only that pair for the three experimental sessions.

A Jamar grip dynamometer was used to measure isometric grip strength in a single grip span while the participant was wearing gloves or bare-handed as a comparison with breakaway strength. Grip strength was measured overhead with the forearm pronated in a posture similar to that of breakaway strength testing. Grip strength and breakaway strength trials were interspersed and trial order randomized.

A mixed-model repeated-measures ANOVA was performed to determine whether the measured force was significantly affected by the fixed effects of gender, glove type, handle orientation, and session (rep), with participant treated as a random effect nested within gender. Post hoc pairwise comparisons (with Bonferroni correction) were performed on significant main effects to compare breakaway strength between treatment levels. A similar analysis was performed to determine whether grip strength was affected by fixed effects of gender and glove type. An alpha level of .05 was considered significant. Statistical analysis was performed using SPSS Version 17 linear mixed-model module software.

Video analysis (Experiments 1 and 2). Video footage was examined to determine the type of breakaway or "coupling failure" that occurred for each trial (Figure 1). There were three possible outcomes per trial: If eccentric extension of the fingers was observed, the failure was coded as +1; if the fingers remained flexed and the hand slipped down and off the end of the cylindrical handle, the failure was coded as –1; and if the type of failure was in any way unclear or if there was a combination of axial sliding and extension of the fingers, the failure was coded as 0. Repeated-measures ANOVA was performed on coded failure results to determine whether the main effects tested in each experiment affected the type of breakaway that was observed.

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TABLE 2: ANOVA for Experiment 1 (Dominant Hand)

Source	*df*	*F*	*p*
Orientation	3	225.38	.000
Gender × Orientation	3	57.40	.000
Session	2	54.18	.000
Size	2	21.12	.000
Gender	1	20.28	.001
Gender × Session	2	3.68	.026
Orientation × Size	6	1.54	.164
Orientation × Session	6	1.24	.287
Size × Session	4	1.21	.305
Gender × Size	2	0.03	.966

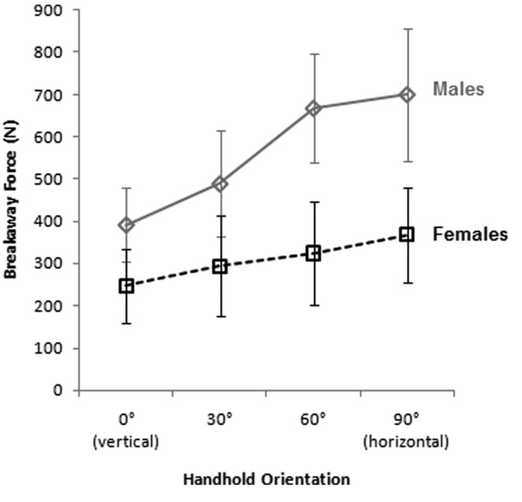

Figure 4. Mean breakaway strength (N) by orientation for male and female participants (dominant hand, size pooled). Strength decreases for handle orientations from horizontal to vertical.

RESULTS

Experiment 1 (Dominant Hand)

Statistical ANOVA results for Experiment 1 are presented in Table 2. All main effects were significant ($p < .001$). There were two significant interactions, the first between gender and orientation ($p < .001$) and the second between gender and session ($p = .026$). Table 3 presents breakaway strength results for each tested condition. Breakaway strength normalized by participant body weight and grip strength is also presented. Mean breakaway force by orientation and gender for all participants is plotted in Figure 4.

The significant interaction between gender and orientation demonstrates that breakaway strength was reduced more in males than in females at the steeper handle orientations (0° and 30°). The interaction between gender and session indicated that breakaway force diminished more in males than in females in each consecutive session, though the effect's contribution to variance was small compared with other significant factors (Table 2). Overall decreases were 10.6% and 8.4% per successive session for males and 9.1% and 8.8% per successive session for females, respectively.

Post hoc analysis for main effects indicates that breakaway strength was greater for males than for females ($p < .01$). For the effect of diameter, breakaway strength for the largest handle (51-mm diameter) was significantly lower than for both the 32-mm handle and the 22-mm handle ($p < .01$); however, breakaway forces measured for the 32-mm and 22-mm handles were not significantly different ($p = .97$). For the effect of orientation, breakaway force was significantly lower for vertical handholds than for 30° handholds ($p < .01$) and significantly lower for 30° handholds than for 60° and 90° orientations ($p < .01$). Differences in breakaway force for 60° and 90° orientations did not reach statistical significance ($p = .07$). For the effect of session, breakaway strength decreased significantly but similarly in each successive experimental session ($p < .02$).

Average dominant hand isometric grip strength measured at Position 1 (36 mm) of the dynamometer was 336 ± 59 N for males and 265 ± 68 N for females; at Position 2 (48 mm), average grip strength was 454 ± 55 N for males and 331 ± 84 N for females. Grip strength was significantly affected by both gender ($p < .022$) and span ($p < .001$) but not session ($p > .05$).

Results from the analysis of the video footage of Experiment 1 are presented in Table 4.

