Hand-Handhold Coupling: Effect of Handle Shape, Orientation, and Friction on Breakaway Strength

Justin G. Young, Charles Woolley, Thomas J. Armstrong, and **James A. Ashton-Miller,** University of Michigan, Ann Arbor

Objective: The aim was to determine the maximum force that can be exerted on an object before it is pulled or slips from the grasp of the hand ("breakaway strength") for fixed overhead handholds of varying orientation, shape, and friction. **Background:** Many studies have quantified hand strength by having participants squeeze, pull on, or create torque on an object or handle, but few studies have measured breakaway strength directly. **Method:** In two experiments, hand strength was measured as both overhead breakaway strength for handholds typical of fixed industrial ladders and as maximum isometric grip strength measured using a common Jamar grip dynamometer. **Results:** Breakaway strength was greatest for a fixed horizontal cylinder ("high friction"; 668 ± 40 N and 691 ± 132 N for Experiments 1 and 2, respectively), then for a horizontal cylinder that simulated low surface friction ("low friction"; 552 ± 104 N), then for a vertical cylinder (435 ± 27 N), and finally, for a vertical rectangular-shaped rail (337 ± 24 N). Participants are capable of supporting only their own body weight with one hand when grasping the fixed horizontal cylinder. Breakaway strength for both the high- and low-friction horizontal cylinders was significantly greater than isometric grip strength (1.58 ± 0.25 and 1.26 ± 0.19 times, respectively). **Conclusion:** Results support the hypothesis that hand-handhold coupling is composed of active (isometric or eccentric finger flexion) and passive (frictional) components. Traditional isometric grip strength alone does not predict the strength of a couple between a hand and a handhold well. **Application:** This research shows that handhold shape, orientation, and friction are important in the safe design of grab rails or ladders.

INTRODUCTION

Motivation

Falls are a major cause of injury and mortality in the working-age population. The Bureau of Labor Statistics reports that 827 fatalities resulted from falls in U.S. workplaces in 2006, with 77 deaths associated with falls from nonmoving vehicles, 132 from ladders, and 21 involving steps or stairs (BLS, 2007). An average of 136,118 nonfatal injuries associated with falls from ladders are treated in U.S. emergency rooms each year, with a 50% increase in the number of injuries from 1990 to 2006 (D'Souza, Smith, & Trifiletti, 2007).

Background

The hand is commonly used to help support the body by gripping handles and other objects in the workplace. There are many situations in which a loss of hand-handhold coupling can result in a fall to the same or a lower level. Examples include climbing into or out of heavy equipment (tractors, semitrucks), climbing on ladders, hanging onto moving vehicles (garbage truck personnel), and using safety rails (stairways, scaffolding, bathroom grab rails) (Barnett & Poczynck, 2000; Bottoms, 1983). In many of these situations, if the individual were to slip or fall, his or her weight would be transferred suddenly from the feet to the hands, and the strength of the couple between the hand and the handhold being grasped would determine whether the individual will support his or her body weight or lose grip of the handhold and be injured.

The hand is also the interface that allows workers to hold and use work objects, such as

Address correspondence to Justin G. Young, 1205 Beal Ave., Industrial and Operations Engineering, University of Michigan, Ann Arbor, MI 48109; jgy@umich.edu. ***HUMAN FACTORS,*** Vol. 51, No. 5, October 2009, pp. 705-717. DOI: 10.1177/0018720809355969. Copyright © 2009, Human Factors and Ergonomics Society.

tools and parts. Handles that minimize active finger flexion or effort when carrying or using heavy items (e.g., stretchers or tools) can reduce the risk of fatigue, injury, and work-related musculoskeletal disorders (Armstrong et al., 1993; Leyk et al., 2006). Furthermore, slippage of the hand from the tool handle can cause the hand to come into contact with part of the work object or another work object that can cause injury (Bobjer, Johansson, & Piguet, 1993). It is therefore prudent to quantify the amount of external force that the coupling between the hand and handhold is capable of withstanding and to determine how handle design properties influence this. Improving the design of safety handholds, grab rails, or rungs may reduce the risk of injury or death.

The amount of force that can be exerted on a grasped object before it slips free or is pulled from the grasp of the hand is defined as "breakaway strength" (Rajulu & Klute, 1993). This exertion is different from that of simply squeezing an object because the hand is responding to an external force on the object that must be resisted to retain grasp of the object. Breakaway strength is the point at which force exerted by the hand on the object no longer exceeds the external load. As breakaway strength is approached, the hand may begin to slip. Shear forces attributable to friction may cause deformation of the skin and underlying tissues and can help resist the external load. Last, the fingers may be forced open, causing the flexor muscles to perform eccentric work.

Hand strength has traditionally been quantified by measuring the hand's maximum ability to squeeze two parallel bars together. The grip dynamometer was created to measure this force and has changed little since the mid-1800s (Lanska, 2000). Isometric grip strength has been measured extensively via grip dynamometers and cylindrical split cylinders and is found to be affected by many factors, such as gender, age, and hand dominance (Mathiowetz et al., 1985; Stegink Jansen et al., 2008); skin temperature (Holewijn & Heus, 1990); wearing gloves (Tsaousidis & Freivalds, 1998); the posture of the arm and wrist (Demsey & Ayoub, 1996; Kattel, Fredericks, Fernandez, & Lee, 1996; Kuzala & Vargo, 1992; Laumoreaux & Hoffer, 1995; McGorry & Lin, 2007; Mogk & Keir, 2003; O'Driscoll et al., 1992); movement of the wrist (Lehman, Allread, Wright, & Marras, 1993; Morse, Jung, Bashford, & Hallbeck, 2006); and grip span (Amis, 1987; Dvir, 1997; Edgren, Radwin, & Irwin, 2004; Kong & Lowe, 2005b; O'Driscoll et al., 1992). These studies, however, measure only the active flexion of the fingers and do not address surface interactions (i.e., friction) or external loading of the object being gripped. Isometric grip strength may therefore not be an accurate functional measure of the hand's ability to hold onto an object in many situations.

In studies examining pull strength or pulling tasks, there is an external load acting on the hand-handle couple. The external force is produced by the action of the participant (Cochran & Riley, 1986; Das & Wang, 2004; Fothergill, Grieve, & Pheasant, 1992; Kong & Freivalds, 2003; Seo, Armstrong, Chaffin, & Ashton-Miller, 2008). Given that muscles in many segments of the body (arms, torso, legs, etc.) create the force on the handle, the weakest segment will limit the measured pull force. Pull strength therefore may underestimate the total strength capability of the hand-handhold couple. It is important for studies examining the hand-handhold couple directly to isolate the couple from the rest of the body.

