Biomechanics of Hand/Handhold Coupling and Factors Affecting the Capacity to Hang On

by

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To Mom and Dad

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When I came to Ann Arbor as a freshman in the fall of 2001, I had no idea that after nine and a half years, eight changes of address, acquiring three engineering degrees and a fiancé, I'd still be a student at the University of Michigan. Looking back over the winding road that brought me to this dissertation, I can honestly say that I have few regrets. I am grateful for all the friends that have shared any part of this experience with me in the city of Ann Arbor which I have grown to love.

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CHAPTER 1

Introduction

1.1 Problem & Motivation

The hand is often the interface between the human and machine environments. Coupling between the hand and grasped objects allows forces to be applied in order to do work. In many common tasks, such as pulling, lifting or climbing, the force applied to the hand/handhold couple can be very large. If the force applied to the grasped object exceeds the functional strength of the hand/object couple, the hand will slip and injury may occur. Of particular importance are situations when the hands are used to support the body, as a loss of hand/handhold coupling could result in a fall.

There are many situations where 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, semi-trucks), climbing on ladders, hanging onto moving vehicles (garbage truck personnel), using safety rails (stairways, scaffolding, bathroom grabrails) (Barnett & Poczynck, 2000; Bottoms, 1983). In many of these situations, if the individual were to slip, their weight would be transferred suddenly from the feet to the hands. According to the Bureau of Labor Statistics there we 827 fatalities from falls in the U.S. workplace in 2006, with 77 deaths associated with falls from nonmoving vehicles, 132 from ladders, and 21 associated with 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 et al., 2007).

Fixed structures in the workplace like ladders, grab rails, and grab bars are commonly employed as a means for workers to climb in, 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. The design and layout of handholds varies greatly in and out of the workplace. Handholds often have many different sizes, shapes, and surface characteristics, and are positioned in varying orientations. Despite the widespread use of fixed handholds for supporting the body, there is little knowledge of the functional capacity of persons to hang onto the various types of existing handholds. It is important to understand how hand/handhold coupling is affected by handhold design in order to provide handholds that reduce required muscular effort when supporting the body and provide the greatest ability to arrest a fall in the event the feet slip.

The hand is also the interface that allows workers to hold and use work objects. When carrying or using heavy items, such as stretchers, luggage, parts or tools, the hand must exert force to retain grasp of the object against gravity. The increased effort needed to carry heavy objects can increase the risk of fatigue, injury and work-related musculoskeletal disorders (Leyk et al., 2006; Armstrong et al., 1993). Furthermore, acute injuries may occur if slippage of the hand from the tool handle causes the hand to come into contact with a hazardous part of the work object or another work object, such as a sharp knife edge (Bobjer et al., 1993). Though much research has investigated the ability of the hand to squeeze objects, little is known about the hand's ability to resist or apply an external load to an object. Insights are needed to predict functional hand strength for tools that are supported by the hand and to provide recommendations for handle designs that reduce the risk of acute or chronic injury.

1.2 Background & Rationale

In the field of ergonomics, the term "strength" generally refers to the maximum force that can be exerted by the body to the surrounding environment in some context. For a given task or job, functional strength is used characterize generalized human capacity and then physical demands are compared to this capacity. Since the hand is usually the interface between the body and the object that force is being exerted upon, a large amount of strength research has been amassed that is directly or indirectly applicable to the characterization of forces at the hand/handhold interface. These include studies in the area of push strength, pull strength, torque strength, lifting capacity, and grip strength. Unfortunately, none of these strength metrics address specifically and directly the strength of the couple between the hand and a handhold. That is, no study in the literature could be used directly to answer the question "How much force does it take to pull a 1" cylinder from a person's grasp?", or more practically, "Can a worker hang onto a rectangular ladder rung and support their weight if their feet slip?"

To characterize the strength hand/handhold couple, it is most logical to characterize the strength of the hand. Hand strength has traditionally been quantified by measuring the maximum ability to flex the fingers against a force gauge that is supported by the palm and base of the thumb. This is commonly referred to as "grip strength". The grip dynamometer was created to measure this force and has changed little since mid-1800's (Lanksa, 2000). Several studies have found that isometric grip strength is affected by many factors, such as the posture of the arm and wrist (Dempsey & Ayoub, 1996; Hazelton et al., 1975; Kattel et al., 1996; Kuzala & Vargo, 1992; Laumoreaux & Hoffer, 1995; McGorry & Lin, 2007; O'Driscoll et al., 1992; Pryce, 1980), and varying size, diameter, or span of the gripped object (Amis, 1987; Dvir, 1997; Edgren et al., 2004; Kong & Lowe, 2005a; Lee & Rim, 1991; O'Driscoll et al., 1992).

While grip strength provides a useful scalar measure of the active flexion of the fingers, extrapolation of grip strength as an overall measure of functional hand strength is unfounded for two significant reasons:

1) Grip strength does not address any applied or external loading of the object being gripped
2) Grip strength does not address surface interactions (i.e. friction) that act between the hand and grasped object

When an object is pulled from the grasp of the hand, not only is there an active resistance from the flexion of the fingers, but also a complex interaction at the interface between the hand and the object (friction, skin deformation, etc.). Isometric grip strength alone is therefore not a good functional measure of the hand's ability to hang onto something. In order to characterize the functional capacity of the hand/handhold couple, the relationship between the strength of the hand, applied loading, and surface interactions needs to be elucidated.

Surface interactions between the hand and the grasped object have been shown to affect other functional measures of strength, such as the ability of the person to create torque on a handle. The ability for workers to create torque on a handle is related to handle surface friction and area of contact (Imrhan & Farahmand, 1999; Kong & Lowe, 2005b; Pheasant & O'Neill, 1975; Yoxall & Janson, 2008). The cross-sectional and longitudinal size and shape of a screwdriver handle also affected the total manual torque output and comfort (Kong & Lowe, 2005b; Kong et al., 2007; Kong et al., 2008). Seo et al., 2007, 2008 found that inward torque on a cylinder (toward the fingertips) increased the normal force on the fingertips and increased torque output when compared to outward torque. Because maximum torque was smaller than wrist strength, it was concluded that friction at the handle interface was the strength limiting factor. These studies show that surface interactions such as friction are important when characterizing functional hand strength, but are limited in application to other situations because no directional external load is applied to the object.

The ability to exert a pull force on an object is perhaps the most relevant strength measure in context to studying hand/handhold coupling because it includes both applied loading of an object and surface interactions between the hand and the object. There have been several studies that examine the ability of subject to push or pull on a handle in many with different configurations of the arms and upper body (Cochran & Riley, 1986; Das & Wang, 2004; Fothergill et al., 1992; Kong & Freivalds, 2003; Seo et al., 2008). However, pull strength gives an accurate characterization of functional hand strength only if the capacity to create pull force with the other body segments exceeds the strength of the hand/handhold couple, which may not be realistic for many voluntary pulling and lifting postures (Fothergill et al., 1992; Woldstad et al., 1995). That is, direct measurement of functional hand strength requires that the hand/handhold couple be isolated from the strength of the elbow, shoulder, torso, etc.

In a situation where the hand/handhold couple is loaded beyond the functional strength, the hand may begin to slip and produce friction against the object. Friction in turn causes deformation of the skin and underlying tissues and both resist the external load. Depending on the direction of the external load, the fingers may be forced open causing the flexor muscles to perform eccentric work. Isokinetic eccentric grip force has been shown to be 13-17% greater than isometric strength (Dvir, 1997). At these high loads, internal friction between the finger tendons and pulleys may become important (Schweizer, 2008).

In the literature, there are very few studies that have quantified the force required to break the hand/handhold couple. Garret et al. (1967) tested the ability of seated subjects to retain two-handed grasp of different ejection seat handles ("grip retention"). The handles were loaded impulsively with pneumatic loads of up to greater than 227 kg (2225 N). They reported the force at which subjects could not retain grasp for any period of time. Rejulu and Klute (1993) measured the force required to pull a single handle from subject's grasp ("breakaway strength") wearing an astronauts' EVA glove. The handle was attached to an instrumented pneumatic cylinder that moved the handle away from the glove which was fixed to an immovable frame. It was found that the breakaway strength was on average 1.7 times greater than isometric grip strength measured by a dynamometer. These few studies show that the strength of the coupling between the hand and object may be related to but higher than grip strength.

1.3 Research Objectives

Current hand strength data are fundamentally insufficient to predict a human's ability to hang onto something. The general aim of this research is to create knowledge that explains the strength of the coupling between the hand and a handheld object. This knowledge can be used the basis for biomechanical models that can be used to predict how much force can be exerted on the object before it slips free or is pulled from the grasp of the hand. Results from this research are intended to provide a basis for recommendations for the safer design of handles and handholds on ladders, fixed equipment, stairwells, tools, and other safety critical items that support the body or are supported by the hand.

1.3.1 Working Hypotheses

It is my hypothesis that hand/handhold coupling is comprised of two components: the ability to flex the fingers and friction between the fingers and the handhold. Flexion of the fingers by muscles in the hand and forearm is the active component, while friction and surface interactions between the hand and handhold surface is the passive component. Based on this hypothesis, measures of only the active component of coupling (i.e. isometric grip strength) should under-predict the strength of the hand/handhold couple. Handhold properties such as size, shape, orientation, and friction may affect active, passive, or both components of handhold coupling and will therefore affect the hand's ability to hold onto that handhold. Hand/handhold coupling force can be measured and the effects of handhold properties quantified. These effects can be explained biomechanically via models of active and passive components and their interactions.

1.3.2 Specific Aims

The following specific aims are proposed to test the working hypotheses and create knowledge that will achieve the general aims outlined above:

1) Develop methods to measure and quantify functional hand strength, specifically the capacity to resist loads on a grasped objects
2) Quantify the role of active and passive components in functional hand strength
3) Evaluate how handhold properties (size, shape, orientation) affect the capacity to hang on
4) Investigate how surface interactions and external loading affect distribution of forces between the hand and handhold and resulting biomechanical loads on the hand

1.4 Dissertation Organization

This dissertation is presented in six chapters. Chapter one provides an introduction to the problem, rationale and aims for this work. Chapters two through five are presented as stand-alone manuscripts which describe four experiments addressing one or more of the specific aims proposed in the introduction. Chapter six is an integration and discussion of the findings from the four previous chapters and presents overall conclusions and recommendations for future work.

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CHAPTER 2

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

2.1 Introduction

2.1.1 Motivation

Falls are major cause of injury and mortality in the working-age population. The Bureau of Labor Statistics reports 827 fatalities resulted from falls in the U.S. workplace in 2006, with 77 deaths associated with falls from nonmoving vehicles, 132 from ladders, and 21 associated with 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 et al., 2007).

2.1.2 Background

The hand is commonly used to help support the body by gripping handles and other objects in the workplace. There are many situations where 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, semi-trucks), climbing on ladders, hanging onto moving vehicles (garbage truck personnel), and using safety rails (stairways, scaffolding, bathroom grabrails) (Barnett & Poczynck, 2000; Bottoms, 1983). In many of these situations, if the individual were to slip or fall, their 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 will determine if a person will support their bodyweight or lose grip of the handhold and be injured.

The hand is also the interface that allows workers hold and use work objects such as 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 (Leyk et al., 2006; Armstrong et al., 1993). 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, 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, grabrails, 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 and Klute, 1993). This situation is different than simply squeezing an object because the hand is responding to an external force on the object that must be resisted in order 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 due to friction may cause deformation of the skin and underlying tissues and can help resist the external load. Lastly, 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-1800’s (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 et al., 1996; Kuzala & Vargo, 1992; Laumoreaux & Hoffer, 1995; McGorry & Lin, 2007; Mogk & Keir, 2003; O’Driscoll et al., 1992), movement of the wrist (Lehman et al., 1993; Morse et al., 2006), and grip span (Amis, 1987; Dvir, 1997; Edgren et al., 2004; Kong & Lowe, 2005a; O’Driscoll et al., 1992). These studies, however, only measure 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 subject (Cochran & Riley, 1986; Das & Wang, 2004; Fothergill et al., 1992; Kong & Freivalds, 2003; Seo, 2008). Since 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 where 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 over the 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 power grip, or "hand grasp breakaway strength", directly by using a mechanical device to force a handle from the subject's grasp. This 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.

2.1.3 Hypotheses and Aims

It is our hypothesis that breakaway strength is comprised of both an active component and 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 compared to isometric grip strength and bodyweight. 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 determine the relative contribution of active (finger flexion) and passive (friction) components to the magnitude of the hand/handhold coupling force.

2.2 Methods

2.2.1 Subjects

Subjects for both experiments were recruited from the University of Michigan community and were paid for their involvement. Twelve healthy young subjects (six males and six females) participated in each experiment. No subjects 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 subjects gave written informed consent prior to testing.

Exp 1. Ladder Breakaway Strength*:* Mean (± SD) age, height, and bodyweight for the twelve subjects 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 by the method of Garrett, 1971) ranged from 15-79th percentile for males and 9-81st percentile for females based on 1946 U.S. Army data (White, 1981). Eleven subjects were right-hand dominant while one was left-hand dominant. Dominant-hand grip strength ranged from 26-78th percentile for males and 19-73rd percentile for females based on grip strength data for persons aged 20-25 years (Mathiowetz et al., 1985). Dominant hand grip strength was on average 38 N greater than non-dominant hand grip strength for all subjects.

Exp 2. Effect of Friction on Breakaway Strength*:* Mean (± SD) age, height, and bodyweight for the twelve subjects 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 by the method of Garret, 1971) ranged from 7-76th percentile for males and 24-93rd percentile for females based on 1946 U.S. Army data (White, 1981). All subjects were right-hand dominant. Dominant-hand grip strengths ranged from 3-71st percentile for males and 68-98th percentile for females based on grip strength data for persons aged 20-25 years (Mathiowetz et al., 1985).

2.2.2 Breakaway Strength Measurement and Apparatus

In order 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 subject already holding onto a fixed overhead handle, an increasing vertical force is created by bodyweight and acts on the hand/handle couple passively through the shoulder 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 and DeLuca, 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 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 subject'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 subject. An instrumented handle was fixed overhead above the platform (Figure 2.2.1a). A weightlifter's dipping belt was used to secure the subject to the platform so that subjects 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 subject and platform constant at 127 kg (1245 N). This ensured that the initial lowering speed of the lift was a constant 14 cm/sec across all subjects and that full strength capability would be reached (Figure 2.2.1b). A six-axis load cell (AMTI® MC-3), amplifier, 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.

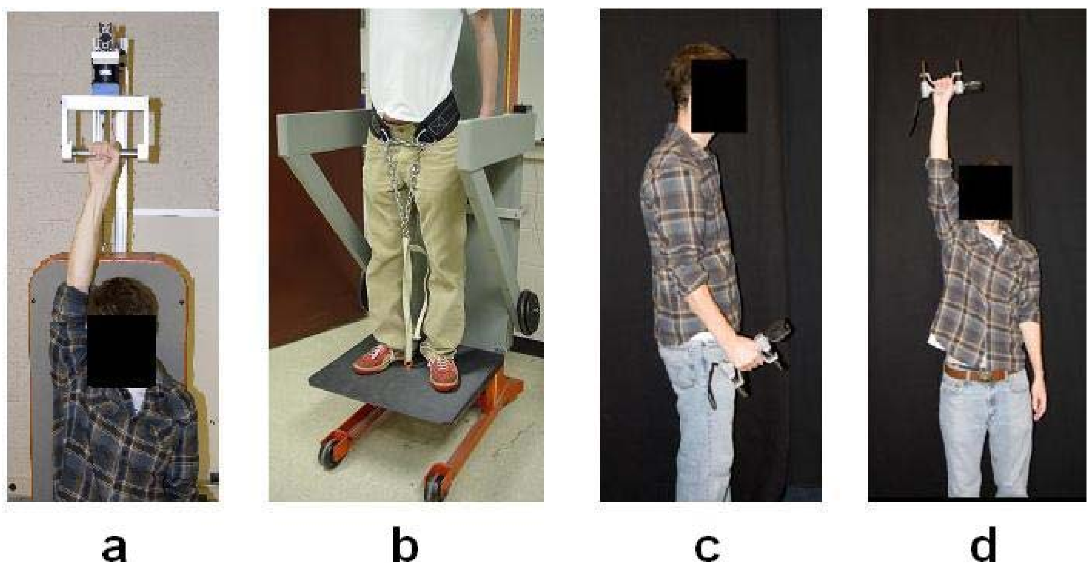

Figure 2.2.1 Experimental setup. (a) Subjects stand on a platform and are lowered while grasping an instrumented, fixed-overhead handle. (b) Subjects are secured to the weighted platform by a weightlifter's dipping belt so they cannot lift themselves off of the platform and always move up or down with it. (c) Subject position for isometric grip strength measurements (Experiment 1 and 2). (d) Subject position for additional isometric grip strength measurement (Experiment 2 only).

2.2.3 Procedure and Design

For each breakaway strength trial, subjects stood on the adjustable platform and were secured using the dipping belt. The subject was then raised until they could firmly grasp the overhead handle in a power grip with a slight bend the elbow. The bend in the elbow ensured that the subject was not impulsively loaded at their extreme reach and that their muscles had time to pre-load before full extension and breakaway was achieved.

Subjects were instructed to exert their maximum strength capability and "to hold onto the handle as long as possible". Subjects 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 2-4 seconds. Isometric grip strength trials were performed (while off of the platform) by asking subjects to squeeze the dynamometer "as hard as possible" for five seconds. Verbal encouragement was provided by researchers during grip strength measurements.

To eliminate effects due to surface contaminants, subjects washed their hands with soap, rinsed with water, and dried with paper towels 10 minutes prior to testing (Buchholz et al., 1988; Comaish & Bottoms, 1971). Subjects also wiped their hands with a clean, dry paper towel before each trial to reduce any effects from perspiration over the course of an experimental session. The stainless steel handles were cleaned with steel wool between subjects.

For both experiments there were three repetitions for each strength measurement. The order of the trials was randomized. A break of at least two minutes was given between successive trials. Statistical analyses were performed using MINITAB® software and a p-value less than 0.05 was considered significant.

<u>Exp 1. Ladder Breakaway Strength</u>*:* Breakaway strength was measured for three different steel handles typically found on fixed industrial ladders. Two vertically-oriented handles simulated typical ladder rails: a 25mm diameter cylinder (Figure 2.2.2b) and a 64mm x 10mm plate (Figure 2.2.2c). The third handle was a 25mm diameter horizontally-oriented cylinder that simulated a typical ladder rung (Figure 2.2.2a). The arm was oriented overhead with the elbow fully extended and the hand pronated for the horizontal cylinder and mid-way between prone and supine for both vertical handles during breakaway strength measurements. A Jamar grip dynamometer (position 2, 45mm) was used to measure the subject's maximum volitional power grip strength (Figure 2.2.2d). Grip strength was measured for both hands with the subject's elbow slightly bent at the subject's side and with the hand mid-way between prone and supine (Figure 2.2.1c).

Maximal strength for each of the three handles was tested for the dominant hand. The horizontal cylinder was also tested for the non-dominant hand. Grip strength was measured for both hands. See Table 2.2.1 for a summary of the independent and dependent variables and the applied treatments in Experiment 1.

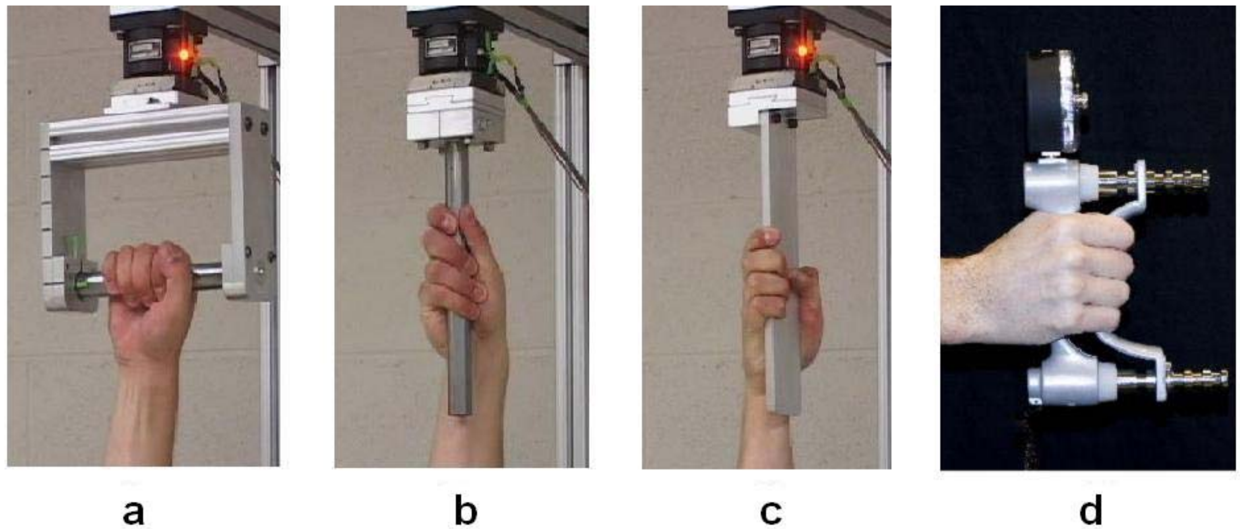

Figure 2.2.2 Handholds tested. (a) 25mm diameter horizontal cylinder (Experiment 1 and 2) (b) 25mm vertical cylinder (Experiment 1 only) (c) 64mm x 10mm vertical plate (Experiment 1 only) (d) Jamar grip dynamometer in position 2 (Experiment 1 and 2).

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 (the three ladder handles and the Jamar) and gender (male and female) with subject as a random effect. Post-hoc Tukey tests were then performed on significant main effects to compare breakaway strength between the three handholds and 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 bodyweight, was different for each of the three handholds. Similar analyses were also performed for breakaway strength for the horizontal handle between dominant and non-dominant hands, and grip strength between dominant and non-dominant hands.

