The Role of Tactile Information in Transfer of Learned Manipulation Following Changes in Degrees of Freedom

by

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ABSTRACT

Humans are capable of transferring learning for anticipatory control of dexterous object manipulation despite changes in degrees-of-freedom (DoF), i.e., switching from lifting an object with two fingers to lifting the same object with three fingers (Fu et al. 2011). However, the role that tactile information plays in this transfer of learning is unknown. In this study, subjects lifted an L-shaped object with two fingers (2-DoF), and then lifted the object with three fingers (3-DoF). The subjects were divided into two groups—one group performed the task wearing a glove (to reduce tactile sensibility) upon the switch to 3-DoF (glove group), while the other group did not wear the glove (control group). Compensatory moment (torque) was used as a measure to determine how well the subject could minimize the tilt of the object following the switch from 2-DoF to 3-DoF. Upon the switch to 3-DoF, subjects wearing the glove generated a compensatory moment (M_{com}) that had a significantly higher error than the average of the last five trials at the end of the 3-DoF block ($p = 0.012$), while the control subjects did not demonstrate a significant difference in M_{com}. Additional effects of the reduction in tactile sensibility were: (1) the grip force for the group of subjects wearing the glove was significantly higher in the 3-DoF trials compared to the 2-DoF trials ($p = 0.014$), while the grip force of the control subjects was not significantly different; (2) the difference in centers of pressure between the thumb and fingers (ΔCoP) significantly increased in the 3-DoF block for the group of subjects wearing the glove, while the ΔCoP of the control subjects was not significantly different; (3) lastly, the control subjects demonstrated a greater increase in lift force than the group of subjects wearing the glove (though results were not significant). Combined together, these results suggest different force modulation strategies are used depending on the amount of tactile feedback that is available to the subject. Therefore, reduction of tactile sensibility has important effects on subjects' ability to transfer learned manipulation across different DoF contexts.

I dedicate this Master’s Thesis
to my mother and father who
have supported me tooth and nail
in all of my academic endeavors.
Thank you for bearing with me!

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TABLE OF CONTENTS

Page

CHAPTER

Page

APPENDIX

LIST OF TABLES

Table Page

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

Investigations involving the neural mechanisms underlying dexterous manipulation have become an area of significant focus in recent years. These studies have been conducted to understand how the brain controls the neuromuscular system with the goal of creating a comprehensive model for use with robotics and neuroprosthetics.

One method that has been used to ascertain knowledge of the human neuromuscular system is having subjects learn to lift an object with an asymmetric mass distribution while preventing the object from tilting. This task requires subjects to apply a compensatory moment (torque) to the object because of its asymmetric mass distribution. This compensatory moment is necessary in order to lift the object in a straight and controlled manner (Salimi et al., 2000, 2003; Lukos et al., 2007, 2008). Thus subjects learn to modulate their digit forces and positions as they attempt to apply the correct compensatory moment (Fu et al., 2010).

More recently, Fu and colleagues performed a study in which they had subjects switch the amount of fingers that they used to lift an object with an asymmetrical mass distribution (see **Figure 1**; Fu et al., 2011). Subjects lifted the object by a handle using two (or three) fingers, then immediately repeated the task using three (or two) fingers. The compensatory moment was measured to determine if subjects were capable of transferring the learned compensatory moment between different combinations of fingers (degrees of freedom, DoF) to manipulate the object. It was found that the subjects were able to transfer the learned manipulation following a change in DoF (Fu et al., 2011). However, the underlying mechanisms remain to be determined. In particular, it is not known the extent to which subjects might use sensory feedback to modulate digit forces to a different contact distribution.

Figure 1: Experimental Apparatus (Fu et al. 2011)

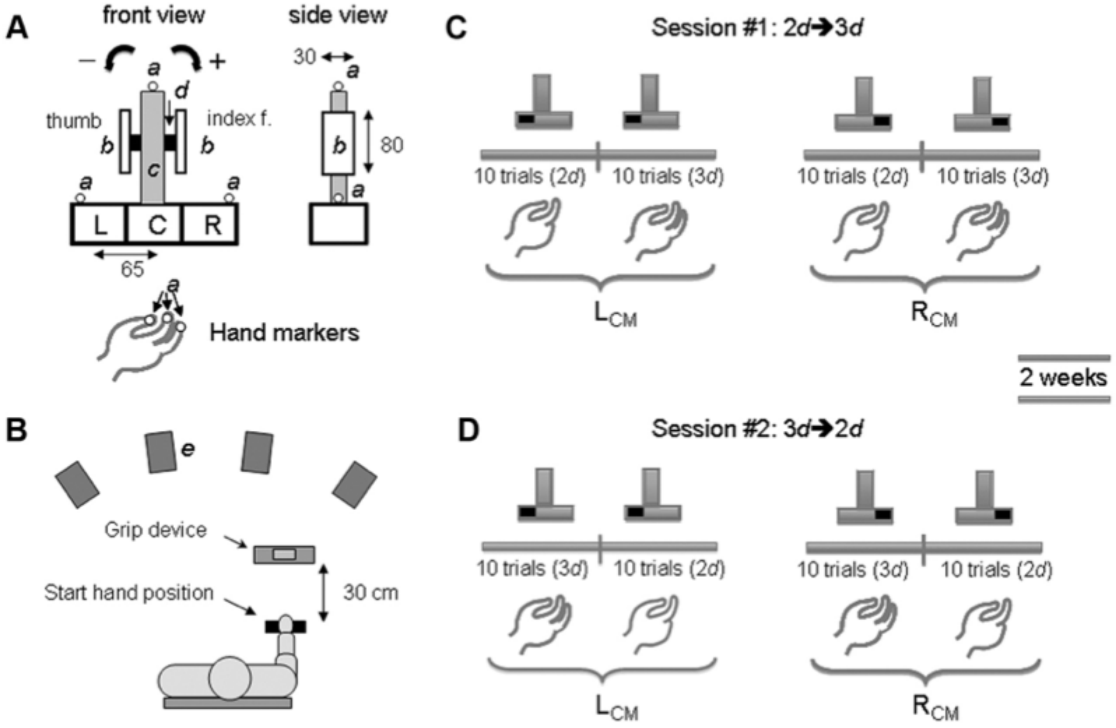


Figure 1 (Fu et al., 2011): A, "Front and side views of the grip device used to measure forces and centers of pressure on the grasp surfaces for the thumb and finger sides (units in millimeters). Object position and orientation were tracked through a motion capture system and active markers (denoted as small spheres, a) were placed on the top and on the extremities in the bottom box of the grip device. Active markers were also placed on the nails of the thumb, index, and middle fingers. A mass (400 g) was inserted in either the left (L) or right (R) compartment in the bottom box of the device to change the center of mass of the object (L_{CM} and R_{CM} conditions, respectively). The convention for defining the direction of object roll (negative and positive toward the thumb or finger side, respectively) is also shown. The configuration of the grip device consisted of a central block (c) and two bars (grip surfaces, b), each mounted on a force/torque sensor (d). **B**, top view of the experimental procedures. Subjects reached to the grip device located at 30 cm from the start position. Infrared cameras (e) were placed around the workspace to track hand and object kinematics. **C**,**D**, Trial sequences associated with switching from two to three digits (2d→3d) and vice versa (3d→2d), respectively. Subjects were tested on experimental session 2, 2 weeks after experimental session 1. All subjects started each experimental session with the L_{CM} using each grip type, followed by an equal number of trials with a different grip type and the R_{CM}."