Because extrapolation of grip or pull strength as a measure of the hand's capability to hold onto a handhold is unfounded, direct investigation of this metric is needed. However, very few studies have investigated grasping at maximal loads when lengthening contraction (eccentric) of flexor muscles may occur and the hand may break free from the handhold. Dvir (1997) measured isometric and isokinetic grip strength across a range of positions on a grip dynamometer-type device and found that grip force increased significantly during eccentric exertions. The isokinetic velocity was also found to significantly influence peak strength.

Rajulu and Klute (1993) investigated the force needed to pull a handle from a power grip, or "hand grasp breakaway strength," directly by using a mechanical device to force a handle from the participant's grasp. This force can be thought of as the functional hand strength for that specific handle. It was found that breakaway strength was much greater than isometric grip strength measured with a dynamometer but that grip strength and breakaway strength were correlated. These studies showed that the breakaway strength can be higher than isometric grip strength.

Hypotheses and Aims

It is our hypothesis that breakaway strength comprises both an active component and a passive component. The active component results from the active flexion of the fingers by muscles in the hand and forearm (isometric or eccentric), and the passive component results from friction between the hand and the handhold. The relative weighting of each component as it contributes to breakaway strength depends on the orientation and shape of the handhold with respect to the hand and the applied force. Therefore, breakaway strength should vary for differently oriented or differently shaped handles or for handles of differing surface friction, as is often the case for handholds used for climbing or support (i.e., ladder rungs and rails).

To test the hypothesis, two separate experiments were conducted. The goal of the first experiment (ladder breakaway strength) was to quantify breakaway strength for handholds that typically are found on industrial fixed ladders. Ladder handholds (i.e., rungs and rails) vary in orientation and shape. Breakaway strength was measured for three typical handholds and was compared with isometric grip strength and body weight. The goal of the second experiment (effect of friction on breakaway strength) was to quantify breakaway strength for horizontal handholds of high and low friction and to determine the relative contribution of active (finger flexion) and passive (friction) components to the magnitude of the hand-handhold coupling force.

METHOD

Participants

Participants for both experiments were recruited from the University of Michigan community and were paid for their involvement. Twelve healthy young participants (6 males and 6 females) participated in each experiment. No participants had 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.

Experiment 1: Ladder breakaway strength. Mean (± *SD*) age, height, and body weight for the 12 participants were 21 ± 2 years, 1.73 ± 0.11 m, and 61.8 ± 14.8 kg (606 ± 145 N), respectively. On average, males were 14.5 kg (142 N) heavier and 0.15 m taller than females. Hand lengths (measured according to the method of Garrett, 1971) ranged from 15th to 79th percentile for males and from 9th to 81st percentile for females on the basis of 1946 U.S. Army data (White, 1981). Eleven participants were right-hand dominant, and one was left-hand dominant. Dominant-hand grip strength ranged from 26th to 78th percentile for males and from 19th to 73rd percentile for females on the basis of grip strength data for persons ages 20 to 25 years (Mathiowetz et al., 1985). Dominant-hand grip strength was on average 38 N greater than nondominant-hand grip strength for all participants.

Experiment 2: Effect of friction on breakaway strength. Mean (± *SD*) age, height, and body weight for the 12 participants were 22 ± 3 years, 1.72 ± 0.09 m, and 70.5 ± 7.5 kg (691 ± 74 N), respectively. On average, males were 5.4 kg (53 N) heavier and 9 cm taller than females. Hand lengths (measured according to the method of Garret, 1971) ranged from 7th to 76th percentile for males and from 24th to 93rd percentile for females on the basis of1946 U.S. Army data (White, 1981). All participants were right-hand dominant. Dominant-hand grip strengths ranged from 3rd to 71st percentile for males and from 68th to 98th percentile for females on the basis of grip strength data for persons ages 20 to 25 years (Mathiowetz et al., 1985).

Breakaway Strength Measurement and Apparatus

To isolate the hand-handle couple as the force-limiting link, the external force applied to the couple must be independent of leg, back, torso, and upper arm strength. By slowly lowering a participant already holding onto a fixed overhead handle, an increasing vertical force is created by body weight and acts on the hand-handle couple passively through the shoulder

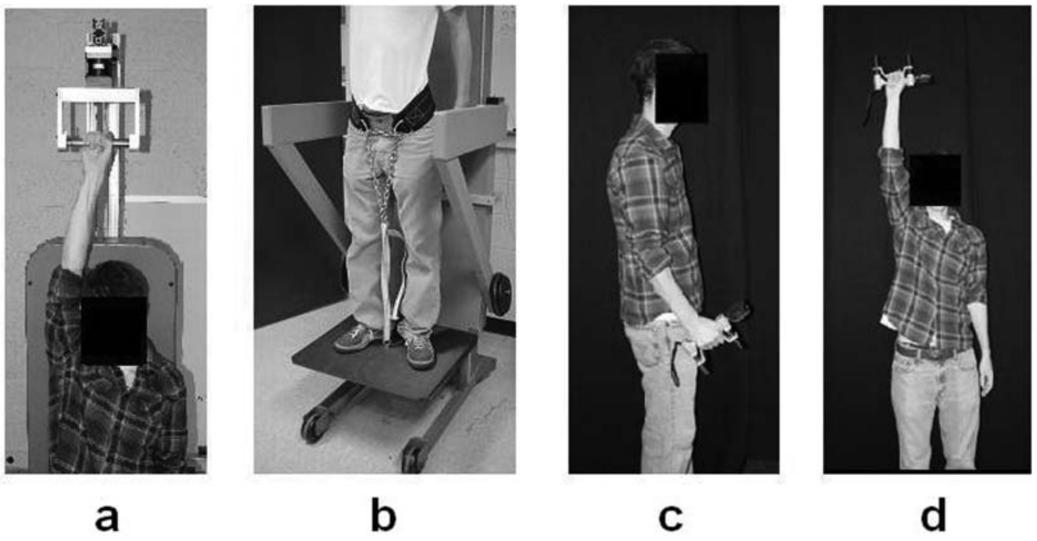


Figure 1. Experimental setup. (a) Participants stand on a platform and are lowered while grasping an instrumented, fixed-overhead handle. (b) Participants are secured to the weighted platform by a weightlifter's dipping belt so that they cannot lift themselves off of the platform and they always move up or down with it. (c) Participant position for isometric grip strength measurements (Experiments 1 and 2). (d) Participant position for additional isometric grip strength measurement (Experiment 2 only).

and arm. Because the shoulder and elbow were placed in full overhead extension, ligaments and stabilizing tissue can bear the traction forces across these joints, and only finger flexor muscles in the forearm and hand will contribute to breakaway strength (Basmajian & De Luca, 1985). In this way, the hand-handle link is isolated from the other joints, and maximal voluntary hand strength can be measured safely.

