Development of Biomechanical Models for Describing Hand and Finger Placements in Handling Work Objects

by

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To My Parents

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Abstract

Development of Biomechanical Models for Describing Hand and Finger Placements in Handling Work Objects

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This work presents new data and models that describe how hand and finger placement is influenced by the design and placement of work objects.

First, a conceptual model was proposed to describe the overall relationship among hand postures, motions, forces, factors, memory, and feedback.

Second, logistic regression models were developed based on a study of 10 male and 10 female subjects that showed relative hand load greater than 34% of maximal strength motivated subjects to reach and grasp cylindrical work objects using underhand posture (rather than overhand), and relative hand load as low as 24% motivated subjects to hold the objects (for about 8s) using palm grip at shoulder height (vs. hook grip at mid-thigh height). The relative hand load threshold increased to 53% for selecting underhand over overhand posture for placing the objects.

Third, a study of relative finger loads for 6 male and 6 female subjects lifting cylinders showed that selection of hand posture appears to be related to the preference of reducing thumb and finger tip forces and joint loads. Subjects demonstrated strong preferences of underhand over overhand grasp, and hook grip over pinch to lift cylinders, while thumb tip and sum of fingertip forces can be reduced up to 60% by selecting the preferred postures. Biomechanical models predicted overhand thumb and finger normal forces similar to data if friction was considered, while predicting about 2 times of measured normal forces if friction force was assumed zero.

Fourth, finger force distribution and placement were determined for 6 males and 6 females holding unbalanced plate objects. The thumb and finger center-of-force (CoF) locations were generally aligned with the load moment arm. The distance between thumb and finger CoF locations increased by 39% as load moment increased from 0.98 Nm to 2.35 Nm, and reduced by 17% as hand length increased from 16.2 cm to 21.1 cm when the plate was held horizontally.

Previous studies showed that posture selection is related to effort (Rosenbaum *et al.* 2006). This work shows that effort can be described quantitatively by relative joint loads, and that posture predictions based on biomechanical analysis of relative finger forces and joint loads account for 45%-87% of variance. The unexplained variance may be due to mechanical inter dependencies among finger motions and finger force measurement errors.

Chapter 1

Introduction

1.1 Problem Statement

Hand placement and force data are needed for ergonomic analysis and design of work objects and methods that provide workers with sufficient control over objects that need to be held, transferred, or manipulated with the hand. Serious injuries and costs result from inability or loss of control to grasp, hold, and manipulate work objects with the hand.

Loss of control can result in injuries or damages to object when the hand slips from the object. Hand slippage can cause acute injuries when the hand is placed in contact with a sharp edge or an electrical conductor. Objects can be damaged when dropped from the hand due to failure of hand-object coupling. The hand was the leading occupationally injured body part treated in U.S. hospital emergency departments, reported over one million incidents annually (Centers for Disease Control 2001). A survey sampled from 23 occupational clinics in five states over 1997-2000 found that 39% of hand injuries were related to hand tool use (Sorock *et al.* 2002). Hand tools with blades can cause injuries such as laceration in case of losing control. Laceration of fingers was ranked the third source in workers' compensation claims associated with manual material handling (MMH), after the strains of lower back area and upper arm (Dempsey and Hashemi 1999).

Workers may compensate for lack of control by changing posture or exerting additional force (Davidson and Wolpert 2005, Flanagan *et al.* 2006, Flanagan *et al.* 2009). Increased hand force is associated with fatigue and increased risks of musculoskeletal disorders (MSDs). Over-exertion and awkward postures have been considered risk factors for developing hand and wrist MSDs, such as carpal tunnel syndrome and tendonitis (Thompson *et al.* 1951, Smith *et al.* 1977, Silverstein *et al.* 1987, Armstrong *et al.* 1993, Roquelaure *et al.* 1997). These disorders cause discomfort and pain of worker, require medical treatment and take time away from work (NRC 1998, NRC and IOM 2001).

Workers may require additional time to grasp or re-grasp objects if they do not sense sufficient control over the object. When object is improperly presented to workers, time can be wasted on modifying grasps to achieve control. Such work time can add up through work cycles, increasing operational cost and impairing competitiveness.

1.2 Background

This section provides a basis for this work by synthesizing knowledge from the areas of biomechanics, psychology, and neuroscience.

Predetermined time systems are widely used to describe a sequence of motions and predict the time required to perform manual tasks (MTM, (Maynard *et al.* 1948); MOST, (Maynard *et al.* 1948)). These systems are based on a conceptual framework in which work is decomposed into basic motion elements such as reach, grasp, move, position, and release. Based on empirical data, the time can be predicted for each element. While these systems highlight the sequential characteristics of object transfer task and describe how certain object and task variables, e.g., object size and reach distance, affect work time, they do not describe the workers' posture or control over work objects.

Kinematic models have been used to describe the spatial relationship between the hand and the work objects. In these models, the hand was approximated as a series of segments connected by revolute joints. The lengths of the segments were scaled as functions of the anthropometry measurements such as the hand length and breadth (Buchholz *et al.* 1992) based on experimental data to account for various hand sizes (Garrett 1971). Finger joint angles were predicted given inputs of object size and hand size using various algorithms, such as regression-based geometrical contact (Buchholz and Armstrong 1992, Choi and Armstrong 2006) and optimizing hand-object fit (Lee and Zhang 2005). The hand postures are predicted primarily for simple geometric objects such as cylinders.

While kinematic models provide important information about the spatial relationship between the hand and the work object, there are still many possible ways of positioning the hand and fingers with respect to the work object, which affect the strength that can be exerted to exercise control over the object. To exert control over a specified object, grasp requires placement of the fingers on the object and application of force to overcome the weight and inertia of the object. Force produced by muscles must be greater than or equal to those produced by the weight and inertia of the work object to prevent the object from slipping from the hand. The forces and moments produced by the work object are related to where the fingers are placed on the object (Lukos *et al.* 2007).

Behavioral studies show that the grasping of objects follows predictable patterns based on object and task variables. Work by Jeannerod (1981, 1984) showed that the kinematics of hand and fingers are affected by various factors, such as object size and distance to object, during reaching and grasping objects. Subsequent studies supported this observation and also showed that hand and finger kinematics are affected by object shape (Santello and Soechting 1998, Cuijpers *et al.* 2004), object location and orientation (Paulignan *et al.* 1997, Roby-Brami *et al.* 2000, Dijkerman *et al.* 2009). Biomechanical factors such as object weight (Eastough and Edwards 2007), and balance (Lukos *et al.* 2007, Duemmler *et al.* 2008, Fu *et al.* 2010) have been found to affect finger placements for grasping in grasp-to-hold tasks. Hand posture is also affected by worker factors such as hand size (Bae *et al.* 2008, Choi 2008). Since grasping usually involves subsequent steps in which the object is placed, it has shown that the intention affect how people initially reach for and grasp an object (Rosenbaum *et al.* 1990, Rosenbaum *et al.* 1996, Cohen and Rosenbaum 2004, Ansuini *et al.* 2006).

Modern motor control theory suggests that "internal models" that mimic physical systems may exist in the cerebellum and are employed to predict the consequences of movements (Wolpert *et al.* 1995, Davidson and Wolpert 2005, Ito 2008), i.e., people predict postures given the knowledge of object and task properties in their brain. There are evidences supporting grasp postures are planned using internal models (Castellini *et al.* 2007, Ansuini *et al.* 2008). Grasping behavior can be learned through practice and stored in the memory, that it can be retrieved in advance of the movement based on sensory inputs about task and object variables and finally modified based on sensory inputs as the movement occurs (Lukos *et al.* 2008).

While the behavioral findings that grasping follows predictable patterns support the use of empirical models, it remains a question of what underlying kinematical and biomechanical mechanisms are used by people to plan and select hand and finger placements. Rosenbaum and colleagues (1990, 1996) found that gross hand placement used in grasping, i.e., overhand approach and finger grip versus underhand approach and palm grip, is affected by how the object will be positioned at the end of a bar transfer task. They demonstrated that subjects' behavior was predictable, i.e., subjects consistently choose underhand grip, which was reported by subjects more discomfort than overhand grip, in order to place the right end of the cylinder down to a target disk, while they choose overhand grip to place the other end down. They termed this as "end-state comfort" effect, which implies that both perceived comfort of posture and intention strongly influence movement selection. These work show that the spatial relationship between the hand and object can be predicted, but does not provide sufficient quantitative information about hand and finger placements on the work object or the required force for given object and task conditions.

It can be argued that the comfort, or effort, can be explained biomechanically. Evidences suggest that perceived comfort is related to biomechanical factors, such as external joint load and joint deviation from neutral (Wiker *et al.* 1990, Genaidy and Karwowski 1993, Carey and Gallwey 2002, Dickerson *et al.* 2007). Rosenbaum explained the comfort from the perspective of joint deviation (awkwardness) in different hand placements. However, perceived comfort is also related to external load on joints (Dickerson *et al.* 2007). Force exertion cause reducing blood circulation to muscles, which leads to fatigue and discomfort. The feedback about the discomfort may alter how people select hand and finger placements.

It is not clear how the biomechanical factors could affect the hand and finger placements used to grasp, transfer, and place work object. Rosenbaum's model (1990, 1996, 2001, 2009) demonstrated that comfort affects grasp posture, but did not consider biomechanical factors or quantitatively predict finger placements. Several behavioral studies (Eastough and Edwards 2007, Lukos *et al.* 2007, Fu *et al.* 2010) support that factors such as object weight and balance affect finger placements. Previous studies also show that subjects will scale fingertip forces to accommodate for the change of external torque when finger positions are constrained (for a review see Zatsiorsky and Latash 2004). However, there has been no model that can be used to predict finger placement based on biomechanical factors.

There is a great deal of knowledge from previous studies that describes how grasping behavior are affected by physical factors. Although the analysis in some of these studies is based on biomechanical concepts, the resulting descriptive models have limited generality. Conceptual model is needed to describe the relationship between factors and hand posture for understanding the underlying mechanisms of grasp selection. Kinematic and biomechanical models can be used with the conceptual model to predict hand and finger placements and required forces in selected conditions. The models should explain not only hand posture used for grasping, but also hand postures used in holding, moving, and positioning work object during transfer tasks. Towards this end, this work aims to propose models to describe how objects are grasped and how hand postures and forces can be computed.

1.3 A Conceptual Model

We propose a conceptual model to describe the relationship among hand postures, motions, forces, factors, memory, and feedback based on previous literature. The conceptual model makes the following assumptions:

1. Object transfer task can be decomposed into a sequence of motions/actions, such as reach, grasp, move, position, as described in MTM and other work method systems;
2. Movement patterns are pre-selected based on knowledge of the task, such as object size and shape; however, movement patterns may be altered by sensory feedback (Fu *et al.* 2010). As experience is gained, anticipatory control of posture and force can be used (Flanagan *et al.* 1993, Flanagan *et al.* 2003, Lukos *et al.* 2008);
3. Finger placement is constrained by kinematic factors of the upper limb and body that affect the reach and hand-object fit;
4. Finger placement can be influenced by feedback of biomechanical factors such as object weight, balance, and friction as force is applied on the object during consecutive grasp trials;
5. The proposed model is limited to tasks involving one hand.

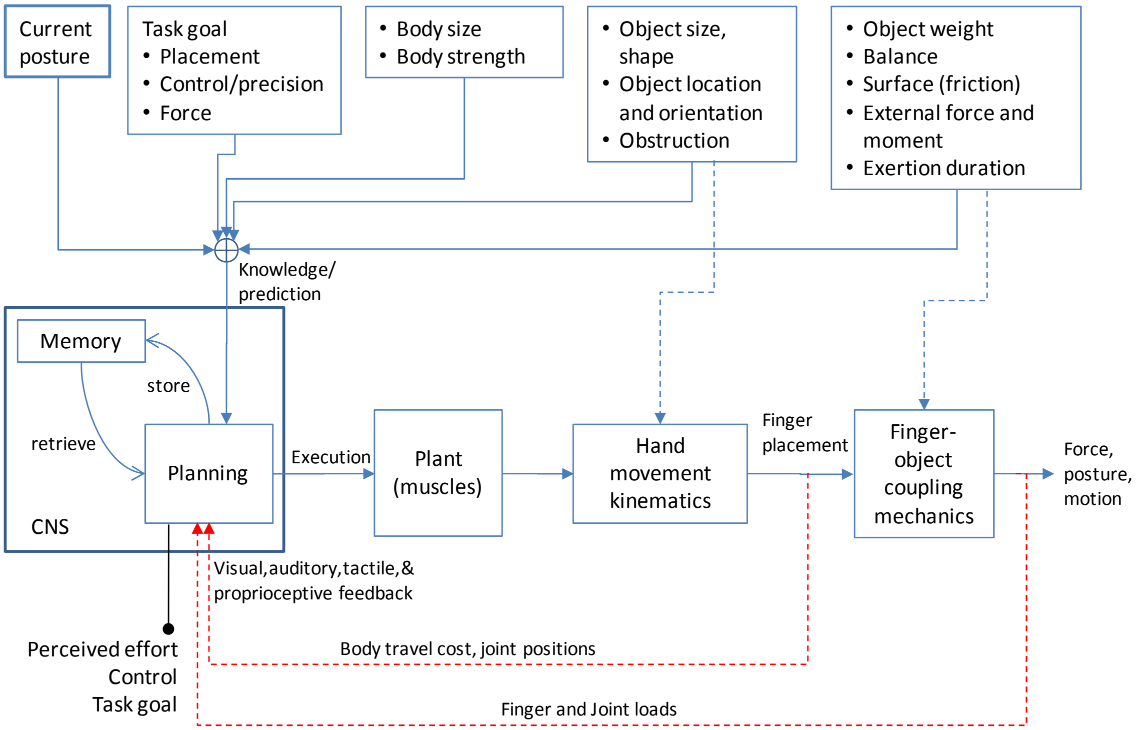

Figure 1.1. A conceptual model that describes the relationship among hand postures, motions, forces, factors, memory, and feedback.

The proposed conceptual model describes the relationship among hand postures, motions, forces, factors, memory, and feedback (Figure 1.1).

Previous studies have shown that hand posture is constrained by kinematics (Jeannerod 1981, Paulignan *et al.* 1997). There are many different ways to grasp an object; however, some are anatomically impossible due to joint range of motion or obstructions around the object ("hard constraints"). The object size, shape, and access limit the number of possible finger locations on work object given the hand, upper limb, and current body location and orientation.

There are still multiple ways to grasp an object. Some ways will require less strength, provide more control, or require less effort than other ("soft constraints"). With feedback, finger placement can be adjusted through consecutive trials. The posture that requires less effort or provides more control has been shown to be selected consistently in experienced situation and selected conditions (Rosenbaum *et al.* 1996, Rosenbaum *et al.* 2006, Lukos *et al.* 2007).

The conceptual model illustrates the above descriptions. As shown in the conceptual model (Figure 1.1), the hand-object fit is predicted at the Central Nervous System (CNS) level based on memory and knowledge about factors such as the current postural state, task goal, body size and strength, and object properties. The knowledge about object size and shape can be obtained through visual feedback. Knowledge about factors such as object weight and balance can be obtained through predictions based on visual cues of object size and shape (Flanagan and Beltzner 2000). Knowledge about task goals such as terminal placement, control, and precision can be obtained from verbal instruction (Rosenbaum *et al.* 1996, Cohen and Rosenbaum 2004). The CNS synthesizes the knowledge and predicts motor command that is needed to drive the plant (muscles) to execute the hand motion and achieve the grasp posture. When the knowledge about the object and task properties is known (i.e., experienced situation), forward models may be employed to drive the plant to achieve target posture while feedback signals are minimally used (Flanagan *et al.* 2003). When the knowledge about the object and task properties is lacking, feedback can provide information about the object and task. Visual and proprioceptive feedback provide information about joint positions within range-of-motion, as well as the travel cost of moving the hand and body from current posture to target posture (with or without an object in the hand). As force is applied and control is exerted over the object, cutaneous and joint receptors provide feedback about the load on muscles and joints (Flanagan *et al.* 2006), and about perceived effort and control over the object. Auditory feedback may provide information about lifting, positioning, and control over the object.

The feedback is processed at the CNS level such that the finger placement may be adjusted for subsequent trial. Practice trials are needed for people to learn how to select preferred finger placements. Through multiple practice trials, the best finger placements can be determined for the specific condition.

In particular, the feedback of biomechanical factors such as object weight, friction, and balance can influence the selection of finger placement. These biomechanical factors are related to static and inertial forces and could affect the load moments on joints. As the joint load increases, it is likely people will attempt to change posture to reduce joint load and perceived effort. Fu et al. (2010) showed that during the first three trials for lifting a novel unbalanced load, subjects tried different finger placements. After that, they consistently used the finger placement that minimized finger forces during lifting. Duemmler et al. (2008) also showed that people grasp object by putting their hand near object Center-of-Mass (CoM) location in a barbell balancing task. Grasping object near its CoM reduces momentum on the hand, thus reducing perceived effort. These observations are consistent with the description that feedback about joint loads is used to adjust finger placement in order to reduce effort. When the duration of exertion increases (such as for holding the object), people may change posture even faster due to muscle fatigue. Memory is needed to store the information about feedback signals during practice so that it can be retrieved later. Candidate hand and/or finger placements may also be stored in memory and can be retrieved for attempting an alternative grasp.

1.4 Research Objectives

This work aims to develop biomechanical models that make it possible to use the conceptual model to predict hand and finger placements with respect to the work object, based on biomechanical and statistical analysis given selected object, task, worker, and workplace factors. The following specific research objectives were established:

1) Examine the effect of object weight on hand placement and develop biomechanical models that can describe the influence of relative joint loads on the probability of posture used to grasp, hold, and place cylindrical object;
2) Examine the relationship among the selection of hand placement, hand force distribution, and object factors including object size and weight;
3) Investigate the influence of object orientation and balance on finger force distribution and selection of finger placement for holding plate object.

1.5 Dissertation Organization

This dissertation is organized into five chapters. Chapter 1 provides an introduction to the problem, background, and aims for this work. A conceptual model was proposed to describe the relationship among hand postures, motions, forces, factors, memory, and feedback in part handling tasks.

Chapter 2 develops biomechanical models for describing the influence of relative joint loads on the probability of posture used to grasp, hold, and place cylindrical object.

Chapter 3 evaluates the relationship among the selection of hand placement, hand force distribution, and object factors including object size and weight.

Chapter 4 examines the influence of object orientation and balance on finger force distribution and selection of finger placement for holding plate object.

Chapter 5 presents discussion and summarizes the major findings and conclusions. The findings were discussed within the framework of the proposed conceptual model. This chapter also includes suggestions for future work.

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Chapter 2

Biomechanical factors affecting part handling behavior: Object weight

Abstract

Self selected hand and upper limb postures to get, hold (8s), and put cylindrical objects with weights of 3.3, 20.0, 36.7, and 53.3 N located at elbow height were determined for 10 male and 10 female subjects. Use of overhand grasp decreased in favor of underhand grasp from 85% to get the lightest cylinders to 0% to get the heaviest cylinders. Subjects held lightest cylinders at elbow height in front of their body 20% of the time, and at mid-thigh height using a hook grip 80% of the time. Subjects held heaviest cylinders 60% of the time at shoulder height using a palm grip. The postures used to place objects were similar to the ones for grasping, but the overhand posture was used more frequent for heavier objects. A biomechanical analysis was performed so that logistic models could be developed to describe the influence of relative joint loads on posture selection. The data show that selection of alternative postures are motivated by relative loads as low as 24%.

2.1 Introduction

This study aims to develop models that can be used to predict probability of posture used to grasp, hold, and place work object. This is needed to improve efficiency and accuracy of simulation which support designing work equipment and methods that provide workers with sufficient control over objects in object transfer tasks. Loss of control can result in injuries or damages to the object when the hand slips from the object. Hand tools with blades or sharp parts, in the case of losing control, can cause injuries such as laceration (Sorock *et al.* 2002). Laceration of fingers was ranked the third source in workers' compensation claims associated with manual material handling (MMH), after the strains of lower back area and upper arm (Dempsey and Hashemi 1999). The worker may also compensate for lack of control by changing posture or exerting additional force (Flanagan *et al.* 2009). Excessive force is associated with fatigue and increased risks of musculoskeletal disorders (Armstrong *et al.* 1993).

Previous studies showed that posture selection is influenced by perceived comfort or effort. Rosenbaum and colleagues (1990, 1996) found that gross hand placement used in grasping, i.e., overhand approach and finger grip versus underhand approach and palm grip, is affected by how the object will be positioned at the end of a bar transfer task. They demonstrated that subjects' behavior was predictable, i.e., subjects consistently choose underhand grip, which was reported by subjects more discomfort than overhand grip, in order to place the right end of the cylinder down to a target disk, while they choose overhand grip to place the other end down. They termed this as "end-state comfort" effect. Subsequent studies supported that perceived comfort of posture strongly influences movement selection (Fischman 1998, Weigelt *et al.* 2006, Dijkerman *et al.* 2009, Cohen and Rosenbaum 2011, Herbort and Butz 2011).

Evidences suggest that postural comfort and discomfort are related to biomechanical factors, such as joint load (Wiker *et al.* 1990, Genaidy and Karwowski 1993, Carey and Gallwey 2002, Dickerson *et al.* 2007). Rosenbaum explained the comfort from the perspective of joint deviation, i.e., awkwardness or internal muscle and ligament force on joint. Perceived comfort or effort is also related to external joint load (Harms-Ringdahl *et al.* 1986, Dickerson *et al.* 2007), such as from object weight. Force exertion can lead to fatigue and discomfort that alter how people select hand and finger placements.

These previous studies support further development of quantitative models for describing posture selection as function of joint loading. Studies have shown that grip force increases and rate of lifting decreases with increasing object weight (Johansson and Westling 1988, Weir *et al.* 1991, Flanagan *et al.* 1995, Frederick and Armstrong 1995); however, these studies did not describe posture or hand placement. Several empirical studies examined the effect of object weight on finger and thumb placements in precision grips while gripping and holding objects (Kinoshita *et al.* 1996, Eastough and Edwards 2007, Domalain *et al.* 2008), but did not propose quantitative model that can be used to predict posture.

The relationship between upper limb posture and object weight can be described biomechanically (Figure 2.1). Assuming one-handed quasi-static posture, the moments at the joints of shoulder, elbow, wrist, and finger can be estimated,

$$
\begin{cases}
\overline{M}_s = \vec{r}_s \times \overline{F}_L + \overline{M}_{hand} + \overline{M}_{forearm} + \overline{M}_{arm} \\
\overline{M}_e = \vec{r}_e \times \overline{F}_L + \overline{M}_{hand} + \overline{M}_{forearm} \\
\overline{M}_w = \vec{r}_w \times \overline{F}_L + \overline{M}_{hand} \\
\overline{M}_f = f(\overline{F}_L, \vec{x}_f, \vec{x}_h)
\end{cases}
\tag{2.1}
$$

where $\overline{M}_s, \overline{M}_e, \overline{M}_w$, and $\overline{M}_f$ denote moments about shoulder, elbow, wrist, and finger joints, respectively. $\vec{r}_s, \vec{r}_e$, and $\vec{r}_w$ denote the moment arms of the load $\overline{F}_L$ for the respective joints. $\overline{M}_{hand}$, $\overline{M}_{forearm}$, and $\overline{M}_{arm}$ are the moments produced by the weight of each segment. $\vec{x}_f$ and $\vec{x}_h$ represent finger and hand placement respectively.

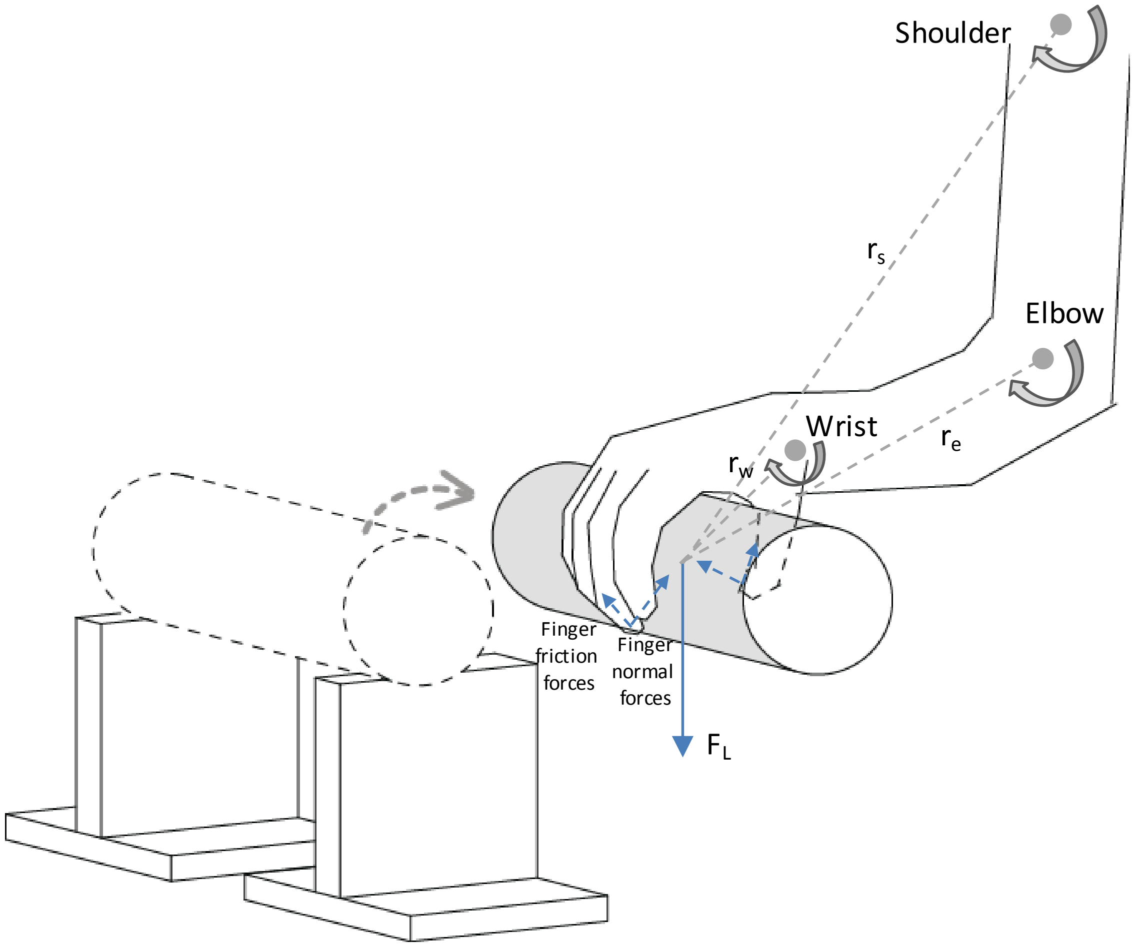


Figure 2.1. Major forces and moments of upper limb joints for grasping a cylindrical object from above using overhand posture.