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TABLE 3: Mean (± *SD*) Breakaway Strength for Experiment 1

Handle Diameter	Peak Force (N)			Peak Force/Body Weight			Peak Force/Grip Strength[a]		
	Males	Females	All Participants	Males	Females	All Participants	Males	Females	All Participants
0° orientation									
Large (51 mm)	373 ± 89	215 ± 81	294 ± 116	0.52 ± 0.15	0.39 ± 0.13	0.46 ± 0.15	0.83 ± 0.20	0.65 ± 0.22	0.74 ± 0.22
Medium (32 mm)	414 ± 73	265 ± 84	340 ± 108	0.57 ± 0.14	0.49 ± 0.12	0.53 ± 0.14	0.91 ± 0.16	0.80 ± 0.23	0.86 ± 0.20
Small (22 mm)	387 ± 100	260 ± 92	323 ± 115	0.54 ± 0.19	0.48 ± 0.14	0.51 ± 0.17	0.86 ± 0.21	0.78 ± 0.26	0.82 ± 0.24
All diameters pooled	391 ± 88	247 ± 87	319 ± 114	0.54 ± 0.16	0.45 ± 0.13	0.50 ± 0.15	0.87 ± 0.19	0.74 ± 0.24	0.80 ± 0.22
30° orientation									
Large (51 mm)	466 ± 129	271 ± 117	369 ± 157	0.65 ± 0.22	0.49 ± 0.19	0.57 ± 0.22	1.03 ± 0.27	0.82 ± 0.36	0.92 ± 0.33
Medium (32 mm)	506 ± 118	301 ± 116	403 ± 155	0.70 ± 0.21	0.55 ± 0.18	0.63 ± 0.20	1.12 ± 0.25	0.90 ± 0.30	1.01 ± 0.29
Small (22 mm)	493 ± 133	309 ± 129	401 ± 159	0.69 ± 0.23	0.57 ± 0.19	0.63 ± 0.22	1.09 ± 0.29	0.93 ± 0.37	1.01 ± 0.34
All diameters pooled	488 ± 125	293 ± 120	391 ± 156	0.68 ± 0.22	0.54 ± 0.19	0.61 ± 0.21	1.08 ± 0.27	0.88 ± 0.34	0.98 ± 0.32
60° orientation									
Large (51 mm)	634 ± 119	297 ± 117	465 ± 207	0.88 ± 0.23	0.55 ± 0.18	0.72 ± 0.26	1.40 ± 0.25	0.92 ± 0.39	1.16 ± 0.41
Medium (32 mm)	688 ± 156	341 ± 135	514 ± 227	0.96 ± 0.28	0.64 ± 0.21	0.80 ± 0.29	1.53 ± 0.36	1.07 ± 0.45	1.30 ± 0.46
Small (22 mm)	682 ± 105	335 ± 117	508 ± 207	0.95 ± 0.23	0.64 ± 0.20	0.79 ± 0.26	1.51 ± 0.23	1.05 ± 0.41	1.28 ± 0.4
All diameters pooled	668 ± 129	324 ± 123	496 ± 213	0.93 ± 0.25	0.61 ± 0.19	0.77 ± 0.27	1.48 ± 0.29	1.01 ± 0.42	1.25 ± 0.43
90° orientation									
Large (51 mm)	652 ± 142	332 ± 115	492 ± 206	0.90 ± 0.24	0.61 ± 0.16	0.76 ± 0.25	1.44 ± 0.3	1.02 ± 0.35	1.23 ± 0.39
Medium (32 mm)	699 ± 153	374 ± 105	537 ± 209	0.98 ± 0.30	0.71 ± 0.17	0.84 ± 0.28	1.55 ± 0.36	1.15 ± 0.28	1.35 ± 0.38
Small (22 mm)	750 ± 170	398 ± 112	574 ± 228	1.04 ± 0.28	0.78 ± 0.27	0.91 ± 0.30	1.67 ± 0.4	1.26 ± 0.44	1.47 ± 0.47
All diameters pooled	700 ± 158	368 ± 112	534 ± 215	0.97 ± 0.28	0.70 ± 0.21	0.84 ± 0.28	1.55 ± 0.36	1.14 ± 0.37	1.35 ± 0.42
All orientations pooled									
Large (51 mm)	531 ± 167	279 ± 115	405 ± 191	0.74 ± 0.26	0.51 ± 0.18	0.62 ± 0.25	1.17 ± 0.36	0.85 ± 0.36	1.01 ± 0.39
Medium (32 mm)	577 ± 176	320 ± 117	448 ± 197	0.80 ± 0.29	0.60 ± 0.19	0.70 ± 0.27	1.28 ± 0.40	0.98 ± 0.35	1.13 ± 0.40
Small (22 mm)	578 ± 193	325 ± 122	452 ± 205	0.80 ± 0.31	0.61 ± 0.23	0.71 ± 0.29	1.28 ± 0.43	1.01 ± 0.41	1.14 ± 0.44
All diameters pooled	562 ± 180	308 ± 119	435 ± 198	0.78 ± 0.29	0.57 ± 0.20	0.68 ± 0.27	1.24 ± 0.40	0.95 ± 0.38	1.09 ± 0.42

[a]Normalized by participant's mean grip strength measured in Position 2 of the grip dynamometer.

