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Assessment of a hand exoskeleton on proximal and distal training in virtual environments for robot mediated upper extremity rehabilitation

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ABSTRACT

**ASSESSMENT OF A HAND EXOSKELETON ON PROXIMAL AND DISTAL
TRAINING IN VIRTUAL ENVIRONMENTS FOR ROBOT MEDIATED UPPER
EXTREMITY REHABILITATION**
by
Kevin Abbruzzese

Stroke is the leading cause of disability in the United States with approximately 800,000 cases per year. This cerebral vascular accident results in neurological impairments that reduce limb function and limit the daily independence of the individual. Evidence suggests that therapeutic interventions with repetitive motor training can aid in functional recovery of the paretic limb. Robotic rehabilitation may present an exercise intervention that can improve training and induce motor plasticity in individuals with stroke. An active (motorized) hand exoskeleton that provides support for wrist flexion/extension, abduction/adduction, pronation/supination, and finger pinch is integrated with a pre-existing 3-Degree of Freedom (DOF) haptic robot (Haptic Master, FCS Moog) to determine the efficacy of increased DOF during proximal and distal training in Upper Extremity (UE) rehabilitation. Subjects are randomly assigned into four groups to evaluate the significance of increased DOF during virtual training: Haptic Master control group (HM), Haptic Master with Gripper (HMG), Haptic Master with Wrist (HMW), and Haptic Master with Gripper and Wrist (HMWG). Each subject group performs a Pick and Place Task in a virtual environment where the distal hand exoskeleton is mapped to the virtual representation of the hand. Subjects are instructed to transport as many virtual cubes as possible to a specified target in the allotted time period of 120s. Three cube sizes are assessed to determine efficacy of the assistive end-effector. An additional virtual task, Mailbox Task, is performed to determine the effect

of training and the ability to transfer skills between virtual settings in an unfamiliar environment. The effects of viewing mediums are also investigated to determine the effect of immersion on performance using an Oculus Rift as an HMD compared to conventional projection displays. It is hypothesized that individuals with both proximal and complete distal hand control (HMWG) will see increased benefit during the Pick and Place Task than individuals without the complete distal attachment, as assisted daily living tasks are often accomplished with coordinated arm and hand movement. The purpose of this study is to investigate the additive effect of increased degrees of freedom at the hand through task-specific training of the upper arm in a virtual environment, validate the ability to transfer skills obtained in a virtual environment to an untrained task, and determine the effects of viewing mediums on performance. A feasibility study is conducted in individuals with stroke to determine if the modular gripper can assist pinch movements. These investigations represent a comprehensive investigation to assess the potential benefits of assistive devices in a virtual reality setting to retrain lost function and increase efficacy in motor control in populations with motor impairments.

ASSESSMENT OF A HAND EXOSKELETON ON PROXIMAL AND DISTAL TRAINING IN VIRTUAL ENVIRONMENTS FOR ROBOT MEDIATED UPPER EXTREMITY REHABILITATION

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ASSESSMENT OF A HAND EXOSKELETON ON PROXIMAL AND DISTAL TRAINING IN VIRTUAL ENVIRONMENTS FOR ROBOT MEDIATED UPPER EXTREMITY REHABILITATION

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Dedicated to Marge and Rose.

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CHAPTER 1

INTRODUCTION

1.1 Significance of the Problem

Stroke is the leading cause of disability in the United States with approximately 800,000 cases per year (Center of Disease Control 2015). Despite current technology and interventions, 30% to 66% of hemiplegic stroke patients remain without arm function after 6 months recovery; while only 5% to 20% demonstrate complete functional recovery of the paretic arm (Kwakkel et al. 2008). Neurological impairments affecting the upper extremities (UE) significantly limit the independence of the affected subjects. Strong evidence suggests that therapeutic interventions that introduce task specific training in the presence of motor practice can enhance recovery (Kwakkel et al. 2008, Loureiro et al. 2011, Maciejasz et al. 2014). However, optimal therapeutic interventions that promote recovery of arm and hand function remain unclear due to discrepancies in current rehabilitation. Robotic rehabilitation may present a complete exercise therapy that can enhance training and standardize clinical practice.

Current technologies for robot assisted therapy lack a complete and comprehensive device that is capable of providing assistance to the arm and hand during training. While most devices are capable of training the UE, the wrist and hand are often ignored due to the large degrees of freedom (Lum et al. 2002). This research addresses the need for a hand exoskeleton with gripper that is capable of providing wrist assistance for roll, pitch, yaw, and pinch. Therapeutic interventions should mimic the synergistic coordination of arm and hand movements that are necessary to accomplish activities of

daily living. These activities require multiple reach-grasp-transfer-release cycles (Loureiro et al. 2007). Many functional gains are more dependent on wrist and hand movements than on the mobility and manipulation of the upper arm (Maciejasz et al. 2014).

The role of rehabilitation is to train or retrain motor coordination to induce neuroplasticity. Virtual reality and robotic therapy systems facilitate repetitive motor movements to enhance cortical reorganization. The standard clinical paradigm to retrain UE and induce neuroplasticity involves rehabilitating the proximal control of the shoulder and elbow before initiating hand training (Lennon et al. 2002). Intensive arm therapy induces an increase in area and density of available motor cortex dedicated to arm movement only, giving the arm a cortical relearning advantage over the hand. The size of the expansion tends to be proportional to the volume and intensity of this interaction (Merzenich et al., 1996). Robot mediated therapy aims to reestablish cortical pathways related to functional movements of the trained area. Proximal and distal cortical representations are dependent on the type of therapy and the performed movements.

Most robotic systems are designed for elbow and shoulder rehabilitation. However, there is a necessity to develop upper extremity devices that focus on hand rehabilitation. It is hypothesized that to improve neuroplasticity and establish appropriate cortical representations, robot mediated therapy should provide a robust approach to incorporate coordination of arm and hand movements. An active hand exoskeleton will be integrated with a pre-existing 3-DOF(degrees of freedom) haptic robot (Haptic Master, FCS Moog) to determine the efficacy of proximal and distal training in UE rehabilitation. The functional system will allow the user to move their arm in space, while

obtaining robotic assistance for wrist movements such as flexion/extension, abduction/adduction, and supination/pronation. Pinch assistance will rely on an active gripper with rotation about the MCP joint of the index finger and rotation of the thumb MCP to provide flexion/extension of each digit. The advantage of the NJIT HandsOn system relies on the benefit of training coordinated proximal and distal movements in a Virtual Environment (VE), compared to proximal only training. The active system will allow patients with residual muscle function to perform the desired movements during training. The intervention provides a consistent environment to facilitate repetitive practice with haptic assistance for distal hand movements and proximal arm movements in three dimensional space. It is hypothesized that training in the VE with additional degrees of freedom at the wrist and hand will lead to greater performance compared to conventional proximal training or reduced DOF at the distal end.

1.2 Investigation Overview

Standard robot mediated therapy relies on an intervention that concentrates on proximal training of the shoulder and elbow. In order to develop a complete intervention to enhance recovery, distal training of the hand should be incorporated to provide functional movements of the paretic limb. This research aims to create an active 4-DOF distal attachment for a haptic robot, Haptic Master, to support arm and hand movements. The device will then be evaluated in a 3-D Virtual Environment to assess significance. Unlike robotic manipulators controlled by switches or joysticks that perform reaching and grasping tasks for individuals with limited arm function, the motion of the device will be controlled intuitively by the users arm motion regardless of strength limitations. It is

hypothesized that the distal attachments will provide greater benefit during proximal and distal training then proximal training alone, as assisted daily living tasks are often accomplished with coordinated arm and hand movement. A comprehensive system that mimics the typical coordination of arm and hand movements and provides additional degrees of freedom at the hand shoulder yield greater benefit. These effects will be evaluated during a Pick and Place Task. The effects of loss of DOF, transferability and immersion will also be investigated to determine the feasibility of developing a complete virtual reality training environment that permits proximal and distal training with the potential for immersive stereoscopic renderings.

1.3 Specific Aims

Aim I.   Design active 4-DOF distal end effector for Haptic Master: NJIT HandsOn

Aim IA.   Design and build a 3-DOF Hand Exoskeleton to support wrist movements.

Aim IB.   Design Modular Gripper for precision pinch.

Aim IC.   Design interactive Unity3D game to interface device with VE.

Aim II.   Evaluate the additive effect of increased degrees of freedom at the hand through task-specific training of upper arm in VE.

Aim IIA.   Evaluate performance post training to assess learning

Aim IIB.   Evaluate loss of proximal DOF post training

Aim III.   Validate effect of transferability of training during alternative virtual task.

Aim IV.   Validate the effect of immersive VE with Oculus

Aim V.   Assess Modular Gripper to assist pinch movements in stroke population.

1.4 Hypotheses

Primary Hypothesis (Aim II): It is hypothesized that increased degrees of freedom at the wrist and hand will contribute to a greater degree of success and improved performance during the Pick and Place task compared to movements without the DOF at the hand and wrist.

Degree of Freedom Assessment (Aim IIA): It is hypothesized that subjects that repeat the Pick and Place Task without the respective DOF will perform worse.

Transferability Assessment (Aim III): It is hypothesized that trained subjects will perform better on an unfamiliar virtual task compared to untrained individuals and demonstrate the ability to transfer skills learned in one virtual environment to another.

Virtual Reality Assessment (Aim IV): It is hypothesized that subjects that use immersive HMD viewing displays will perform better compared to those that train with conventional projection displays.

Modular Gripper Assessment (Aim V): It is hypothesized that the modular gripper will assist flexion and extension of the thumb and index finger during pinch movements in individuals even in the presence of weakness. Under the admittance control paradigm, the user only needs to apply a slight force to generate the desired movement. It is hypothesized that if the user can generate slight forces, the modular gripper will be able to assist flexion and extension of the digits.

CHAPTER 2

BACKGROUND

2.1 Cerebrovascular Accident

A cerebrovascular accident (CVA), or stroke, results when blood flow is restricted to a particular area of the brain. The decrease in oxygenated rich blood results in damaged tissue in the brain and significant impairments. These brain lesions contribute to decreased sensory and motor functions that significantly limit the independence of the individuals affected by stroke. The severity of the impairments can impact the ability of these individuals to perform activities of daily living (Maciejasz et al. 2014). Activities of daily living are reduced due to high spasticity, loss of sensation, muscle weakness, inability to isolate motor movements, which lead to secondary complications such as decreased coordination, decreased movement speed, and limited range of motion (NINDS, 2010). Robot mediated therapy may provide a method to systematically retrain lost function and improve patient performance to restore independence and enhance the quality of life.
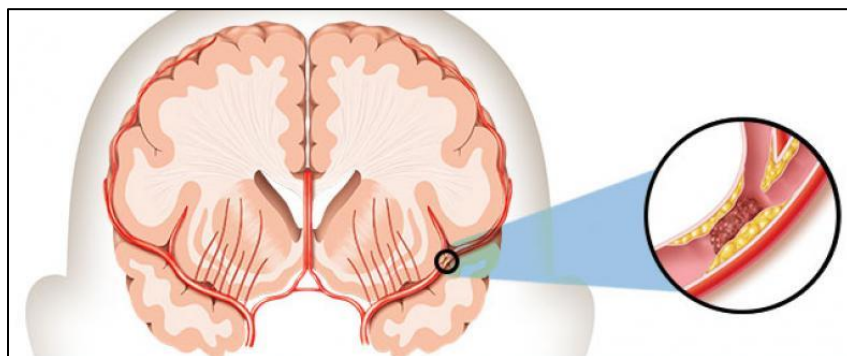
Figure 2.1 Schematic representation of stroke as a result of occluded blood vessels
Source: National Stroke Association "What is Stroke?" http://www.stroke.org/understand-stroke/what-stroke, accessed February 27, 2016.

2.2 Robot Mediated Therapy

Standard rehabilitation of the upper limb after hemiparetic stroke focuses on motor recovery to improve function and coordination of the paretic limb. Repetitive movement training has positive effects in improving function of the affected limb. Therapeutic interventions that incorporate repetitive motor rehabilitation have demonstrated greater changes in brain plasticity and cortical organization than those that do not reinforce repetitive movements (Loureiro et al. 2011). The extent of recovery is related to the degree to which the intervention challenges the neuromuscular system. Training should be repetitive, functional, meaningful, and challenging to the patient in order to elicit greater benefits during recovery (Kwakkel et al. 2008, Schaechter 2004). Stroke rehabilitation therapies that utilize task-oriented repetitive training can improve muscle strength and coordination (Riener et al. 2005). Robotic systems may provide the appropriate assistance to implement repetitive training.

Robotic devices have been identified as a possible strategy to support training paradigms that assist repetitive volitional movements in patients with neurological impairments. The goal of robotic therapy is to provoke motor plasticity and improve motor recovery through controlled use of the device. A potential role for rehabilitative robotics is to facilitate highly repetitive, active assisted movement training for more severely impaired patients (Lum et al. 2006). High intensity repetitive movements constitute an important contributor to the effectiveness of RMT (Kwakkel et al. 2008). Robot mediated therapy presents a consistent and reproducible strategy to retrain arm and hand function. Patients can benefit from the ability of the device to adapt to progress and quantitatively evaluate performance.

Patients benefit from robotic devices based on the type of assistance employed in the therapy. Robot mediated therapy can be prescribed based on the facilitation of the movement to initiate a motor response. The devices implemented in the intervention can be categorized as passive, active, or interactive. Passive movements are used to maintain the range of motion at the joints and provide no actuation. Therapeutic interventions that use passive movements can influence the intrinsic properties of muscle and connective tissue, resulting in a temporary reduction in hypertonia and decreased resistance at the active joint (Lum et al. 2006). Active assistance provides movement of the upper limb with motion assistance through actuation. This method can provide assistance to individuals where neurological signals are intact but the muscles are too weak to perform the intended movement. Active assistance can help patients move weakened or paretic limbs in desired patterns during grasping, reaching or walking tasks (Crespo et al. 2009). Interactive systems are characterized by the ability to respond to patient effort through the use of actuation. Sophisticated control strategies like admittance and impedance control provide a suitable method to identify patient effort and assist the intended movement (Riener et al. 2005). Each type of assistance provides proprioceptive or somatosensory information that can induce cortical plasticity and aid in functional recovery of the paretic limb.

Movement assistance reflects the ability of the system to engage the patient's paretic limb. However, the movement assistance does not describe how the movement is transferred from the device to the patient's upper extremity. Rehabilitation robots for the upper limb can be further characterized to describe the coupling between the individual and the device as end-effector based and exoskeleton based systems. End-effector based

systems contact the upper limb at the most distal part (i.e., hand). Movements at the distal end translate to changes in the position of the upper limb. Exercises are defined in Cartesian space with respect to the end-effector and the assistance is modulated under impedance/admittance control (Louriero et al. 2011). Exoskeleton based systems represent an assistive technology that is easy to don, responds to user needs and is able to achieve large reachable workspace, a necessity for individuals training to recover lost function. These systems are joint specific and provide rotations and movements at the desired joint to control the orientation of the arm. Exoskeleton based robots must meet design requirements so they are adapted or adaptable to the human limb in terms of segment lengths, range of motion, and the number of degrees of freedom (Riener 2005).

Although many devices have been designed to assist in upper arm therapy for individuals with stroke, five devices clinically established the efficacy of robot mediated therapy. The MIT-MANUS (MIT), the ARM-GUIDE (Assisted Rehabilitation and Measurement Guide), the MIME (Mirror Image Motion Enabler), the InMotion Shoulder and Elbow Robot, and the Bi-Manu-Track were tested in at least one Randomized Clinical Trial (RCT) and are summarized in Appendix A. The MIT-MANUS is a two degree of freedom robot manipulator that assists with shoulder and elbow movement during reaching tasks in a horizontal plane (Lum et al. 2002, Kwakkel et al. 2008). The ARM-GUIDE is a trombone like device with 4-DOF to assist reaching (Lum et al. 2002, Kwakkel et al. 2008). The MIME robot consists of 6-DOF shoulder-elbow movement, where the non-paretic arm guides the paretic arm (Kwakkel et al. 2008). The InMotion device is a commercialized version of the MIT-MANUS and provides the same support for elbow and shoulder training in the horizontal plane. A wrist attachment can be applied

to the shoulder and elbow robot to provide active flexion/extension, pronation/supination, and abduction/adduction movements at the distal end of the arm. The BI-Manu-Track is designed to train the distal segments of the arm and supports wrist flexion and extension in a mirror (Reha-stim.de 2015). The clinical results for these devices suggest that robotic devices that support upper extremity rehabilitation have therapeutic value. Results from the MIT-MANUS justify use in conjunction with regular therapy and the results from the MIME indicate that robotic devices can provide benefits that conventional therapy cannot offer (Lum et al. 2002). Results from the ARM-GUIDE indicate that even a simple 1-DOF device can contribute to patient benefit. These devices have demonstrated through RCT that high intensity repetitive movements can have a therapeutic effect on individuals with paretic arm function due to stroke (Lum et al. 2002).