Exp 2. Effect of Friction on Breakaway Strength: Breakaway strength was measured for a high- and “low-friction” handle. Each handle was the same 25mm 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 that allowed the handle to spin unconstrained about the long axis of the cylinder.

When grasping a fixed handle, as the body and arm is pulled down, the fingers that are wrapped around the cylindrical handle exert a shear frictional force on the surface. These forces cause a torque about 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 sliding over the surface of a handle with zero friction (Figure 2.2.3). The "low-friction" handle here is simulated, but biomechanically is similar to a very slippery fixed handle. Thus the high-friction handle in this experiment is constrained about the long axis, while the low-friction handle is unconstrained about 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.

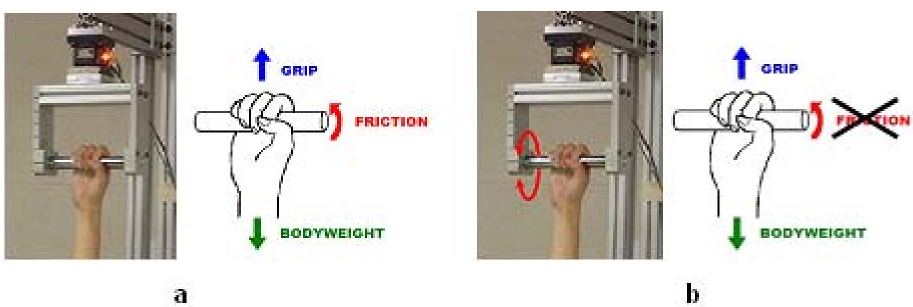

Figure 2.2.3 Breakaway handholds tested in Experiment 2. (a) Fixed 25mm horizontal cylinder. Friction resists the slipping of the hand. (b0 Unconstrained 25mm horizontal cylinder. The cylinder can rotate about the long axis, nullifying the effect of friction that would resist slipping of the hand.

As in Experiment 1, a Jamar grip dynamometer was used to measure the subject's grip strength. However, two grip strength measurements were performed in this experiment: the first was measured with the subject's elbow slightly bent at the subject's side and with the hand mid-way between prone and supine (as in Experiment 1; Figure 2.2.1c), 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 2.2.1d).

A total of twelve maximum strength trials were performed: six maximum voluntary grip strength tests and six breakaway strength tests. Each of the two handles was tested for the dominant hand. Grip strength was measured the dominant hand in two positions. See Table 2.2.1 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 subject 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 and isometric grip strength measured at the two arm positions. As a separate analysis, two-way, repeated measures analysis of variance was used to determine if breakaway strength, normalized by grip strength or bodyweight, was different for each of the three handholds and if results for the fixed handle were different between Experiments 1 and 2.

Table 2.2.1 Experimental design summary for Experiments 1 and 2.

	Exp 1: Ladder Breakaway Strength	Exp 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 (non-dominant hand)	Gender (2): male, female Handle (2): horizontal cylinder, Jamar	------
Dependent Variables	Peak force	Peak force
Total Exertions per Subject	Dominant Hand: 4 handles x 3 reps = 12 Non-dominant Hand: 2 handles x 3 reps = 6	Dominant Hand: 4 handles x 3 reps = 12

2.3 Results

2.3.1 Exp 1. Ladder Breakaway Strength

Mean (±SD) peak forces measured for the dominant-hand for each handle are presented in Table 2.3.1, 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. Males were stronger than females for all handles. Post-hoc analysis indicates breakaway strength observed for the 25mm horizontal cylinder was greater than for the 25mm vertical cylinder ($p <.001$), which in turn was greater than for the 64mm x 10mm vertical plate ($p< .001$). Breakaway force for the 25mm vertical cylinder was not significantly different than isometric grip strength measured with a grip dynamometer ($p >.05$).

Table 2.3.1 Peak breakaway strength and grip strength (mean ± SD), by handle and gender, for typical ladder handholds (Exp 1).

Handle	Peak Force (N)		Peak Force / Bodyweight		Peak Force / Grip Strength	
	Males	Females	Males	Females	Males	Females
25mm horizontal cylinder	842 ± 207	494 ± 93	1.17 ± 0.13	0.94 ± 0.18	1.52 ± 0.26	1.53 ± 0.20
25mm vertical cylinder	516 ± 120	354 ± 46	0.72 ± 0.10	0.68 ± 0.12	0.93 ± 0.15	1.10 ± 0.13
64mm x 10mm 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

In fall situations, it is useful to normalize breakaway strength with respect to the bodyweight of the individual as this provides an indicator of the subject's ability to hang on with one hand. Peak force normalized by bodyweight differences were significant for the main effect of handle grasped ($F(2,92) = 284.75$, $p < 0.001$) 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 the vertical handles. Breakaway strength normalized by bodyweight was greater than 1 for only the fixed horizontal cylinder.

Peak breakaway strengths normalized by grip strength were similarly significant for the main 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 the horizontal cylinder. Breakaway strength on the horizontal handle exceeded grip strength by 52% when all subjects 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 for the non-dominant 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 non-dominant hands.

2.3.2 Exp 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 2.3.2, 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 breakaway strength was greater for the high-friction handhold than 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), though overhead grip strength was consistently slightly greater than when measured at the side.

Table 2.3.2 Peak breakaway strength and grip strength (mean ± SD) by handle and gender, for high- and low-friction handholds (Exp 2).

Handle	Peak Force (N)		Peak Force / Bodyweight		Peak Force / Grip Strength	
	Males	Females	Males	Females	Males	Females
25mm horizontal cylinder	766 ± 121	617 ± 97	1.07 ± 0.18	0.93 ± 0.14	1.61 ± 0.25	1.55 ± 0.25
25mm 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

Peak breakaway force normalized by bodyweight differences were significantly greater for the high- than 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 bodyweight was greater than 1 for only the fixed horizontal cylinder.

As when normalized by bodyweight, peak breakaway strength normalized by grip strength was similarly greater for the high- than 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 strength for the high-friction and low-friction handhold exceeded grip strength by and average of 58% and 26% respectively for all subjects pooled. These ratios were slightly higher for males than for females.

The 25mm horizontal cylinder (high-friction) was exactly the same handhold used for both experiments. Breakaway strength for this handhold was not significantly different ($F(1,48) = 0.09$, $p > 0.05$) between Experiments 1 and 2.

2.4 Discussion and Conclusions

Experiment 1 showed that breakaway strength (i.e., the force required to pull a handle from power grip) for a 25mm diameter cylindrical steel handhold orientated horizontally (i.e., perpendicular to the external force) was, on average, 54% greater than for the same 25mm diameter cylindrical steel handle orientated vertically (i.e., parallel to the external force). Additionally, breakaway strength for a 25mm diameter cylindrical steel handhold was 29% greater than for a 64mm x 10mm 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 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 2.4.1a). 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 for 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 only acts to influence friction. There is no direct mechanical resistance against the external force from the finger flexors in this orientation (see Figure 2.4.1b).

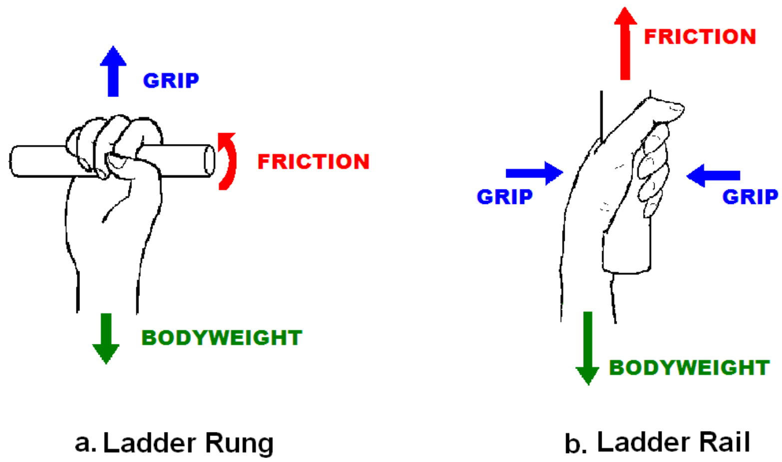

Figure 2.4.1 Forces when holding onto a typical ladder rung or rail. (a) When holding a rung, active gripping forces act to resist the opening of the fingers and passive friction forces act to resist the hand from sliding open over the curved surface and off the rung. Both active and passive forces resist bodyweight. (b) When holding a rail, active gripping forces squeeze the rail and create normal forces which increase passive friction forces that act to resist the hand from sliding down the rail. Only passive forces resist bodyweight.

Data from Experiment 2 further support the hypothesis that breakaway strength is comprised of 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 139N 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. The above results demonstrate that these devices significantly under-predict the ability of subjects 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. Functional hand strength measurements for situations where 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, 2005b; Pheasant & O'Neill, 1975; Seo et al., 2007; Yoxtall & Janson, 2008; Seo et al., 2008). Our data show that the shape of the handhold in this situation affects the total frictional force. This may be due to the amount of surface contact the hand has on the handle, or 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, subjects noted that the 64mm x 10mm 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 subjects grasping a handle perpendicular to the forearm while wearing gloves. Those gloves may have increased friction between the hand and handle or have stiffened the fingers.

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

When compared to overhead pull strength, breakaway strength for the horizontal rung more than doubles the force that subjects could exert by active pulling, as reported by Das and Wang (2004). This 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 highlights the importance of loading the hand without having the subject provide the external force, as they 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 subject bodyweight insights can be obtained on the relative ability of a worker to hold onto a handhold in the case of a fall. The fixed 25mm horizontal cylinder ("rung") afforded the greatest breakaway strength between the hand and handle (1.05 and 1.00 times bodyweight on average for Experiment 1 and 2 respectively), followed by the "low-friction" horizontal rung (0.81 times bodyweight). The two vertical handholds, typical of ladder rails, afforded much less breakaway strength (0.70 and 0.53 time bodyweight for the 25mm cylinder and the 64mm x 10mm plate, respectively).

These results show that relatively strong or relatively light subjects can support their full bodyweight with one hand on a 25mm fixed steel rung, as long as there is sufficient friction. Few people can support their full body weight with one hand using either a 25mm diameter rod or a 64mm x 10mm plate type rail. When climbing, two hands may be available to support the body in a fall. Males had higher breakaway strength-to-bodyweight ratios than females in both experiments. Females, therefore, may be at higher risk in climbing situations than males. Male breakaway strength-to-grip strength ratios are not always higher than for 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 due to wrist ulnar deviation may have accounted for some of the decrease in breakaway strength measured for vertical as compared to horizontal handholds.

Though each handle was made of the same material, the coefficient of friction between the hand and the handle may have varied between each subject. 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 over the course of data collection. Additionally, maximal effort may be different between subjects, with some subjects "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 centimeters per second. 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. if 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, though 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 bodyweight increases, the ability to hang onto handholds in fall situations will be reduced. Further research should include subjects 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 (like a thin rectangular plate) are less desirable for gripping in a fall. However, this study only examined 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/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, OSHA 29 CFR 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 as cylindrical rails. Further research can provide specific shape and surface guidelines for handholds in applicable safety standards.

2.5 Acknowledgements

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CHAPTER 3

Effect of handhold cross-sectional shape on hand/handhold breakaway strength

3.1 Introduction

The hands are used to support the body in many workplace situations such as when climbing on fixed ladders or into elevated vehicle cabins. Climbing on vertical or near vertical structures can cause the center of body mass to be outside the plane of the foot support and the structure so that one or both of the hands must continuously exert force to prevent the body from falling away from the structure (Armstrong et al. 2009). At the same time, a loss of footing will suddenly transfer the weight of the body from the feet to the hands. In this type of fall scenario, the functional strength of the hand on the specific handhold being grasped will determine if falling workers can save themselves. It is the general aim of this research to assess hand/handhold breakaway strength and to understand how handhold properties will affect the ability to hold on.

Structures, handholds or surfaces used for climbing or supporting the body occur in a variety of designs and implementations. Though they may be specifically designed to support the worker, they are often more for the feet rather than for the hands. In many cases, the edge of a structure or work surface may be improvised as a handhold. As a result, objects used to support the body may be poorly suited for the hand. This is mirrored in current safety regulations that are mainly based on structural considerations and not on worker ability. Generally, applicable regulations and standards require that handholds be not less than 0.75 inches diameter; be free from sharp edges, splinters or burrs; and permit full grasp or power grip by the hand (fixed ladders: OSHA 29 CFR 1910.27, ANSI-ASC A14.3-2008; vehicles: FMCSA-DOT 49 CFR 399.207, SAE J185, SAE J2703). Therefore, handholds of common stock metal shapes (cylindrical rod, square rod and rectangular plate), in various sizes, are frequently employed and equally accepted in the workplace.

Despite the range of handhold shapes that are used in the workplace, the ability of people to exert a force or hold onto differently shaped objects has received relatively little attention. There have been some studies of handle shape and the ability to exert torque or pull on a work object (i.e. screwdrivers, meat-hook handles) -- often with conflicting recommendations (Cochran and Riley, 1986; Drury, Faggiono, and Stuempfle, 2004; Fothergill, Grieve and Pheasant, 1992; Kong et al. 2007; Kong and Freivalds, 2003; Mital and Channaveeraiah, 1988; Pheasant and O'neill, 1975; Shi and Wang, 1996). In conditions where friction was reduced by applying oil or slippery film, triangular handles and handles with corners afforded more capability (Shi and Wang, 1996; Cochran and Riley, 1986). Shapes with corners may provide a mechanical interference to the hand slipping but they also may produce local areas of high stress (both compression and shear), which could be uncomfortable and decrease overall force output (Pheasant and O'neill, 1975; Fothergill, Grieve and Pheasant, 1992; Shi and Wang, 1996). In situations where adequate friction is present, increasing surface contact and spreading the load over a cylindrical surface may be advantageous (Pheasant and O'neill, 1975; Kong and Freivalds, 2003; Kong et al. 2007).

While the above studies may provide useful insight for tool handle design, the forces applied to the hand/handhold couple when producing torque or pull is much less than what may be experienced in a fall. In a fall, the strength of the hand/handhold couple is isolated from the strength of other parts of the body and subjected to a large external load which may force the fingers open. The amount of force needed to pull a grasped handhold out of the hand ("breakaway strength") has been investigated directly by only a few studies, and has been shown to be significantly greater than grip strength (Rejulu and Klute, 1993; Young et al., 2009). Young et al. (2009) measured overhead breakaway strength for simulated falls and found that vertical cylinders provided much greater capability than vertical rectangular handholds. While it was shown that shape is a significant factor in the ability to hold on, the study did not compare shape for horizontal handholds. The specific aims of this research are to measure breakaway strength for horizontal handholds of different cross-sectional shape that are common in the workplace and to provide data that can be used to recommend safer designs for climbing handholds.

3.2 Methods

3.2.1 Participants

Twelve healthy, young participants (six males and six females) were recruited from the university community to participate in the experiment. Subjects did not report current or previous injuries or surgeries that would affect performance of study tasks. Subjects of different stature and gender were chosen in order to include a range of hand lengths and strengths. Subject profiles are presenting in Table 3.2.1. The experimental setup and protocol was approved by the University of Michigan Institutional Review Board and subjects gave written informed consent prior to testing. All subjects were right-hand dominant.

Table 3.2.1 Subject Characteristics

Gender	Height (cm)	Weight (kg)	Age (years)	Hand Length (mm)	Hand Breadth (mm)	Palm Length (mm)
M	178	88	22	188	90	108
F	170	56	23	184	77	100
M	166	68	22	176	82	105
M	185	75	21	197	85	113
M	196	88	20	216	90	125
F	165	64	23	171	70	98
F	161	60	26	162	70	99
F	165	59	19	179	73	100
M	185	103	20	203	94	115
F	160	58	21	168	76	100
M	163	68	30	170	82	96
F	163	78	23	173	76	91
Males	179±13	82±14	23±4	192±17	87±5	110±10
Females	164±4	63±8	23±2	173±8	74±3	98±4
All	171±12	72±15	23±3	182±16	80±8	104±10

3.2.2 Handholds

Four common stock metal shapes that are used in workplace fixed ladder installations were chosen for testing. Handle cross-sections were: circular, square in two orientations (“square” and “diamond”), and rectangular (Figure 3.2.1). The handholds were tested in the horizontal orientation, like ladder rungs. All handles were aluminum and had smooth surfaces.

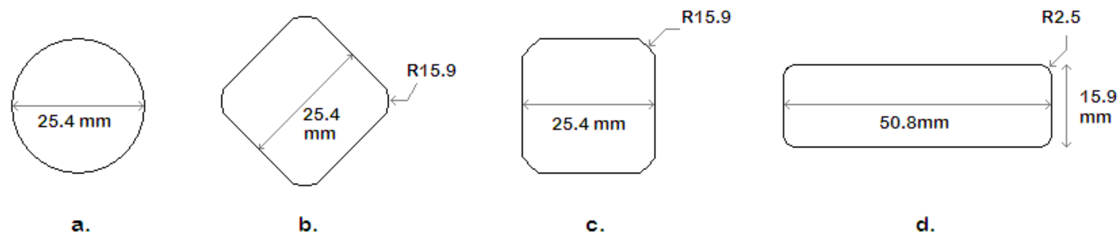

Figure 3.2.1 Handle cross-sections. (a) "cylinder": circle of diameter 25.4mm (b) "diamond": 25.4mm square rotated 45° (c) "square": 25.4mm square (d) "rectangle": 50.8x15.9 mm rectangle. R=corner radius of curvature in mm.

3.2.3 Protocol and Design

To achieve the stated aims, breakaway strengths were determined for the four differently shaped handles. The protocol and equipment for this study are very similar to those described in Young et al. (2009), so they will be describe here briefly. Breakaway strength was measured by having subjects perform a low-speed simulated fall while attempting to hold onto overhead handholds. Subjects stood on a platform and held onto an instrumented handle mounted overhead with one hand. 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. The platform was then lowered slowly while the subject held onto the handle as long as they could until the subject let go or the handle slipped from their grasp. The maximum applied vertical force was considered the breakaway strength for that specific-shaped handle.

The experimental apparatus was updated with the following changes: subjects wore a fall harness (which did not restrict overhead reach) as a precaution; the six-axis load cell and amplifier was updated (ATI® Theta); the handle attachment structure mounted to the load cell was modified to allow for different shaped handles to easily be interchanged.

Breakaway strength was tested only for the subject's dominant hand. Subjects were instructed to grasp the shaped handholds so that the metacarpophalangeal joint ("MCP" joint) of their fingers were placed either on the top corner of the diamond, or on the closest top corner to the palm for the square or rectangular handles (Figure 3.2.2). Subjects were asked not to fold their thumb over the distal fingertips when grasping.

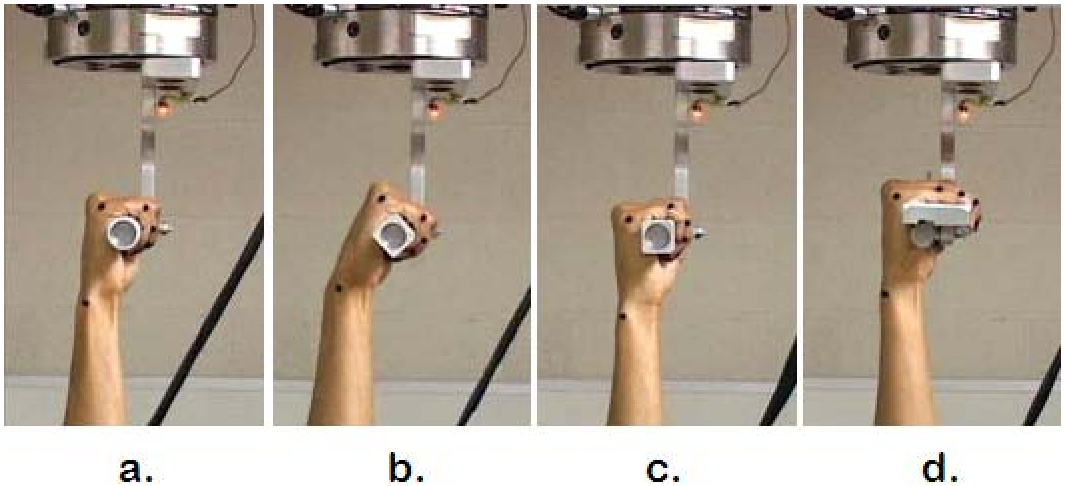

Figure 3.2.2 Initial subject hand posture when performing breakaway strength measurements. Small markers indicate finger joints. For the cylinder, no starting hand position was specified. For other shapes, subjects placed the palmar skin crease of the finger MCP joint on the top corner of the (b) diamond or closest corner of the (c) square or (d) rectangle. As loading increases the skin can translate slightly with respect to the underlying bones.

In addition to breakaway strength measured for each handle, grip strength was measured for both hands with a Jamar-type grip dynamometer (position 2, 45mm). For both breakaway and grip strength measurements the arm was oriented overhead with the elbow fully extended and the hand pronated. There were three repetitions for each strength measurement, yielding twelve breakaway strength and three grip strength trials per subject for the dominant hand. Trial order was randomized and at least two minutes rest was provided between trials. Subjects washed and dried their hands and the handles were cleaned prior to the start of each session. Subjects also wiped their hands with a clean, dry paper towel before each trial to control for perspiration during a session. Subjects were bare-handed during all trials.

3.2.4 Data Analysis

Two-way repeated measures analysis of variance was performed to determine whether the peak applied force was significantly affected by the fixed effects of handle (4 shapes, grip strength) and gender (male and female) and their interaction. Subject was treated as a random effect nested in gender. A *p* value of less than 0.05 was considered significant. Post-hoc pairwise Tukeys comparisons were then performed on significant main effects. A similar statistical analysis was performed for breakaway strengths normalized by subject body weight. A two-way analysis of variance was used to compare grip strength between right and left hands for males and females. Statistical analysis was performed with Minitab® software (State College, PA, USA).