Essentially, this method of measuring breakaway strength simulates attempting to arrest a vertical fall by holding the handhold with one hand. In each of the two experiments conducted, breakaway strength was measured in this fashion. The maximum vertical force recorded by the instrumented overhead handle as it was pulled or slipped from the participant's grasp was deemed breakaway strength for that handle.

A height-adjustable platform (a modified passive hydraulic lift truck) was used to raise and lower each participant. An instrumented handle was fixed overhead above the platform (Figure 1a). A weightlifter's dipping belt was used to secure the participant to the platform so that participants could not plantarflex their ankles or be lifted off the platform. Before each experiment, weights were attached to the sides of the platform to keep the combined weight of the participant and platform constant at 127 kg (1,245 N). This step ensured that the initial lowering speed of the lift was a constant 14 cm/s across all participants and that full strength capability would be reached (Figure 1b). A six-axis load cell (AMTI® MC-3), an amplifier, a 12-bit data acquisition card (National Instruments USB-6008), and LabVIEW™ software were used to record the forces at 200 Hz that were exerted on the handle. A video camera, synchronized with force recordings, was used to record hand motion during each trial.

Procedure and Design

For each breakaway strength trial, each participant stood on the adjustable platform and was secured using the dipping belt. The participant was then raised until he or she could firmly grasp the overhead handle in a power grip with a slight bend at the elbow. The bend in the elbow ensured that the participant was not impulsively loaded at his or her extreme reach and that his or her muscles had time to preload before full extension and breakaway was achieved.

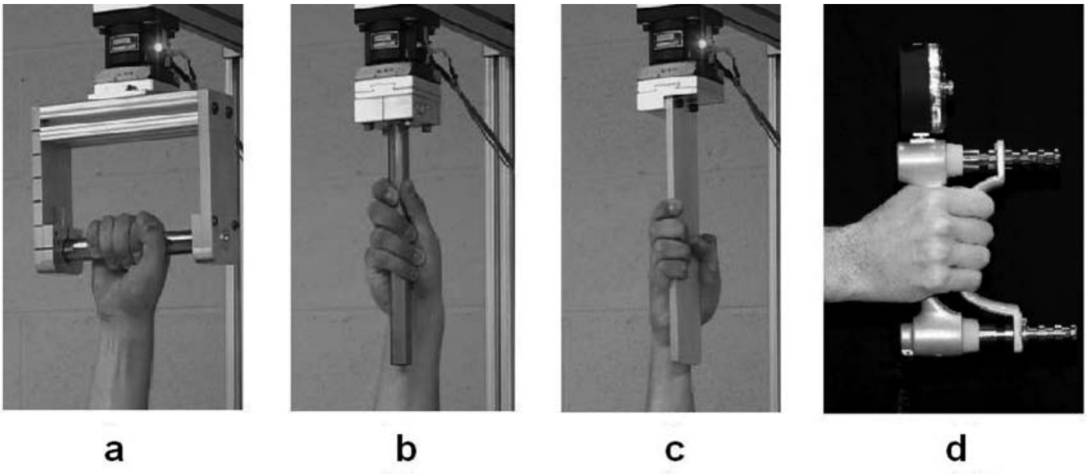


Figure 2. Handholds tested. (a) 25-mm-diameter horizontal cylinder (Experiments 1 and 2). (b) 25-mm vertical cylinder (Experiment 1 only). (c) 64-mm × 10-mm vertical plate (Experiment 1 only). (d) Jamar grip dynamometer in Position 2 (Experiments 1 and 2).

Participants were instructed to exert their maximum strength capability and "to hold onto the handle as long as possible." Participants were asked if they were ready and were then lowered until their hand decoupled from the handle or they let go. Forces exerted on the handle were recorded. Total time from the beginning of lowering to breakaway was 2 to 4 s. Isometric grip strength trials were performed (while participants were off of the platform) by asking participants to squeeze the dynamometer "as hard as possible" for 5 s. Verbal encouragement was provided by researchers during grip strength measurements.

To eliminate effects attributable to surface contaminants, participants washed their hands with soap, rinsed them with water, and dried them with paper towels 10 min prior to testing (Buchholz, Frederick, & Armstrong, 1988; Comaish & Bottoms, 1971). Participants also wiped their hands with a clean, dry paper towel before each trial to reduce any effects from perspiration during the course of an experimental session. The stainless steel handles were cleaned with steel wool between participants.

For both experiments, there were three repetitions for each strength measurement. The order of the trials was randomized. A break of at least 2 min was given between successive trials. Statistical analyses were performed with Minitab® software, and a *p*-value less than .05 was considered significant.

Experiment 1: Ladder breakaway strength. Breakaway strength was measured for three different steel handles typically found on fixed industrial ladders. Two vertically oriented handles simulated typical ladder rails: a 25-mm-diameter cylinder (Figure 2b) and a 64-mm × 10-mm plate (Figure 2c). The third handle was a 25-mm-diameter horizontally oriented cylinder that simulated a typical ladder rung (Figure 2a). The arm was oriented overhead with the elbow fully extended and the hand pronated for the horizontal cylinder and midway between prone and supine for both vertical handles during breakaway strength measurements. A Jamar grip dynamometer (Position 2, 45 mm) was used to measure the participant's maximum volitional power grip strength (Figure 2d). Grip strength was measured for both hands with the participant's elbow slightly bent at his or her side and with the hand midway between prone and supine (Figure 1c).

Maximal strength for each of the three handles was tested for the dominant hand. The horizontal cylinder was also tested for the nondominant hand. Grip strength was measured for both hands. See Table 1 for a summary of the independent and dependent variables and the applied treatments in Experiment 1.