Dexterous object manipulation tasks consist of different action phases that are separated by contact events (Johansson and Flanagan 2009). Before the subject reaches to lift the object, he can only make visually-based estimations about its mass or mass distribution. However, as the subject reaches for the object, planning mechanisms can be used to predict sensory consequences (i.e., fingertip trajectory) and make corrections if expected and actual movements do not coincide. Once the subject contacts the object for the first time, visual and sensory feedback also play an influence in how the subject modulates his finger forces and positions in the subsequent trials (Fu et al. 2010). Each action-phase controller generates appropriate motor commands and predicts sensory events. As a result, the brain is able to monitor task progression and produces corrective action if a mismatch is detected (Johansson and Flanagan 2009). **Figure 2** illustrates this mechanism.

Figure 2: Dexterous Object Manipulation Action Phase Diagram

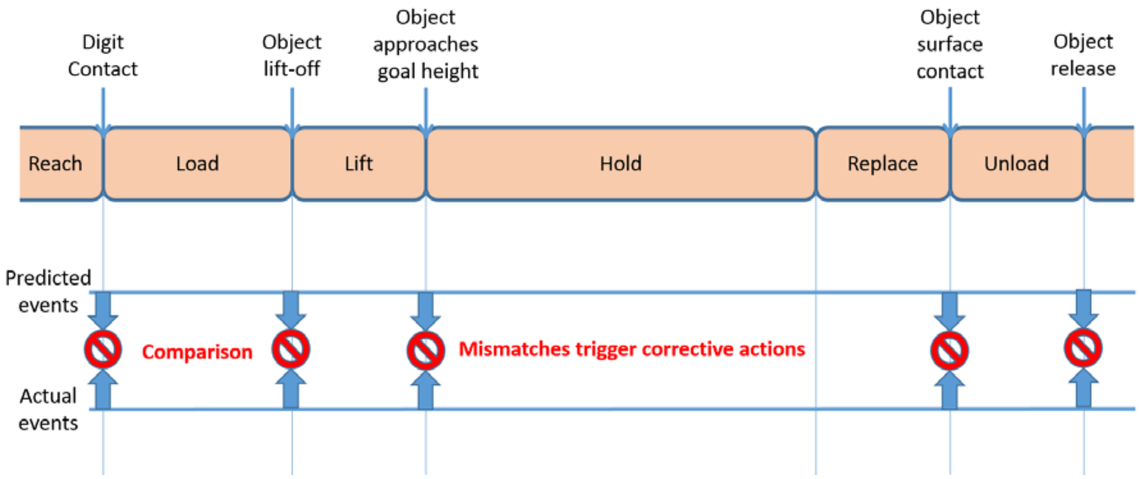


Figure 2: Flow diagram describes the action phases that occur during dexterous object manipulation. Initially, the subject uses only visual estimation and planning to modulate finger forces and positions. Once the subject contacts the object for the first time, visual and sensory feedback also play an influence in how the subject modulates his finger forces and positions in the subsequent trials (Johansson and Flanagan 2009).

Motor equivalence is defined as the ability to perform the same behavioral task using different effectors, i.e., fingers (Lashley 1930; Fu et al. 2011). This occurrence was documented in early neuromotor control studies (Lashley 1930; Bernstein 1967), but has not been a frequent topic of study until recent years (Fu et al. 2011; Ingram et al. 2010). The main question concerning motor equivalence concerned whether neural representations of motor actions rely on the effectors (fingers, limbs, etc.) used to perform a given task, or if the expression of these neural representations are independent of the effectors. The results from Fu and colleague’s study in 2011 provide evidence to suggest that neural representations of motor actions are independent of their corresponding effectors. So neural representations are likely effector independent, meaning that they rely on high-level neural representations.

The main question that was examined in this study is the extent that tactile information (one type of sensory feedback) plays a role in transfer of learning. Evidence is needed to determine if the availability of tactile information from the fingers has an effect on transfer of learned manipulation across different grasp types (i.e., with different DoFs). If a reduction in tactile sensitivity does have a significant effect on transfer of learning, this would provide evidence to suggest that feedback plays an important role in motor equivalence. It has been argued that motor control models that are solely based on planning (or feedback) mechanisms do not fully capture the process underlying sensorimotor control, but hybrid models combining both planning and feedback mechanisms are more representative of the actual process (Desmurget and Grafton 2000). It has also been shown that tactile signals are necessary for dexterous and skilled manipulation (Flanagan et al. 2006). Therefore, I hypothesized that sensory feedback would play an important role in motor equivalence and reducing it will have a negative effect on the transfer of learned manipulation.

CHAPTER 2

MATERIALS AND METHODS

Fourteen right-handed subjects volunteered for this study (control group—median age: 21, 3 females, 4 males; glove group—median age: 21, 4 females, 3 males). Subjects had no neurological or psychological issues or permanent damage to their hands due to a motor injury. All participants were naïve to the purpose of the experiment and consented to their participation in accordance with the Declaration of Helsinki. The Office of Research Integrity and Assurance at Arizona State University approved the protocols that were used. The subjects were divided into two groups: **glove** and **control**.

Subjects in the **glove group** lifted an L-shaped object for two blocks of fifteen trials each, separated by one hour. In the first block, subjects lifted with their thumb and index fingers (2 DoF). In the second block, subjects lifted with their thumb, middle, and index fingers (3 DoF). The reason for starting with two fingers in the first block and then switching to three fingers in the second block was to avoid the possibility of mechanical disadvantage that would result from a reduction in the degrees of freedom (going from three fingers to two fingers). A reduction in degrees of freedom would possibly cause another source of error that would skew the results. Between the blocks, the glove subjects put a glove on their hand in order to reduce their tactile feedback. The time-delay between the blocks was 1 hour. The purpose for the one-hour time delay was to mimic the amount of time it would take to administer anesthesia, another component of the experiment that will be explored in a future study.