3.3 Results

Mean (±SD) peak forces and normalized forces measured for the different handholds are presented by gender in Table 3.3.1. Peak breakaway force differences were significant for main effects handle shape ($F(4,160) = 49.52$, $p < .001$) and gender ($F(1,160) = 32.10$, $p < .001$). There was a significant interaction between handle shape and gender ($F(4,160) = 3.61$, $p < .01$): males could resist a greater force on the diamond shaped handle compared to the square, whereas females could resist near equal force on the diamond and square handles. For normalized force (by subject bodyweight), the main effect handle shape was significant ($F(4,160) = 47.52$, $p < .001$), and though the effect of gender was conspicuous, it failed to reach statistical significance ($F(1,160) = 4.90$, $p = .051$). There was not a significant interaction between handle shape and gender ($F(4,160) = 2.07$, $p < .087$).

Table 3.3.1 Peak breakaway strength and grip strength (mean ± SD), by handle and gender, dominant hand

	Breakaway Force (N)			Breakaway Force / Bodyweight		
Handle	Males	Females	All	Males	Females	All
Cylinder ●	835 ± 193	502 ± 106	669 ± 228	1.07 ± 0.33	0.83 ± 0.21	0.94 ± 0.30
Diamond ◆	747 ± 153	381± 72	564 ± 220	0.96 ± 0.28	0.62 ± 0.11	0.79 ± 0.27
Square ■	648 ± 126	383 ± 130	515 ± 184	0.83 ± 0.21	0.63 ± 0.25	0.73 ± 0.20
Rectangle ▬	584 ± 119	325 ± 80	455 ±165	0.75 ± 0.21	0.54 ± 0.15	0.64 ± 0.21
Grip dynamometer (Jamar 45mm)	546 ± 44	301 ± 51	423 ±133	0.70 ± 0.15	0.50 ± 0.11	0.60 ± 0.19

Post-hoc analysis indicates that breakaway force for the cylindrical handle was significantly greater than all other handles and grip strength ($p <.01$). The next highest force could be exerted on the diamond and squared handles, which were significantly greater than for the rectangular handhold or grip strength on the Jamar ($p <.02$), but diamond and square handles were not significantly different ($p =.10$). The least breakaway force could be exerted on the rectangular handle, which was not significantly different than grip strength ($p =.49$). Overall, males could exert larger forces than females for all treatments.

Post-hoc analysis for normalized breakaway force yield the same results as absolute breakaway force. The cylindrical handle was significantly greater than all other handles and grip strength ($p <.01$). Normalized forces for diamond and squared handles were significantly greater than for the rectangular handhold or normalized grip strength ($p <.01$), but diamond and square handles were not significantly different ($p =.21$). The least normalized breakaway force could be exerted on the rectangular handle, which was not significantly different than normalized grip strength ($p =.52$). Overall, males had greater normalized strength than females for all treatments.

Grip strength measured with the grip dynamometer was significantly greater for the dominant hand than for the non-dominant hand ($p<.01$). Grip strength for the dominant hand was 37 N (7%) greater than for the non-dominant hand on average for males and 18 N (6%) greater on average for females.

3.4 Discussion and Conclusions

The results show that the shape of a handhold affects the ability to hold onto that handhold in similar conditions that would be experienced in a fall. Subjects could exert 1.47, 1.30, and 1.19 times the amount of force on cylindrical handles than on rectangular, square, or diamond shaped handles of similar size, respectively. This implies that cylindrical handle designs are easier to hold than handles that have corners (square, diamond, rectangle, etc.). This confirms similar results for cylindrical and rectangular handholds vertically oriented (Young et al, 2009).

These findings disagree with voluntary pull strength studies that found triangular shaped handles to be advantageous (Cochran & Riley, 1986; Drury, Faggiono, and

Stuempfle, 2004). Triangular handles are functional similar to diamond shaped handles in our tested orientation. This discrepancy may be due to the lesser force experienced during voluntary pull exertions than during breakaway exertions. Under high loads, shapes with corners will produce areas of high pressure and the effect of pain may become unbearable. In this study, subjects could let go of the handle at any point, and pain may have caused subjects to relinquish grasp at a lower force on different shapes. The rectangular handle had the sharpest corners (smallest radius of curvature) and corresponded to the least ability.

Friction between the fingers and the handle surface will also play a role in which handle design is advantageous. Cochran & Riley (1986) measured pull strength under very low friction conditions (a slippery film was applied to the handles) whereas this study was performed under normal (dry skin on aluminum) conditions. In low friction conditions, handles with corners may provide mechanical barriers to the hand slipping over the surface. With friction present, corners may isolate contact and shear forces, whereas a cylindrical surface will increase contact area and permit normal and shear forces to distribute more evenly over the contact surface. This may allow the skin and palmar tissues to increase capability significantly in a manner similar to a belt over a pulley.

Breakaway strength measured for each shaped handle is greater than grip strength measured on a dynamometer. Because grip strength does not account for resultant applied or shear forces, breakaway strength is a more useful strength metric for the analysis and design of hand-work tasks with very high loading. Breakaway strength for the 25mm cylindrical handle in this experiment (669N) is similar to values for breakaway strength on a fixed 25mm cylindrical handles (668-692N) reported in Young et al (2009), showing good repeatability of the strength metric.

Normalizing breakaway strength by the body weight of the subject provides important insight to climbing and ingress/egress tasks or where a fall from elevation can occur. In these situations, the body weight of the falling individual is the force that needs to be resisted by the hands to arrest the fall. For the handhold shapes tested in this study, the majority of male subjects can support their bodyweight with one hand only for the cylindrical handle. Strong or light male subjects can support their body weight for the diamond cross section handle with one hand. Female subjects could not support their own body weight with one hand for any handles, except for exceptionally strong or light females holding the cylindrical handle. It is unlikely that any person can support their body weight with one hand when holding the rectangular shaped handle in the situations tested here. However, bodyweight can be supported, at least briefly, for any of the tested handle shapes assuming both hands are holding the handhold.

Results presented here may actually overestimate the capability of the working population to support their bodyweight in a fall, as subjects in this study were lighter than the average US population (Ogden et al, 2004). Male subjects were 49.6 N lighter and female subjects were 116.3 N lighter than population norms, on average. Furthermore, the hand-handhold coupling in a fall would be subjected to the inertia of the falling worker, requiring higher strength to hold on. In this study breakaway strength was measured only for the dominant hand. Breakaway strength may be lower for the non-dominant hand (as indicated by grip strength).

At the same time, result presented here may underestimate the capability of the working population as the subjects tested were students by occupation. Depending on the profession, workers and laborers may have greater upper limb strength than students. These results present data for maximum voluntary exertions in a safe lab environment. In a true falling situation, motivation to hang onto the handle would likely be increased.

These results show that handhold shape has a significant influence on the ability to support one's own bodyweight in a fall.   Previous studies show that climbers tend to naturally move the foot and hand together during climbing. This leads to several occurrences when there is only one hand touching the structure at a time (Hammer & Schmalz 1992; Armstrong et al, 2009). If the feet slip at this point, then the handhold being grasped should be able to allow the worker to prevent a fall with one hand. Though every theoretical cross-sectional shape could not be tested, results indicate that cylindrical or handles without corners allow people to resist the greatest force with the hand.   The only shape in which most subjects can hold their own body weight with one hand was the cylinder. This has significant design implications for handholds, rails, and rungs that are to be grasped by the hands. Workplace safety regulations and standards should be updated to reflect this knowledge. More research should be conducted to test worker ability to hold onto handholds in orientations other than horizontal and vertical, of different size or diameter, and under differing surface conditions.

3.5 Acknowledgements

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CHAPTER 4

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

4.1 Motivation

Coupling between the hand and handholds is important for many tasks, such as pulling, lifting or climbing. Of particular importance are situations when 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 like ladders, grab rails, and grab bars are commonly employed as a means for workers to climb in, 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 will extend previous knowledge about hand/handhold coupling and allow for development of biomechanical models that can be applied to the broad range of existing handholds. Results can be used to establish design criteria and safety standards for handles and handholds on ladders, fixed equipment, stairwells, tools, and other safety critical items.

4.2 Background & Hypotheses

Hand/handhold coupling is comprised of active components from finger flexion and passive components from friction between the grasped object and the hand (Woldstad et al., 1995; Young et al., 2009). Friction between the handle and hand has been shown to increase the amount of force needed to pull an overhead handhold from the grasp of the hand ("breakaway strength") by 26% compared to a simulated zero-friction condition (Young et al., 2009). This means that breakaway strength and maximum isometric grip strength ("grip strength") are related, but neither alone is directly predictive of the other (Rejulu & 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 generally agree that grip strength is minimal at very small or very large sizes or finger spans and a maximal value lies somewhere in between. Maximum grip strength occurs at cylinder diameters of approximately 31-38 mm (Amis, 1987; Lee & Rim, 1991; Edgren et al., 2004) or at position 2 or 3 (48-60 mm) on a Jamar-type dynamometer or similar device (Blackwell et al., 1999; Dvir, 1997; Harkonen et al., 1993; Lee et al., 2009). However, the optimal cylinder diameter may be different for breakaway strength because the fingers flex the grasped handle against the external load rather than 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). For horizontally oriented handholds, the fingers must be forced open and slide over the handhold surface in order to break the couple (active + passive forces directly resist breakaway). For vertical handholds, the fingers are not forced open and only friction between the hand and handhold resists the downward pull of bodyweight (only passive forces directly resist breakaway). These two situations exhibit two different ways that the hand/handhold couple may be broken: by forcing the fingers open or by sliding off the end of a handhold without opening the fingers. At what angle obliquely-oriented handholds between horizontal and vertical transition from one type of breakaway to the other is unknown, but it 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 4.2.1, where 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 bodyweight in order to keep the block in from moving. By simple calculation, static equilibrium can only be maintained for a given μ if the handhold angle is greater than cotangent-1(μ). This is independent of the weight of the block.

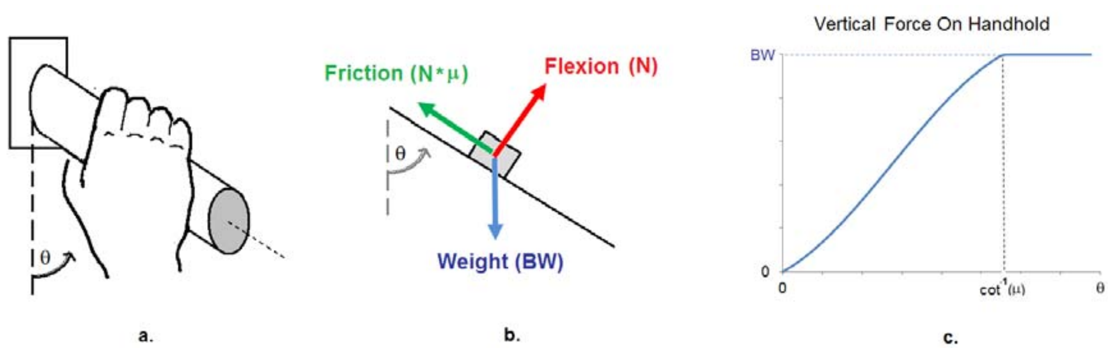

Figure 4.2.1 (a) Simple model of a breakaway strength for a hand holding onto a fixed handhold resisting a vertical load. (b) The hand is modeled as a block of weight BW on a ramp with coefficient of friction μ. Normal force can be thought of as flexion of the fingers and has a corresponding orthogonal friction force. (c) Plot of vertical calculated force applied to the handhold by the block vs. handhold angle. The angle at which the block will slide is independent of the weight of the block and is related to μ.

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

Based on the this background, the specific aims of this experiment were to test the hypotheses that breakaway strength for overhead handholds (1) would be reduced as handhold orientation changes from horizontal to vertical, (2) increased for handhold sizes that correspond to maximal grip strength, and (3) 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 will be discussed.

4.3 Methods

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 subjects, while the second experiment tested the effects of handhold orientation and glove use for only the non-dominant hand of the subjects. The breakaway strength measurement apparatus and test procedures are similar to those described in Young et al. (2009), so they will be described briefly here with any differences noted.

Breakaway strength was measured as the maximum force subject's could exert on overhead handholds during a simulated vertical fall. Subjects stood on a platform and held onto an instrumented handle mounted overhead with one hand. The platform was then lowered slowly while the subject held onto the cylindrical handle as long as they could until either the subject let go or the handle slipped from their grasp. The maximum applied vertical force was considered the breakaway strength for that specific handle.

The subject wore a fall harness attached to a fall arrestor for additional safety; this did not interfere with the subject's range of motion. A custom made handle attachment structure was mounted to the load cell (ATI® Theta) that allowed for different cylindrical handles of different diameter to be easily interchanged and oriented at increments of 15° between horizontal and vertical (Figure 4.3.1). When grasping the handle in any orientation, the subject's forearm was pronated. This resulted in an ulnar deviation of the wrist when the handle was at an angle other than horizontal (90°). A video camera recorded hand motion during all breakaway trials.

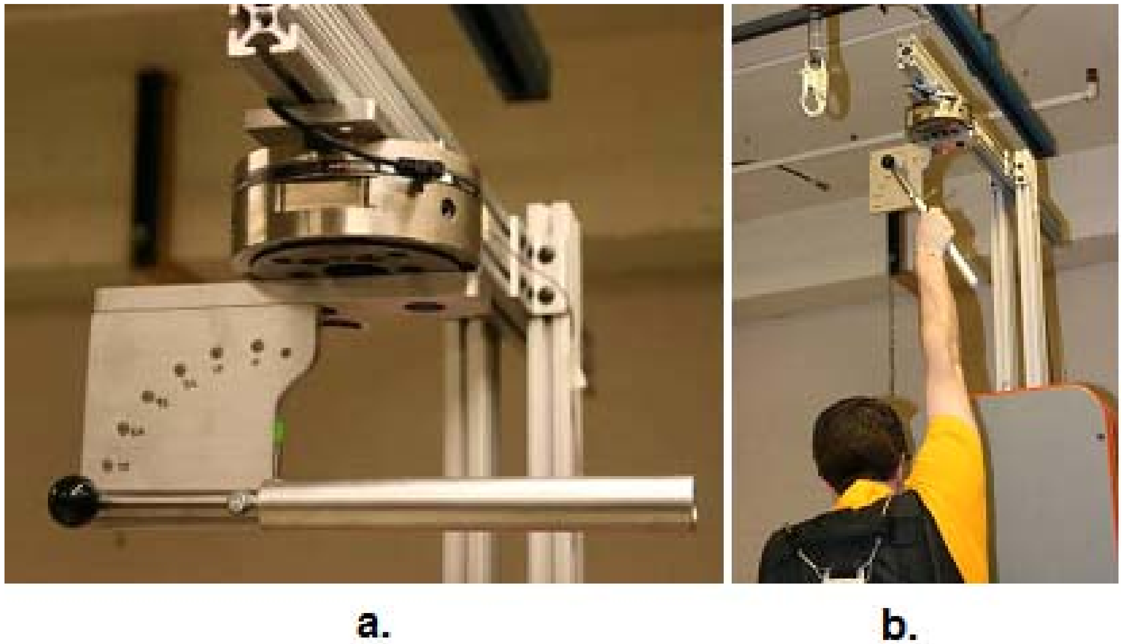

Figure 4.3.1 Experimental apparatus. a) An adjustable handle was attached to a 6-axis load cell. The handle could be adjusted to be oriented in 15° increments between horizontal and vertical. Different diameter metal cylinders can be easily interchanged. b) Subject position during breakaway trials.

4.3.1 Subjects

Participants for both experiments were recruited from the University of Michigan community and were paid for their involvement. Twelve healthy young participants (6 females) participated in each experiment. No participants had 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. Eleven participants were right-hand dominant, and one was left-hand dominant.

4.3.2 Design

For this study, each hand (dominant or non-dominant) performed a different experiment. This was done because it is assumed that each upper limb is independent of the other and differences in overall strength between the dominant and non-dominant hand will only affect the total breakaway strength and not the effects of treatment variables. Because each breakaway trial involved a maximum voluntary eccentric exertion, the total number of trials for each hand needed to be minimized. Also, because of the two-minute 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.

In order to control for fatigue, each subject performed the experiment in three sessions, each at least five 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 4.3.1 Experimental Design

	Experiment 1 (subject's dominant hand)	Experiment 2 (subject's non-dominant hand)
Independent Variables (for breakaway testing)	Gender (2): male, female Handle Diameter (3): 22mm (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 (36mm), 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 Subject	(3 sizes x 4 orientations + 2 grip strength) x 3 repetitions* = 42	(3 glove type x 4 orientations + 3 grip strength) x 3 repetitions* = 45

* repetitions of treatments performed in 3 experimental sessions

4.3.3 Experiment 1 (dominant hand)

For the dominant hand, breakaway strength was measured for three different size aluminum cylinders (22 mm, 32 mm, 51 mm diameter) at four different 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 to 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 analysis of variance was performed to determine whether breakaway force was significantly affected by the fixed effects of gender, handle size, handle orientation, and session (rep), with subject treated as a random effect nested within gender. Post-hoc pairwise comparisons (with Bonferroni correction) were then performed on significant main effects to compare breakaway strength between treatment levels. A similar analysis was performed to determine if grip strength was affected by fixed effects gender and span. An alpha level of 0.05 was considered significant. Statistical analysis was performed using SPSS® v.17 (Chicago, IL, USA) linear mixed model module software.

4.3.4 Experiment 2 (Non-dominant hand)

For the non-dominant hand, breakaway strength was measured for a single cylinder while bare-handed or wearing one of two different common work gloves at four different 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 two types of breakaway that can occur.

The two glove types that were tested (Figure 4.3.2) were Home Depot® brand “All-Purpose Brown Jersey Gloves” (70% polyester/30% Cotton) and 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 $\mu \approx 0.70$ while the plain jersey cotton (“low-friction”) glove had coefficient of friction of approximately $\mu \approx 0.27$. Each subject was given a new set of gloves at the beginning of the experiment and used only that pair for the three experimental sessions.

Figure 4.3.2 Gloves tested in Experiment 2 (non-dominant hand). (a) PVC dotted "high-friction" glove, $\mu \approx 0.70$ (b) plain jersey cotton "low-friction" glove, $\mu \approx 0.27$. 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.

A mixed-model repeated measures analysis of variance 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 subject treated as a random effect. Post-hoc pairwise comparisons (with Bonferroni correction) were then performed on significant main effects to compare breakaway strength between treatment levels. A similar analysis was performed to determine if grip strength was affected by fixed effects gender and glove type. An alpha level of 0.05 was considered significant. Statistical analysis was performed using SPSS® v.17 (Chicago, IL, USA) linear mixed model module software.

4.3.5 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 4.3.3). There were three possible outcomes per trial: if the fingers were forced open the failure was coded as '+1', if the fingers were not forced open 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 there was a combination of axial sliding and opening of fingers the failure was coded as '0'. Repeated measures analysis of variance was performed on coded failure results to determine whether the main effects tested in each experiment affected the type of breakaway that was observed.

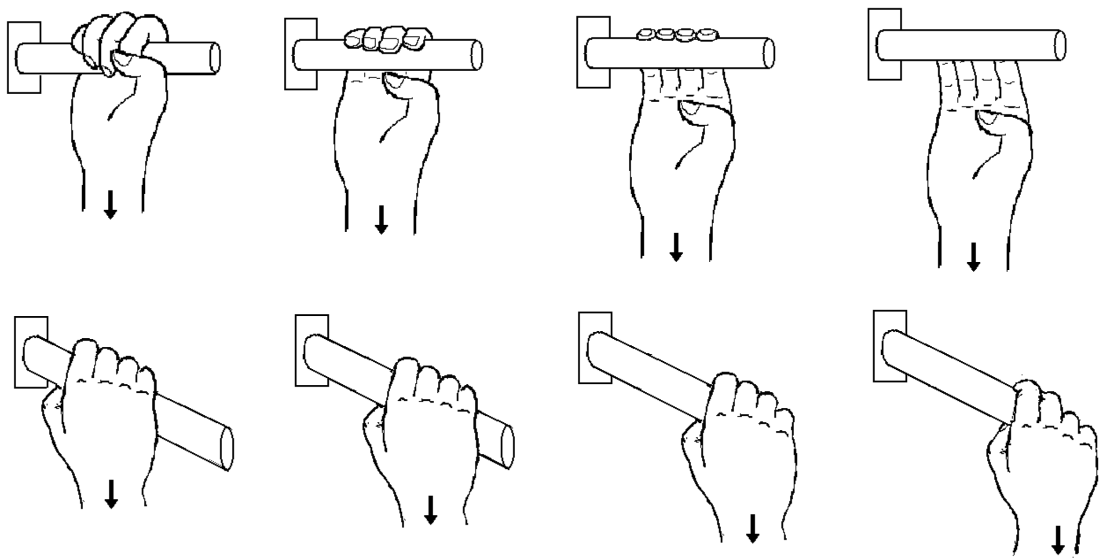

Figure 4.3.3 Types of coupling failures. In the horizontal handhold orientation (top row), the fingers must be forced open under the vertical load. The fingers slide over the circumference of the cylinder as fingers are forced open (coded '+1'). As the handhold orientation moves from horizontal to vertical (bottom row), the fingers may not be forced open and the vertical load causes the hand to slide down the long axis of the handle and off the end (coded '-1').

4.4 Results

4.4.1 Experiment 1 (dominant hand)

Statistical ANOVA results for experiment 1 are presented in Table 4.4.1. All main effects were significant ($p<0.001$). There were two significant interactions, the first between gender and orientation ($p<0.001$) and the second between gender and session ($p=0.026$). Table 4.4.2 presents breakaway strength results for each tested condition. Mean breakaway force by orientation and gender for all subjects is plotted in Figure 4.4.1.

