Characterizing Feedforward and Feedback Grasp Control Mechanisms in Early

Phases of Manipulation

by

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ABSTRACT

Anticipatory planning of digit positions and forces is critical for successful dexterous object manipulation. Anticipatory (feedforward) planning bypasses the inherent delays in reflex responses and sensorimotor integration associated with reactive (feedback) control. It has been suggested that feedforward and feedback strategies can be distinguished based on the profile of grip and load force rates during the period between initial contact with the object and object lift. However, this has not been validated in tasks that do not constrain digit placement.

The purposes of this thesis were (1) to validate the hypothesis that force rate profiles are indicative of the control strategy used for object manipulation and (2) to test this hypothesis by comparing manipulation tasks performed with and without digit placement constraints.

The first objective comprised two studies. In the first study an additional light or heavy mass was added to the base of the object. In the second study a mass was added, altering the object's center of mass (CM) location. In each experiment digit force rates were calculated between the times of initial digit contact and object lift. Digit force rates were fit to a Gaussian bell curve and the goodness of fit was compared across predictable and unpredictable mass and CM conditions. For both experiments, a predictable object mass and CM elicited bell shaped force rate profiles, indicative of feedforward control.

For the second objective, a comparison of performance between subjects who performed the grasp task with either constrained or unconstrained digit

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contact locations was conducted. When digit location was unconstrained and CM was predictable, force rates were well fit to a bell shaped curve. However, the goodness of fit of the force rate profiles to the bell shaped curve was weaker for the constrained than the unconstrained digit placement condition.

These findings seem to indicate that brain can generate an appropriate feedforward control strategy even when digit placement is unconstrained and an infinite combination of digit placement and force solutions exists to lift the object successfully. Future work is needed that investigates the role digit positioning and tactile feedback has on anticipatory control of object manipulation.

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INTRODUCTION

Overview

Dexterous object manipulation relies on the formation and retrieval of

sensorimotor memories, which are generated from previous hand-object

interactions (Johannsson et al. 1984, 1988a). Sensorimotor memories allow digit

forces to be planned prior to object manipulation in an anticipatory fashion, which

is critical for successful dexterous object manipulation. One key advantage of

anticipatory (feedforward) planning of digit forces is that it bypasses inherent

delays in sensory integration and responses associated with reactive (feedback)

control, as the latter may lead to unsuccessful object manipulation. One likely

indicator of anticipatory planning during object manipulation is the shape of grip

force and load force rate profiles during object lifts (Johansson et al. 1984,

1988a).

The research done in this thesis investigated the shape of digit force-rate

profiles in order to identify the control strategies (feedforward and feedback) used

for object manipulation. Research by Johansson et al. (1984, 1988a) has indicated

that bell shaped force rate profiles are indicative of feedforward grasp control

strategies. A major limitation of these studies was that digit locations were

constrained, thus this conclusion has not been validated in tasks that do not

constrain digit location (Johansson et al. 1984, 1988a). This is a significant gap in

the understanding of the control of dexterous object manipulation as digit location

is typically unconstrained in tasks of daily living. Furthermore, it seems unlikely

that the brain would be able to plan exactly how much force to provide for every

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object grasped regardless of finger position without the use of sensory feedback. Thus, it was hypothesized that the constrained digit placement condition would result in the use of a feedforward strategy and the unconstrained digit placement condition would result in the use of a feedback strategy. This thesis will validate these findings as well as determine whether or not there is a significant difference in the feedforward grasp control strategy between object manipulation tasks for which digit location is constrained and unconstrained.

Statement of the Problem

The purposes of this thesis were (1) to validate the hypothesis that force rate profiles are indicative of the control strategy used for object manipulation in tasks which do not constrain digit placement and (2) to test this hypothesis in manipulation tasks performed with and without digit placement constraints. Specifically, this was evaluated in tasks in which subjects lifted an inverted T-shaped object using a two-digit precision pinch grip performed with and without digit placement constraints.

For purpose (1) above, it was hypothesized that force-rate profiles could be well fit by a Gaussian bell curve, thus indicating the use of a feedforward grasp control strategy. In contrast, force rate profiles with multiple peaks and troughs, and thus a poor fit to a Gaussian bell curve would indicate feedback grasp control. This was shown in two studies. In the first study the mass of the object altered between light and heavy masses. In the second study object center of mass (CM) location was altered, with constant mass being altered with unconstrained digit placement. Digit force rates were fit to a Gaussian bell curve and the goodness of

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fit was compared between predictable and unpredictable mass and CM conditions. For both experiments, predictable object mass and CM elicited bell shaped force rate profile, indicative of feedforward control.

Previous research (Fu et al. 2010) has shown that the digit location is more variable on a trial-to-trial basis when digit location is unconstrained than constrained. Therefore, for the purpose (2) above it was hypothesized that the central nervous system would rely on feedback of digit locations to produce an appropriate force when digit locations were unconstrained. Conversely, it was hypothesized that feedforward grasp control strategies would be used when digit location was constrained, as digit location is consistent across trials and presumably sensorimotor memories of digit forces do not need to be significantly updated with sensory information of digit location on a trial-to-trial basis. A Gaussian fit approach and analyses of task temporal landmarks were used to establish differences between the constrained and unconstrained digit placement conditions and CM locations.

REVIEW OF LITERATURE

Introduction

The field of motor control has mostly focused on how subjects learn digit

force modulation by grasping an object at a fixed location that is often constrained

by the position of force sensors. In contrast, the studies that have examined the

modulation of digit placement as a function of task or object properties have not

measured the concurrent modulation of individual forces. It is therefore unknown

how the removal of digit placement constraints (unconstrained) influences digit

force control. Allowing subjects the choice of digit placement results in a wider

range of possible relations between digit forces and positions, which may lead to a

more optimal digit force distribution (Cohen and Rosenbaum, 2004; Friedman

and Flash, 2007; Lukos et al. 2007, 2008; Ciocarlie et al., 2009). Recent work has

also suggested that subjects learn object manipulation by integrating sensorimotor

memories with sensory feedback of digit positions (Fu et al. 2010).

Anticipatory planning of digit positions and forces as a function of object

properties and task is critical for successful dexterous object manipulation.

Anticipatory (feedforward) planning allows for a bypass of inherent delays in

sensory integration and responses associated with reactive (feedback) control as

the latter may lead to unsuccessful object manipulation. One indicator of

anticipatory planning during object manipulation is the rate of grip and load force

development during object lifts. Specifically, it was suggested by Johansson et al.

(1984, 1988a) that a force rate profile that resembled a bell shaped curve between

the times of initial digit contact with the object and object lift indicated that

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feedforward control mechanisms were utilized. However, there is an important

gap in knowledge of feedforward grasp control because it is unknown if allowing

subjects the choice of contact points limits the brains ability to utilize feedforward

mechanisms for dexterous object manipulation, as previous experimental tasks

have constrained digit locations (Johansson et al 1984, 1988a). This literature

review focuses on research relevant to the objective of this thesis and gaps in the

literature.

Tasks

Prehension tasks usually involve reaching with the arm and hand to grasp

and manipulate an object. The manner in which prehension is performed is

usually defined by the action that will be performed with the object and its

properties, e.g. its shape or weight. Prehension studies have focused on how the

hand is transported and configured to grasp and manipulate objects, as well as the

kinematics of hand and finger movements, the coordination of fingertip forces as

the object is grasped, and the role of visual and somatosensory feedback in these

processes. Generally, studies that were more concerned with the emphasis of the

kinematic features have focused on the hand and arm movements as the hand

reaches to grasp an object and have been performed independently from those

concerned with grasping. Grasping studies usually assess the point of contact

with the object and concentrate on analyzing how the forces produced by the

fingers as an object is grasped and lifted are adapted to the properties of the object

(Jones and Lederman, 2006).

Reach to Grasp

In general, there are several classes of reaching movements that can be differentiated on the basis of the accuracy requirements of the movement and the configuration of the hand as the arm moves. Grasping movements that include pointing, aiming and reaching will generally involve similar kinematic features of the hand even though the reach-to-grasp movements can involve changing of the posture of the hand as movement progresses so that the hand can grasp the object. Additionally, an increased duration of movement can be seen as task difficulty increases in terms of the movement distance and object size (Jones and Lederman, 2006; Marteniuk, Jeannerod, Athenes, & Dugas, 1987).

Reaching and grasping an object involves three distinct phases: (1) moving the arm from its initial position to a location near the object (the reaching or transport phase), (2) adjusting the posture of the hand as it approaches the objet so that it can be grasped (the grasp phase), and lastly (3) the manipulation of the object (manipulation phase). The first phase, the reaching or transport phase of the movement, is usually defined by the kinematics of the wrist's movements so that variables such as movement time, velocity profile, peak acceleration and peak height can be analyzed from data recorded from sensors, passive reflective markers or infrared emitting diodes (IREDs). Additionally, the transport phase of reaching can be characterized by a bell-shaped velocity curve and a single peak in-between the acceleration and deceleration phases is typically considered evidence for feedforward control (Jeannerod, 1984; Jones and Lederman, 2006).

In reach-to-grasp movements, the posture of the hand changes shape in order to conform to the dimensions and shape of the target object. Different methods have been employed to characterize the minimal number of kinematic features that can be used to effectively describe how the hand's posture changes as the arm moves toward the target object and how the arm and hand trajectories are coordinated in space and time. The movement of the hand is usually recorded from markers or sensors, which are placed on the tips of the thumb and index finger and sometimes on the joints of other fingers if more comprehensive analysis of the grasping motion required (Mason, Gomez & Ebner, 2001; Jones et al., 2006). In addition, a motion-analysis system is used to calculate the position the body points in which the markers or IREDs are mounted (Gentilucci, Castiello, Corradini, Scarpa, Umilta, & Rizzolatti, 1991; Jones and Lederman, 2006).

Grasping research first began to receive attention in the 1980's. The topics covered ranged from how the intrinsic properties of an object can influence grasping forces to how task constraints influence the choice of a particular hand configuration. When performing tasks that use manipulative hand functions, such as grasping, there is a need for the precise coordination of forces generated at the fingertips in order for the fingers to have a stable grasp of an object (Johansson & Westling, 1984; Jones and Lederman, 2006).

Johansson and Westling (1984) developed the first experimental apparatus (Figure 1) and procedure for grasping. In this procedure a person was required to grasp an object between the thumb and the index finger and lift it from a

supporting surface. Johansson and Westling (1984) broke down the sequence of

events for the grasping apparatus into a temporal sequence. The first part of the

sequence comprised an initial *preload phase,* which was the time period between

digit contact and the onset of load force, followed by a *loading phase*, in which

there was a parallel increase in the grip force that was normal to the object surface
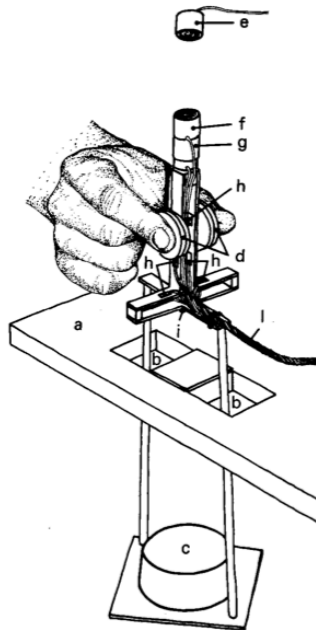
Figure 1. Original Schematic Drawing of the Grip Force Apparatus used by Johansson and Westling in 1984.
a: table; b: holes through table; c: exchangeable weight shielded from the subjects view by the table; d: exchangeable discs; e and f- vertical position transducer with an ultrasonic receiver (e) and an ultrasonic transmitter (f); g: accelerometer; h: strain gauge force transducers for measurement of grip and load force (vertical lifting force); i: peg with an hemispherical tip on which the object rests while placed on the table (Legend and figure reprinted from Johansson et al. 1984).

and the load force that was tangential to the surface. This corresponding increase

occurred until the load force overcomes the force of gravity. The next part of the

sequence, described as the *transitional phase,* occurred when the object was lifted

to the desired position, which was followed by the *static phase* in which the

object was held stationary and the forces reached a steady state. The final two

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steps were the *replacement phase* where the object was lowered to the resting position and the *unloading phase* where the object was released from the hand (Johansson and Westling, 1984; Westling and Johansson, 1987).