TABLE 1: Experimental Design Summary for Experiments 1 and 2

	Experiment 1: Ladder Breakaway Strength	Experiment 2: Effect of Friction on Breakaway Strength
Independent variables (dominant hand)	Gender (2): male, female Handle (4): horizontal cylinder, vertical cylinder, vertical plate, Jamar	Gender (2): male, female Handle (4): high-friction horizontal cylinder, low-friction horizontal cylinder, Jamar in two arm positions
Independent variables (nondominant hand)	Gender (2): male, female Handle (2): horizontal cylinder, Jamar	—
Dependent variables	Peak force	Peak force
Total exertions per participant	Dominant hand: 4 handles × 3 reps = 12 Nondominant hand: 2 handles × 3 reps = 6	Dominant hand: 4 handles × 3 reps = 12

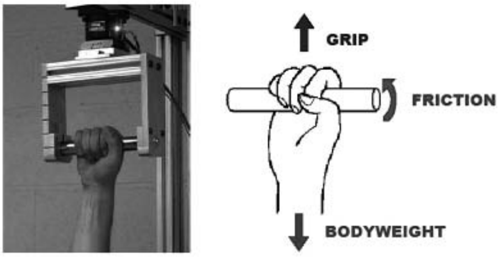
A two-way, repeated-measures analysis of variance was performed to determine whether the measured force was significantly affected by the fixed effects of handle grasped (the three ladder handles and the Jamar) and gender (male and female) with participant as a random effect. Post hoc Tukey tests were then performed on significant main effects to compare breakaway strength between the three handholds with isometric grip strength measured with the dynamometer. As a separate analysis, a two-way repeated-measures analysis of variance was used to determine if breakaway strength, normalized by either grip strength or body weight, was different for each of the three handholds. Similar analyses were also performed for breakaway strength for the horizontal handle between dominant and nondominant hands and for grip strength between dominant and nondominant hands.

Experiment 2: Effect of friction on breakaway strength. Breakaway strength was measured for a high- and low-friction handle. Each handle was the same 25-mm-diameter horizontally oriented cylinder that simulated a typical ladder rung in Experiment 1. However, this handle was designed so that a pin could be removed on the handle assembly, which allowed the handle to spin unconstrained along the long axis of the cylinder.

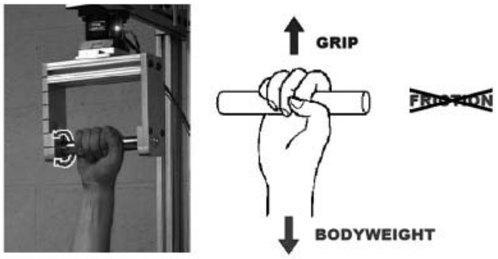
When grasping a fixed handle, as the body and arm are pulled down, the fingers that are wrapped around the cylindrical handle exert a shear frictional force on the surface. These forces cause a torque along the long axis of the handle. When the pin is removed and the handle is allowed to spin, these torques caused by friction meet no resistance, and the handle rotates. This is analogous to the hand's sliding over the surface of a handle with zero friction (Figure 3). The low-friction handle here is simulated, but biomechanically, it is similar to a very slippery fixed handle. Thus, the high-friction handle in this experiment is constrained along the long axis, whereas the low-friction handle is unconstrained along the long axis.

The arm was oriented overhead with the elbow fully extended and the hand pronated for both these breakaway strength measurements. It should be noted that translational friction (in the direction of the long axis of the handle) is not eliminated by allowing the handle to spin; however, its contribution to breakaway strength in this orientation is likely negligible.

As in Experiment 1, a Jamar grip dynamometer was used to measure the participant's grip strength. However, two grip strength measurements were performed in this experiment: The first was measured with the participant's elbow slightly bent at the his or her side and with the



a. **Fixed Cylinder**



b. **Unconstrained Cylinder**

Figure 3. Breakaway handholds tested in Experiment 2. (a) Fixed 25-mm horizontal cylinder. Friction resists the slipping of the hand. (b) Unconstrained 25-mm horizontal cylinder. The cylinder can rotate along the long axis, nullifying the effect of friction that would resist slipping of the hand.

hand midway between prone and supine (as in Experiment 1; Figure 1c); the second was measured with the arm oriented overhead with the elbow fully extended and the hand pronated (i.e., in the same position as the breakaway force measurements; Figure 1d).

A total of 12 maximum strength trials were performed: 6 maximum voluntary grip strength tests and 6 breakaway strength tests. Each of the two handles was tested for the dominant hand. Grip strength was measured with the dominant hand in two positions. See Table 1 for a summary of the independent and dependent variables and the applied treatments in Experiment 2.

A two-way, repeated-measures analysis of variance was performed to determine whether the measured force was significantly affected by the fixed effects of handle grasped (high- and low-friction handles and the Jamar in two positions) and gender (male and female) with participant as a random effect. Post hoc Tukey tests were then performed on significant main effects to compare breakaway strength between the high- and low-friction handholds with isometric grip strength measured at the two arm positions. As a separate analysis, a two-way, repeated-measures analysis of variance was used to determine whether breakaway strength, normalized by grip strength or body weight, was different for each of the three handholds and whether results for the fixed handle were different between Experiments 1 and 2.

RESULTS

Experiment 1: Ladder Breakaway Strength

Mean (± *SD*) peak forces measured for the dominant hand for each handle are presented in Table 2, along with normalized results. Peak force differences were significant for main effects handle grasped, $F(3, 126) = 170.53$, $p < .001$, and gender, $F(1, 126) = 13.99$, $p < .001$. There was a significant interaction between handle grasped and gender, $F(3, 126) = 18.21$, $p < .01$; the gender effect was greater for the horizontal cylinder and the Jamar than for vertical handles. Men were stronger than women for all handles. Post hoc analysis indicates that breakaway strength observed for the 25-mm horizontal cylinder was greater than for the 25-mm vertical cylinder ($p < .001$), which in turn was greater than for the 64-mm × 10-mm vertical plate ($p < .001$). Breakaway force for the 25-mm vertical cylinder was not significantly different than isometric grip strength measured with a grip dynamometer ($p > .05$).