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TABLE 4: Mean (± *SD*) Coded Coupling Failure Type for Each Orientation (Dominant Hand, All Sizes Pooled)

	0° (Vertical)	30°	60°	90° (Horizontal)
Males	−1.0 ± 0.0	−1.0 ± 0.1	0.6 ± 0.7	1.0 ± 0.0
Females	−1.0 ± 0.0	−1.0 ± 0.2	−0.1 ± 0.8	1.0 ± 0.0
All participants	−1.0 ± 0.0	−1.0 ± 0.2	0.3 ± 0.8	1.0 ± 0.0

Note. A value of +1 indicates the fingers joint became extended and grasp of the handle was lost. A value of –1 indicates the hand slipped down the long axis of the handle and fingers remained flexed around the handle.

Coded values represent the mean type of coupling failure that was observed in the video footage of that treatment condition. A value of +1 indicates eccentric contraction of the finger flexors, and a value of –1 indicates the hand slipped down the long axis of the handle and the fingers were not extended (see Figure 1). Statistical results show that only the main effect of orientation (F = 743.95, $p < .001$) on the observed type of coupling failure was significant. There was also a significant interaction between orientation and gender (F = 19.56, $p < .001$). No other effects or interactions were significant ($p > .05$).

Experiment 2 (Nondominant Hand)

Statistical ANOVA results for Experiment 2 are presented in Table 5. All main effects were significant ($p < .001$). All first-order interactions were significant ($p \leq .010$) with the exception of the interaction between orientation and session (p = .545). Table 6 presents breakaway strength results for each condition. Breakaway strength normalized by participant body weight and grip strength is also presented. Mean breakaway force for all participants by orientation and glove is plotted in Figure 5.

TABLE 5: ANOVA for Experiment 2 (Nondominant Hand)

Source	*df*	*F*	*p*
Glove	2	238.30	.000
Orientation	3	91.31	.000
Session	2	56.50	.000
Gender × Glove	2	25.54	.000
Gender	1	21.06	.001
Gender × Orientation	3	18.51	.000
Orientation × Glove	6	9.12	.000
Gender × Session	2	4.64	.010
Glove × Session	4	3.64	.006
Orientation × Session	6	0.83	.545

Significant interactions showed that breakaway strength was reduced more for males than for females wearing the low-friction glove. Breakaway strength was decreased more for males than for females as handle inclination increased from the horizontal. The interaction between inclination and glove type shows that for the low-friction glove, breakaway strength decreased more dramatically for 60° and 45° handhold orientations than for bare hands or high-friction gloves (see Figure 5). Interactions between session and glove type show that the reduction in breakaway force was greater for bare hands than for gloved hands between the first and second experimental sessions. The interaction between session and gender indicated that breakaway force decreased equally per session for males and less for the third session than for the second for females. Overall decreases were 9.4% and 9.3% per successive session for males and 11.4% and 5.9% per successive session for females.

Post hoc analysis for main effects indicates that breakaway strength was greater for males than for females ($p < .01$). For the effect of glove type, breakaway strength when wearing the low-friction glove was significantly lower than when bare-handed ($p < .01$), which in turn was significantly lower than when wearing the

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TABLE 6: Mean (± *SD*) Breakaway Strength for Experiment 2