Equation 2.1 shows that the joint moments are related to the upper limb posture and hand load. Figure 2.1 shows major forces and moments of the upper limb joints for grasping a cylindrical object. The figure shows an example of overhand grip, in which the thumb and fingers exert force to avoid the object slipping from the hand. As the object weight increases, the finger joint moments required to maintain the grip increase, as do the moments in the proximal joints of the limb. Consequently, depending on the posture, the maximum hand load may be limited by the strengths of the finger, wrist, elbow, or shoulder. The increased load on limiting joint could affect posture selection.

This study aims to develop statistical models that predict upper limb posture used to grasp, hold, and place cylindrical object as function of joint load. Towards this end, it is hypothesized that there is relative load threshold for each joint that influence posture selection. Increased object weight is related to increased joint loads for a given posture. As the joint load increases, people may seek postures that reduce the load on one or more joints.

2.2 Methods

2.2.1 Procedure

To test the proposed hypothesis and develop models, an experiment that consists of three parts was conducted for each subject. Part I examined the effect of object weight on subject-selected upper limb posture. Part II examined the effect of posture and object size on maximum voluntary isometric lifting strength. Part III measured isolated upper limb joint strengths. The three parts were performed in order such that posture selection in the first part was not biased by the posture specifications in the subsequent parts of the experiment.

In Part I, standing subjects were instructed to get, hold, and put cylindrical objects. The objects were 25.5 cm in length and 7 cm in diameter with four different weights (3.3, 20.0, 36.7, and 53.3 N). A wide range of weight was selected based on the data of a survey in which operators performed one-handed pickup-transfer tasks in 32 automotive assembly jobs (Wagner 2008). The object initially rested horizontally at elbow height on two wood supports (fixture) that were 25 cm apart and provided 17 cm clearance between the object and table (see Figure 2.1). Subjects stood one forearm length from the object, facing towards the object, and with the right arm aligned with the object's center. The subject's right hand rested on the side of the body initially. For each trial, subjects reached and grasped the object, held it as if they were waiting to install or pack a part for approximately eight seconds, then placed the cylinder at a self-selected location and orientation.

Trials were blocked on weight, with the weight order randomly selected for each subject. There were practice trials for each weight condition. Subjects were encouraged to explore different postural strategies in practice trials. After the subject reported sufficient practice, three trials were performed for each condition. The experimenter always handled the objects with both hands, underneath the objects with palm facing up, so that subjects received no cue about object weight or posture they could copy. The objects with different weights also visually appeared the same, so that subjects may not be biased by appearance to infer the weight before practice.

Part II was conducted at least ten minutes after Part I to examine the effect of posture on maximum lifting strength. Overhand, underhand, and hook grasp postures were examined, based on previous observations of subjects performing the task described in Part I. In addition to the 7 cm cylinder used in Part I, a 3.2 cm cylinder was also studied for a separate analysis of hand-object coupling mechanics. Subjects were asked to "pull the handle in vertical up direction as hard as they can" without jerking it (Caldwell *et al.* 1974) using the specified posture. There were two repetitions for each size and posture combination. The order of the trials was randomized for each subject. A break of at least two minutes was given between successive trials.

In Part III, functional strength tests were conducted to measure isolated wrist, elbow, and shoulder joint strengths in overhand and underhand posture. Subjects were seated on a chair and instructed to flex a specific joint (wrist, elbow, shoulder) and exert their maximum capable force against a strap. Restraints were employed to prevent undesired movements and isolate the muscle or group of muscles being tested. There were two repetitions for each strength test, with the test order randomized for each subject. A break of at least two minutes was given between successive trials.

Table 2.1. Stature, body weight, and hand length of subjects by gender (mean ± SD).

	Stature (cm)	Weight (kg)	Hand length (cm)*
Male (N=10)	179.1 ± 5.2	76.8 ± 8.6	19.1 ± 1.2 (1%ile – 88%ile)
Female (N=10)	166.5 ± 5.0	57.6 ± 7.3	17.4 ± 0.9 (1%ile – 72%ile)

* The percentiles of hand lengths are based on the population data from Garrett (1971).

2.2.2 Subjects

Twenty university students (10 males and 10 females, age between 19 and 32 years, mean age 22.0 ± 2.8) volunteered to participate in the experiment. All participants were right-handed and were free of any movement disorders. They gave written informed consent in accordance with our University IRB regulations. The stature, body weight, and hand length for the subjects are summarized in Table 2.1.

2.2.3 Apparatus

In Part I and II, an eight-camera Qualisys motion tracking system (Qualisys Inc., Sweden) was used to record the upper limb kinematics and calculate moment arms of upper limb joints. Retro-reflective markers were attached to the dorsal side of middle metacarpophalangeal (MCP) joint of the right hand, the radial and ulnar sides of the wrist, lateral and medial epicondyles, and the acromion of the right arm similar to others (Schmidt *et al.* 1999, Rab *et al.* 2002). The position of the cylindrical object was tracked using two markers placed on the centers of the two ends of the object. The Qualisys system was sampled at 60 Hz. All trials were also videotaped using a camcorder. In Part II, the handle was connected to a one-degree-of-freedom force transducer. The force transducer was connected to the ground via a length-adjustable chain. In Part III, the strap was connected to a one-degree-of-freedom force transducer, which was connected to the chair via a length-adjustable chain.

The upper limb postures that subjects used to grasp, hold, and place objects were categorized based on the forces and moments required to maintain control over the object. The load moment arms from the object center to upper limb joints were calculated from motion data. The motion data were filtered using a bidirectional second order Butterworth filter with a cut-off frequency of 6 Hz. The object center was calculated as the average of the positions of markers at each end of the object. The wrist and elbow joint centers were assumed as the average of the positions of the lateral and medial wrist markers, and the average of the positions of lateral and medial epicondyle markers, respectively. The shoulder joint center was assumed to be 10% of the upper arm length inferior to the acromion marker in laboratory coordinate system (De Leva 1996). The load moment arms were calculated from the object center to joint centers in x-y plane of the laboratory coordinate system (equivalent to a sagittal plane).

Isolated joint strengths for wrist, elbow, and shoulder were calculated using the force data obtained in Part III. The wrist, elbow, and shoulder joint strengths were calculated as the corresponding forces multiplied by the distance from middle MCP joint to distal wrist crease, the distance from distal wrist crease to lateral epicondyle, and the distance from the center of the strap to shoulder joint, respectively.

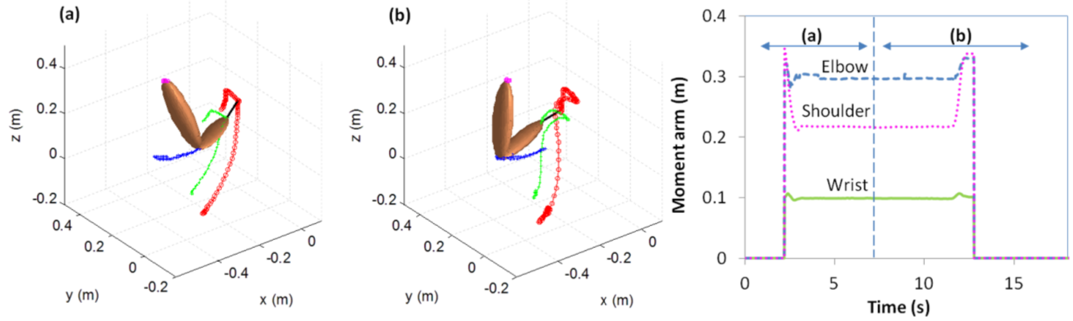
2.3 Results

2.3.1 Part I: Part Handling Behavior

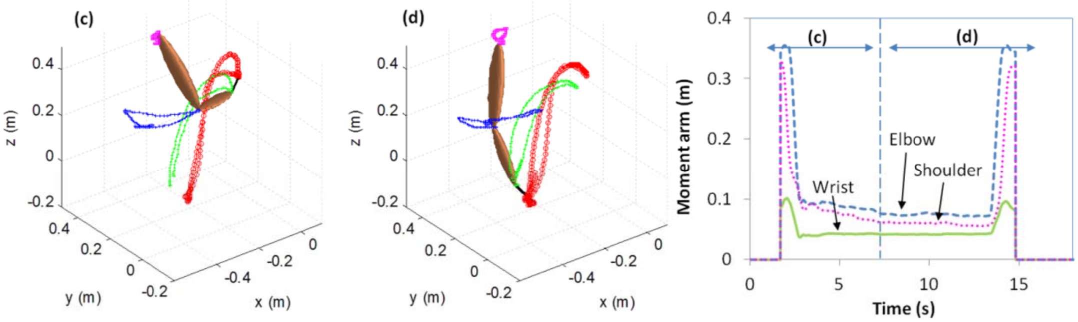
The experimental task consisted of get, hold, and put. For purposes of this analysis, get begins with the reach, is followed by grasp where the subject gains control over the cylinder and ends with the move to the hold position. Hold begins with the end of the get and ends with the beginning of the movement to return the cylinder to the fixture or table. Put begins with the end of the hold and the subject begins moving the object to the fixture, placement of the object and release of the object.

Sample plots of the hand motion for the three elements are shown in Figure 2.2. Three general movement patterns were observed. In each case the subject started with the hand at the side of the body and with a semi-pronated forearm. In the first case, forearm pronation increases during the reach and the cylinder was grasped from above using a “horizontal overhand grip” (see Figure 2.2A, 3.3 N cylinder). The cylinder is then held vertically at elbow height in a “vertical grip”. In some cases subjects tended to move their elbow behind their torso, which reduced the moment on the shoulder. The get path was then re-traced and the cylinder was put on the fixture using the overhand grip. In the second case, the overhand grip again was used to get the cylinder, but it was held horizontally using a “hook grip” at mid-thigh height with a semi-pronated forearm (see Figure 2.2B, 20.0 N cylinder). The get path was re-traced to put the cylinder back on the fixture using horizontal overhand grip. In the third case, the forearm supination increased during the reach and the cylinder was grasped from below using a “horizontal underhand grip” (see Figure 2.2C, 36.7 N cylinder). The cylinder was then moved to the shoulder height where it appears to be primarily supported with “palm grip”. The get path was re-traced to put the cylinder back on the fixture using horizontal underhand grip.

(A) Reach grasp a 3.3 N cylinder using overhand posture, hold it using vertical grip posture at elbow height, then place it down



(B) Reach grasp a 20.0 N cylinder using overhand posture, hold it using hookgrip posture at mid-thigh height, then place it down



(C) Reach grasp a 36.7 N cylinder using underhand posture, hold it using palm grip at shoulder height, then place it down

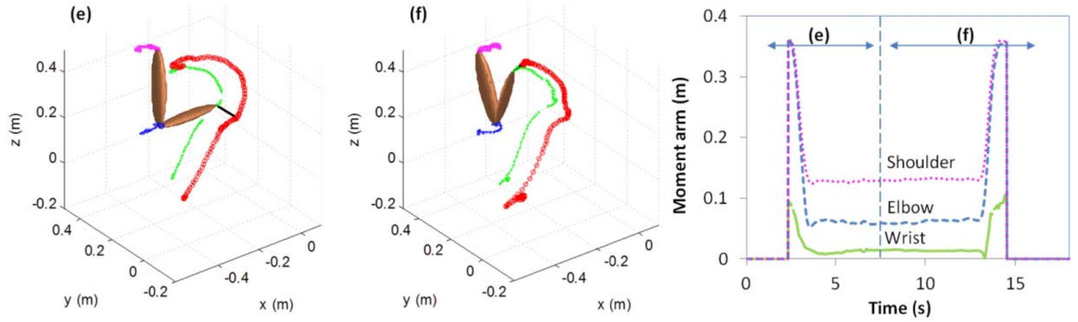


Figure 2.2. Trajectories of the right hand middle MCP joint marker, wrist, elbow, and shoulder joint centers in three representative trials in laboratory coordinate system. The moment arms of wrist, elbow, and shoulder as function of time are also shown.

The frequency of each observed posture category for grasp, hold and place is shown in Figure 2.3. Overhand and underhand grip were used 38% and 62% of the time respectively to grasp the cylinder. Horizontal underhand grip and vertical grip were used only 9% of the time to hold the cylinder at elbow height, while horizontal hook grip at mid-thigh height and palm grip at shoulder height were used 62% and 29% of the time respectively. Over and underhand horizontal grips were each used about 50% of the time to place the cylinder.

Posture frequencies to grasp, hold and place the cylinders were stratified by object weight and are shown in Figure 2.4. Use of the overhand posture to grasp the cylinder decreased steadily from 85% for the 3.3 N cylinder to 0% for the 53.3 N cylinder (see Figure 2.4A). Use of over, under and vertical grip to hold the cylinder at elbow height decreased from 20% for the 3.3 N case to 0% for the 36.7 N case (see Figure 2.4B). Use of the hook grip to hold the cylinder at mid-thigh height decreased from 80% for the 3.3 N case to 35% for the 53.3 N case. Use of palm grip to hold the cylinder at shoulder height increased from 0% for the 3.3 N and 20.0 N cases to 60% for the 53.3 N case. The relationship between the posture used to place the cylinders back to the fixture and weight were very similar to those used to grasp the cylinders (see Figure 2.4C). The relationship between posture and weight for grasp, hold and place are all found to be significant at $p<0.01$ using the likelihood ratio test.

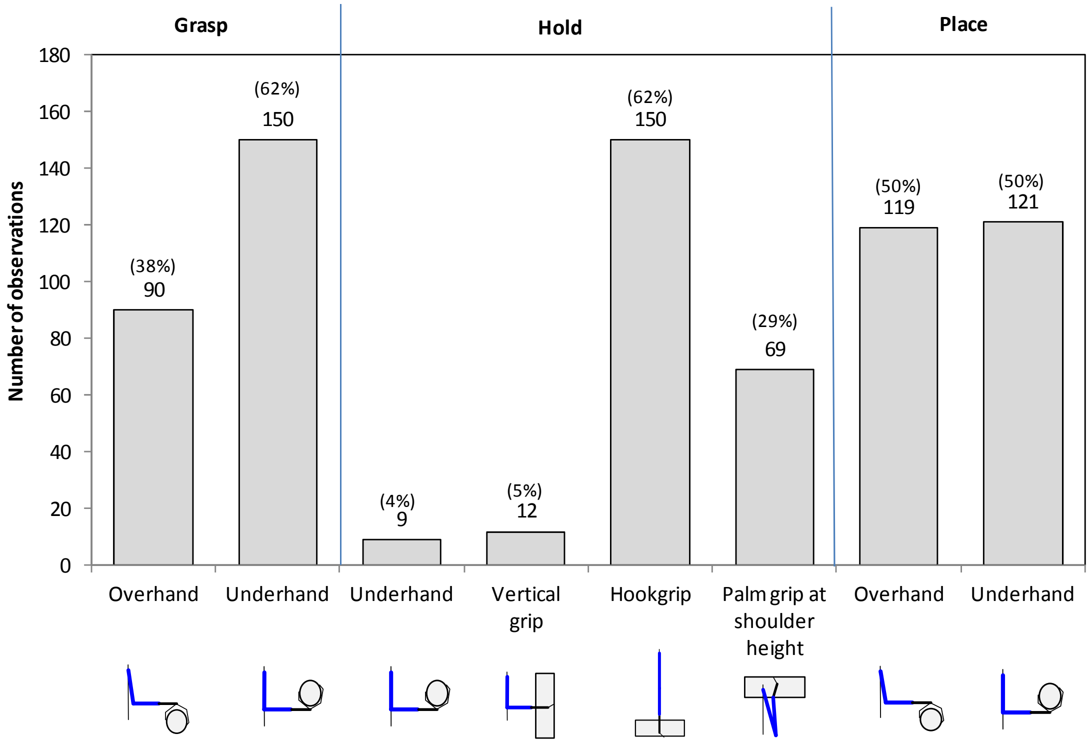


Figure 2.3. Observed postures for grasping, holding, and placing cylindrical objects. The number of observations for the postures is also shown.

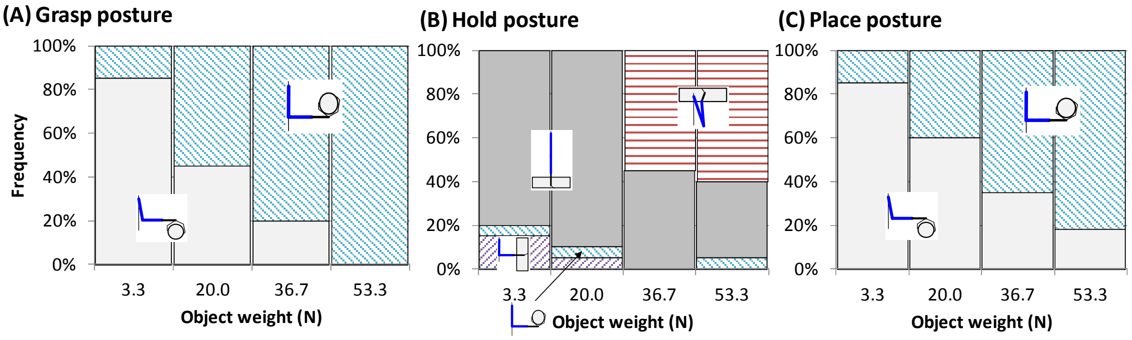


Figure 2.4. Frequency of posture categories for grasping, holding, and placing object as function of object weight (pooled for all subjects).

Table 2.2. Moment arms from the load to wrist, elbow, and shoulder joints by posture during grasping, holding, and placing (cm, mean ± SD)

Posture		Wrist (cm)	Elbow (cm)	Shoulder (cm)
Grasp	Overhand	9.9 ± 1.9	34.7 ± 2.6	35.6 ± 3.3
	Underhand	10.1 ± 1.4	34.9 ± 3.6	32.9 ± 4.9
Hold	Underhand	10.9 ± 3.0	34.6 ± 3.6	27.0 ± 7.4
	Vertical grip	10.2 ± 0.7	34.7 ± 3.8	26.4 ± 3.2
	Hookgrip	3.5 ± 1.5	10.5 ± 2.8	8.5 ± 2.5
	Palm grip at shoulder height	4.2 ± 1.3	8.1 ± 4.3	11.5 ± 3.3
Place	Overhand	8.9 ± 2.1	33.9 ± 3.0	35.0 ± 4.6
	Underhand	10.1 ± 1.4	35.0 ± 2.7	33.6 ± 5.3

Average moment arms computed as the horizontal distance between the center of the cylinder and the wrist, elbow and shoulder joints at the completion of the get, hold and put steps using the motion capture data are shown Table 2.2. The moment arms increased significantly ($p<0.01$) from the wrist, to the elbow or the shoulder for the get element; but the differences between over and underhand grip were within 10% of respective joints. The average moment arm for the elbow was 2.8 times that for the wrist during the hold (posture pooled; $p<0.01$). Except for the palm grip at shoulder height, the average moment arms were significantly (20%) less for the shoulder than for the elbow ($p<0.01$). During placing, the moment arms from the load to wrist, elbow, and shoulder joints are similar for overhand and underhand postures.

2.3.2 Part II: Lifting Strength

Maximum voluntary lifting strengths for overhand, underhand, and hook grip postures are summarized by gender in Figure 2.5. Average male strength was 2.2

times that of females for the 7cm cylinder used in Part I (posture pooled; $p<0.01$). For the 7cm cylinder used in Part I (gender pooled), the average hook grip lifting strength was 1.7 times and 3.7 times of the average underhand and overhand lifting strengths, respectively; and average underhand lifting strength was 2.2 times of the average overhand lifting strength (all significant at $p<0.01$).

The average lifting strength with 3.2 cm handle was 56% greater than that for the 7cm cylinder (posture and gender pooled; $p<0.01$). Average overhand, underhand and hook grip lifting strengths (gender pooled) were 32% ($p<0.01$), 9% ($p>0.05$), and 46% ($p<0.01$) respectively less for the 7 cm cylinder than for the 3.2 cm cylinder.

2.3.3 Part III: Isolated Joint Strength

Average isolated joint strengths for the posture corresponding to the end of the get element are summarized by joint and gender in Table 2.3.The underhand female/male wrist, elbow, and shoulder strengths were 3/10%, 4/6%, 13/17% greater than the ones for overhand posture respectively, but were not statistically significant for either gender (two-sample t test; all $p>0.05$).

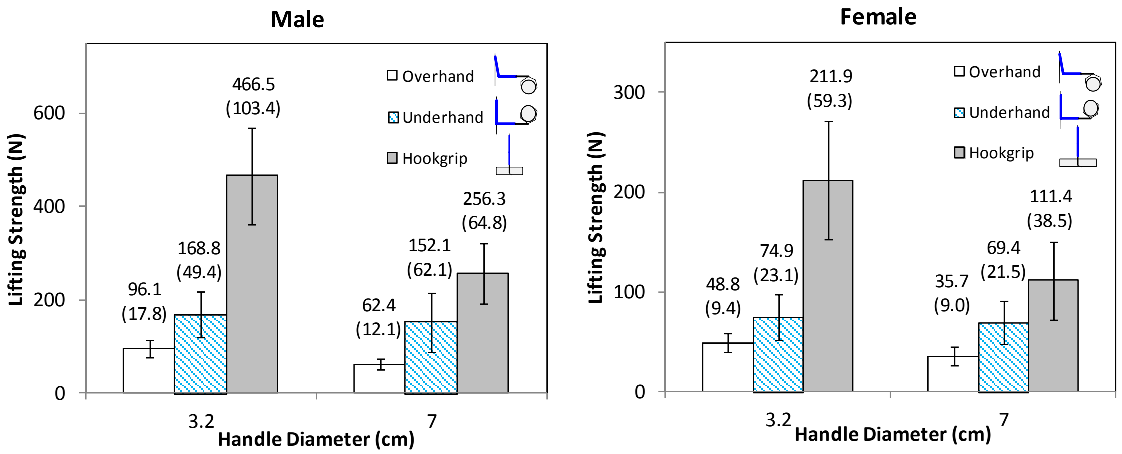


Figure 2.5. Lifting strengths (N) for overhand, underhand, and hookgrip postures and two cylinder diameters (3.2 cm, 7 cm) by gender. The values in brackets are standard deviations.

Table 2.3. Wrist, elbow, and shoulder joint strengths in overhand and underhand postures (Nm, mean ± SD).

Posture	Isolated joint strength (Nm)					
		Male			**Female**	
	Wrist	Elbow	Shoulder	Wrist	Elbow	Shoulder
Overhand	12.7 ± 4.4	59.4 ± 16.7	69.2 ± 22.4	5.9 ± 1.5	26.3 ± 3.5	26.4 ± 5.1
Underhand	14.0 ± 4.7	62.8 ± 22.8	81.1 ± 21.8	6.1 ± 2.1	27.4 ± 3.5	29.8 ± 8.0

2.4 Discussion and Proposed Models

2.4.1 Grasping and Placing

Figure 2.4 shows that that the postures used to grasp, hold and place a cylindrical object are influenced by object weight between 3.3 and 53.3 N when subjects are not constrained by mechanical barriers or instructions on how to handle the object. The posture frequency data summarized in Figure 2.4 show that subjects have a clear preference for overhand grip (85%) versus underhand grip (15%) for the lightest load (3.3 N). This is consistent with Fischman (1998) who found that 78% out of 206 subjects grasped light horizontal cardboard paper-towel cores (31.1 cm long x 3.8 cm diameter) using overhand grip while only 22% used an underhand when they were not concerned with the placement of the object. Rosenbaum et al. (1990, 1996, 2006) observed that underhand grip was perceived to be less comfortable than overhand grip and proposed that this was due to extreme forearm pronation, which approached the limits of the range-of-motion (ROM). It can be argued that both overhand and underhand postures require extreme forearm pronation/supination while shoulder abduction angle is zero. In overhand posture though, forearm pronation can be reduced by abducting the shoulder; while in underhand posture, shoulder adduction is constrained by mechanical interference with the torso. This study was not designed to examine shoulder adduction and abduction, but examination of the motion capture data showed that the average elbow height in overhand posture was 11.5 cm higher than that of the underhand posture, and the average shoulder abduction angle for overhand posture was 33° comparing to 6° for underhand posture.

The posture frequency data in Figure 2.4A and Figure 2.4C show that subjects shifted to underhand posture as object weight increased. Findings in previous studies were less consistent, but this may be due to posture instructions, or the range of weights studied. Kinoshita et al. (1996) found that finger placement around the top of 5.0, 7.5, and 10.0 cm diameter vertical cylinders was not affected by weight between 4.9 and 19.6 N when subjects were given specific instruction to grasp them from above. Eastough and Edwards (2007) observed that subjects positioned their fingers closer to the object center of mass to lift 7.1, 8.7, and 11.0 cm diameter vertical cylinders as weight increased from 1.4 to 12.9 N when subjects were asked to grasp them from side using fingertips. These studies and the present study show that grasp posture and finger position are influenced by object weight and balance when subjects have the freedom to choose.