In fall situations, it is useful to normalize breakaway strength with respect to the body weight of the individual, as this provides an indicator of the person's ability to hang on with one hand. Peak force normalized by body weight differences were significant for the main effect of handle grasped, $F(2, 92) = 284.75$, $p < .001$, but not gender, $F(2, 92) = 3.19$, $p = .104$. A significant interaction between main effects, $F(2, 92) = 10.62$, $p < .001$, indicated that the gender effect was greater for the horizontal cylinder than for the vertical handles. Breakaway strength normalized by body weight was greater than 1 for only the fixed horizontal cylinder.

Peak breakaway strengths normalized by grip strength were similarly significant for the main

TABLE 2: Peak Breakaway Strength and Grip Strength (*M* ± *SD*) by Handle and Gender for Typical Ladder Handholds (Experiment 1)

	Peak Force (N)		Peak Force/Body Weight		Peak Force/Grip Strength	
Handle	Males	Females	Males	Females	Males	Females
25-mm horizontal cylinder	842 ± 207	494 ± 93	1.17 ± 0.13	0.94 ± 0.18	1.52 ± 0.26	1.53 ± 0.20
25-mm vertical cylinder	516 ± 120	354 ± 46	0.72 ± 0.10	0.68 ± 0.12	0.93 ± 0.15	1.10 ± 0.13
64-mm × 10-mm vertical plate	410 ± 166	264 ± 73	0.55 ± 0.14	0.50 ± 0.13	0.73 ± 0.23	0.81 ± 0.19
Grip dynamometer	551 ± 57	320 ± 34	0.85 ± 0.20	0.61 ± 0.08	1.00	1.00

effect of handle grasped, $F(2, 92) = 286.43$, $p < .001$, but not gender, $F(2, 92) = 0.83$, $p = .383$. A significant interaction between main effects, $F(2, 92) = 3.13$, $p < .05$, indicated that the gender effect was greater for the vertical handles than for the horizontal cylinder. Breakaway strength on the horizontal handle exceeded grip strength by 52% when all participants were pooled.

The dominant hand had significantly greater grip strength, $F(1, 58) = 59.76$, $p < .001$, and breakaway strength on the horizontal rung, $F(1, 58) = 3.13$, $p < .05$, than did the nondominant hand (1.11 ± 0.09 times and 1.06 ± 0.15 times, respectively). Males were significantly stronger than females for both grip strength, $F(1, 58) = 50.71$, $p < .001$, and breakaway strength, $F(1, 58) = 17.17$, $p < .01$, for both dominant and nondominant hands.

Experiment 2: Effect of Friction on Breakaway Strength

Mean (± *SD*) average peak forces measured for the dominant hand for each handle and the Jamar are presented in Table 3, along with the normalized results. Peak force differences were significant for main effects handle, $F(3, 126) = 167.58$, $p < .001$, and gender, $F(1, 126) = 10.43$, $p < .01$. Males were significantly stronger than females for all handles grasped. A significant interaction between main effects, $F(3, 126) = 4.17$, $p < .01$, indicated that the gender effect was greater for breakaway forces measured on the horizontal cylinders than for the Jamar in either arm position.

Post hoc analysis indicates that breakaway strength was greater for the high-friction handhold than for the low-friction handhold ($p < .001$). Both breakaway strengths were significantly greater than grip strength in either arm position ($p < .001$). Differences between isometric grip strength measured at the side of the body versus overhead were not significant ($p > .05$), although overhead grip strength was consistently slightly greater than when measured at the side.

Peak breakaway force normalized by body weight differences were significantly greater for the high- than for the low-friction handle, $F(1, 58) = 86.87$, $p < .001$, but the effect of gender failed to reach statistical significance, $F(1, 58) = 4.13$, $p = .069$. There was no significant interaction between handle grasped and gender, $F(1, 58) = 0.09$, $p > .05$. Similar to the results from Experiment 1, breakaway strength normalized by body weight was greater than 1 for only the fixed horizontal cylinder.

As when normalized by body weight, peak breakaway strength normalized by grip strength was similarly greater for the high- than for the low-friction handle, $F(1, 58) = 86.87$, $p < .001$. Neither the main effect of gender, $F(1, 58) = 0.69$, $p > .05$, or interaction effect was significant, $F(1, 58) = 0.74$, $p > .05$. Breakaway

TABLE 3: Peak Breakaway Strength and Grip Strength (*M* ± *SD*) by Handle and Gender for High- and Low-Friction Handholds (Experiment 2)

	Peak Force (N)		Peak Force/Body Weight		Peak Force/Grip Strength	
Handle	Males	Females	Males	Females	Males	Females
25-mm horizontal cylinder	766 ± 121	617 ± 97	1.07 ± 0.18	0.93 ± 0.14	1.61 ± 0.25	1.55 ± 0.25
25-mm horizontal cylinder (low friction)	628 ± 95	477 ± 33	0.88 ± 0.15	0.73 ± 0.10	1.32 ± 0.22	1.21 ± 0.12
Grip dynamometer (overhead measurement)	481 ± 76	399 ± 46	0.68 ± 0.13	0.61 ± 0.10	1.00	1.00
Grip dynamometer	474 ± 84	390 ± 44	0.67 ± 0.14	0.59 ± 0.09	0.98 ± 0.05	0.98 ± 0.05

strength for both the high-friction and the low-friction handhold exceeded grip strength by an average of 58% and 26%, respectively, for all participants pooled. These ratios were slightly higher for males than for females.

The 25-mm horizontal cylinder (high friction) was exactly the same handhold used in both experiments. Breakaway strength for this handhold was not significantly different, $F(1, 48) = 0.09$, $p > .05$, between Experiments 1 and 2.

DISCUSSION AND CONCLUSION

Experiment 1 showed that breakaway strength (i.e., the force required to pull a handle from power grip) for a 25-mm-diameter cylindrical steel handhold orientated horizontally (i.e., perpendicular to the external force) was, on average, 54% greater than for the same 25-mm-diameter cylindrical steel handle orientated vertically (i.e., parallel to the external force). Additionally, breakaway strength for a 25-mm-diameter cylindrical steel handhold was 29% greater than for a 64-mm × 10-mm steel plate when both are oriented vertically. This supports the hypothesis that shape and orientation will affect the strength of the couple between the hand and the handhold. Furthermore, breakaway strength for the horizontal cylinder was significantly greater (1.52 times, on average) than isometric grip strength measured with a common grip dynamometer. This result suggests that active finger flexion alone is not entirely responsible for breakaway strength and that maximum voluntary grip strength may grossly underestimate breakaway force.