2.3 Virtual Environments with Haptic Intervention

Robotic therapy devices can be used as haptic interfaces to promote training in a virtual environment. Object manipulation and feedback are critical elements that can assist with simulations of daily living. These features provide increased benefit in motor recovery and correspond directly to real world tasks (Crespo et al. 2009). Virtually Reality settings grant the ability to consistently and systematically manipulate the intensity of practice and feedback to augment therapies. This type of setting provides a variable patient setting where the intensity and frequency of practice can be controlled to induce motor learning and enhance recovery. Exercise environments can be rendered virtually in order to create a systemic therapy where the intensity of practice as well as the rewarding

feedback can be consistently monitored and used to increase motivation during learning tasks. Virtual environments possess the ability to provide a more appealing and motivating environment for therapy, offering realistic scenarios with challenging tasks that can better prepare the patient for ADLs (Mihelj et al. 2009). Virtual environments that implement haptic feedback represent a suitable method to mimic activities of daily living and object manipulation in a consistent and controlled manner.

Virtual environments that incorporate haptic feedback systems render forces to augment user immersion to provide tactile feedback and proprioceptive feedback during interaction. Devices that utilize haptic feedback can provide resistance, assistance; modify elasticity, viscosity, and friction to render simulations of force and the perception of interaction through touch (Maciejasz et al. 2014). Through these characteristics, haptic devices can provide the impression of manipulating virtual objects through tactile sensation and support training of basic ADLs. Pilot data has suggested that subjects are more motivated to exercise for longer periods of time when a VE with haptic feedback is present compared to VEs without haptic feedback (Loureiro et al. 2011). Additional data has demonstrated improvement in motor performance in individuals with dystonia after training with a combination of visual and haptic feedback (Maciejasz et al. 2014). Rhythmic motor movement tasks like walking or juggling rely on haptic feedback to transition from one state of movement to another, thus reducing variability and improving performance (Koritnik et al. 2010). It has been demonstrated that skill training of a particular motor task in a virtual environment through practice and repetitive training can transfer or even be superior to practice and training of the real world task (Todorov et al. 1997). Proprioceptive feedback in the form of haptics is a critical element that can

influence motor recovery in persons with stroke, especially when the feedback is necessary to coordinate hand function and object manipulation.

2.4 Haptic Systems

An extensive review of robotic devices has been compiled by Maciejasz et al. 2014 and provides a detailed list of upper limb rehabilitation systems categorized by supported movements. All systems that did not support shoulder, elbow, forearm, wrist, and finger movements were excluded. The rehabilitation systems were then sorted based on haptics and the incorporation of the Haptic Master (FCS Moog) and are summarized in Table 2.2 based on the compilation from Maciejasz et al 2014. Haptic Master based systems were considered to accurately establish a standard representation for proximal/distal rehabilitation to conform to Specific Aim I (development of a Haptic Master Based Rehabilitation System: NJIT HandsOn). The Gentle/G (Loureiro et al. 2007) the HenRiE (Mihelj et al. 2008) and the NJIT RAVR (Qiu et al 2009) are the only upper limb rehabilitation systems to support these criteria. The Gentle/S uses 3-DOF from the Haptic Master haptic interface coupled to a passive 3DOF gimbal to facilitate arm and hand movements. The Gentle/G improves upon the Gentle/S by incorporating an active grasp exoskeleton to achieve six active and three passive degrees of freedom. This system allows for relatively large reaching movements supported by the Haptic Master. The Haptic Master is coupled to three passive degrees at the wrist to allow arbitrary positioning of the hand and three active degrees of freedom (Grasp Robot Exoskeleton) for hand grasp and release training (Louriero et al. 2007). The HenRiE (Haptic Environment for Reaching and Grasping Exercise) is a Haptic Master based robot that

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has three active degrees, two passive degrees, and a grasping device with one degree. The Haptic Master is coupled to a gimbal with two passive degrees of freedom to allow reorientation of the subject's hand (hand pronation/supination is constrained). The degrees of freedom of the system are increased with a passive 1-DOF gripper that provides finger training, grasping, and reaching capabilities (Mihelj et al. 2008). Each system supports proximal and distal movements for reach and grasp with haptic feedback generated from the haptic master. The NJIT RAVR is a six DOF haptic robot that utilizes admittance control to support proximal and distal movements. Three active degrees of freedom are generated from the Haptic Master and three additional degrees of freedom are provided by a ring gimbal. The ring gimbal grants the ability for active forearm rotation (roll) and passive pitch and yaw movements (Qiu et al. 2009).

Despite the benefits of a system that incorporates haptic feedback with support for both proximal and distal movements, each system is still incomplete with respect to subject effort. While each system gives partial consideration to subject adaptability, mostly proximal, the wrist is subject to passive coupling mechanisms in these systems. The Gentle/G assists arm movements at the wrist using a splint, while the HenRiE couples the hand to the Haptic Master with a passive gimbal. Each therapeutic intervention does not support active movement about the wrist, while only the Gentle/G supports active movement for grasp. Studies have suggested that motor recovery of the upper extremity after stroke may spread more effectively from distal to proximal because the active practice at the wrist movements have demonstrated superior results to conventional NDT approach favoring a proximal concept (Bütefisch et al. 1995). The implementation of an active wrist will allow the patient to practice repetitive movements

over time and provide an adaptable system that can respond to residual strength of the paretic arm and hand. One of the most basic decisions is whether or not to provide mechanical assistance during training movements for patients who are too weak or uncoordinated to move successfully by themselves (Kahn et al. 2001). Active assistance therapies help a patient complete an arm movement which allows the muscles and soft tissue to stretch and offers somatosensory stimulation which may aid in cortical reorganization. To provide the same benefit as the Haptic Master, or an active assistance approach, proximal and distal joints should be active to establish a therapeutic system that is complimentary to patient adaptability and can provide sustained movement.

Table 2.2 Robot Mediated Interventions with Haptics

Device	DOF	Joint	Active/Passive	Description
NJIT RAVR	*6*	*Shoulder + elbow + forearm*	*Active / Passive*	***3 Active DOF from Haptic Master*** *3 passive DOF from gimbal at end effector*
Gentle/S	*6*	*Shoulder + elbow + forearm*	*Active/Passive*	***3 Active DOF from Haptic Master*** *3 passive DOF from gimbal at end effector in the form of wrist splint*
HEnRiE	*6*	*Shoulder + elbow + wrist + grip*	*Active/Passive*	***3 Active DOF from Haptic Master*** *2 Passive degrees from locked gimbal Passive grasp system*
NJIT HandsOn	*7*	*Shoulder + elbow + wrist + grip*	*Active*	***3 Active DOF from Haptic Master*** *3 Active degrees from wrist exoskeleton Active gripper*

2.5 Admittance Control Paradigm

Admittance control can be used to implement an assistive control system that can complement patient progress and facilitate functional recovery. The overall objective of a haptic device is to provide the user with force feedback related to the interactions in a virtual environment. Haptic devices rely on two control strategies to simulate the force feedback in a VE: impedance and admittance control. Impedance control relies on the user position and renders the force or torque based on the interaction in the virtual world. Admittance control utilizes user force and determines the position according to the virtual interaction. Contrary to impedance control, admittance control allows the user to input a force and translates that force into motion. This motion can be represented as a velocity or a position.

Under the admittance control paradigm, when a force is applied to a force transducer, the control algorithm will calculate the position to move based on Newton's second law of motion. This law dictates that the acceleration of a mass is directly proportional to the force applied. The second law can be mathematically described as $F = m * a$ (F=force, m = mass, a = acceleration). Acceleration can also be defined as the rate of change in velocity, which is also the rate of change of position. Simply, acceleration is the second derivative of position(x''). Based on Newton's second law, if the user applies a force to a known mass, the acceleration can be calculated and integrated twice to obtain the position. Newton's Second Law can be expanded to include variable system damping where: F(x)= Force (N), I=Inertia (kgm^2) , B = damping (Ns/m), x'(t)=velocity (m/s), x''(t)=acceleration(m/s^2). This second order

differential equation (Equation 2.1) provides the ability to reduce system oscillation and vibration in order to achieve smooth movement.

$$x''(t) = \frac{F(x)}{M} - \frac{B * x'(t)}{M} \qquad (2.1)$$

Neuro-rehabilitation aims to improve the patient's motor performance, shorten the rehabilitation time, and provide objective parameters for patient evaluation. Robot mediated therapy relies on interactive control systems that react to inputs from the subject. Admittance control provides the capabilities for the user to manipulate these robotic devices with their applied force. The positive features associated with an admittance control paradigm include: force amplification, intuitive control, back-drivability, and proportional control. Under admittance control, the user senses only the inertia of the small virtual mass which can be very small compared to the inertia and load capabilities of the actual robot actuators. This makes it useful for individuals with significant muscle weakness to employ their residual motor control to effectively drive a powerful robot (Hu et al. 2011). These features reflect essential characteristics for a complementary control system that can provide active assistance and facilitate motor movements during therapy.

2.6 Conclusion

The purpose of this study is to establish the effectiveness of the NJIT HandsOn (7-DOF active system) and the ability to augment performance with haptic assistance in a virtual environment on healthy subjects. This research observes the effects of increased DOF for reaching and grasps mechanics in a simulated real-world task (Virtual Pick and Place Task). Populations such as stroke exhibit problems initiating motor output in response to sensory cues. This impairment may also contribute to delays in distal movements (grip-lift performance). Higher initial grip forces constitute a compensatory strategy to stabilize grip prior to the lift. Factors that can influence the motor response to initiate a suitable grip force include: altered descending commands, difficulty adjusting force rates, reduced force rates, and disorganized motor recruitment (Huesler et al. 1998). Impaired tactile sensibility has a larger impact than motor impairment on altered pinch performance. It is likely that people with stroke need repetitive practice to form internal models of the object to learn from completed attempts at the pinch task. (Blennerhassett et al. 2006).

This research investigates if the NJIT HandsOn can provide assistance and haptic cues during proximal (shoulder/arm) and distal (hand/finger) training to provide a more biomechanically effective system to generate biological movement. Combined coordination during VE training can potentially provide a modality with which motor deficits can be overcome and independence can be re-established. Simulations where the DOF are reduced after training with the distal components will be investigated in Chapter 5 to determine the overall benefit of increased DOF at the hand. The ability to transfer skills from virtual simulations to the real world is a critical feature for effective rehabilitation paradigms. The Mailbox Task was designed to investigate the ability of

trained subjects to transfer skills learned in one task to another unfamiliar and untrained task. Transferability of learned skills will be explored in Chapter 6. Viewing mediums have the potential to influence performance and will also be investigated to determine the effect of immersion on VE training. A comparative analysis was performed between viewing mediums to determine if immersive HMD can enhance performance and is documented in Chapter 7.

Feasibility for stroke or populations with neurological impairment affecting motor control will be assessed based upon motor learning in the healthy experimental groups; primarily through assessments in efficiency in movements (successful attempts, spatial smoothness, trajectory lengths). The feasibility study presented in Chapter 8 evaluated the potential of the Modular Gripper to assist pinch movements in individuals with stroke. These features reflect the necessary components to provide a comprehensive system to retrain lost function and increase efficacy in motor control in populations with motor impairments in order to optimize therapeutic interventions. This research aims to establish the benefits of increased DOF at the distal end to provide proximal and distal training in a virtual environment and to validate the effects of transferability of learned skills, as well as the effect of immersive VE. These factors represent essential features that have the potential to augment rehabilitation paradigms and enhance recovery of individuals with stroke to improve functional movement.

CHAPTER 3

END EFFECTOR

3.1 Introduction

The Haptic Master is a three DOF admittance control robot that supports proximal arm movements in three-dimensional space. The Haptic Master provides the ability to create haptic objects with which the user can interact and receive tactile feedback. Despite the positive features associated with the Haptic Master, it does not provide the ability to support distal hand rotations, movements essential for activities of daily living and independence. To enhance the positive features associated with the Haptic Master, an end effector was created to grant the ability to perform wrist movements (roll, pitch, and yaw) and power pinch to satisfy Specific Aim I.

3.2 Wrist Exoskeleton (Specific Aim IA)

A 3-DOF wrist exoskeleton was designed to mimic the range of motion of the wrist and serve as a distal attachment for the Haptic Master. The Haptic Master operates in real time at a rate of up to 1000 Hz to interface virtual movements with assisted movements from the device (Qiu et al. 2009). The distal attachment incorporates 3-Dynamixel Motors (Robotis) to provide roll, pitch, and yaw (Figure 3.1). The motors are coupled to 3-D printed constructs to support the wrist. The system provides assistance to the user to move their hand in space and achieves such wrist movements as flexion/extension, abduction/adduction, and supination/pronation. It should be noted that intended movements are assisted regardless of strength limitations.
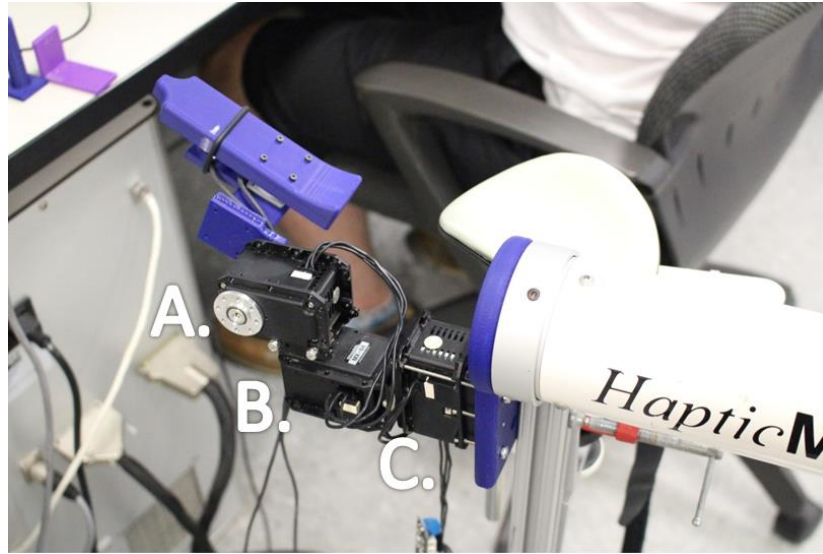
Figure 3.1 3-DOF distal end effector attached to the Haptic Master to provide pitch (A.), yaw (B.), and roll (C.).

Under the admittance control paradigm, individuals will intuitively control the device based on wrist motion, more specifically, directional force the wrist applies during movement. The intended force is sensed in the x,y,z direction by two force sensors (Optoforce Ltd) embedded in the wrist cuff. The force values are collected at 1000Hz and converted to angular position using custom kinematics in MATLAB. The angular position is computed by solving the differential equation (Equation 2.1) using CVode (Ordinary Differential Equation Solver) developed at Eindhoven University. In the impedance loop, angular position values are converted to motor angles and sent to the motor to perform the desired command using onboard 1000 Hz PID controller. All calculations and movements are performed in real time at 100 Hz.