The field of motor control has mostly focused on how subjects learn digit force modulation by grasping an object at a fixed location that is often constrained by the position of force sensors (Figure 1). For example, in the grip apparatus experiments by Johansson et al. (1984), force transducers were mounted on the object being grasped in order to record the normal and tangential forces, but digit locations were confined by the dimensions of the force transducer (constrained digit location) (Figure 1; Johansson et al. 1984). Additional investigations have examined the effects on grip forces of various object properties such as the texture of the grasp surface (Johansson et al. 1984; Westling et al. 1987; Johansson et al. 1987), the shape and the curvature of the object, and object weight (Jenmalm et al. 2006; Jones et al. 2006).

When a subject lifts an object, the grip force and load force must be coordinated so that the object does not slip. For example, increases in load force must be accompanied by a corresponding increase in grip force otherwise the object will slip. More specifically the ratio of the grip force to the load force must exceed the inverse of the coefficient of friction for a grip to be stable and for the object to be secure In fact studies have shown that grip and load forces during two digit precision grip tasks increase and are maintained at an approximately constant ratio throughout the grasp (Johansson and Westling 1987; Johansson and Westling 1988). This finding is consistent with a coordinated pattern of muscle

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activation in the hand and arm muscles (Johansson and Westling 1987; Johansson and Westling 1988). The slip force, which is the minimum force at which an object begins to slip between the fingers, has been measured experimentally by asking subjects to extend the thumb and index finger slowly until the object begins to slip from the fingers while measuring the digit forces at the moment of object slip. The slip force was found to be proportional to the load force (Johansson and Westling, 1984) and varied as a function of the friction between the skin and the object (Jones et al. 2006; Johansson and Westling, 1987; Westling and Johansson, 1987). Furthermore, stability of the grasp can be maintained during manipulation by modulating digit grip and load forces in parallel. If an object begins to slip between the fingers, there will be a reflexively driven increase in the grip force in order to maintain a more stable grasp. This will usually occur within 70 ms of the slip (Jones et al. 2006; Johansson and Westling, 1987; Westling and Johansson 1987).

As mentioned previously, manipulation tasks can be characterized by a sequence of action phases that are separated by contact events that define task subgoals. These subgoals can be visualized in Figure 2. This thesis focuses on the time between digit contact and the onset of object lift (Figure 2). Figure 2 highlights that the time of initial digit contact with the object and the time of object lift (lift onset) are crucial instances for grasp control. Specifically, it is thought that at these times a comparison is made between the motor plan and expected object properties and the sensory information, which is used to update the motor plan if necessary. Specifically, for each digit, information is conveyed
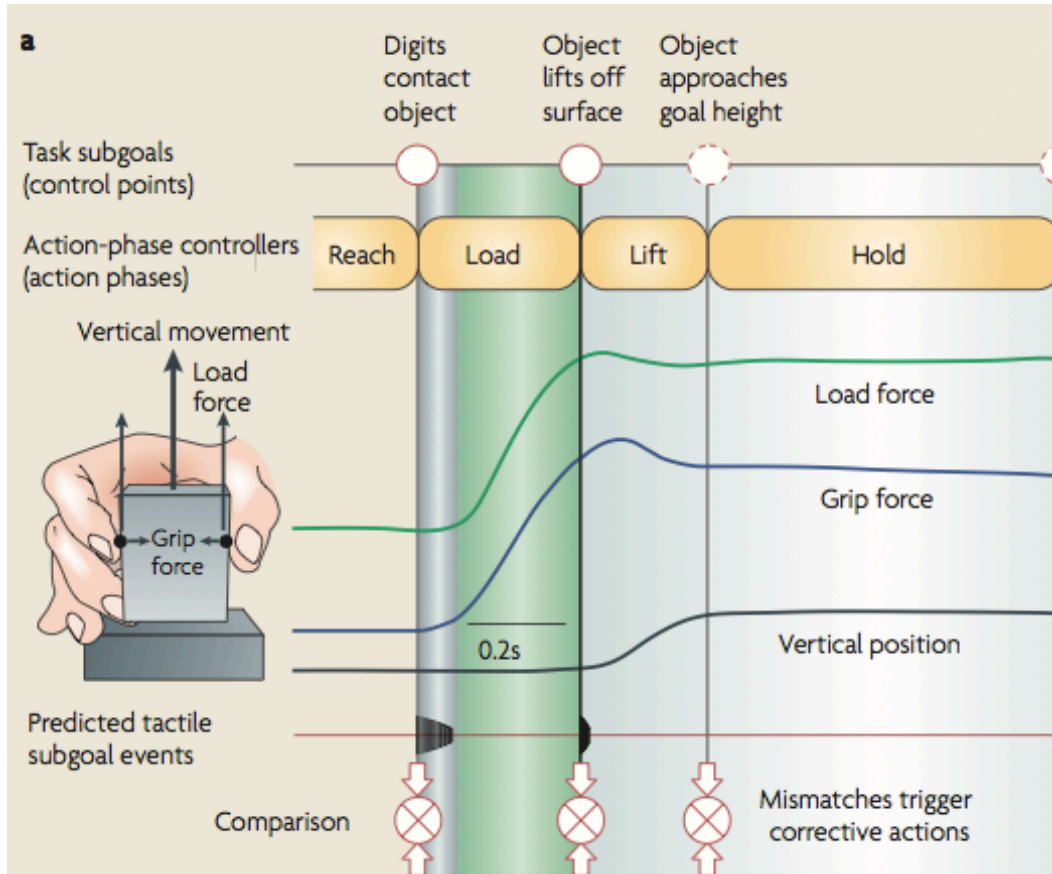
Figure 2. Sensorimotor Control Points in a Prototypical Object Manipulation Task.
Manipulation tasks are characterized by a sequence of action phases, which are separated by
contact events that define task subgoals. The figure denotes important temporal landmarks
in the motor control process. Represented in this figure is a task in which an object is
grasped, lifted from a table, held in the air and then replaced. The initial reach phase is
marked by the digits contacting the object. The load phase is marked by a parallel increase
in the grip and load forces. The lift phase is marked when the object lifts off the surface of
the table (Reprinted from Johansson et al. 2009).

to the central nervous system about digit contact time, the contact site of the digit,

the direction of digit contact force, friction, mass, and kinematic properties of the

object (Johansson et al. 1984, 1988a; Johansson and Flanagan 2009).

Tactile Afferents

When an individual performs object manipulation, the brain uses tactile

afferent information related to the time course, magnitude, direction and spatial

distribution of contact forces, and properties of the contacted surfaces, such as

shape and friction. The human hand has four different types of tactile afferents. FA-I (fast-adapting type I) afferents are sensitive to dynamic skin deformations of high frequencies (5-50 Hz) and the afferents are most dense in the fingertips. SA-I (slow-adapting type I) afferents are sensitive to low-frequency dynamic skin deformations (< 5 Hz) and are also most dense in the fingertips. The FA-II (fast-adapting type II) afferents are extremely sensitive to mechanical transients and high-frequency vibrations (40-400 Hz). The hundreds of FA-II afferents are distributed throughout the hand and can be excited when hand-held objects contact or break contact with other hand-held objects. Lastly, SA-II (slowly-adapting type II) afferents have low dynamic sensitivity and are also sensitive to static force. Additionally SA-II afferents are able to sense tangential shear strain to the skin. The SA-II afferents are found in most fibrous tissues (Johansson et al. 1984, 1988a).

A primary goal of individuals when manipulating an object is to ensure a stable grasp of the object. Once a subject is in contact with an object, the digits are usually able to apply normal or tangential forces to the object surface in order to move and manipulate the object. In order to maintain grasp stability, grip forces normal (perpendicular) to the object surfaces change in phase with and in proportion to the applied tangential forces. Grasp stability is identified as the control of grip forces such that the forces are adequate to prevent accidental slips, but not so large as to cause unnecessary fatigue or damage to the object or hand (Johansson et al. 1984, 1988a).

Friction and its Influence on Grip Force

The amount of friction that exists between the fingers and the object, which is being grasped, is dependent on the material of the grasping surface, the amplitude of the grip force, the contact area, and the degree of hydration of the skin. Several studies have examined the influence of friction on the forces that are used to grasp objects using materials such as silk and sandpaper (Johansson and Westling, 1984; Jones et al. 2006; Johannsson and Westling, 1987). Johansson and Westling found that as the friction between the skin and the object decreased, there were higher normal forces than were required to maintain grasp stability. The main effect of different materials being placed on grasping surface was based on the rate with which the normal force changed during the preloading and loading phases. (Johansson & Westling, 1984; Jones et al, 2006; Johansson & Westling, 1987).

Influence of Object Shape and Size on Digit Grip Forces

An individual uses different tactile and visual cues of an objects shape and size in order to modulate digit forces while grasping an object. These cues may influence the timing, amplitude, and direction of digit forces at different times in the grasping process. Visual information may be used primarily to identify the properties of the object, to determine the grasp requirements, and to make anticipatory adjustments to the grip forces when the hand comes in contact with the object. Features that are observed when grasping an object include shape, surface curvature, and object weight as predicted from its size (Johansson and Westling, 1984; Gordonet al. 1991a, 1993; Jenmalm et al. 2000). When lifting an

object, the tangential forces that the subject applies have to be larger than the gravitation force acting on the object mass (Jones and Lederman, 2006; Jenmalm & Johansson, 1997).

Object's Center of Mass and Grasping

For the majority of past studies on prehension, objects have been grasped with symmetrical mass distribution with the center of mass located in the middle of the fingers in the plane of the two surfaces of contact. In such tasks the load force for each digit need only equal half the object's weight. In contrast when the object's center of mass does not lie on the grip axis (i.e. the object has an asymmetrical mass distribution), then torques need to be developed by the digits prevent the object rotating or rolling towards its center of mass. Furthermore, in order to prevent these object rolls, the grip forces must be scaled appropriately for each digit (Jones and Lederman 2006).

One strategy that individuals could use to create a torque about the object to counter the torque created by the object's asymmetrical mass distribution would be to partition digit load forces unequally. In order to lift an object without tilting, a torque equal in magnitude and opposite in direction to the torque created by the object's mass distribution needs to be generated by the digits. When lifting such objects, in which the mass distribution is unknown prior to the first manipulation, it has been found that within three to five lifts subjects are able to modulate digit load forces in order to lift the object with minimal roll (Jones et al. 2006; Salimi et al. 2000). Similarly, when digit location is unconstrained, subjects have been found to learn to minimize object roll within the first three

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trials by changing the digit placement and altering the force distribution applied by the fingers (Fu et al. 2010; Lukos et al. 2007; Zhang et al. 2010). These findings suggest that subjects are able to learn relatively quickly (within the first three trials of a lifting task) to coordinate digit position and forces to successfully manipulate novel objects despite a lack of visual information related to the objects mass distribution properties.

Anticipatory Planning

The human ability to manipulate objects relies on predictive control mechanisms that parametrically adapt the force motor commands to the relevant physical properties of the target object (Johansson 1998). These predictive motor commands are likely formed with the aid of sensorimotor memories, which are acquired during previous object manipulations (Johansson and Cole 1992). In everyday life object properties may be unpredictable because they can change without our knowledge. When the weight of a lifted object is unpredictably changed, the fingertip forces that are applied will either be too large or too small and the sensory information will indicate a deviation from the predicted outcome (Johansson and Westling, 1988). Furthermore, this sensory information could be used to update the motor command during the loading phase and may result in a drastically different force rate profile than that observed when object weight is predictable and the motor command is not significantly updated. The validation phase of this thesis will explore whether individuals are able to use anticipatory planning when digit placement is unconstrained and there is an unpredictable change in object weight and center of mass location as previous and similar work

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has shown for tasks that constrained digit placement location (Johansson et al. 1984, 1988a; Jenmalm et al., 2006).