Table 4.4.1 ANOVA for Experiment 1 (dominant hand)

Source	DF	F	P
Orientation	3	225.38	**0.000**
Gender*Orientation	3	57.40	**0.000**
Session	2	54.18	**0.000**
Size	2	21.12	**0.000**
Gender	1	20.28	**0.001**
Gender*Session	2	3.68	**0.026**
Orientation*Size	6	1.54	0.164
Orientation*Session	6	1.24	0.287
Size*Session	4	1.21	0.305
Gender*Size	2	0.03	0.966

The significant interaction between gender and orientation demonstrates that breakaway strength was reduced more in males than females at the steeper handle orientations (0° and 30°). The interaction between gender and session indicated that breakaway force diminished more in males than females in each consecutive session, though the effects contribution to variance was small compared to other significant factors (Table 4.4.1). 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 breakaway strength was greater for males than females ($p<0.01$). For the effect of diameter, breakaway strength for the largest handle (51 mm diameter) was significantly less than both the 32 mm handle and the 22 mm handle ($p<.01$), however, breakaway forces measured for the 32 mm and the 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 ($p<.01$); 30° handholds were significantly lower than the 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 ($p<.02$).

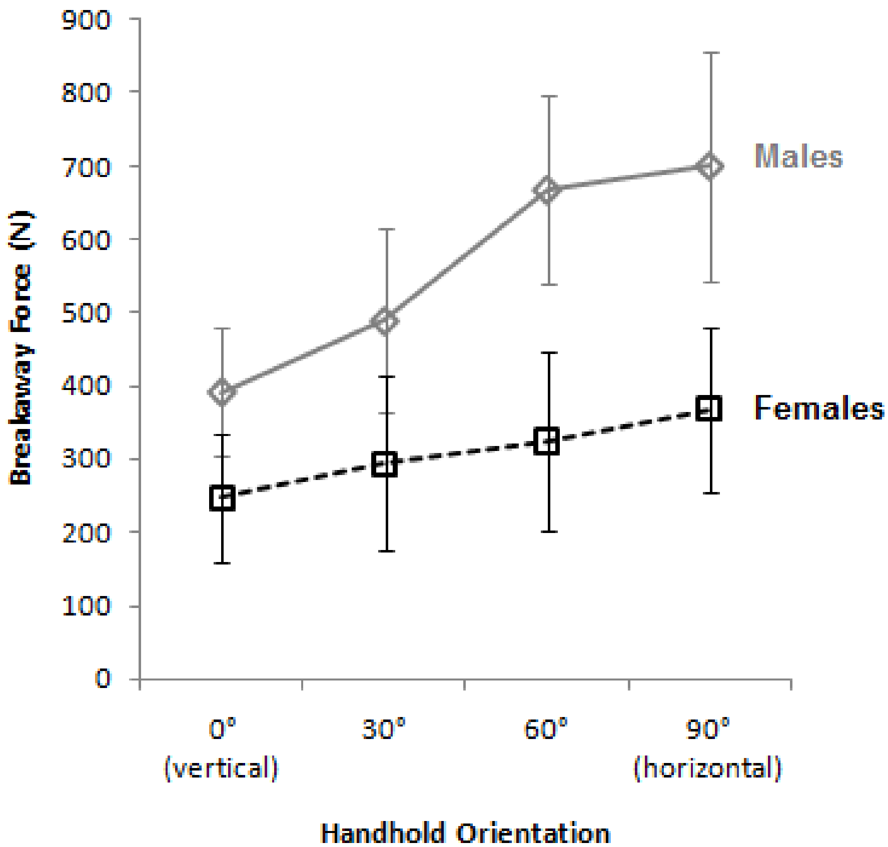

Figure 4.4.1 Mean breakaway strength (N) by orientation for male and female subjects. Strength decreases for handle orientations from horizontal to vertical.

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 ($p<0.022$) and span ($p<0.001$), but not session ($p>0.05$).

Table 4.4.2 Mean (±sd) breakaway strength for Experiment 1 (dominant hand)

	Peak Force (N)			Peak Force / Bodyweight			Peak Force / Grip Strength[1]		
Handle Diameter	Males	Females	All Subjects	Males	Females	All Subjects	Males	Females	All Subjects
	0° Orientation			0° Orientation			0° Orientation		
Large (51mm)	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 (32mm)	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 (22mm)	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			30° Orientation			30° Orientation		
Large (51mm)	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 (32mm)	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 (22mm)	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			60° Orientation			60° Orientation		
Large (51mm)	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 (32mm)	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 (22mm)	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			90° Orientation			90° Orientation		
Large (51mm)	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 (32mm)	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 (22mm)	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			All Orientations Pooled			All Orientations Pooled		
Large (51mm)	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 (32mm)	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 (22mm)	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

[1]Normalized by subject's mean grip strength measured in position 2 of the grip dynamometer

Results from the analysis of the video footage of Experiment 2 are presented in Table 4.4.3. 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 the hand was forced open, a value of -1 indicates the hand slipped down the long axis of the handle and the fingers were not forced open (see Figure 4.3.3). Statistical results show that only the main effect of orientation (F = 743.95, p<0.001) on the observed type of coupling failure was significant. There was also a significant interaction between orientation and gender (F = 19.56, p<0.001). No other effects or interactions were significant (p>0.05).

Table 4.4.3 Mean (±sd) coded coupling failure type[1] 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 Subjects	-1.0±0.0	-1.0±0.2	0.3±0.8	1.0±0.0

[1] A value of +1 indicates the hand was forced open, a value of -1 indicates the hand slipped down the long axis of the handle and the fingers were not forced open (see Figure 4.3.3)

4.4.2 Experiment 2 (Non-dominant hand)

Statistical ANOVA results for Experiment 2 are presented in Table 4.4.4. All main effects were significant (p<.001). All first-order interactions were significant (p≤.010) with the exception of the interaction between orientation and session (p=.545). Table 4.4.5 presents breakaway strength results for each condition. Breakaway strength normalized by subject bodyweight and grip strength is also presented. Mean breakaway force for all subjects is plotted in Figure 4.4.2.

Table 4.4.4 ANOVA for Experiment 2 (non-dominant hand)

Source	DF	F	P
Glove	2	238.30	**0.000**
Orientation	3	91.31	**0.000**
Session	2	56.50	**0.000**
Gender*Glove	2	25.54	**0.000**
Gender	1	21.06	**0.001**
Gender*Orientation	3	18.51	**0.000**
Orientation*Glove	6	9.12	**0.000**
Gender*Session	2	4.64	**0.010**
Glove*Session	4	3.64	**0.006**
Orientation*Session	6	0.83	0.545

Table 4.4.5 Mean (±sd) breakaway strength for Experiment 2 (non-dominant hand)

Glove type	Peak Force (N) Males	Females	All Subjects	Peak Force / Bodyweight Males	Females	All Subjects	Peak Force / Grip Strength[1] Males	Females	All Subjects
	45° Orientation			45° Orientation			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			60° Orientation			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			75° Orientation			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			90° Orientation			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			All Orientations Pooled			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

[1]Normalized by subject's mean grip strength measured while wearing corresponding glove type on the grip dynamometer (position 2)

Significant interactions showed that breakaway strength was reduced more for males than females by wearing the low-friction glove. Breakaway strength was decreased more for males than females as handle inclination increased from the horizontal. The interaction between inclination and glove type (Figure 4.4.2) 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. Interactions between session and glove type show that the reduction in breakaway force was greater for bare hands than gloved hands between the first and second experimental session. The interaction between session and gender indicated that breakaway force was decreased equally per session for males, and less for the third session than 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.

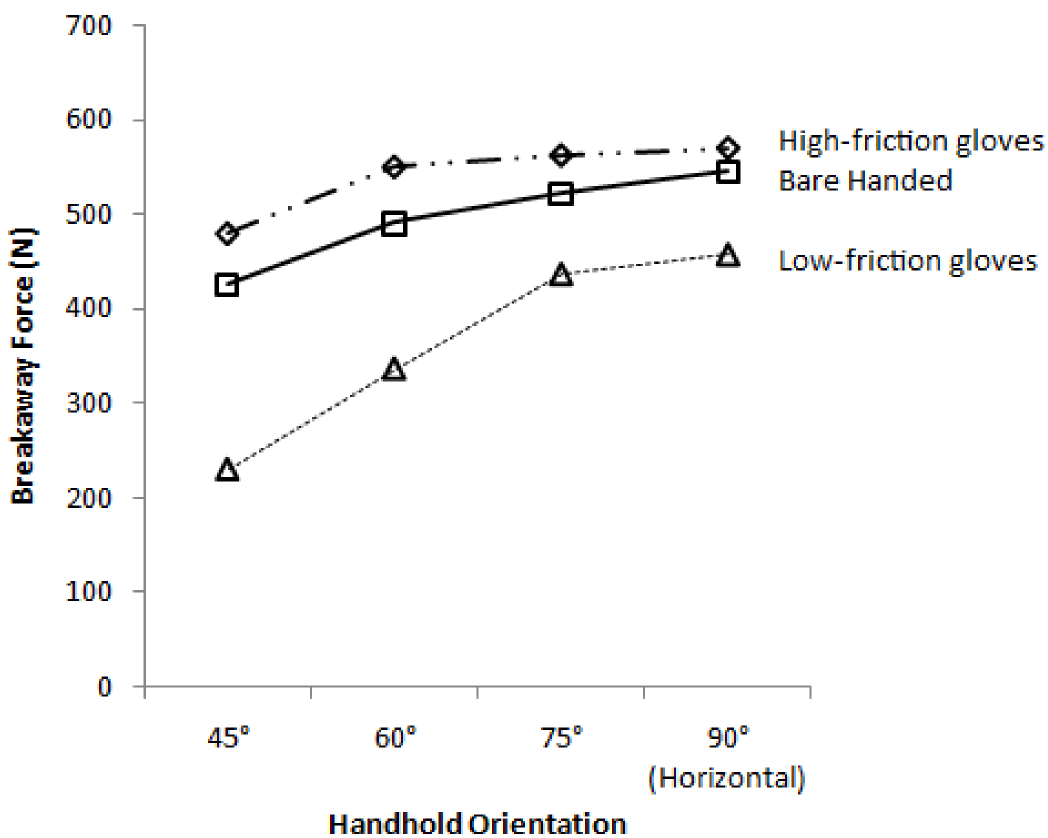

Figure 4.4.2 Breakaway strength (N) by orientation and glove type (non-dominant hand) across all subjects. Strength decreases non-linearly as the handle inclination was increased from the horizontal for all glove types over this range of handle orientations. Strength was consistently least for the low-friction glove and greatest for the high-friction glove.

Post-hoc analysis for main effects indicates breakaway strength was greater for males than females ($p<.01$). For the effect of glove type, breakaway strength when wearing the low-friction glove was significantly less than when bare-handed ($p<.01$), which in turn was significantly less than when wearing the high-friction glove ($p<.01$). For the effect of orientation, breakaway force was significantly lower for handholds oriented at 45° than for 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 third experimental session ($p=.06$).

Average isometric grip strength for non-dominant 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 ($p=0.002$) and glove type ($p=0.002$), but not session ($p>0.05$).

Results from the analysis of the video footage from Experiment 2 are presented in Table 4.4.6. Coded values represent the mean type of coupling failure that was observed in video footage of that treatment condition. A value of +1 indicates the hand was forced open, a value of -1 indicates the hand slipped down the long axis of the handle and the fingers were not forced open (see Figure 4.3.3). Statistical results show that the main effect of glove type ($F = 112.63$, $p<0.001$) and orientation ($F = 430.51$, $p<0.001$) on the observed type of coupling failure were significant, as well as their interaction ($F = 31.73$, $p<0.001$). No other effects or interactions were significant ($p>0.05$).

Table 4.4.6 Mean (±sd) coded coupling failure type[1] for each orientation (non-dominant 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

[1] A value of +1 indicates the hand was forced open, a value of -1 indicates the hand slipped down the long axis of the handle and the fingers were not forced open (see Figure 4.3.3)

4.5 Discussion

4.5.1 Handhold Orientation

Results from both Experiment 1 and Experiment 2 show that the coupling between the hand and the handhold was decreased as handle inclination increases from the horizontal (or perpendicular to the applied load), supporting our hypothesis. The decrease in breakaway strength due to change in orientation is not linear: the breakaway force decrement was smaller for orientations near horizontal than for orientations approaching vertical (Figure 4.4.1 and Figure 4.4.2). It is interesting that this result (breakaway strength vs. orientation) is similar in shape to results predicted by the simple model of a block on an inclined plane (Figure 4.2.1c). For orientations near horizontal, resistive forces against the vertical load of bodyweight 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 upon to create the force. This behavior is illustrated by the type of coupling failure that occurs at these different handle orientations (Table 4.4.3 and Table 4.4.6).

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 4.4.3). For the non-dominant hand, the type of coupling failure is affected by both handle orientation and the type of glove (Table 4.4.6): the transition orientation is between 45° and 60° for high-friction gloves; the transition orientation is near 60° for the bare hand; the transition between failure types occurs near 75° for low-friction gloves.

Using the simple model presented in the Introduction (Figure 4.2.1), 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, 2003; Tomlinson, 2007), measuring an accurate value directly is difficult. It may be useful to estimate this value based on the observed transition angle for the bare hand. 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 subjects (Table 4.4.5).

While 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. Non-horizontal 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 non-horizontal 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 in order to grasp the overhead handhold (Figure 4.5.1).

Figure 4.5.1 Typical wrist and finger posture on 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.

4.5.2 Handhold Size

The results show that breakaway strength increased for small (22 mm) and medium (32 mm) handholds as compared to large–size handholds (55 mm) for all handle orientations. Based on results from previous research of grip strength, we would expect that the greatest breakaway strength would be observed for medium sized handles, and reduced for the smaller and larger diameters. However, 32 mm and 22 mm handles over 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 suggests that optimal handle diameter is a function of the handle orientation with respect to the direction of the applied load.

As described above, when the long axis is perpendicular to the applied pull force, the fingers must be forced open in order to break hand/handhold coupling. In this situation smaller handhold 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 open 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 et al., 2010). This conclusion is supported by the results that grip strength for the smaller Jamar span (36 mm) was significantly lower than the larger span (48 mm), while breakaway strength for the smallest cylinder (21 mm) was the greater than both larger handles.

As the handhold orientation becomes increasingly parallel to the applied pull force, the situation is more like that typical of a test for isometric grip strength. The fingers are not forced open and the hand needs to squeeze the handle into the palm to create friction forces on the surface. In this situation, it can be expected that the size of cylinder which affords the greatest grip strength would also afford the greatest breakaway strength (Figure 4.5.2).

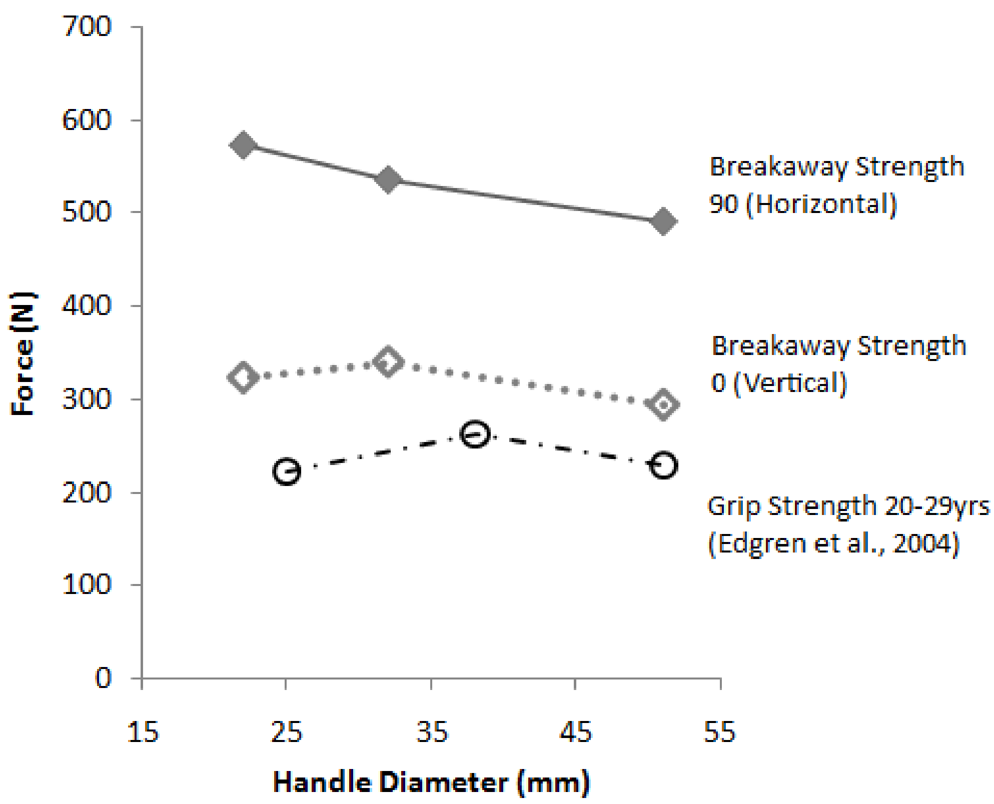

Figure 4.5.2 Mean breakaway strength vs. handhold size for horizontal and vertical handholds (Experiment 1) and voluntary isometric grip strength vs. handle size for subjects aged 20-29 from Edgren et al.. (2004). Males and females are pooled. Strength was consistently least for the largest cylinder. Strength was greatest for the 32 mm diameter handle in the vertical orientation, while strength was greatest for the smallest diameter in the horizontal orientation.

Handle size affects the contact area between the hand and the handle (Aldien, 2005; Seo &Armstrong, 2008). Contact area has been shown to affect skin friction (Comaish & Bottoms 1971; Bobjer 1993; O'Meara 2002) and pain or discomfort during forceful exertion (Fothergill et al., 1992; Hall, 1997). We may hypothesize that a very small diameter handle will be optimal for pulling tasks where 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 may occur. This is supported by results that handles with corners have been shown to afford less breakaway strength than cylinders (Young & Armstrong, 2010). It is therefore necessary to determine the relationship between biomechanical advantage and psychophysical limitations when modeling hand function at high loads.

4.5.3 Wearing Gloves

The results show that wearing gloves with PVC dots (high-friction gloves) increases breakaway strength across all orientations. This result is likely due to friction for reasons discussed above. Plain cloth gloves decreases friction and therefore coupling. However, this may not be the case for handles that have rough or knurled surfaces, where the cloth may actually have greater friction. Specific handle/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 subjects wore each glove type and it was found that wearing gloves did reduce grip strength significantly (6-8% compared to 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 ability. This may not be true for particularly thick or stiff gloves, which have been shown to affect grip strength more greatly (Hertzberg, 1995; Wimer et al. 2010).

4.5.4 The Ability to Hang On with One Hand

Normalizing breakaway strength by bodyweight will provide insight into the ability to hang onto a handhold in the event that the feet slip and bodyweight is suddenly transferred to one or two hands. Out of all the handholds tested in this study, mean breakaway strength was greater than bodyweight for only three conditions and only for males: the 90° orientation and small diameter for the bare dominant hand (Table 4.4.2), and the 75° and 90° orientations for the non-dominant 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 4.4.2 and Table 4.4.5). Grip strength to bodyweight ratio has similarly been shown to be significantly less for females than males (Gunther et al., 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 bodyweight (Table 4.4.2). When friction is reduced by wearing the low-friction glove, subjects could support only 36% of their bodyweight (Table 4.4.5). This means that for these handhold orientations, even if two hands were available to hang on, it is unlikely that a person could support themselves with the hands and arrest an impending fall.

The results presented here may actually overestimate the capability of the working population to support their bodyweight in a fall, as male and female subjects were 114 N and 193 N lighter than population weight norms, on average, respectively (Ogden et al., 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 (Gunther et al., 2008; Mathiowetz et al., 1985).

4.5.5 Breakaway Strength vs. 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 confirms previous findings (Rejulu & Klute, 1993; Woldstad et al., 1995; Young et al., 2009, Young & Armstrong under review) and verifies the need for 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 loading. However, the development of models that can reliably predict breakaway strength base on voluntary grip strength and other measurable handhold properties would reduce the need to measure functional hand strength directly.

Because the simple model presented in Figure 4.2.1 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. Using 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 we assume that grip force acts to squeeze the handle like a pinch, then the applied 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 4.4.2). 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 data. This underestimate may due to reduced grip strength for hand/wrist postures on vertical handles.

While 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 strength measured in some fashion, as it is a measure of finger flexion force. This 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 strength at every finger and wrist posture observed to quantify this active component.

The active component is also influenced by the passive friction component through the tissues of the fingers and palm. When the handhold is perpendicular to the applied load, the fingers must be forced open, and friction acts solely to keep the finger joints wrapped around the circumference. Friction at the surface will cause normal forces on the proximal joints to increase. This situation may be conceptualized by imagining a belt wrapped around a fixed pulley. Further research should investigate how circumferential friction affects loading on the finger segments and how passive components may reduce required muscular effort.

4.5.6 Limitations

Measurements of breakaway strength have several limitations, as discussed in Young et al (2009). These include the possibility that skin friction and maximal effort can vary between subjects, much higher rates of loading will occur during a real fall when inertial factors may become more significant, and our subjects were relatively young individuals and not trained workers.

Another limitation is the ratio of handle size to hand length. For this study, subjects 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, 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 subjects were either 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 though it is difficult to interpret the overall meaning of this interaction. Maximal eccentric exertions have been shown to be particularly fatiguing (Clarkson & Hubal, 2002), future studies might allow for greater rest periods (more than 5 days) between sessions.

4.5.7 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 means that vertical or near vertical handholds should only be utilize if sufficient friction is ensured.