3.3 Modular Gripper (Specific Aim IB)

A modular gripper was added to the active wrist orthosis to provide the ability to manipulate objects in space. A single degree of freedom gripper allows rotation of the metacarpal joints (MCP) of the thumb and index finger. The MCP rotation is generated at the index joint using a Robotis Dynamixel RX-28 motor and is coupled to the thumb MCP to provide passive rotation (Appendix C). This movement provides a precision pinch grip which is critical to hand function for daily life. Impaired pinch skill significantly affects dexterity function for stroke survivors, leading to higher dependency of daily activities and poor quality of life (Faria-Fortini et al. 2011). It is important that the patient is able to see the hand on the mechanism, especially the thumb to facilitate grasp pre-shaping, maintain grasp and release (Louriero et al. 2007). The integrated exoskeleton grants the user increased range of motion and the ability to manipulate objects; features essential for independence in activities of daily living (Figure 3.2).

Figure 3.2 User with Modular Gripper performing pinch task in VE.

Based on the admittance control paradigm, the gripper can be interfaced with a virtual system that provides haptic feedback. Using the same algorithm as the wrist exoskeleton (Specific Aim 1A), a user applies a force with their index finger to the force sensor (Optoforce) implemented in the index ring to facilitate pinch movement. The gripper will be used to augment the virtual therapy and provide force feedback sensation during repetitive task training. This capability is achieved by creating new boundary conditions for each object collision in the admittance control algorithm when an object is gripped in the VE. The virtual environment indicates that a collision has occurred and the ODE sets the boundary condition with the position obtained during the collision. The features presented by the Modular Gripper offer a universal design that can be adapted to each patient to increase manipulation and mobility.

3.4 Virtual Environment (Specific Aim IC)

Exercise environments can be rendered virtually in order to create a systematic therapy where the intensity of practice as well as the rewarding feedback can be consistently monitored and manipulated to aid in motor learning tasks. Subjects who trained in the virtual environment showed accelerated learning rates as compared with control subjects (Todorov et al. 1997). Virtual environments possess the ability to provide a more appealing and motivating environment for therapy, offering realistic scenarios with challenging tasks that can better prepare the patient for ADLs.

Unity3D is a cross platform 3D engine that can be used to develop powerful games and applications for therapeutic interventions. A virtual environment was created using Unity3D to develop an interface for the hand exoskeleton. The trajectories of the

wrist and finger are mapped to the virtual representation of the hand, Figure 3.3. The force values are collected in MATLAB and processed by the admittance control algorithm. The rotations and positions are then sent to Unity3D using a TCP connection (transmission control protocol). TCP communication establishes a handshake form of communication that relays information between the programs. Connections must be properly established in a multi-step handshake process before entering the data transfer phase. This method of communication is accomplished by transmitting and receiving data on the same port. It is a reliable form of communication that provides an effective mechanism for flow control.

The Unity 3D interface provides visual feedback with trajectories mapped to arm and shoulder movement. The VE interface provides an accurate representation of kinematic arm movement and articulations of the wrist and fingers. Proximal arm positions are acquired from the Haptic Master and sent via TCP communication and mapped to the virtual hand to control global hand movement. Haptic feedback can be implemented in the form of the Haptic Master (springs, dampers, forces) or created using the admittance control paradigm. Haptic boundary conditions were applied to the gripper to simulate gripping interactions with virtual objects and were rendered with colliders. The combination of haptic effects from the Haptic Master and modular gripper can be used simultaneously to augment interactions in the virtual environment. The proposed study utilized haptics generated by the modular gripper to provide the sensation of grip. When the object is grasped, the colliders apply the appropriate physics and collision information is transmitted to MATLAB to apply the appropriate initial conditions to the ODE. Using VR, intensity of practice and sensory feedback (visual, auditory and

sometimes touch) can be systematically manipulated to provide the most appropriate, individualized motor training in a realistic scenario (Kamal et al. 2011). Holden et al. demonstrated that subjects not only improved on a virtual task, but also showed transfer of that improvement to similar real world tasks, both trained and untrained. The result of the VE is an interactive environment that provides an impression of manipulating virtual objects for proximal and distal training for a simulated Pick and Place task and can be easily adapted and customized to provide an extensive library of simulations that can also adapt to patient performance and progress.

Figure 3.3 Virtual representation of hand and task rendered in Unity3D.

3.5 Conclusion

The motivation was to develop a single active system that operates under admittance control, where the benefits of arm and hand training in a virtual environment could enhance motor learning and translate to daily living tasks. Combined training suggests a paradigm that is more suitable for activities of daily living, which require both arm movements and grasping (Podobnik et al. 2010). The NJIT HandsOn offers the ability to perform proximal arm movements with the Haptic Master, distal rotations with the wrist exoskeleton, and fine motor control movements for pinch with the modular gripper. The system is interfaced with a VE generated in Unity 3D that is capable of simulating physical interactions with 3D visual and haptic feedback.

CHAPTER 4

PICK AND PLACE TRAINING

4.1 Introduction

The primary objective of Specific Aim I was to design the components that would provide the necessary degrees of freedom for evaluation in the experimental setup. Specific Aim II will utilize the developed device and Virtual Environment using the TCP protocol to assess the impact of the additional degrees of freedom provided by the wrist and gripper exoskeleton during virtual training in Unity3D. This task demonstrates that virtual movements kinematically resemble interactions with physical objects and reflect the benefits obtained during virtual training transfer to real life situations (Viau et al. 2004). The Pick and Place Task (PPT) is designed to incorporate both reaching and grasping to simulate activities of daily living. The distal wrist and gripper components provide expanded DOF of the Haptic Master and grant the ability to manipulate objects during the virtual Pick and Place Task. The comprehensive training system is referred to as the NJIT HandsOn and can be seen in Figure 4.1.

Figure 4.1 NJIT HandsOn System complete with 3 proximal DOF at the shoulder, 3 DOF at the wrist, and 1 DOF for pinch.

4.2 Pick and Place Task

The objective of the PPT is to transport as many cubes as possible to a specified target in the allotted time period of 120s. Several cube sizes will be used throughout the training to determine the response of the additional DOF. Subjects must move the arm to the virtual object using the Haptic Master and orient the hand to grasp it using the hand and gripper end effector. Distal component use will be determined by the randomized experimental protocol where subjects will be placed in groups with varied DOF. Once the object is grasped, the subject must transport the object to the designated location and place it on a specified target. When the object is placed on the target, a new virtual object appears at the origin of the workspace. If the subject does not grip the object properly or apply enough force, the object will fall and reset to the initial position and constitutes a cube error. Additionally, if the object is not placed on the specified target, the object resets and the user must repeat the operation. Collisions between the hand and object provide tactile feedback to the user. Feedback is provided showing real-time information to the user, such as specified target, points scored, and time remaining. The task is constrained to one plane to provide greater consistency between the experimental groups.
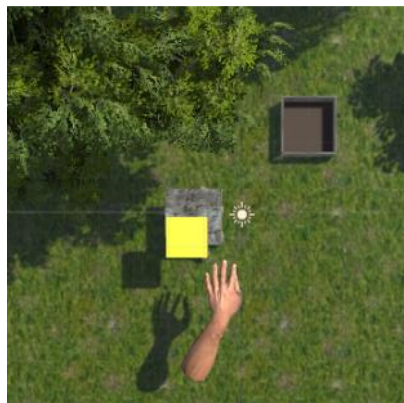
Figure 4.2 Virtual PPT setup with highlighted cube and specified target location.

4.3 Methods

Healthy subjects with no visual or motor impairments that are right hand dominant were recruited to participate in the study. Subjects were seated in a comfortable chair in front of the haptic interface. An arm orthosis attached to the Haptic Master was used to support the left forearm of the subject. The left hand was placed in the wrist exoskeleton mounted to the end effector of the Haptic Master. A neutral hand position was maintained (no wrist flexion) to aid donning/doffing procedures. The grasping exoskeleton was then applied to the left hand and securely fastened to provide precision pinch. Subjects were randomly assigned into one of four groups: Haptic Master control group (HM), Haptic Master with Gripper (HMG), Haptic Master with Wrist (HMW), and Haptic Master with Gripper and Wrist (HMGW) to simulate different proximal and distal DOF combinations. The HM control group served as the conventional clinical training paradigm to rehabilitate proximal movements in isolation, whereas the HMWG group offered simultaneous training of proximal and distal DOF.

Subjects were instructed to perform the PPT and pick up a virtual cube of varied thickness (0.45in, 0.35in, and 0.25in) and place it on the specified target as many times as possible during the 120s trial. Each subject participated in six training sessions, where each session consists of eight trials each. Subjects were required to perform two sessions per cube size thickness for eight trials each and only transport one cube type for each trial in the respective session. Rest periods of 120s were applied in between trials.

Subjects returned for two additional sessions after the completion of training to determine skill retention and skill transfer. The retention session was performed with the big cube and each subject was asked to repeat PPT. Subjects were required to transport

the virtual cube to the specified target as many times as possible in their previously trained group. The subject performed eight total trials (120s each) with 120s rest in the retention task. The subject was then assigned to a group with more or less DOF depending on the original group. The subjects then performed the PPT with the big cube in the new group for eight trials (120s each) with 120s rest in between trials. Subjects were then asked to schedule the final training session to assess performance in the Mailbox Task in the originally trained group.

Figure 4.3 Experimental groups for Pick and Place Task in order of increasing DOF. All groups use Haptic Master(HM) with the respective DOF.

4.4 Training Assessment

The virtual PPT was designed to provide a setting where a common activity of daily living could be practiced and assessed quantitatively. Physical interactions in the virtual environment were rendered through the PhysX Engine in Unity to incorporate realistic elements. Each participant was randomly assigned into a group with different degrees of freedom: Haptic Master (HM), Haptic Master Wrist (HMWG), Haptic Master Gripper (HMG), and Haptic Master Wrist and Gripper (HMWG). The HM Group had no

additional DOF at the distal end. Participants in this group relied on proximal shoulder movements for transport. The HMW, HMG, and HMWG incorporated combinations of distal hand DOF to provide both proximal and distal support during transportation. Each participant was required to transfer the cube to the specified target within in the two-minute period. A retention test was performed one week post training and was split into two sessions. The first component of the Retention Task involved a retest of the big cube. Participants were asked to repeat the PPT for eight trials with the big cube in the original experimental group. For the second component of the Retention Task, DOF Assessment, subjects were asked to perform the PPT without distal DOF for eight trials. HMW, HMG, and HMWG were required to perform the task with HM support only. The HM control group was granted distal DOF in the form of the wrist exoskeleton. The DOF Assessment component of the Retention Task served to further validate the efficacy of the distal components at the hand while the first component of the Retention Task aimed to assess learning. The DOF Assessment will be further explored in Chapter 5.

Comparative analyses for each group and respective DOF were performed in order to determine the efficacy of increased DOF during the virtual Pick and Place Task. Metrics used to assess each experimental group included: Cube Success (CSX), Cube Error (CER), cube success ratio (CSR), trajectory length (TRL), Delta Cube Time (DTC), smoothness (NIJ), and R-squared coefficient (RSQ). Each metric was recorded for each experimental group and respective cube size throughout training for each task and averaged for each subject per training session.

Cube Success (CSX). Number of cubes accurately transported to the specified target. A successful transport of the cube includes lifting the cube from the table with the virtual

hand and placing the cube in the specified box target. Larger numbers indicate greater success.

Cube Error (CER). Number of cubes that do not successfully reach the intended target or are dropped during transport. Cube Errors are recorded when the cube is knocked off the table, contacts the ground of the VE, or are misplaced at the target box. Smaller numbers indicate fewer errors.

Cube Success Ratio (CSR). This ratio indicates the complete success based on the number of attempts. The number of attempts accounts for both CSX and CER. The ratio is defined as $\frac{CSX}{CSX+CER}$. This ratio will be converted to a percentage where percentages close to 100% represent greater CSR.

Trajectory Length (TRL). The length of a trajectory of a successfully transported cube. The length of the path is measured from the initial pickup to the final deposit. This measurement represents a change in transport efficiency. Shorter trajectory lengths represent more direct paths towards the target.

Delta Cube Time (DCT). Represents the average time of success. Indicates the rate of change of success and is defined as the average time to complete a successful transfer. This metric indicates the improvement in the rate of transport. Lower DCT accounts for faster transports.

Smoothness (NIJ). A quantitative value to represent the ability to produce smooth and coordinated movements during object transport. Smoothness is characterized as normalized integrated jerk and is calculated as $NIJ = \sqrt{\frac{T^5}{2L^2}} \int J^2$, where T=duration, L=

trajectory length, J=$\dddot{x}$, NIJ= normalized integrated jerk (Adamovich et al. 2009). Smaller values indicate smoother movements with less sub-movements.

R-squared value (RSQ). Used to assess the quality of the whole trajectory. RSQ measures the linear regression coefficient of the planar trajectory for both the forward transport and return trajectory. Higher RSQ values represent more direct transports and returns with less variability.

4.5 Pick and Place Results

Subjects were randomly assigned into each experimental group and completed six training sessions each with eight trials. Each cube size was standardized per session across groups and consisted of the following training paradigm: Training Session 1 (Big cube), Training Session 2 (Big cube), Training Session 3 (Medium cube), Training Session 4 (Medium cube), Training Session 5 (Small cube), Training Session 6 (Small cube). Each group performed two training sessions per cube size where the size gradually decreased as training progressed. Average values for CSX, CER, CSR, TRL, DCT, NIJ, and RSQ were recorded per training day per group. Standard Error of Mean (SEM) was calculated for each metric to assess the standard deviation with respect to the population mean. SPSS statistical software was used to determine the significance for each comparative analyses. The statistical software was used to generate descriptive statistics and assess homogeneity and normality. A two-factor mixed design ANOVA was performed to determine main interaction effects between two independent factors (DOF and Training Sessions). Simple effects for the between subjects factor (DOF) were treated with the appropriate statistical test (ANOVA or Kruskal-Wallis) following the

normality assessment. The simple effects for the within-subjects factor (Training Sessions) was assessed with the appropriate statistical test (rmANOVA or Friedman) following the normality assessment. Levene's test was performed to determine homogeneity, while Shapiro-Wilk test was performed to assess normality. Mauchly test for Sphericity was computed to determine interaction effects. Greenhouse Geisser method was employed when sphericity assumptions were violated. Multiple comparison tests that satisfied the Shapiro-Wilk test were evaluated using an ANOVA, while those that failed the Shapiro-Wilk test were evaluated using Kruskal-Wallis test. Within subject comparisons for Training Sessions that satisfied Shapiro-Wilk test were evaluated using a rmANOVA, while those that failed the test for normality were evaluated with a Friedman test. Bonferroni corrections were performed for pairwise comparisons for the repeated measures assessment and automatically corrected by SPSS to correct for multiple comparisons and assessed at the significance level of $\alpha=0.05$. Statistical significance for the between subject factor (DOF) was assessed with a Bonferroni Post Hoc test with a Bonferroni Correction to adjust alpha to $\alpha=0.0071$ to correct for each determined metric for the between subject comparison. Statistical significance was reported at the corrected level based on multiple comparisons to protect from Type 1 error.

4.6 Cube Success Results
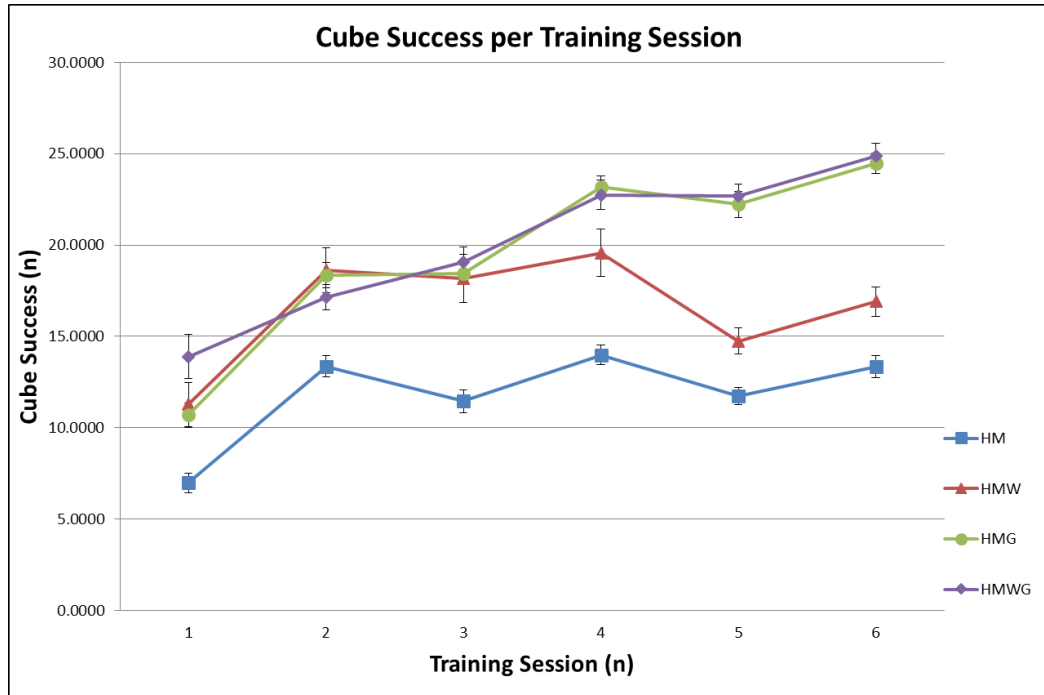
Figure 4.4 Average cube success with SEM per training session for each respective experimental group.