The preference for underhand posture versus overhand posture appears to be motivated by the coupling between the hand and object. Table 2.2 shows that the wrist, elbow, and shoulder moment arms are within 10% differences for overhand and underhand postures. Table 2.3 shows that the wrist, elbow and shoulder are slightly stronger for the supinated forearm than for the pronated forearm during vertical lifting. Even if the differences were statistically significant, it probably would be too small to explain the strong effect of weight on posture shown in Figure 2.4. The difference is most likely due to the mechanical coupling between of the hand and the cylinder in the overhand versus the underhand grasp postures. It can be seen in Figure 2.1 that the weight is mainly support by normal and friction forces on the ends of the fingers for overhand grip. Studies by Pylatiuk et al. (2006), Seo et al. (2007) show that the forces exerted to grip cylinders are concentrated at fingertips and thumb tip. In the underhand case, the weight of the cylinder is supported mainly by normal forces acting on the palm and base of the fingers. In this case, finger active flexion forces are not required.

Table 2.4 shows wrist, elbow, and shoulder joint moments during maximum voluntary isometric lifting (see Figure 2.5) computed as decimal fraction of respective strength (Table 2.3). In underhand posture, wrist appears to be the limiting joint for the 7 cm cylinders used in Part I (one-sample t test; $p>0.1$). In overhand posture, subjects were only able to exert 46%, 40%, and 38% of their wrist, elbow, or shoulder strengths for the 7 cm cylinder (one-sample t test; $p<0.001$ for all joints). This shows that hand coupling, rather than wrist, elbow or shoulder strength limits lifting strength for overhand grip. In both overhand and underhand postures, wrist joint has the highest relative load reaching 106% of isolated strength for underhand grip. As the wrist approaches its maximum it may be forced into greater extension of flexion. Wrist strength increases as it approaches the limits of its range-of-motion.

The relative joint load data (see Table 2.4) shows that for overhand posture, the relative load increases faster for the hand than for other upper limb joints for overhand grip, which motivates subjects to adapt alternative postures, i.e., an underhand posture, which reduce relative hand load. This finding provides a basis for a model that can be used to predict the probability of alternative hand postures for grasping and placing cylindrical objects.

Table 2.4. Wrist, elbow, and shoulder joint moments as fraction of respective strength during maximum voluntary isometric lifting exertions by posture (gender pooled, mean ± SD).

Posture	Joint moment as fraction of strength in maximum lifting exertion (7 cm cylinder, gender pooled)		
	Wrist	Elbow	Shoulder
Overhand	0.46 ± 0.16	0.40 ± 0.11	0.38 ± 0.11
Underhand	1.06 ± 0.25	0.85 ± 0.16	0.64 ± 0.17

2.4.2 Holding

Figure 2.4B shows that in this study where the subjects were not given specific instructions how to hold the object and were not subjected to mechanical constraints that affected their posture, the subjects' selection of a posture for an eight second hold was strongly influenced by object weight. Even at the for the lightest object 80% of the subjects selected a hook grip posture to hold the load at the side of the body, which minimizes the moments on wrist, elbow and shoulder (Table 2.2). Elkus and Basmajian (1973) showed that subjects tend utilize passive ligament forces to resist traction forces across joints, which would reduced perceived effort. Also, use of the hook grip enables subjects to utilize friction to help support the weight of the cylinder, which reduces the required muscle force and perceived exertion (Young *et al.* 2009). The preferenced for underhand palm grip at shoulder height increased from zero to 50% and 60% respectively for the was heaviest (36.7 and 53.3 N) cylinders – event though load on the shoulder increased 15% from the hook grip posture. Most of the cylinder in this position appears to be supported by the palm and fingers are used only to stabilize the load. Although the moment on the wrist is 30% higher for this position than the hook grip position and it involves additional enery expenditure to move the object to the shoulder height, it is likely that the weight of the cylinder results in force extension of the wrist, which enables the subjects to utilize passive ligament and muscle-tendon forces to support the weight (Rijnveld and Krebs 2007, Formica *et al.* 2012). This may help to explain why waiters often carry heavy trays with a similar posture.

The selection of the hold posture may also be affected by fatigue. A review of the literature by Law and Avin (2010) shows that edurance times at 15%, 40% and 80%

MVC as 478, 79, and 22 seconds for the shoulder, 1,190, 136 and 29 seconds for the elbow; and 712, 147 and 48 seconds for hand grip. These observations suggest that shoulder fatigue is significantly more sensitive to load than is the hand and that the hand is significantly more sensitive to load than is the elbow. The selection of a posture for a short hold may be influenced most by the joint with the highest relative load moment, but for longer holds, a lower relative shoulder moment may be preferred over a higher relative hand load.

2.4.3 Proposed Models

Logistic models were developed to predict postures as function of relative load of specific upper limb joint, which were identified as the sensitive joint that motivates posture change in previous discussions, using a repeated random sub-sampling validation method. Specifically, the original data set (20 subjects) was randomly split into a training set and a validation set. The training set included the data of 16 randomly selected subjects (8 males and 8 females) while the validation set included the other 4 subjects (2 males and 2 females). The training set therefore included 80% of data while the validation set included 20% of data. The logistic models were fit to the training data set using mnrfit routine (MATLAB®, Mathworks Inc., MA), and predictive accuracy was assessed for the validation data set. The predictive accuracy was defined as classification accuracy rate (%), which is the number of correctly classified instances divided by the total number of instances. The predict posture is defined as the one with the highest probability for a specific condition. The random split was repeated 10 times.

The probability model for predicting grasping posture was proposed as a function of relative hand load,

$$\pi = \frac{e^{\beta_0 + \beta_1 M}}{1 + e^{\beta_0 + \beta_1 M}} \tag{2.2}$$

where the independent variable M is the predicted relative hand load estimated as the load (object weight) over the overhand lifting strength since the hand is limiting in this posture. The dependent variable π is the probability of overhand posture. The probability of underhand posture is therefore $1-\pi$. The parameter estimates for this model based on training set are, on average, $\beta_0 = 1.350$ (p<.001), $\beta_1 = -3.935$ (p<.001). The classification accuracy rate on out-of-sample data is 71.9 ± 7.5 %. The threshold of hand relative load corresponding to 50% posture change is 34 ± 4 % (Figure 2.6). The model predicts that as the hand load increases, the probability of overhand posture decreases.

Predicted probability from logistic regression of selecting holding posture at elbow height (underhand and vertical grip posture pooled), or at shoulder or mid-thigh height (hookgrip and palm grip at shoulder height pooled) is shown in Figure 2.7 as function of the relative load (%strength) of wrist, elbow, or shoulder at the time the weight of the object is transferred to the hand. The parameter estimates for the wrist model based on training set are, on average, $\beta_0 = -1.399$ (p<.01), $\beta_1 = -3.246$ (p<.05). The parameter estimates for the elbow model based on training set are, on average, $\beta_0 = -1.548$ (p<.01), $\beta_1 = -3.142$ (p>0.05). The parameter estimates for the shoulder model based on training set are, on average, $\beta_0 = -1.557$ (p<.01), $\beta_1 = -3.893$ (p>0.05). The classification accuracy rates on out-of-sample data for the three models are, 91.2 ± 7.1 %, 91.4 ± 7.0 %, and 91.6 ± 6.7 %, respectively.

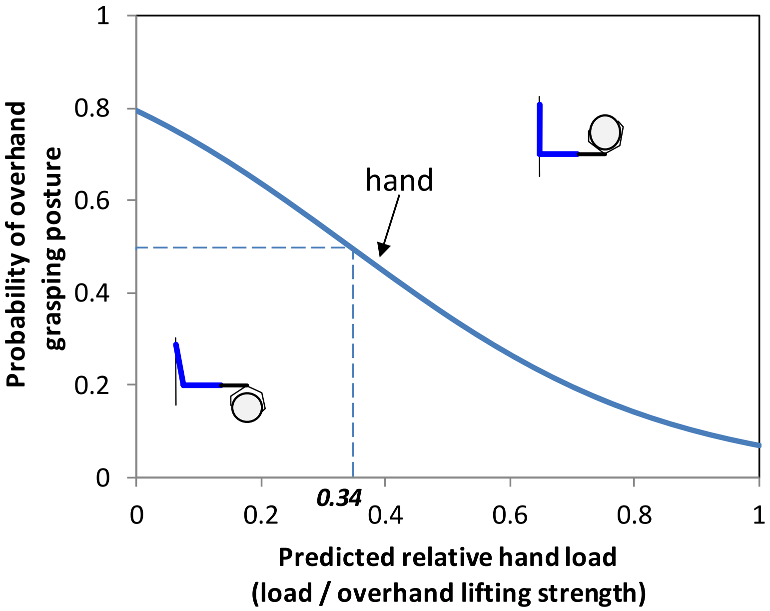


Figure 2.6. Predicted probability from logistic regression of selecting grasping posture as a function of predicted relative hand load (averaged from 10 randomly sampling of training set). The predicted relative hand load is estimated as object weight divided by overhand lifting strength.

For low load, about 20% of the subjects maintained the same arm posture in which they first gained control of the object, while 80% selected held the object at thigh or shoulder height. As the relative load moment on the wrist, elbow, and shoulder increased to 30% of maximum, approximately 90% assumed at shoulder or mid-thigh height posture and as the load increased to 90% nearly every one chose the at shoulder or mid-thigh height posture.

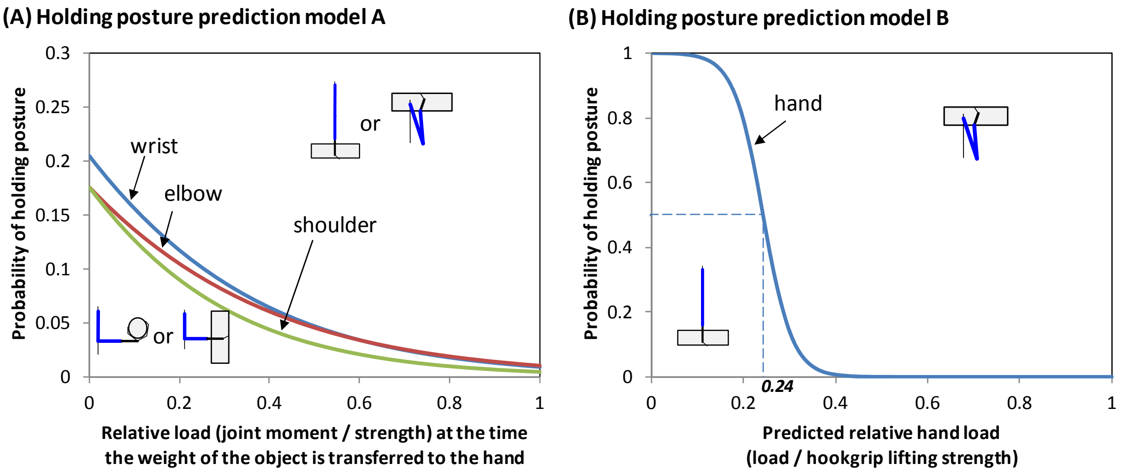


Figure 2.7. (A) Predicted probability from logistic regression of selecting holding posture at elbow height, or at shoulder or mid-thigh height as function of the relative moment (%strength) of wrist, elbow, or shoulder at the time the weight of the object is transferred to the hand (averaged from 10 randomly sampling of training set); (B) Predicted probability from logistic regression of selecting hookgrip or palm grip at shoulder height posture as a function of predicted relative hand load (averaged from 10 randomly sampling of training set). The predicted relative hand load is estimated as object weight divided by the hookgrip lifting strength.

The predicted probability of selecting hookgrip or palm grip at shoulder height posture is shown in Figure 2.7 as a function of predicted relative hand load, which was estimated as the load divided by the hookgrip lifting strength since the hand is limiting in this case. The parameter estimates for this model based on training set are, on average, $\beta_0 = 7.627$ (p<.001), $\beta_1 = -31.508$ (p<.001). The classification accuracy rate on out-of-sample data is 90.8 ± 6.7 %. The threshold of hand relative load corresponding to 50% posture switch is 24 ± 1 %.

The predicted probability of placing posture, specifically the selection of underhand or overhand posture, is shown in Figure 2.8. The independent variable is the predicted relative hand load estimated as the load (object weight) over the overhand lifting strength. The parameter estimates for this model based on training set are, on average, $\beta_0 = 1.727$ (p<.001), $\beta_1 = -3.270$ (p<.001). The classification accuracy rate on out-of-sample data is 68.6 ± 6.2 %. The threshold of hand relative load corresponding to 50% posture switch is 53 ± 4 %.

The 50% threshold for overhand placing is 53% of corresponding hand strength (Figure 2.8), which is higher than the one for grasping (34% as shown in Figure 2.6). This may be due to the requirement of control during placing. Placing object may require more control of object to place the object at specific location and orientation than grasping the object from a known location. Overhand posture enables finger manipulation that can provide more advantage of such control than underhand posture. This is also qualitatively consistent with Rosenbaum's finding that hand placement selection is affected by task specification (Rosenbaum *et al.* 2006, Rosenbaum *et al.* 2009).

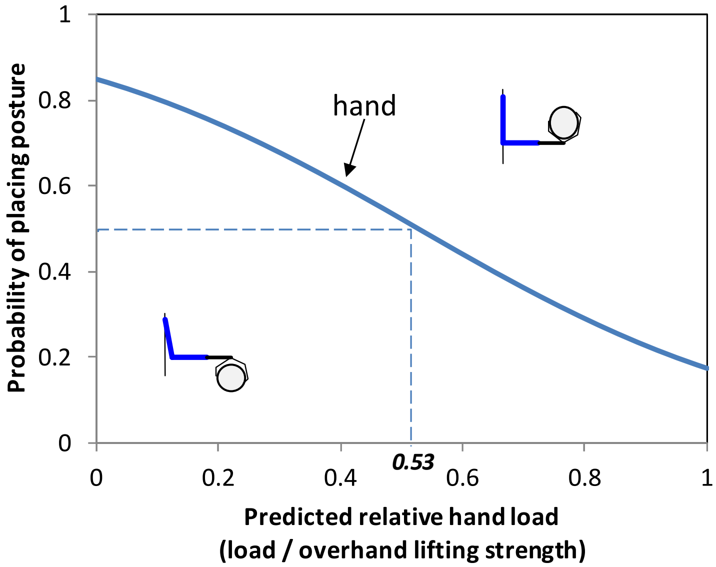


Figure 2.8. Predicted probability from logistic regression of selecting placing posture as a function of predicted relative hand load (averaged from 10 randomly sampling of training set). The predicted relative hand load is estimated as object weight divided by overhand lifting strength.

The relative hand load threshold for changing to the palm grip at shoulder height posture (24%, Figure 2.7B) was lower than the ones for grasping (34%) or placing (53%). This is probably because that holding requires longer exertion duration than grasping or placing. Longer exertion duration requires more energy expenditure. As a trade-off, a less exertion force is favorable for a longer exertion. In addition, holding frees the constraint of object placement. As a result, people have more freedom of positioning the arm even at lower loads.

The proposed models demonstrate that biomechanics can help to explain posture planning and prediction. Modern motor control theory suggests that "internal models" that mimic physical systems may exist in the cerebellum and are employed to predict the consequences of movements (Wolpert *et al.* 1995, Davidson and Wolpert 2005, Ito 2008), i.e., people predict postures given the knowledge of object and task properties in their brain. There are evidences supporting grasp postures are planned using internal models (Castellini *et al.* 2007, Ansuini *et al.* 2008). Grasping behavior can be learned through practice and stored in the memory, that it can be retrieved in advance of the movement based on sensory inputs, such as joint loads, and finally modified based on sensory inputs as the movement occurs (Lukos *et al.* 2008).

2.4.4 Application

For light weight cylinders (W < 18.6 N) or other objects (<34% relative hand load) that can be easily grasped, an overhand grasp will be used most frequently (>50%) in the studied task configuration of a horizontal object at elbow height. Space should be provided from the starting position of the hand to reach over the object. If possible, the objects should be designed to resist slipping out of an overhand grasp and reduce finger forces, e.g., tapering the edges, adding ridges, and increasing friction.

For heavier cylinders (W > 18.6 N) or objects (>34% relative hand load) that can be held with a palm up posture, an underhand grasp will be used most frequently (>50%). Space should be provided from the starting position of the hand to the reach under the object. Where possible, heavier objects should be designed to fit a palm-up, cupped hand.

Unless the object is to be immediately moved with the arm to another position, it is likely that a heavy object will be held over or near the shoulder using the palm or at the side of the thigh using the fingers (hook grip). Space should be provided so that objects can be transferred to these locations without bumping other objects. The stability of the load should be considered. A shift in the center of gravity could result in dropping an object as it is transferred above the shoulder.

2.4.5 Limitations

This study was limited that only cylindrical objects with one size and one starting location in the behavior study. However, it is possible to use the proposed biomechanics-based models to work objects with different shapes and sizes. Only one object friction condition was investigated, while many object properties can affect hand-object coupling and thus behavior. The hand relative load was estimated using isometric, isolated joint strength data for each joint. Further studies should be conducted to quantify hand force distributions in the different postures. In addition, further studies are needed to determine the moment sensitivity of wrist, elbow, or shoulder, particularly when the postures of adjacent joints are changed.

It is clear that the selection of hand posture is sensitive to the coupling between the object and the hand. Most of the object weight is supported by the tips of the fingers and thumb for overhand grasp using a complex combination of normal finger flexion forces and friction forces. The overhand grip involves flexion of the fingers via contraction of the forearm finger flexor muscles, but also contraction of the wrist extensor muscles. In underhand grip the load is supported mainly by the palm and proximal portions of the fingers. While friction still is important in underhand grip, it is not as critical as in overhand grip. The forearm finger flexor muscles and wrist flexor muscles work synergistically for underhand grip. Further studies are required to understand and model the loads on the finger and wrist muscles and the important role of friction in determining part handling behavior.

2.5 Conclusions

This study has shown that subject-selected posture used for grasping, holding, and placing cylindrical object is influenced by object weight. The probability of choosing overhand posture to grasp cylinders reduces from 85% to 0 while the one of underhand posture increases from 15% to 100% as cylinder weight increases from 3.3 N to 53.3 N. In overhand posture, relative load increases faster for the hand than for other upper limb joints, which motivates subjects to adapt underhand posture that reduces relative hand load. Subjects held light cylinders (3.3 N) at elbow height 20%

of the time, and at mid-thigh height using a hook grip 80% of the time. The probabilities of holding cylinder at elbow height and at mid-thigh height decrease as object weight increases; Subjects held heavy cylinders (53.3 N) 60% of the time at shoulder height using a palm grip. Subjects placed cylinders using postures similar to the ones for grasping, but the overhand posture was used more frequent for heavier objects.

Logistic models were proposed to describe the posture probabilities for grasping, holding, and placing cylindrical object as function of relative joint load. The preference for underhand posture versus overhand posture to grasp and place cylindrical objects appears to be motivated by the coupling between the hand and object based on biomechanical analysis. The relative hand load threshold for grasping and placing are 34% and 53% respectively which correspond to a 50% probability change from overhand to underhand posture. The relative hand load threshold for holding is 24% which corresponds to a 50% probability change from hookgrip posture at mid-thigh height to palm grip posture at shoulder height. The relative wrist, elbow, and shoulder loads are low when people change postures to hold an object. For very low load, about 20% of the subjects maintained the same arm posture in which they first gained control of the object, while 80% held the object alongside the thigh close to the shoulder, both postures that reduce shoulder and elbow moments relative to the initial grasp posture.

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Chapter 3

The Influence of Hand Force Distribution on the Selection of Hand Posture

Abstract

This study aims to provide a biomechanical explanation for hand posture selection for grasping work object. Twelve subjects (6 males and 6 females) lifted and placed cylindrical object with two sizes (38 mm and 70 mm in diameters), two weights (26.5 and 43.1 N), and four hand postures (overhand, underhand, pinch, and hook grip). The results show that the average thumb tip force and sum of fingertip forces for grasping (at lifting onset) decreased by 57% and 38% respectively from overhand to underhand posture, while the force on MCP region increased by 5.6 times. Fingertip force was reduced by 60% from pinch to hook grip posture. As object size increased, more forces concentrated on thumb and finger tips. Hand force increased as object weight increased. 81% of subjects preferred underhand to overhand posture at elbow height, and 98% of subjects preferred hook grip to pinch at mid-thigh height. Selection of posture appears to be related to the preference of reducing thumb and finger tip forces and relative joint loads.

3.1 Introduction

The aim of this study was to provide a biomechanical explanation for hand posture selection for grasping work object. This information is needed for ergonomic analysis and design of work objects and methods that provide workers with sufficient control over objects that need to be grasped, held, or manipulated with the hand. Loss of control can cause acute injuries when the hand is placed in contact with a sharp edge (Dempsey and Hashemi 1999, Sorock *et al.* 2002). Excessive force for compensating for lack of control is associated with fatigue and increased risks of musculoskeletal disorders (Byström and Kilbom 1990, Armstrong *et al.* 1993, Roquelaure *et al.* 1997).

Previous studies have shown that posture selection is related to task factors and relative loads. Napier (1956) proposed that power grip is often used for maximum strength and is best suited for forceful exertions of the hand that do not require great precision, while pinch grip is a position of maximum control and is best suited for exertions that require great precision and low force. Studies (Johansson and Westling 1988, Frederick and Armstrong 1995, Kinoshita *et al.* 1996) show that a) Individual tend to exert forces that are proportional to the minimum force required to prevent objects from slipping out of the hand; b) Force exerted to transfer objects from one location to another is proportional to object weight and friction; and c) It is common to exert a little extra force than is necessary to support the object or a “safety margin” (Westling and Johansson 1984, Grieshaber and Armstrong 2007).

Studies of finger/hand force distributions on cylindrical handles show that forces are concentrated on the finger tips. For cylinders that are smaller that the inside grip diameter, the thumb and fingers work together to press the handle against the palm (Lee and Rim 1991). As the diameter increases the tips of the thumb and fingers work in opposition against each other (Radhakrishnan and Nagaravindra 1993, Seo *et al.* 2007, Seo and Armstrong 2008). Gripping large objects is similar to pinch grip in that the fingers and thumb work in opposition, but similar to power grip in that external contact forces help to stabilize the proximal sections of the fingers and thumb.

Rosenbaum et al. (1990, 1996) showed that hand posture selection is affected by the subjects' perception of effort to place the object at the end of transfer task. They found that subjects chose underhand grip, which was reported by subjects more discomfort than overhand grip, in order to place the right end of the cylinder down to a target disk, while the subjects chose overhand grip to place the other end down. But they didn't show how much effort, or relative loads that affects hand posture selection.

Studies by Zhou et al. (2011a) suggest relative joint load thresholds associated with grasping cylinders under or overhand and for holding using hook grip. The probability of choosing overhand posture to grasp cylinders reduces from 85% to 0% while the one of underhand posture increases from 15% to 100% as cylinder weight increases from 3.3 N to 53.3 N. As subjects gained control over the cylinder, they shifted to hook grip posture at mid-thigh height or palm grip posture at shoulder height to hold the object. The relative loads on the wrist, elbow and shoulder could be computed from motion tracking data and object but, but the relative loads on the finger joints were inferred from strength measurements. Computation of joint loads requires estimating both the joint center locations and the hand force distribution.

Equipment is available for measuring normal forces, but shear force distributions due to friction can only be inferred.

For the purpose of the study, we will 1) examine the hand-object force distribution for overhand, underhand, pinch, and hook grip postures for lifting cylinders of varying size and weights; 2) examine the hand force distribution for maximal power grip and pinch exertions for small and large cylinders; and 3) examine preferred postures for lifting cylinders.

3.2 Methods

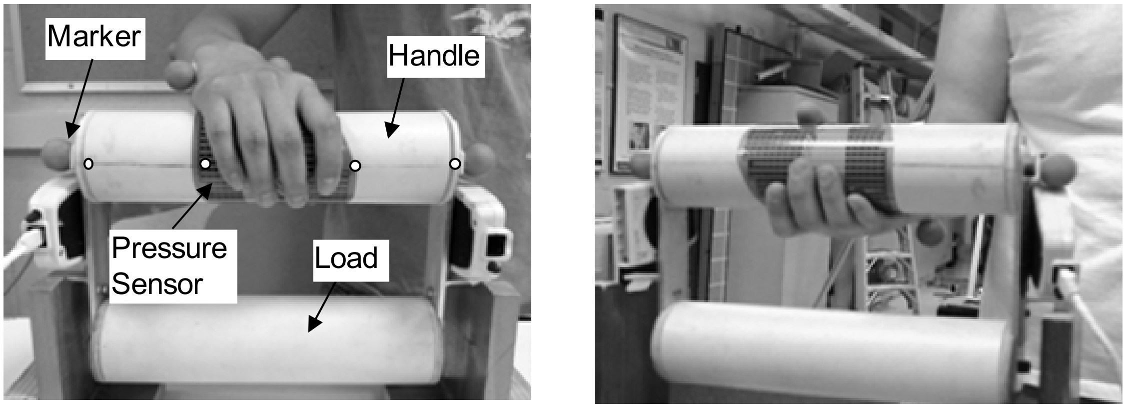
3.2.1 Procedure

An experiment was conducted in which subjects 1) performed maximum grip and pinch of cylindrical objects; 2) grasped, lifted, and placed cylindrical objects using specified hand postures; and 3) performed preferred trials using self-selected posture.

Hand force distributions of right hand power grip and pinch maximal exertions were measured with flexed elbows (90°) and horizontal forearms using a vertical 38 and 70 mm cylindrical handle. There were two repetitions for each size and posture combination.