Current US safety regulations and standards limit the minimum diameter of handholds to 19mm (fixed ladders: OSHA 29 CFR 1910.27, ANSI-ASC A14.3-2008; vehicles: FMCSA-DOT 49 CFR 399.207). While 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 4.5.2).

4.6 Conclusions

- Breakaway strength is maximized for handhold orientations that are perpendicular to the applied force and decreased as the handle is oriented more towards the direction of applied pull force.

- When the applied 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 applied 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 which reduce friction between the hand and the handle will reduce the ability to hang on.

- Only male subjects could support their bodyweight 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 non-dominant hand wearing high-friction gloves in the 90° and 75° orientations. In situations where worker may only have one handhold to support their 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.

4.7 Acknowledgements

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CHAPTER 5

The effect of friction on the normal force distribution at the hand/handle interface for grip and pull tasks

5.1 Introduction

Previous studies have shown that isometric grip strength significantly underestimates the capacity of the hand to resist or apply force on a cylindrical handle that is perpendicular to the applied force (Rejulu & Klute, 1993; Young et al., 2009; Young & Armstrong, under review; Young et al., under review). Friction between skin and the handle surface increases the capacity to hang on by an average of 26% for a 1-inch diameter cylindrical aluminum handle (Young et al., 2009). This supports the hypothesis that the functional strength of the hand is comprised of both active finger flexion capacity and passive frictional components; however, the biomechanical mechanism through which passive forces can increase coupling beyond muscular capacity is unclear.

Seo *et al* (2007) proposed a model for manual torque production on cylindrical handles where shear forces between the skin and the cylinder surface will increase or decrease the moment on distal finger joints depending on the direction of twist. Friction can therefore work with or against the flexion of finger joints by the finger flexor muscles depending on the task. When a pull force is applied to cylindrical handles that are oriented perpendicular to the applied force, shear forces due to friction from the handle surface act to pull the digital skin distally away from the palm. Friction may therefore act to keep the fingers wrapped around the circumference of the handle, but concurrently increase the moment on the distal finger segments that the finger flexor muscles must oppose. To develop biomechanical models of functional hand tasks such as pulling, normal and shear forces between the hand and grasped handle need to be quantified.

Normal pressures at the interface between the hand and a grasped object have been measured by some investigators using thin pressure sensors placed between the hand and the object at specific locations (Hall, 1997; Gurram et al., 1993; Gurram et al., 1995; Fellows & Freivalds, 1991; Kargov et al., 2004; Kong & Freivalds, 2003; Kong et al., 2004; Kong & Lowe, 2005; Pylatiuk et al., 2006) or using a pressure sensitive array wrapped around a handle (Aldien, 2005; Dong et al., 2008; Lee & Rim, 1991; Seo et al., 2007; Wimer, 2010). These studies have shown that the pressure distribution between the hand and handle is affected by the functional task being performed (i.e. gripping, pushing, or pulling). Aldien et al. (2005) found that the peak force during forceful pushing occurred at the base of thumb (thenar region) and that high force was only seen at the finger tips if subjects were instructed to concurrently exert high grip force and little or no push force. Hall (1997) found high pressure in the thenar region for gripping, but not for pulling handles. Most studies agree that during isometric grip tasks the greatest force is concentrated at the fingertips. However, Kong and Freivalds (2003) and Kong, Freivalds, and Kim (2004) found that when pulling on various handles the greatest contact pressure occurred on the proximal rather than the distal segments of the fingers. No study has examined circumferential pressure distribution over the surface of a handle for pulling exertions.

As the fingers press against the handle, the palmar skin and soft tissue of the fingers deform and conform to the surface under normal compression. When a pull force is applied, shear forces at the skin surface will cause tension between adjacent palmar tissues and will place traction across finger joints. We hypothesize that friction between the hand and handle will alter the normal force distribution over the handle circumference in a similar fashion as a belt stretched around a pulley (Figure 5.1.1). That is, friction during pulling causes the normal pressure distribution to shift in the direction of belt or impending slip, which is in our case, the proximal finger joints (Beer, 2007). Though we cannot measure the distribution of shear forces at the hand/handle interface directly, the effect of these shear forces can be observed by comparing the surface pressure distribution in the presence and absence of friction.

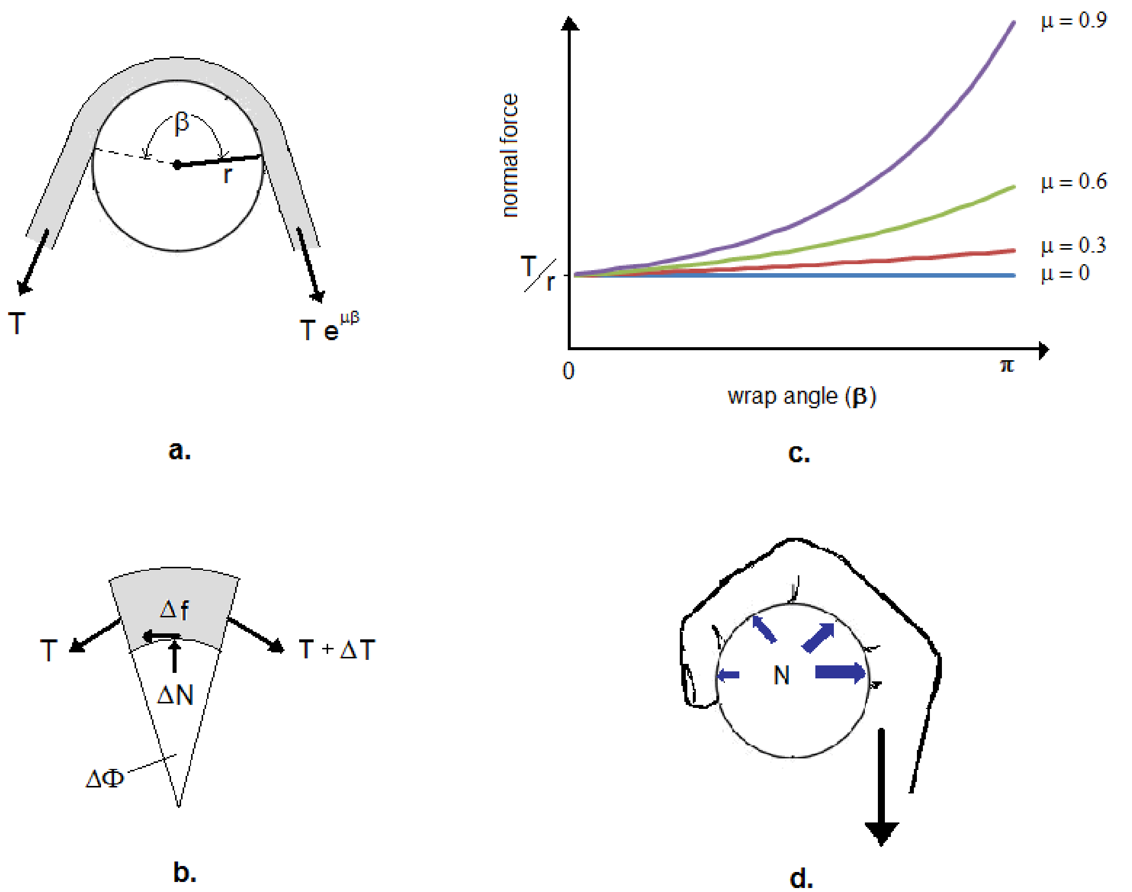

Figure 5.1.1 Effect of friction on belt normal force distribution. (a) Tension on two ends of a belt wrapped around a fixed pulley are related by the initial tension, T, the angle of wrap, β, and the coefficient of friction, μ. (b) Forces on an elemental section of belt. Friction causes normal force on the next element to be greater than the previous. (c) Normal force over the angle of contact for a belt given various values of μ. Without friction the normal force is constant over the wrap angle. (d) Like a belt over a fixed pulley, it is hypothesized that normal force distribution for a hand pulling downward on a handle with friction present will shift proximally away from the fingertips.

The purpose of this experiment was to test the aforementioned hypothesis and to investigate how surface pressure distributions change during gripping and pulling on cylindrical handles. This will create knowledge that can be used to develop alternative hand models that include applied loading and surface interactions. They can be used to evaluate biomechanical loading and required muscular effort of the hand to hang on and exert force on cylindrical handles or prevent objects from slipping out of the hand.

5.2 Methods

To accomplish stated aims, an experiment was designed to record and compare normal contact pressure distributions during isometric squeezing and isometric pulling exertions on an instrumented cylindrical handle that could simulate high- and low-friction surface conditions.

5.2.1 Apparatus

An instrumented handle was designed to quantify the distribution of surface pressure on the hand during pulling and squeezing. A 3.18cm diameter cylindrical handle was covered with two Tekscan® Model 3000 pressure sensors (862 kPa pressure rating). Each sensor grid was cut to a length of 24.9cm and a width of 5.08cm (49 rows and 10 columns) and was attached to the surface of the cylindrical handle by 3M® Super 77 spray adhesive. The sensors were aligned so the edge of each sensor met evenly along the top and in line with the long axis of the handle (see Figure 5.2.1). No overlapping occurred, but this created a small seam at the points where the two sensors met. The result was that the entire surface of the cylinder was covered by a 49x20 sensor grid (see Figure 5.2.2b).

Each sensor was comprised of an array of 5mm by 5mm "sensels". Each sensel measures the force applied to an area of 25.8mm^2. The cylindrical handle covered by the pressure sensors was mounted to a six-axis load cell (ATI® Theta) which measured pull forces in orthogonal directions and the corresponding torques. The cylindrical handle mount was designed so that a pin could be removed that would allow the cylinder to be free to rotate about the long axis of the cylinder ("unlocked"). This free rotation effectively negates circumferential friction on the handle surface (Young et al, 2009). A potentiometer was use to track the rotation angle of the cylinder when the handle was unlocked. Load cell and potentiometer voltages were calibrated and acquired via a custom LabVIEW® interface at 100 Hz while the pressure sensor data was acquired by F-scan® software at 100 Hz.

5.2.2 Pressure Sensor Calibration

A custom calibration device was constructed to allow the sensors to be calibrated while in the wrapped position that they would encounter on the surface of the handle. The device consisted of an aluminum pipe with an inner diameter matching the outer diameter of the tested handle and inflatable rubber tube-type bladder which had a deflated diameter just slightly smaller than the handle. Pressure sensors were placed between the bladder and the inner wall of the aluminum pipe and the bladder was inflated to apply a uniform surface pressure along the inner wall of the cylinder. Equilibration and two-point calibration procedures at 207 and 414 kPa were performed using F-scan® software tools. This process was completed for each sensor separately before attachment to the handle with adhesive.

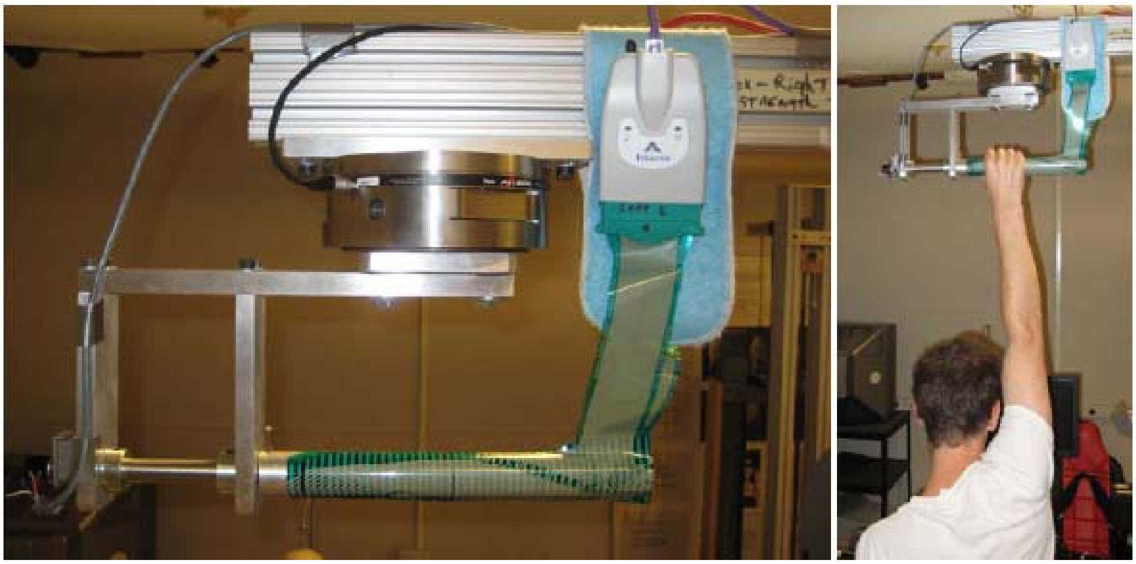

Figure 5.2.1 Experimental setup. A cylindrical handle is attached to a six-axis load cell and a pressure sensitive mesh is wrapped around the surface of the handle (left). Subjects grasped the overhead handle and either squeezed or pulled downward on the handle while watching a computer screen to match a desired force (right).

5.2.3 Subjects & Procedure

Six male subjects were recruited for this study. Subject characteristics are shown in Table 5.2.1. Subject hand length ranged from 0-66 percentile and hand breadth ranged from 0-99 percentile based on data from Garrett (1971).

Table 5.2.1 Subject anthropometry

	Subject						
	1	2	3	4	5	6	All
Height (cm)	168	180	175	185	173	172	176±6
Weight (kg)	64	72	100	100	66	72	79±17
Age (yrs)	24	27	31	20	26	29	26±4
Dom. Hand	R	R	R	R	L	R	
Grip Strength (N)	516	483	699	615	519	523	559±82
Hand Length (mm)	186	178	193	201	191	170	187±11
Hand Breadth (mm)	81	78	93	94	100	82	88±9
Finger Length* (mm)							
I	67	56	61	72	62	53	62±7
II	73	67	72	75	69	65	70± 4
III	78	73	83	81	80	66	77±6
IV	65	71	72	79	71	64	70±5
V	60	60	62	61	58.5	49	58±5

*Finger length measured as distance fingertip to crotch level (Garrett, 1971)

First, subject anthropometry was collected and subjects washed and dried their hands. Subjects then performed three isometric grip strength trials using a Jamar® grip dynamometer set at position two (49mm). Their mean grip strength was used to specify target force levels for pull conditions. Subjects then performed eighteen pull exertions and three maximum isometric grip trials on the instrumented handle. The trials were randomized and tested only the subject's dominant hand (Table 5.2.2). Subjects were given at least a two-minute rest period between trials.

Table 5.2.2 Experimental Design

Independent Variables	Handle friction (2): locked or unlocked
(subject's dominant hand)	Pull effort (4): 30%, 60%, 90% of grip strength or Grip only
Dependent Variables	Circumferential surface pressure, Handle rotation angle
Total Exertions per Subject	(3 pull forces × 2 handle frictions + 1 grip) x 3 reps = 21 trials

For each trial, subjects stood on a height adjustable platform directly beneath the instrumented handle. The platform was positioned so the subjects could grasp the overhead handle with forearms pronated and a slight bend in their elbow. At the start of each trial, subjects were instructed to lightly tap the instrumented handle for software synchronization and then to grasp the handle so that their proximal interphalangeal (PIP) joints of their fingers would be at the top of the handle (0°), along the crease created by the adjoining pressure sensors. The distal interphalangeal (DIP) joints were located between -90° and 0°and the metacarpophalangeal (MCP) joints would be near +90°, depending on the length of each digit (see Figure 5.2.2). The DIP joints of the middle and ring fingers were generally located more distally than the index and little finger. Subjects were coached on hand placement before starting the experiment.

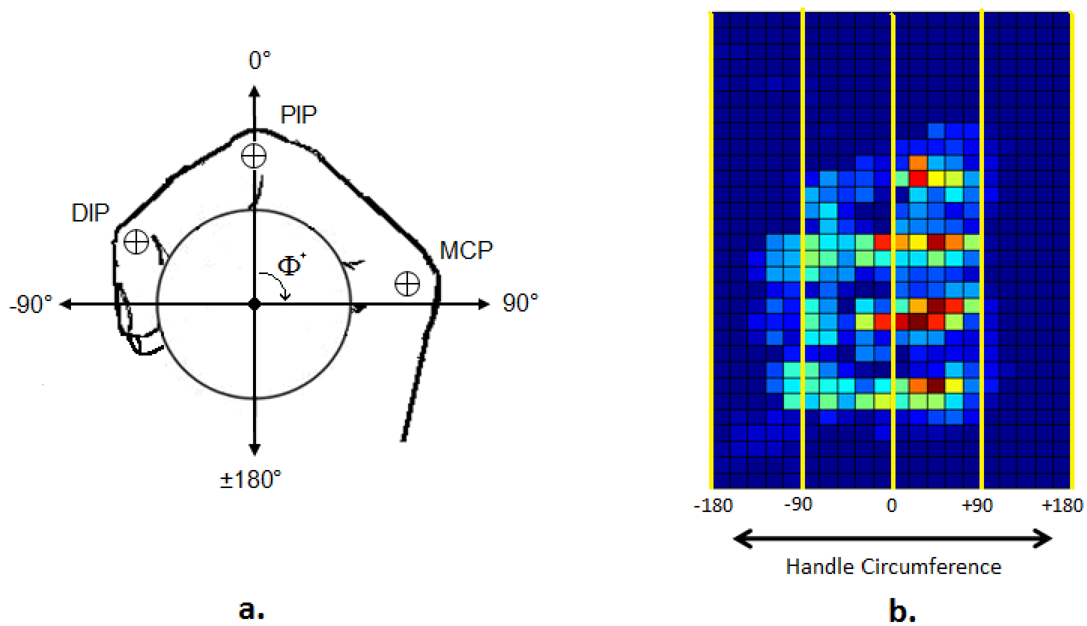

Figure 5.2.2 Approximate placement of fingers on the handle. (a) Subjects were instructed to place the crease of their fingers at the PIP joint on the top of the handle (0°). Since digits are different lengths, exact location of DIP and MCP joints will vary. (b) Example raw pressure distribution map (49 rows × 20 columns) for a locked pulling trial. The top of the handle (0°) is in the center of the 20 columns. Normal force in vertical column was summed. For this subject, the tip of the little finger does not apply pressure beyond -90°, the index finger does not apply pressure beyond -126°, and the middle and ring fingers do not exert pressure beyond -144°.

For pull trials, subjects pulled downwards on the instrumented handle until the pull force matched a target force (within ±5%) displayed on a screen positioned directly in front of them. The desired target pull force (30, 60, and 90 percent of their isometric grip strength measured by the Jamar) was maintained for five seconds. Subjects were instructed to utilize their bodyweight to create the pull force in order to provide better control and ensure vertical downward pull direction. For maximum grip strength trials on the instrumented handle, subjects were instructed to squeeze the overhead handle as hard as possible for five seconds while exerting no pull forces.

5.2.4 Data Analysis

For each trial, data from the middle three seconds of the five-second time period when the subjects matched the target vertical pull force was further analyzed. This resulted in a 100Hz pressure distribution and corresponding load cell forces for each trial. For the purposes of this experiment, the distribution of forces along the long axis of the handle (i.e. for individual fingers) was not of interest. Instead, data were summed along each long-axis column of sensels, yielding a 100Hz circumferential pressure distribution. Pressure was integrated over the sensel area to give total normal force at discrete 18° increments in the center of each of the 20 sensel columns around the handle circumference (see Figure 5.2.2b).

For trials where the handle was unlocked and free to rotate, the location of the sensor rows may change with respect to the initial position. The top of the handle is defined as 0° (vertical) and therefore the potentiometer gives the angular location of the PIP joint with respect to vertical. The angle of handle rotation measured by the potentiometer was used to shift the distribution of forces at every time-point during the 3 seconds of trial data so that 0° is always vertical for comparison across trials. In addition to circumferential normal distribution, the sum of normal force components in the in the vertical and forward/backward direction (vertical and horizontal resultant force) were calculated and normalized by the magnitude of the vertical force measured by the load cell.

A repeated measures analysis of variance was performed to determine the effects of friction and pull effort on the resultant vertical and forward/backward normal force components, and the mean handle rotation angle and mean angular velocity of the handle (for unlocked handle only). Subject was considered a random effect. Statistical analysis was performed with Minitab® GLM software.

5.3 Results

Mean normal force distributions for the three pull levels on the locked handle are presented in Figure 5.3.1. A bimodal distribution is observed with a local minimum near 0° (the top of the handle and the crease of the PIP joint). Local maximums occur at -63° (the distal segments of the fingers, near the DIP joints) and at 45° (mid-way along the proximal phalanx). Force distribution is similar in shape for each level of pull. Greatest pressure occurs on the proximal side of the handle. Forces on the underside of the handle are very small.