Cube success was recorded for each Training Session (TS) for each experimental DOF. Figure 4.4 indicates the average scores for CSX obtained throughout training for each TS. All significant differences for each training session other than TS5 were evaluated using Kruskal-Wallis test due to violation of the Shapiro-Wilk test of normality. Training session five passed the Shapiro-Wilk test of normality and was evaluated using a one-way ANOVA. Bonferroni Post Hoc with a Bonferroni Correction was applied to each statistical test in order to protect significance levels.

The HMWG was able to successfully transport more cubes on TS1 than the HM control group. Significant effects were observed between the HMWG and HM control group on TS1. Subjects in the HMWG had significantly greater CSX ($p<0.001$) than the

HM control group. There was no statistical significance observed between DOF. The HMW group was trending towards significance (p=0.009). Based on the Bonferroni Correction (α=0.0071) to protect significant levels, the HMW and HMG had significantly greater CSX (p<0.001) than the HM control group on TS2. There was no statistical significance observed between the DOF. The medium cube was introduced in TS3 and a noticeable decrease in CSX can be observed in Figure 4.4 for experimental groups that did not have the ability to manipulate aperture (HMW and HM). Groups with the gripper were able to maintain the previous level of success (HMG) and even improve CSX (HMWG). Each experimental group had significantly greater CSX (p<0.001) than the HM control group. There were no effects reported between the DOF. The medium cube was retested during TS4 where the HM control group still performed the worst compared to the other DOF. Subjects in the HMW, HMG, and HMWG had significantly greater CSX (p<0.001) than the HM control group. Subjects in possession of a gripper were able to obtain CSX scores greater than 20 on TS3, but there were was no statistical significance observed for the greater CSX between experimental DOF. The small cube was introduced in TS5 and resulted in statistically significant differences between the HM control group and experimental DOF. Subjects in the HMW, HMG, and HMWG had significantly greater CSX (p<0.001) than the HM control group. Statistically significant differences in cube success between DOF were also observed. The HMG and HMWG groups had greater cube success than the HMW group (p<0.001). There was no statistical significance observed between the HMG and HMWG. The HMW group had the greatest decrease in CSX by approximately 5 points, but was still more successful than the HM control group. Experimental groups with the gripper were able to continually improve

despite the change in cube size. The last training session TS6 concluded with a retest of the small cube. Experimental groups with the gripper were able to continuously improve from TS1 to TS6 based on the CSX scores. Subjects in the HMW, HMG, and HMWG group had significantly greater CSX (p=0.002, p<0.001, p<0.001) than the HM control group for TS6. Statistically significant differences in cube success between DOF were observed. The HMG and HMWG groups had greater cube success than the HMW group (p<0.001). There was no statistical significance observed between the HMG and HMWG. The HMG and HMWG were able to improve throughout the training sessions even with the decrease in cube size. The HM control group had significantly lower scores throughout training whereas the HMWG improved with each session.
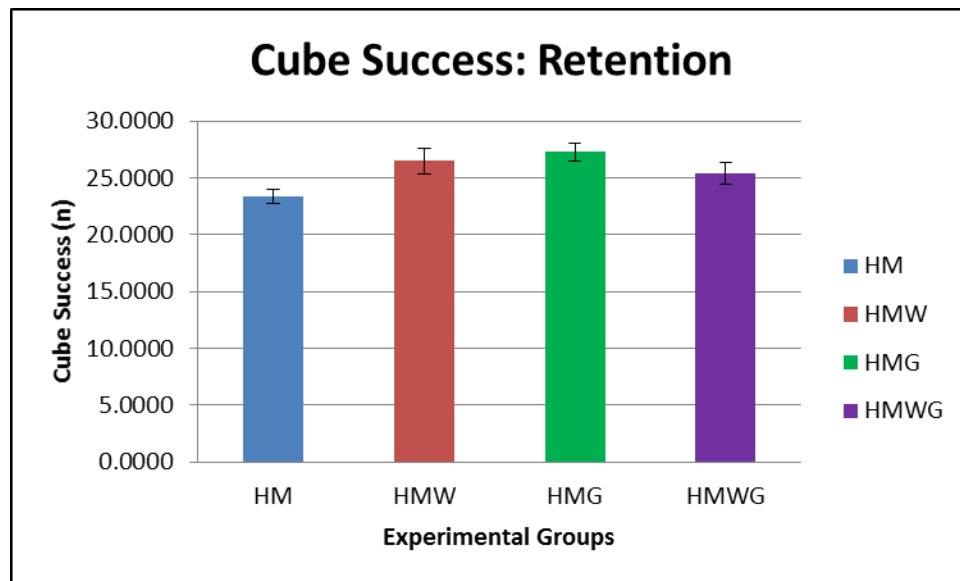
Figure 4.5 Cube Success for retention test administered 1 week after completion of training. Participants repeated the PPT with the big cube.

The two-way mixed ANOVA revealed a significant interaction between Training Sessions and DOF for cube success $F(15,80)=4.258$, $p<0.0005$. The interaction suggests that the DOF contributed to significant improvements across Training Sessions. The

change in cube size had a significant effect on groups without the gripper as depicted in Figure 4.4. The HMG and HMWG experienced the greatest success over the course of training despite the change in cube size between sessions.

A retention test (TSR) was administered one week after completion of training. Participants performed the Pick and Place Retention Task with the big cube in order to determine overall influence of training. There was no statistical significance in CSX between experimental groups, Figure 4.5, during the Retention Test. Each experimental group had CSX scores greater than 20 points. The big cube was retested to determine the overall effect of training and infer learning from TS1 to post training session. The effects of TS1 to TSR are documented in Figure 4.6. The figure suggests that each experimental group was able to improve with respect to CSX. The HM group still had the lowest CSX scores on both the first and last training session compared to the experimental DOF. Interestingly, the experimental DOF had similar post training scores.
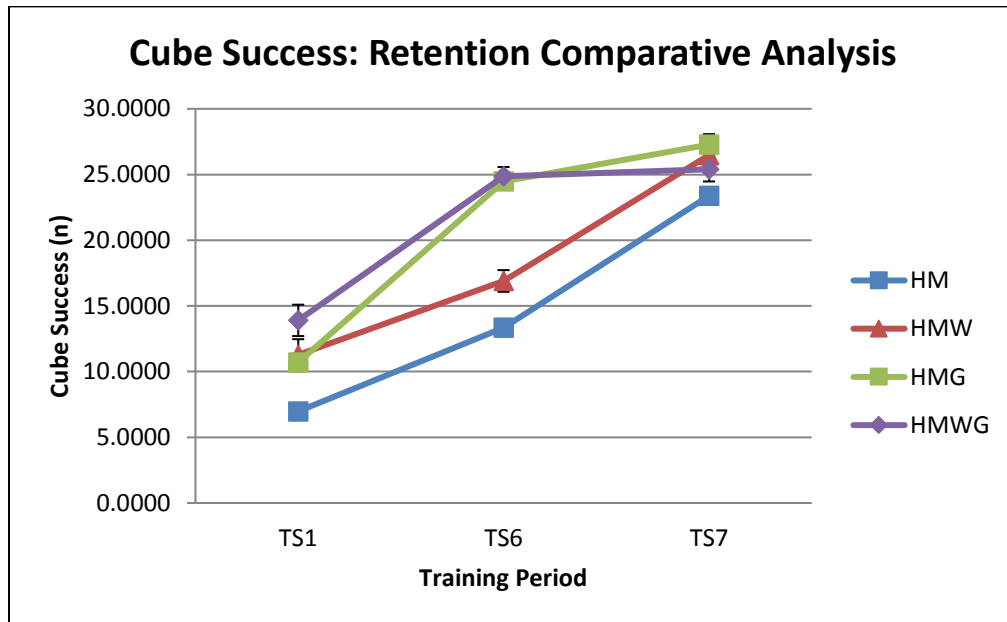
Figure 4.6 Cube success for Training Session 1 (TS1), Training Session 6 (TS6), and Training Session 7 (TS7). Training Session 7 was performed 1 week post training.

To assess the significance between the first session (TS1), the last session (TS6), and the retention session (TS7) for each experimental group, a non-parametric Friedman test was performed to assess significant changes in cube success between the respective training sessions for the HM control group. A Bonferroni Post Hoc with alpha corrected to $\alpha=0.0167$ to correct for multiple comparisons was used to assess significance in cube success between training sessions. Statistically significant differences were observed for cube success between TS6 and TS7 compared to TS1 ($p<0.001$). The HM control group generated greater success on TS6 and TS7 compared to TS1. Significance was also observed between TS6 and TS7 for the HM control group ($p<0.001$). The retention test performed during TS7 resulted in greater cube success than TS6 when the test was performed with the big cube again for the HM control. Statistically significant differences were observed for cube success between TS6 and TS7 compared to TS1 ($p=0.001$, $p<0.001$) for the HMW group. The HMW group generated greater success on TS6 and TS7 compared to TS1. Significance was also observed between TS6 and TS7 for the HMW group ($p<0.001$). The retention test performed during TS7 resulted in greater cube success than TS6. The HMG group generated greater success on TS6 and TS7 compared to TS1 ($p<0.001$). Significance was also observed between TS6 and TS7 for the HMG group ($p=0.013$). The retention test performed during TS7 resulted in greater cube success than TS6. The HMWG group generated greater success on TS6 and TS7 compared to TS1 ($p<0.001$). No significant differences in cube success were observed between TS6 and TS7 ($p=1.00$).

Statistical analysis was also performed between training days to determine the effect of cube size for each experimental group over the course of training. The retention task was designed to provide a comparative analysis to assess performance during three training periods: the initial session (TS1), the final session (TS6), and a one-week follow up (TS7). The nonparametric Friedman test for repeated measures was performed to determine significance between Training Sessions for each experimental group. Alpha values were automatically adjusted with Bonferroni correction to account for multiple comparisons between Training Sessions and evaluated at a confidence level of $\alpha=0.05$. Figure 4.4 indicates that subjects in the HM control group had significantly higher CSX for the second session of each cube size compared to TS1. HM control group had significantly greater scores on TS2 ($p=0.035$), TS4 ($p=0.026$), and TS6 ($p=0.026$). There were no effects observed between training days other than TS1. Despite the lack of significance between the training days, a trend can still be observed for the progression of the HM control group. From TS2 to TS3, the HM CSX decreased when the medium cube was introduced. The same effect can be observed when the cube changes size again from medium to small for TS4 and TS5 respectively. The HMW group was also able to improve consistently after TS1. HMW subjects had significantly higher CSX on TS4 compared to TS1 ($p=0.02$). The HMW group had the greatest success on TS4 and was statistically significant compared to TS1. The wrist group was able to transport the Medium cube with the greatest success. No effects were observed between the other training sessions. The HMW group did experience similar trends to that of the HM control group in terms of size effect. There was a decrease in CSX from TS2 to TS3 and reflects the change from the Big cube to the Medium cube. The largest decrease in

success for the HMW group can be observed on TS5. The HMW group had the largest decline in CSX when the Small cube was introduced. The trend suggests that the Small cube was more difficult to transport for the wrist group, as the scores for the Medium cube were greater (TS3=18.1750±1.32, TS4=19.5±1.3, TS5=14.75±0.73, TS6=16.9±0.82571). HMG subjects had higher CSX for the second session of the medium cube and the small cube. Statistical significance was observed on TS4 (p=0.015) and TS6 (p=0.001). The HMG group was able to improve CSX with more training despite the change in cube size. The HMG group was able to improve throughout the training and experienced minimal changes to CSX with the change in cube size between TS2 to TS3 and TS4 to TS5 (TS2=18.35±0.70579, TS3=18.4250±0.52488, TS4=23.1750±0.60752, TS5=22.2250±0.55469). The change in cube size had a small effect on transport for the HMG group. The HMG group was able to significantly improve CSX despite the changes (TS4, TS6) in cube size which suggests that the gripper may have had a significant effect on the ability to transport objects of different sizes.

Additional observations were documented for the HMWG group with respect to CSX. HMWG group had higher CSX for the last training session (TS6) compared to the first training session (TS1) with p=0.002. Statistical significance was observed between additional training days. Training Session 2 resulted in greater CSX than TS6 (p=0.026). This improvement indicates that the HMWG group was able to adapt to the change in cube size (big to small). HMWG group was able to constantly improve throughout training and exhibited a trend comparable to a linear increase in CSX, Figure 4.4. It should be noted that the HMWG group was the only group to experience the smallest change when the cube size was decreased from medium to small for TS4 to TS5

(TS4=22.7±0.820, TS5=22.7±0.641). Overall, the HMWG was able to improve on a session basis and did not experience setbacks comparable to CSX in the other experimental groups. While the HMG group had greater CSX than the HMW and HM control group, the HMWG did not experience the step response observed for the HMG group, which suggests that the combination of wrist and gripper components may attribute to greater CSX based on the linear trend, that is, the ability of the HMWG to improve regardless of cube size.

4.7 Cube Error Results

Cube error was assessed during the transportation of each cube size for each experimental group. Errors were recorded when the cube was not successfully transported to the target location. Common instances observed for cube error were as followed: cube knock-offs, cube drops, misplacements, and forceful transports. A cube knock-off constituted a cube that was knocked off the virtual table and did not reach the target. A cube drop was the result of failure to secure the cube in the hand. Cubes that reached the target but were not successfully placed in the target box also resulted in errors. The final method to produce an error was the result of forceful transports. Transports that were placed in the box with excessive force were penalized to reflect repercussions that would be evident during a real world task, such as breaking or damaging the object. Inaccurate attempts due to movement speed would also result in a greater CER.
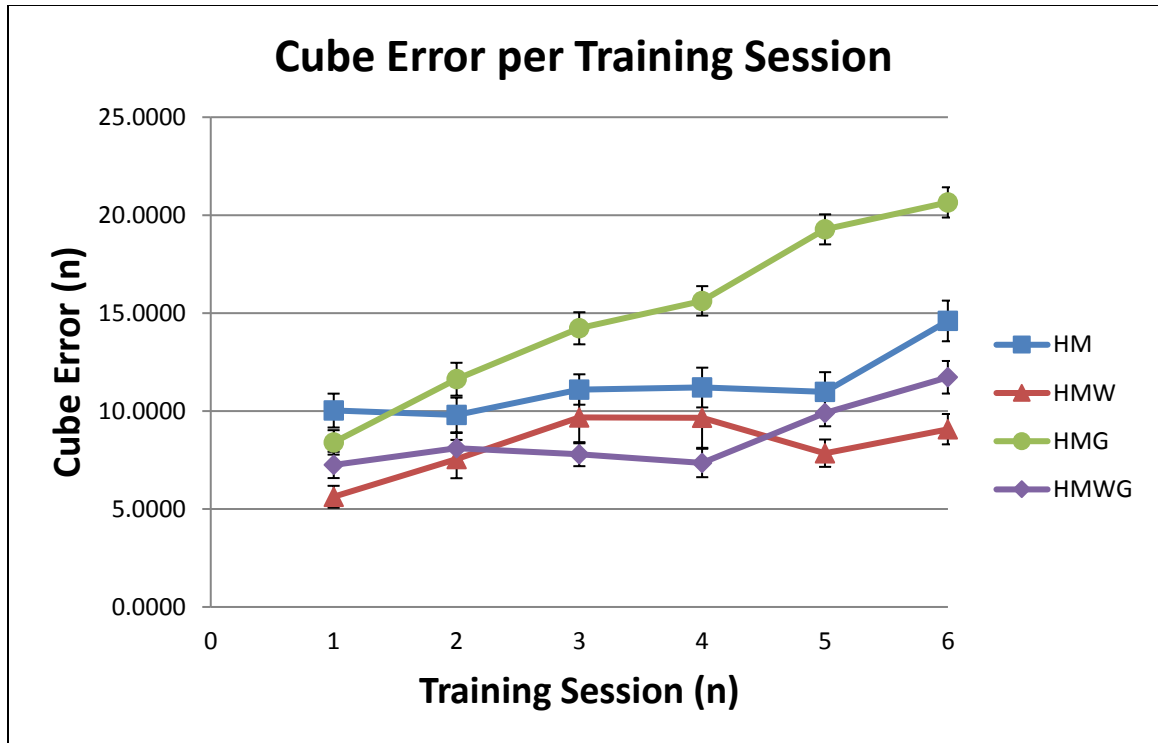
Figure 4.7 Average cube error measured for each training session for each group.