In tasks that constrained digit location, and required several lifts of an object with a predictable mass, force development was adequately programmed for the current weight during the loading phase (Johansson et al. 1988a). The grip and load force rate trajectories were primarily single-peaked, bell shaped and approximately proportional to the final force (Figure 3). The weight of the object influenced the rate of force increase during the loading phase and the duration of the loading phase. However, when subjects performed several lifts of an object with unexpected weight changes between the lifts, force rate profiles seemed to be programmed on the basis of the previous weight. When subjects lifted an object in which, the weight of the object was decreased compared to the preceding trial, without the subject's knowledge, researchers observed a pronounced overshoot in the grip force and position signals and the force profile was characterized by several peaks and troughs (Figure 3). These findings led Johansson et al. (1984, 1988a) to suggest that a force profile developed between the times of initial contact with the object and object lift that resembled a bell shaped curve indicated that feedforward control mechanisms were utilized (Johansson et al. 1984, 1988a).
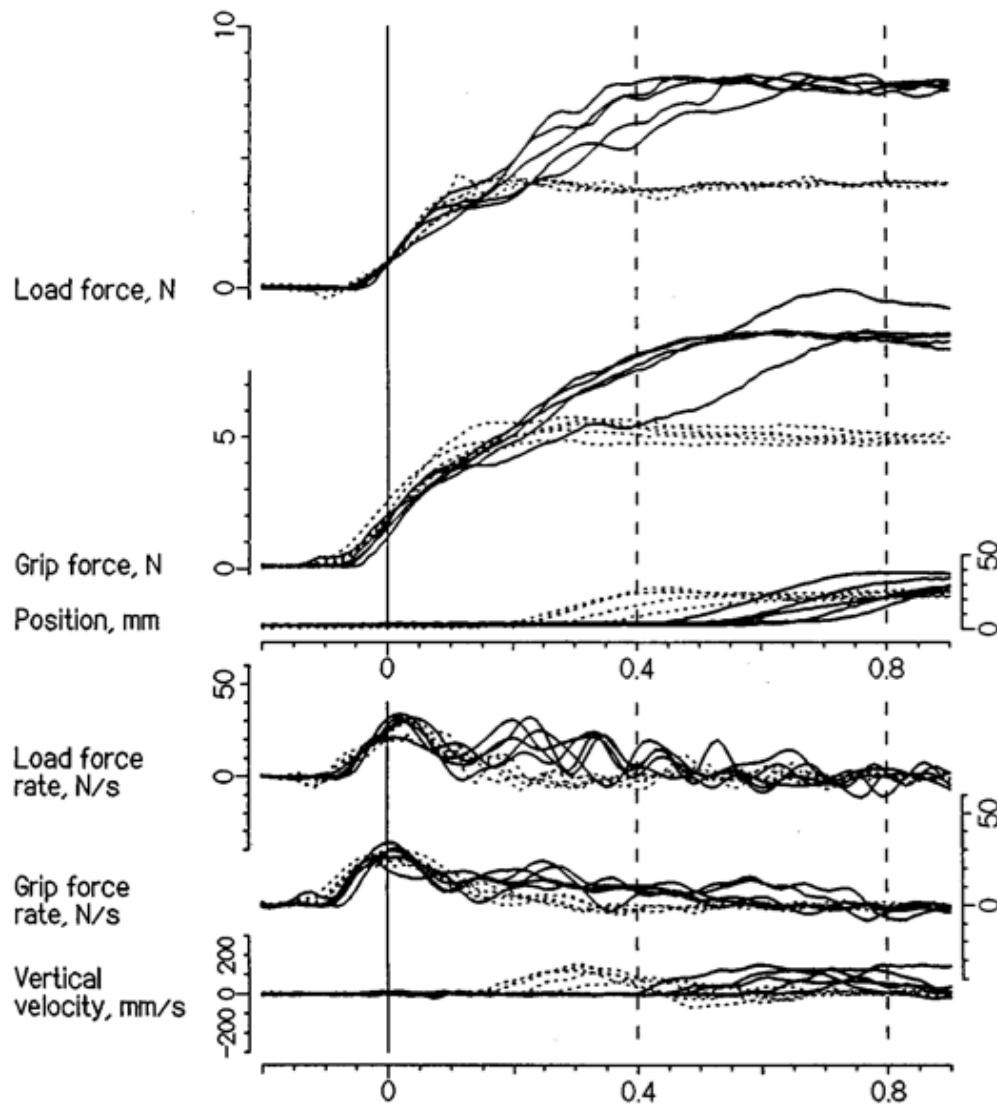
Figure 3. Experimental variables from previous research with initial parts of lifts with 800g that are erroneously programmed for a lighter weight of 400g.
The load force, grip force, vertical position and their time derivatives as a function of time for 5 sample trials with 800g(—) were preceded by adequately-programmed 400g lifts (- - -). Rates of grip force and load force exhibited a bell shaped profile in adequately-programmed lifts. (Reprinted from Johansson et al. 1988a).

Task Mechanics

Lifting and manipulating an object requires the generation of forces and moments (torques), which are coordinated with the position of digit locations. In tasks in which object roll minimization is used during lift, subjects are required to

use a compensatory moment (Mcom) on the object which cancels out the external

moment that is generated by the product of an additional mass used in the

manipulation task and its distance from the midline of the object (Zhang et al.

2010). Mcom is produced by the sum of the net moments of the tangential forces

(Mtan) and normal forces (Mn) that are produced by the thumb and index finger:

$Mcom = M\tan + Mn$. The Mtan is the net moment of the tangential forces

produced by the thumb and index finger about the CM of the object shown as:

$M\tan = (F\tan 1 - F\tan 2) \times \dfrac{d}{2} = \Delta F \tan \times \dfrac{d}{2}$ in which d is the grip width and $\dfrac{d}{2}$ is

the moment arm of tangential forces generated by the thumb (Ftan1) and the

index finger (Ftan2) about the object's CM. The moments produced by the thumb

and index finger are opposite to one another, which causes Mtan to be

proportional to the difference between Ftan1 and Ftan2 (ΔFtan) (Zhang et al.

2010). The normal force that is exerted by the thumb and index finger both have

equal magnitude but are applied on opposite sides of the object (Zhang et al.

2010; Fu et al. 2010). Mn is the product of the normal force that is applied by the

thumb (Fn1) or the index finger (Fn2) and the vertical distance between the

centers of pressure (ΔCoP) of the thumb and index finger on the lifting object

shown by the equation: $Mn = Fn1 \times \Delta CoP$ (Zhang et al. 2010). In previous

research involving lifting tasks, the width of the object (d) remains constant.

Therefore, the Mcom can be described by the variables: ΔCoP, ΔFtan and Fn as

shown in the equation: $Mcom = \Delta F \tan \times \dfrac{d}{2} + Fn1 \times \Delta CoP$. This suggests that by

simply changing the digit placements on the object, the compensatory moment

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can be manipulated. If grip force remains constant, resulting in a constant Mcom, as the vertical distance of the centers of pressure ΔCoP increase or decrease then the ΔF*tan* will decrease or increase respectively (Zhang et al. 2010).

These equations suggest, and it has been shown in previous research with unconstrained digit placement (Fu et al. 2010) the coordination between digit forces and positions is critical in order for successful objet manipulation to occur. It has been indicated that the position of the fingertips at the time of object lift onset are already defined shortly after contact, despite small changes in the digit CoPs that occur as forces are exerted (Fu et al. 2010). Therefore, it was suggested that a comparison is made following contact between the expected and actual feedback of digit placement. A mismatch between the expected and actual feedback would cause a change in the planned digit forces and could possibly update sensorimotor memories for future tasks. It has been found that there is an inverse relation between the load forces that are applied by the thumb and index finger and the vertical spacing between the two fingers (Fu et al. 2010).

In object manipulation tasks subjects obtain feedback of the digit position grip and load forces, and object properties. The feedback and sensorimotor information are stored and used on a trial-to-trial basis in order to update the motor plan for subsequent lifts, typically resulting in an anticipatory compensatory moment that more closely matches the object external moment (Fu et al. 2010). Additionally, digit position and forces are also updated on a trial-to-trial basis in which an anticipatory control mechanism is used and updated based

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off of the feedback from previous trials and is continually updated to improve the anticipatory control mechanism as tasks progress.

A major limitation of the studies by Johansson et al. (1984, 1988a) was that digit locations were constrained. This is a significant gap in the understanding of the control of dexterous object manipulation as in tasks of daily living digit location is typical unconstrained. This is important because anticipatory planning of digit positions and forces as a function of object properties and task is critical for successful dexterous object manipulation. One indicator of anticipatory planning during object manipulation is the rate of grip force and load force development during object lifts (Johansson et al. 1984, 1988a). This thesis will validate the findings of Johansson et al. (1984, 1988a) as well as determine whether or not there is a significant difference in the feedforward grasp control strategy between constrained and unconstrained digit location.

METHODS

This thesis consists of two sections: (1) validating the hypothesis that force rate profiles are indicative of the control strategy used for object manipulation in tasks which do not constrain digit placement and (2) to test this hypothesis in manipulation tasks performed with and without digit placement constraints.

Subjects

In the first experiment, the validation stage of the work, four right-handed subjects were used (2 male and 2 female, ages 20-26 years) to validate whether or not a bell shaped profile occurred in the grip and load force rates with unconstrained digit placement. In the second experiment, the testing component of the work, twenty-four right-handed subjects (12 males and 12 females, ages 20-26 years) with normal or corrected-to-normal vision took part in the experiments. The conditions of the subjects for the first experiment are the same as for the second experiment. All of the subjects had no history of musculoskeletal or neurological disorders. Additionally, the subjects were naïve to the experimental purpose of the study and gave written informed consent prior to participation in the experiment. The experimental procedures were approved by the Institutional Review Board at Arizona State University and were in accordance with the Declaration of Helsinki (Fu et al. 2010).

Experimental apparatus

For Experiment 1, the validation phase and Experiment 2, the testing phase, subjects reached to, grasped, lifted and replaced one of two custom-made

inverted T-shaped grip devices. For Experiment 1, subjects only used custom

made inverted T-shaped grip device that did not constrain digit locations (Figure 4

A). For Experiment 2, different groups of subjects used objects that either

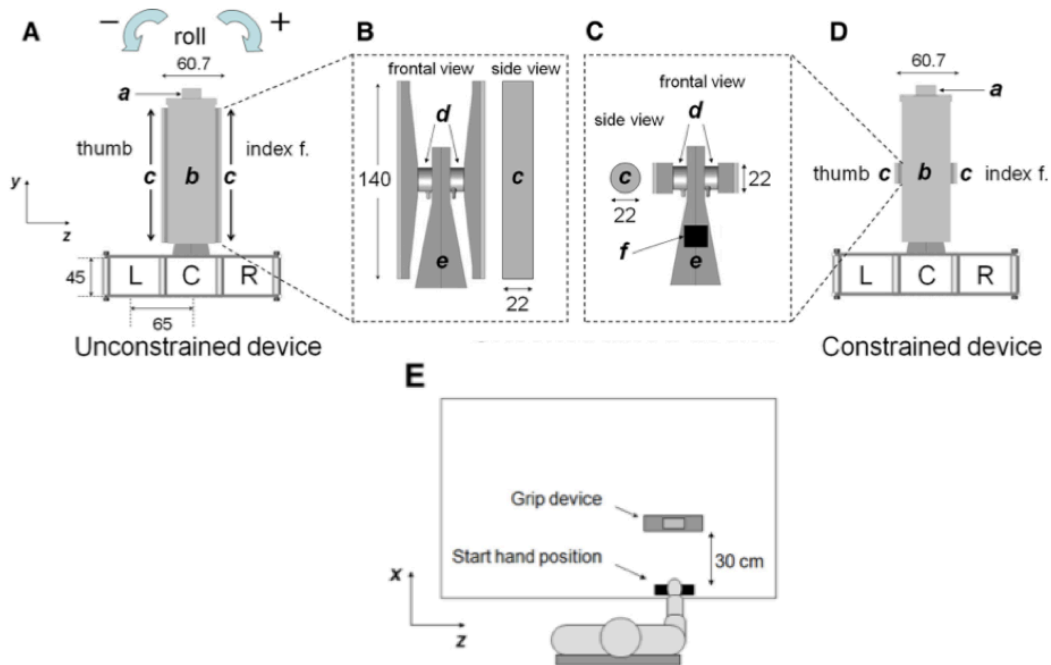constrained or did not constrained digit locations (Figure 4 A, D). These devices

Figure 4. Experimental setup of the custom built grip devices used for the study.
The unconstrained device *A* allows subjects to choose digit placement on two long, graspable
surfaces (*A*, c). *B* provides a frontal and side view of the unconstrained device. *D*, the
constrained device can only be grasped on two small graspable surfaces (*D*, c). *C* provides
side and front views of the constrained device. The force/torque sensors measured the x-, y-,
and z- components of forces and torques that are applied by the thumb and index finger.
Additionally, a magnetic tracker (*A*, *D*, a) was mounted on top of both constrained and
unconstrained grip devices in order to measure the device's position and orientation. There
are two panels (*A*, *D*, b) mounted on the front and back of each grip device to block the
sensors from view. A light mass (50g; *C*, f) was added to the constrained device in order of
making the weight of both devices match. The units of dimensions for the grip device
components are in millimeters. *A*, *D*, A mass (400g) was added to the left, center, or right
slots at the bottom of the device (L, C and R, respectively). The dimensions of the slots
prevented motion of the mass during movement of the object. *E*, The position of the
subject's hand relative to the object before reach onset (top view; figure is not to scale)
(Legend and Figure from Fu et al., 2010).

consisted of a vertical block which housed the force transducers attached to a

horizontal base that had three separate compartments, in which an additional mass

could be added to alter the mass or mass distribution of the object (Figure 4 A, D). The unconstrained (Figure 4 A) and constrained devices (Figure 4 D) differed by the dimension of the graspable surfaces for digit placement. The graspable surface of the first of the two devices (unconstrained) had two parallel PVC bars (length = 140 mm; width =22 mm) (Figure 4 A, B). The second grip device (constrained) had graspable surfaces, which consisted of two collinear circular plates (diameter = 22 mm) (Figure 4 C, D), which are similar to the grip devices used in the previous studies of two-digit grasping (Johansson et al. 1984; Salimi et al. 2000, 2003; Bursztyn and Flanagan 2008). The unconstrained grip device allowed subjects to choose digit placement anywhere along the vertical graspable bars (Figure 4 A). The constrained device allowed digit placement only at fixed locations on the object (Figure 4 D). For both of the grip devices (constrained and unconstrained), the horizontal distance between the two graspable surfaces was 60.7 mm. Each of the graspable surfaces was mounted on a force/torque transducer (Fig. 4 B, D) (see Data Recording section below for more details) (Fu et al., 2010).