Glove Type	Peak Force (N)			Peak Force/Body Weight			Peak Force/Grip Strength[a]		
	Males	Females	All Participants	Males	Females	All Participants	Males	Females	All Participants
45° orientation									
Low-friction glove (cotton)	274 ± 69	185 ± 53	230 ± 76	0.38 ± 0.10	0.35 ± 0.11	0.36 ± 0.10	0.69 ± 0.16	0.67 ± 0.18	0.68 ± 0.17
Bare hand	550 ± 127	300 ± 92	425 ± 167	0.76 ± 0.21	0.57 ± 0.18	0.67 ± 0.22	1.30 ± 0.29	1.00 ± 0.27	1.15 ± 0.32
High-friction glove (PVC dots)	598 ± 126	362 ± 114	480 ± 168	0.83 ± 0.23	0.69 ± 0.21	0.76 ± 0.23	1.45 ± 0.19	1.30 ± 0.33	1.38 ± 0.28
All glove types pooled	474 ± 180	282 ± 115	378 ± 179	0.66 ± 0.28	0.54 ± 0.22	0.60 ± 0.25	1.14 ± 0.4	0.99 ± 0.37	1.07 ± 0.39
60° orientation									
Low-friction glove (cotton)	424 ± 98	249 ± 61	336 ± 120	0.58 ± 0.16	0.47 ± 0.11	0.53 ± 0.14	1.06 ± 0.2	0.89 ± 0.13	0.98 ± 0.19
Bare hand	650 ± 149	331 ± 112	490 ± 207	0.90 ± 0.25	0.62 ± 0.18	0.76 ± 0.26	1.53 ± 0.34	1.10 ± 0.34	1.31 ± 0.40
High-friction glove (PVC dots)	709 ± 153	391 ± 142	550 ± 217	0.99 ± 0.29	0.74 ± 0.24	0.87 ± 0.29	1.72 ± 0.27	1.40 ± 0.40	1.56 ± 0.37
All glove types pooled	582 ± 182	324 ± 123	459 ± 206	0.82 ± 0.29	0.61 ± 0.21	0.72 ± 0.28	1.44 ± 0.39	1.13 ± 0.37	1.28 ± 0.41
75° orientation									
Low-friction glove (cotton)	575 ± 114	298 ± 77	436 ± 170	0.79 ± 0.19	0.57 ± 0.14	0.68 ± 0.20	1.44 ± 0.2	1.07 ± 0.21	1.26 ± 0.27
Bare hand	691 ± 145	352 ± 143	521 ± 223	0.96 ± 0.28	0.66 ± 0.24	0.81 ± 0.30	1.63 ± 0.37	1.17 ± 0.44	1.40 ± 0.46
High-friction glove (PVC dots)	716 ± 175	408 ± 179	562 ± 234	1.00 ± 0.33	0.77 ± 0.28	0.88 ± 0.32	1.73 ± 0.28	1.44 ± 0.49	1.58 ± 0.42
All glove types pooled	660 ± 157	353 ± 144	507 ± 215	0.92 ± 0.28	0.67 ± 0.24	0.79 ± 0.29	1.60 ± 0.31	1.23 ± 0.42	1.41 ± 0.41
90° orientation									
Low-friction glove (cotton)	596 ± 115	318 ± 95	457 ± 176	0.82 ± 0.19	0.60 ± 0.17	0.71 ± 0.21	1.49 ± 0.17	1.14 ± 0.27	1.31 ± 0.29
Bare hand	717 ± 133	374 ± 133	545 ± 218	0.99 ± 0.23	0.71 ± 0.21	0.85 ± 0.26	1.69 ± 0.32	1.25 ± 0.43	1.47 ± 0.44
High-friction glove (PVC dots)	743 ± 173	396 ± 128	570 ± 231	1.03 ± 0.31	0.76 ± 0.23	0.90 ± 0.30	1.81 ± 0.31	1.43 ± 0.40	1.62 ± 0.40
All glove types pooled	685 ± 154	362 ± 122	524 ± 213	0.95 ± 0.26	0.69 ± 0.21	0.82 ± 0.27	1.66 ± 0.30	1.27 ± 0.39	1.47 ± 0.40
All orientations pooled									
Low-friction glove (cotton)	467 ± 164	263 ± 88	365 ± 167	0.64 ± 0.24	0.50 ± 0.16	0.57 ± 0.22	1.54 ± 0.36	1.13 ± 0.38	1.33 ± 0.42
Bare hand	652 ± 150	339 ± 122	495 ± 208	0.90 ± 0.26	0.64 ± 0.21	0.77 ± 0.27	1.17 ± 0.37	0.94 ± 0.27	1.06 ± 0.34
High-friction glove (PVC dots)	691 ± 164	389 ± 141	540 ± 215	0.96 ± 0.30	0.74 ± 0.24	0.85 ± 0.29	1.68 ± 0.29	1.39 ± 0.40	1.53 ± 0.38
All glove types pooled	604 ± 187	330 ± 129	467 ± 211	0.84 ± 0.30	0.63 ± 0.23	0.73 ± 0.28	1.46 ± 0.40	1.15 ± 0.40	1.31 ± 0.43

[a]Normalized by participant's mean grip strength measured while he or she was wearing corresponding glove type on the grip dynamometer (Position 2).

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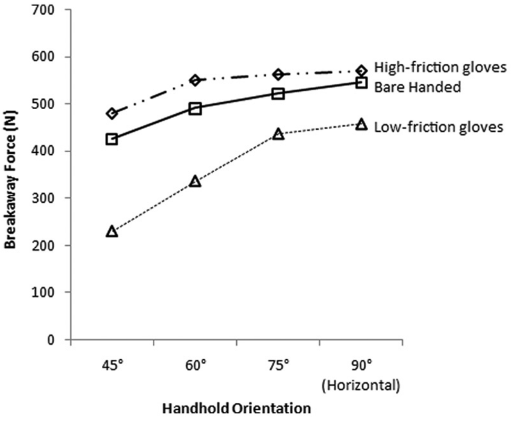

Figure 5. Breakaway strength (N) by orientation and glove type (nondominant hand) across all participants, gender pooled. Strength decreases nonlinearly as the handle inclination increased away from the horizontal for all glove types across this range of handle orientations. Strength was consistently lowest for the low-friction glove and greatest for the high-friction glove.

high-friction glove ($p < .01$). For the effect of orientation, breakaway force was significantly lower for handholds oriented at 45° than for those at 60° ($p < .01$), and breakaway force for 60° handholds was significantly lower than for 75° handholds ($p < .02$). Breakaway force for 75° and 90° orientations was not significantly different ($p = .71$). For the effect of session, breakaway strength decreased significantly from the first to the second experimental session ($p < .01$) but did not quite decrease significantly from the second to the third experimental session ($p = .06$).