Cube error was assessed on each training day to determine the level of improvement across sessions for each DOF. A Shapiro-Wilk test was conducted to assess the normality of the sample population. The data for TS1 through TS6 was in violation of the Shapiro-Wilk test and a non-parametric test was conducted to determine the significance. A Kruskal-Wallis test was performed to assess significance at the level of α=0.0071 to protect significance. Initial training during TS1 resulted in significant differences in CER between the HMW group and HM control group, Figure 4.7. The HMW group had significantly fewer errors on TS1 compared to the HM control group (p<0.001). There were no significant effects observed between the experimental DOF. No statistical significance was reported for TS2 between control and experimental DOF. Transition from the big cube to medium cube resulted in statistically significant effects in cube error between the experimental DOF for TS3. The HMW and HMWG group had

significantly less CER compared to the HMG group (p=0.003, p<0.001). There were no significant effects observed for CER between the experimental DOF and the HM control group. Similar observations were recorded for TS4 where there was no statistical significance between the experimental DOF and HM control group. The HMW and HMWG group had significantly lower CER scores compared to the HMG group (p=0.001, p<0.001). The second transition from the medium cube to the small cube resulted in statistically significant CER during TS5. Statistical significance was reported between the HMG and HM Control Group. The HM control group had fewer errors than the HMG group (p<0.001). Significance was observed between DOF. HMW and HMWG group had less errors than the HMG group (p<0.001). All groups had significantly lower CER on TS5 compared to the HMG group. Subjects in the HMW group had significantly less errors than the HM control group (p<0.001), while subjects in the HMG group had significantly more errors than the HM control group (p<0.001) for TS6. Statistical significance was observed between DOF. The HMW and HMWG had fewer errors than the HMG group (p<0.001). The HMW group also had significantly less errors than the HMWG (p<0.001).

Throughout the course of training the HMG group consistently accumulated more errors. The HM control group CER was relatively consistent throughout training until TS6, where the group experienced the greatest change in CER from TS5 (CER=10.9750±1.01) to TS6 (CER=14.6±1.03763). Figure 4.7 illustrates that the HMWG group was able to continual improve from TS2 to TS4 and had the smallest CER values when the medium cube was tested on TS3 and TS4. The small cube resulted in an increase in CER from TS4 (CER=7.35±0.72461) to TS6 (CER=11.7250±0.832) for the

HMWG group. The HMW group exhibited the lowest CER with respect to the small cube on TS5 (CER=7.85±0.698) and TS6 (CER=9.075±0.775).

The high CER for the HMG group might be explained by the greater number of attempts performed by this group. The HMG group had the largest number of attempts compared to the other groups (HMG=34.53± 0.66174). The HM, HMW, and HMWG exhibited on average less attempts over the course of the training session (HM=23.06±0.50842, HMW=24.79±0.842, HMWG= 28.73±0.60). A statistical analysis was performed to determine the significance of the average number of attempts performed per session. A Kruskal-Wallis test was performed since the data violated the Shapiro-Wilk test for normality. The HMG and HMWG had significantly more attempts compared to the HM control group (p<0.001). Statistical significance was observed for the number of attempts between experimental DOF. The HMG and HMWG had significantly more attempts compared to the HMW group (p<0.001). The HMG group had significantly more attempts than the HMWG group (p<0.001). The HMG group had a significantly greater number of attempts compared to the other experimental groups. A greater number in attempts could potentially result in a greater accumulation of error and provide high CER scores.

The two-way mixed ANOVA revealed that there was a significant interaction between DOF and Training Sessions. There was a statistically significant interaction between Training Session and Degree of Freedom on cube error as estimated with Greenhouse-Geisser method due to violation of Mauchly's test for Sphericity $F(9.476,50.539)=2.47$, $p=0.019$. Figure 4.7 illustrates the cube error for each DOF group

and indicates that the change in cube size over the training sessions had a significant effect on cube error for the experimental DOF.

A retention test was administered a week after completion of training to observe the effect of training on CER and is documented in Figure 4.8. Statistical significance was reported between the HM control group and HMW group. The HM control group had significantly more errors than the HMW group (p=0.002). Effects were documented between DOF groups. The HMW group had significantly fewer errors than the HMG group (p=0.004). There was no significance observed between the HMW and HMWG. The results suggest that upon completion of training the HM control group generated significantly more errors than the HMW group. Despite the lack of significance from the comparative analysis with the HM control group, the CER for the HMG and HMWG were still lower. The results propose that the ability to provide local rotations at the wrist may reduce the number of errors. The wrist component is necessary to stabilize the hand during transport, while the gripper is a critical element to maintain timing.
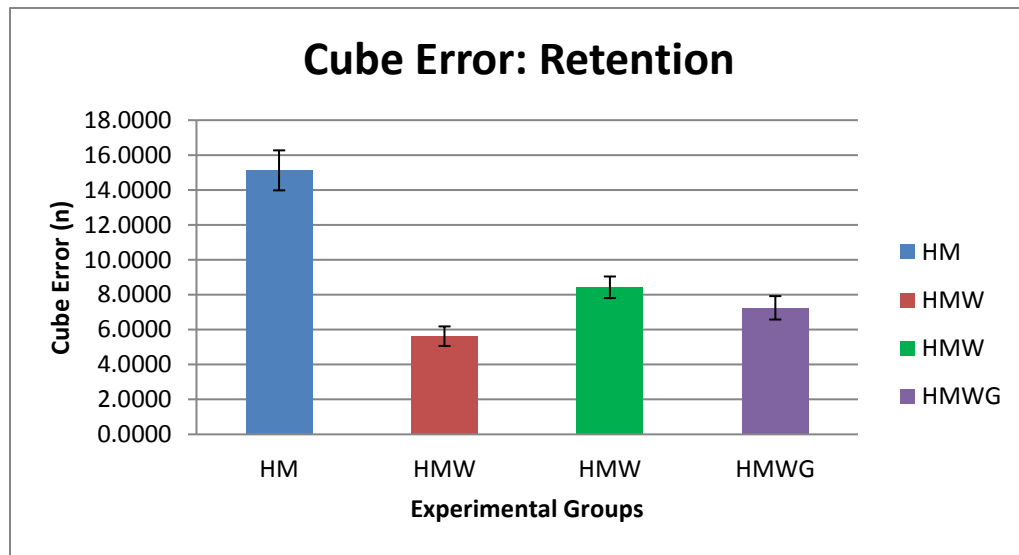
Figure 4.8 Cube error for each experimental group from retention training session

To assess the significance between the initial training session (TS1), the final training session (TS6), and the one week retention session (TS7) for each experimental group, a non-parametric Friedman test was performed to assess significant changes in cube error between the respective training sessions for the HM control group as a repeated measure. A Bonferroni Post Hoc with alpha corrected to $\alpha=0.0167$ was used to assess significance in cube error. The cube error for each experimental group for the designated training sessions is documented in Figure 4.9. Statistically significant differences were observed for cube error between TS6 and TS7 compared to TS1 for the HM control group ($p=0.003$, $p=0.001$). Training sessions 6 and 7 resulted in significantly more errors compared to TS1. There were no significant differences in cube error between TS6 and TS7 for the HM control group. Statistically significant differences were observed for cube error between TS6 and TS7 compared to TS1 for the HMW group ($p=0.011$, $p<0.001$). Training sessions 6 and 7 resulted in significantly fewer errors compared to TS1. The local rotations provided by the wrist component led to greater stabilization of the cube during transport.
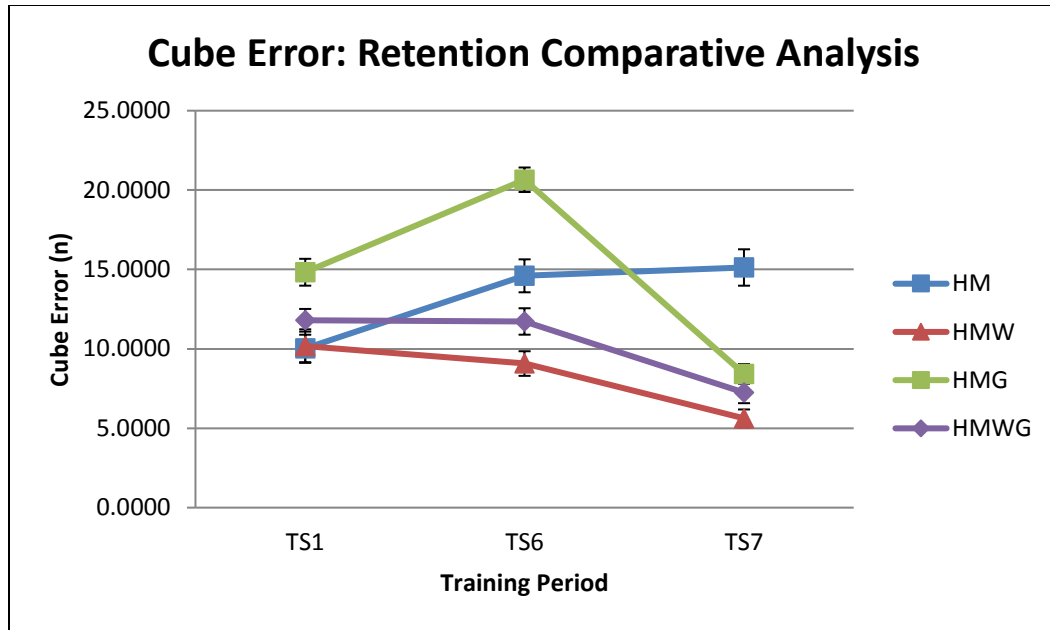
Figure 4.9 Comparative analysis between TS1, TS6, and TS7 for cube error.

Statistically significant differences were observed for cube error between TS6 and TS7 compared to TS1 for the HMG group ($p<0.001$). Training sessions 6 resulted in greater errors than TS1. The HMG group generated more errors during the final training session with the smaller cube. Significantly fewer errors were observed for TS7 compared to TS1 for the HMG group when the task was performed with the Big cube one week post training. Significant differences were observed between TS6 and TS7. Training Session 7 resulted in significantly fewer errors for the HMG group ($p<0.001$). Statistically significant differences were observed for cube error between TS6 and TS7 compared to TS1 for the HMWG group ($p<0.001$). Training Session 6 and Training Session 7 resulted in significantly fewer errors compared to TS1 for the HMWG. No significant differences were observed between TS6 and TS7 for the HMWG group. The

wrist component may have contributed to increased stability with greater distal directness during transport.

The CER values observed in TSR may be a result of the average number attempts made by each group (HM=39.95±1.60, HMW=36.65±2.07, HMG=42.10±1.26, HMWG= 37.2±1.19). There was no statistical significance observed for the average number of attempts between experimental groups. Each training group averaged over 35 attempts in the TSR. The HMG group had the greatest number of attempts (HMG=42.10±1.26) and the second highest CER during TSR. The HM control group had the second greatest number of attempts (HM=39.95±1.60) and the largest CER for TSR.
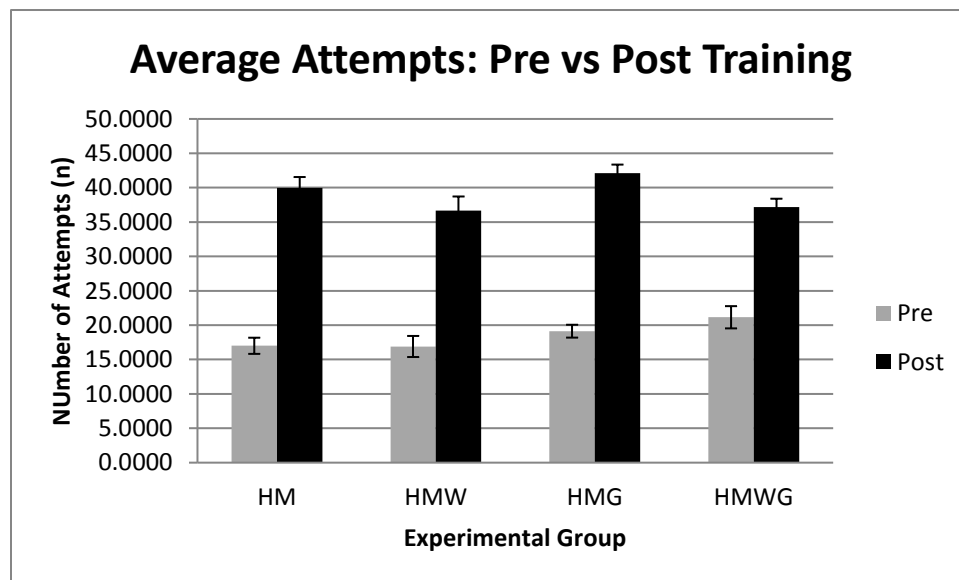
Figure 4.10 Average number of attempts pre training vs post training.

Comparative analysis from TS1 to TSR reveals that TS1 resulted in fewer attempts (HM=17.00±1.176, HMW=16.9±1.532, HMG=19.125±0.934, HMWG=21.15±1.619). Each group had significantly fewer attempts on TS1 compared to TSR based on Wilcoxon-W Test (p<0.001). Each group performed twice as many attempts during TS7

than TS1. The overall effect of CSX, CER, and attempts will be resolved with the analysis of CSR.

Statistical analysis was also performed between training days for individual experimental groups to determine the differences observed in cube error for each cube size. The retention analysis observed the effects of three periods (first, last, and retention) of training with respect to CER with the Big cube but did not observe significance of cube error as a result of cube size on different training days for each experimental group. Figure 4.7 indicates that there was no significance observed between training sessions for both the HMG group. Multiple comparisons between the training days were assessed using a Friedman Test to account for repeated measures due to violation of the Shaprio-Wilk Test for Normality. Significant effects were observed between training sessions for the HMG group. There was a significant increase in errors from TS1 to TS5 (p=0.006) and TS1 to TS6. The trend reported in Figure 4.7 illustrates that there was an approximately linear increase in the number of errors from TS1 to TS6. The HMG group did make significantly more attempts on average throughout the training. There were no statistical differences reported for CER for the HMWG between training sessions. Cube size had a significant effect on the HMG group while there were no other statistical differences in CER for the other experimental groups.

It should be noted that subjects were inclined to knock the cube off the table when it appeared to be in a compromised position. A compromised position was determined to be a location along the virtual surface where an edge was not exposed or the cube was at the furthest boundary on the table. This adapted transaction would result in an increased CER and provide a new cube positioned at the edge of the virtual table. In certain

instances, it was a necessary feature to have the cube reset in this manner. To normalize the effects of this action, CSR was calculated to determine the percentage of successful attempts, based on the ratio of success to the total number for attempts. This metric will be examined in the next section and represents the cube success ratio to the total number of attempts, which incorporates the summation of CER and CSX.