For each of the devices, constrained and unconstrained, the center of mass (CM) of the object could be changed across blocks (Left, Center or Right) of trials by adding a mass (400g) in one of three slots at the base of the object (Figure 4 A, D). The 400g mass was consistently added for all trials of all experiments to one of the CM locations. The external torques that resulted from the added mass with respect to the CM of the unloaded grip devices were -255, 0, and 255 N•mm when the mass was added to the left, center or right slot, respectively. When CM

locations are noted throughout the text they refer to the mass added on the thumb side (left CM) and index finger side (right CM) of the grip device respectively. Both of the constrained and unconstrained grip devices have a total mass of the object (grip device plus the added mass) of 0.796 kg. The unconstrained device had larger grasping panels then the constrained device, therefore the difference between the weights of the graspable surfaces of the unconstrained and constrained devices was eliminated by adding a 50 g mass to the middle slot of the lighter, constrained device (Figure 4 C) (Fu et al., 2010).

Experimental task

For Experiment 1, the validation phase, four subjects lifted the unconstrained device (Figure 4 A). For the second experiment, the testing phase, subjects were assigned to one of two groups (n = 12 for each group), in which one group lifted the unconstrained device and the other lifted the constrained device.

The object (constrained and unconstrained) was placed on a table at a distance of 30 cm from the hand start position and was aligned with the subject's right shoulder (Figure 4 E). The object's and the subject's frontal planes were aligned parallel to each other (Figure 4 E). All subjects sat on a height-adjustable chair with the wrist resting on a table, the forearm pronated, and an approximately 90° angle between the upper and lower arm (Figure 4 E). Subjects started the reach movement after the experimenter gave a verbal go signal. Instructions to the subjects were same for Experiments 1 and 2 and were as follows: (1) reach, grasp, lift, and replace the object at a speed that feels natural; (2) grasp the object only with the thumb and index fingertips, with the remaining fingers stretched

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out, and grasp only on the graspable surface area (different areas for constrained and unconstrained); (3) lift the object vertically, 15-20 cm above the table, while trying to maintain its vertical alignment (minimize roll); (4) hold the object for approximately one second; and (5) to replace the object on the table. The object was placed on a table between chest and waist height, in order for subjects to be able to have a full view of the object and their hand throughout the reach to grasp movement (Fu et al., 2010).

Before data collection occurred subjects were asked to perform three practice trials to ensure that they understood the experimental instructions and were capable of performing the task in accordance with the instructions. Furthermore, the practice trials allowed subjects to become familiar with the weight and frictional properties of the object. The additional mass was added to the center slot of the grip device for both the demonstration and the practice trials. One of the experimenters visually verified that subjects performed the task in accordance with all the above instructions for each trial (Fu et al., 2010).

Experiment 1, the validation phase, comprised two different studies, each involving four subjects. In the first study digit location was unconstrained, the object's mass distribution was symmetrical, and the mass of the object was randomly changed from light (no additional mass added) to heavy (400g mass added) between trials. Subjects performed thirty consecutive trials (lifts) for this experiment (Figure 4 A). In the second study subjects performed thirty consecutive trials with the unconstrained device (Figure 4 A). Between trials object CM location was randomly changed from side to center or from center to

side using the unconstrained device. Subjects 1 and 3 experienced left and center CMs and subjects 2 and 4 experienced right and center CMs. The order of CM location was randomized, but the same random order was used for all 4 subjects.

For Experiment 2, the testing phase, subjects performed three blocks of 10 consecutive trials per CM location (block) for a total of 30 experimental trials (Figure 4 A, D). Subjects were not able to anticipate CM location at the beginning of each block of trials (trial 1, trial 11, trial 21), but they were informed that the CM locations would remain the same for the entire block of trials (Left, Right or Center). By consecutively presenting the same CM location subjects were able to implicitly learn from previous object lifts about the magnitude and direction of the external torque caused by the added mass (Fu et al. 2010; Lukos et al. 2007, 2008). Additionally, the consecutive presentation of CM locations allowed for the quantification of the time course of trial-to-trial learning of anticipatory control of digit forces and position. Each subject was given a different CM order and each combination of order was balanced across all subjects (Fu et al. 2010).

Data Recording

Two 6-axis force/torque sensors (ATI Nano- 17 SI-50-0.5, ATI Industrial Automation; force range: 50, 50, and 70 N for x-, y-, and z-axes, respectively; force resolution: 0.012 N; torque range: 500 N • mm; torque resolution: 0.063 N •mm) (Fig. 3 B, C) were used to record the forces and torques exerted by the thumb and index fingers. In order to record the position and orientation of the grasping objects (constrained and unconstrained), a magnetic tracker (Fastrack,

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Polhemus) was fixed on the top of the vertical block (Fig. 3 A, D). The force and

torque data were recorded through two analog-to-digital converter boards (PCI-

6220 DAQ, National Instruments; sampling rate, 1 kHz). The position data was

recorded through a serial port (sampling rate, 120 Hz). Additionally, the

collection of the force and position data were synchronized with custom written

software (LabView v 11, National Instruments) (Fu et al., 2010).

Data Processing

Position data was linearly interpolated to match the sampling rate of the

force data. The position data and force data were low pass filtered with a cutoff

frequency of 30 Hz (5th order Butterworth). Custom written programs (MATLAB

v R2010A Mathworks) were used to compute the following variables:

(1) *Grip force and load force*, which were defined as the normal and

tangential components of each digit force that were exerted at the digit center of

pressure with respect to each of the graspable surfaces. The sum of the load force

of the thumb and index fingers was used due to subjects relying on one finger

more than another finger for load force (Figure 5);

(2) *Digit center of pressure* (CoP), which is defined as the vertical

coordinates of the center of pressure of the contact between the finger pad and the

graspable surface (Figure 4 A, D);

(3) *Grip force and load force rate*, which were computed as the derivative

of the grip force and load force respectively. The sum of the load force rate of the

thumb and index fingers were used due to subjects relying on one finger more

than another finger for load force (Figure 5);

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(4) *Digit initial contact*, which was defined as the time at which the normal force produced by both digits crossed and remained above a threshold (mean + 2 SD of the signal baseline) for 100 ms (Figure 5);

(5) *Object lift onset*, which was defined as the time at which the vertical position of the grip device crossed and remained above a threshold (mean + 2SD of the signal baseline) for 100 ms (Figure 5);

(6) *Digit grip* and *load force onset*, which was calculated as the time that the thumb or index finger grip and load forces increased above a value of zero (non-zero value of grip and load force that continually increased for 120 ms between the times of digit contact and lift onset in Figure 5);
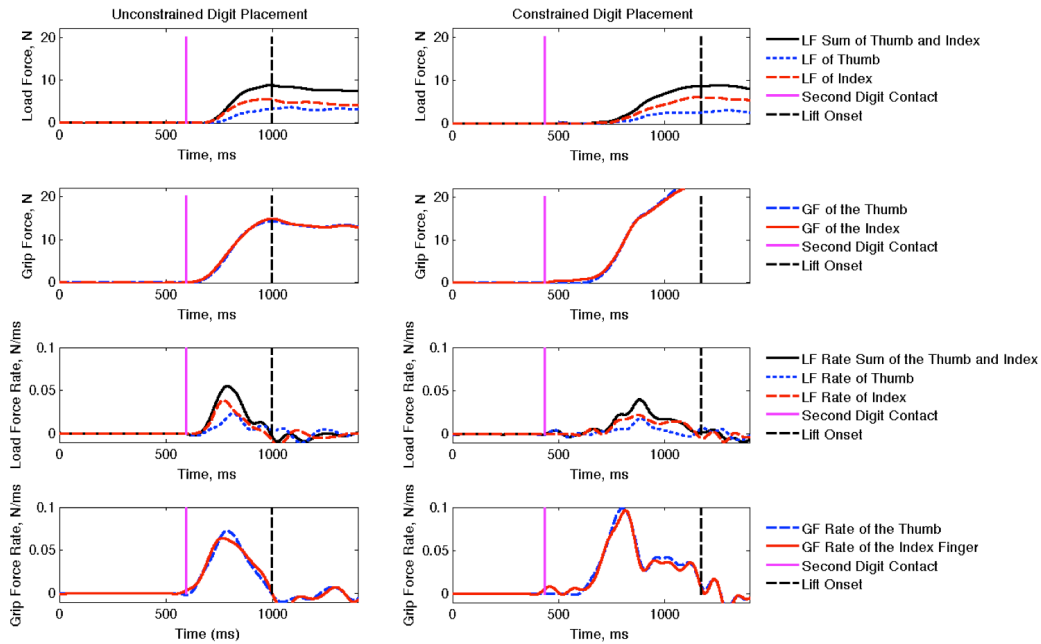

Figure 5. Experimental Variables.
The experimental variables analyzed in this study are shown for unconstrained and constrained digit placement conditions. Data is from two representative subjects. The first vertical line (—) represents the point in time when the second digit (either thumb or index finger) made contact with the object. The second vertical line (- - -) represents the point in time when lift onset occurred. From top to bottom for both constrained and unconstrained digit placement, are object load force, grip force, load force rate and grip force rate.

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(7) *Digit grip and load force peak rates,* which were calculated by finding the time when Grip force rate (derivative of the grip force) was at its highest for both the thumb and the index fingers (highest value of the rates of grip force between the times of digit contact and lift onset in Figure 5);

(8) *Thumb and index load force peak rates*, which were calculated by finding the time when load force rate (derivative of the load force) was at its highest for both the thumb and index fingers (highest value of the rates of load force between the times of digit contact and lift onset in Figure 5) (Fu et al. 2010; Zhang et al. 2010).

To verify that the goodness of fit measure was indicative of feedforward and feedback control, several time durations between and including the time of initial digit contact and object lifts were quantified. These variables were used to calculate different temporal measures which include the time between: *(a)* second finger touch and load force onset; *(b)* load force onset to lift; *(c)* onset of grip force for the thumb and index fingers; *(d)* onset of load force for the thumb and index fingers; *(e)* grip force peak rates for the thumb and index fingers; *(f)* load force peak rates for the thumb and index fingers; and *(g)* second finger touch and lift; and second finger touch and the onset of moment (Mcom) (obtained by the moment generated by the digit tangential forces and the moment generated by the digit normal forces only for the temporal measure).

MATLAB's Curve Fitting Toolbox was used to compare the grip force rate and load force rate profiles to a Gaussian bell curve. The Gaussian bell curved was defined according to the following general model:

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$$f(x) = a1 * \exp\left(\frac{-((x - b1))}{c1}\right)^2$$, where *a1* represents the amplitude coefficient, *b1*

and *c1* represent timing coefficients of the fitted Gaussian. The Root Mean

Square Error (RSME) was calculated from each fit to determine the goodness of

fit between the general Gaussian curve and the force rate profiles. The Gaussian

bell curve was fit to the grip force and load force rates between the times of the

second digit contact and onset of lift of the object.