The biomechanical explanation for these results is as follows: When a fixed handle is oriented perpendicular to the applied load (i.e., horizontal for our experiments), the mechanical resistance of the forearm muscles to the extension of the finger joints (i.e., grip strength) and a frictional traction from the palmar skin slipping over the surface of the handle will act together to apply a torque between the hand and handhold (see Figure 4a). The total force (eccentric grip capability plus frictional resistance) in this situation then should be greater than the isometric grip strength measured by a grip dynamometer, as our results show.

When the handle is oriented parallel to the external force (i.e., vertical in our experiments), active grip strength will provide a normal force that will influence friction as the hand slides along the handle. In this situation, friction determines breakaway strength, whereas the grip force acts only to influence friction. There is no direct mechanical resistance against the external

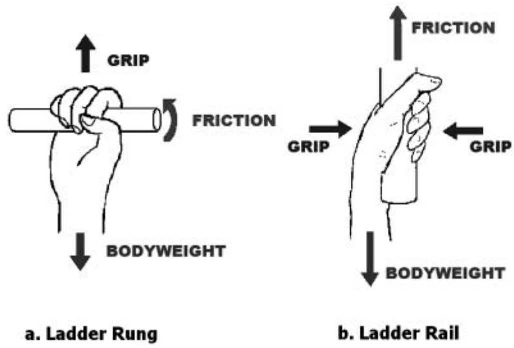


Figure 4. Forces when holding onto a typical ladder rung or rail. (a) When an individual is holding a rung, active gripping forces act to resist the opening of the fingers, and passive friction forces act to resist the hand's sliding open over the curved surface and off the rung. Both active and passive forces resist bodyweight. (b) When an individual is holding a rail, active gripping forces squeeze the rail and create normal forces, which increase passive friction forces that act to resist the hand's sliding down the rail. Only passive forces resist body weight.

force from the finger flexors in this orientation (see Figure 4b).

Data from Experiment 2 further support the hypothesis that breakaway strength comprises both an active (grip) and a passive (friction) component. The breakaway strengths for the high- and low-friction horizontal handhold of the same shape, orientation, and material were significantly different: Breakaway strength for the high-friction handhold was 139 N greater, on average, than for the low-friction handle. This difference suggests that friction plays an important role in the strength of the hand-handhold couple.

These results can be used to estimate the relative magnitude of the active and passive components. Breakaway strength for each of the handholds was significantly greater than isometric grip strength (58% greater and 26% greater for the high- and low-friction handholds, respectively). This difference suggests that a lengthening contraction of the finger flexor muscles increases the hand-handhold coupling capability by up to 26% beyond isometric grip strength. By increasing friction further, a greater capability to "hang on" to the support with one hand is achieved (32% more for the high-friction than for the low-friction handhold on average).

Most hand strength studies are based on devices such as the Jamar grip dynamometer. Our results demonstrate that these devices significantly underpredict the ability of individuals to hold onto a horizontal cylinder. Only isometric finger flexion force is measured—the friction that is produced as the hand slides from the handhold or the increase in strength from isometric to eccentric flexions is not accounted for. Consequently, the amount of force that can be exerted to support the body when holding handholds that are perpendicular to the applied force may be significantly underestimated by isometric grip strength metrics. Researchers measuring functional hand strength for situations in which there may be significant external loading therefore need to take these factors into account.

When the handhold is oriented parallel to the applied force, only friction forces along the long axis of the handhold act support the body. This frictional force is related to, but not equal to, grip force (Imrhan & Farahmand, 1999; Kong & Lowe, 2005a; Pheasant & O'Neill, 1975; Seo et al., 2008; Seo, Armstrong, Ashton-Miller, & Chaffin, 2007; Yoxall & Janson, 2008). Our data show that the shape of the handhold in this situation affects the total frictional force. This finding may be attributable to the amount of surface contact the hand has on the handle or to the amount of grip force that can be applied to that shape. When asked informally about the three handholds that were tested in Experiment 1, participants noted that the 64-mm × 10-mm plate was the least comfortable handhold to grasp. Discomfort when grasping that handhold likely reduced the breakaway force developed.

Breakaway strength for the horizontal cylinder was 1.52 and 1.58 times grip strength for Experiment 1 and Experiment 2, respectively (these are not statistically different values). Rajulu and Klute (1993) reported average breakaway strength of 1.7 times grip strength for participants grasping a handle perpendicular to the forearm while wearing gloves. Those gloves may have increased friction between the hand and handle or may have stiffened the fingers.

Greater forces can be exerted by active muscles during lengthening than during isometric contraction (Katz, 1939). Dvir (1997) found that eccentric isokinetic contractions yielded 1.13 to 1.15 times greater peak forces than did isometric measurements. Our finding that breakaway strength for a low-friction handle was 1.26 times greater than isometric grip strength slightly exceeds than that of Dvir. Differences may be attributable to the handle shape's being a cylinder versus two parallel bars or may be because friction in the rotating handle was not completely reduced to zero.

When compared with overhead pull strength, breakaway strength for the horizontal rung more than doubles the force that participants could exert by active pulling, as reported by Das and Wang (2004). This result implies that the highest active strength of the person pulling on a handle does not approach the total capability of the hand-handle couple. Even for the vertical rail, the average grasp capability is higher than the average pull strength reported by Das and Wang (2004). This finding highlights the importance of loading the hand without having the individual provide the external force, as he or she may not be able to generate enough to approach breakaway strength. If isolation of the hand-handle couple from other force-limiting structures in the body is not accomplished, breakaway strength of the hand and handhold may be confounded with the strength of other body linkages.

The three handholds tested are typical of industrial fixed ladders found on buildings and heavy equipment. When breakaway force is normalized by participant body weight, insights can be obtained on the relative ability of a worker to hold onto a handhold in case of a fall. The fixed 25-mm horizontal cylinder (rung) afforded the greatest breakaway strength between the hand and the handle (1.05 and 1.00 times body weight on average for Experiments 1 and 2, respectively), followed by the low-friction horizontal rung (0.81 times body weight). The two vertical handholds, typical of ladder rails, afforded much less breakaway strength (0.70 and 0.53 times body weight for the 25-mm cylinder and the 64-mm × 10-mm plate, respectively).