Average isometric grip strength for nondominant hands measured at Position 2 (48 mm) of the dynamometer was 429 ± 70 N for males and 303 ± 63 N for females when bare-handed, 411 ± 59 N for males and 279 ± 54 N for females when wearing high-friction gloves, and 398 ± 55 N for males and 278 ± 47 N for females when wearing low-friction gloves. Grip strength was significantly affected by both gender ($p = .002$) and glove type ($p = .002$) but not session ($p > .05$).

Results from the analysis of the video footage from Experiment 2 are presented in Table 7. Coded values represent the mean type of coupling failure that was observed in video footage of that treatment condition. A value of +1 indicates eccentric contraction of the finger flexors, and a value of –1 indicates the hand slipped down the long axis of the handle and the fingers were not extended (see Figure 1). Statistical results show that the main effects of glove type ($F = 112.63$, $p < .001$) and orientation ($F = 430.51$, $p < .001$) on the observed type of coupling failure were significant, as were their interaction ($F = 31.73$, $p < .001$). No other effects or interactions were significant ($p > .05$).

DISCUSSION

Handhold Orientation

Results from both Experiment 1 and Experiment 2 show that the coupling between the hand and the handhold decreased as handle inclination increased from the horizontal (or perpendicular to the pull direction), supporting our hypothesis. The decrease in breakaway strength attributed to change in orientation is not linear: The breakaway force decrement was smaller for orientations near horizontal than for orientations approaching vertical (Figure 4 and Figure 5). It is interesting that this result

TABLE 7: Mean (± *SD*) Coded Coupling Failure Type for Each Orientation (Nondominant Hand, Gender Pooled)

Glove Type	45°	60°	75°	90° (Horizontal)
Low-friction glove (cotton)	−1.0 ± 0.0	−1.0 ± 0.0	−0.1 ± 0.8	1.0 ± 0.0
Bare hand	−0.9 ± 0.5	0.1 ± 0.9	1.0 ± 0.2	1.0 ± 0.0
High-friction glove (PVC dots)	−0.8 ± 0.5	0.6 ± 0.7	1.0 ± 0.0	1.0 ± 0.0

Note. A value of +1 indicates fingers joint became extended and grasp of the handle was lost. A value of –1 indicates the hand slipped down the long axis of the handle and fingers remained flexed around the handle.

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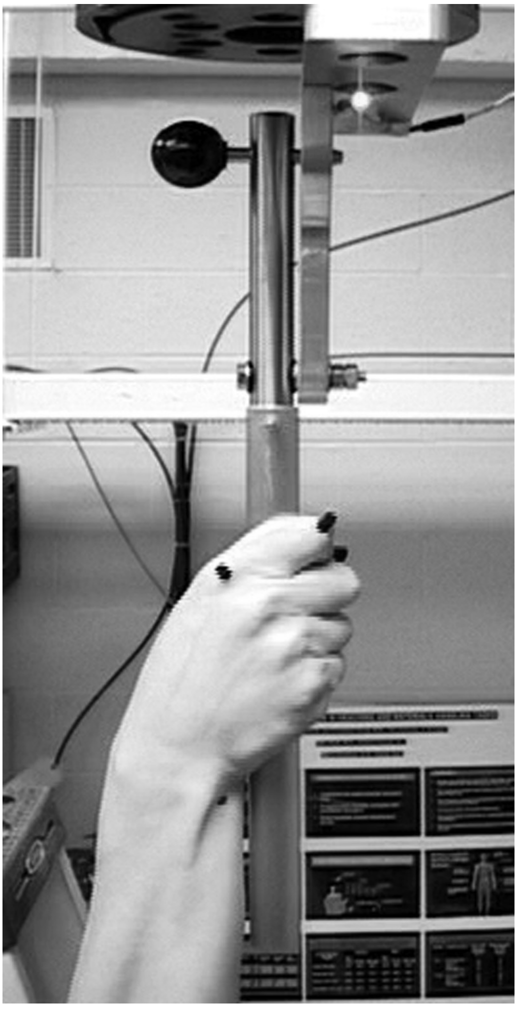

Figure 6. Typical wrist and finger posture when grasping a vertical handhold. The wrist is ulnar deviated and individual finger's joints are flexed at different amounts: small finger flexed greatest, index finger least.

(breakaway strength vs. orientation) is similar in shape to results predicted by the simple model of a block on an inclined plane (Figure 2c). For orientations near horizontal, resistive forces against the vertical load of body weight are created by both the mechanical flexion of the fingers and friction that acts to keep the fingers wrapped around the handle. As the orientation becomes more vertical, friction at the surface becomes increasingly responsible for resisting the vertical load. Breakaway force decreases more greatly as friction is increasingly relied on to create the force. This behavior is illustrated by the type of coupling failure that occurs at these different handle orientations (Tables 5 and 7).