Statistical Analysis

      For Experiment 1, Gaussian Bell Curves were fit to predictable and

unpredictable grip and load force rates. To determine how well the Gaussian Bell

Curve fit the rate of grip and load force, the Root Mean Square Error (RMSE)

values for each trial were calculated. Repeated-measures Analysis of Variance

(ANOVA) was used to examine the effect of predictability (predictable vs.

unpredictable; within-subjects factor) and mass (light vs. heavy; between-subjects

factor) on the RMSE values for grip force and load force rate profiles. Repeated-

measures ANOVA was also used to compare the RMSE values for grip and load

force rate profiles in the predictable vs. unpredictable (between-subjects factors)

conditions across the three CM locations (within-subjects factor; left, center,

right). This experiment served as the testing stage, in order to quantify how well a

Gaussian bell curve fit to the rate of grip or load force.

      In Experiment 2, a repeated-measures ANOVA was used to compare the

RMSE values for the grip force and load rate profiles between the unconstrained

and constrained tasks (between-subjects factor) and across the three CM locations

(left, center, right; within-subjects factor). Only the last 7 trials were used for each CM location to avoid the influence that the initial learning that occurs during the first three trials may have on the force rate profiles (Fu et al. 2010).

Repeated-measures ANOVA was used to compare the temporal variables mentioned in the above section, between the constrained and unconstrained groups (between-subjects factor), predictable and unpredictable conditions (within-subjects factor), and across the three CM locations (left, center, and right; within-subjects factor).

Independent samples t-tests with a modified Bonferroni were used when appropriate to determine differences in the dependent variable between predictable and unpredictable for each CM locations. Paired samples t-tests were used when appropriate to determine the differences in the dependent variables between the predictable and unpredictable light and heavy object conditions. An alpha level of 0.05 (0.025 modified Bonferroni) was considered significant and values are reported as mean $\pm$ standard deviation in the text and mean $\pm$ standard error in figures.

RESULTS

Gaussian Bell Curve Approach

Figure 6 shows representative data from two subjects who performed

object lifts in the predictable and unpredictable mass (light and heavy) conditions.

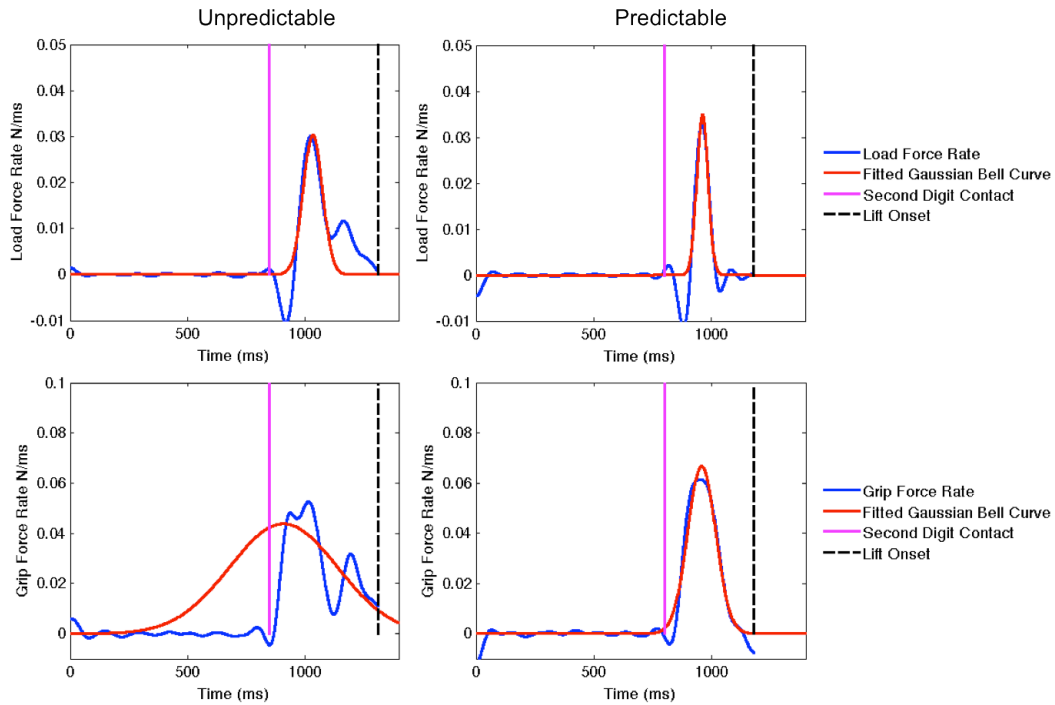Grip force and load force rates were fit to a Gaussian bell curve. Consistent with

**Figure 6. Unpredictable vs. predictable change of mass fit to Gaussian bell curves.
In the first experiment, the validation stage, mass was changed unpredictably with
unconstrained digit placement and compared to the results when mass was predictable.
Center of Mass location was centered in the unconstrained object. Data is representative of
two subjects for a predictable trial with a light mass and when the mass was unpredictably
changed from heavy to light. The first vertical line (—) represents the point in time when
the second digit (either thumb or index finger) made contact with the object. The second
vertical line (- - -) represents the point in time when lift onset occurred. Note that the fitted
Gaussian bell curve is a good estimator of the shape of the rate of grip and load forces for
the predictable unconstrained digit placement condition, but for the unpredictable condition
the force rates due not resemble a single peaked bell shaped profile.**

the results of Johansson et al. (1984, 1988a) the force-rate profiles switched from

bell shaped to profiles with several large peaks when subjects encountered an

object with a mass other than expected (unpredictable condition). Additionally,

the grip force and load force rates for the predictable condition exhibited a bell shaped profile.

In Figure 7, the RMSE values obtained for the fit between the digit grip force rate profiles and the Gaussian bell curve were significantly greater in the unpredictable than predictable conditions for the index finger ($P = 0.023$) and tended to be greater in the unpredictable condition for the thumb ($P = 0.095$). Furthermore, these effects were similar for the light and heavy conditions ($P \geq 0.286$).
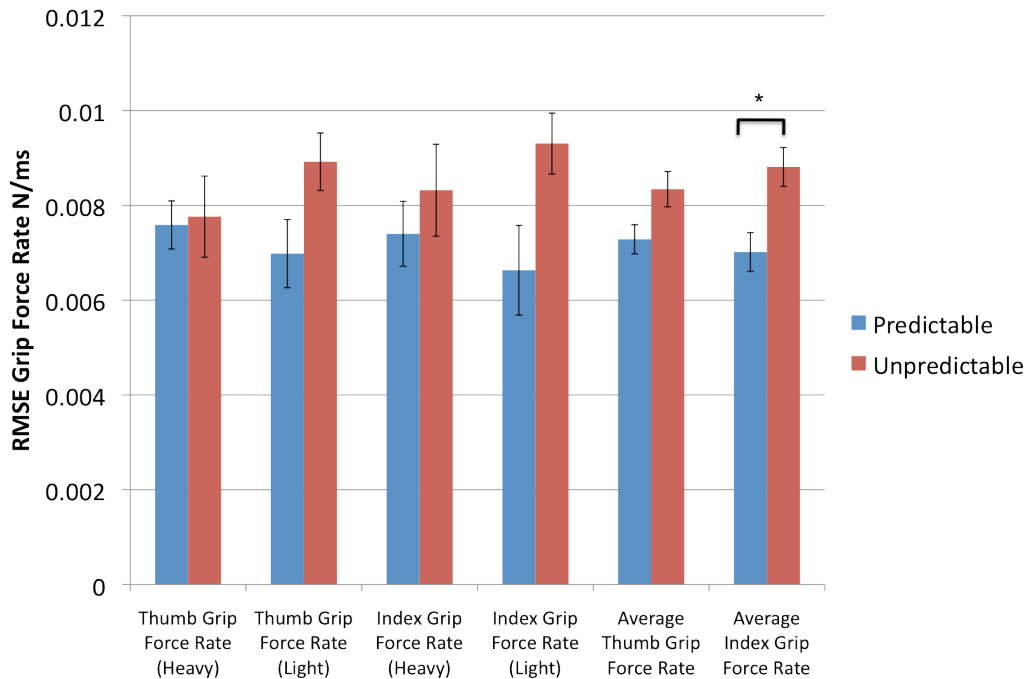

Figure 7. Comparison of RMSE values of fitted Gaussian bell curves for grip force rate between predictable and unpredictable mass conditions.
The overall average of the RMSE of the goodness of fit of grip force rates to fitted Gaussian bell curves in object lifts with predictable and unpredictable mass conditions (light and heavy). Higher RMSE values represent a worse fit to the fitted Gaussian bell curve.

Figure 8 shows that the RMSE values for the fit between the Gaussian bell curve and index finger load force rate was greater for the unpredictable than predictable condition ($P = 0.002$). Furthermore, the RMSE values were only

greater for the unpredictable than predictable light mass condition for the index

finger ($P = 0.024$; post hoc). Also the RMSE values for load force rates of the

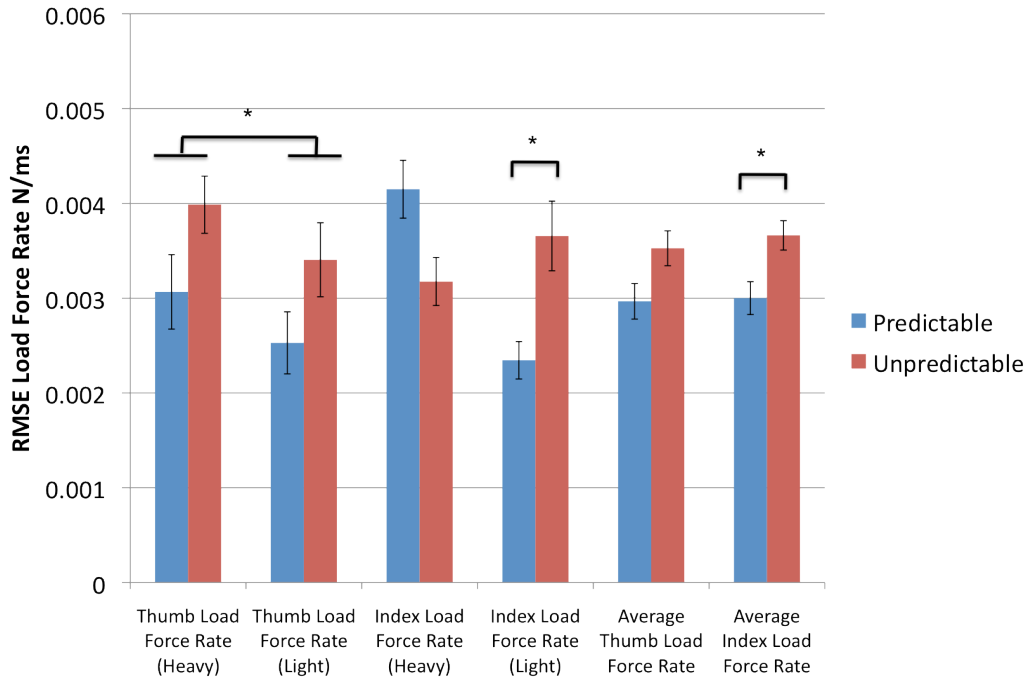thumb were greater for the heavy mass than the light mass condition ($P = 0.002$).

Figure 8. Comparison of RMSE values of fitted Gaussian bell curves for grip force rate between the predictable and unpredictable mass conditions
The overall average of the RMSE of the goodness of fit of load force rates to fitted Gaussian bell curves in object lifts with predictable and unpredictable mass conditions (light and heavy). Higher RMSE values represent a worse fit to the fitted Gaussian bell curve.