Subjects in the **control group** performed the same task, but did not wear the glove for the second block (when the subject lifted with three fingers).

Apparatus

The object used in the experiment will be called the L object. It had a base made of white plastic (18.5 × 5 × 5 cm^3) and one vertical handle (6.5 × 8 × 3 cm^3) made of gray plastic at the left end of the long side of the base. The total mass of the object was 710 g. The handle was placed at the left end instead of the right end in order to maximize finger modulation (the ability of the subject to modulate his fingers across the contact plates). The handle was equipped with two hidden force-torque sensors (one for each of the contact plates). The torque required to successfully lift the object straight was approximately 320 N·mm in the counterclockwise direction. The six-axis torque sensors were ATI Nano-25 sensors obtained from ATI Industrial Automation. The force-torque sensors measured the forces and torques applied by the digits grasping the object, from which various force data can be derived (i.e., compensatory moment). The object is shown in **Figure 3** below.

Figure 3: The L Object

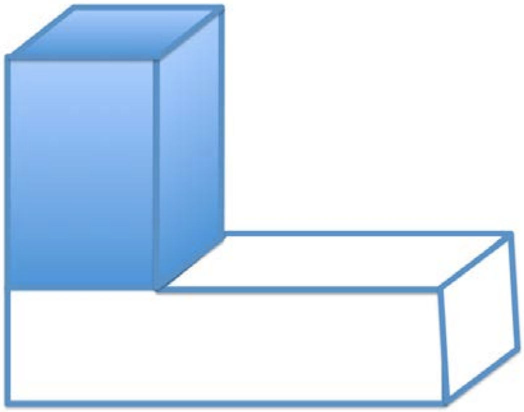


Figure 3: The L object used in this experiment. See the *Apparatus* section for details regarding the properties of this object.

Protocol

Subjects were instructed to lift the object as straight as possible and prevent the object from tilting as if trying to "stop water from spilling out of a cup." They could only use the index and middle fingers of the right hand on the right plate of the grasping handle, and the thumb of the right hand on the left plate of the grasping handle. They were instructed to lift the object approximately 5 cm from the table it was sitting on and hold it in the air for 2-3 seconds after hearing a verbal "Go!" signal. Subjects were seated so that their right shoulder was properly aligned with the object handle. The subjects were told that the handle was securely attached to the base and were allowed to briefly touch the handle to infer the texture. The task required the subject to generate an anticipatory moment to compensate for the torque caused by the object's asymmetric mass distribution. Subjects' ideal compensatory moment to lift the L object without tilt was 320 N·mm (in the counterclockwise direction). In the first block of 15 trials, the subject lifted the object using two fingers—the thumb for the left plate and the index for the right plate. In the second block, the subject lifted the object using three fingers—the thumb for the left plate, and the index and middle finger for the right plate. There was an hour break between each block. During the hour break, subjects did not perform any dexterous manipulation tasks with their hands to avoid possible interference with sensorimotor memory. Subjects in the glove group put a glove on their hand for the second block, while subjects in the control group did not put on the glove. The experimental protocol is summarized in **Figure 4**.

Figure 4: Experimental Protocol

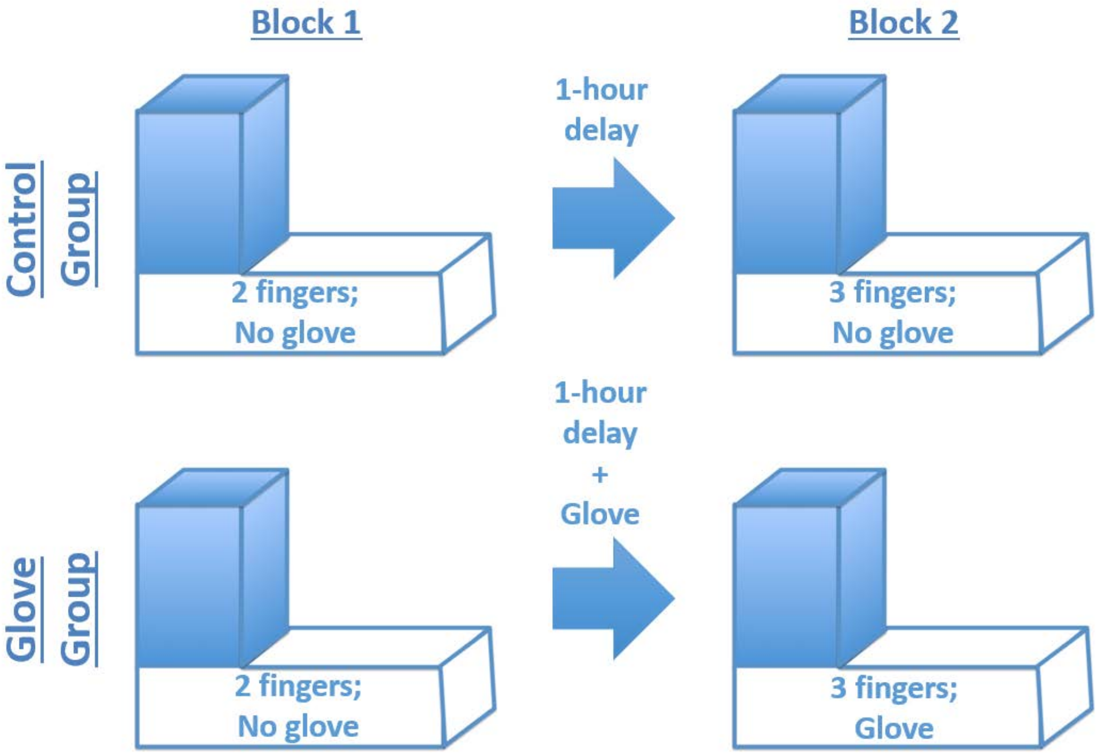


Figure 4: Summary of experimental protocol used for the control and glove (test) groups.

Quantification of Tactile Sensitivity

In order to determine the effect that the glove had on reducing subjects' tactile sensitivity, it was necessary to perform a test that quantifies the amount of tactile information available to the subjects with and without the glove.

Monofilament testing for peripheral nerve sensory function is a commonly used method in hand therapy (Bell-Krotoski and Tomancik 1987). Originally used to detect only light thresholds of touch recognition with horse hairs (Hunter et al. 1983), the method has evolved to include a greater range of filament forces by Semmes (Semmes et al. 1960) and Weinstein (Weinstein 1962) with the use of nylon filaments. The filaments do not provide specific measurable thresholds of force or stress; rather, they simply provide a mode of quantifying tactile sensitivity in the nerve endings of humans (Bell-Krotoski and Tomancik 1987).