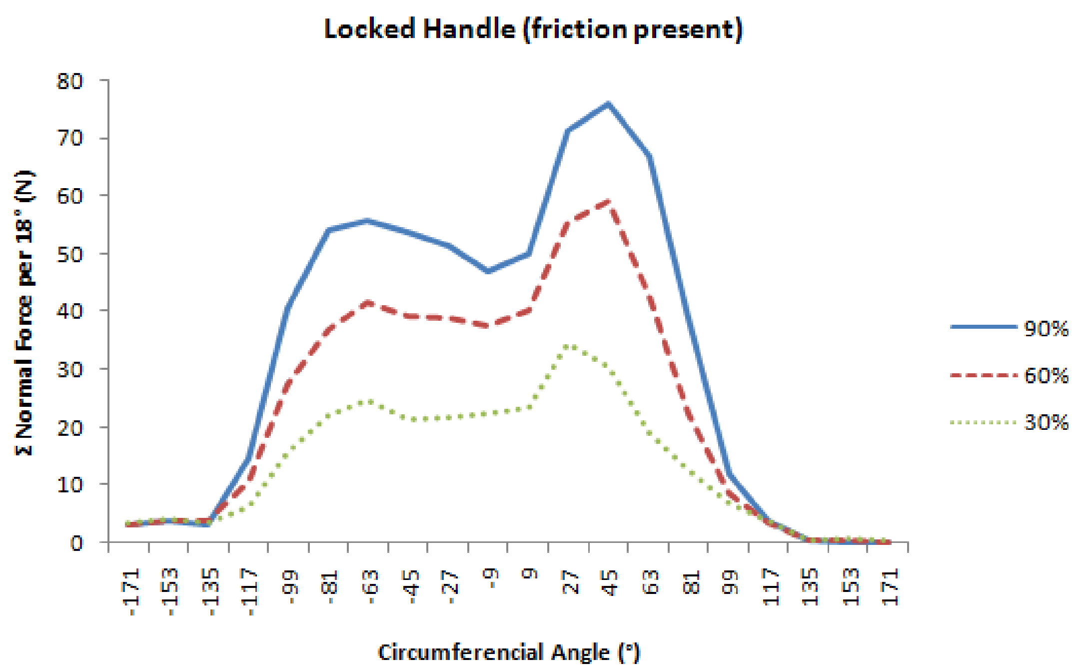

Figure 5.3.1 Integrated forces for each 18°band along long axis of handle for 30, 60 and 90% pull forces on the locked handle (friction present). The top of the handle is in the center of the graph (0°) and is the approximate location of the PIP joints. The bottom of the handle is at both ends of the graph (±180°).

Mean normal force distributions for the three pull levels on the handle that was free to rotate are presented in Figure 5.3.2. A bimodal distribution is observed with a local minimum near 0° (the top of the handle and the crease of the PIP joint). Local maximums occur at -63° (the distal segments of the fingers, near the DIP joints) and at 45° (mid-way along the proximal phalanx). For the 30% pull level, the distribution resembles that of the locked handle, however, for the 60% and 90% pull levels the distal peaks are increased in comparison to the proximal. For the 90% pull level, peak forces on the distal side of the handle are greater than on the proximal. Forces on the underside of the handle are very small.

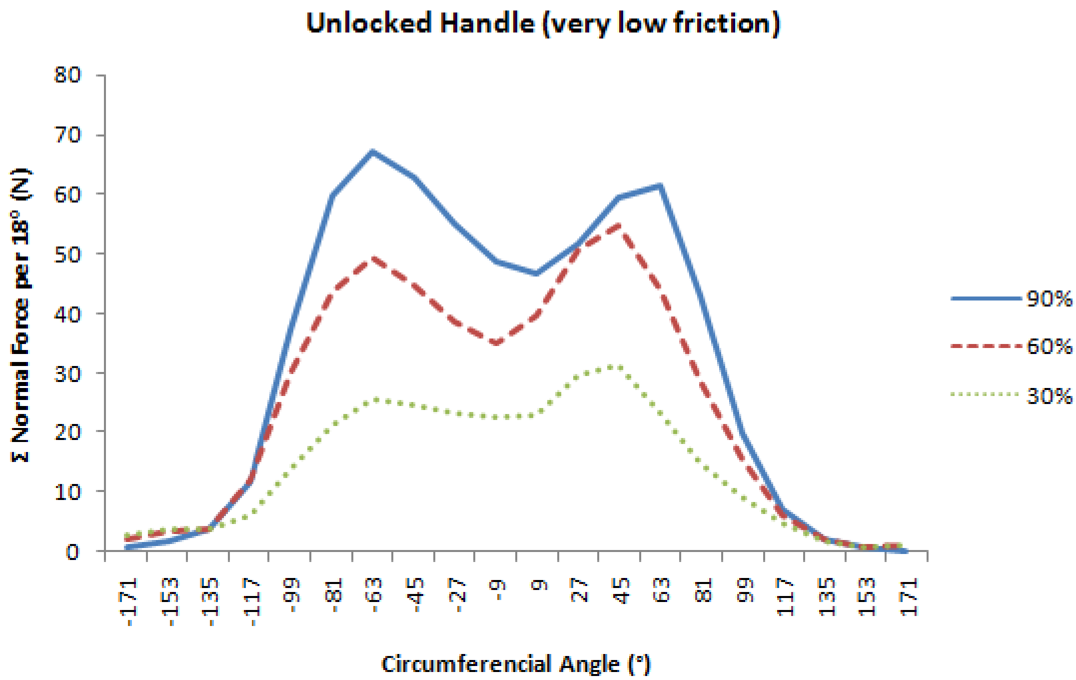

Figure 5.3.2 Integrated forces for each 18° band along long axis of handle for 30, 60 and 90% pull forces on the unlocked handle (very low friction). The top of the handle is in the center of the graph (0°) and the bottom of the handle is at both ends of the graph (±180°).

Mean normal force distributions for 90% pull levels and 100% grip are presented in Figure 5.3.3. In contrast to pulling, gripping the handle produces forces on the underside of the handle. Two main peaks are observed, the first is at the fingertips (-63°) and the second is at 117° (the palmar area), directly opposite the fingertips.

Mean handle angle and mean angular velocity for each level of effort on the unlocked handle, as well as the normalized resultant forces in the vertical and horizontal direction for each condition are presented in Table 5.3.1.

Analysis of variance for handle rotation angle shows that pull effort significantly affected rotation of the handle on the unconstrained handle ($F=12.71$, $p<0.001$). For lower levels of pull effort (30% and 60%) there was little rotation of the handle, and mean rotation was not significantly different ($p>0.05$) between the two levels. However, mean rotation for the 90% pull effort level was significantly greater than the lower levels of effort ($p<0.01$) and showed a significant clockwise rotation of the hand, with the finger joints moving away from the vertical toward the proximal side of the handle surface.

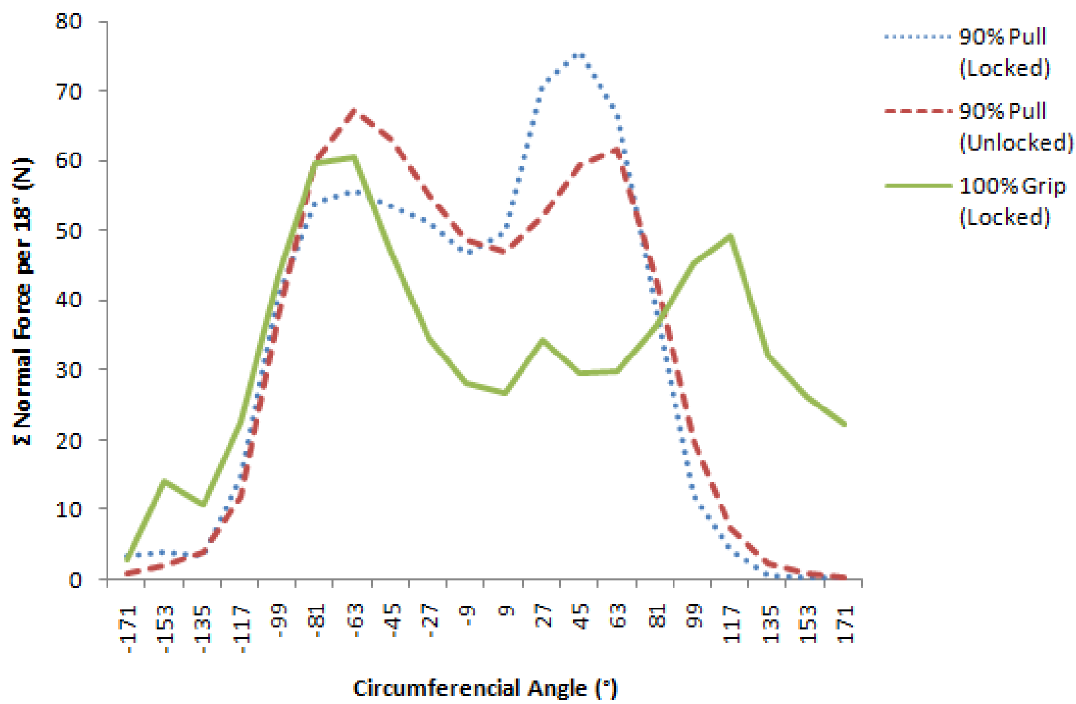

Figure 5.3.3 Integrated forces for each 18° band along long axis of handle for 90% pull forces on the locked and unlocked handles and 100% gripping effort (no pull force).

Angular velocity profiles for all trials over the 3-seconds of collected data were plotted and appeared to be linear. Analysis of variance for mean angular velocity shows that pull effort significantly affected angular velocity for the unconstrained handle ($F=14.18$, $p<0.001$). Angular velocity over the 3 seconds of fixed target downward pull force was non-zero and positive (clockwise) for all levels of pull. Post hoc tests show mean angular velocity for the 90% pull effort level was significantly greater than the lower levels of effort ($p<0.01$), which were not significantly different ($p>0.05$).

Resultant vertical force measured by the pressure array normalized by vertical force measured by the load cell was below 1 for each condition. Analysis of variance for normalized resultant vertical force showed that the effect of pull effort was significant

(F=104.44, p<0.001) but the effect of handle friction and their interaction were not (F>1.81, P>0.05). Post hoc analysis shows that normalized vertical force decreased significantly (7-14%) as pull effort was increased from 30% to 60% and 60% to 90% (p<0.01).

Analysis of variance for normalized resultant horizontal force showed that the effect of pull effort was significant (F=3.97, p=0.022) as well as the effect of friction (F=21.92, p<0.001). The interaction between pull effort and handle friction was also significant (F=3.17, p=0.046): for the unlocked handle normalized horizontal force was similar across pull efforts while for the locked handle horizontal force decreased as effort increased. Post hoc analysis shows that normalized horizontal force was significantly greater for 90% than 30% effort (p<0.03) but was not different between 30% and 60% or 60% and 90% effort levels (p<0.05). Normalized horizontal force was significantly greater for unlocked handles than for locked handles (p<0.01).

Table 5.3.1 Mean (±SD) handle rotation angle, angular velocity, and normalized resultant force components for each condition

Condition	Normalized resultant horizontal force	Normalized resultant vertical force	Rotation angle (°)	Angular velocity (°/s)
30% Unlocked	0.09±0.06	0.85±0.07	1.4±10.4	0.8±0.6
60% Unlocked	0.09±0.05	0.77±0.06	3.7±14.9	1.3±0.7
90% Unlocked	0.09±0.04	0.66±0.05	19.8±14.4	2.5±1.6
30% Locked	0.08±0.05	0.83±0.06	--	--
60% Locked	0.04±0.05	0.77±0.04	--	--
90% Locked	0.03±0.06	0.68±0.04	--	--

5.3.1 Resultant Joint Moment

The mean circumferential distribution of normal forces can be used to calculate the resultant moments about each finger joint. If each finger segment is considered as a rigid body that conforms precisely to the surface of the handle and each joint as a frictionless pin, then resultant joint moments are calculated in a similar fashion as if the finger was analogous to a long shoe brake (Orthwein, 2004):

$$-\text{Moment}_{joint} = \text{Moment}_{normal} + \text{Moment}_{friction} \quad (1)$$

$$-\text{Moment}_{joint} = \Sigma\,(R_{joint}\cdot\sin(\phi_i)) \times N_i + \Sigma\,(R_{joint}\cdot\cos(\phi_i)-r) \times \mu N_i \quad (2)$$

where r is the handle radius, R is the distance from the center of handle to the center of the joint, and μ is the coefficient of static friction, N_i is the normal force at the relative angular location φ_i distal to the joint center (Figure 5.3.4).

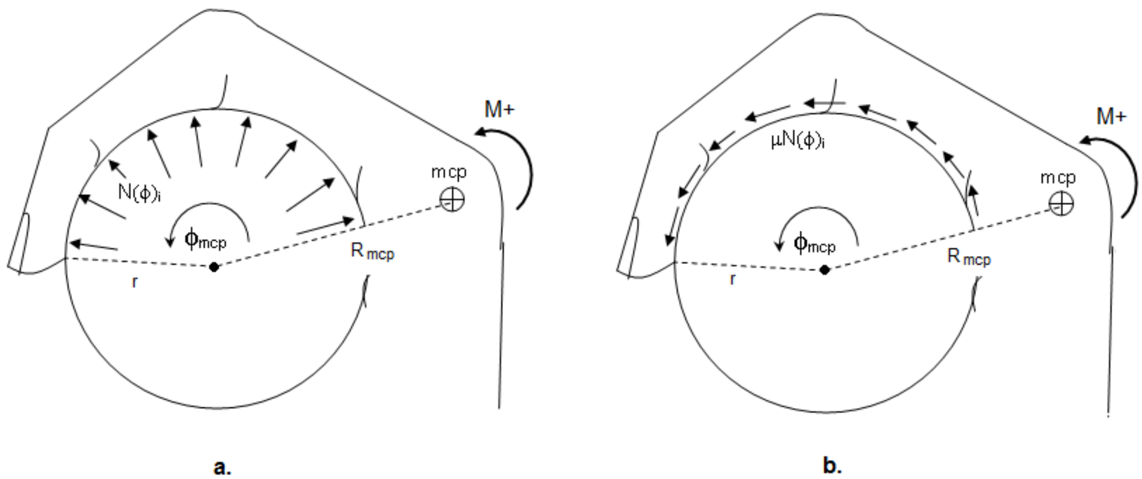

Figure 5.3.4 Illustration of parameters used to calculate resultant joint torque for the MCP joint. Normal forces (a) and frictional forces (b) over the contact arc of the finger cause a resultant moment about the MCP joint that must be balanced by internal flexion moment in order to maintain static equilibrium about the MCP joint. By definition, the joint center is at φ=0°.

To calculate resultant joint moment, the unknown input parameters R and μ need to be specified. Additionally, the absolute angular location (Φ) of the joint center on the handle surface needs to be known in order to map the correct normal forces to relative angular locations over the arc of contact (ϕ). The mean circumferential normal distributions presented in the results represent the four fingers summed together. Since the location of each joint and the contribution of each to total normal force will vary for each digit, estimations of input parameters for a single "lumped" finger need to be made. Input parameters used for moment calculations are presented in Table 5.3.2.

Table 5.3.2 Input parameters used to calculate resultant joint torque (Equation 2)

Joint	R* (m)	Φ (°)	ϕ (°)
DIP	0.0255	-72	45
PIP	0.0279	0	117
MCP	0.0355	90	207

*Handle radius plus 60% of average male middle finger (III) joint depth (Irwin & Radwin, 2008) measured by Garrett, 1971.

Resultant joint moments were calculated using mean circumferential normal distributions for each condition presented in the previous results section. Resultant moments are presented in Table 5.3.3 for the unlocked handle assuming zero ($\mu \approx 0$) friction and the locked handle for various values of friction. When no friction is present, resultant moments on each joint are similar for unlocked and locked handles (locked values are between 88% and 105% of unlocked values). When friction is present, joint moments are increased for the DIP (17% per +0.2 in friction) and slightly decreased for the PIP joints (2-3% per +0.2 in friction) on the locked handle. Moment created on the MCP joint is reduced 17-18% for every +0.2 in friction when on the locked handle.

Table 5.3.3 Resultant joint torque (N·m) caused by normal and frictional shear forces (Equation 2) for pull exertions on joints of the lumped finger

Pull Effort	30%	60%	90%
		Unlocked normal distribution (μ=0)	
DIP	-0.362	-0.743	-0.941
PIP	-2.674	-5.095	-7.034
MCP	-5.476	-9.534	-12.295
		Locked normal distribution (μ=0.2)	
DIP	-0.445	-0.445	-0.445
PIP	-2.536	-2.536	-2.536
MCP	-4.405	-4.405	-4.405
		Locked normal distribution (μ=0.4)	
DIP	-0.509	-0.877	-1.249
PIP	-2.479	-4.319	-5.803
MCP	-3.439	-6.294	-7.940
		Locked normal distribution (μ=0.6)	
DIP	-0.574	-0.574	-0.574
PIP	-2.421	-2.421	-2.421
MCP	-2.472	-2.472	-2.472

5.4 Discussion

The results show that pulling on a cylindrical handle created a bimodal circumferential normal force distribution with two modes corresponding to the distal digital phalanges and the middle of the proximal phalanges (Figure 5.3.1 and Figure 5.3.2). Normal force was reduced at the top of the handle in the location of the PIP joints. The local reduction is likely due to significant flexion of the PIP joint, which geometrically inhibits contact between the joint and the curved handle surface. The shape of the distribution would likely change for different size cylinders and different hand placement with respect to the direction of the pull force. A larger cylinder, for example, may smooth out the distribution because the finger joints would not be flexed as much as with a smaller handle.

For the locked handle, the circumferential distribution was similar in shape for each level of pull effort (Figure 5.3.1). This suggests that the biomechanical or motor strategy did not change for increasingly higher levels of pull force, but was scaled up uniformly. Future studies should examine muscular activation to test this hypothesis.

For the unlocked handle, however, the circumferential distribution shifted for increasing levels pull effort. (Figure 5.3.2) Also the peak force between the DIP and tip is close to that on the PIP and DIP segment. For the 30% pull levels, the distribution on the unlocked handle looks similar to that of the locked handle, with force on the proximal segments larger than the distal segments. As pull effort was increased, force on the distal segments becomes increasingly proportionally greater and at 90% pull effort the force on the distal segments was larger than the on the proximal. The change in distribution between locked and unlocked handles at higher levels of pull effort supports the hypothesis that friction acts to shift the distribution proximally.

For gripping exertions, average circumferential distribution was bimodal, with the largest mode at the fingertips and a smaller mode at the base of the thumb/hand. (Figure 5.3.1 and Figure 5.3.2) These results agree with observations from previous studies; the force distribution shape matches well with results reported by Dong et al. (2009), though their reported peak unit length pressures on the fingertips (~ 20 N/mm) were slightly higher than results observed in this study (~12 N/mm). This is likely due to differences in instrumentation.

In contrast to maximal gripping, little force was produced on the underside of the handle for high levels of pull effort, which is expected because the handle structure bears the finger force for pulling rather than the palm and thumb for gripping. However, even for low levels of pull (when the subject has the capacity to concurrently create pull force and squeeze the handle) the fingers act only to resist the applied load and do not exert any more force than is necessary. Therefore, extrapolation of biomechanical conclusions from analysis of grip-based tasks to other functional tasks such as pushing or pulling should be done so with caution.

Normalized resultant vertical forces (Table 5.3.1) showed similar values for unlocked and locked handles. Despite the proximal shift in circumferential distribution of peak normal forces for locked handles, the sum of normal components in the vertical direction was not significantly different between the two cases. This would indicate that frictional forces do not directly contribute to vertical force. Any friction that contributes to vertical force on the proximal side of the handle surface is balanced by opposite forces on the distal side.

Normalized vertical force decreased significantly as pull force was increased, showing an increasing discrepancy between the vertical force measured by the load cell and vertical force calculated from the pressure sensor matrix (Table 5.3.1). It is possible that since the pressure sensor was wrapped over a curved surface, the rated pressure range was reduced, and pressure response was nonlinear at locally high pressures. This would result in attenuation of peak forces in the higher pull efforts, which means that the peak pressure modes observed at the fingertips and on the proximal segments would likely be higher than results show.

Normalized resultant horizontal forces were small in comparison to vertical forces (<10%). For the unlocked handle, horizontal force (+90° direction) was constant over the levels of pull effort, but for the locked handle, decreased as pull force increased, which would be expected as the distribution of forces becomes greater on the proximal finger segments.

For the unlocked handle, subjects are free to rotate the handle and correspondingly alter the angular position of their finger joints from the initial position once the trial begins. For low levels of pull, handle rotation was small and finger joints stayed close to initial placement. However for 90% pull effort, a significant clockwise change in angular position of the handle was observed. Because the direction of pull is downward and constant, this suggests that the subjects alter the position of the joints on the handle as force builds up in a way that enables the finger flexors to produce a large downward force. According to our results (Table 5.3.1), the highest force is produced with the PIP joints an average +20° from the axis of pull for this diameter cylinder and in the absence of friction.

Angular position for the unlocked handle was not constant over the 3-second period of constant pull force, meaning that subject did not hold the handle in mechanical equilibrium over the exertion duration. Average angular velocity for the 90% pull effort condition, 2.5±1.6 °/s (Table 5.3.1), was greatest and means that over the 3-second time period where a constant pull force is exerted the handle is rotated an average of 7.5°. The hand is slowly opening during this time. Because the subject knows they only have to exert a constant target force for a brief period of time, the subject may be utilizing internal friction between the finger tendons and pulleys or in the lengthening flexor muscles to reduce the required muscular effort to maintain a constant pull force. This may also be due to increased motor recruitment for slow lengthening contractions (Semmler et al., 2002).

The analysis of resultant joint moments that normal forces exert on the finger joints suggests that friction changes the required moment that needs to be produced by the finger flexors to create the pull force. Friction between the hand and the handle can reduce the required moment needed from the finger flexors for the MCP joint. This is mainly due to the angle of contact the fingers have over the surface of the handle (Figure 5.3.4), as friction on the distal finger segments ($\phi \geq 64°$) causes a positive (flexion) moment about the MCP joint (Equation 2). However, if the contact arc is small, such as with the DIP joint, surface friction forces will always act to extend the joint. These results suggest that surface friction may increase required forces from the flexor digitorum profundus (FDP), which inserts on the distal phalanges, and decrease required forces from the flexor digitorum superficialis (FDS), which inserts on the intermediate phalanges. Friction reduces any required loading of the intrinsic finger muscles (radial interosseus, RI, ulnar interosseus, UI, and lumbrical, LUM), which can act to flex the MCP joint (Li et al, 2002).

The analysis of resultant joint forces here is intended only to provide a framework for interpreting the results. Further work will be required to develop a predictive model. These results warrant further investigation of the influence of surface friction on functional hand tasks. Future studies should examine surface pressure distributions for each finger separately and track the location of finger segments and joint centers during exertions, as well as well as the activation of flexor muscles. This will allow better estimation of input parameters for biomechanical models.