Figure 9 shows representative data from two subjects who performed

object lifts in the unpredictable and predictable CM location conditions. Grip

force and load force rates were fit to a Gaussian bell curve. The force-rate

profiles switched from bell shaped to profiles with several large peaks when

subjects encountered an object with a CM location other than expected

(unpredictable condition). Additionally, the grip force and load force rates for the

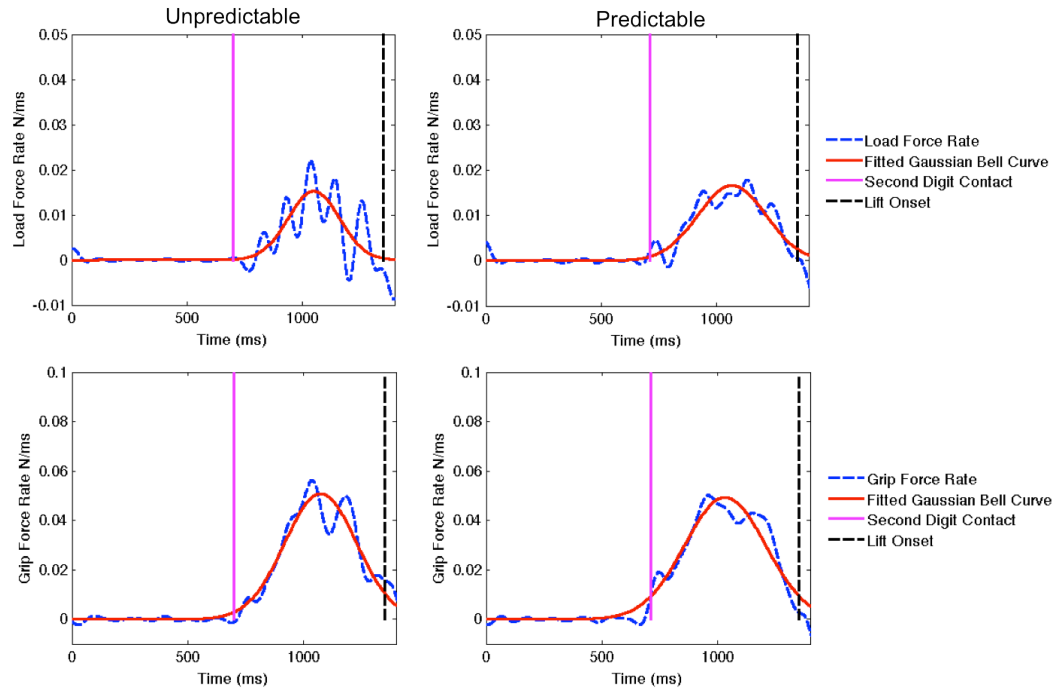predictable condition exhibited a bell shaped profile.

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Figure 9. Unpredictable vs. predictable change of CM location fit to Gaussian bell curves. In the first experiment, the validation stage CM location was changed unpredictably with unconstrained digit placement and compared to predictable CM location . Gaussian Bell Curves are fit to each of the different CM locations (Left, Right and Center). Data is representative of two subjects for Left CM in order to visualize the difference. The first vertical line (—) represents the point in time when the second digit (either thumb or index finger) made contact with the object. The second vertical line (- - -) represents the point in time when lift onset occurred. Note that the fitted Gaussian bell curve is a good estimator of the shape of the rate of grip and load forces of predictable unconstrained digit placement.

It can be seen in Figure 10 that the fitted Gaussian bell curve to the grip force rate of the thumb and load force rates of the thumb and index finger had a significantly worse fit when CM location was unpredictable vs. predictable ($P <$ 0.001). Grip force rate for the index finger did not differ between the unpredictable and predictable CM location conditions ($P = 0.177$).
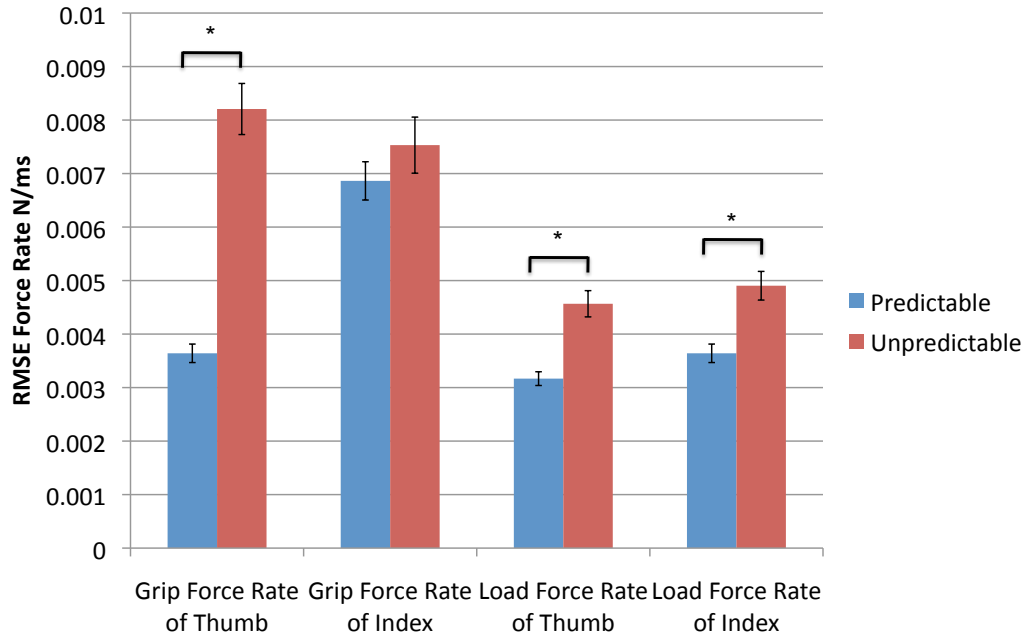
Figure 10. Comparison of RMSE Values of Fitted Gaussian Bell Curves for Grip and Load Force Rates of Predictable vs. Unpredictable CM Location.
The overall average of the RMSE of the goodness of fit of different force rates to fitted Gaussian bell curves in object lifts with unpredictable and predictable CM location conditions. Higher RMSE values represent a worse fit, greater error to the fitted Gaussian bell curve.

For Experiment 2, constrained vs. unconstrained digit placement was compared. Figure 11 shows typical grip force and load force data in the unconstrained and constrained digit position conditions for both the thumb and index fingers of two subjects. Gaussian bell curves were fit to the time between second digit contact with the object and lift onset, denoted by vertical lines in the figure. Rates of grip force and load force were both fit to Gaussian bell curves. It should be noted that there is a distinguishable difference in the amplitude and duration of the bell shaped profile and Gaussian bell curve between the constrained and unconstrained conditions.
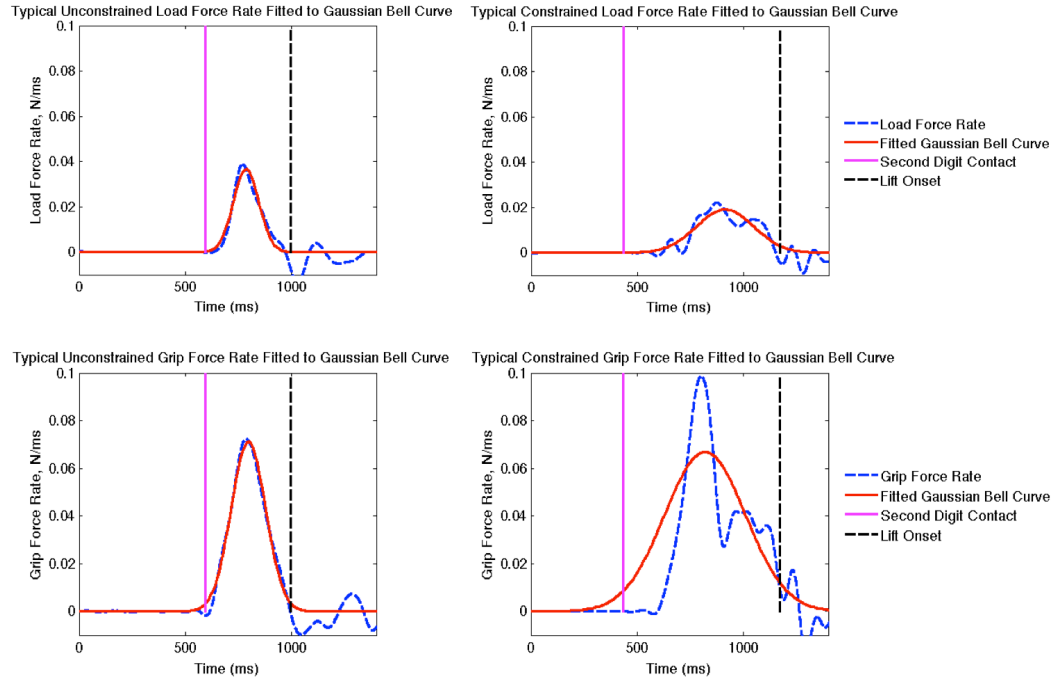
Figure 11. **Typical grip force and load force rates are shown with fitted Gaussian bell curves for both the constrained and unconstrained conditions.**
Data is representative of two subjects in the second experiment, the testing state, with predictable CM location. The first vertical line (—) represents the point in time when the second digit (either thumb or index finger) made contact to the object. The second vertical line (- - -) represents the point in time when lift onset occurred. Note the distinguishable difference in the amplitude and duration of the bell shaped profile between unconstrained and constrained digit placement conditions.

Figure 12 shows the goodness of fit of the Gaussian bell curve to the grip

force rate of the thumb. The RMSE values for the constrained digit placement

condition were significantly greater than the RMSE values for the unconstrained

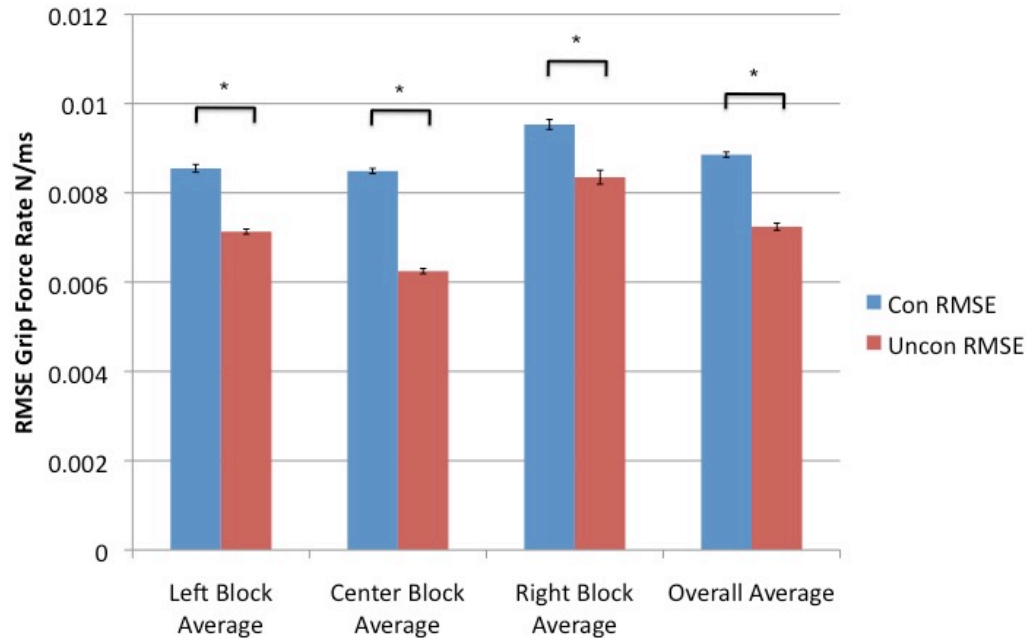digit placement condition across all CM locations ($P < 0.001$).

Figure 12. Comparison of RMSE Values for Fitted Gaussian Bell Curves to Grip Force Rate of the Thumb Between Unconstrained and Constrained Digit Placement Conditions.
The RMSE of the goodness of fit of the Gaussian bell curves to the grip force rate of the thumb was used in order to compare the constrained and unconstrained digit placement condition. The overall average of all trials, as well as the averages of trials with left, right and center CM locations showed that constrained digit placement locations had significantly greater error than the unconstrained.