4.8 Cube Success Ratio Results

To standardize the scores relative to CSX and CER, the CSR was calculated for each experimental group. This ratio encompasses the level of success based on the number of attempts performed by each subject. The number of attempts incorporates the number of cubes scored and the number of cube errors obtained in a training session. This ratio is a measure of efficiency for each experimental group. Ratio values closest to a score of 1.0 are ideal and indicate better performance and greater efficiency. CSR scores closer to 0.0 indicate poor performance and reduced efficiency. Exceled performance can be attributed to efficient movements with high CSX and low CER. The CSR responses for each group during each training session are documented in Figure 4.11.

There was no significant interaction between Training Session and Degree of Freedom on Cube Success Ratio as estimated with Greenhouse-Geisser method due to violation of Mauchly's test for Sphericity $F(9.064, 48.341) = .758$, $p = 0.656$.
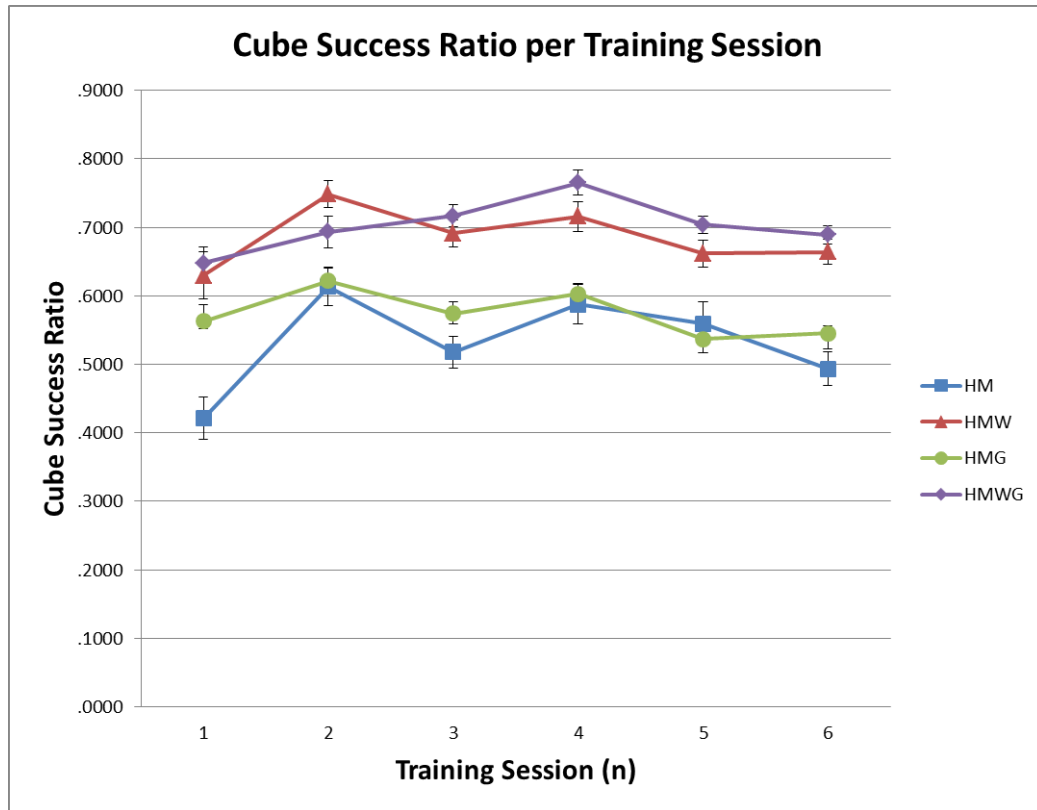
Figure 4.11 CSR per training session for each experimental group.

The data for each training session did not satisfy the Shapiro-Wilk Test for Normality and was assessed using the non-parametric Kruskal Wallis test. A significance of α=0.0071 was used to determine the probability of detecting significant differences between CSR values. All DOF (HMW,HMG,HMWG) groups showed greater CSR than the HM control group on TS1 ($p<0.001$, $p=0.004$, $p<0.001$) . There was no statistical significance observed between DOF. Training session 2 resulted in significantly greater CSR between the HMW group and the HM control group ($p<0.001$). Significant effects between DOF were observed. The HMW group had greater CSR than the HMG group ($p=0.001$). The transition from the big cube to the medium cube resulted in significantly greater CSR scores on TS3. The HMW and HMWG group had significantly greater CSR than the HM Control Group ($p<0.001$). Effects were reported between DOF. The HMW

group had greater CSR than the HMG Group (p<0.001). The HMWG Group had greater CSR than the HMG group (p<0.001). There was no significance reported between HMW and HMWG. The HMW and HMWG Group had significantly greater CSR than the HM control group on TS4 (p<0.001). Effects were reported between DOF on TS4. The HMW group had greater CSR than the HMG Group (p<0.001). The HMWG group had greater CSR than the HMG group (p<0.001). There was no significance between HMW and HMWG. The transition from the Medium cube to the Small cube on TS5 resulted in significant differences in CSR between experimental groups. The HMW and HMWG group had significantly greater CSR than the HM Control group (p=0.004, p<0.000). Effects were reported between DOF. The HMW group had greater CSR than the HMG Group (p<0.001). The HMWG group had greater CSR than the HMG group (p<0.001). There was no significance observed between HMW and HMWG group. The final training session TS6 also resulted in similar effects present in TS5. The HMW and HMWG group had significantly greater CSR than the HM Control group (p<0.001). Effects were reported between DOF. The HMW group had greater CSR than the HMG Group (p<0.001). The HMWG group had greater CSR than the HMG group (p<0.001). There was no significance between HMW and HMWG.

The HMW and HMWG group had significantly greater CSR values than the HM control group and the HMG group for TS3 through TS6. TS1 resulted in significant effects for all experimental groups. TS2 was the only training session that the HMW group had greater success than the HMWG group. Figure 4.11 illustrates that overall the HMW and HMWG were more efficient than the HM control group and the HMG group. The HMWG had a linear increase in CSR from TS1 to TS4 but then experienced a

decrease in CSR when the Small cube was tested. The HMWG had the greatest CSR value on TS4. The HMW group exhibited a step response when the cube size changed between training sessions. The HMG group consistently fluctuated between 0.5 and 0.6 throughout the training. The HM control had significantly lower CSR values throughout the entire training session compared to the HMW and HMWG. It also had the lowest CSR score on TS3. The results suggest that groups with the wrist component are more efficient than the groups without the wrist. There were no significant effects observed between the HMW and the HMWG. Despite the lack of significance between the HMW and HMWG group, the HMWG group was able to continuously improve CSR and had greater CSR scores throughout training after TS3. The data suggests that the combination of the wrist and gripper may result in greater efficiency evident by HMWG CSR values.
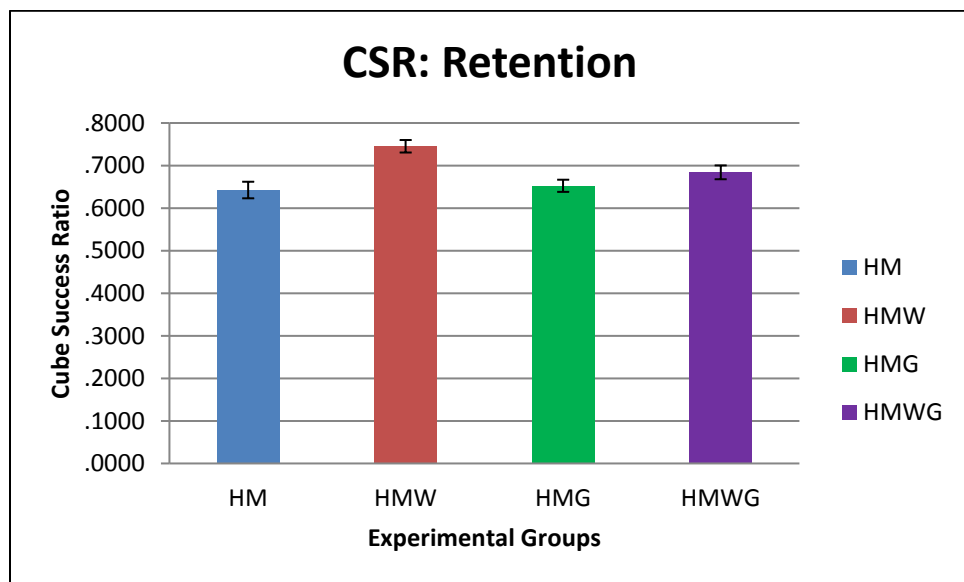
Figure 4.12 CSR retention values for each experimental group.

The retention test revealed statistically significant results between the experimental groups. The observed CSR for TSR is recorded in Figure 4.12. The HMW group had significantly greater CSR than the HM control group ($p<0.001$). Effects were reported between DOF. The HMW group had greater CSR than the HMG control group ($p<0.001$). There was no statistical significance reported between the HMW and HMWG group. Based on Figure 4.12, the HM group had the lowest CSR score, while the HMW group had the greatest CSR score. It should be noted that the HMWG group had similar scores to the previous training session, TS6, with the Small cube, compared to TSR (TS6=0.689±0.013, TSR=0.684±0.016). This suggests that the HMWG might not have been as affected by cube size as the other experimental DOF based on the relative maintenance of CSR from TS6 to TSR. Another notable observation concerns the HMW group. Performance for the TSR was similar to TS2 with the Big cube (TS2=0.748±0.0198, TSR=0.745±0.01471).

The results suggest that upon completion of training the HM control group was the least efficient as determined by the low CSR value. Despite the lack of significance from the comparative analysis between the HMWG group and the HM control group, the CSR for the HMWG was still greater. The HMW group had significantly higher CSR scores than the HM control group and had greater CSR scores than the other experimental DOF, although there was no statistical significance.
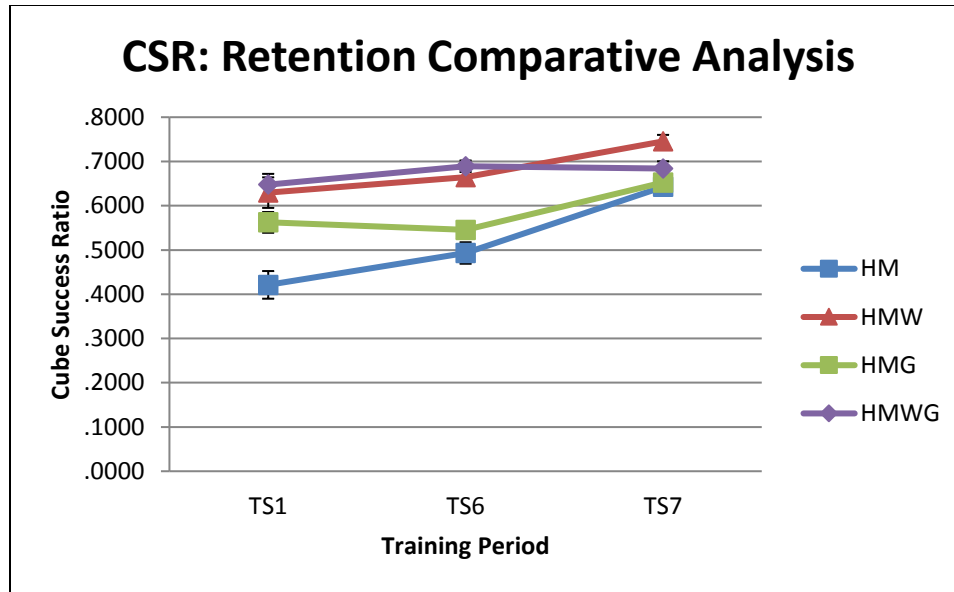
Figure 4.13 Comparative analysis for CSR values between TS1, TS6, and TS7.

Statistical analysis was performed to determine the significance of improvement in CSR scores between TS1 and TSR. A The non-parametric Friedman test was performed to assess significant changes in cube success ratio between the respective training sessions for the HM group as a repeated measure. A Bonferroni Post Hoc with alpha corrected to $\alpha=0.0167$ was used to assess significance in the Cube Success R atio. Statistically significant differences were observed for TS6 and TS7 compared to TS1 for the HM control group ($p<0.001$). Significant differences were observed between TS6 and TS7. Training Session 7 resulted in significantly greater CSR values compared to TS1 for the HM control group. Statistically significant differences were observed for and TS7 compared to TS1 for the HMW group ($p=0.003$). There were no significant differences observed between TS6 and TS7. Statistically significant differences were observed for the HMG group for TS7 compared to TS1 ($p=0.001$). Significant differences were observed between TS6 and TS7. The HMG group had significantly greater CSR values on TS7 compared to TS6 ($p<0.001$). There were no significant differences observed

between the training sessions for the HMWG group. Figure 4.13 suggests that the improvement in efficiency is based on an increase in success, with a decrease in error. The HM control group had the greatest improvement in CSR with a change of 0.22 points from the initial training to the final training (TS1=0.4211±0.03124, TSR=0.643±0.019). Each group statistically improved from TS1 to TSR. This proposed factor of CSR indicates that the improved efficiency may be a result of learning since increased CSR values reflect an increase in success with a decrease in error. The groups with the wrist component were able to generate greater CSR values during the retention task and over the course of training based on fewer errors with greater success. The normalized success demonstrates the importance of each component and the influence of greater success with the gripper and greater stability to reduce errors with the wrist component and is evident with the HMWG group.

To determine the effect of cube size throughout training, statistical analysis was performed to assess the significance between training sessions for each experimental group. A Friedman Test was performed for each experimental group based on violation of Shapiro-Wilk Test for Normality to determine the repeated measures performance over the course of training. Bonferroni correction was applied to adjust alpha in order to correct for multiple comparisons and protect significance. The data in Figure 4.11 suggests that the HM control group was able to efficiently transport the different sized cubes present in TS2, TS4, and TS5 compared to TS1. There was no significance observed between training days for each experimental group. no other significant results reported between training days. Subjects in each experimental group were more efficient by the end of TSR compared to TS1, as determined during the pre vs post investigation.

While there was minimal statistical difference observed among training sessions, the fundamental principal demonstrated by increased CSR from TS1 to TSR, reflects the ability to increase efficiency over the course of training. This result suggests that learning may contribute to greater CSR scores as the essential elements involved are improved CSX with reduced CER.

4.9 Trajectory Length Results

Each transport trajectory that generated a successful response was measured for each experimental group over the duration of training. The trajectory length (TRL) encompasses the end-effector path measured from the initial position of the virtual table to the specified target. Successful forward trajectories were measured and averaged for each session. Trajectories that did not satisfy a successful attempt, were incomplete or partial due to user error (CER), were not incorporated into TRL measurement. TRL was calculated to determine directness of transport and potentially identify instances of compensated excursions. More direct trajectories are represented by low TRL values. Indirect trajectories as a result of increased or compensated movements reflect high TRL values. An estimate of the linear relationship between the planar trajectory for forward and return trajectories will be explored with RSQ values.

Statistical analysis was performed on the average trajectory length for each training session and compared across experimental groups to determine statistical differences in TRL. Each training session for each experimental group was in violation of the Shapiro-Wilk Test for Normality. A Kruskal-Wallis test was performed to evaluate

significant changes in TRL with an alpha value of α=0.0071. The trajectories for each training session are documented in Figure 4.14.