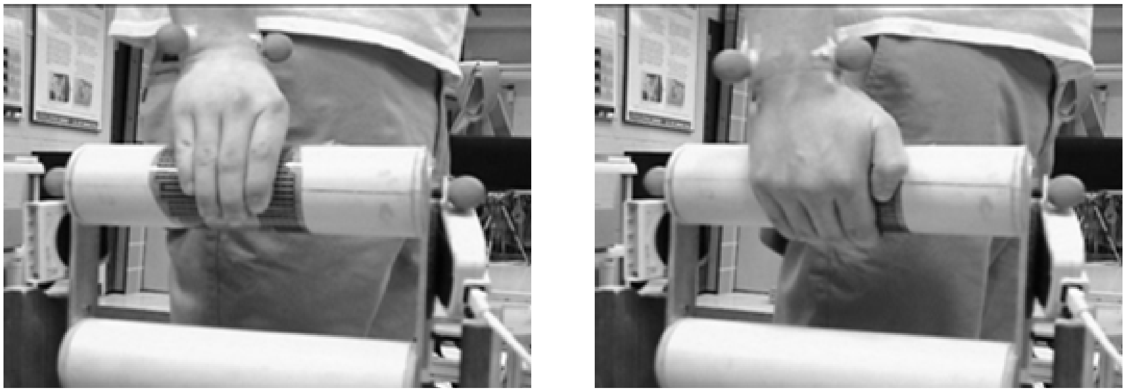
Subjects then reached, grasped, lifted an object about 3 cm vertically from its original location using specified posture, held it for about 3 seconds, and placed the object with the right hand. The independent variables were object size, weight, and posture. The dependent variable was hand force distribution. The object was a weight suspended from a cylindrical handle (Figure 3.1). Two handle diameters were tested, 38 mm and 70 mm in diameter and levels of object weight were 26.5 N and 43.1 N. Four postures were tested, overhand grasp, underhand grasp, pinch, and hook grip (see Figure 3.1). The object was located with its handle at the elbow height vertically and one forearm length horizontally for the overhand grasp and underhand grasp. The handle was at mid-thigh height vertically and about 2 cm horizontally for the pinch and hook grip postures. The subjects performed the task at their own natural speed while standing. Trials were blocked on size and weight, with the order randomly selected for each subject. The order of posture was randomized within block for each subject. There were practice sessions for each condition so that subject can get familiar with specified posture and object properties. Each condition was tested twice.

Subjects also performed two “preferred” trials using their self-selected posture from the specified postures for each object size and weight condition at either the elbow or mid-thigh height. The preferred trials were always performed after the lifting trials.



(A) Overhand

(B) Underhand



(C) Pinch

(D) Hook

Figure 3.1. The object to be grasped consists of a handle and load connected by aluminum bars on both sides. Two handle sizes were tested, 3.8 cm and 7 cm in diameter. The sensor was wrapped around the cylindrical handle. The object rested horizontally on two wood supports. Overhand posture was shown.

3.2.2 Subjects

Twelve university students (6 males and 6 females, age between 19 and 27 years, mean age 21.8 ± 2.5) participated in the experiment. All participants were right-handed and were free of any movement disorders. They gave written informed consent in accordance with our University IRB regulations. The average stature was 179.9 ± 4.1 cm for males and 167.2 ± 7.6 cm for females. The average hand length was 19.2 ± 0.8 cm for males and 17.6 ± 0.7 cm for females. The hand lengths ranged from 5th percentile to 73rd percentile for males, and from 8th percentile to 75th percentile for females based on the population data from Garrett (1971).

3.2.3 Apparatus

A pressure mapping system, F-Scan (Tekscan Inc., South Boston, MA) was used to measure hand normal force at 60Hz (Seo *et al.* 2007, Young *et al.* 2010a). The sensor was wrapped around the cylindrical handle of the object. The pressure sensor consists of an array of sensels which have the size of 5.08 mm by 5.08 mm. One sensor pad was used for the 7 cm cylinder, while two sensor pads were used for the 38 mm cylinder. To ensure the weight and balance are consistent across object size, two sensor connectors (VersaTek Cuff) which the sensor attached to were always attached to the object.

The pressure sensor was equilibrated and calibrated using custom-made devices prior to test (Figure 3.2). The device consists of an acrylic cylinder and a rubber bladder which can be inflated to create an outward pressure against the cylinder (Young *et al.* 2010a, Nicholas *et al.* 2012). Two devices were built with the inner diameters of the cylinders matching the object sizes tested. The sensor was placed between the cylinder and the rubber bladder so that the sensels can be evenly loaded. An air pump was used to maintain the pressure to counter leaking. The pressure sensors were calibrated at pressures of 34.5 kPa and 206.8 kPa (5 PSI and 30 PSI) based on pilot data.

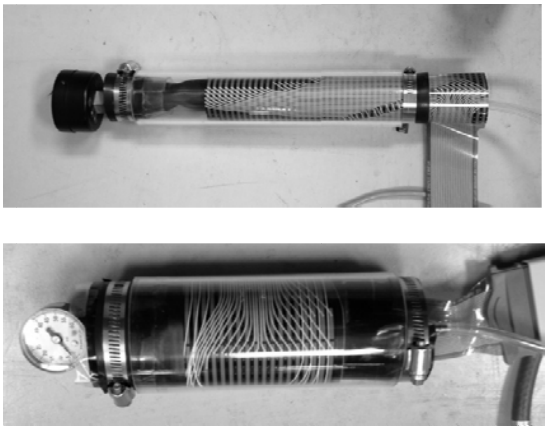


Figure 3.2. Equilibration and calibration devices for the two object diameter (3.8 cm and 7 cm) for the Tekscan pressure sensor.

An eight-camera Qualisys motion tracking system (Qualisys Inc., Sweden) was used to record object location at 60Hz. Retro-reflective markers were attached to centers of the two ends of the handle of the object to track object position.

3.2.4 Data Analysis

For lifting trials, the hand force distribution at lifting onset (the time of grasping) was analyzed. The lifting onset was determined from the marker data. The marker data were filtered using a bidirectional second order Butterworth filter with a cut-off frequency of 6 Hz. The lifting onset was estimated as the time at which the vertical positions of both object markers (the two on each end of the cylinder) exceeded 5 mm and remained above it for 200 ms. For strength trials, hand force data were averaged over 2 seconds during maximum exertion.

The hand force data was segmented into regions, specifically, the distal phalanges of the four fingers and the thumb (tips), middle and proximal phalanges, thenar region and proximal phalanx of the thumb, and metacarpophalangeal (MCP) region, as described by Nicholas et al. (2012). Analysis of variance was performed using MINITAB® software to determine significant factors on hand forces. Model included object size, weight, posture, and gender as fixed variables, their second order interactions, and subject as a random variable. Post-hoc Tukey tests were performed on significant main effects and interactions to identify hand force differences among conditions.

3.3 Results

3.3.1 Hand Force Distribution during Maximum Power and Pinch Grips

Hand force distributions for maximum power grip and pinch are summarized in Table 3.1 by gender. The Resultant forces computed by summing up force component vertical to a split plane which was aligned with the wrist are also shown in Table 3.1. The total normal forces of power grip and pinch postures were 1.9 times and 1.5 times greater for males than for females, respectively (size pooled, both $p<0.01$). The resultant force of power grip decreased 50% and 62% for males and females respectively as handle size increased from 38 cm to 70 mm ($p<0.01$). The resultant force of maximum pinch was not significantly different for the two sizes for both male and female ($p>0.1$).

As handle size increased from 38 mm to 70 mm, the total normal force of power grip decreased by 57% (gender pooled, $p<0.01$), resultant force of power grip decreased by 54% (gender pooled, $p<0.01$), MCP region force for power grip decreased by 84% (gender pooled, $p<0.001$). The normal and resultant forces for pinch grip were not significantly different for the two handle sizes ($p>0.05$).

Table 3.1. Hand force distribution for maximal power and pinch grips of two handle sizes (mean ± SD).

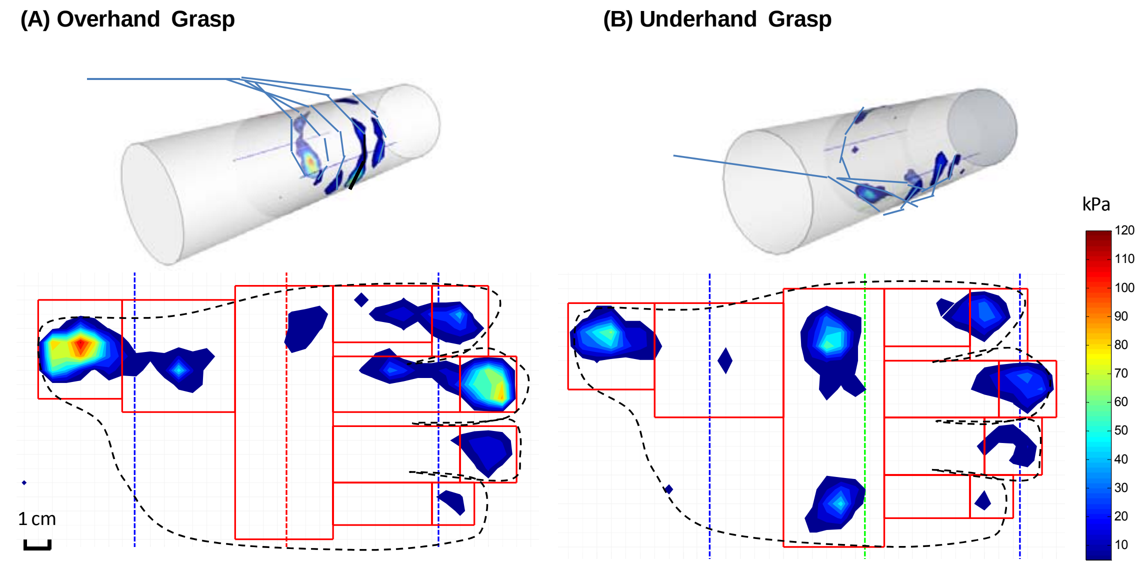
				Region Forces (N)				
Posture	Object Diameter (mm)	Total Normal Force (N)	Resultant Force* (N)	Thumbtip	Thumb thenar & phalanx	MCP region	Sum of finger middle & proximal phalanges	Sum of fingertips
Male								
Power	38	779 ± 136	489 ± 97	53 ± 24	112 ± 43	252 ± 55	123 ± 57	182 ± 64
	70	362 ± 82	245 ± 54	77 ± 19	83 ± 39	35 ± 24	47 ± 18	109 ± 34
Pinch	38	141 ± 32	113 ± 26	60 ± 17	<1	<1	3 ± 6	73 ± 10
	70	165 ± 29	144 ± 29	77 ± 15	<1	<1	10 ± 15	71 ± 20
Female								
Power	38	435 ± 67	263 ± 78	27 ± 20	52 ± 21	146 ± 32	81 ± 40	116 ± 36
	70	159 ± 30	100 ± 17	31 ± 6	21 ± 14	29 ± 21	15 ± 11	58 ± 11
Pinch	38	108 ± 18	94 ± 26	50 ± 13	<1	<1	<1	54 ± 8
	70	92 ± 19	82 ± 18	46 ± 7	<1	<1	2 ± 5	41 ± 12

* Resultant force was computed by summing up force component vertical to a split plane which was aligned with the wrist.

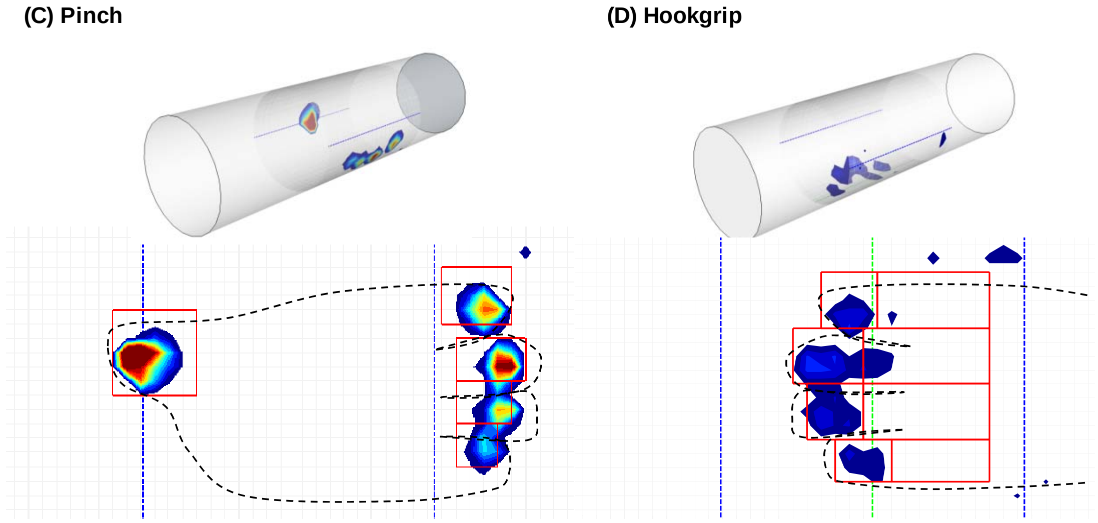
The relative distributions of the index, middle, ring, and little fingers for power grip were 29%, 36%, 23%, and 12%, respectively (size pooled). The relative distributions of the four fingers for pinch were 37%, 34%, 20%, and 8%, respectively (size pooled).

3.3.2 Hand Force Distribution during Grasping and Lifting

Sample hand force distributions for one male subject grasping (at lifting onset) a 70 mm diameter, 43.1 N cylinder using the four postures are shown in Figure 3.3.


(A) Overhand Grasp

(B) Underhand Grasp


(C) Pinch

(D) Hookgrip

Figure 3.3. Sample hand force distributions for grasping (at lifting onset) a 70 mm diameter, 43.1 N cylinder using four postures (overhand, underhand, pinch, and hook grip) from a male subject. Hand forces are segmented into regions, i.e., the distal phalanges of the four fingers and the thumb (tips), middle and proximal phalanges, thenar region and proximal phalanx of the thumb, and metacarpophalangeal (MCP) region. The dash lines are vertical top (red), vertical bottom (green), and horizontal (blue) in laboratory coordinate system. The hand contour is estimated for illustration.

The sample hand force distribution shows that for this cylinder size, hand forces are highly concentrated at thumb tip (distal phalanx) and finger tips. The tip forces appear to be the largest for pinch, then for overhand grasp, then for underhand grasp, and the lowest for the hook grip.

Hand force distributions during grasping for the two object sizes (38 mm and 70 mm in diameter), two weights (26.5 N and 43.1 N), and four postures are summarized in Table 3.2. Hand force distributions by posture are shown in Figure 3.4. Two female subjects were unable to lift the 7 cm, 43.1 N cylinder using overhand posture and their trials were excluded from analysis.

As subjects changed from overhand to underhand posture, the average forces on thumbtip (distal phalanx), thumb thenar and proximal phalanx, finger middle and proximal phalanges, and fingertips decreased by 57%, 38%, 11%, and 38%, respectively, while the force on MCP region increased by 5.6 times (size and weight pooled, all $p<0.001$). Gender was not found significant for these forces (all $p>0.05$) except for the finger middle and proximal phalanges forces ($p=0.015$). Specifically, for 38 mm cylinder, the forces on thumbtip and fingertips were reduced by 55% and 48%, respectively, while the MCP region force increased by 4.7 times (weight pooled, all $p<0.001$). For 70 mm cylinder, the forces on thumbtip and fingertips were reduced by 58% and 22%, respectively, while the MCP region force increased by 13 times (weight pooled, all $p<0.001$). Specifically for the sum of fingertip forces of overhand posture, the relative distributions of the index, middle, ring, and little finger tips were 20%, 34%, 30%, and 16%, respectively (size and weight pooled).

For overhand lifting, regression models were fitted to thumb force and sum of fingertip forces with factors of hand length, object size, and object weight. Thumb force was negatively related with hand length (Coefficient=-0.721, $p>0.1$), while sum of fingertip forces was positively related with hand length (Coefficient=2.027, $p<0.01$).

The forces on thumbtip and fingertips are the greatest for pinch posture comparing to the other postures (size and weight pooled, both $p<0.001$). As subjects changed from pinch to hook grip posture, the thumbtip force was reduced to almost zero; the sum of fingertip forces was reduced by 60%; the sum forces of finger middle and proximal phalanges increased by 2.4 times (size and weight pooled, $p<0.001$). The fingertip forces for the hookgrip were 69% of the one for the overhand posture (size and weight pooled, $p<0.001$), and were similar to the one for the underhand posture (size and weight pooled, $p=0.8$).

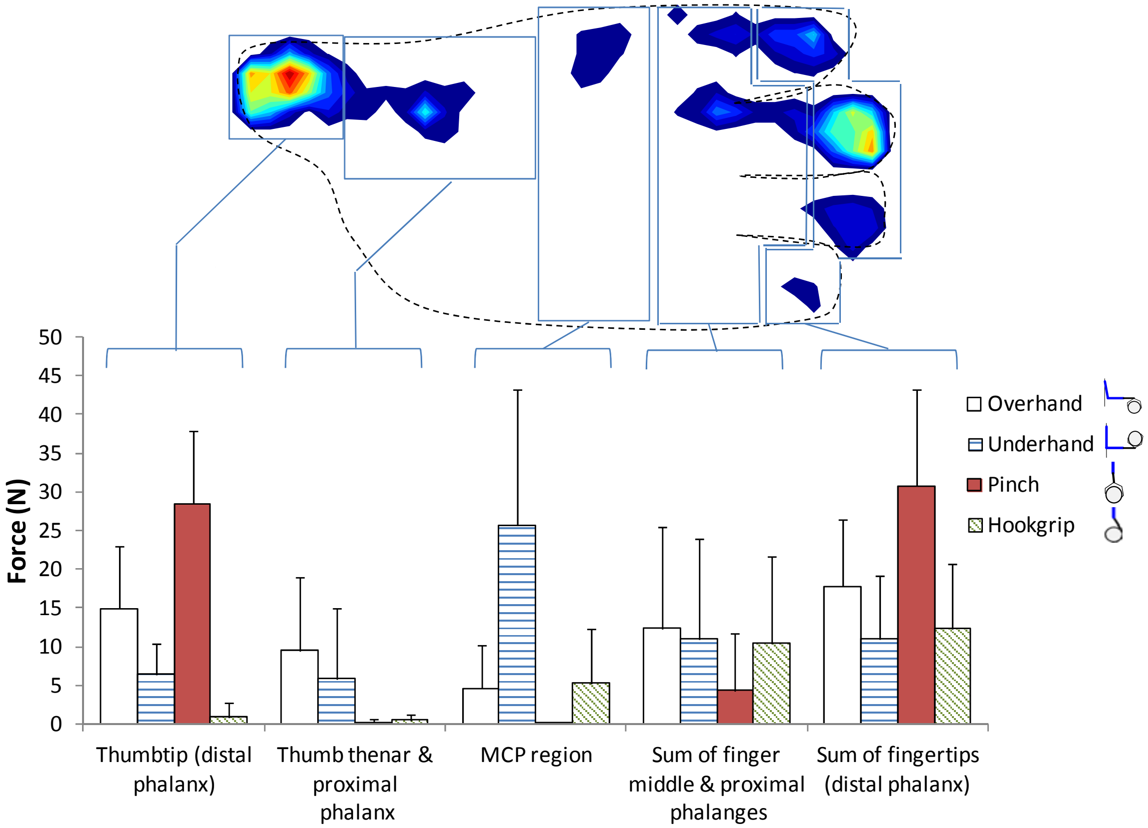


Figure 3.4. Hand force distribution during grasping (at lifting onset) by posture (object size and weight pooled, mean ± SD).

Total normal force was greater for the 38 mm cylinder than for the 70 mm cylinder (weight and posture pooled; $p<0.001$). For overhand posture, as object size increased from 38 mm to 70 mm, the hand force became more concentrated at thumb and finger tips. There is about 42% of total normal force concentrated at the distal phalanges for the 38 mm cylinder, comparing to 70% for the 70 mm cylinder (weight pooled).

Table 3.2. Hand force distribution during grasping (at lifting onset) for two handle sizes, two weights, and four postures (mean ± SD).

				Region Forces (N)				
Object Weight (N)	Posture	Total Normal Force (N)	Resultant Force* (N)	Thumbtip	Thumb thenar & phalanx	MCP region	Sum of finger middle & proximal phalanges	Sum of fingertips
				38 mm Cylinder				
26.5	Overhand	61 ± 38	20 ± 7	8 ± 5	10 ± 9	7 ± 6	13 ± 16	19 ± 8
	Underhand	71 ± 44	17 ± 8	4 ± 3	7 ± 9	31 ± 12	14 ± 14	10 ± 9
	Pinch	60 ± 13	5 ± 6	23 ± 6	<1	<1	3 ± 7	29 ± 8
	Hookgrip	30 ± 14	17 ± 7	<1	<1	5 ± 4	8 ± 7	12 ± 7
43.1	Overhand	88 ± 29	27 ± 8	11 ± 5	17 ± 12	10 ± 6	22 ± 14	25 ± 8
	Underhand	104 ± 44	23 ± 8	4 ± 3	10 ± 14	47 ± 15	22 ± 16	14 ± 10
	Pinch	91 ± 19	7 ± 8	36 ± 10	<1	<1	9 ± 11	42 ± 13
	Hookgrip	59 ± 32	27 ± 12	<1	2 ± 3	11 ± 11	23 ± 14	19 ± 9
				70 mm Cylinder				
26.5	Overhand	38 ± 11	11 ± 5	18 ± 5	3 ± 3	<1	4 ± 2	10 ± 5
	Underhand	30 ± 10	6 ± 4	7 ± 3	2 ± 3	9 ± 3	3 ± 2	8 ± 5
	Pinch	49 ± 14	6 ± 4	23 ± 7	<1	<1	3 ± 3	21 ± 8
	Hookgrip	14 ± 7	9 ± 3	<1	<1	2 ± 4	4 ± 2	6 ± 4
43.1	Overhand	60 ± 11	14 ± 6	23 ± 6	8 ± 5	<1	10 ± 7	17 ± 5
	Underhand	51 ± 21	12 ± 8	10 ± 3	5 ± 6	16 ± 7	5 ± 4	13 ± 7
	Pinch	71 ± 18	12 ± 8	33 ± 8	<1	<1	3 ± 4	32 ± 11
	Hookgrip	23 ± 11	15 ± 7	<1	<1	3 ± 4	7 ± 6	11 ± 7

* Resultant force was the net difference of bottom half normal force and upper half normal force in vertical direction in laboratory coordinate system.

As object weight increased from 26.5 N to 43.1 N (63% increase), total normal force increased (size and posture pooled, $p<0.001$). For overhand posture, thumbtip and finger tip forces increased by 22% and 47% respectively ($p<0.01$). For underhand posture, MCP region force increased by 52% ($p<0.01$). Thumb tip force increased by 17% ($p<0.05$) while the sum of finger tip forces increased by 20% ($p>0.05$). For pinch posture, thumbtip and finger tip forces increased by 48% and 49% respectively (both $p<0.01$). For hookgrip posture, sum of finger tip forces increased by 40% ($p<0.01$).

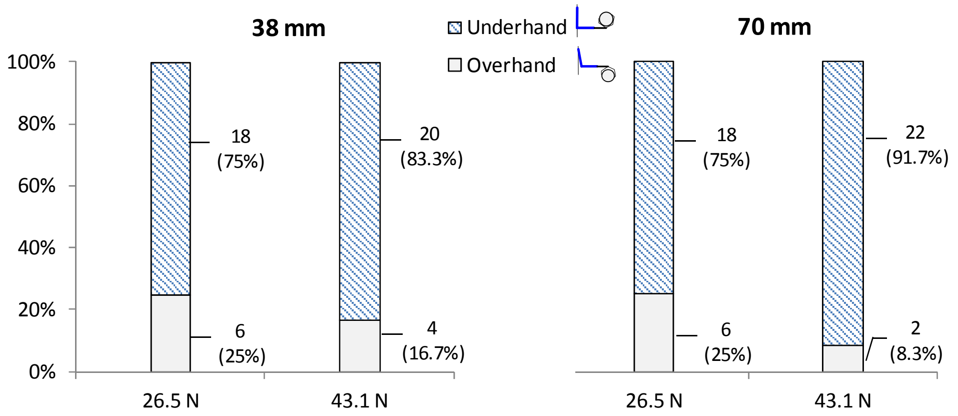
3.3.3 Selection of Preferred Posture for Lifting Cylinders

The frequencies of self-selected postures during preferred trials are shown in Figure 3.5 by object size, weight, and grasp height (elbow or mid-thigh height). 81% of subjects preferred underhand to overhand posture at elbow height, and 98% of subjects preferred hook grip to pinch at mid-thigh height (size and weight pooled).

There are 71% of male subjects and 92% of female subjects selected underhand instead of overhand posture at elbow height, respectively (size and weight pooled). There are 96% of male subjects and 100% of female subjects selected hook grip instead of pinch at mid-thigh height, respectively (size and weight pooled).

More than 50% subjects preferred to use underhand grasp and hook grip for both object sizes and weights. As object weight increased from 26.5 N to 43.1 N, the frequency of selecting underhand posture increased from 75% to 89% (size pooled); the frequency of selecting hook grip increased from 96% to 100% (size pooled).