These results show that relatively strong or relatively light individuals can support their full body weight with one hand on a 25-mm fixed steel rung, as long as there is sufficient friction. Few people can support their full body weight with one hand using either a 25-mm diameter rod-type or a 64-mm × 10-mm plate-type rail. When a person is climbing, two hands may be available to support the body in a fall. Males had higher ratios of breakaway strength to body weight than females in both experiments. Females, therefore, may be at higher risk in climbing situations than males. Males' ratios of breakaway strength to grip strength are not always higher than those of females, however.

When comparing horizontally to vertically oriented handholds, it is important to note that the position of the wrist is altered. The wrist was ulnar deviated for vertical handholds and neutral for horizontal handholds. Ulnar deviation has been shown to decrease isometric grip strength (Demsey & Ayoub, 1996; Kattel et al., 1996; Laumoreaux & Hoffer, 1995; O'Driscoll et al., 1992). The reduction of grip strength when holding a vertical handhold attributable to wrist ulnar deviation may have accounted for some of the decrease in breakaway strength measured for vertical as compared with horizontal handholds.

Although each handle was made of the same material, the coefficient of friction between the hand and the handle may have varied between each participant. Differences in skin surface properties (such as calluses) and perspiration rate may have introduced error despite attempts to control this. Slight variations in room temperature and humidity may have also influenced results, as this was not monitored during the course of data collection. Additionally, maximal effort may be different between participants, with some "giving up" and letting go before their true maximum grasp capability is reached.

In this study, breakaway strength measurements were based on a loading rate of approximately 14 cm/s. Much higher rates of loading could occur during a fall, and inertial factors may become more significant. The loading rate may also depend on how the fall event occurs (e.g., whether the individual is already grasping a handhold or needs to reach and grab hold after the fall has started). The effect of higher or lower loading rates on breakaway strength remains unknown, although the values reported here are likely conservative estimates of maximum possible strength.

This study tested breakaway strength for relatively young individuals. Because grip strength has been shown to be diminished for older individuals (Mathiowetz et al., 1985), our results may overestimate breakaway strength for the older population. As the working population ages and average body weight increases, the ability to hang onto handholds in fall situations will be reduced. Further research should include participants in multiple age groups.

This study shows that breakaway strength is increased for handles that have higher friction and that are horizontally oriented. It also shows that handles with corners (such as a thin rectangular plate) are less desirable for gripping in a fall. However, this study examined only a small subset of the range of handholds employed in the real world. Further research is needed to develop models for predicting breakaway strength for a given handle size, shape, and material as well as handles that are oriented at angles other than horizontal or vertical. Such studies might also consider the effect of gloves, which could be used to increase friction and strength.

It is reasonable to hypothesize that factors affecting grip strength, torque generation, and pull strength that have been identified in previous studies will also be important in determining the strength of the hand-handhold coupling. These factors may influence both active components (finger flexion strength) and passive components (friction and skin or tissue deformation) of functional hand strength. Investigation and incorporation of these and new parameters into underlying biomechanical models will help to develop a comprehensive model of hand-handhold coupling.

These models can be used to describe the best shape and size for ladder rungs and rails as well as safety handholds and tool handles. For example, the Occupational Safety and Health Administration (OSHA) 29 Code of Federal Regulations 1910.27(b)(2) requires that ladder side rails, which might be used as a climbing aid, be of such cross sections as to afford adequate gripping surface without sharp edges, splinters, or burns. Our results clearly show that rails constructed of plate steel that meet OSHA standards afford much less hand coupling ability than do cylindrical rails. Further research can provide specific shape and surface guidelines for handholds in applicable safety standards.

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REFERENCES

Amis, A. A. (1987). Variation of finger forces in maximal isometric grasp tests on a range of cylinder diameters. *Journal of Biomedical Engineering*, *9*, 313–320.

Armstrong, T. J., Buckle, P., Fine, L. J., Hagberg, M., Jonsson, B., Kilbom, A., Kuorinka, I. A., Silverstein, B. A., Sjogaard, G., & Viikari-Juntura, E. R. (1993). A conceptual model for work-related neck and upper-limb musculoskeletal disorders. *Scandinavian Journal of Work, Environment and Health*, *19*, 73–84.

Barnett, R., & Poczynck, P. (2000). Ladder rung vs. siderail hand grip strategies. *Safety Brief (Triodyne Inc.)*, *16*(4), 1–15.

Basmajian, J. V., & De Luca, C. J. (1985). *Muscles alive: Their functions revealed by electromyography.* Baltimore: Williams and Wilkins.

Bureau of Labor Statistics. (2007). *2006 census of fatal occupational injuries (revised data).* Washington, DC: Author.

Bobjer, O., Johansson, S. E., & Piguet, S. (1993). Friction between the hand and handle. Effects of oil and lard on textured and non-textured surfaces; perception of discomfort. *Applied Ergonomics*, *24*, 190–202.

Bottoms, D. J. (1983). Design guidelines for operator entry-exit systems on mobile equipment. *Applied Ergonomics*, *14*, 83–90.

Buchholz, B., Frederick, L. J., & Armstrong, T. J. (1988). An investigation of human palmar skin friction and the effects of materials, pinch force and moisture. *Ergonomics*, *31*, 317–325.

Cochran, D. J., & Riley, M. W. (1986). The effects of handle shape and size on exerted forces. *Human Factors*, *28*, 253–265.

Comaish, S., & Bottoms, E. (1971). The skin and friction: Deviations from Admanton's laws, and the effects of hydration and lubrication. *British Journal of Dermatology*, *84*, 37–43.

Das, B., & Wang, Y. (2004). Isometric pull-push strengths in workspace: 1. Strength profiles. *International Journal of Occupational Safety and Ergonomics*, *10*, 43–58.

Dempsey, D. G., & Ayoub, M. M. (1996). The influence of gender, grasp type, pinch width, and wrist position on sustained pinch strength. *International Journal of Industrial Ergonomics*, *17*, 259–273.

D'Souza, A., Smith, G., & Trifiletti, L. (2007). Ladder-related injuries treated in emergency departments in the United States, 1990–2005. *American Journal of Preventive Medicine*, *32*, 413–418.

Dvir, Z. (1997). The measurement of isokinetic finger flexion strength. *Clinical Biomechanics*, *12*, 473–481.

Edgren, C. S., Radwin, R. G., & Irwin, C. B. (2004). Grip force vectors for varying handle diameters and hand sizes. *Human Factors*, *46*, 244–251.