Using a Semmes-Weinstein monofilament kit, each subject's tactile sensitivity with and without the glove was recorded (for both control and glove groups). A mini-kit of five filament sizes was used (diameters: 2.83, 3.61, 4.31, 4.56, 6.65). Using kits with a greater number of different diameters has been shown to have misleading results since the force of some filaments overlap with those of others (Bell-Krotoski and Tomancik 1987). Thus, not all the filaments are necessary (Levin et al. 1978).

A test was performed in which each subject was touched three times with a filament in the thumb, index, or middle finger. The trials were randomly dispersed within other trials in which no touch was made (to check for false-positives). The testing continued by increasing the diameter of the filament until subjects were capable of feeling at least two out of three of the touches made to each finger and did not feel more than two phantom touches (touches in which subjects claimed to feel pressure when none was applied, or touches in which subjects claimed to feel pressure in a finger that was not poked).

In the control group, five out of seven subjects felt the 2.83 monofilament, while two out of seven subjects felt the 3.61 monofilament.

In the glove group (without wearing the glove), five out of seven subjects felt the 2.83 monofilament, while two out of seven subjects felt the 3.61 monofilament. When the subjects wore the glove, three out of seven subjects felt the 4.56 monofilament while four out of seven subjects felt the 6.65 monofilament.

This test proves that the glove successfully reduced the subjects' tactile sensibility and provides a quantitative measure for the amount of tactile feedback that was removed.

Data Analysis

The compensatory moment (M_{com}) was used to quantify the subjects' ability to correctly manipulate the object. M_{com} is defined as the torque that the subject placed on the handle to lift the object straight in the air.

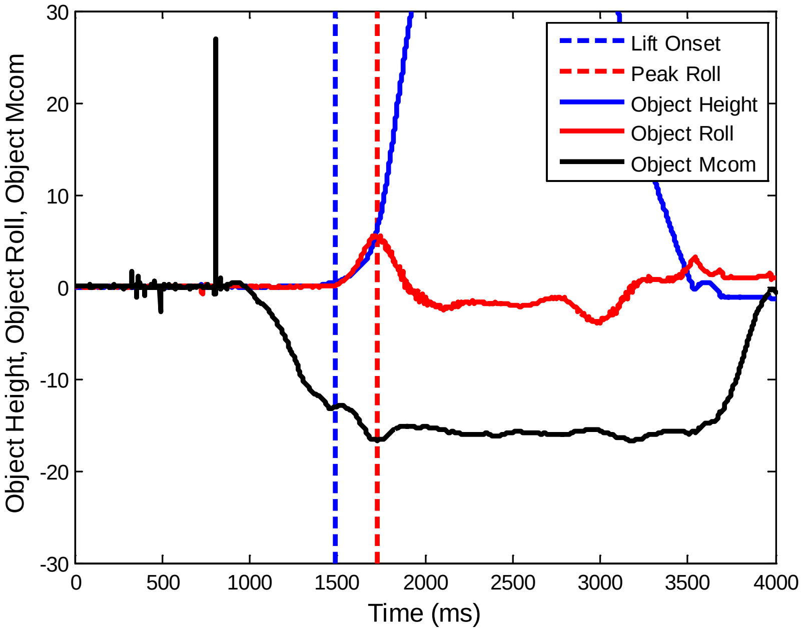
Specifically, $\mathbf{M_{com} = \Delta F_{tan} \times d/2 + F_n \times \Delta CoP}$, in which $\mathbf{\Delta F_{tan}}$ is the difference in tangential force exerted by the thumb and index finger on each side of the handle being grasped, **d** is the distance between the graspable surfaces (i.e., the moment arm of the tangential forces), $\mathbf{F_n}$ is the normal (grip) force applied perpendicularly to the grasp surfaces, and **ΔCoP** is the vertical distance between thumb and fingers center of pressure on each side of the handle (for block 1, the CoP on the fingers side is the CoP of the index; for block 2, the CoP on the fingers side is the aggregate CoP of the index and middle fingers). Previous studies have shown that recording the compensatory moment (M_{com}) required to lift an object straight in the air is correlated with learning object tilt minimization, hence learning of anticipatory dexterous manipulation (Fu et al. 2010, 2011). Therefore, compensatory moment (torque) is directly related to sensorimotor learning. The absolute value of the difference between the actual compensatory moment and the ideal compensatory moment (320 N•mm, counterclockwise) was calculated and analyzed. Transfer of M_{com} between blocks 1 and 2, along with grip force (F_n), ΔCoP, and difference in lift force (ΔF_{tan}) were analyzed using ANOVA (repeated measures, with trials as a within-subject factor) and the t-test.

From these analyses, the main goals were to: (1) determine if there are significant differences in transfer pre-switch and post-switch; (2) determine if there is significant learning in each block of trials by examining the compensatory moment; and (3) analyze differences in force modulation strategies between control and glove subjects. All tests were conducted at the $p \leq 0.05$ significance level.

Figure 5 shows data from a subject lifting the object without a glove (top graph), and a subject lifting the object with the glove (bottom graph). Note the more variable M_{com} in the graph of the subject lifting with the glove.

Figure 5: Graphical Output from MATLAB

(a)



(b)

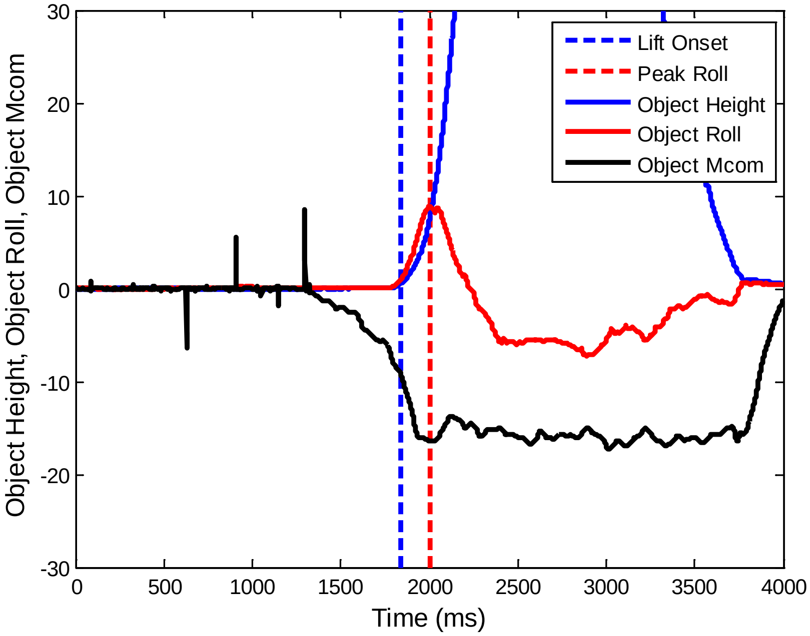


Figure 5: Two examples of graphical output from MATLAB used to help analyze the data. (a) represents a subject lifting the object without a glove, (b) represents a subject lifting the object with the glove.