The results from the video analysis indicate the orientation for which the type of breakaway transitions from one failure to the other. If the mean coded value is 1 or –1, then all coupling failures are the same. When the value is somewhere in between, both types of failures are observed, which indicates the orientation of transition between failure types. For the dominant hand, the transition orientation is near 60° for females and slightly lower than 60° for males (Table 4). For the nondominant hand, the type of coupling failure is affected by both handle orientation and the type of glove (Table 7): The transition orientation is between 45° and 60° for high-friction gloves, the transition orientation is near 60° for the bare hand, and the transition between failure types occurs near 75° for low-friction gloves.

Using the simple model presented in the Introduction (Figure 2), it is possible to solve for the transition orientation, given a value for the coefficient of friction. The static coefficients of friction for the high- and low-friction gloves are approximately 0.70 and 0.27, which correspond to a calculated transition orientation of 55° and 75°, respectively. The measured results from the video analysis fit the calculated values remarkably well. Because the coefficient of friction for skin varies greatly with force, moisture, and many other factors (Sivamani, Goodman, Gitis, & Maibach, 2003; Tomlinson, Lewis, & Carre, 2007), measuring an accurate value directly is difficult. It therefore may be useful to estimate this value for high-force tasks on the basis of the observed transition orientation from the bare-hand trials in this study. Solving for the coefficient of friction using a transition orientation of 60° yields an estimated value of friction between dry skin and aluminum of 0.58. The corresponding breakaway force for this condition is 490 N, on average, across all participants (Table 6).

Although friction plays a dominant role in creating force for near-vertical handles, it should be noted that the ability to flex the fingers and squeeze the handle may be also decreased for orientations that are not horizontal.

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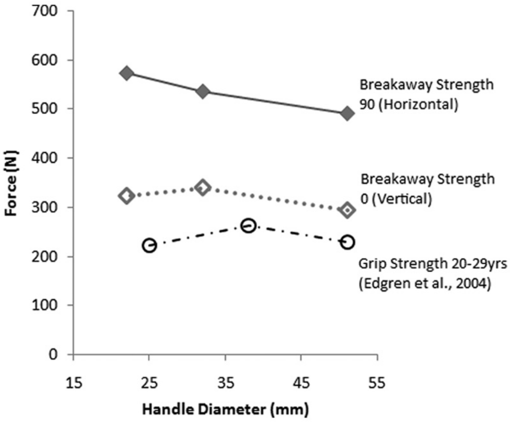

Figure 7. Mean breakaway strength versus handhold size for horizontal and vertical handholds (Experiment 1) and voluntary isometric grip strength versus handle size for participants ages 20 to 29 from Edgren, Radwin, and Irwin (2004). Gender is pooled. Breakaway strength was consistently lowest for the largest cylinder. For the vertical orientation, breakaway strength was greatest for the 32 mm–diameter handle, and the shape of the handhold diameter-versus-strength curve is similar to that of isometric grip strength. However, in the horizontal orientation, breakaway strength was greatest for the smallest diameter handhold.

Nonhorizontal overhead handholds cause the wrist to become deviated when applying a vertical load because the forearm is always vertically oriented. Previous studies have shown that that wrist postures away from the neutral will decrease isometric grip strength, so some of the decrease in breakaway strength for nonhorizontal handles may be explained by reduced ability to flex the fingers in ulnar-deviated postures (Li, 2002; Pryce, 1980). It is impossible to ulnar deviate the wrist to 90°, so the fingers flex at different values (small most, index least) for steeply inclined handhold angles to grasp the overhead handhold (Figure 6).

Handhold Size

The results show that breakaway strength increased for small (22-mm) and medium (32-mm) handholds as compared with large-size (55-mm) handholds for all handle orientations. On the basis of results from previous research of grip strength, we would expect that the greatest breakaway strength would be observed for medium-sized handles and that it would be reduced for the smaller and larger diameters. However, 32-mm and 22-mm handles for all orientations were not found to be significantly different. In fact, the greatest breakaway strength was observed for the smallest handle in the horizontal (90°) orientation. For vertical (0°) handle orientations, however, the medium handle afforded greatest breakaway strength. This finding suggests that optimal handle diameter is a function of the handle orientation with respect to the direction of the applied pull force.

As described earlier, when the long axis is perpendicular to the applied pull direction, eccentric contraction of the fingers' flexors must occur to break hand-handhold coupling. In this situation, smaller handholds may afford greater breakaway strength because the fingers are closed around a smaller surface, reducing the moment arm of normal forces acting against the internal flexion moment at each finger joint. The fingers are also free to extend to a joint configuration in which the finger flexor muscles are at their optimum length and the handle does not need to be pressed into the palm to create force (Young, Sackllah, & Armstrong, 2010). This conclusion is supported by the results that grip strength for the smaller Jamar span (36 mm) was significantly lower than for the larger span (48 mm), whereas breakaway strength for the smallest cylinder (22 mm) was greater than for both larger handles. As the long axis of the handhold becomes increasingly parallel to the applied pull direction (approaching 0°), grasp is maintained and the fingers squeeze the handle into the palm to create friction forces on the surface. Because this situation is similar to an isometric gripping exertion, it can be expected that the size of cylinder that affords the greatest grip strength would also afford the greatest breakaway strength (Figure 7).