Similarly, the RMSE values were greater on average for the grip force rate of the index finger in the constrained digit placement condition than the unconstrained digit placement condition (Figure 13; $P < 0.001$). Additionally, it was found that the constrained digit placement condition had significantly greater RMSE values than unconstrained digit conditions for both the left ($P = 0.003$) and right ($P < 0.001$) CM locations. However, the constrained digit placement condition did not exhibit a significant difference from unconstrained digit placement for the center CM condition ($P = 0.279$; modified Bonferroni correction).
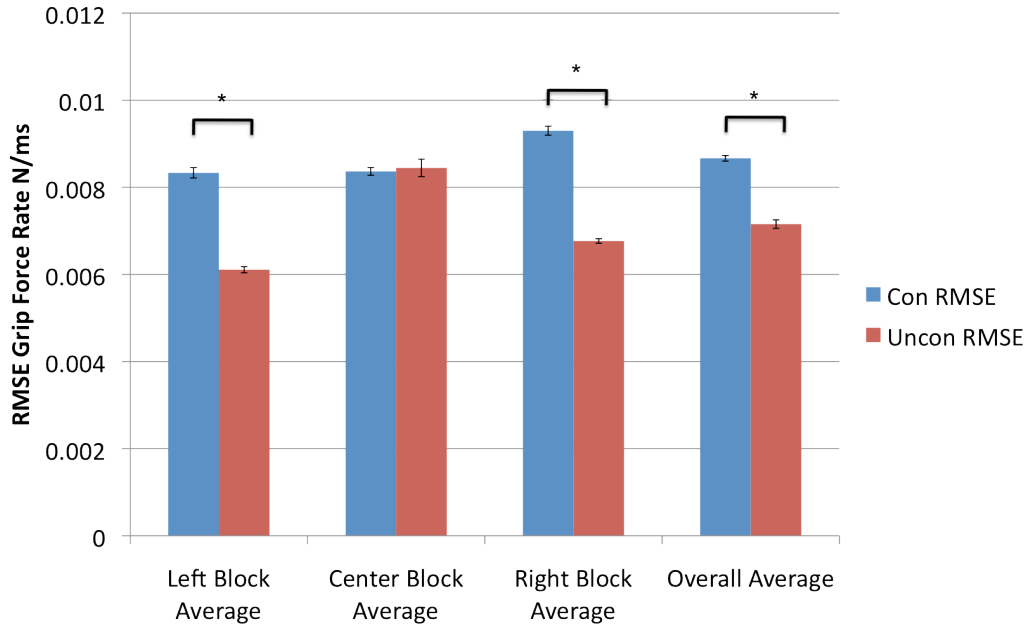
Figure 13. Comparison of RMSE Values for Fitted Gaussian Bell Curves to Grip Force Rate of the Index Finger Between Unconstrained and Constrained Digit Placement Conditions. The RMSE of the goodness of fit of the Gaussian bell curves to the grip force rate of the index finger was used in order to compare the constrained and unconstrained digit placement condition. The overall average of all trials, as well as the averages of trials with left, right CM locations showed that constrained digit placement locations had significantly greater error than the unconstrained. The average of Center CM locations was not found to have a significant difference.

Similar to the findings for grip force rate, the RMSE values representing the error between the load force rates for the thumb and the Gaussian bell curve were greater on average for the constrained versus unconstrained condition (Figure 14; $P \leq 0.008$) and there was no interaction between mass locations and constrained versus unconstrained condition ($P = 0.1331$).
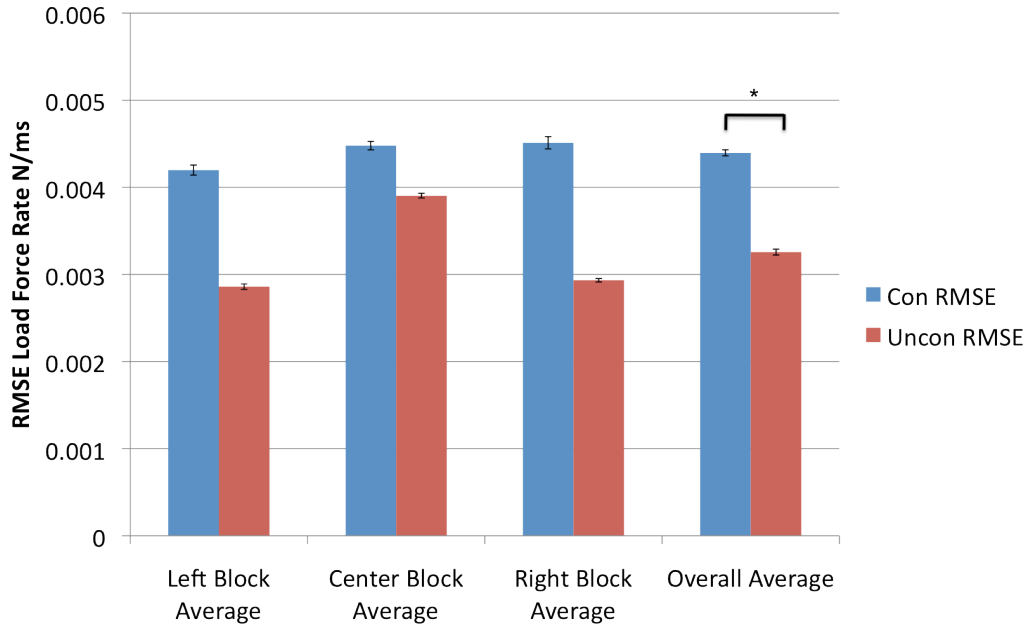
Figure 14. Comparison of RMSE Values for Fitted Gaussian Bell Curves to Load Force Rate of the Thumb Between Unconstrained and Constrained Digit Placement Conditions.
The RMSE of the goodness of fit of the Gaussian bell curves to the load force rate of the thumbs was used in order to compare the constrained and unconstrained digit placement condition. The overall average of all trials, as well as the averages of trials with left, right and center CM locations showed that constrained digit placement locations had significantly greater error than the unconstrained.

However, the RMSE values for the index finger load-force rate profiles were greater for the constrained than unconstrained conditions when CM locations was shifted towards the right or left (Figure 15; $P < 0.001$), but RMSE values did not differ significantly between constrained and unconstrained digit placement condition when CM locations was in the center ($P = 0.808$; modified Bonferroni correction).
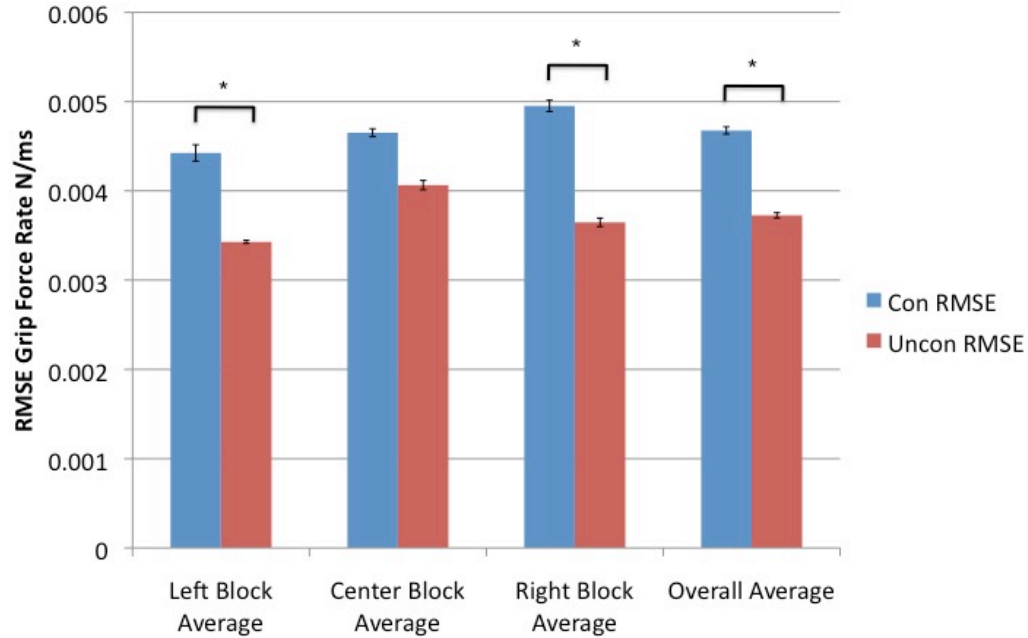
Figure 15. Comparison of RMSE Values for Fitted Gaussian Bell Curves to Load Force Rate of the Index Finger Between Unconstrained and Constrained Digit Placement Conditions. The RMSE of the goodness of fit of the Gaussian bell curves to the load force rate of the index finger was used in order to compare the constrained and unconstrained digit placement condition. The overall average of all trials, as well as the averages of trials with left, right CM locations showed that constrained digit placement locations had significantly greater error than the unconstrained. The average of Center CM locations was not found to have a significant difference.

Based on the findings from the Gaussian fit approach (Figures 9-12), it appears that the constrained digit placement condition had significantly worse fit (greater RMSE) then the unconstrained digit placement condition.

Temporal Landmark Approach

Temporal landmarks were used in order to determine another way of finding a statistically significant, quantifiable difference between the constrained and unconstrained digit placement conditions. These results would then be used to confirm findings from the Gaussian fit approach or perhaps reveal a different understanding of our findings from the Gaussian fit approach. Figures 16-17 present different temporal landmarks that were calculated in order to find the

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statistically significant, quantifiable differences between the constrained and unconstrained digit placement conditions.

Similar to the findings in the Gaussian fit approach, the time differences calculated from the contact of the second finger to the object to the time when load force onset of the object were greater in the constrained than unconstrained conditions (Figure 16; $P < 0.0261$). This difference was similar for each CM condition as indicated by the lack of interaction between the constrained and unconstrained conditions and object CM location ($P = 0.972$).
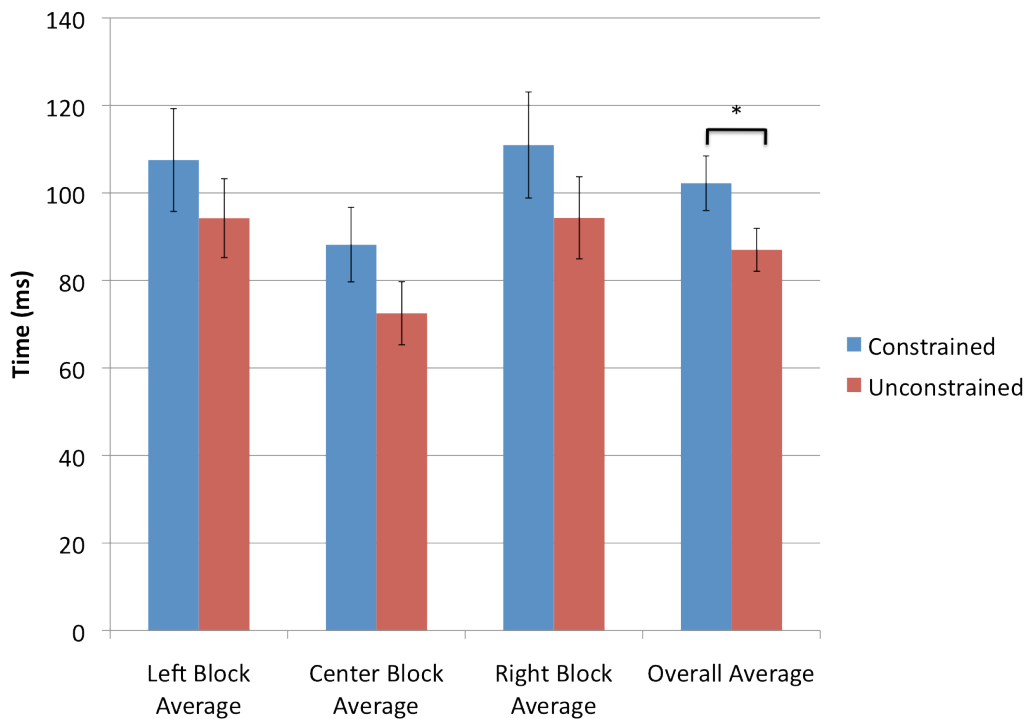
Figure 16. Time Calculated from Touch to Load Force Onset.
The time difference calculated from the second digit touch to load force onset averages are shown. Overall averages and standard errors of all subjects are calculated for constrained and unconstrained digit positions. It was found that the constrained digit placement condition exhibited a statistically significant longer time to get from touch to load force onset then did the unconstrained finger digit placement condition.