CHAPTER 3

RESULTS

The results are described in four sections: (1) compensatory moment; (2) grip force; (3) adaptation of digit centers of pressure; and (4) adaptation of lift force. The main theme uniting these sections is the progression of the transfer of learning to the first trial in block 2 and the subsequent force adaptations through the end of block 2. The equation $\mathbf{M_{com} = \Delta F_{tan} \times d/2 + F_n \times \Delta CoP}$ will be used to analyze how these results relate to each other in the discussion section.

Compensatory Moment

Control group:

Figure 6 shows the compensatory moment that subjects (n = 7) placed on the object during both blocks. There was significant learning in the first block because the first three trials were different from each other (p = 0.050; F = 3.896). By the end of block 1, subjects were able to retain a steady compensatory moment for the last five trials (p = 0.924; F = 0.221). After the hour break, when the subjects transferred from 2-DoF to 3-DoF, there was no significant learning in the first three trials (p = 0.844; F = 0.172). In fact, the first trial in the second block was not significantly different from the average of the last five trials in the first block (p = 0.777; t = 0.296). However, there was a significant difference between the first trial in the first block and the average of the last five trials in the second block (p = 0.050; t = 2.450). In addition, the first trial in the second block was not significantly different from the average of the last five trials in the second block (p = 0.343; t = 1.030). These results indicate that a one-hour time delay between the switch did not interfere with retention of learned manipulation.

Figure 6: Compensatory Moment (Control Group)—Block 1 (without glove), Block 2 (without glove)

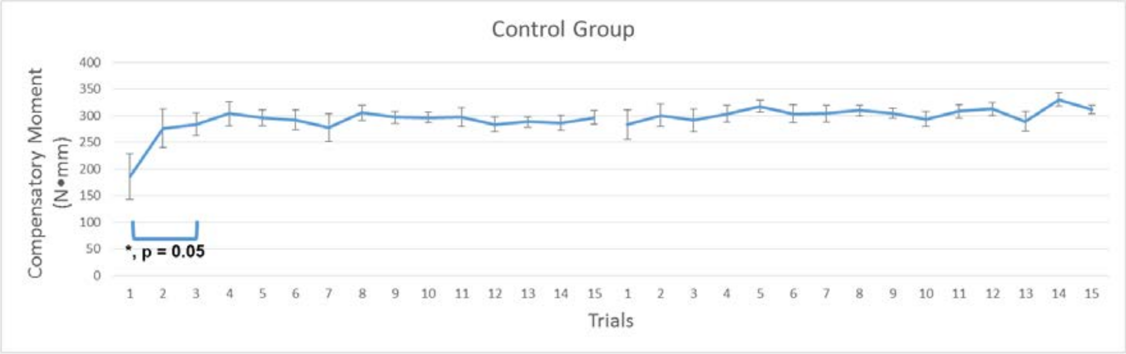


Figure 6: Learning curves for the control group. Block 1 (the first continuous line; when the subjects use 2-DoF) shows significant learning (p = 0.050), while block 2 (the second continuous line; when the subjects use 3-DoF) does not demonstrate significant learning (p = 0.844). The data are averages of all subjects (error bars represent ± 1SE). [* = $p \leq 0.05$]

Glove group:

In the glove group, subjects wore a thick glove and lifted the object in the second block after an hour break. **Figure 7** shows the compensatory moment that subjects (n=7) placed on the object during both blocks. There was significant learning in the first block because the first two trials were different from each other ($p = 0.044$; $F = 6.485$). By the end of block 1, subjects were able to retain a steady compensatory moment for the last five trials ($p = 0.257$; $F = 1.423$). After the hour break, when the subjects transferred from 2-DoF to 3-DoF, there was not significant learning in the first three trials ($p = 0.233$; $F = 1.651$). In fact, the first trial in the second block was not significantly different from the average of the last five trials in the first block ($p = 0.138$; $t = 1.712$). However, there was a significant difference between the first trial in the first block and the average of the last five trials in the second block ($p = 0.021$; $t = 3.108$). Importantly, the first trial in the second block was significantly different from the average of the last five trials in the second block ($p = 0.012$; $t = 3.560$). This significance suggests that reducing tactile sensitivity interfered with the subjects' manipulation strategies of the object, as indicated by the learning trend in the second block. To determine what is causing this interference, it is necessary to investigate the individual components that make up the M_{com}.

Figure 7: Compensatory Moment (Glove Group)—Block 1 (without glove), Block 2 (with glove)