(A) Self-selected posture (preference) at elbow height (overhand or underhand grasp)



(B) Self-selected posture (preference) at mid-thigh height (pinch or hook grasp)

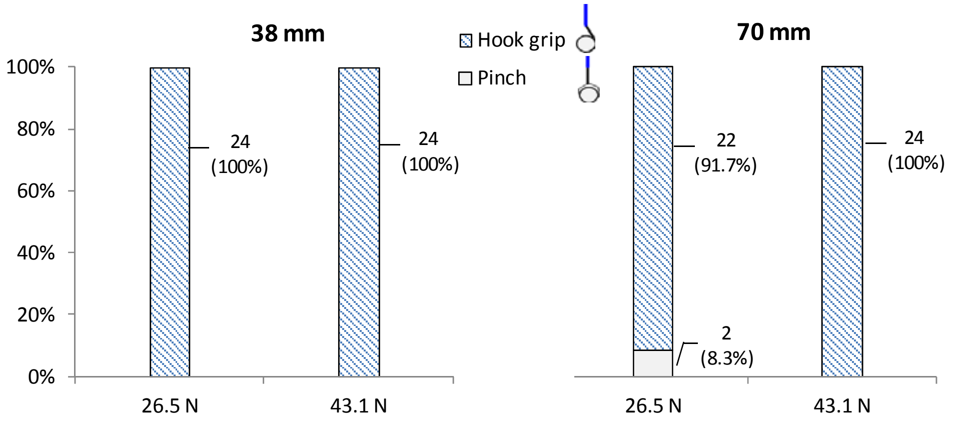


Figure 3.5. Frequency of self-selected posture (posture preference) at elbow height (either an overhand or an underhand grasp), or at mid-thigh height (either a pinch or a hook grip).

3.4 Discussion

3.4.1 Effect of Hand Posture on Hand Force Distribution

This study shows new data on the effect of hand posture on hand force distribution. The result shown in Table 3.2 show that by using overhand instead of underhand posture, the average forces on thumbtip (distal phalanx) and fingertips decreased by 57% and 38%, respectively, while the force on MCP region increased by 5.6 times (size and weight pooled; see Table 3.2). The forces on thumbtip and fingertips are the greatest for pinch posture comparing to the other postures (size and weight pooled). When subjects used hook grip posture, the thumbtip force was reduced to almost zero; the fingertip forces was reduced by 60% (size and weight pooled; see Table 3.2).

While overhand and underhand grips are both similar to power grip defined by Napier (1956), their hand force distributions are biomechanically different due to alignment with the gravitational force during grasp-to-lift tasks. The data in Table 3.2 show that most of the object weight is supported by active flexion forces of the fingers and thumb for overhand posture. These forces produce moment about finger joints. As a contrary, finger forces are not required to support the object weight for underhand posture. Load can be supported mainly by the palm (MCP region). In this case fingertip forces are reduced from the ones in overhand posture. The remaining fingertip forces may be due to the motivation for stabilization in horizontal plane. Hand forces can concentrate at different regions even when postures are similar, which is consistent with previous findings in push and pull tasks (Kong and Freivalds 2001, Aldien *et al.* 2005, Young *et al.* 2010b, Nicholas *et al.* 2012) and axial torque exertion with opposite directions (Seo *et al.* 2007). Pylatiuk et al. (2006) also showed that grip force distribution of the whole hand changed during different phases of a cylindrical grasp-pour task.

The result in Table 3.2 shows that hand forces are concentrated at finger tips in pinch posture, while the forces shifted to middle and proximal phalanges with a reduction of fingertip forces in hook grip. The data show that by changing from pinch to hook grip posture, the sum of fingertip forces was reduced by 60%; the sum forces of finger middle and proximal phalanges increased by 2.4 times. The resultant forces of pinch grip in Table 3.2 are small, indicating that object weight is mostly supported by friction forces exerted by active flexion of fingers in this case.

3.4.2 Effect of Object Size and Weight on Hand Force Distribution

Consistent with previous studies (Amis 1987, Lee and Rim 1991, Radhakrishnan and Nagaravindra 1993, Seo *et al.* 2007), this paper shows that total normal forces decrease as object diameter increases. In addition, the data shows that for overhand posture, as object size increased from 38 mm to 70 mm, 70% of total normal force is concentrated at thumb and finger tips comparing to 42% for the 38 mm cylinder (weight pooled). Seo *et al.* (2007) explained that in a static power grip of small cylindrical object, the major forces on the thumb and fingertips work against the palm. As cylindrical diameter increases, the major forces on the thumb and fingertips gradually become opposition and work against each other. This appears to be true for lifting cylinder as shown in this study (see Figure 3.6). For smaller cylinder, the fingers and thumb can go underneath the object. Both distal phalanges and middle phalanges can exert force against the palm to counterbalance the gravitational force. As cylinder diameter increases, the fingers and thumb has to be more opposite. They have to exert more normal forces to provide sufficient friction forces to lift the object.

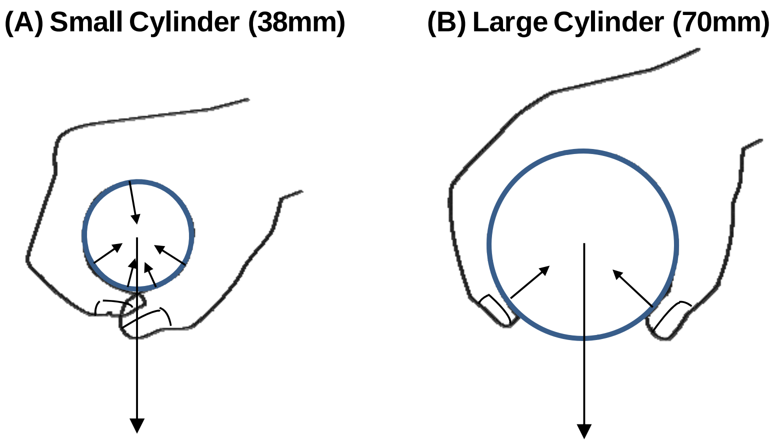


Figure 3.6. Illustration of the effect of object size on hand force distribution for overhand grasp. As object size increased from 38 mm to 70 mm, 70% of total normal force is concentrated at thumb and finger tips comparing to 42% for the 38 mm cylinder (weight pooled).

Thumb and finger forces of pinch postures increases as object weight increases (see Table 3.2). This is consistent with previous studies (Johansson and Westling 1988, Frederick and Armstrong 1995, Kinoshita *et al.* 1996). This is also the case for overhand posture. In hook grip, finger forces also increases as weight increases. As a contrary, finger forces are similar for lifting different weights for underhand posture. This may be attributable to that finger flexion forces are used primarily for stabilizing the object instead of counterbalancing the gravitational force. In this case, wrist flexion is required to counterbalancing the gravitational force.

3.4.3 Relative Load and Selection of Preferred Hand Posture

Relative thumbtip and fingertip forces of lifting 70mm cylinder normalized by corresponding hand region forces during strength test for each subject (in %, mean ± SD) are shown in Table 3.3. Hand forces for overhand and underhand postures were normalized by max hand forces for power grip posture. Hand forces for pinch and hookgrip postures were normalized by max hand forces for precision grip posture. Table 3.3 shows that the thumbtip is the weak segment for overhand and underhand postures.

By shifting from overhand to underhand posture, or from pinch to hook grip, the relative loads on thumbtip and fingertips were reduced. Selection of preferred hand posture appears to be related to relative load. Subjects demonstrated preferred postures with less thumbtip and fingertip load (Figure 3.5 and Table 3.3). This is consistent with previous finding that subject tend to reduce wrist, elbow, and shoulder joint load by changing from overhand grip to hook grip at mid-thigh height or palm grip at shoulder height for holding (Zhou *et al.* 2011b).

Table 3.3. Relative thumbtip and fingertip forces of lifting cylinder normalized by corresponding hand region forces during maximum exertion tests (in %, mean ± SD). Hand forces of overhand and underhand postures were normalized by max power grip forces. Hand forces of pinch and hookgrip postures were normalized by max pinch grip forces.

Object Weight (N)	Posture	**Male**		**Female**		**Gender Pooled**	
		Thumbtip	Sum of Fingertips	Thumbtip	Sum of Fingertips	Thumbtip	Sum of Fingertips
38 mm Cylinder							
26.5	Overhand	16 ± 10	13 ± 4	29 ± 14	15 ± 7	21 ± 13	14 ± 6
	Underhand	7 ± 7	8 ± 7	14 ± 19	11 ± 12	10 ± 14	9 ± 10
	Pinch	49 ± 18	52 ± 20	49 ± 22	51 ± 15	49 ± 20	51 ± 17
	Hookgrip	2 ± 4	22 ± 15	2 ± 2	22 ± 9	2 ± 3	22 ± 12
43.1	Overhand	19 ± 15	15 ± 3	40 ± 27	20 ± 10	29 ± 23	17 ± 8
	Underhand	11 ± 6	7 ± 5	15 ± 11	10 ± 6	13 ± 8	8 ± 6
	Pinch	58 ± 19	55 ± 21	67 ± 25	71 ± 29	62 ± 22	63 ± 26
	Hookgrip	2 ± 4	27 ± 14	2 ± 3	28 ± 12	2 ± 3	27 ± 12
70 mm Cylinder							
26.5	Overhand	22 ± 7	10 ± 3	64 ± 18	17 ± 8	43 ± 25	13 ± 7
	Underhand	9 ± 3	5 ± 3	26 ± 13	19 ± 8	17 ± 12	12 ± 9
	Pinch	30 ± 12	28 ± 8	53 ± 17	58 ± 27	42 ± 19	43 ± 25
	Hookgrip	<1	10 ± 10	<1	15 ± 8	<1	12 ± 10
43.1	Overhand	31 ± 6	16 ± 3	76 ± 13	32 ± 10	49 ± 25	22 ± 11
	Underhand	14 ± 7	10 ± 7	35 ± 15	27 ± 11	25 ± 16	19 ± 12
	Pinch	45 ± 14	47 ± 17	68 ± 13	83 ± 28	57 ± 18	66 ± 29
	Hookgrip	<1	15 ± 15	<1	33 ± 19	<1	24 ± 19

3.4.4 Limitations

This study was limited that only cylindrical objects were examined. Only one object friction and center-of-mass condition was investigated, while these object properties can affect hand force distribution. It has been shown friction force is important (Johansson and Westling 1984, Frederick and Armstrong 1995) in object transfer tasks. The present study only examined the normal force component due to the limitation of the Tekscan pressure mapping system.

The hand pressure data was manual segemented in this study. This could produce some errors as noted by Pataky et al. (2011). It is possible in future studies to attach optical markers directly to the dorsal side of finger joints and automatically segement hand forces based on marker data.

3.5 Conclusions

- Hand posture affects hand force distribution for grasping and lifting cylinders. In particular, the data show that as subjects changed from overhand to underhand posture, the average forces on thumbtip (distal phalanx) and fingertips decreased by 57% and 38%, respectively, while the force on MCP region increased by 5.6 times. The forces on thumbtip and fingertips are the greatest for pinch posture comparing to the other postures (size and weight pooled). As subjects changed from pinch to hook grip posture, the thumbtip force was reduced to almost zero; the fingertip forces was reduced by 60%;

- Total normal forces decrease as object diameter increases. In addition, the data shows that for overhand posture, as object size increased from 38 mm to 70 mm, 70% of total normal force is concentrated at thumb and finger tips comparing to 42% for the 38 mm cylinder;
- As object weight increased from 26.5 N to 43.1 N (63% increase), total normal force increased (size and posture pooled). For overhand posture, thumbtip and finger tip forces increased by 22% and 47% respectively. For underhand posture, MCP region force increased by 52%. For pinch posture, thumbtip and finger tip forces increased by 48% and 49% respectively;
- 81% of subjects preferred underhand to overhand posture at elbow height, and 98% of subjects preferred hook grip to pinch at mid-thigh height (size and weight pooled);
- Selection of posture appears to be related to the preference of reducing thumb and finger tip forces and relative joint loads.

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Chapter 4

The Influence of Object Orientation and Balance on Finger Force Distribution and Selection of Finger Placement

Abstract

This study examines the effect of object orientation and balance on finger force distribution and selection of finger placement for grasping work object. Twelve subjects (6 males and 6 females) were asked to get, hold with 3 orientations (horizontal 0°, 45°, and vertical 90°), and put a plate object with 5 load locations (Center, Left Near, Right Near, Left Far, and Right Far). Total hand normal force decreased by 26% and 56% as the plate was held from horizontal (0°) to 45°, and to vertical (90°), respectively. The thumb and finger center-of-force (CoF) locations were generally aligned with the load moment arm. The distance between thumb and finger CoF locations increased by 39% as load moment increased from 0.98 Nm to 2.35 Nm, and reduced by 17% as hand length increased from 16.2 cm to 21.1 cm when the plate was held horizontally.

4.1 Introduction

This study aims to describe the effect of object orientation and balance on finger force distribution and placement for grasping work object. This is needed for the design of work equipment and methods that provide workers with sufficient control over objects in part handling tasks. Unbalanced and sharp-edged work object, in the case of losing control and slipped from the hand, can cause hand injuries such as laceration (Sorock et al. 2001). Worker may also need to compensate for lack of control by exerting excessive force, which is associated with fatigue and increased risks of musculoskeletal disorders (Silverstein et al. 1987, Armstrong et al. 1993, Roquelaure et al. 1997).

Previous studies show that self-selected gross hand placement is related to task factors and relative joint load. Rosenbaum et al. (1990, 1996) showed that subjects preferred underhand grip to overhand grip to place the right end of a cylinder down, and vice versa. Subjects appeared to desire to minimize “awkwardness” at the end of the task. Studies by Zhou et al. (2011) suggest relative joint load thresholds associated with grasping cylinders under or overhand and for holding using hook grip. The probability of choosing overhand posture to grasp cylinders reduces from 85% to 0% while the one of underhand posture increases from 15% to 100% as cylinder weight increases from 3.3 N to 53.3 N. As subjects gained control over the cylinder, they shifted to hook grip posture at thigh height or palm grip posture at shoulder height to hold the object. The relative loads on the wrist, elbow and shoulder could be computed from motion tracking data and object but, but the relative loads on the finger joints were inferred from strength measurements.

Finger placement and force distribution are related to relative joint load. Studies (Lederman and Wing 2003, Lukos et al. 2007, Duemmler et al. 2008, Lukos et al. 2008, Fu et al. 2010) showed that subjects shifted their fingertips while external joint moments were produced by unbalanced center-of-mass location. As a contrary, if finger positions are constrained, subjects will scale fingertip forces to accommodate for the change of external torque (for a review see Zatsiorsky and Latash 2004). This indicates that the change of grasp posture is preferred to the modulation of finger force in object-roll-minimizing tasks. Such change of posture implies the preference of less muscle effort in grasping. However, it is not known that in more general and meaningful grasp-to-hold tasks, how object balance could affect grasp since subject could rotate object after lifting.

Friction force is less examined in this context. Studies (Johansson and Westling 1984, Johansson and Westling 1988, Frederick and Armstrong 1995, Kinoshita *et al.* 1996) show that force exerted to transfer objects from one location to another is proportional to object weight and friction. Previous studies shown that texture does not affect grasp posture (Weir *et al.* 1991), but probably due to the relative light weight (150 g) and small size (10.3 cm high, 2.5 cm diameter) of object that are insufficient for observing friction effect on postures.

This study examines the effect of object orientation and balance on finger force distribution and placement for grasping object. Object orientation can affect friction component of finger forces. Object center-of-mass location affects the moment arms from the load to fingers, and may affect the selection of finger forces and placement to reduce load on finger joints.

4.2 Methods

4.2.1 Procedure

An experiment was conducted in which subjects were asked to reach for, grasp, hold, and place a plate object with varying center-of-mass locations and orientations. The independent variables were center-of-mass location and plate orientation. The dependent variables were hand force distribution and finger placements during holding the plate. The plate was 35 cm by 35 cm (see Figure 4.1). The net weight of the plate was counter-balanced by a pulley system. A 710 g load can be attached to the bottom side of the plate at one of five locations (Center, Left Near, Right Near, Left Far, and Right Far). When the plate is at 0° (horizontal), the load at center, left/right near, and left/right far produced an external moment of 0.98 Nm, 1.22 Nm, and 2.35 Nm to the center point of the edge of the plate where the hand grasps (the origin, see Figure 4.2D), respectively.

The plate was initially located horizontally on a fixture at elbow height. Subjects stood about forearm distance from the plate with their right arm aligned with the plate center, and were asked to get the plate, hold it at specified orientation (horizontal 0°, 45°, and vertical 90°) for about 6 seconds, and then put it back.

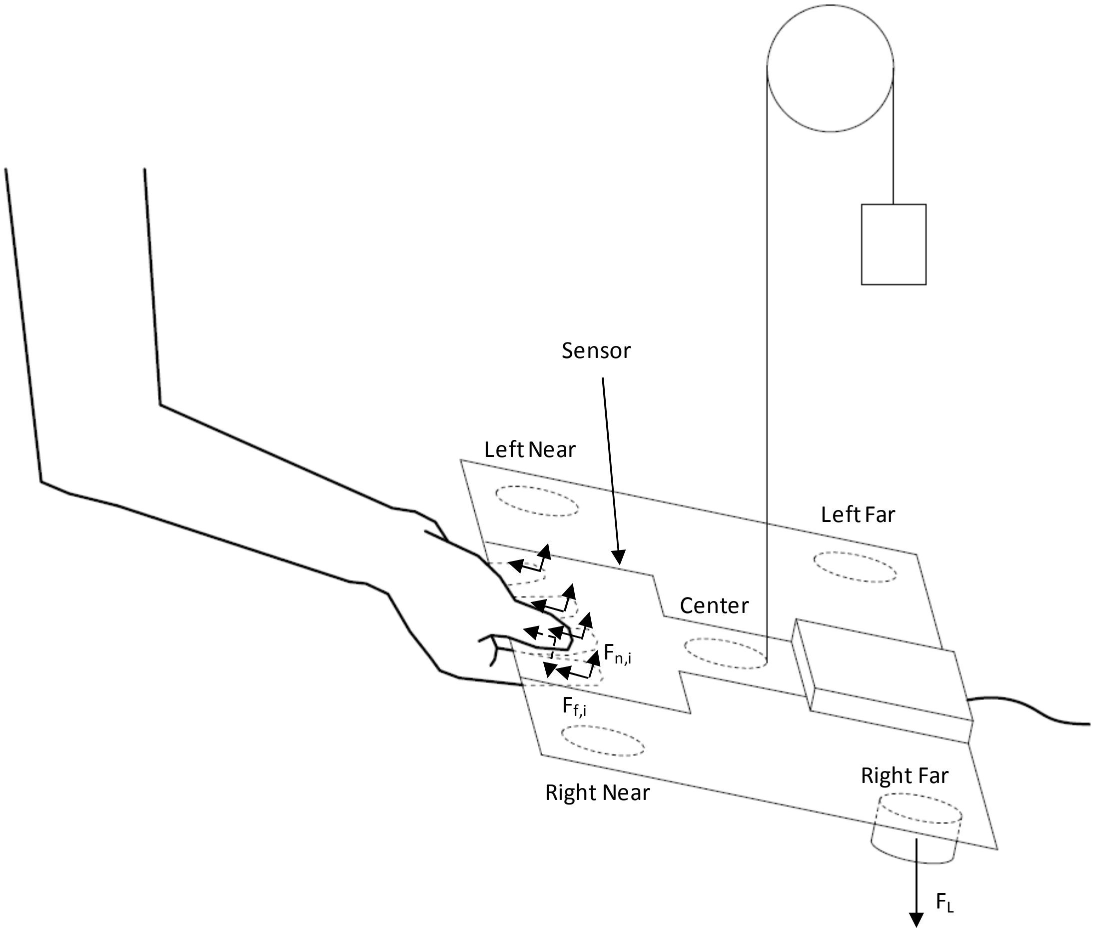

Figure 4.1. Subjects held a plate object at 3 orientations (horizontal 0°, 45°, and vertical 90°) for about 6 seconds. The net weight of the plate (including the pressure sensors and handles) was counter-balanced by a pulley system. An additional 710 g load can be attached to the bottom side of the plate at one of five locations (Center, Left Near, Right Near, Left Far, and Right Far).

The subjects performed the task at their own natural speed while standing. Trials were blocked on object orientation, with the order randomly selected for each subject. The order of load location was randomized within block for each subject. The plate with different load locations appeared visually the same since the load was attached to the bottom side of the plate. The experimenter also always changed load location out of the view of the subjects so that they received no visual cue about the center-of-mass location. There were practice sessions for each condition so that subject can get familiar with specified object properties. Each condition was tested twice.

4.2.2 Subjects

Twelve right-handed university students (6 males and 6 females, age 19-25 years, mean age 21.9 ± 2.2) volunteered to participate in the study. All subjects gave written informed consent in accordance with our University IRB regulations. They were free of any movement disorders. The average stature was 181.3 ± 4.6 cm for males and 166.9 ± 5.3 cm for females. The average hand length was 19.6 ± 0.9 cm for males and 17.4 ± 1.0 cm for females. The hand lengths ranged from 21st percentile to 96th percentile for males, and from 3rd percentile to 81st percentile for females based on the 1988 ANSUR data (Gordon et al. 1989). The average grip strength for the right hand was 485 ± 50 N for males and 332 ± 34 N for females as measured by a Jamar® grip dynamometer at position two (49 mm span). The average thumb-index finger pinch strength was 75 ± 7 N for males and 56 ± 11 N for females as measured by a B&L® pinch gauge.

4.2.3 Apparatus

The finger force distribution was measured by I-Scan™ pressure mapping system (Tekscan Inc., South Boston, MA) at 60 Hz. The pressure sensor has an effective sensing area of 111.8 mm by 111.8 mm, which consists of an array of sensels that have the size of 2.5 mm by 2.5 mm. Two sensors were placed on opposite sides close to one edge of the plate (see Figure 4.1). The sensors were calibrated at pressures of 34.5 kPa and 206.8 kPa (5 PSI and 30 PSI).

Frictional characteristics of the hand were estimated by measuring the force at onset of movement required to pull a 1 kg aluminum plate covered with the pressure sensor from the hand and fingers. There were two replicates for each subject. The average coefficient of friction was 1.5 ± 0.2 between the hand and sensor pad.

The thumb and finger forces during holding the plate were determined by segmenting the hand force data to regions similar to the method described by Nicholas et al. (2012). Finger placement was evaluated using the center-of-force (CoF) location, which was defined as the coordinates of the center of force of the contact between the finger pad and the plate (Fu *et al.* 2010). The CoF location for each finger was computed from force data. Analysis of variance was performed using MINITAB® software to determine significant factors on finger forces. Model included object balance and orientation as fixed variables, their second order interactions, and subject as a random variable. Post-hoc pairwise Tukey tests were performed on significant main effects and interactions to identify main effect differences among conditions. A similar statistical analysis was performed for finger CoF location.

4.3 Results

4.3.1 Finger Force Distribution

Finger force distributions for holding plate with 5 load locations and 3 orientations are shown in Figure 4.2 and Table 4.1. Total hand normal force decreased by 26% and 56% as the plate was held from horizontal (0°) to 45°, and to vertical (90°), respectively (both $p<0.01$).

In particular, the thumb force reduced by 14% and 43%, and the sum of the four finger forces reduced by 33% and 67% as the plate was held from horizontal (0°) to 45°, and to vertical (90°), respectively (all $p<0.05$).

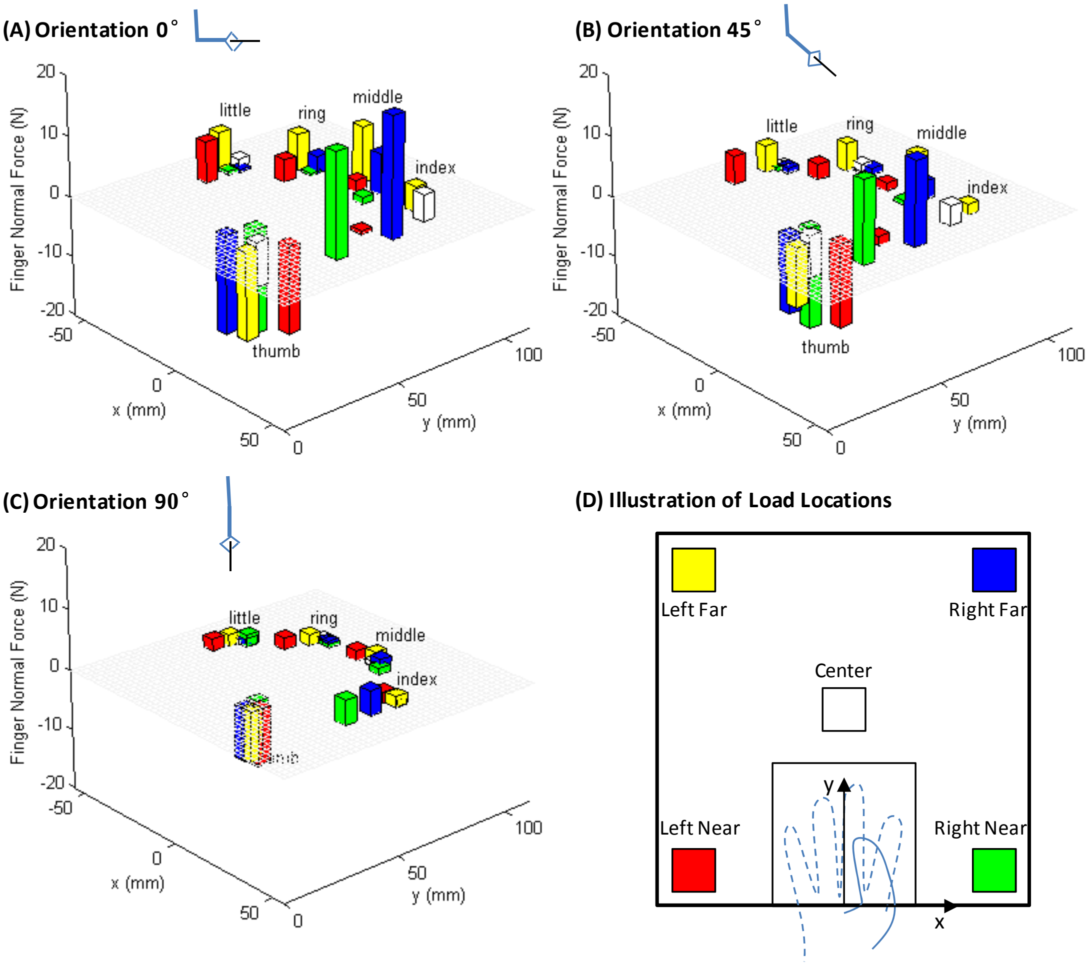

Figure 4.2. Average normal forces and center-of-force locations for the thumb, index, middle, ring, and little fingers for holding plate with 5 load locations and 3 orientations (pooled for all subjects). Thumb forces were plotted as negative magnitudes. The coordinate system was defined as shown in (D) illustration of load locations. The origin was defined at the center point of the edge of the plate where the hand grasps.