The two-way mixed ANOVA revealed that there was no significant interaction between Training Session and Degree of Freedom on Trajectory Length as estimated with Greenhouse-Geisser method due to violation of Mauchly's test for Sphericity $F(6.671,35.579)=.608$, $p=0.738$. Simple main effects for between subjects and with-in subject comparisons were performed to determine significance of DOF and assess training sessions.
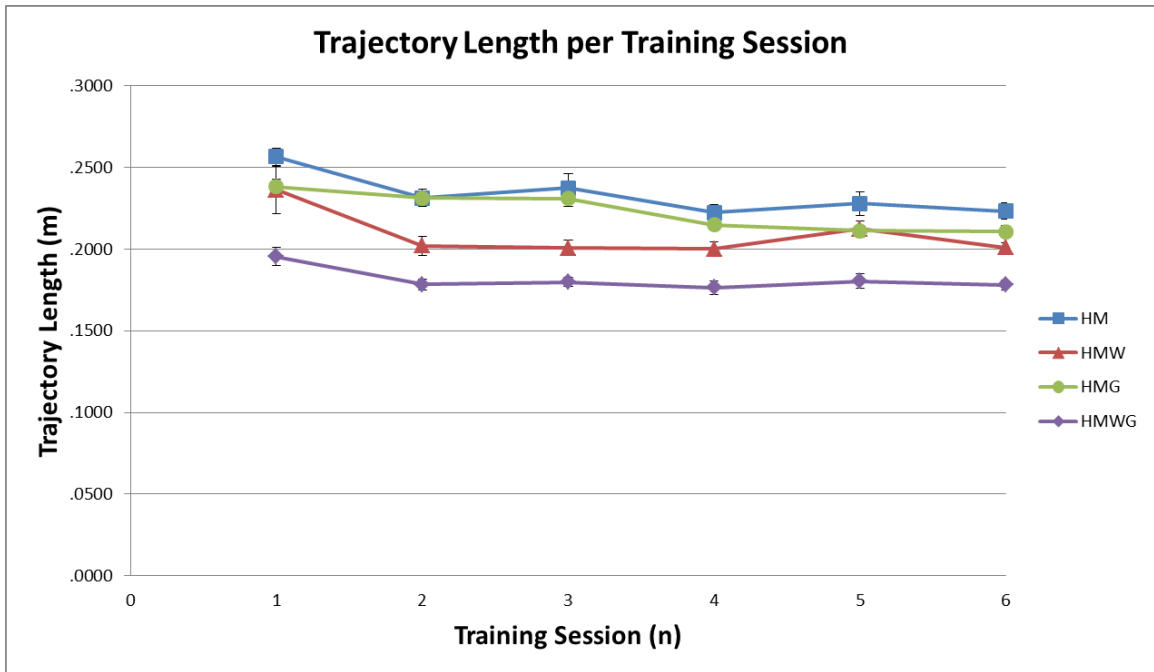
Figure 4.14 Average trajectory lengths for each experimental group per training session measured in meters.

Subjects in HMWG group had significantly shorter trajectory lengths ($p<0.001$) than the HM control group on TS1. The HMW group was trending towards significance compared to the HM control group ($p=0.007$). Statistically significant differences in TRL between DOF were observed. The HMWG group had shorter trajectory lengths compared

to both the HMW and HMG on TS1 (p<0.002, p<0.001). Training session 2 resulted in significant differences in TRL values compared to the control group. Subjects in the HMW and HMWG group had significantly shorter trajectory lengths than the HM control group for TS2 (p=0.001, p<0.001). Statistically significant differences in trajectory length were observed between DOF on TS2. The HMWG group had shorter trajectory lengths compared to HMW group (p=0.003) and the HMG group (p<0.001). Significant interactions between the HMW and HMG were also reported (p<0.001). TRL for HMWG group for TS2 was statistically significant for all comparisons and had the overall lowest TRL. Significance was detected for TS3 between the HM control group and the experimental DOF. Subjects in the HMW and HMWG group had significantly shorter trajectory lengths than the HM control group (p<0.001). Statistically significant differences in TRL between DOF were observed on TS3. The HMWG group had shorter TRL compared to the HMG group (p<0.001). There was no significant difference in TRL between HMW and HMWG. The HMW group had significantly shorter TRL compared to the HMG group (p=0.002). The HMWG had significantly lower scores than the HM control group and HMG group. While not statistically significant, the HMWG group had lower TRL than the HMW group on TS3. Training session 4 resulted in statistically significant results. Subjects in the HMW and HMWG group had significantly shorter trajectory lengths than the HM control group on TS4 (p=0.002, p<0.001). Statistically significant differences in TRL were determined for the experimental DOF. The HMWG group had shorter trajectory lengths compared to the HMW group and the HMG group (p<0.001). The HMWG had the significantly shortest TRL on TS4 compared to all the experimental groups. Subjects in the HMWG group had significantly shorter trajectory

lengths (p<0.001) than the HM control group on TS5. Statistically significant differences in TRL between DOF were observed. The HMWG group had shorter trajectory lengths compared to the HMW group and HMG group (p<0.001). The HMWG group had statistical lower TRL values for TS5 compared to all other experimental groups. Training sessions 6 had statistically significant difference in TRL among experimental DOF. Subjects in the HMW and HMWG group had significantly shorter trajectory lengths (p<0.001) than the HM control group on TS6. Statistically significant differences in trajectory length between DOF were observed. The HMWG group had shorter trajectory lengths compared to the HMW and HMG group (p<0.001). The HMWG had statistically significant TRL values compared to all experimental DOF on TS6.

Overall, the HMWG had significantly lower TRL values compared to the HM control for every training session. The HMW group also had statistically lower TRL compared to the HM control group for every training session except TS5. The HMWG had statistically lower TRL values compared to the HMW and HMG group for every training session except TS3. There was no significance observed between the HMW and the HMWG for this training session (p=0.06). The results in Figure 4.14 suggest that the combination of the wrist and gripper led to statistically significant TRL values with more direct modes of transport. The HM control group had statistically higher TRL values compared to the HMWG group suggesting that a lack of wrist and gripper contributed to less direct transports with potentially compensate movements.

Post training analysis was performed to estimate improvement in TRL upon completion of training. The trajectories are depicted in Figure 4.15. Kruskal-Wallis Test was performed to determine the significance with α=0.0071 since the data was not

normal. Subjects in the HMW and HMWG group had significantly shorter trajectory lengths than the HM control group (p=0.002, p<0.001). Statistically significant differences in trajectory length were present between DOF. The HMWG group had significantly smaller TRL compared to the HMG (p<0.001). The HMWG had the lowest trajectory length for TSR and was significantly lower than the HM control group and the HMG group. The HMWG group was able to continue to improve TS6 to TSR despite the change in cube size (TS6=0.1781±0.003, TSR=0.1743±0.003). The greatest difference (0.024m) between groups can be observed between the HM control group and the HMWG group (HM=0.1981±0.00241, HMWG=0.1743±0.00325).
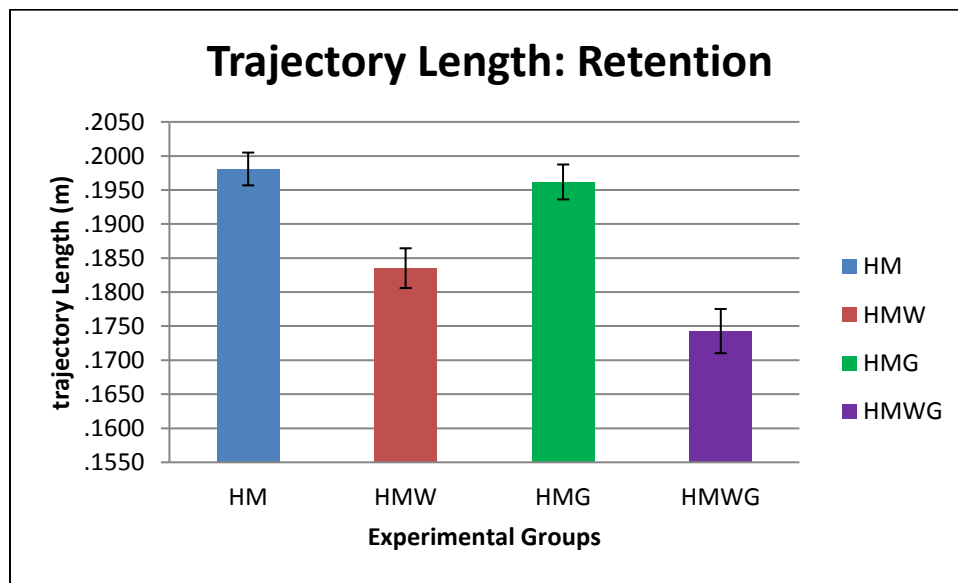
Figure 4.15 TRL values measured during the retention phase of training.

Trajectory lengths from the initial training session (TS1) were compared to trajectory lengths from the final training session (TS6) and the retention session (TS7) to determine the degree of improvement or change in trajectory length over the course of training. The comparative analysis represents an estimate in improvement of directness during transport and may identify instances of learning with less compensated

movements. To determine these effects, a non-parametric Friedman test was performed to assess significant changes in trajectory length between the respective training sessions for each experimental group. A Bonferroni Post Hoc with alpha adjusted to $\alpha=0.0167$ to correct for multiple comparisons was used to assess significance in trajectory length. The trajectory lengths for each respective session are evident in Figure 4.16. A downward trend indicates improvement in trajectory length and indicates that subjects were able to transport in a more direct manner.

Statistically significant differences were observed for TS6 and TS7 compared to TS1 for the HM control group ($p<0.001$). Training session 6 and 7 resulted in significantly shorter trajectories than TS1. Training session 7 resulted in significantly shorter trajectories compared to TS6 ($p<0.001$). The HM control group was able to utilize more direct pathways after training with various cube sizes. Significant differences were observed for TS6 and TS7 compared to TS1 for the HMW group ($p=0.004,p<0.001$). Training Session 6 and 7 resulted in significantly shorter trajectories than TS1 for the HMW group. There were no significant differences between TS6 and TS7. Statistically significant differences were observed for the HMG group between TS6 and TS7 compared to TS1 ($p<0.001$). Training Session 6 and 7 resulted in significantly shorter trajectories than TS1 with more direct modes of transport. Training Session 7 resulted in significantly shorter trajectories compared to TS6 ($p=0.015$) for the gripper group. Additional significance was observed for the HMWG group. Significant differences were observed for TS6 and TS7 compared to TS1 ($p=0.013,p=0.002$). Training Session 6 and 7 resulted in significantly shorter trajectories than TS1. There were no significant differences observed in trajectory lengths between TS6 and TS7.
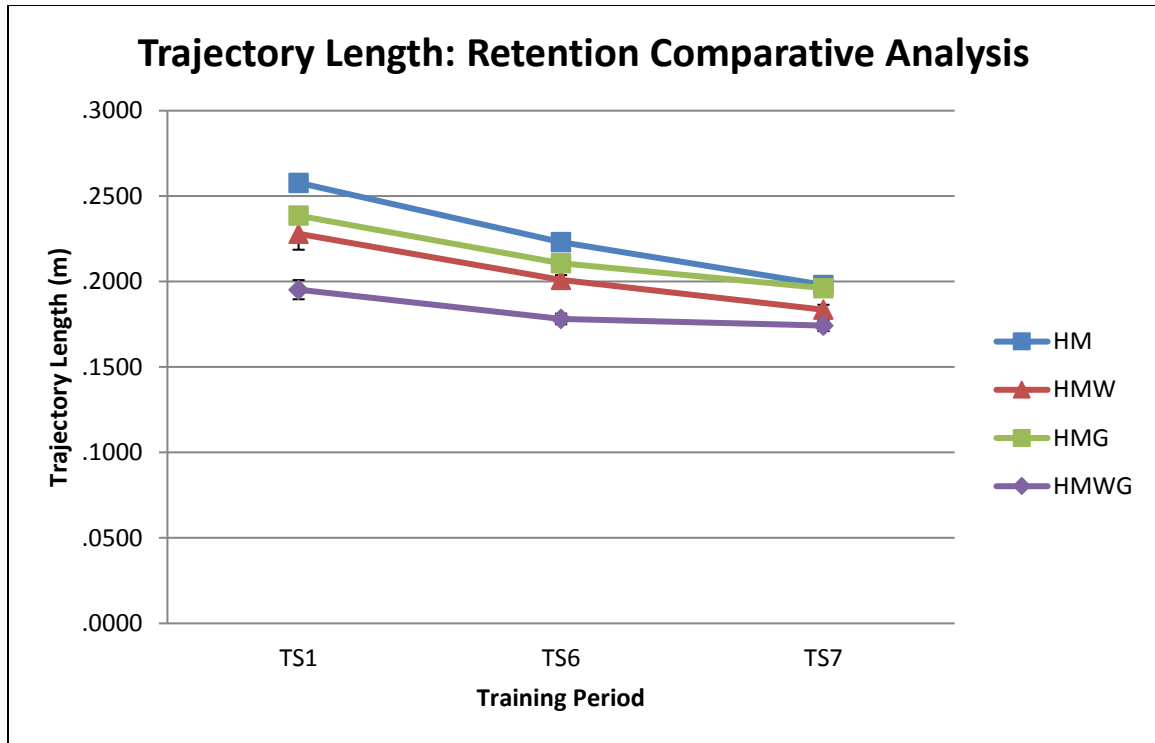
Figure 4.16 Comparative analysis for trajectory length between TS1, TS6, and TS7.

All groups exhibited a downward trend which suggests that each group was able to improve over the course of training. Each group had statistically significant improvements in TRL from TS1 to TSR. The HMWG group had the lowest TRL values and had the most direct transports from the virtual table to the virtual target. The HM control group had the greatest change in TRL from TS1 to TSR with a $\Delta=0.059m$ (TS1=0.2578 ± 0.0058, TSR=0.1981 ± 0.00241). The HMWG had the smallest change in TRL $\Delta=0.021m$ (TS1=0.195 ± 0.0056, TSR=0.1743 ± 0.00325). While each group was able to improve, the higher values of TRL for the HM control group suggest that indirect paths were taken relative to the HMWG group, possibly due to compensated excursions with longer path lengths. The combination of the wrist and gripper offer modes of more direct transport that emphasize the importance of distal degrees of freedom. The increased distal

degrees of freedom provide greater local rotations that minimize proximal global movements evident by the shorter paths taken by the HMWG group. The effect of cube size will be explored in the following section.

Statistical analysis was performed to assess the significance between training sessions for each experimental group and to determine the effect of cube size on TRL. A Friedman Test was performed for each experimental group based on violation of Shapiro-Wilk Test for Normality to assess the repeated measures for each Training Session. Bonferroni adjusted alpha was used to protect significance for multiple comparisons and evaluated at a significance level of $\alpha=0.05$. Effects between cube sizes can be observed in Figure 4.14. There was no statistical significance observed for the Training Sessions for the HM control group. There was no statistical significance observed on TRL between Training Sessions for the HMW group. Significance was observed for the HMG group but with the Bonferroni correction for multiple comparisons, no significance was observed. There was no statistical significance observed on trajectory length during the HMWG Training Sessions. The fundamental principal demonstrated by decreased TRL from TS1 to TSR for all experimental groups, reflects an improvement in the ability to directly transport. The results obtained from TSR suggests that improved TRL may be a result of learning to increase directness.