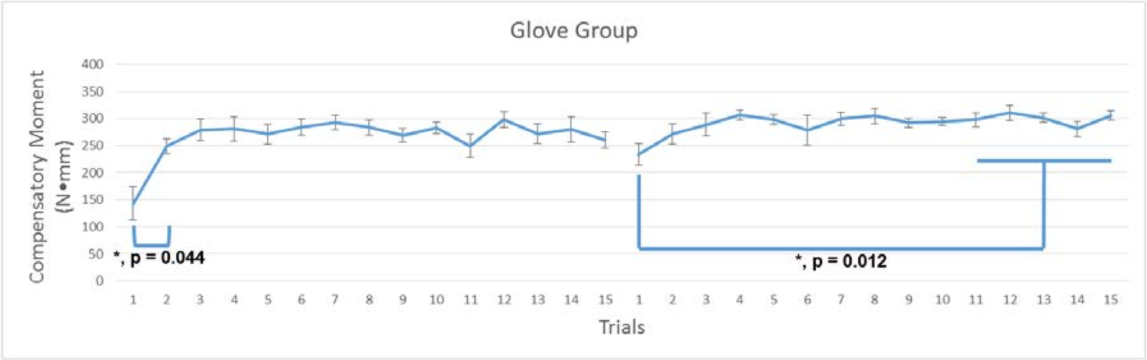


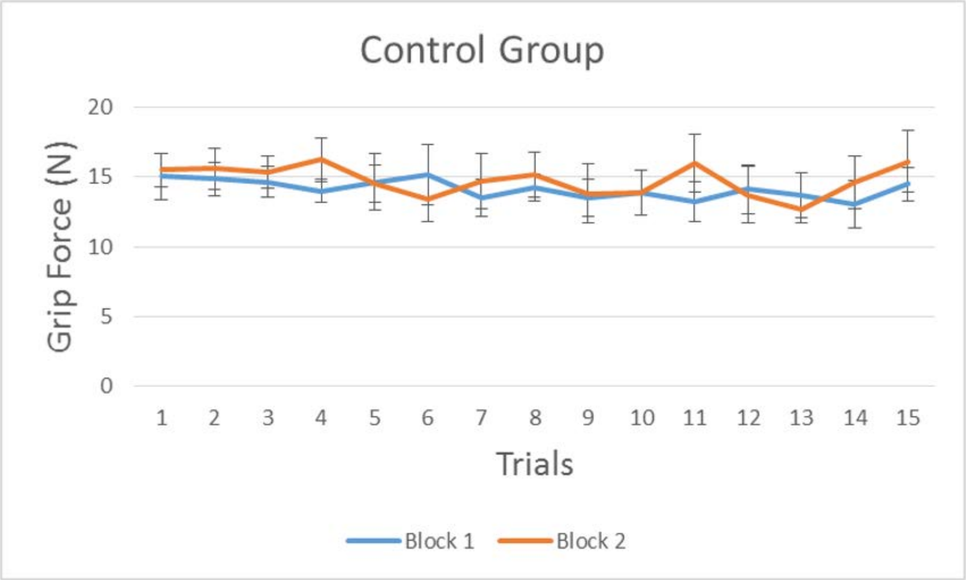
Figure 7: Learning curves for the glove pilot group. Block 1 (the first continuous line; when the subjects use 2-DoF) shows significant learning (p = 0.044), while block 2 (the second continuous line; when the subjects use 3-DoF + glove) does not demonstrate significant learning (p = 0.233)—note: the significance of the p-value comparing the first switch trial with the last five trials of the second block; this may indicate that there is some effect on manipulation strategies from loss of tactile information. The data are averages of all subjects (error bars represent ± 1 SE). [* = $p \leq 0.05$]

Grip Force

One component of the M_{com} that was analyzed was the grip force for each trial. Grip force was found to be stable across all trials in each block (control—*Block 1:* p = 0.928, F = 0.498, *Block 2:* p = 0.346, F = 1.129; glove—*Block 1:* p = 0.796, F = 0.671, *Block 2:* p = 0.330, F = 1.148). For the control group, grip force was not significantly different between the blocks (p = 0.689, t = 0.421). For the glove group, grip force was significantly different between the the blocks (p = 0.009, t = 3.845). **Figure 8** displays the grip force for each block. One can visually see a clear difference between block 1 and block 2 in the glove group. It seems that wearing the glove reduces tactile sensitivity, thus causing subjects to grip with more force.

Figure 8: Grip Force Comparison (Pre-Switch vs. Post-Switch)

(a)



(b)

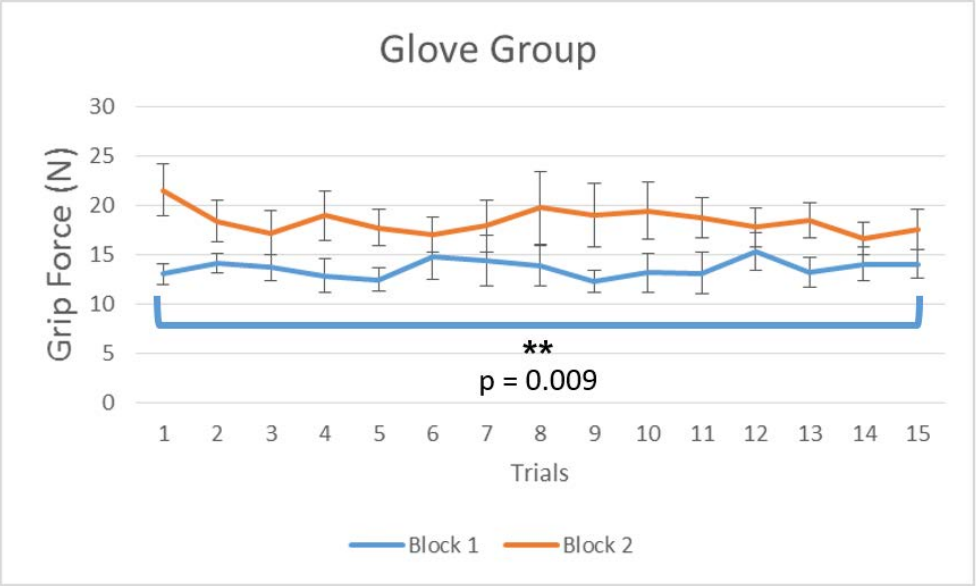


Figure 8: The grip force for each of the groups. The difference between grip force is not significant for the control group (p = 0.689), but significant for the glove group (p = 0.0009). [** = p ≤ 0.01]

Adaptation of Digit Centers of Pressure

The next component that will be examined is the difference in center of pressures between the fingers and the thumb (ΔCoP). In both the control and glove groups, subjects exhibited significantly (or nearly significant) different ΔCoP upon switching DoF-contexts (control: $p = 0.055$, $t = 2.383$; glove: $p = 0.022$, $t = 3.083$). Subjects decreased ΔCoP upon adding their middle finger to manipulate the object, as shown in **Figure 9**.

When examining how the ΔCoP changed in the second block, however, both groups demonstrated different trends. The control subjects slightly increased their ΔCoP values, but it was not significant ($p = 0.190$; $t = 1.477$). Conversely, the glove subjects significantly increased their ΔCoP values ($p = 0.028$; $t = 2.878$). This difference indicates that there was a different force modulation strategy that was used between the control and glove groups.

Figure 9: Difference in Finger Center of Pressures, Pre-Switch vs. 1st Trial After Switch