Finger forces are affected by load locations. Thumb force for centered load is smaller than the ones for other load conditions. At 0°, subjects exerted greater index finger force when the load is on the right side (17 N for right near and 20 N for right far) comparing the load on the left side (1 N for left near and 4 N for left far). They exerted greater little finger force vice versa (<1N for the load on the right near or right far, and 7 N for left near and 6 N for left far). Thumb forces for the four unbalanced cases were larger than the one when load was in the center ($p<0.01$); however, they were not significantly different from each other ($p>0.05$). As plate orientation increased, finger forces are less different for balanced and unbalanced cases. At 90°, the index and little finger forces are less different for different load conditions.

Table 4.1. Finger force distribution of holding plate with 3 orientations (horizontal 0°, 45°, and vertical 90°) and 5 load locations (Center, Left Near, Right Near, Left Far, and Right Far) (mean ± SD).

Object Orientation (°)	Load Location	Total Normal Force (N)	Finger Forces (N)				
			Thumb	Index	Middle	Ring	Little
0	Center	20 ± 5	7 ± 3	5 ± 2	5 ± 1	2 ± 1	1 ± 1
	Left Near	28 ± 7	15 ± 5	1 ± 1	2 ± 1	4 ± 2	7 ± 2
	Right Near	37 ± 7	17 ± 4	17 ± 4	1 ± 1	<1	<1
	Left Far	41 ± 10	15 ± 6	4 ± 3	9 ± 3	6 ± 1	6 ± 3
	Right Far	48 ± 8	16 ± 4	20 ± 7	7 ± 3	3 ± 5	<1
45	Center	15 ± 7	7 ± 3	3 ± 3	2 ± 2	1 ± 1	<1
	Left Near	24 ± 13	14 ± 7	1 ± 2	1 ± 1	3 ± 2	5 ± 2
	Right Near	32 ± 10	17 ± 5	14 ± 6	<1	<1	<1
	Left Far	26 ± 8	10 ± 4	2 ± 2	5 ± 3	5 ± 2	5 ± 2
	Right Far	32 ± 14	13 ± 6	14 ± 7	3 ± 2	1 ± 1	<1
90	Center	9 ± 5	5 ± 3	1 ± 1	<1	1 ± 1	<1
	Left Near	17 ± 8	9 ± 5	2 ± 1	2 ± 1	2 ± 1	2 ± 2
	Right Near	19 ± 11	11 ± 7	4 ± 4	1 ± 1	<1	2 ± 2
	Left Far	16 ± 6	8 ± 4	2 ± 1	2 ± 1	2 ± 1	2 ± 1
	Right Far	17 ± 13	9 ± 8	4 ± 4	2 ± 2	1 ± 1	1 ± 1

4.3.2 Finger Placement

Finger center-of-force (CoF) locations for holding plate with varying orientation and load location are shown in Table 4.2. The average locations are depicted in Figure 4.2. At 0°, subjects modulated thumb center-of-force location for the left near and right near cases. In particular, their thumb center-of-force x location was 9 mm ($p<0.01$) and 4 mm ($p>0.05$) deviated from the ones for center load case to hold plate with load on the left near and left far location, and was -8 mm ($p<0.01$) and -10 mm ($p<0.01$) deviated from the ones for center load case to hold plate with load on the right near and right far location. Their thumb center-of-force y location was 6 mm ($p<0.01$) and 6 mm ($p<0.01$) deviated from the ones for center load case to hold plate with load on the left near and right near location, and was -8 mm ($p<0.01$) and -4 mm ($p<0.05$) deviated from the ones for center load case to hold plate with load on the left far and right far location.

As plate orientation increased, the thumb and finger CoF locations for unbalanced cases were less deviated from the ones for the balanced case. At 90°, the finger center-of-force locations are similar across different load conditions. In particular, the thumb center-of-force x locations were not significantly different across the varying load conditions (all $p>0.05$). The thumb center-of-force y locations for left near and right near conditions are slightly different from the ones of the other cases.

Table 4.2. Finger center-of-force locations for holding plate with 3 orientations (horizontal 0°, 45°, and vertical 90°) and 5 load locations (Center, Left Near, Right Near, Left Far, and Right Far) (mean ± SD).

Object Orientation (°)	Load Location	Finger Center-of-Force Locations (mm)									
		Thumb		Index		Middle		Ring		Little	
		x	y	x	y	x	y	x	y	x	y
0	Center	12 ± 9	27 ± 11	36 ± 8	79 ± 10	6 ± 9	88 ± 9	-20 ± 7	82 ± 8	-41 ± 7	62 ± 8
	Left Near	20 ± 9	33 ± 9	30 ± 6	57 ± 27	2 ± 8	79 ± 9	-20 ± 8	66 ± 13	-37 ± 6	45 ± 16
	Right Near	3 ± 8	33 ± 9	39 ± 5	37 ± 12	12 ± 8	74 ± 10	-18 ± 8	77 ± 8	-38 ± 8	56 ± 10
	Left Far	15 ± 7	19 ± 9	28 ± 11	83 ± 7	-2 ± 10	86 ± 9	-25 ± 9	77 ± 8	-43 ± 6	56 ± 9
	Right Far	1 ± 11	23 ± 11	39 ± 6	62 ± 13	10 ± 8	84 ± 10	-19 ± 9	80 ± 10	-37 ± 9	60 ± 10
45	Center	10 ± 8	33 ± 8	35 ± 8	74 ± 10	5 ± 11	84 ± 11	-19 ± 9	81 ± 8	-38 ± 6	61 ± 11
	Left Near	21 ± 10	36 ± 5	31 ± 7	45 ± 29	-1 ± 12	76 ± 14	-24 ± 9	65 ± 11	-39 ± 6	41 ± 15
	Right Near	5 ± 9	36 ± 8	39 ± 5	31 ± 13	12 ± 7	73 ± 18	-18 ± 9	80 ± 9	-39 ± 6	59 ± 6
	Left Far	14 ± 8	23 ± 8	32 ± 8	84 ± 7	2 ± 10	88 ± 8	-23 ± 8	78 ± 8	-40 ± 6	56 ± 10
	Right Far	6 ± 9	28 ± 10	40 ± 7	53 ± 16	13 ± 9	81 ± 8	-15 ± 8	82 ± 7	-35 ± 7	61 ± 8
90	Center	5 ± 10	29 ± 8	37 ± 7	67 ± 20	8 ± 10	83 ± 14	-18 ± 10	82 ± 6	-38 ± 9	60 ± 9
	Left Near	8 ± 9	31 ± 11	32 ± 7	65 ± 20	± 8	82 ± 7	-24 ± 8	69 ± 11	-39 ± 8	50 ± 10
	Right Near	3 ± 11	34 ± 10	37 ± 8	44 ± 18	14 ± 10	80 ± 8	-15 ± 11	82 ± 6	-34 ± 11	61 ± 7
	Left Far	8 ± 12	27 ± 8	37 ± 6	66 ± 20	6 ± 8	85 ± 11	-20 ± 10	78 ± 6	-39 ± 9	57 ± 7
	Right Far	5 ± 9	27 ± 8	36 ± 7	55 ± 22	11 ± 9	83 ± 11	-15 ± 8	82 ± 7	-35 ± 9	61 ± 11

Finger CoF locations by gender are shown in Figure 4.3 (load condition and plate orientation pooled). The range (95% confidence ellipse) for index finger was larger than the ones for other fingers for both males and females. Female appeared to spread middle, ring, and little fingers more than male subjects. The ranges of CoF locations for middle, ring, and little fingers for females were larger than the ones for male subjects, indicating larger variability for these finger locations.

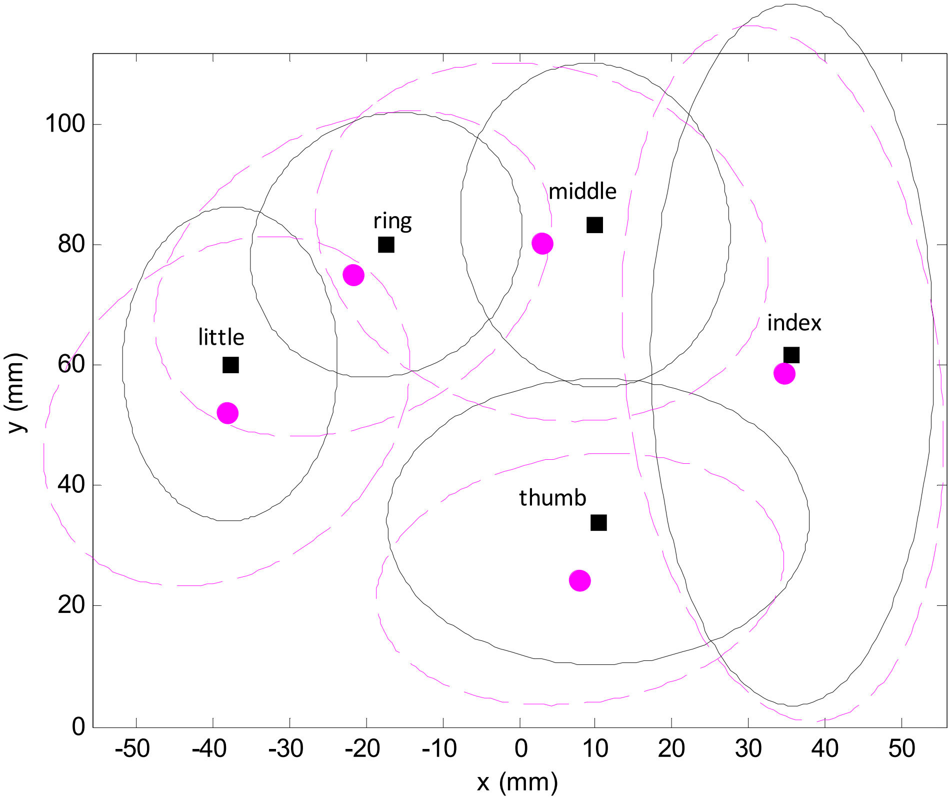

Figure 4.3. Finger center-of-force (CoF) locations by gender (load condition and plate orientation pooled). Average CoF locations for the thumb and fingers are denoted for male (□) and female (○). 95% confidence ellipses for male (solid line) and female (dash line) are also shown.

In particular when the plate was held at 0° (horizontal), the distance between the thumb and finger CoF locations (sum of all four fingers) increased by 39% as external moment increased from 0.98 Nm to 2.35 Nm, and reduced by 17% as hand length increased from 16.2 cm to 21.1 cm. Individual finger CoF locations by gender for varying load conditions when plate was held at 0° (horizontal) are shown in Figure 4.4. The figure also shows the shift of CoF locations from balanced condition (when load was in the center of the plate) to the four unbalanced conditions for individual fingers by gender. For the two near load cases, shift of CoF locations appeared similar for the male and female subjects. However, females exhibited larger shift of the fingers for the left far case than males.

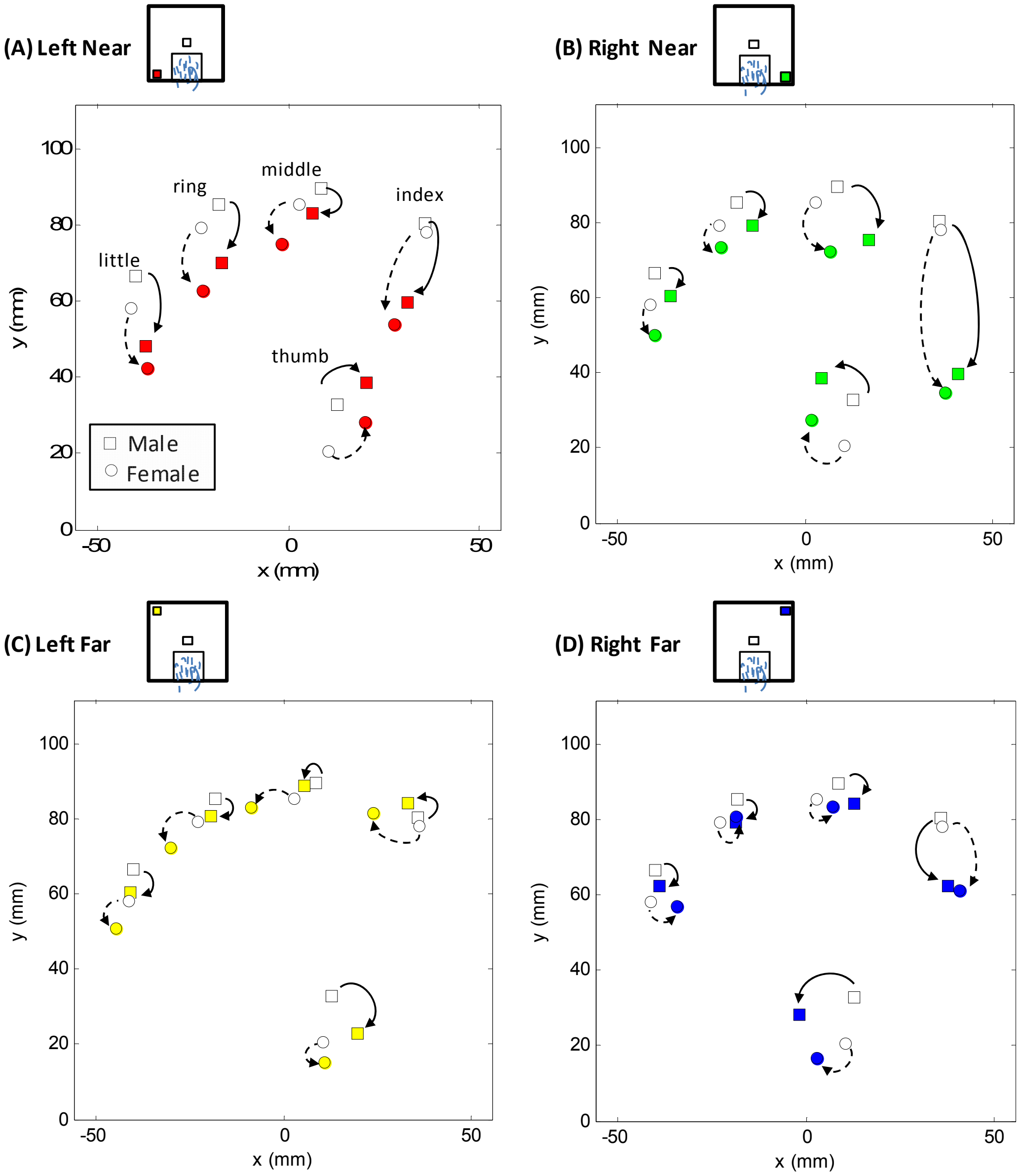

Figure 4.4. Shift of finger placement (center-of-force location) by gender from balanced to the 4 unbalanced load conditions when plate was held at 0° (horizontal). Average CoF locations for the thumb and fingers are denoted for male (□) and female (○). Solid and dash lines denote shift of CoF location from balanced condition (load in the center of the plate) to unbalanced condition for male and female, respectively.

4.4 Discussion

4.4.1 Effect of Load Location

The results show that load location affects both finger forces (Table 4.1) and self-selected placements (Table 4.2), in particular for the case of holding the plate at 0° (horizontal). In this case finger normal forces are required to counter-balance the external torque produced by the load. Subjects chose to alter both finger forces and finger placement (center-of-force location) even if they were allowed not to do so. This strategy might be related to minimizing effort to exert finger forces and hold the plate. These results are consistent with previous findings where subjects modulate their finger placement (Lukos *et al.* 2007, Lukos *et al.* 2008, Fu *et al.* 2010), or scaling fingertip forces to accommodate for external torque if finger positions are constrained (Zatsiorsky *et al.* 2002, Salimi *et al.* 2003, Zatsiorsky *et al.* 2003, Shim *et al.* 2005).

Thumb, index, and little fingers were mostly used to hold the plate in unbalanced conditions. In Left Near condition, little finger acts as a pivot while thumb was used to balance the torque by the load. In Right Near condition, index finger acts as pivot while thumb force balances the external torque. In this case, thumb location shifted to the left side of the middle finger to increase the moment arm so that its force can be reduced. For the Left Far and Right Far cases, thumb center-of-force locations shifted closer to the edge of the plate than the one in balanced case to increase the moment arms.

The data in Table 4.2 show that subjects actively shifted thumb CoF location while the other fingers demonstrated less variations for different load conditions (also see Figure 4.4). This is consistent with the finding by Lukos *et al.*(2007) in which subjects lifted a T-shape unbalanced object with precision grip. Their subjects primarily varied thumb and index finger contact points, whereas the other digits exhibited smaller variations. This might be because thumb has greater degree of independence while the other fingers are more mechanically coupled (Lang and Schieber 2004).

Female appeared to spread middle, ring, and little fingers more than male subjects (see Figure 4.3). More spread fingers may help stabilizing the object, particularly while females have weaker finger strength. In addition, spread fingers can help increase moment arm in case of unbalanced load, thus reducing finger load.

Regression models were fitted to force and finger placement data when plate was held horizontally (see Figure 4.5). The results are shown in Figure 4.6 and Figure 4.7. The parameter estimations for the regression models are summarized in Table 4.3. The independent variables were moment about the x axis (M_x), moment about the y axis (M_y), and the thumb-index finger pinch strength (F_{pinch}). The dependent variables were thumb force, thumb placement (CoF location), finger force (sum of all four finger forces), and finger placement (center location of finger forces). The four finger forces were reduced to the resultant force of a "virtual finger" (Iberall *et al.* 1986).

Generally, as the moment about the y axis (M_y) increases from -1 Nm to 1 Nm, the thumb and finger placements are aligned with the moment arm to satisfy moment equilibrium. As the moment about the x axis (M_x) increases, thumb moves back towards forearm while finger CoF moves towards the load. The distance between thumb and finger CoF locations increases as external moment increases. This provides a biomechanical advantage that hand forces can be reduced. The model (see Table 4.3) predicted that people with less pinch strength tend to separate thumb and finger more than people with greater strength. People with less pinch strength also tend to increase the distance from the load to the fingers. Since hand strength is correlated with hand size (Pearson Correlation = 0.85), the model shows that people with smaller hand have to compensate for the lack of strength by separating their fingers and thumb more than people with larger hand.

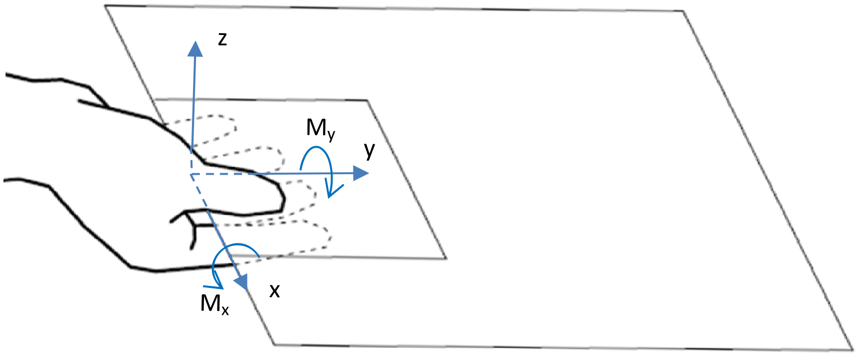

Figure 4.5. The coordinate system and independent variables for the regression models to predict force and finger placement data when plate was held at 0° (horizontal). The independent variables were moment about the x axis (M_x), moment about the y axis (M_y), and the thumb-index finger pinch strength (F_{pinch}). The dependent variables were thumb force, thumb placement (CoF location), finger force (sum of all four finger forces; "virtual finger"), and finger placement (center location of finger force).

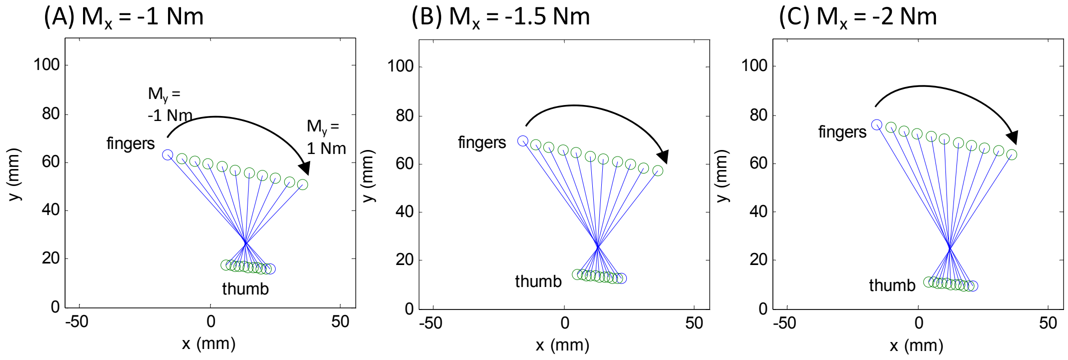

Figure 4.6. Regression model predictions about the effect of M_x and M_y on thumb and finger placement when plate was held at 0° (horizontal). The CoF locations of thumb and finger are shown in circles. The effect of M_y on CoF locations of thumb and finger are shown by the trajectories. The effect of M_x is shown in the separate figures. The thumb-index finger pinch strength was assumed as 40 N.

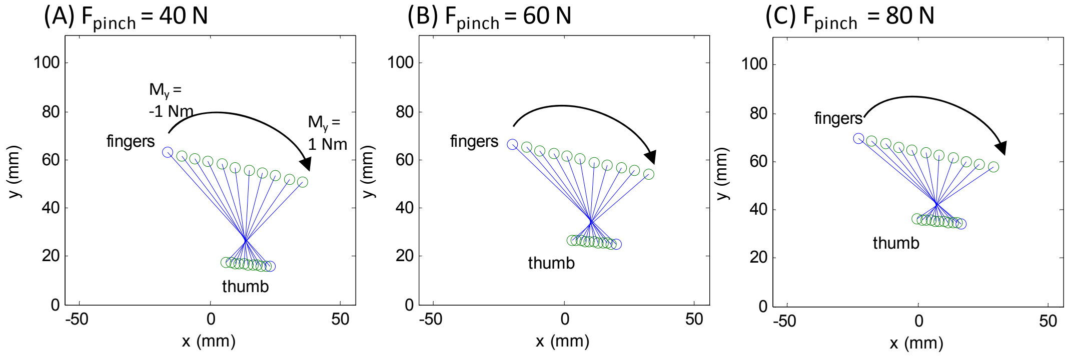

Figure 4.7. Regression model predictions about the effect of M_y and pinch strength on thumb and finger placement when plate was held at 0° (horizontal). The CoF locations of thumb and finger are shown in circles. The effect of M_y on CoF locations of thumb and finger are shown by the trajectories. The effect of pinch strength is shown in the separate figures. M_x was assumed as -1 Nm.

Table 4.3. Parameter estimation for the regression models fitted to force and finger placement data when plate was held at 0° (horizontal).

	Predictor								
Response	Constant		Moment about x axis (Nm)		Moment about y axis (Nm)		Pinch Strength (N)		R^2
	Coeff.	*p*-value	Coeff.	*p*-value	Coeff.	*p*-value	Coeff.	*p*-value	
F_{thumb} (N)	8.69	0.01	0.219	0.74	1.33	0.04	0.0872	0.05	7%
X_{thumb} (cm)	2.31	0.00	0.196	0.04	-0.848	0.00	-0.0159	0.01	45%
Y_{thumb} (cm)	0.45	0.28	0.651	0.00	0.090	0.32	0.0465	0.00	49%
F_{finger} (N)	17.5	0.00	-6.51	0.00	2.709	0.00	-0.0734	0.07	55%
X_{finger} (cm)	1.60	0.00	-0.050	0.60	2.600	0.00	-0.0167	0.01	87%
Y_{finger} (cm)	3.71	0.00	-1.302	0.00	-0.602	0.00	0.0170	0.09	46%
$DIS_{thumb\text{-}finger}$ (cm)*	5.65	0.00	-0.874	0.00	-0.744	0.00	-0.0240	0.00	53%

* Distance between thumb and finger center-of-force locations

Fu et al. (2010) showed learning effect of subjects lifting an unbalanced T-shaped object using thumb and index finger. On the first practice trial, their subjects tended to position digits collinear to each other regardless of Center-of-Mass (CM) location. After trial 1, subjects moved thumb and index finger oppositely based on left or right CM location. The thumb and finger locations became stable after about 3 trials. Their statistical analysis showed that only significant change was found between trials 1 and 2 for unbalanced cases. While our study only focuses on experienced situation, we found similar behavior when subjects performed practice trials to lift unbalanced plate objects. Subjects attempted to use a “default” finger placement as they used for grasping a balanced object, then changed placement right after the first attempt. Since subjects only gain the knowledge about CoM location by consecutive practice (visual is blocked), the implicit learning suggests that sensory feedback about the load condition is obtained from biomechanics and is used by the central nervous system to select finger force and placement in subsequent tasks.

4.4.2 Effect of Object Orientation

As object orientation increases, the moment arms from the hand to the far side load decrease. This reduces the external torque on the fingers and contributes to the reduction of the finger forces as shown by the force data in Table 4.1.