Handle size affects the contact area between the hand and the handle (Aldien, Welcome, Rakheja, Dong, & Boileau, 2005; Seo Armstrong, 2008). Contact area has been shown to affect skin friction (Bobjer, Johansson, & Piguet, 1993; Comaish & Bottoms 1971; O'Meara & Smith, 2002) and pain or discomfort during forceful

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exertion (Fothergill, Grieve, & Pheasant, 1992; Hall, 1997). We may hypothesize that a very-small-diameter handle will be optimal for pulling tasks in which the handle is perpendicular to the pull direction, because a small surface will have a correspondingly small moment arm to open the flexed finger joints (e.g., hanging onto a string or wire). However, greater pull force will increase the local pressure over the small contact area, and pain can be expected to increase until it becomes unbearable and/or injury occurs. This pain may cause subjects to relinquish grasp at lower breakaway forces, which is supported by results that handles with corners have been shown to afford less breakaway strength than do cylinders (Young, 2011; Young et al., 2009). It is therefore necessary to determine the relationship between biomechanical advantage and psychophysical limitations when modeling hand function at high loads.

Wearing Gloves

The results show that wearing gloves with PVC dots (high-friction gloves) increases breakaway strength across all orientations. This result is attributable to friction for reasons discussed earlier. Plain cloth gloves decrease friction and, therefore, coupling on the handholds tested. However, this may not be the case for handles that have rough or knurled surfaces, whereby the cloth may actually increase friction. Specific handle and glove friction properties need to be considered for the best choice of glove.

Previous studies have shown that gloves reduce the ability to squeeze objects. Grip strength was measured while participants wore each glove type, and it was found that wearing gloves did reduce grip strength significantly (6% to 8% compared with bare hand). However, it appears that the effect of frictional characteristics of gloves on breakaway strength is more influential than the effect of wearing gloves on finger flexion strength. This finding may not hold for particularly thick or stiff gloves, which have been shown to affect grip strength more greatly (Hertzberg, 1955; Wimer et al., 2010).

The Ability to Hang On With One Hand

Normalizing breakaway strength by body weight will provide insight into the ability to hang onto a handhold in the event that the feet slip and body weight is suddenly transferred to one or two hands. Out of all the handholds tested in this study, mean breakaway strength was greater than body weight for only three conditions and only for males: the 90° orientation and small diameter for the bare dominant hand (Table 3) and the 75° and 90° orientations for the nondominant hand wearing the high-friction gloves (Table 6). These conditions also afforded the greatest strength for females, but on average, females could not hold greater than 78% of their bodyweight (Table 3 and Table 6). The ratio of grip strength to body weight has similarly been shown to be significantly smaller for females than for males (Günther, Bürger, Rickert, Crispin, & Schulz, 2008).

For vertical handholds of any size and for the largest size in the 30° orientation, females on average could support less than half their body weight (Table 3). When friction is reduced by wearing the low-friction glove, participants could support only 36% of their body weight (Table 6). This finding means that for these handhold orientations, even if two hands were available to hang on, it is unlikely that a person could support himself or herself with the hands and arrest an impending fall.

The results presented here may actually overestimate the capability of the working population to support their body weight in a fall, as male and female participants were 114 N and 193 N lighter than population weight norms, on average, respectively (Ogden, Fryar, Carroll, & Flegal, 2004). Furthermore, demographic changes, such as obesity and aging, will reduce the ability to hang on and arrest a fall with the hands, as grip strength is reduced for older individuals (Günther et al., 2008; Mathiowetz et al., 1985).

Breakaway Strength Versus Grip Strength and Coupling Biomechanics

Breakaway strength was greater than grip strength as measured by a grip dynamometer in almost all size and glove type conditions for handle orientations from 60° to 90° (Tables 3 and 6). This result confirms previous findings (Rajulu & Klute, 1993; Woldstad et al., 1995; Young et al., 2009) and verifies the need for

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using alternative metrics, such as breakaway strength, when assessing functional hand capability. Functional strength of the hand involves both active and passive components, which are influenced by object properties and the direction of applied pull force. However, the development of models that can reliably predict breakaway strength on the basis of voluntary grip strength and other measurable handhold properties would reduce the need to measure functional hand strength directly.

It is important to note that grip strength as measured by a dynamometer is a single-axis scalar that is affected by the orientation of the measurement axis (Wimer, Dong, Welcome, Warren, & McDowell, 2009). This characteristic may in part explain differences between grip strength and breakaway strength. When the hand grasps a cylinder, contact forces are applied over the handle surface (Dong, Wu, Welcome, & McDowell, 2008). The normal contact force distribution during maximum isometric grip may be more useful in the development of models for predicting breakaway strength, because passive forces (friction) can be estimated. The contact force distribution during maximal gripping is particularly relevant for pull exertions with handhold orientations parallel to the pull direction (whereby the hand squeezes the handhold and passive forces determine coupling strength) but not for handhold orientations that are perpendicular to the pull direction, because the finger can extend and there may be no contact between the handle and the palm (Young et al., 2010).