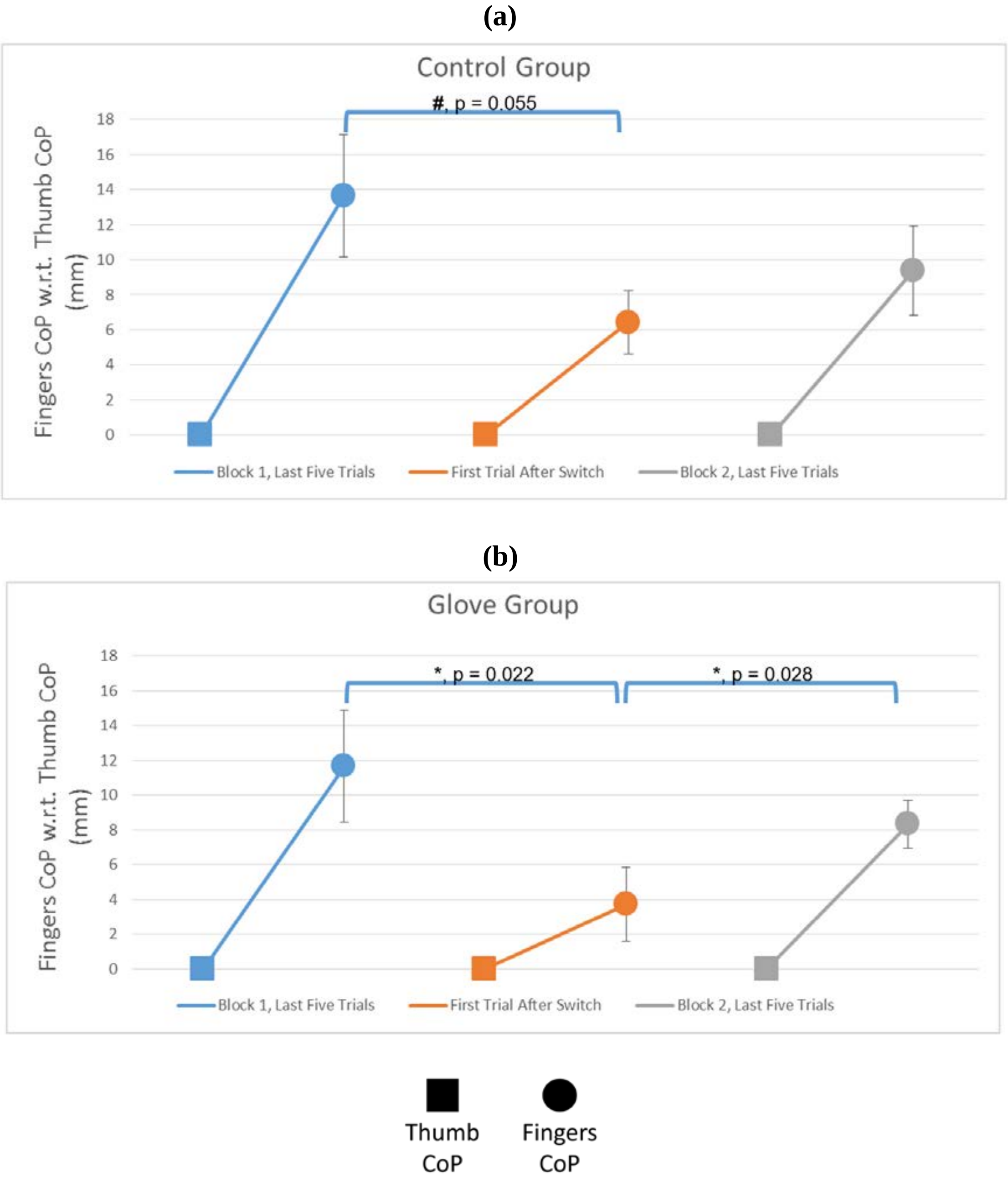


Figure 9: Difference in ΔCoP between the average of the last five trials in block 1 (2-DoF; pre-switch), the first trial in block 2 (3-DoF), and the average of the last five trials in block 2. The ΔCoP was significantly less (or nearly significantly less) in both groups (<u>Control</u>: $p = 0.055$, $t = 2.383$; <u>Glove</u>: $p = 0.022$, $t = 3.083$), indicating that there is an effect on digit force adaptation. The data are averages of all subjects (error bars represent ± 1 SE). [# = near significance; * = $p \leq 0.05$]

Lift Force Adaptation

Neither group showed a significant difference in ΔF_{tan} between the first trial after the switch and the last five trials of block 1 (control group: $p = 0.241$; glove group: $p = 0.368$). In addition, neither group showed a significant difference in ΔF_{tan} between the first trial after the switch and the last five trials of block 2 (control group: $p = 0.690$; glove group: $p = 0.836$). It is important to note, however, that the control group did exhibit greater increases in ΔF_{tan} than the glove group. This is important in explaining the differences in force modulation and positioning between the control and glove groups.

Table 1: Control and Glove Comparisons between the First Trial after Switch and the Last Five Trials of the Second Block

	Control	**Glove**
M_{com}	p = 0.343 t = 1.030	**p = 0.012*** t = 3.560
ΔCoP	p = 0.190 t = 1.477	**p = 0.028*** t = 2.878
Grip Force	p = 0.630 t = 0.508	**p = 0.022*** t = 3.073
ΔF_{tan}	p = 0.690 t = 0.418	p = 0.836 t = -0.217

Table 1: This table summarizes the results for the control and glove group comparisons between the average of the last five trials in block 2 and the first trial after the switch. *Significant p-values are bolded.

CHAPTER 4

DISCUSSION

From this data, it is clear that reducing tactile sensibility has an effect on reducing subjects' ability to transfer learning from one degrees-of-freedom (DoF) context to another. (1) In terms of compensatory moment, reduction of tactile sensitivity (via wearing a glove) appears to play a significant role in transfer of learning between DoF contexts and subsequent force modulations. However, the reduction in tactile sensitivity did not produce significant differences between the 'glove' and 'no glove' conditions in all of the statistical tests. Statistical significance might have been found across all tests if tactile feedback had been inhibited by more extreme means (i.e., via administration of local anesthetic to the digits). Analysis of the individual components of M_{com} supports this conclusion. (2) Upon transfer of manipulation, subjects in both groups produced significantly lower (or nearly significantly lower) ΔCoP values but the subjects in the glove group had a significantly higher ΔCoP by the end of the second block. This result is most likely due to different force strategies employed by the control and glove subjects. (3) Lastly, the grip force for the glove group was significantly higher when subjects manipulated the object while wearing the glove.

These results suggest that tactile feedback plays an important role in transferring manipulation between DoF contexts. Thus, the high-level neural representations learned in one DoF context must incorporate tactile feedback to some degree.

Availability of Tactile Information Affects Digit Force Modulation Strategies

Upon the switch to three degrees of freedom, the middle finger decreases the ΔCoP in both groups. This decrease in ΔCoP caused the normal component of M_{com} ($M_n = F_n \times \Delta CoP$) to decrease. Control subjects slightly increased F_{tan} forces in their index and middle digits to compensate for this discrepancy. In addition, the control subjects gradually increased their ΔCoP to further improve M_{com} and provide a stable transfer of learning.

People with reduced tactile sensitivity have been shown to have increased grip force (Monzée et al. 2003, Nowak et al. 2001). Thus, the glove subjects had increased grip force, which compensated for the decrease in ΔCoP. However, glove subjects did not properly adjust ΔF_{tan} to allow for stable transfer. Instead, they adjusted the ΔCoP to achieve a better M_{com}. These results indicate that the glove subjects had reduced capabilities of proper force and position modulation as a result of decreased tactile sensibility.