While the plate was held other than horizontal, friction force is required to counterbalance the gravitational force of the load. Since the friction coefficient is 1.5, it is expected that subjects can exert less finger normal forces to hold the plate at 45° or 90° (vertical). The results shown in Table 4.1 support this hypothesis. This is consistent with the finding that individual tend to exert force that are proportional to the minimum force required to prevent objects from slipping out of the hand (Johansson and Westling 1988, Frederick and Armstrong 1995, Kinoshita *et al.* 1996). Total hand normal forces reduced for 45° from 0°, and reduced further for the 90° case.

4.4.3 Limitations

In this study, only one friction condition was tested although object orientation could alter friction force component. Future studies should examine the effect of friction on hand force distribution and placement.

Finger placement during holding may be altered by intention or instruction of subsequent steps. Previous studies have shown that hand placement for initial grasping can be affected by the specification of terminal orientation (Rosenbaum *et al.* 1990, Rosenbaum *et al.* 1996, Rosenbaum *et al.* 2006, Zhou *et al.* 2011), terminal position (Cohen and Rosenbaum 2004), and following tasks (Ansuini *et al.* 2008).

The only instruction for subjects in this study was to hold the object and place the object back to the fixture at elbow height. It is likely finger placement for holding may be altered if a following placement task is specified, which is common in industrial tasks such as inserting plate object with a specific orientation, location, and force. Further studies are needed to determine the effect of intention on finger placement.

Hand forces were analyzed by fingers. Future studies should examine phalange forces of individual fingers. The finger center-of-force data showed that there were shifts of forces between phalanges, probably due to the motivation of reducing finger joint moments. Motion tracking system can be used together to measure joint locations and calculate joint load.

It should be noted that the hand placement in this study was constrained by the pressure sensor. While hand placement is not constrained, Duemmler *et al.* (2008) showed that subjects chose to place their hand close to the center-of-mass location. It is likely that subject would demonstrate similar behavior in this study if hand placement is not constrained.

4.5 Conclusions

Total hand normal force decreased by 26% and 56% as the plate was held from horizontal (0°) to 45°, and to vertical (90°), respectively. Thumb force for centered load was smaller than the ones for other load conditions. At 0°, subjects exerted greater index finger force when the load is on the right side comparing the load on the left side. They exerted greater little finger force vice versa. At 90°, the index and little finger forces are less different for different load conditions. Subjects also modulate finger placement (center-of-force location) to reduce load on fingers for unbalanced conditions. The thumb and finger center-of-force (CoF) locations were generally aligned with the load moment arm. The distance between thumb and finger CoF locations increased by 39% as load moment increased from 0.98 Nm to 2.35 Nm, and reduced by 17% as hand length increased from 16.2 cm to 21.1 cm when the plate was held horizontally.

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Chapter 5

Discussion and Conclusions

5.1 Summary of Major Findings

There is an infinite number of ways to place fingers on work object. Candidate posture can be retrieved from the memory (see Figure 1.1 a and b) and can be executed through the motor system (Figure 1.1 c). When the hand is in contact with the object, finger placement affects forces through finger-object coupling mechanics (Figure 1.1 d). Neural pathways provide sensory input to the brain where forces and joint loads are interpreted as effort (Figure 1.1 e). The input allows the Central Nervous System (CNS) to select posture from the many candidate postures for execution.

Previous studies showed that posture selection is related to effort (Rosenbaum *et al.* 1990, Rosenbaum *et al.* 1996, Rosenbaum *et al.* 2006), but didn't show how effort can be quantified biomechanically as finger forces and joint loads (see Figure 1.1 e). This work extended previous findings by showing that models can be developed to predict posture selection based on biomechanical analysis of finger forces and joint loads. New data and biomechanical models were presented to describe hand and finger placements in handling work objects. The studies (Chapter 2-4) were organized within the proposed conceptual model as shown in Figure 1.1.

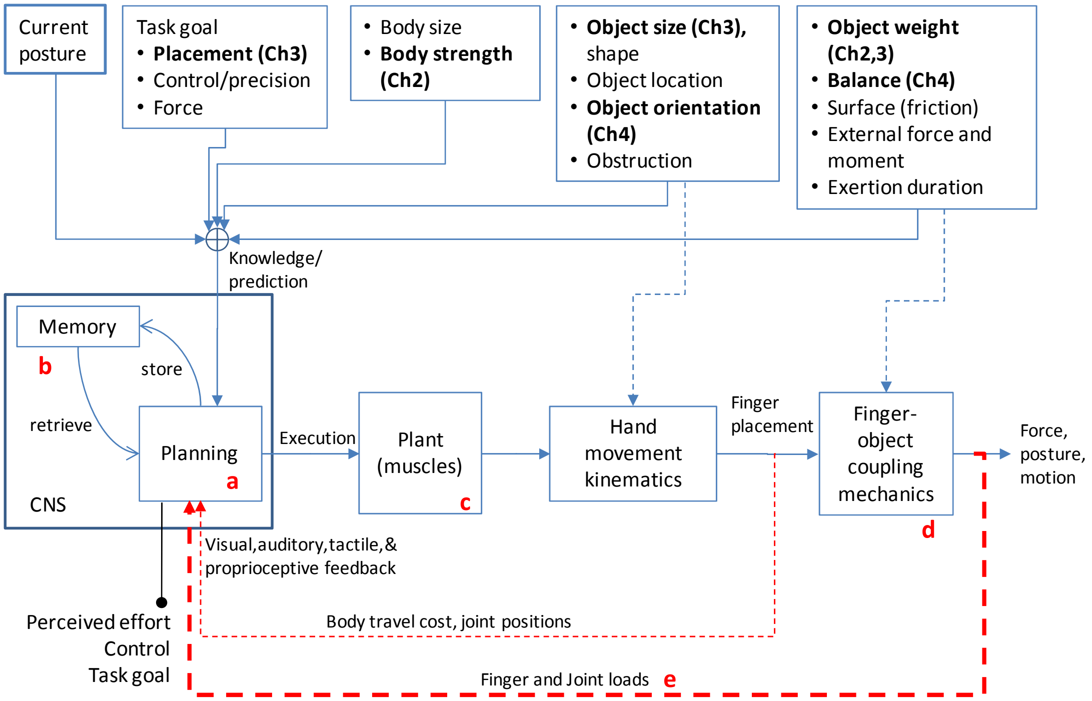


Figure 5.1. The present studies were organized within the proposed conceptual model that describes the relationship among hand postures, motions, forces, factors, memory, and feedback.

The major findings of this work can be summarized as follows:

- Subject-selected posture used for grasping, holding, and placing cylindrical object is influenced by object weight. The probability of choosing overhand posture to grasp cylinders reduces from 85% to 0 while the one of underhand posture increases from 15% to 100% as cylinder weight increases from 3.3 N to 53.3 N. Subjects held light cylinders (3.3 N) at elbow height 20% of the time, and at mid-thigh height using a hook grip with elbow fully extended 80% of the time. The probabilities of holding cylinder at elbow height and at mid-thigh height decrease as object weight increases; Subjects held heavy cylinders (53.3 N) 60% of the time at shoulder height with elbow flexed using a palm grip. Subjects placed cylinders using postures similar to the ones for grasping, but the overhand posture was used more frequent for heavier objects.

- The probability of self-selected posture for grasping, holding, and placing cylindrical object can be predicted by logistic model as function of relative joint load. Specifically, the preference for underhand posture versus overhand posture to grasp and place cylindrical objects appears to be motivated by the coupling between the hand and object based on biomechanical analysis. The relative hand load threshold for grasping and placing are 34% and 53% of overhand lift strength respectively which correspond to a 50% probability change from overhand to underhand posture. The relative hand load threshold for holding is 24% of hook grip lift strength which corresponds to a 50% probability change from hookgrip posture at mid-thigh height to palm grip posture at shoulder height.
- For very low load, about 20% of the subjects maintained the same arm posture in which they first gained control of the object, while 80% held the object alongside the thigh or close to the shoulder, both postures that reduce shoulder and elbow moments relative to the initial grasp posture.
- Selection of hand posture appears to be related to the preference of reducing thumb and finger tip forces and relative joint loads. Average thumb tip force and sum of fingertip forces for grasping (at lifting onset) cylinder decreased by 57% and 38% respectively from overhand to underhand posture, while the force on MCP region increased by 5.6 times. Fingertip force was reduced by 60% from pinch to hook grip posture. 81% of subjects preferred underhand to overhand

posture at elbow height, and 98% of subjects preferred hook grip to pinch at mid-thigh height.

- 42% of total hand normal force concentrated at the distal phalanges for 38 mm cylinder, while 70% of total normal force concentrated at the distal phalanges for 70 mm cylinder. Hand force increased as object weight increased.
- Thumb force for centered load was smaller than the ones for unbalanced load conditions when subjects held plate object. When the plate was held at 0° (horizontal), subjects exerted greater index finger force when the load is on the right side comparing the load on the left side. They exerted greater little finger force vice versa. At 90° (vertical), the index and little finger forces are less different for different load conditions.
- Subjects also modulate finger placement (center-of-force location) to reduce load on fingers for unbalanced conditions. The thumb and finger center-of-force (CoF) locations were generally aligned with the load moment arm. The distance between thumb and finger CoF locations increased by 39% as load moment increased from 0.98 Nm to 2.35 Nm, and reduced by 17% as hand length increased from 16.2 cm to 21.1 cm when the plate was held horizontally.
- Total hand normal force decreased by 26% and 56% as the plate was held from horizontal (0°) to 45°, and to vertical (90°), respectively due to friction force and reduction of moment arms.

5.2 Discussion

5.2.1 Strategy for Controlling Finger Placement and Force

There are many ways to place fingers on work objects and many muscle coactivation patterns that can get the hand and fingers to the desired position. This has been traditionally known as the problem of motor redundancy (Bernstein 1967). However, despite obvious variability in motor patterns, previous studies and this work show that the grasping of objects follows consistent patterns based on object and task variables.

Optimization approach has been used to explain the predictable patterns. This approach assumes that the Central Nervous System (CNS) finds a single optimal solution based on minimizing or maximizing a cost function, such as energy, norm, jerk, or fatigue. Models have been proposed to predict finger forces based on minimizing a certain norm of the forces (Zatsiorsky *et al.* 2002), or relative force values (Zatsiorsky *et al.* 1998, Zatsiorsky *et al.* 2002), and to predict finger positions by minimizing the sum of distance from finger joints to the object shape (Lee and Zhang 2005), or minimizing tendon and joint forces (Harding *et al.* 1993). The selection of the cost function was usually based on researcher's intuition or theoretical view of the problem. As a result, the optimal solution was often limited to the particular problem.

This work and more recent studies showed that optimality of observed behaviors may not be absolute. Park et al. (2010, 2012) found substantial variability across trials with the same values of the task constraints. The variability was structured and can not be simply explained by neuromotor noise, suggesting that multiple solutions may be acceptable. Chapter 2 (Figure 2.6-2.8) showed that multiple postures are possible for a given object, task, and strength condition for grasping, holding, and placing work objects. Chapter 2 (Figure 2.6-2.8) showed that the hand load threshold was 53% for placing the object, comparing to 34% for grasping the object and 24% for holding the object for about 8 seconds. Selection of hand posture appears to be affected not only by effort, but also by the duration of exertion and the desire for maximizing control. If multiple goals are to be achieved, the behavior may show more randomness; multiple solutions may be acceptable due to trade-offs among multiple optimization process for respective goals.

The probability characteristic of the behaviors shown in Chapter 2 may be explained by the "constraint hierarchy" theory proposed by Rosenbaum et al. (2001, 2009). Rosenbaum et al. proposed that selection of posture is a process of winnow (pruning) rather than optimize. Posture is selected or tweaked from stored candidate postures with respect to constraint hierarchy, which is a ranking of constraints such as avoiding collision, and reducing effort. If more than one candidate posture satisfies the constraints, the choice among the solutions is made at random. It is also possible that the posture that is the most recently used is selected. The findings from Chapter 2 can be explained by selecting posture that satisfies both reducing effort and increasing control constraints. Since there are two constraints, a trade-off has to be made between the two goals. For grasping, subjects selected underhand posture to reduce hand effort from overhand posture as the relative hand load increased above 34% of maximum overhand strength. But for placing which may require more fine control than grasping, the relative hand load threshold increased to 53% of maximum overhand strength, indicating the control constraint may have greater weight than effort constraint in placing than in grasping.

The structured variance observed in Chapter 4 may be explained by another model called principle of abundance (Gelfand and Latash 1998, Latash 2012a, Latash 2012b). This model also assumes that families of solutions are all equally able to solve the task. Based on the framework of uncontrolled manifold (UCM) hypothesis (Scholz and Schöner 1999) and analytical inverse optimization (Terekhov *et al.* 2010), this model assumes that the center of behavioral distribution reflects an optimality criterion, while the shape of the distribution is structured, i.e., relatively large variance ("good" variance) is allowed within a sub-space (UCM) corresponding to the desired response to important external factors, and variance in directions orthogonal to the UCM ("bad" variance) is limited by the CNS. Chapter 4 showed that the thumb and fingers (sum of the four fingers; "virtual finger" as proposed by (Iberall *et al.* 1986)) exerted forces to counter-balance the external load moment. Figure 4.5 showed that the thumb and finger placements are generally aligned with the line which corresponds to the moment arm of the external load to satisfy force and moment equilibrium. While subjects could possibly place the thumb and fingers arbitrarily along the moment arm line, they chose to align the finger positions on the line more carefully as load moment increased. This reflects that the variability along the line (sub-space of force and moment equilibrium) is allowed and can be explained by the magnitude of the moment while the variability in other directions is more random.

This work extends the previous studies by showing that biomechanics can help refine posture planning. The conceptual model (Figure 1.1 and Figure 5.1) showed how the biomechanical feedback affects the selection of alternate postures. The results and models presented in the three studies showed quantitatively how the relative joint loads can be computed and can affect the probability of posture. For example, considering two postures, i.e., overhand or underhand postures, are stored in the memory, the relative joint load showed in Chapter 2 determines the probability of selecting an underhand over an overhand posture.

Subject factors, which have been overlooked in motor control models, have biomechanical implications in posture selection in the present work. Motor control studies usually do not consider individual strength or body size, but these factors have shown importance in previous studies of the kinematics of finger motions (Choi and Armstrong 2006b, Bae and Armstrong 2011), and in the present studies. Chapter 2 (Figure 2.6-2.8) showed that probability of part handling posture was affected by relative joint strength. In Chapter 3, regression models were fitted to thumb force and sum of fingertip forces with factors of hand length, object size, and object weight for overhand lifting. Thumb force was negatively related with hand length (Coefficient=-0.721, $p>0.1$), while sum of fingertip forces was positively related with hand length (Coefficient=2.027, $p<0.01$). Chapter 4 (Table 4.3) showed that hand length significantly affects thumb force, finger force, and thumb placement. The regression model showed that people with smaller hand tend to spread thumb and finger more than people with larger hand. The distance between the thumb and finger was reduced by 17% as hand length increased from 16.2 cm (smallest hand of female subject) to

21.1 cm (largest hand of male subject). Considering hand size is highly correlated with strength, this has a biomechanical advantage of increasing moment arm and reducing the thumb and finger loads for people with less strength. These findings showed biomechanical considerations of how subject factors can affect behavior.

5.2.2 Finger Placement and Forces for Lifting Cylindrical Object

The proposed conceptual model shows finger forces and joint loads are inputs for the brain to select alternate finger placements (Figure 1.1 e). The relative loads on the wrist, elbow, and shoulder joints can be computed from motion tracking data and object (see moment arms in Chapter 2 Table 2.2 for an example). The loads on the finger joints can be inferred from lifting strength measurement (see Chapter 2 Discussion Section 2.4.1), or computed from joint center locations and finger forces. Chapter 3 showed finger force data for alternate finger placements. But a model that can predict finger forces would be helpful for better predicting finger placement.

We propose a model for predicting static hand forces as fingers are in contact with cylindrical objects during lifting. The model assumes voluntary lifting in which forces are applied gradually so that dynamic forces can be neglected. The model is based on static equilibrium of normal finger flexion forces and tangential friction forces between the fingers and the handle. In this instance we focus primarily on large handle due to limitations of the F-scan force arrays. The results of this study and others (Pylatiuk *et al.* 2006, Seo *et al.* 2007) show that 70% of hand normal forces are concentrated at thumb tip and finger tips for overhand lifting of large cylinders.

Assuming quasi-static and only thumb tip and the four finger tips exert forces to counterbalance the gravitational force of the object, the minimally required finger forces must satisfy force and moment equilibrium (Figure 5.2),

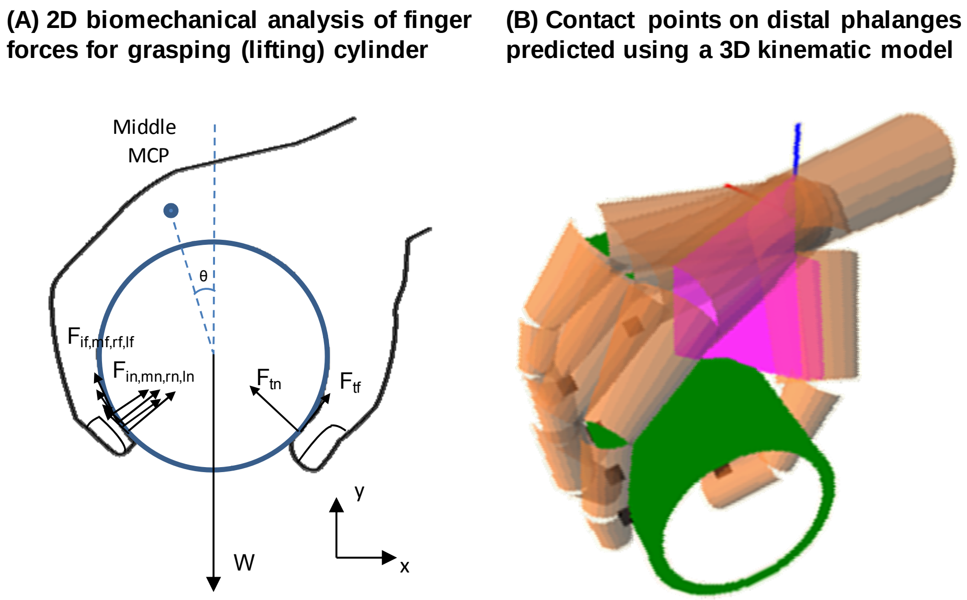
$$\begin{aligned} \sum F &= \overline{F}_t + \overline{F}_i + \overline{F}_m + \overline{F}_r + \overline{F}_l + \overline{W} = 0 \\ \sum M &= \overline{M}_t + \overline{M}_i + \overline{M}_m + \overline{M}_r + \overline{M}_l = 0 \end{aligned} \tag{5.1}$$

The normal and friction forces by thumb and finger tips in the 2D cross-section plane of the cylinder must satisfy,

$$\begin{aligned} &\sum F_{normal,x} + F_{friction,x} = 0 \\ &\sum F_{normal,y} + F_{friction,y} - W = 0 \\ &\sum M_{friction} = 0 \end{aligned} \tag{5.2}$$

The contact locations of the thumb tip and fingertips can be predicted from a contact algorithm of power grip computed by a hand kinematic model (Choi and Armstrong 2006b, Choi and Armstrong 2006a). Hand orientation with respect to gravitational force was defined by the angle between middle MCP joint to center of the cylinder and vertical (middle MCP angle, see Figure 5.2A).

Two cases were considered: A) a simplified case where friction force was neglected; B) friction force was not neglected.



(A) 2D biomechanical analysis of finger forces for grasping (lifting) cylinder

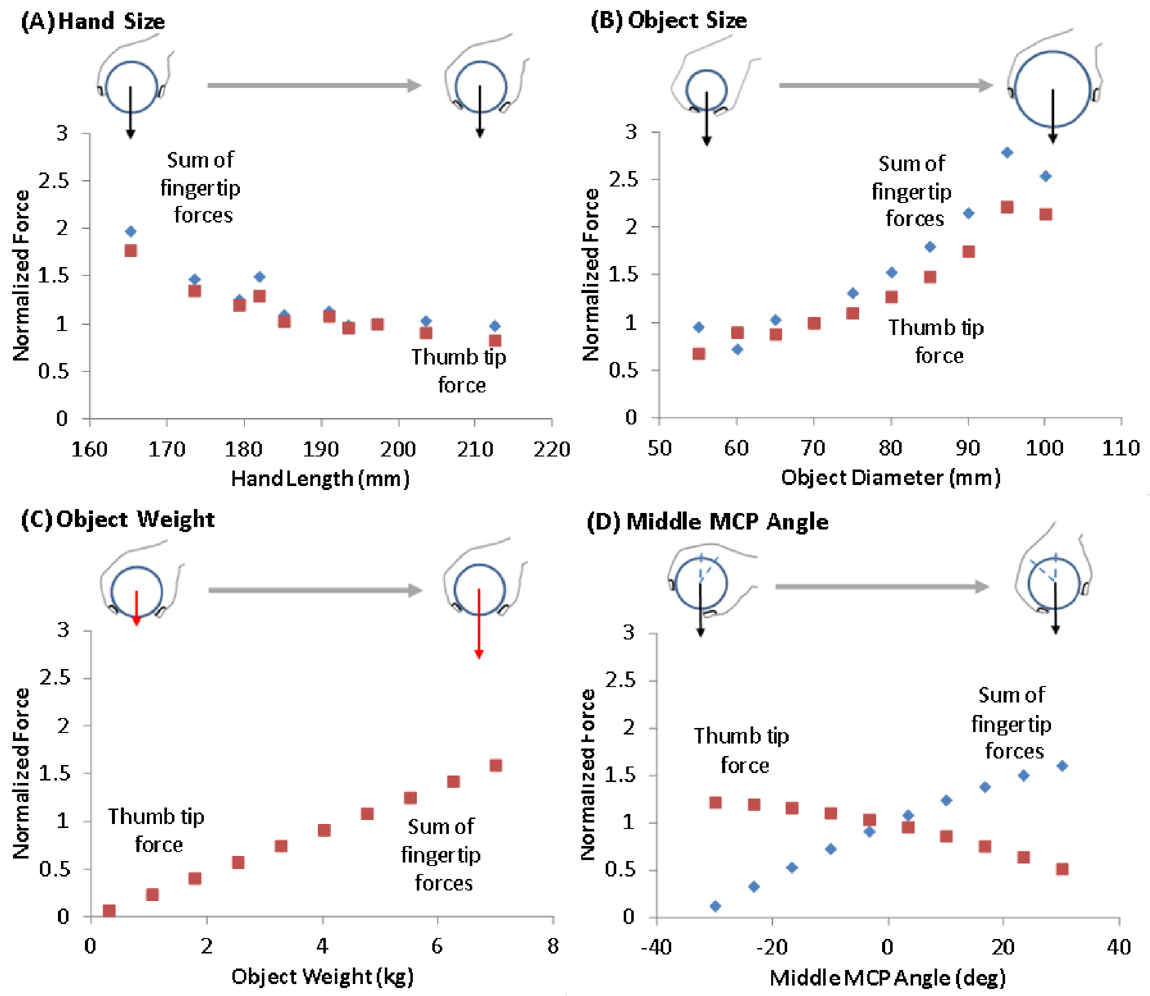
(B) Contact points on distal phalanges predicted using a 3D kinematic model

Figure 5.2. (A) Assuming quasi-static and only thumb tip and the four finger tips exert forces to counterbalance the gravitational force of relatively large cylinder, the minimally required finger forces must satisfy force and moment equilibrium; (B) Contact locations of the thumbtip and fingertips were calculated from a contact algorithm of power grip predicted by a hand kinematic model (Choi and Armstrong 2006b, Choi and Armstrong 2006a).

(A) Model A: Assuming zero friction force

Assuming a simplified case in which friction forces are zero, and the relative distributions of the index, middle, ring, and little fingertips were 20%, 34%, 30%, and 16% of total fingertip force, respectively (see Chapter 3 result section), the normal forces exerted by thumb and finger tips can be determined from Equation 5.2.

Effect of model parameters (hand length, object diameter, object weight, and middle MCP angle with respective to vertical) on finger force prediction is shown in Figure 5.3. All forces are normalized by the forces predicted for a 50%ile male hand grasping a 70 mm diameter, 43.1 N cylinder with middle MCP angle with respect to vertical at 0 degree. As hand size increases or object size decreases, the thumb and finger tip forces decreases. As object weight increases, the thumb and finger tip forces increases. As the middle MCP angle increases, the fingertip forces increases, while the thumb tip force is reduced.


(A) Hand Size

(B) Object Size

(C) Object Weight

(D) Middle MCP Angle

Figure 5.3. Effect (sensitivity) of model parameters (hand length, object diameter, object weight, and middle MCP angle with respective to vertical) on finger force prediction. All forces are normalized by the forces predicted for a 50%ile male hand grasping a 70 mm diameter, 43.1 N cylinder with middle MCP angle with respect to vertical at 0 degree.