Fothergill, D. M., Grieve, D. W., & Pheasant, S. T. (1992). Influence of some handle designs and handle height on the strength of the horizontal pulling action. *Ergonomics*, *35*, 203–212.

Garrett, J. W. (1971). The adult human hand: Some anthropometric and biomechanical considerations. *Human Factors*, *13*, 117–131.

Holewijn, M., & Heus, R. (1992). Effects of temperature on electromyogram and muscle function. *European Journal of Applied Physiology and Occupational Physiology, 65*, 541–545.

Imrhan, S. N., & Farahmand, K. (1999). Male torque strength in simulated oil rid tasks: The effects of grease-smeared gloves and handle length, diameter and orientation. *Applied Ergonomics*, *30*, 455–462.

Kattel, B. P., Fredericks, T. K., Fernandez, J. E., & Lee, D. C. (1996). The effect of upper-extremity posture on maximum grip strength. *International Journal of Industrial Ergonomics*, *18*, 423–429.

Katz, B. (1939). The relation between force and speed in muscular contraction. *Journal of Physiology*, *96*, 45–64.

Kong, Y. K., & Freivalds, A. (2003). Evaluation of meat-hook handle shapes. *International Journal of Industrial Ergonomics*, *32*, 13–23.

Kong, Y. K., & Lowe, B. D. (2005a). Evaluation of handle design characteristics in a maximum screwdriving torque task. *Ergonomics*, *50*, 1404–1418.

Kong, Y. K., & Lowe, B. D. (2005b). Optimal cylindrical handle for grip force tasks. *International Journal of Industrial Ergonomics*, *35*, 495–507.

Kuzala, E. A., & Vargo, M. C. (1992). The relationship between elbow position and grip strength. *American Journal of Occupational Therapy*, *46*, 509–512.

Lanska, D. J. (2000). William Hammond, the dynamometer, the dynamograph. *Archives of Neurology*, *57*, 1649–1653.

Laumoreaux, L., & Hoffer, M. M. (1995). The effect of wrist deviation on grip and pinch strength. *Clinical Orthopaedics and Related Research*, *314*, 152–155.

Lehman, K. R., Allread, G. W., Wright, P. L., & Marras, W. S. (1993). Quantification of hand grip force under dynamic conditions. In *Proceedings of the Human Factors and Ergonomics Society 37th Annual Meeting* (pp. 715–719). Santa Monica, CA: Human Factors and Ergonomics Society.

Leyk, D., Rohde, U., Erley, O., Gorges, W., Wunderlich, M., Ruther, T., & Essfeld, D. (2006). Recovery of hand grip strength and hand steadiness after exhausting manual stretcher carriage. *European Journal of Applied Physiology*, *96*, 593–599.

Mathiowetz, V., Kashman, N., Volland, G., Weber, K., Dowe, M., & Rogers, S. (1985). Grip and pinch strength: Normative data for adults. *Archives of Physical Medicine and Rehabilitation*, *66*, 69–74.

McGorry, R. W., & Lin, J. H. (2007). Power grip strength as a function of tool handle orientation and location. *Ergonomics*, *50*, 1392–1403.

Mogk, J., & Keir, P. (2003). The effects of posture on forearm muscle loading during gripping. *Ergonomics*, *46*, 956–975.

Morse, J. L., Jung, M., Bashford, G. R., & Hallbeck, M. S. (2006). Maximal dynamic grip force and wrist torque: The effects of gender, exertion direction, angular velocity, and wrist angle. *Applied Ergonomics*, *37*, 737–742.

O'Driscoll, S. W., Horii, E., Ness, R., Cahalan, T. D., Richards, R. R., & An, K. N. (1992). The relationship between wrist position, grasp size, and grip strength. *Journal of Hand Surgery*, *17*, 169–177.

Pheasant, S., & O'Neill, D. (1975). Performance in gripping and turning: A study in hand/handle effectiveness. *Applied Ergonomics*, *6*, 205–208.

Rajulu, S. L., & Klute, G. K. (1993). *A comparison of hand grasp breakaway strengths and bare-handed grip strengths of the astronauts, SML III test subjects, and the subjects from the general population* (NASA Technical Paper 3286). Washington, DC: National Aeronautics and Space Administration, Office of Management, Scientific and Technical Information Program.

Seo, N. J., Armstrong, T. J., Ashton-Miller, J. A., & Chaffin, D. B. (2007). The effect of torque direction and cylindrical handle diameter on the coupling between the hand and a cylindrical handle. *Journal of Biomechanics*, *40*, 3236–3243.

Seo, N. J., Armstrong, T. J., Chaffin, D. B., & Ashton-Miller, J. A. (2008). The effect of handle friction and inward or outward torque on maximum axial push force. *Human Factors*, *50*, 227–236.

Stegink Jansen, C. W., Niebuhr, B. R., Coussirat, D. J., Hawthorne, D., Moreno, L., & Phillip, M. (2008). Hand force of men and women over 65 years of age as measured by maximum pinch and grip force. *Journal of Aging and Physical Activity*, *16*, 24–41.

Tsaousidis, N., & Freivalds, A. (1998). Effects of gloves on maximum force and the rate of force development in pinch, wrist flexion and grip. *International Journal of Industrial Ergonomics*, *21*, 353–360.

Yoxall, A., & Janson, R. (2008). Fact or fiction: A model for understanding the openability of wide mouth closures. *Packaging Technology and Science*, *21*, 137–147.

White, R. M. (1980). *Comparative anthropometry of the hand.* U.S. Army Research and Development Command, Natick, Massachusetts Technical Report NATICK/TR-81/010 (AD A101070). Retrieved October 30, 2009, from http://handle.dtic.mil/100.2/ADA101070

Justin G. Young is a PhD candidate in the Department of Industrial and Operations Engineering at the University of Michigan, Ann Arbor, where he received his MSE in industrial and operations engineering in 2008.

Charles Woolley is an ergonomics research engineer in the Center for Ergonomics at the University of Michigan, Ann Arbor, where he received his MS in bioengineering in 1980.

Thomas J. Armstrong is a professor in the Department of Industrial and Operations Engineering at the University of Michigan, Ann Arbor, where he received his PhD in ergonomics in 1976.

James A. Ashton-Miller is a research professor in the Department of Mechanical Engineering at the University of Michigan. He received his PhD in biomechanics from the University of Oslo, Norway, in 1982.

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