Although models of hand-handhold coupling need to include both active muscle and passive surface interaction components, it is unclear how these components can be easily incorporated and implemented. One avenue could be to assume that the active component is equal to the maximum grip force measured in some fashion, as it is a measure of finger flexion force. This approach becomes problematic, however, because during a pulling task, the finger joints can open, and depending on orientation, each finger may be flexed at a different length and the wrist deviated. It would therefore be necessary to measure grip force at every finger and wrist posture observed to quantify this active component.

The active component can also be influenced by the passive friction component through the tissues of the fingers and palm. When the handhold is perpendicular to the applied pull direction, extension of the fingers must occur, and as the fingers slip against the handhold surface, friction acts to keep the finger joints wrapped around the circumference. In this configuration, friction at distal finger segments may cause normal forces on the proximal joints to increase. This situation may be conceptualized by imagining a belt wrapped around a fixed capstan (Beer, 2007). Researchers should investigate how circumferential friction affects loading on the finger segments and how passive components may reduce required muscular effort.

Because the simple model presented in Figure 2 is independent of the weight of the block, it is useful in predicting when the hand will begin to slide axially down the handle but has little value in predicting breakaway strength. In the simple model, normal and corresponding frictional forces trend to zero as the handhold approaches vertical. The model can be improved by allowing the hand to provide a squeezing or gripping force on the opposite side of the handle in these orientations. For example, in the vertical (0°) orientation, breakaway force is entirely composed of frictional forces. If one assumes that grip force acts to squeeze the handle like a pinch, then the coupling force would be calculated as 2μ times grip strength. Mean breakaway force for the vertical cylinder was 0.87 and 0.74 times grip strength for males and females, respectively (Table 3). Solving for the coefficient of friction yields 0.44 and 0.37 for males and females, respectively, values that are less than the 0.58 suggested by video observations. This underestimate may be attributable to reduced grip strength for hand and wrist postures on vertical handles.

Limitations

Measurements of breakaway strength have several limitations, as discussed in Young et al. (2009). These limitations include the possibility that skin friction and maximal effort can vary between participants, much higher rates of loading will occur during a real fall when inertial factors may become more significant, and

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our participants were relatively young individuals and not trained workers.

Another limitation is the ratio of handle size to hand length. For this study, participants were chosen to provide a wide range of anthropometries for general measurements of functional capability. If the goal were to recommend an optimal handle size for a specific task, then target user population hand lengths should be incorporated in the experimental design. Furthermore, the interaction between handle diameter and gender was not significant (p = .97), suggesting that hand length is not an important factor for breakaway strength measured for the three tested diameters.

The effect of session was significant for both experiments (i.e., both hands), indicating that either participants were fatigued in successive sessions or their motivation to perform maximal exertions decreased. The interaction between session and size in Experiment 1 was not significant, nor was the interaction between session and orientation in either experiment. In both experiments, the interaction between session and gender was also significant, although it is difficult to interpret the overall meaning of this interaction. Maximal eccentric exertions have been shown to be particularly fatiguing (Clarkson & Hubal, 2002), so future studies might allow for greater rest periods (more than 5 days) between sessions.

Handhold Design Recommendations

Results from this study suggest that handholds that are horizontal rather than vertical will reduce the effort required to exert climbing forces and increase the chance of supporting the body in the event that the feet slip. As handholds are oriented away from horizontal, the dependence on surface friction is increased. This finding suggests that handholds intended for climbing purposes should not be oriented in vertical or near-vertical orientations unless sufficient friction is ensured.

Current U.S. safety regulations and standards limit the minimum diameter of handholds to 19 mm (fixed ladders; Occupational Health and Safety Administration, n.d.; American National Standards Insitute, n.d.; vehicles; Federal Motor Carrier Safety Administration, n.d.). Although this minimum diameter is mainly based on structural considerations, it should also provide for increased hand coupling in horizontal orientations. However, for vertical orientations, the minimum diameter should be increased to provide better capacity (Figure 7).

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KEY POINTS

- Breakaway strength is maximized for handhold orientations that are perpendicular to the direction of applied pull force and decrease as the handle is oriented more in line with the direction of applied pull force.
- When the direction of applied pull force is parallel to the handhold, the handle diameter that affords the greatest breakaway strength is likely a medium-sized handle similar to handles optimized for isometric gripping. When the direction of applied pull force is perpendicular to the handhold, smaller diameter handles increase breakaway strength.
- Despite reducing isometric grip strength slightly, high-friction gloves will increase breakaway strength. Gloves that reduce friction between the hand and the handle will reduce the ability to hang on.
- Only male participants could support their body weight with one hand on average and only in three conditions: with the bare dominant hand in the 90° orientation on the small-diameter handle and with the nondominant hand wearing high-friction gloves in the 90° and 75° orientations. In situations in which a worker may have only one handhold to support his or her body, it must be oriented in the horizontal orientation to increase the chances of arresting a fall caused by the unexpected loss of foot support.

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