Isometric gripping exertions have often been used to validate biomechanical models of the hand (Chao et al., 1976; Sancho-Bru et al., 2003a). Measured forces at the handle surface are used to predict tendon tension and muscular effort so that “optimal” diameters for cylindrical work objects such as tool handles can be recommended (Sancho-Bru et al., 2003b; Irwin & Radwin, 2008). Results presented here suggest models should be updated to include applied directional loading and shear forces in order to properly characterize optimal handles for functional tasks other than squeezing.

This research only measured surface pressure on a single cylindrical handle. The distribution of normal forces and hand configurations for pulling tasks will likely change for larger or smaller cylinders; future research should examine this effect as “optimal” handle size may be different for pulling than for gripping. In addition to surface normal pressure, tangential forces should be measured directly to fully understand frictional effects. To this end, new instrumentation technologies that can measure both normal and tangential surface forces in high resolution are needed to fully characterize hand/object coupling.

In summary, study of the circumferential normal force distribution on a cylindrical handle showed that pulling distributions were different than gripping distributions, and that peak normal forces shifted from the distal finger segments to the proximal segment in the presence of friction during pulling. Calculation of resultant moments on finger joints using a simple biomechanical model showed that resultant moment on each joint was similar in both friction and no-friction handle conditions. However, it can be shown that inclusion of tangential surface friction increases the resultant moments on the DIP joints, and decreased on the PIP and MCP joints. This suggests that increased friction between the hand and a grasped handle can decrease required effort to hold, pull, or carry items.

5.5 Acknowledgments

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CHAPTER 6

Discussion & Conclusions

6.1 Discussion of Aims and Findings

This dissertation was organized into an Introduction and four Chapters that presented results and analysis from human subject experiments. Each experiment was chosen to test specific hypotheses and address on or more of the four specific aims of this dissertation. The four specific aims were:

1) Develop methods to measure and quantify functional hand strength, specifically the capacity to resist loads on a grasped objects
2) Quantify the role of active and passive components on functional hand strength
3) Evaluate how handhold properties (size, shape, orientation) affect the capacity to hang on
4) Investigate how surface interactions and external loading affect distribution of forces between the hand and handhold and resulting biomechanical loads on the hand

This chapter will discuss the findings, limitations, and future implications from each experiment as they relate to the specific aims, and as each chapter relates to the general aim of this work: to create knowledge that explains the strength of the coupling between the hand and a handheld object.

6.1.1 Develop methods to measure and quantify functional hand strength, specifically the capacity to resist loads on a grasped objects

Several criteria were outlined in Chapter that a specific strength metric must meet in order to provide an accurate functional capacity for hanging onto an object. These were:

1) An external load vector must be applied to the grasped object in sufficient magnitude to approach failure of the hand/object couple

2) The strength of the hand/object couple must be isolated with respect to the strength of other body segments
3) Surface interactions/friction must be included, measurable, and controllable

Traditional metrics, where the subject creates force on an object (grip strength, pull strength, etc.), do not meet these criteria. Instead, the metric we have chosen is the amount of force that can be resisted when a grasped object is loaded by an external force, before it slips or is pulled from the grasp of the hand. In this dissertation, this is referred to as "breakaway strength".

The very few studies that have actually measured breakaway strength did so by placing an external load on a grasped handle via pneumatic or mechanical system. In either case the handle was actuated away from the subject's hand. This required that the subject remain stationary and not move along with the handle; which requires that an equal and opposite load be applied to the body at some point proximal to the hand. Rejulu and Klute (1993) did this by placing the hand in a glove that was fixed to an immovable structure at the wrist. This isolates the hand from the rest of the body, but requires that a glove be worn at all times. Garret et al. (1967) used pneumatics to pull a handle downward and away from both hands of a seated subject. The arms and hands were extended fully so the load on the hands was likely balanced by muscular action from the torso. This is evident because the study was ended prematurely when the 10th subject suffered a hernia during a trial. Based on this shocking occurrence, the development of a method for placing large loads on the hands, while at the same time keeping loading on other parts of the body at tolerable levels, was needed.

The solution to this problem that we arrived upon was to use gravity and one's own bodyweight to create downward load on the hand rather than muscles at any proximal body linkage creating the pull force. It has been shown that joint ligaments and connective tissue can bear traction across joints and do not require contraction of muscles to bear a load (Basmajain & DeLuca, 1985; Elkus & Basmajain, 1973). In a posture with the arm fully extended vertically overhead, the loading vector (gravity) acts in the direction of arm bones and through the shoulder. Muscles from the arms, legs, or torso do not need to create force. By adopting this posture, the hand is isolated from the strength of proximal body joints and no joint is placed under harmful loads.

In this testing posture, the handle would then be actuated upward with respect to the subject, or the subject lowered with respect to the handle. By adjusting or altering handle properties, different coupling scenarios can be presented to the subject. However, if the capacity of the hand to hang onto the handle is greater than bodyweight, the subject will be lifted off of the ground. A belt or similar method of securing the subject is required and additional force greater than bodyweight may need to be applied. The apparatus used to measure breakaway strength is described in detail in Chapter 2.

This method of measuring breakaway strength has an additional advantage in that it supports the overall aim of this research because this testing posture is the posture that a falling person would be in. However, our method of testing moved the hand and handhold apart at an initial rate of 14 cm/s, which is slower than actual rates occurring in a fall. Also, the total external load applied to the handle was kept constant at 1245N. This may be much smaller than loads applied in a fall. For example: if a person holding onto a ladder rung falls 0.5m before reaching the end of their overhead grasp then they will be moving at 313 cm/s and if we assume the person weighs 100kg, and it takes 0.5 seconds to slow the fall, then the impulsive load on the hand is 980 * 3.13 / 0.5 = 6135 N.

It is likely that impulsive loading of the hand could produce higher breakaway strength values than reported here, but also increase the risk of injury. The overall breakaway strength values presented in the experiments should therefore be considered as lower-bound estimates of the actual capacity to hang on.

Future breakaway strength methodologies should allow the rate of loading on the hand to be adjusted. This may be accomplished by using a mechanical system to raise and lower the handle with respect to stationary subject, or by installing a valve to control the speed of the lowering platform. Due to the very large loads placed on the hand during breakaway tests, the rate of loading was limited to prevent injuring subjects. Lower loading rates may allow the subject to let go if they feel pain, so for coupling conditions where breakaway strength is expected to be very high (i.e. high-friction situations), reducing the rate of loading may be prudent.

The breakaway strength method we have chosen allows any surface characteristic to be presented to the subject, but what the coefficient of friction actually is between that handle surface and skin remains the subject of an entire field of study and is beyond the scope of this dissertation. In the experiments presented here, we attempted to maintain equal friction for all participants. This is necessary for interpretation of breakaway strength across different studies.

Four experiments measuring breakaway strength in total were performed on 48 subjects (12 subjects each), which are presented in Chapters 2, 3, and 4. Only one adverse effect occurred: one subject got a blister. The within subject coefficient of variation (3 reps) for breakaway strength in the first experiments (Chapter 2) ranged from 0.07-0.10 for horizontally oriented cylinders as compared to 0.04 for grip strength on the Jamar dynamometer. Because of the influence of friction on breakaway strength, the coefficient of variation should be affected for different handle orientations or properties.

Mean breakaway strength for 25mm diameter horizontal cylinders was 668 N for Experiment 1 in Chapter 2, 692 N for Experiment 2 in Chapter 2, 669 N in Chapter 3. This shows good repeatability of the breakaway strength metric for three different sets of twelve young adult subjects. Breakaway strength is susceptible to fatigue as shown by a significant session effect in Chapter 4 (Table 4.4.1 and Table 4.4.4), so care should be taken to minimize the number of trials and maximize rest between experimental sessions.

Breakaway strength can be much greater or much less than grip strength, depending on the specific handhold (shape and orientation) presented to the subject. This confirms the need for this new strength metric when evaluating functional capacity in high-loading conditions. However, if the coefficient of friction is very small, or coupling between the hand and object is precarious (like a pinch grip), then it is likely that other body segments can produce enough force to break the hand/object couple. Pull strength can therefore be used to characterize functional capacity because the hand/object couple would be the force limiting link. This would eliminate the need for a breakaway strength apparatus and make data collection easier. However, if the subject creates the external load, it may be difficult to control the rate of loading and the direction of pull.

6.1.2 Quantify the role of active and passive components in functional hand strength

It isn't hard to observe that both muscular action (active) and friction (passive) play a role in holding onto an object. Just try holding onto a wet bar of soap. However, quantifying specifically how each relates to breakaway strength requires careful planning. In order to determine the relative weight of active or passive components to hand/handhold coupling, experiments must be designed to compare coupling scenarios that isolate each component from the other. In Chapter 2, breakaway strength for a smooth steel, horizontally-oriented cylindrical handle was measured. The method we developed to present a friction and a zero-friction condition to the subject was to measure breakaway strength for a fixed cylinder and for a cylinder that was allowed to rotate about its long-axis. By unlocking the cylinder, any torque from friction that acts to keep the hand wrapped around the handle would meet no resistance and the handle would rotate. While this isn't a true "zero-friction" condition, it offers advantages over alternatives, such as coating the handle with a slippery film, because it doesn't introduce any contamination to the subject's skin. By comparing breakaway strength between the two scenarios, we determined that steel-to-skin friction increased the capacity of the hand/handhold couple by 1.25 times, or 25%.

In Chapter 3, the method that was used to present different friction conditions to the subject was to have the subject wear thin gloves of different surface-friction characteristics. This method does not introduce contamination to the subject's skin, but the gloves may influence strength. For horizontal handholds, breakaway strength was reduced 25% for an approximate 0. 43 decrease in coefficient of friction. For 45° handhold orientations, the mean decrease was 108%.

The standard measure of active finger flexor muscle capacity is grip strength. We can compare breakaway strength to grip strength as long as grip strength is measured so that the fingers are in similar posture during breakaway exertions. Because the fingers open to their maximal force posture during breakaway exertions, breakaway strength should be compared to maximum grip strength at the optimal finger span. For the experiments presented here, grip strength was measured at position 2 on a Jamar grip dynamometer. Results from Chapter 2 show that breakaway strength for the low-friction horizontal cylinder was 1.26 times greater than isometric grip strength. This suggests that surface friction alone is not responsible for the discrepancy between breakaway strength and grip strength. Since breakaway strength for the fixed cylinder was 1.58 times grip strength, surface friction explains 20.3% of breakaway strength, active finger flexion (grip strength) explains 63.3% of breakaway strength, and 15.8% is due to some other factor.

In contrast to grip strength, breakaway strength is not an isometric contraction for horizontal handholds. As the applied load on the hand/handhold couple is increased, the fingers are forced open and breakaway occurs. Breakaway strength is an eccentric contraction. This means that passive internal forces (e.g. tendon-pulley friction) and/or lengthening muscle forces can contribute to breakaway strength. Friction between the flexor tendons and the finger pulleys may contribute to the external force by up to 9-12% of the (An et al., 1993; Moor et al., 2009; Schweizer et al., 2003; Schweizer, 2008) for large finger loads. Eccentric exertions have been shown to be 13-17% greater than isometric contractions (Dvir, 1997), and may be due to mechanical or motor control mechanisms (Katz, 1939; Duchateau & Enoka, 2008).

The comparison between breakaway strength and isometric grip strength is relatively straightforward for horizontal handhold orientations but if the handle is not oriented horizontally, then the wrist and fingers will not be in the same positions for the two measurements. In the experiments presented here, grip strength was measured for only one posture (wrist in the neutral position), so direct comparison is not warranted for oblique or vertical handholds, where the wrist or hand may be in a different posture.

For vertically oriented handholds, only friction directly opposes the applied vertical load. That means that passive forces are directly responsible for 100% of breakaway strength. However, to create frictional force, the handle must be squeezed by the hand. We would assume that breakaway strength for these situations is therefore proportional to the active component. However, the accurate characterization of coefficient of friction between the hand and handle in order to determine this proportionality is difficult.

There are many studies that have described the coefficient of friction between the skin and an object. Reviews of skin friction and finger-object friction studies are presented by Sivamani et al. (2003) and Tomlinson et al. (2007). Several methods have been used to measure friction, though most measure quasi-static or dynamic friction and do not address the hand other than the fingertips (Savescu, 2008; Sivamani et al., 2003; Tomlinson et al., 2007). Only a few studies have attempted to quantify the coefficient of friction for whole-hand tasks such as twisting a handle, opening a jar or sliding along a rail (Lewis et al., 2007; O'meara & Smith, 2002; Seo et al., 2008). Some general parameters that influence friction are the normal force applied to the surface, the area of contact, the direction of motion, the speed of the motion, and hydration of skin (Sivamani et al., 2003).

Skin friction decreases as normal force is increased (Figure 6.1.1). No studies have measured friction for the very high forces that occur during breakaway exertions. Breakaway strength may therefore be a valuable tool in estimation of skin friction under high loads. If an accurate biomechanical model of breakaway strength is developed for situations with known or stable friction coefficients (e.g. for glove materials), then breakaway strength for bare handed situations can provide values for skin friction.

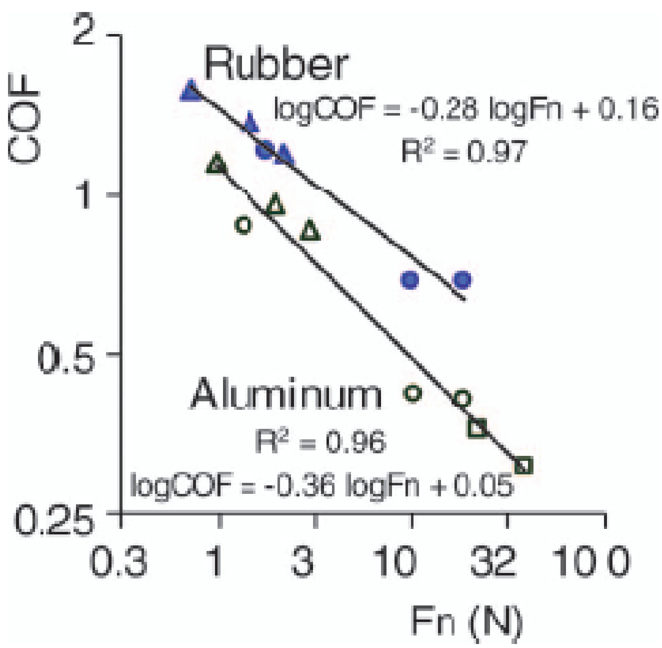

Figure 6.1.1 Friction coefficient as a function of normal force for rubber (filled symbols) and for aluminum (unfilled symbols) from three studies (Δ), Seo et al. accepted; (o), the present study; (□), Buchholz et al. 1988) in log scales. COF = coefficient of friction. (From Seo & Armstrong, 2009)

6.1.3 Evaluate how handhold properties (size, shape, orientation) affect the capacity to hang on

Shape:

The effect of handhold cross-sectional shape on the capacity to hang on is the focus of Chapter 3. In that chapter it was shown that cylindrical handles afford the greatest breakaway strength as compared to any shape with corners (square, diamond, or rectangle; see Table 3.3.1). This result is interesting because it seems intuitive that a shape that fits the contours of the three finger segments would be most comfortable and therefore provide better coupling. However, at the very high loads that are exerted during breakaway, any corner (even those which are rounded) will create an area of locally high pressure on the hand. Since these are voluntary exertions, subjects may have let go due to pain at the locations of high pressure.

Pain may illicit a psychophysical response that influences capacity. For these laboratory voluntary exertions, motivation to hang on may not be the same as if a person were about to fall to their death. Elkus and Basmajain (1973) measured endurance for subjects hanging by two hands either with bare hands or when wearing gauntlets that would not allow the fingers to open and found pain to be the limiting factor:

> "Even when the hands are forcibly kept in a grip position, the subjects cry out for relief. Thus we cannot even fault fatigue in the gripping muscles. Severe discomfort—even naked pain—is the central feature and this develops in just a few seconds in some persons. This pain seems to be in the skin, ligaments and muscles in differing proportions, but there is no doubt that it is the major reason why people lose their grip on the support to which they are clinging."

Biomechanical models of hand/object coupling therefore need to include threshold limits for localized pressure (Fransson-Hall & Kilborn, 1993). Handle designs that may be biomechanically optimal in theory may not actually be due to psychophysical constraints.

Current regulations and standards require that handholds be free from sharp edges, splinters or burrs and permit full grasp or power grip by the hand (fixed ladders: OSHA 29 CFR 1910.27, ANSI-ASC A14.3-2008; vehicles: FMCSA-DOT 49 CFR 399.207, SAE J185, SAE J2703). Therefore, handholds of common stock metal shapes (cylindrical rod, square rod and rectangular plate), in various sizes, are frequently employed and equally accepted in the workplace. Cylindrical cross-sections were found to afford 16-47% greater breakaway strength than other shapes and were the only shape that subjects could support their own bodyweight on average (Table 3.3.1). This supports the use of cylindrical shapes for handholds in the workplace.

Size:

In Chapter 4 it was shown that, as with isometric grip strength, breakaway strength was affected by cylinder diameter. Grip strength literature shows that grips strength is greatest for diameters 31-38 mm (Amis, 1987; Lee & Rim, 1991; Edgren et al., 2004) and decreases for handles smaller or larger. However, this was not the case for horizontally oriented handles, as smaller diameters provided 7-17% better coupling than other tested diameters (Table 4.4.2 and Figure 4.5.2).

When the long axis is perpendicular to the applied pull force (horizontal), the fingers must be forced open in order to break hand/handhold coupling. In this situation smaller handhold 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 (Figure 6.1.2). We may hypothesize that a very small diameter handle will be optimal for pulling tasks where 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 (think of hanging onto a string or wire). However, at ever increasing pull forces the local pressure over the small contact area will become so high that pain will become unbearable and/or injury may occur. For structural reasons, safety standards and regulations do not allow handhold diameters less than 0.75 inches (19mm). This diameter is only slightly smaller than the 22mm handhold tested in Chapter 4, so it is unlikely that pain will reduce the ability to hang onto the smallest allowable cylinders.

As the orientation of the handle moves away from perpendicular and more parallel to the applied pull force, the situation becomes more like that typical of a test for isometric grip strength. The fingers are not forced open and the hand needs to squeeze the handle into the palm to create friction forces on the surface. From the results presented in figure, optimal cylinder size may be slightly smaller than for isometric gripping. For vertical orientations hand and wrist posture are deviated, which cause the fingers to approach pinching (key or lateral pinch) when the handle diameter is small.

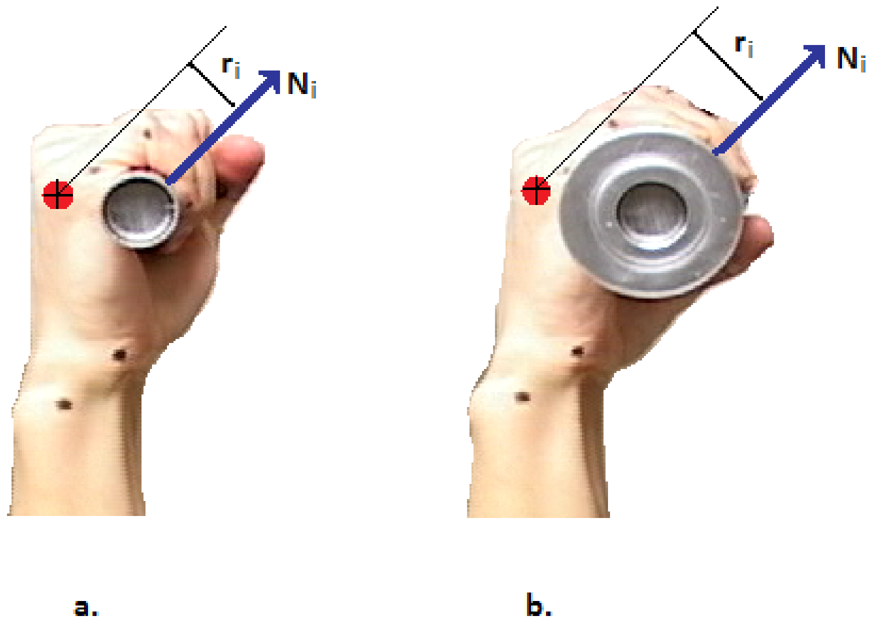

Figure 6.1.2 Normal force acting against the MCP joint for (a) 22mm and (b) 51mm handholds. The finger flexor muscles act to close the fingers creating a flexion moment about each finger joint. The surface of the handle acts against those moments. As the cylinder size increases, so does the moment arm (r_i) of a surface normal force (N_i) on the finger joint and hence increases the moment against the finger flexors. Contact area decreases as handle size decreases.

Orientation:

The effect of handhold orientation on breakaway strength was presented initially in Chapter 2 and explored more deeply in Chapter 4. Breakaway strength decreased as the handhold orientation moved from perpendicular to the applied load (horizontal) to parallel to the applied load (vertical). Breakaway strength is always greatest when the fingers must be forced open in order to break the hand/handhold couple. For climbing situations, this implies that horizontal handholds are optimal.

The relationship between orientation and strength was not linear; breakaway strength decreases more greatly once the hand begins to slide down the handle. As the handhold becomes more steeply inclined, frictions is relied upon more greatly to produce breakaway force. This means that the coefficient of friction is very important for steeply inclined or vertical handholds. Additionally, the coefficient of friction will determine when the hand starts to slide down the long axis and off the end of the handle rather than having the fingers be forced open. The type of coupling failure that is observed for different handhold orientations is presented in Table 4.4.3 and Table 4.4.6.