(B) Model B: Assuming non-zero friction force

If friction forces are not neglected, we formulate an optimization problem to solve for the normal and friction forces of the thumb and fingers (10 variables):

$$\arg\min_{F_n,\,F_f} \sum_{i=1}^{5} F_{ni} \tag{5.3}$$

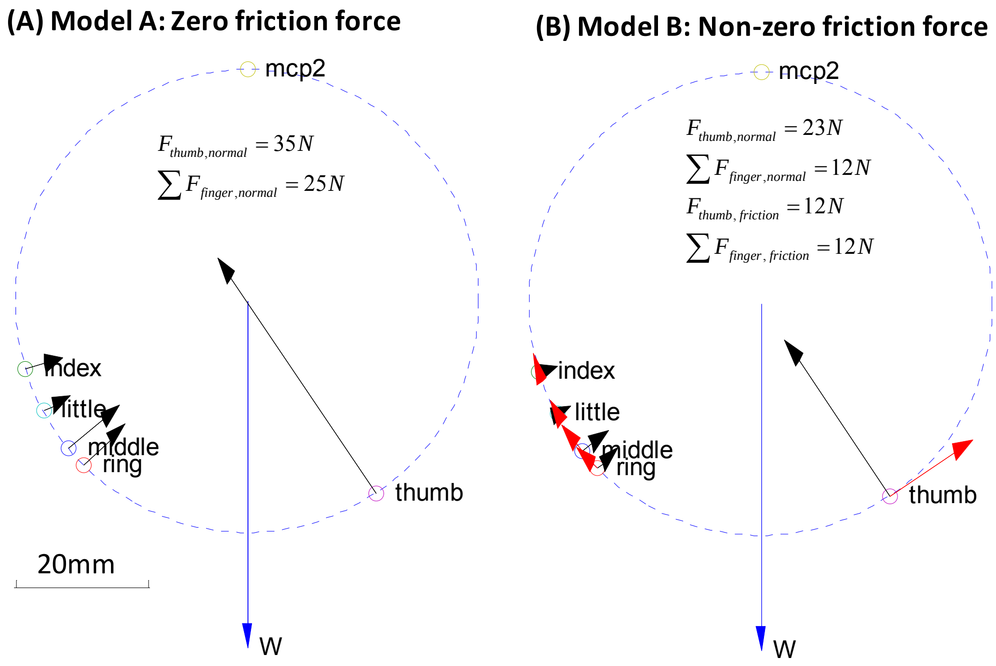
subject to the following equality constraints:

$$\begin{aligned}
&\sum F_{n,x} + F_{f,x} = 0\\
&\sum F_{n,y} + F_{f,y} - W = 0\\
&\sum F_f = 0\\
&\frac{20}{34} F_{n,middle} = F_{n,index}, \frac{30}{34} F_{n,middle} = F_{n,ring}, \frac{16}{34} F_{n,middle} = F_{n,little}
\end{aligned}$$

and the following inequality constraints:

$$\begin{aligned}
&\left|F_f\right| \le \mu F_n \text{ for each finger}\\
&F_n \ge 0 \text{ for each finger}
\end{aligned}$$

The assumption of minimizing the norm of normal forces was similar to the others (Zatsiorsky *et al.* 2002). The model was implemented in MATLAB® (Mathworks Inc., MA) using quadprog routine (quadratic programming). Figure 5.4 shows finger normal and friction forces predicted using (A) zero-friction model and (B) non-zero friction model for a 50%ile male hand grasping and lifting a 70 mm diameter, 43.1 N cylinder with middle MCP angle with respect to vertical at 0 degree. The non-zero friction model assumes a friction coefficient of 1.0 between the hand and object. The friction coefficient was assumed arbitrarily and was similar to the one between the hand and aluminum (Seo *et al.* 2009).



(A) Model A: Zero friction force

(B) Model B: Non-zero friction force

Figure 5.4. Finger normal and friction forces predicted using (A) zero-friction model and (B) non-zero friction model for a 50%ile male hand grasping and lifting a 70 mm diameter, 43.1 N cylinder with middle MCP angle with respect to vertical at 0 degree. The non-zero friction model assumes a friction coefficient of 1.0 between the hand and object.

Model sensitivity of friction coefficient on finger force prediction is shown in Figure 5.5. Other parameters of the model are assumed for a 50%ile male hand grasping a 70 mm diameter, 43.1 N cylinder with middle MCP angle with respect to vertical at 0 degree. As the friction coefficient increases, the normal forces for the thumb and finger tips decrease, while the friction forces increases. This is consistent with the observation that high friction surface can help reduce finger forces for lifting object.

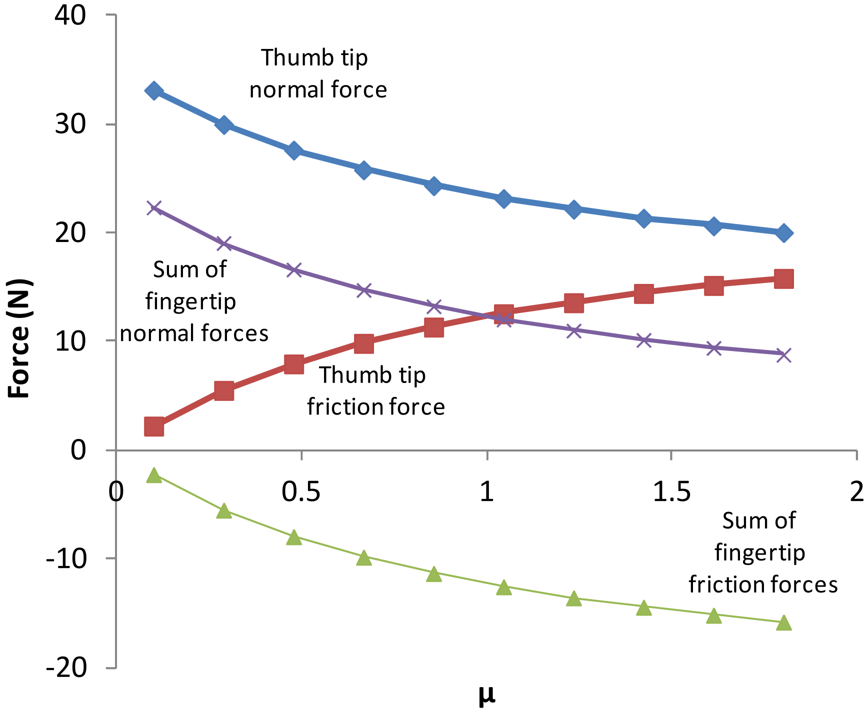


Figure 5.5. Effect of friction coefficient on finger force prediction. Other parameters: a 50%ile male hand grasping a 70 mm diameter, 43.1 N cylinder with middle MCP angle with respect to vertical at 0 degree.

Table 5.1 and Figure 5.6 show model prediction of normal forces at thumb tip and finger tips compared with measurement from Table 3.2 for the 70 mm cylinder.

Table 5.1. Prediction of normal forces at thumb tip and fingertips compared with measurement from Table 3.2 for 70 mm cylinder (mean ± SD). The predicted forces are based on assumption of middle MCP angle with respect to vertical at 0 degree. The hand sizes are estimated from the hand lengths of subjects. Model B assumes a friction coefficient of 1.0 between the hand and object.

Hand region	Object weight (N)	Measurement of Normal Force (N)	Prediction (N)	
			Model A	Model B
Thumb tip	26.5	18 ± 5	28 ± 7	15 ± 1
	43.1	23 ± 7	46 ± 11	24 ± 2
Sum of fingertips	26.5	10 ± 5	22 ± 7	8 ± 1
	43.1	17 ± 5	36 ± 11	13 ± 1

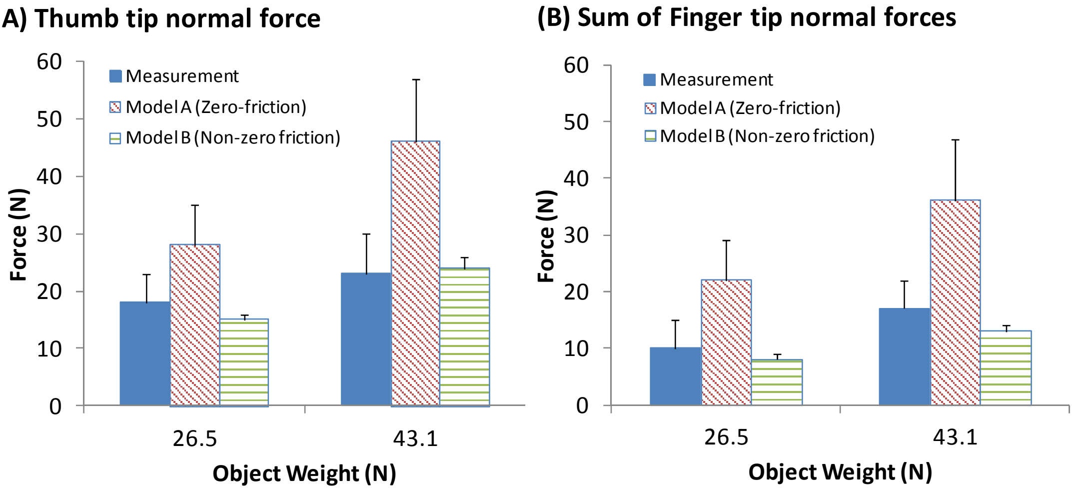


Figure 5.6. Prediction of normal forces at thumb tip and fingertips compared with measurement from Table 3.2 for 70 mm cylinder (mean ± SD). The predicted forces are based on assumption of middle MCP angle with respect to vertical at 0 degree. The hand sizes are estimated from the hand lengths of subjects. Model B assumes a friction coefficient of 1.0 between the hand and object.

Model A (zero friction model) predicted about 2 times of the measured forces. Friction force has been shown to be an important component in lifting object (Johansson and Westling 1988a, Johansson and Westling 1988b, Frederick and Armstrong 1995). The existence of friction force can reduce finger normal forces. Model B (non-zero friction model) predicted similar normal forces to the measurement by taking friction force into consideration. However, the predicted standard deviation is much less than the data.

It should be noted that both models assume no forces on middle and proximal phalanges of the thumb and fingers. As shown in Table 3.2, there are about 20% or 30% forces on thumb proximal phalanx and finger middle and proximal phalanges during lifting the 70 mm cylinder. The models were limited to predict relative large size cylinders.

The finger forces predicted in Figure 5.6 are the minimally required forces that satisfy quasi-static equilibrium based on assumptions. It is common to exert a little extra force than is necessary to support the object or a “safety margin” (Westling and Johansson 1984, Grieshaber and Armstrong 2007). The cost function of the optimization (Equation 5.3) was selected based on minimizing the summation of finger normal forces. The prediction agreed with data reasonably well. Zatsiorsky *et al.* (2002) tested four cost functions in the form of the cubic norms of finger force or relative finger force to predict finger forces, and found that these cost functions predicted well for zero external torque case, but failed to predict antagonist finger moments for non-zero external torque cases. The selection of cost function was usually subjective and dependent on the problem, and thus limited the use of optimization approach.

5.2.3 Implementation of Conceptual Model

The key features of the proposed conceptual model include kinematics, biomechanics, feedback, and memory. The model provides a framework for predicting finger placement and postures for grasping, transferring, and manipulating work objects. Some model features can be implemented using kinematic or biomechanical models, while some can be approximated using empirical models (see Figure 5.7). The present data and proposed models can be used as shown in Table 5.2.

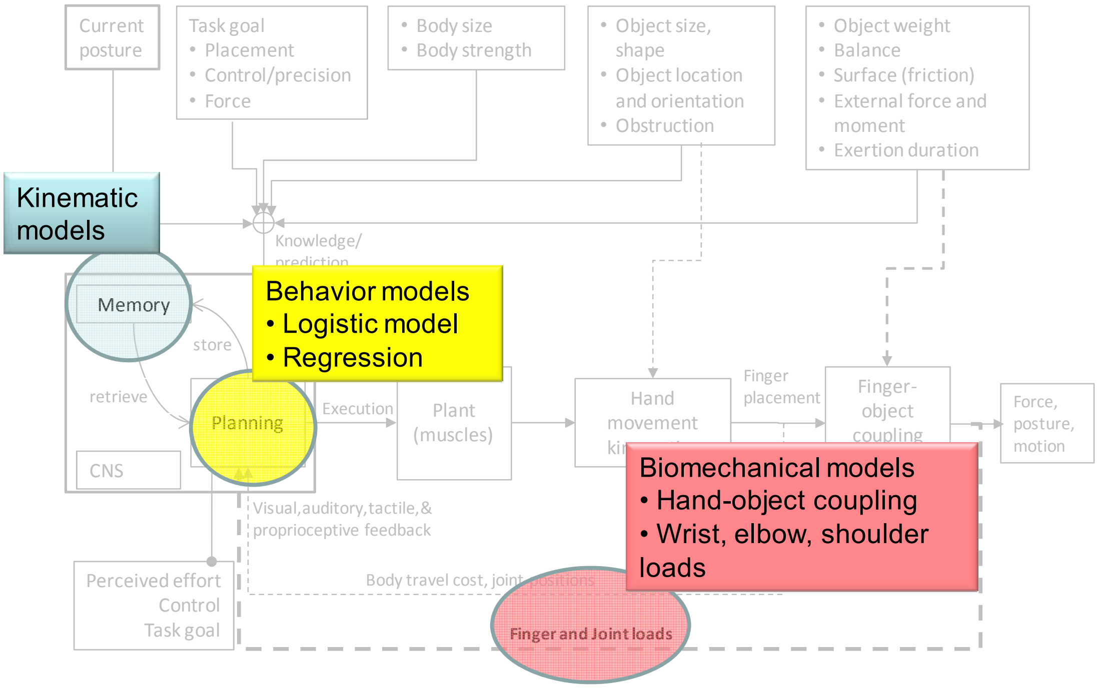


Figure 5.7. Implementation of the conceptual model: memory can be implemented by a database of candidate motions and posture as predicted by empirical models and contact algorithm. Planning can be implemented based on biomechanical analysis and empirical data of load threshold (probability models). Biomechanical feedback can be implemented by biomechanical analysis of posture or force prediction models.

Table 5.2. Key features and implementation of the conceptual model

Feature	Implementation	Available models
Memory/knowledge based prediction	A database of candidate motions and posture as predicted by empirical models and contact algorithm. For example: • Alternative finger placements: power grip, precision pinch • Alternative hand placements: overhand grip, underhand grip, etc	• Finger motion model (Choi and Armstrong 2006b, Bae and Armstrong 2011) • Grasp model in HUMOSIM Framework (Reed *et al.* 2011)
Feedback of biomechanical factors	Biomechanical analysis of movement and posture, i.e., • Load moments on wrist, elbow, and shoulder joints • Hand-object coupling force	• Simple biomechanical analysis is available based on Jack/3DSSPP functionality; • Biomechanical analysis of hand, wrist, elbow, and shoulder relative load as shown in Chapter 2 • Simplified finger force prediction model as shown in Chapter 3&5
Planning based on feedback of biomechanical factors	Based on biomechanical analysis and empirical data of load threshold, • Probability (logistic) model to select among candidate finger placements • Regression model to predict finger placement	• Model that predicts the load threshold for postural change as shown in Chapter 2 • Regression models for predicting finger placement as shown in Chapter 4

5.2.4 Use of Major Findings

To demonstrate the potential application of the proposed models, an example of get, carry, and place an iPad (plate object) was selected for further analysis. The task includes reach and grasp an iPad, carry it for transfer, and place it on a desk. An iPad with Retina display (Wi-Fi version) has a dimension of 241.2 mm (H) x 185.7 mm (W) x 9.4 mm (D), and a weight of 6.4 N (652 g).[1] We assume its center-of-mass location is in the center. The friction coefficient between skin and an object has been shown as a complex function of normal force, contact area, hydration, and texture (Seo *et al.* 2009). We assume a friction coefficient μ of 1 (similar to the one between hand and aluminum) under normal load condition. We also assume that the task will be conducted by a female subject with 50%ile hand and average strength.

The object can be initially located in different orientations (i.e., vertical or horizontal, see Figure 5.8). If the object is vertical, subject may need to get it using thumb and finger tips (see pinch posture in Figure 5.8). In this case, thumb and finger tips exert normal forces, which produce friction forces to counterbalance the gravitational force of the object. The thumb and finger normal force can be calculated by quasi-static force equilibrium (Frederick and Armstrong 1995),

$$F_t = F_f \geq \frac{W}{2\mu} \tag{5.4}$$

The minimally required forces F_t or F_f is calculated as 3.2 N. Based on the pinch strength data from Chapter 3 Table 3.1, average female pinch strength is 47 N (based on the resultant force of 38 mm cylinder precision pinch). The thumb or finger

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[1] iPad with Retina display (Wi-Fi version) specification, From http://www.apple.com/ipad/specs/

force is about 7% of maximum strength. Therefore, the pinch posture is likely to be used since it is less than the hand load threshold of 34% for grasping (Chapter 2 Figure 2.6). However, if the object is heavy, such as 64 N, the finger normal force will increase to 32 N as calculated using Equation 5.4. This force exceeds the load threshold of 34% (32/47 = 68%) and the subject will prefer another posture such as the hook grip (Figure 5.9) to lift the object from underneath. Space should be provided under the object so that it can be lifted using hook grip. If the friction is low, the required hand load may also exceed the threshold for posture change. Clearance should also be provided for this case.

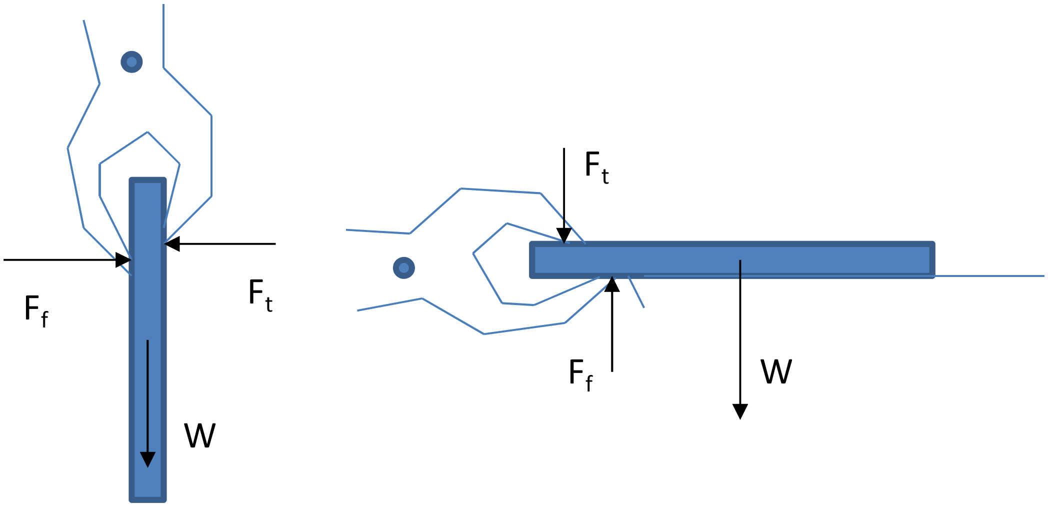

Figure 5.8. Pinch postures to grasp the plate object (iPad) vertically and horizontally and biomechanical analysis of thumb and finger forces.

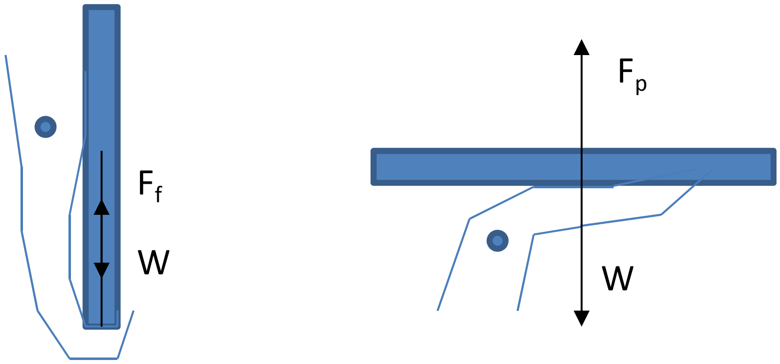

Figure 5.9. Hook grip posture and palm grip posture to hold the plate object.

If the object is initially horizontal, subject grasps it using thumb and finger tips (see pinch posture in Figure 5.8). In this case, thumb and finger tips exert normal forces and produce a moment to counterbalance the gravitational force of the object. If the object can be grasped in the center along the edge, the finger force can be predicted by the regression models (Chapter 4 Table 4.3). Here M_x is -0.77 Nm (6.4 N x 241.2 mm / 2), M_y is 0, thumb-index finger pinch strength for the female subject is 56 N (Chapter 4). The predicted thumb force and finger force are 13.4 N and 18.4 N, respectively.

If the subject's hand blocks the view of the screen, she may prefer to place the hand at the right corner rather than in the center along the edge. Another possibility is that the center along the edge is blocked by an obstruction. The subject has to grasp the object at the corner. In this case the object becomes unbalanced from the hand. The finger force and placement can be predicted by the regression models (Chapter 4 Table 4.3). Assuming Mx is -0.77 Nm, My is -0.59 N (6.4 N x 185.7 mm / 2), the predicted thumb force and finger force are 12.6 N and 16.8 N, respectively. The thumb will shift towards the right side and finger will shift towards the left side.

Whether presenting the object vertically or horizontally to the subject depends on friction. The hand normal force can be reduced from horizontal to vertical placement if the friction coefficient is large (Chapter 4 Figure 4.2 and Table 4.1). In this case the object should be presented to the subject vertically.

The object may be also located at different heights. The present studies were limited to postures at elbow height. It is possible that for lower height, the subject may use pinch posture more than hook grip posture since it requires less travel distance of the hand and body.

After the subject gains control of the object, she may use the hook grip posture to carry the object (Figure 5.9). This posture is the most frequent posture used for light object (Chapter 2 Figure 2.4). It can reduce finger forces up to 60% compared to pinch posture (Chapter 3 Figure 3.4), and minimize the load moments about the wrist, elbow, and shoulder. The horizontal pinch posture (Figure 5.8) may also be used if the subject prefers to look at the screen while walking. In this posture the object load produces moments about the wrist, elbow, and shoulder. If the object is heavy and requires greater than 24% of hook grip strength, the probability model (Chapter 2 Figure 2.7) predicts that the subject will use the palm grip at shoulder height with elbow flexed to carry the object (see Figure 5.9).

The subject may use the pinch posture again to place the iPad vertically if required by the task. Since the thumb or finger force is about 7% of maximum strength for pinch posture and less than the hand load threshold of 53% for grasping (Chapter 2 Figure 2.8), the pinch posture is likely to be used. However, if the object is heavy and the finger load exceeds the threshold, the subject may prefer to use the hook grip to place the object. Space should be provided under the object.

5.2.5 Recommendations

The following recommendations are made based on the results from the three studies:

1. For light weight 70 mm diameter cylinders ($W < 18.6$ N) or other objects that require less than 34% relative hand load and can be easily grasped, an overhand grasp will be used most frequently (>50%) in the studied task configuration of a horizontal object at elbow height. Space should be provided from the starting position of the hand to reach over the object. If possible, the objects should be designed to resist slipping out of an overhand grasp and reduce finger forces, e.g., tapering the edges, adding ridges, and increasing friction.
2. For heavier 70 mm diameter cylinders ($W > 18.6$ N) or objects that require greater than 34% relative hand load and can be held with a palm up posture, an underhand grasp will be used most frequently (>50%). Space should be provided from the starting position of the hand to the reach under the object. Where possible, heavier objects should be designed to fit a palm-up, cupped hand.
3. Unless the object is to be immediately moved with the arm to another position, it is likely that a heavy object will be held over or near the shoulder using the palm or at the side of the thigh using the fingers (hook grip). Space should be provided so that objects can be transferred to these locations without bumping other

objects. The stability of the load should be considered. A shift in the center of gravity could result in dropping an object as it is transferred above the shoulder.

4. For objects that require greater than 53% relative hand load to place or put to target location, space should be provided underneath the objects so that an underhand posture can be used to place the object.
5. Clearance should be provided around the object so that people can use hook grip to carry the object versus using pinch grip.
6. For an unbalanced object, clearance should be provided so that people can grasp the center-of-mass location. In case the hand location is constrained, clearance should be provided on the surface of the object so that people can change their thumb and finger placements to reduce joint loads.

5.3 Future Work

The aim of this work was to develop biomechanical models that describe hand and finger placements in handling work objects. While the models proposed in this dissertation can be used to predict hand postures, further work is needed to improve the capability of the model prediction and expand the model. The following suggestions are therefore made for future studies:

1. The influence of friction on hand and finger placements needs further investigation. It has been shown friction force is important (Johansson and Westling 1984, Frederick and Armstrong 1995) in object transfer tasks. The present studies only examined the normal force component due to the limitation of the Tekscan pressure mapping system. A previous study (Weir *et al.* 1991)

shows that object slipping was related to increased time between contact with the object and object lift, possibly reflecting the greater amount of time required to assess and generate the necessary grip force. Johansson and Westling (1984) also show that surface friction affects grip force and friction force. Based on the conceptual model, the finger load could affect the selection of hand and finger placements. For instance, as the object weight increases, if the friction is not sufficient to provide lifting force, subject will use a different grasp to lift object.

2. The influence of object and task factors such as task goal, obstruction, and duration of exertion needs to be determined. It can be hypothesized that the relative load threshold for posture selection is also related to the duration of force exertion. As the exertion duration increases, the load threshold for posture change decreases.
3. Other factors may account for unexplained variance. For example, fingers do not move independently. The placement of one finger is affected by another (Häger-Ross and Schieber 2000, Lang and Schieber 2004). Further studies are needed to develop models that can incorporated into the conceptual model (i.e., a model that describes finger dependency can be implemented in Figure 1.1 c).
4. Motion capture system can be used to measure finger joint locations during object handling tasks. Investigation in Chapter 2 used motion tracking system to measure wrist, elbow, and shoulder joint locations. But finger joint location data is lacking. Previous studies (Lee and Zhang 2005, Choi and Armstrong 2006a, Lukos *et al.* 2007, Bae and Armstrong 2011) have demonstrated that motion

tracking technique can be used to record finger joint locations. This could help determine finger postures and calculate finger joint loads with hand pressure data.

5. Relative finger joint load needs further examination to determine which joint(s) motivate the selection of hand posture. To calculate relative finger joint load, individual joint strength data is needed. A 3D hand biomechanical model could be useful in this case.

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