Figure 17 shows the time difference between the absolute value of the grip force onset of the thumb and index finger. Also similar to the Gaussian Fit

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approach, it was found that the time difference was significantly greater on average for the constrained versus the unconstrained condition (Figure 17; $P<0.001$) and there was no interaction between mass locations and constrained versus unconstrained condition ($P = .095$).
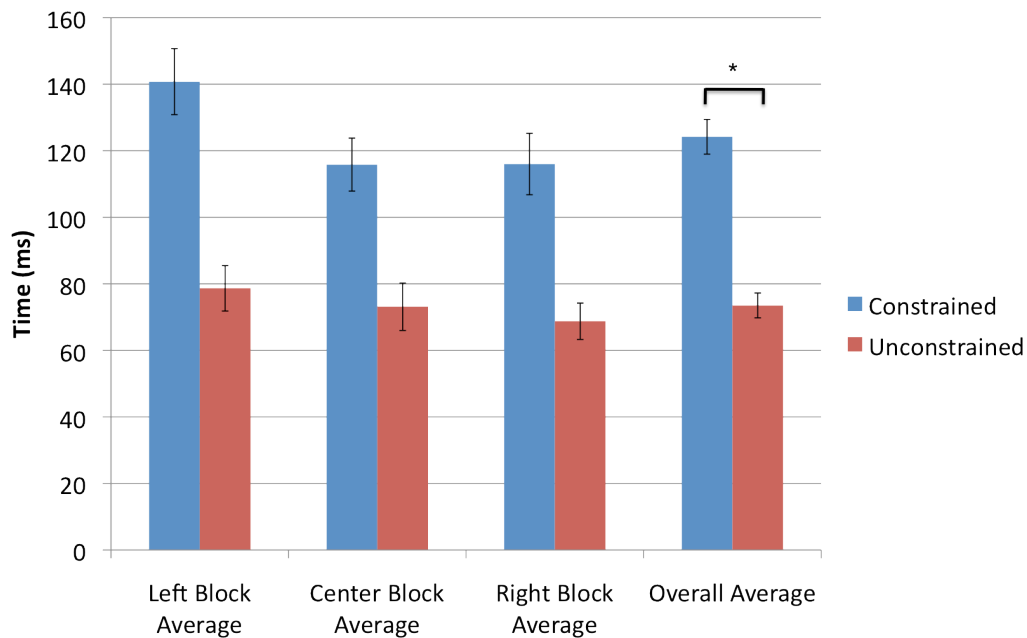
Figure 17. Time Difference between the Absolute Value of the Grip Force Onset of the Thumb and Index Finger.
The time difference between the absolute value of the grip force onset of the thumb and index finger is shown. Overall averages and standard deviations of all subjects are calculated for constrained and unconstrained digit positions. It was found that the constrained digit placement condition exhibited a statistically significant longer time to get from touch to load force onset then did the unconstrained finger digit placement condition.

The remaining temporal variables had a p-value of greater than 0.05 for unconstrained versus constrained (between-group factors) and a p-value of greater then 0.025 for comparisons of constrained versus unconstrained CM (within subject factor; left, center, and right) using the modified Bonferroni correction. The temporal variables found to be significant, the time from second digit contact to load force onset (Figure 16) and the time difference between the absolute value

of the grip force onset of the thumb and index finger (Figure 17) confirm the

findings from the Gaussian Fit approach.

DISCUSSION

The purposes of this thesis were (1) to validate the hypothesis that force rate profiles are indicative of the control strategy used for object manipulation in tasks which do not constrain digit placement and (2) to test this hypothesis in manipulation tasks performed with and without digit placement constraints. It was hypothesized that force-rate profiles well fit by a Gaussian bell curve would indicate the use of a feedforward grasp control strategy, whereas those profiles with troughs, peaks and a poor fit to the bell curve would indicate the use of feedback grasp control. To validate these hypothesis two studies were performed. In the first study the mass of the object altered between light and heavy masses. In the second study object center of mass (CM) location was altered, with constant mass being altered with unconstrained digit placement. Digit force rates were fit to a Gaussian bell curve and the goodness of fit was compared between predictable and unpredictable mass and CM conditions. For both experiments, predictable object mass and CM elicited bell shaped force rate profile, indicative of feedforward control.

Consistent with the results of Johansson et al. (1984, 1988a) the force-rate profiles switched from bell shaped to profiles with several large peaks and troughs when subjects encountered a mass other than expected (Figures 6-8) as well as a CM location other than expected (9-10). In agreement with previous data reported by Johansson et al. (1984, 1988a) for constrained digit placement conditions, grip force and load force rates in the unconstrained digit placement conditions exhibited a bell shaped profile when mass was predictable, indicative

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of anticipatory planning (Figure 6-10). Lack of significance in some force rates may be due to the small number of subjects used, however, results from Experiment 1 validated Johansson's data with constrained digit placement, allowing testing between constrained and unconstrained digit placement to occur in Experiment 2.

The testing stage of this work, Experiment 2, sought to investigate how the force rate profiles and temporal measures in the constrained digit placement condition may differ from those in the unconstrained digit placement condition. It was hypothesized that force rate profiles in the constrained digit placement condition would exhibit a profile more closely matched to a Gaussian bell shaped profile than those observed in the unconstrained digit placement task (Johansson et al. 1984, 1988a, Fu et al. 2010).

When subjects lifted the object in the predictable conditions it is likely that minimal updating of the motor plan was needed especially, in trials 4-10 after subjects learned to successfully manipulate the object. Thus, we presumed that these trials were largely driven by feedforward motor processes (Johansson et al., 1984, 1988a, Fu et al. 2010). A notable feature of the lifts performed in the predictable condition for both the constrained and unconstrained groups were that the force rate profiles between the time of digit contact and lift onset were well fit by a Gaussian bell curve. This finding is in accordance and appears to validate the assertion that force rate profiles that have a Gaussian bell shape may be indicative of feedforward processes (Johannson et al. 1984, 1988a). However, a significant difference in the fit of the Gaussian bell curve (amount of error

exhibited) between the constrained and unconstrained digit placement conditions was observed in Experiment 2, the testing stage (Figures 12-15). The difference in RMSE between the constrained and unconstrained groups may be a result of greater difficulty in positioning fingers on a relatively small surface area. Furthermore, in the left and right CM conditions when digit location was unconstrained subjects modulated digit position along with digit load forces to create a compensatory torque about the object (Fu et al. 2010; Zhang et al. 2010). The ability to partition digit location was removed in the constrained task, therefore, as shown previously subjects seemed to exert larger grip and load forces to prevent the roll of the object (Fu et al. 2010). These differences between conditions may contribute to the differences in the goodness of fit of force rate profiles to a Gaussian bell curve (Fu et al. 2010).

In order to compensate for moment that is generated by the object's asymmetric mass distribution, subjects can alter the grip force, load force or position of the digits on the object. Force rate profiles when mass or CM location is unpredictable show several peaks and troughs rather than a Gaussian bell shaped profile, which are a result of a mismatch of the expected grip force, load force and position of the digits on the object in relation to the actual feedback of the digit placement of the current task. Therefore, the results of this thesis are in accordance with previous work, which indicates that after every manipulation task, subjects utilize sensorimotor memories from previous objects lifts to anticipate the appropriate force distribution on a trial-to-trial basis (Fu et al. 2010). The difference between constrained and unconstrained digit placement is

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that subjects are unable to alter the position of the digits which suggests that larger tangential forces are necessary in tasks of asymmetrical mass distribution with constrained digit placement. This suggests that object lifts with constrained digit placement are more difficult to perform due to the accuracy requirements and lack of ability to modulate digit position than unconstrained digit placement (Fu et al. 2010).

Interestingly, the RMSE values of the fitted Gaussian bell curves to the grip force and load force rates of the index finger in the center CM location did not significantly differ between the constrained and unconstrained digit placement location conditions. A possible reason for this finding is that in both the constrained and unconstrained conditions digit placement is typically collinear (Fu et al. 2010; Zhang et al. 2010). A collinear digit alignment provides an efficient option for minimizing roll because grip forces can be minimized and load forces can be equal. Allowing subjects the choice of digit placement (unconstrained) enables them to explore a wider range of relations between digit forces and positions (Lukos et al. 2007). Perhaps, the digit position of the index finger may be more variable than the thumb during lifts with center CM. This may account for the lack of significant difference between center-constrained and center-unconstrained digit placement conditions in the index finger.

A temporal landmark approach was used to determine if other parameters (during the crucial time period between digit contact and the time of object lift) could be used to investigate the differences in control strategies (feedforward vs. feedback) between constrained and unconstrained digit placement conditions

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(Johansson et al. 1984, 1988a). Figure 2 illustrates crucial instances for grasp control in which comparisons can be made between sensory information and the motor plan and expected object properties to determine if updates need to be made to the motor plan. Temporal landmarks such as the time calculated from the touch of the second finger to the object to the time when load force onset occurred (Figure 16) and the time between the absolute value of the thumb grip force onset time and the index finger grip force onset time (Figure 17) showed that the constrained digit placement condition took on average significantly longer than the unconstrained digit placement condition (Figure 16). This may be because the constrained digit placement condition requires more accurate digit positioning than the unconstrained condition. This increase in position accuracy requirements for the constrained task may have caused subjects to rely more on sensory information to accurately position the fingers and resulted in the longer times in the temporal variables for the constrained condition. Furthermore, longer times may have been associated with the constrained digit location condition because subjects may have been more uncertain of digit position in the constrained versus unconstrained tasks.

These temporal landmarks may be an interesting area to look at in future work as it may suggest that feedforward control mechanisms may be developed during this time period. Furthermore, the use of temporal landmarks may help to validate the results from a Gaussian fit approach. The longer time observed for the temporal landmarks in the constrained condition seem to be further indication that the constrained digit condition is more difficult to perform than the

unconstrained digit placement condition. Other temporal landmarks that did not provide significant findings when comparing constrained versus unconstrained digit placement. All the variables related to the load period (after the subject initiates load onset) are not significantly different. After this time period, the control mechanism is the same for both group. Therefore, since constrained digit placement condition takes significantly longer to perform then the unconstrained digit placement (Figures 16-17) it confirms assumptions made by the Gaussian fit approach that that the differences in constrained and unconstrained conditions may have been due to task difficulty.

Results of this experiment uncovered that unconstrained and constrained digit placement both exhibited a bell shaped profile indicative of a feedforward signal. However, contrary to our initial hypothesis, unconstrained digit placement exhibited a better bell shaped profile then constrained digit placement. Findings from this study may lead to the improvement of computational models on how object manipulation is learned and controlled. Additionally, future experiments may investigate grasp control with unconstrained digit placement, as digit placement is unconstrained in daily activity.

In conclusion, this thesis was able to validate the conclusions of Johansson et al. (1984, 1988a) that the force-rate profiles can be indicative of the control strategy used for object manipulation in tasks that do and do not constrain digit locations. Furthermore, it was found that the conditions in which digit placement was unconstrained resulted in a greater reliance on feedforward planning than in the constrained digit placement conditions. Temporal landmarks were found to

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sometimes confirm the findings of the Gaussian fit approach. These findings

suggest that the constrained task may have an increased difficulty for subjects to

coordinate digit locations and forces compared to the unconstrained task.

Future Work

Future work will need to look at new ways to determine where an accurate

feedforward profile does occur in order to better understand the feedforward

mechanism. One way could be to perform an experiment in which subjects would

have non-collinear constrained digit placement conditions. In this scenario, the

CM locations would still be changed from left, center and right every 10 trials.

However, one set of subjects will be required to place the thumb higher than their

index finger and another set of subjects will be required to place the index finger

be higher than the thumb. These digit placement locations would resemble the

digit placement locations subjects typically choose for the unconstrained digit

placement conditions for left and right CM locations, respectively. This

experiment would test whether or not the results in this experiment were from the

difficulty of the task rather than constrained vs. unconstrained digit placement. If

goodness of fit data of the Gaussian bell curve to force rate profiles is similar for

non-collinear constrained digit placement conditions as was found for

unconstrained digit placement conditions shown in the testing stage of this thesis,

this would suggest that constrained digit placement is not more difficult to

perform then unconstrained digit placement conditions due to the difficulty of

positioning the fingers on a relatively small area. Rather the difference may be the

result of other task variables, such as the requirement to partition digit load forces

when the digits are placed collinear on an object with an asymmetrical mass distribution. This would be shown by a Gaussian bell shaped profile similar to what was found to the constrained digit placement condition in this thesis.

Additionally, analyzing the data when there is a lack of sensation of touch would help us better understand the mechanism of feedforward signaling. Without tactile feedback subjects will not have an option but to use feedforward control. This will help enlighten the understanding of anticipatory control by learning if the feedforward controller is updated on a trial-to-trial basis. In this experiment subjects can be given anesthetic in the thumb and index finger causing a lack of feeling of touch when trying to grasp and lift the inverted T-shape object. When there is a lack of touch it is hypothesized that the feedback signal will also be uncharacteristic of the typical bell shaped profile. If experimental results provide data that is uncharacteristic of a bell shaped profile when looking at the grip and load force rates, it would allow for a better understanding of the anticipatory control. This task would provide information on whether or not tactile feedback is used for anticipatory control.

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