Handhold orientation also affects the posture of the wrist and fingers. In order to compare breakaway strength to grip strength, grip strength needs to be measured in the same posture the hand adopts on inclined handholds. This may not be possible with traditional dynamometry. It may be more useful to measure the surface normal distribution for these situations. This can be done with pressure sensitive arrays like the experiment in Chapter 5. This would be more useful in calculating frictional forces which depend on the normal force around the handle, rather than a scalar vector like grip strength.

<u>Relative Influence of Shape, Size and Orientation:</u>

The greatest observed difference in breakaway strength for handholds of different size was 98N between the 22mm handhold and 51mm handhold in the horizontal orientation for males (Table 4.4.2). The greatest observed difference in breakaway strength for handholds of different shape was 251N between the cylindrical handhold and the rectangular handhold in the horizontal orientation for males (Table 3.3.1). The greatest observed difference in breakaway strength for handholds in different orientations was 363N between horizontal and vertical orientations for the 22mm cylinder for males (Table 4.4.2).

In general, orientation is found to be the most influential of these factors affecting breakaway strength. However, there are several interactions between factors that are important. Specifically, the optimal size of a handhold varies for different orientations. These results are also not exhaustive of the range of possible handhold designs. For example, there may be handhold shapes that perform equally well at many different orientations (such as knob or ball).

<u>Example Design Case: Industrial Fixed Ladders</u>

A common tool used for climbing is the ladder. Fixed ladders are installed in and on buildings, heavy machinery, and vehicles (e.g. semi-truck tractor trailers). Ladders are unique in that both the feet and the hands are supported by the same structure (as opposed to grab bars which are meant only for the hands). The majority of bodyweight is supported by the feet during climbing, although constant force is required by the hands to maintain balance. Average peak forces on the hands during climbing can range from 28-34% of bodyweight when climbing with cylindrical rails (vertical orientation) and 42-47% of bodyweight when climbing with cylindrical rungs (horizontal orientation) depending on ladder orientation (Armstrong et al., 2009). It is unknown whether the difference in exerted climbing hand force between rungs and rails are due to postural differences or differences in the ability to exert force on each handhold.

Based on the breakaway strength data presented in this dissertation, workers would be able to support themselves best by climbing with cylindrical rungs (horizontal orientation) that had a small (22mm) diameter. By wearing gloves with a high coefficient of friction the required effort to exert force would be reduced and the capacity to hang on in a fall would be increased. However, because the hands and feet are both supported by the rungs, and the feet support most of the bodyweight during climbing, it may be more important to design rungs to best support the feet to prevent slips. The design of footholds and the mechanisms of slips and falls are beyond the scope of this dissertation.

If the rungs are design to prevent foot slippage they may not be suitable for use by the hands. The hands must therefore use the rails to aid in climbing, balance, and support the body in the event of a fall. In Chapter 2, breakaway strength for 25mm cylindrical rails was reduced by 34% compared to 25mm cylindrical rungs, and subjects could support 70% of their bodyweight with the rail (Table 2.3.1). In Chapter 4, it was found that the optimal size handhold is different for rungs and rails, and increasing rail diameter from 22mm to 32mm increased capacity by 5%, or 1-2% of subject bodyweight (Table 4.4.2).

For industrial fixed ladders, horizontal cylindrical rungs are often supported by vertical rectangular plate rails. This is due to ease of manufacturability and the ability to inspect welds between the rungs and rails. Using these rails is a worst case scenario for the hands however, as the orientation is vertical and the rectangular shape afforded the least strength of all shapes tested (Table 3.3.1). Plate rails afforded 26-34% less strength than cylindrical rails and half as much strength as a horizontal cylindrical rung (Table 2.3.1). If rails are to be used by the hands, they should not be rectangular plate stock.

6.1.4 Investigate how surface interactions and external loading affect distribution of forces between the hand and handhold and resulting biomechanical loads on the hand

The surface pressure distribution that the hand exerts on handholds during pulling exertions is presented and discussed in Chapter 5. Circumferential force distributions were different for pulling than gripping distributions and peak normal forces shifted from the distal finger segments to the proximal segment in the presence of friction during pulling. It is hypothesized that friction between the skin and the surface of the handhold causes shear deformation of the internal soft tissues, which in turn act on the rigid bone/ligament links of the fingers and keeps the hand wrapped over the curved surface of the handhold. This is conceptualized by the effect of a belt over a pulley or capstan.

Calculation of resultant moments on finger joints using a simple biomechanical model showed that resultant moment on each joint was similar in both friction and no-friction handle conditions. However, it can be shown that inclusion of tangential surface friction increases the resultant moments on the DIP joints, and decreased on the PIP and MCP joints. This led to the conclusion that friction plays an important role in determining muscular loading, and can reduce the load on the FDS and the intrinsic hand muscles. This suggests that increased friction between the hand and a grasped handle can decrease required effort to hold, pull, or carry items.

The simple model that was used to calculate resultant hand moments treated all four fingers as a single rigid long-shoe brake (Figure 6.1.3). The pivots for the brakes were considered the finger joints (DIP, PIP, MCP). This calculation requires the correct distance between the joint center and the center of the handhold. Several studies have characterized the anatomical or functional location of finger joints in free movements or in various configurations (An et al. 1979; Buchholz & Armstrong, 1991; Buchholz et al., 1992; Chao et al., 1976), but few have attempted to identify or specify the location of these joints in relation to the surface of a grasped handhold (Lee & Rim, 1991; Lee & Zhang, 2005; Sinsel et al., 2010). No studies have examined the location of finger joints during pulling exertions.

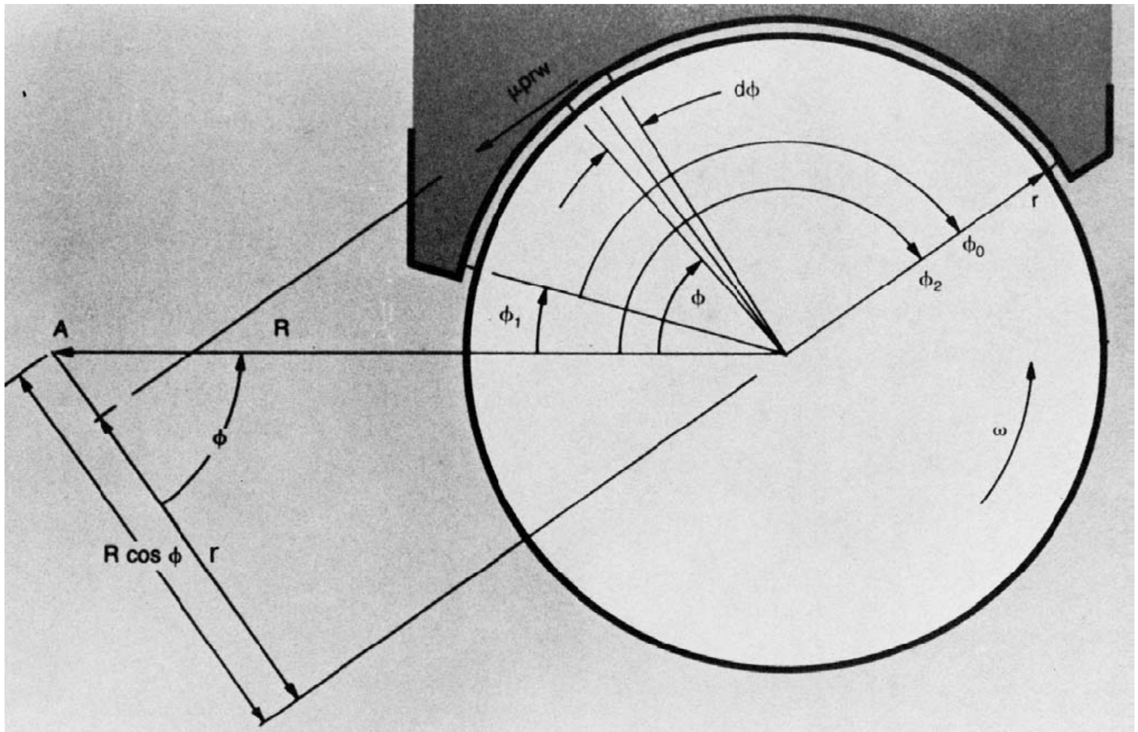

Figure 6.1.3 Geometry for calculating the moment due to friction about pivot about point A. From: Orthwein (2004).

In order to provide a better estimate of loading on the joints (and consequently the required muscular forces) the location of finger bones should be recorded along with surface force distributions. This type of experiment has recently been performed by Sinsel et al. (2010), who used a similar but higher resolution Tekscan® surface pressure sensor along with a motion capture system to record force and joint position during grasping. To use this method to prescribe kinetic inputs for inverse dynamic models requires the proper identification of bone, joint center, and tendon location from surface markers. This is made further difficult because force is transferred to the rigid bone not via a single contact location, but through the compression and deformation of skin and subcutaneous tissues.

The skin is made up of several layers of tissue that deform as it's loaded. It is a non-linear anisotropic viscoelastic membrane which has complex and varied properties (Tomlinson et al., 2007). Skin and subcutaneous fat tissue compressive properties have been investigated by very few studies (Wu et al., 2007). In addition to compression, friction against the skin will produce a shear deformation on finger tissues (Seo &

Armstrong, 2009). The shear deformation properties of the fingertip pad display linear visoelastic behavior during loading (Pataky et al., 2005). In order to predict the force distribution on a handhold based on muscular activation (forward kinematics), skin and finger tissue properties must be researched. Properties and also needed to develop useful finite element models of the skin (Wu et al., 2005).

6.1.5 Development of a biomechanical model: concept maps

This dissertation provides knowledge that will be valuable in the development of a model of breakaway strength. A model that explains the strength of the coupling between the hand and handhold will reduce the need to perform breakaway tests and allow for simulation and prediction of human capability. Figure 6.1.4 shows a broad overview of factors influencing breakaway strength. Generally, external factors can be lumped into the categories of task, handhold, individual, and environmental factors. This map can be focused to a much finer level (Figure 6.1.5).

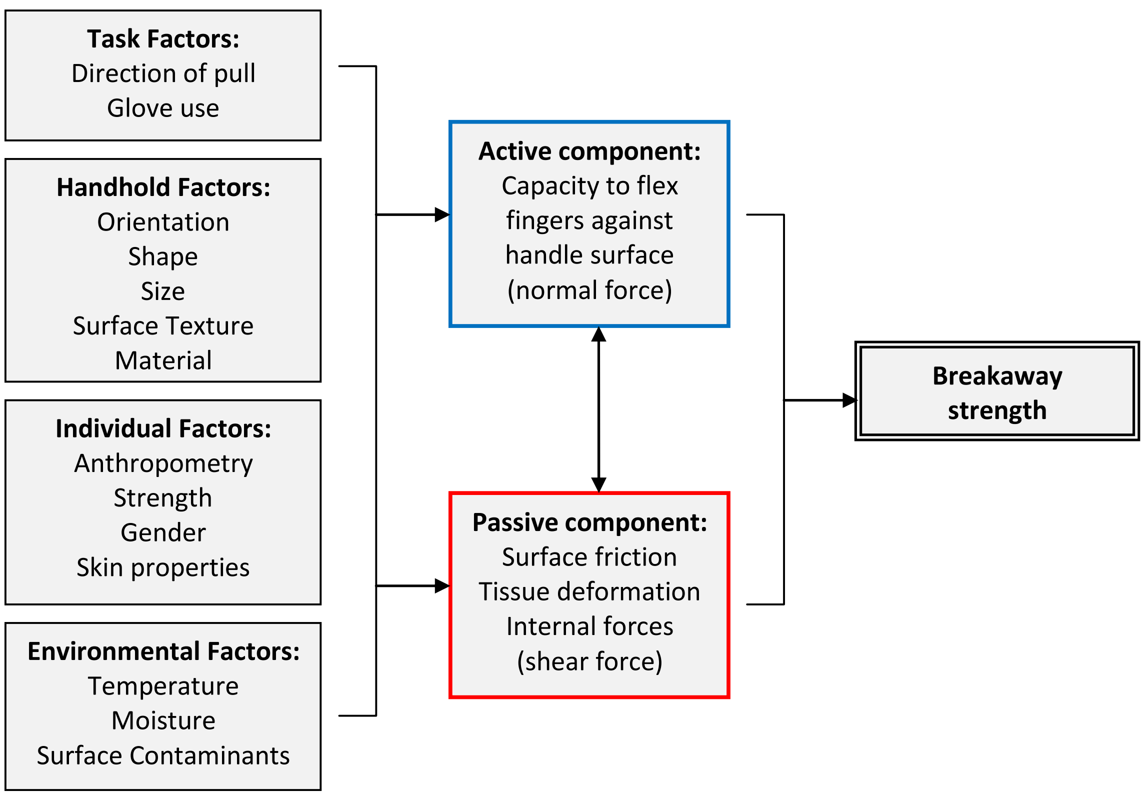

Figure 6.1.4 High-level overview of factors affecting breakaway strength. Hand/handhold coupling is comprised of both active and passive components that influence each other.

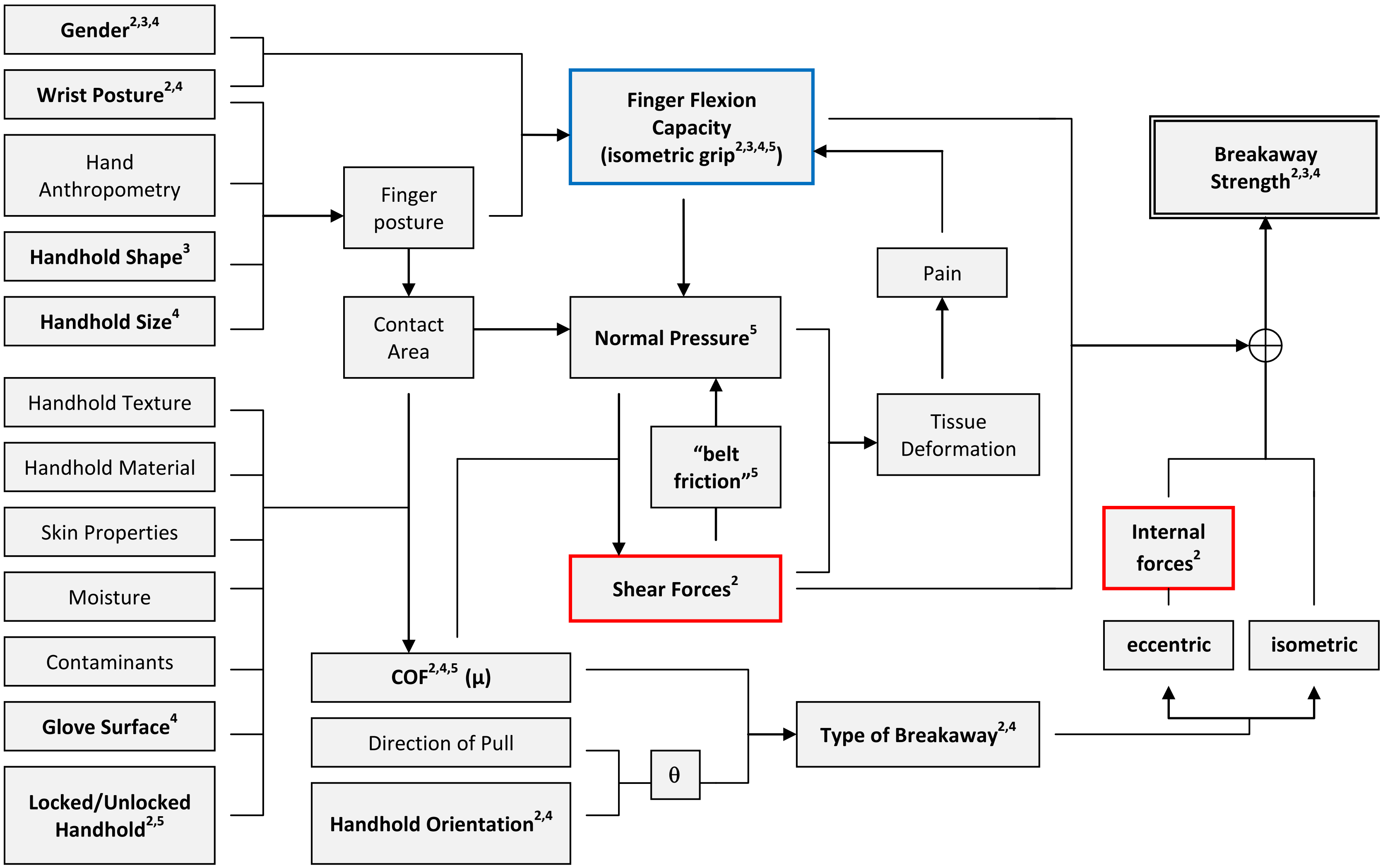

Figure 6.1.5 Schematic of factors influencing breakaway strength. Items in bold are addressed either directly or indirectly by experiments presented in this dissertation (Chapter numbers indicated by superscripts). Several factors (left side) act to generally affect either the capacity to flex the fingers (active) or the coefficient of friction (passive). Both active and passive components act to influence each other (center area) and total breakaway strength (right side).

6.2 Future Research Directions

The following are brief research questions that would complement the body of knowledge established by the research presented in this dissertation. While these may address some of the specific limitations discussed previously or create information to improve proposed biomechanical models, my intention is to suggest new research avenues inspired by this work.

6.2.1 The role of internal forces in retaining grasp

Since breakaway force is greater than grip strength even when surface friction is minimized, internal forces may be important in hanging onto objects. These internal forces could be friction between the finger tendons and pulleys or may be related to lengthening of activated muscle fibers. Subjects slowly extended their finger joints during pull exertions on handles that were free to rotate while exerting a constant pull force. Why would they employ this motor strategy? Are they utilizing internal friction to reduce require effort?

6.2.2 Fall mechanisms and dynamic ability to arrest vertical falls

While breakaway strength can give an estimate of the hand's capacity to arrest a vertical fall when the arm is at the end of reach, it does address the initiating fall mechanisms or even the ability of persons to reach, grasp, and exert forces with the upper limb. If the fall victim cannot reliably perform these actions, the capacity of the hand/handhold coupling may be inconsequential to the outcome.

6.2.3 Tissue deformation and joint configuration for grasp and pull exertions

Though there is some information about compressive and shear deformation of the fingertip, we could find no studies that attempt to characterize skin deformation over the entire loading surface during grasp. Because the skin and subcutaneous tissue of the hand varies along its length, investigation of deformation during grasp and pull is needed. This deformation will change the surface area of contact, the distribution of normal forces at the handle surface, and the geometry of the internal tissue fiber orientations. It may be possible to observe and measure these deformations by imaging the hand with MRI.

Using plastic handles of different shapes, the hand can be loaded and the tissue deformation observed. Smaller extremity MRI machines have small enough magnetic fields to place load cells outside the machine to measure forces on the plastic handle.

6.3 Summary of Major Findings and Conclusions

- Traditional metrics of upper limb strength such as isometric grip strength and pull strength are unreliable for predicting the capacity to hang onto a grasped object or handhold.
- A technique was developed to measure the maximum force that can be exerted on an object before it's pulled or slips from the grasp of the hand. This strength metric is referred to as "breakaway strength" and is a functional measure of the strength of the couple between the hand and a handhold.
- Breakaway strength can be significantly greater or significantly less than grip strength for similar grasped objects. This supports the hypothesis that hand/handhold coupling is comprised of active (isometric or eccentric finger flexion) and passive (frictional) components.
- Breakaway strength is significantly affected by surface friction, handhold shape, handhold size, and handhold orientation.
- 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). This suggests that internal friction resist the opening of the fingers.
- Breakaway strength is maximized for handhold orientations that are perpendicular to the applied force and decreased as the handle is oriented more towards the direction of applied pull force.
- Breakaway strength is increased 75-94% as the orientation of the handhold moves from vertical to horizontal for overhead handholds.
- Breakaway strength is greatest for cylindrical handholds compared to rectangular, square, or diamond shaped handles of similar size. Handhold shapes with corners reduce the ability to hang on.

- When the applied 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 (32mm). When the applied force is perpendicular to the handhold, smaller diameter handles increase breakaway strength (22mm).
- Wearing gloves may increase or decrease the ability to hang on depending on frictional properties of the glove/handhold interface.
- Despite reducing isometric grip strength slightly, high-friction gloves will increase breakaway strength. Gloves which reduce friction between the hand and the handle will reduce the ability to hang on.
- For the subjects tested in this dissertation, only male subjects could support their bodyweight with one hand on average.
- The only handholds on which average subjects are capable of supporting their own bodyweight with one hand are fixed horizontal cylinders of 22-25mm diameter or 32mm cylinders while wearing high-friction gloves in the 90° and 75° orientations.
- In situations where worker may only have one handhold to support their body, it must be oriented horizontally to increase the chances of arresting a fall caused by the unexpected loss of foot support.
- Circumferential normal force distribution on a cylindrical handle is different for isometric pulling than for isometric gripping.
- In contrast to gripping, when exerting a pull force on a handhold, normal pressure on the palm (underside of the handle) is negligible.
- Consistent with previous studies, the greatest normal pressure is exerted on the distal segments of the phalanges and at the base of the thumb and palm during maximum isometric gripping.

- Most pull pressure was distributed over the fingers unevenly in a bimodal distribution, with the greatest pressures occurring at the distal segments (DIP joints) and midway along the proximal phalanx.
- Peak normal forces shifted from the distal finger segments to the proximal segment in the presence of friction during pulling. This supports the hypothesis that friction acts through the soft tissues of the fingers and creates an increased normal force in the direction of proximal segments (i.e. "belt friction").
- Calculation of resultant moments on finger joints using a simple biomechanical model showed that tangential surface friction increases the resultant moments on the DIP joints, and decreased on the PIP and MCP joints. This suggests that increased friction can decrease required effort to hold, pull, or carry items by reducing the force required from the FDS and intrinsic muscles.

6.4 References

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