Grip Force

Previous studies have shown that lack of tactile feedback induced by anesthesia causes subjects to exert a greater grip force on the object during object manipulation (Macefield et al. 1996; Nowak et al. 2001; Augurelle et al. 2003; Monzée et al. 2003). The results from this study demonstrate similar findings because subjects exerted a greater grip force on the L object when wearing a glove.

Subjects may have placed a higher grip force on the object when tactile information was inhibited as a result of their need to sense more tactile information. Squeezing harder enables subjects to receive more adequate tactile feedback to perform better on later trials. In addition, subjects may have increased force to maintain an adequate safety margin (Nowak et al. 2001).

Subjects may have also increased grip force as a result of an increase in the slip force, which is the minimum grip force necessary to prevent slips between the fingers and the surface of the object (Nowak et al. 2001). Digital anesthesia reduces the hydration of a subject's skin because of the blockage of autonomic control of sweat glands; this results in a decrease in the friction between the skin and the object grasping surface (Nowak et al. 2001). Similarly, in this study, wearing the glove put a barrier between the fingers and the object that reduced moisture between the surface of the fingers and grasping surface. Also, the texture of the finger pads of the glove was smooth and silky, which has also been shown to increase slip force (Johansson and Westling 1984).

Overall, the increase in grip force is likely due to an added safety margin, and (to a smaller degree) decreased friction resulting in increased slip force (Nowak et al. 2001).

Wearing a glove or anesthetizing fingers does not completely eliminate feedback. Even when anesthetized, sensation from areas proximal to the hand can still be felt—such sensations include proprioceptive cues from skin stretch of the dorsal hand or Pacinian-like units in the palm (Cole and Abbs 1988; Johansson et al. 1992; Häger-Ross and Johansson 1996). Even though these areas can be felt, they cannot serve as a perfect substitute for the lack of tactile information in the digits. When afferent information can be accessed from all sources, the central nervous system (CNS) opts to tactile signals in the digits for object manipulation (Augurelle et al. 2003). When tactile feedback of the digits is taken away, the CNS may switch to alternative (though subordinate) sources for afferent information (Collins et al. 1999).

Neural Correlates

According to Fu et al. (2011), transferring manipulation from one DoF context to another (with the same hand) involves three neural processes: (1) generation of high-level representation (i.e., compensatory moment) from feedback sensed through arbitrary sensory elements (i.e., digits); (2) storage, update, and retrieval of the high-level representation; and (3) effective implementation of the high-level representation into arbitrary degrees of freedom.

The posterior parietal cortex (PPC) is thought to be involved in transformation of relative positions and forces in each of the digits of the hand to high-level neural representation of the net compensatory moment placed on the object (Jenmalm et al. 2006; Avillac et al. 2005).

Storage, update and retrieval of the compensatory moment are thought to be stored in the same cortical network involving secondary sensorimotor cortices (Rijntjes et al. 1999). Some areas of this network include the cerebellar hemispheres, anterior part of the ventral premotor and dorsal cortices, thalamus, middle & ventral intraparietal areas in the intraparietal sulcus, and the supplementary motor area (Rijntjes et al. 1999). Therefore, this network could be involved in storing and retrieving the compensatory moment independent of the limbs and digits used to implement the moment.

Lastly, the implementation of the compensatory moment occurs at the planning stage (and is further improved via somatosensory feedback; Fu et al. 2011). Before object contact, the anterior intraparietal sulcus and ventral premotor cortex are used to plan digit forces and positions (Davare et al. 2007; Olivier et al. 2007). After object contact, it is speculated that the same networks are used for force modulation and digit position sensing (Fu et al. 2010). More information about the neural representations involved in a task similar to the one in this study can be found in Fu et al. (2011).

CHAPTER 5

CONCLUSION

It is clear that reduction of tactile sensitivity has an influence on one's ability to transfer learned manipulation from one degree-of-freedom (DoF) context to another. Although inhibiting this tactile feedback did not significantly affect all areas of the compensatory moment production, it is clear that there was some effect on compensatory moment along with some of its components (e.g., grip force and ΔCoP). To further elucidate these findings, it would be necessary to perform a test in which anesthesia is used to block cutaneous feedback of the thumb, index, and middle digits of the finger. Although subjects may find other modes of tactile feedback, even with the anesthetized digits (Cole and Abbs 1988; Johansson et al. 1992; Häger-Ross and Johansson 1996), this would take away a more significant amount of feedback than the glove. Additionally, it would be interesting to determine the threshold of tactile feedback reduction that would produce a significant effect on the transfer of learning via a haptic display device (i.e., Phantom) in which object feedback can be monitored and adjusted.

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APPENDIX A

AUTHOR’S WRITTEN PERMISSION TO USE FIGURE 1

April 5, 2014

Dear Nathan Gaw,

I give you my permission to use Figure 1 from my paper titled Transfer of Learned Manipulation following Changes in Degrees of Freedom published in The Journal of Neuroscience (2011) in your Master's Thesis. If you have any additional questions, please let me know.

Sincerely,

Qiushi Fu
qiushifu@asu.edu

BIOGRAPHICAL SKETCH

In August 2010, Nathan chose to pursue biomedical engineering at Arizona State University (ASU). He was interested in learning how the human brain operates. To pursue that interested, he started to work in the Neural Control of Movement Laboratory (NCML) with Marco Santello in September 2010. While performing different experiments in NCML, Nathan became interested in neurorehabilitation and developed a glove that quantifies upper-limb stroke rehabilitation. Using a 6-DoF (degrees of freedom) inertial measurement unit (IMU), the glove was capable of detecting motion of the patient. Nathan plans to improve the glove so that it can provide data to determine the number/type of repetitions, average acceleration, and distance traveled during each rehabilitation session. Nathan also volunteered at the Spinal Biomechanics Laboratory at Barrow Neurological Institute starting in May 2012, and created a device that was used in an experiment that tested the stability of spinal rod combinations. In May 2013, Nathan graduated with his B.S.E. in biomedical engineering from Barrett, the Honors College. His Honor's Thesis examined the role of retention in context dependent sensorimotor memory of dexterous manipulation. As a Master's student, Nathan continued working on the stroke rehabilitation glove with his team and presented the project at the Society for Neuroscience's 2013 conference in San Diego, CA. During the summer after receiving his B.S.E., Nathan conducted research that involved data mining the Encyclopedia of DNA Elements (ENCODE) genetic database. From this research, he decided that he wanted to hone his skills in data mining and pursue a Ph.D. in industrial engineering at Arizona State University with Dr. Jing Li. Nathan wants to continue research in the medical field and work with Mayo Clinic for his doctoral research.