4.10   Delta Cube Time Results

Delta Cube Time provides an estimate of the average time to complete a successful transport. The recorded period indicates the amount of time to transport the cube from the virtual surface to the virtual target until the next successful attempt. The time for each attempt was averaged over the course of the session. The average time for a transport accounts for the time spent on the initial grasp phase and the time spent to complete transport until the cube is placed in the target area. Time intervals between successful attempts were recorded to observe the rate of change of success and potential improvement throughout training. Quick transports have low DCT values, while slower attempts are represented by high DCT values.
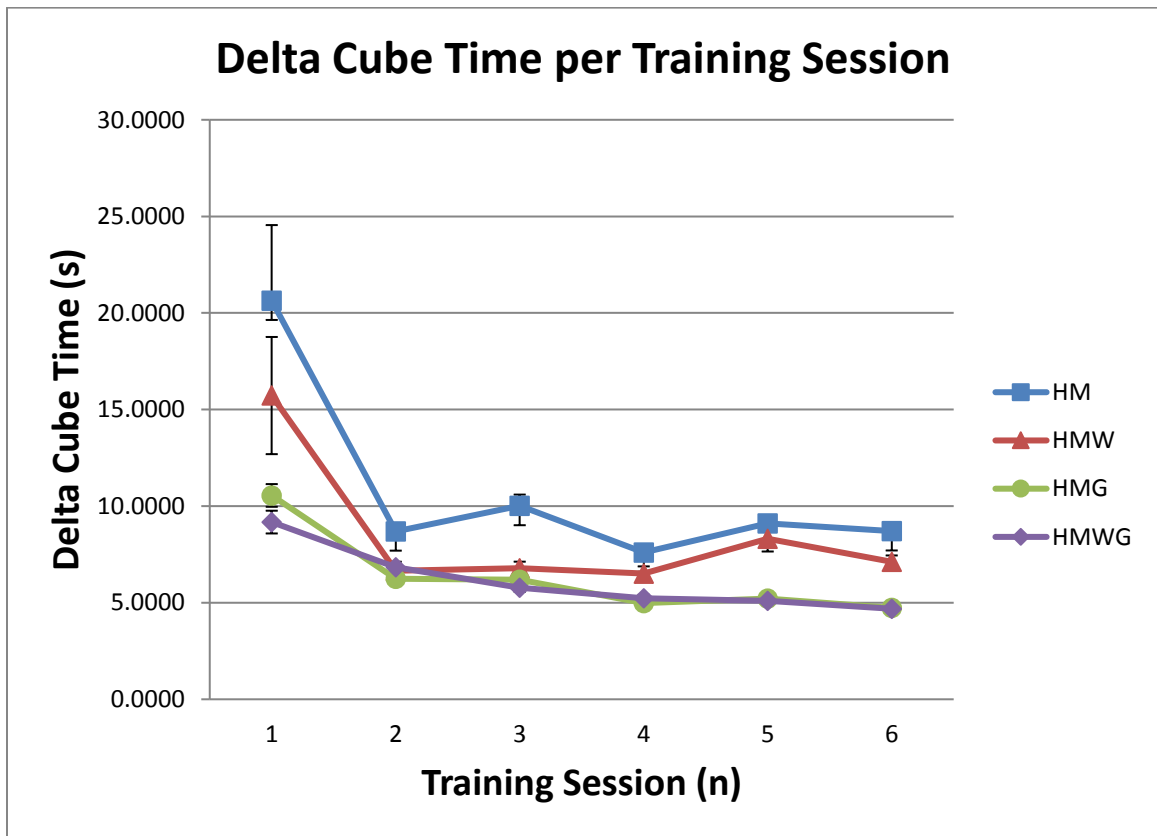
Figure 4.17 Average DCT in seconds for each experimental group for each TS.

A two-way mixed ANOVA revealed that there was no significant interaction between Training Session and Degree of Freedom on Delta Cube Time as estimated with Greenhouse-Geisser method due to violation of Mauchly's test for Sphericity $F_{(3.186, 16.993)} = 1.096$, $p = 0.380$. Statistical analysis was performed to assess significance and evaluate simple main effect between DCT values for each experimental group. Each training session for each experimental group was in violation of the Shapiro-Wilk Test for Normality. A Kruskal-Wallis test was performed to evaluate significant changes in DCT with an alpha value of $\alpha = 0.0071$. The DCT responses for each training session are evident in Figure 4.17.

There was no statistical significance observed on TS1 for DCT between DOF and HM control. There were no significant effects between DOF on TS1. Significance was observed on TS2 between the experimental groups and the control group. All DOF had significantly faster DCT than the HM control group on TS2 ($p < 0.001$). There was no statistical significance reported between DOF. All experimental groups had significantly faster DCT than the HM control group on TS3 ($p < 0.001$). There was no statistical difference between HMG and HMWG on TS3. Training session 4 resulted in significant effects between the experimental DOF and the HM control group. The HMG and HMWG group had significantly faster DCT than the HM control group on TS4 ($p < 0.001$). DCT significance was reported between experimental DOF on TS4. The HMG and HMWG had faster transport times than the HMW group ($p < 0.001$). There was no statistical difference between HMG and HMWG. HMG and HMWG groups had significantly faster DCT than the HM control group on TS5 ($p < 0.001$). DCT significance was also observed between experimental DOF on TS5. The HMG and HMWG had faster transport times

than the HMW group (p<0.001). There was no statistical difference between HMG and HMWG. The final training session, TS6, also resulted in significant effects between the experimental DOF and the HM control group. HMW, HMG, and HMWG groups had significantly faster DCT than the HM control group (p<0.001). DCT significance was reported between DOF. The HMG and HMWG had faster transport times than the HMW group (p<0.001). There was no statistical difference between HMG and HMWG groups.

The HM control group had slower response times as exhibited by the high DCT values. The HM control group was statistically slower than the experimental DOF groups for all training sessions except TS1 and TS5. There was no significant difference in cube times on the first day of training. However, TS5 resulted in significant differences between the HMG and HMWG group. The HM control group exhibited the greatest improvement in DCT (Δ=10.4s) from TS1 to TS2 compared to the experimental DOF (TS1=19.1±3.36, TS2=8.71±0.403). The introduction of a different cube size was accompanied by an increase in DCT for the first session of each new cube. This effect can also be observed in the HMW group in Figure 4.17. The cube size effect does not appear to be evident for the HMG and HMWG group. Each response from the HMG and HMWG group appeared to improve over the course of training as DCT values approached 5.0s. Statistically significant differences in DCT were observed between the HMW group and the experimental DOF that utilized the gripper (HMG, HMWG). The HMG and HMWG were significantly faster at transport throughout the training sessions except for the training sessions that relied on Big cube transport (TS1 and TS2). Figure 4.17 suggests that the HM control group was the slowest compared to the experimental DOF and the HMG and HMWG were significantly faster than the HMW group. No

statistical significance was observed between DCT values for the HMG and HMWG group.
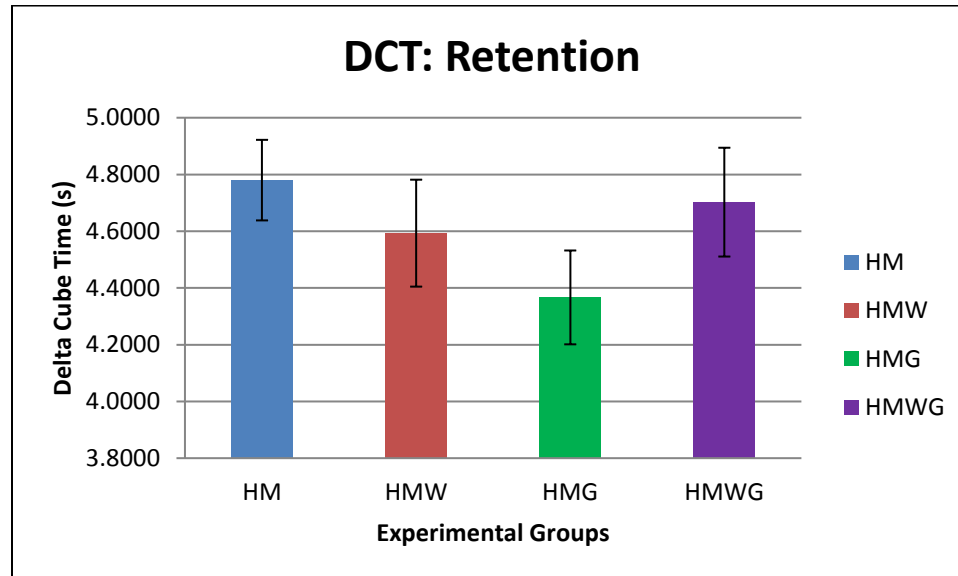
Figure 4.18 Average DCT values in seconds recorded during retention test.

Post training analysis was performed to estimate improvement in DCT upon completion of training. The average times of success are evident in Figure 4.18. Kruskal-Wallis Test was performed to determine the significance with $\alpha=0.0071$ since the data did not satisfy the Shapiro-Wilk Test for normality. There was no statistical significance found between DCT values for the experimental DOF and HM control during the Retention Task. There was no significant differences between DCT between DOF. Despite the lack of significance between the groups, Figure 4.18 indicates that each group was able to generate successful movement under 5.0s. Qualitatively, the HMG group had the lowest DCT values, which reflects the ability to score more quickly than the other groups. While not statistically significant, the HM control group had the highest DCT values for the retention session, suggesting slower movements.
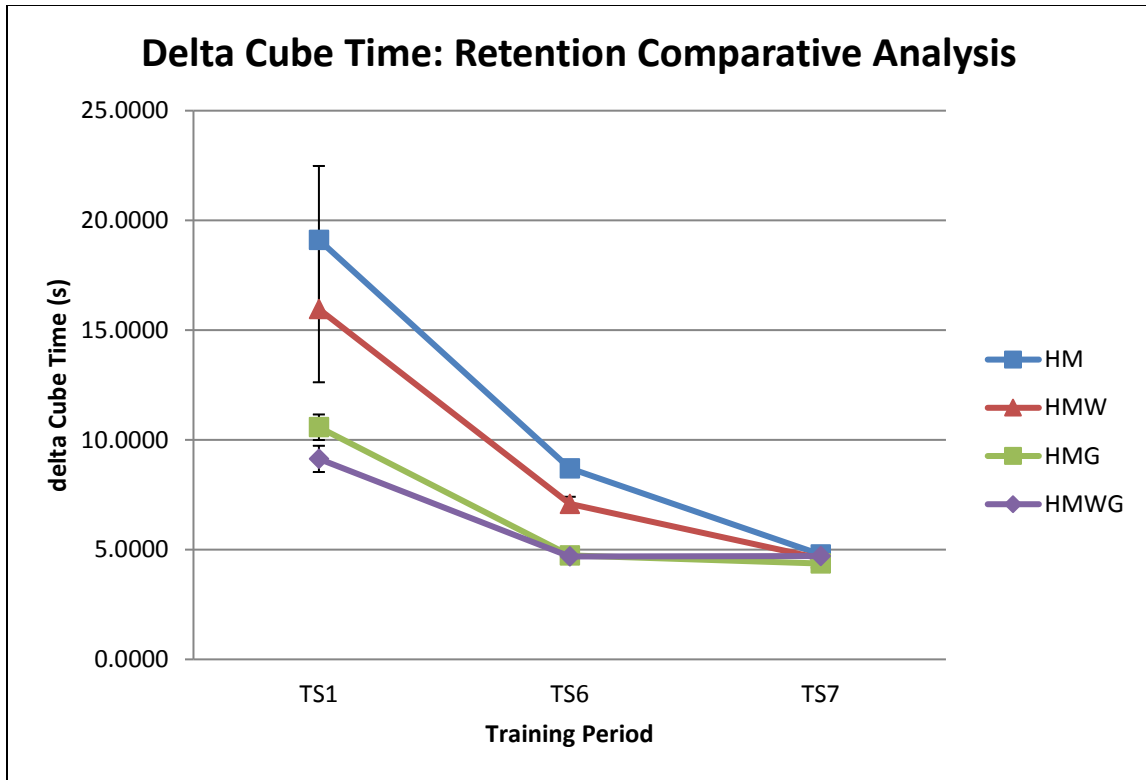
Figure 4.19 Comparative analysis for DCT retention between TS1, TS6, and TS7.

A comparative analysis was performed to determine if there were statistically significant changes in DCT between the initial, final, and retention training sessions. The comparisons observed in Figure 4.19 indicate that there was statistical significance observed between the training sessions for each experimental group. A non-parametric Friedman test was performed to assess significant changes in delta cube time between the respective training sessions for the HM control group as a repeated measure. A Bonferroni Post Hoc with alpha corrected to $\alpha=0.0167$ was used to assess significance in delta cube time. Statistically significant differences were observed for TS6 and TS7 compared to TS1 ($p<0.001$). The HM control group generated faster movements during TS6 and TS7 compared to TS1. There were no significant differences between TS6 and TS7. Statistically significant differences were observed for TS6 and TS7 compared to

TS1 for the HMW group (p=0.002,p<0.001). The HMW group generated faster movements during TS6 and TS7 compared to TS1. There were no significant differences in delta cube time between TS6 and TS7. Significant differences were also observed for the HMG group. The HMG group had significantly faster responses for TS6 and TS7 compared to TS1 (p<0.001). There were no significant differences in delta cube time between TS6 and TS7. Statistically significant differences were observed for TS6 and TS7 for the HMWG compared to TS1 (p<0.001). The HMWG group generated faster movements during TS6 and TS7 compared to TS1. There were no significant differences in Delta Cube Time between TS6 and TS7.

The HM control group exhibited the greatest change in DCT (Δ=14.33s, TS1=19.155±3.36, TSR=4.78±0.142) over the course of training. The comparison each time course of training reveals that each experimental group was able to conduct significantly faster transport upon completion of training evident by the downward trend in Figure 4.19. All groups exhibited significantly faster times during the retention session. This significant improvement from TS1 to TSR provides evidence that suggests that each experimental group learned to transport the cube faster after training.

Effects between training days for each experimental group were also investigated to determine the significance of cube size throughout training. Each training session for each experimental group was analyzed to determine if training days were statistically significant. A Friedman test for repeated measures was performed to assess statistical significance for each Training Session for each experimental group. Significance was evaluated using α=0.05 with internal adjustments for multiple comparisons applied by SPSS. The results between each group are indicated in Figure 4.17. The data suggests

that the HM group had slower response times (high DCT) for TS1 compared to TS4(p=0.004). The HM group exhibited the fastest response time for TS4 and was significantly faster than TS1. The HMW Group had significantly slower response times (high DCT) for TS1 and TS4 (p=0.02, p=0.035). Figure 4.17 reveals that the HMG group had slower movements (high DCT) for TS1 compared TS4 (p=0.02) and TS6 (p=0.035). Significant observations were reported for Training Session 2. Training Session 6 had significantly faster response times (low DCT) compared to TS2 (p<0.001). HMWG group also had significantly slower movements (high DCT) during TS1 compared to the final Training Session, TS6 (p=0.011). The HMWG recorded the fastest time for TS6. Training Session 2 was significantly slower than TS6 (p=0.001). Training Session 2 had slower response times (low DCT) compared to TS6. The HMG and HMWG had statistically significant effects between training days. The results indicate that groups with the gripper had significantly lower DCT in the later stages of training with different cube sizes compared to the HM control group and HMW group. The HMG and HMWG group demonstrated statistical improvements in transport time between training sessions other than TS1.

4.11   Smoothness Results

To determine the smoothness of virtual transportation with robotic assistance, the third derivative of position was calculated to quantify jerk and determine the quality of movement. Smoothness is characterized as normalized integrated jerk and is calculated as $NIJ = \sqrt{\frac{T^5}{2L^2} \int J^2}$, where T=duration, L= trajectory length, J=$\dddot{x}$, NIJ= normalized

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integrated jerk (Adamovich et al. 2009). This feature provides a representation of the smoothness of transport as defined by the end effector trajectory for each experimental group. For the CNS to move a limb smoothly from one point to another, it should minimize the sum of the squared jerk along its trajectory (Hogan et al. 1984). This result quantifies the ability to produce smooth movements as the experimental groups transport the virtual cube to the specified target. Smaller values of smoothness (NIJ) represent movements with minimal jerk and fewer sub-movements, whereas large values of NIJ indicate increased jerk along the defined trajectory with constant changes in movement.

Statistical methodologies were applied to determine the significant differences between NIJ values amongst experimental groups. The two-way mixed ANOVA revealed that there was no significant interaction between Training Session and Degree of Freedom on smoothness as estimated with Greenhouse-Geisser method due to violation of Mauchly's test for Sphericity $F_{(3,16)}=0.931$, $p=0.449$. Simple main effects between experimental groups were statistically evaluated. The data for each experimental group did not satisfy the Shapiro-Wilk Test for Normality and was assessed using the non-parametric Kruskal-Wallis Test to test for simple main effects between experimental groups. A Bonferroni Post Hoc test was performed to determine the significance between experimental groups. Significance was evaluated with an alpha value of $\alpha=0.0071$ to protect significance and reduce the risk of type I error. Smoothness values are indicated in Table 4.1 for TS1 and represent large values with increased jerk and sub movements. There was no statistical significance for NIJ between experimental groups for TS1. Smoothness as NIJ for the remaining training sessions are summarized in Figure 4.20.

Table 4.1 Smoothness Values as NIJ for each Experimental Group during TS1

Group	HM	HMW	HMG	HMWG
Smoothness	239116914862.7570	57599710575.9998	73777767.3998	36920020.1986
Stdev	154523667166.04900	32491509006.83660	41056471.38336	19661806.48746
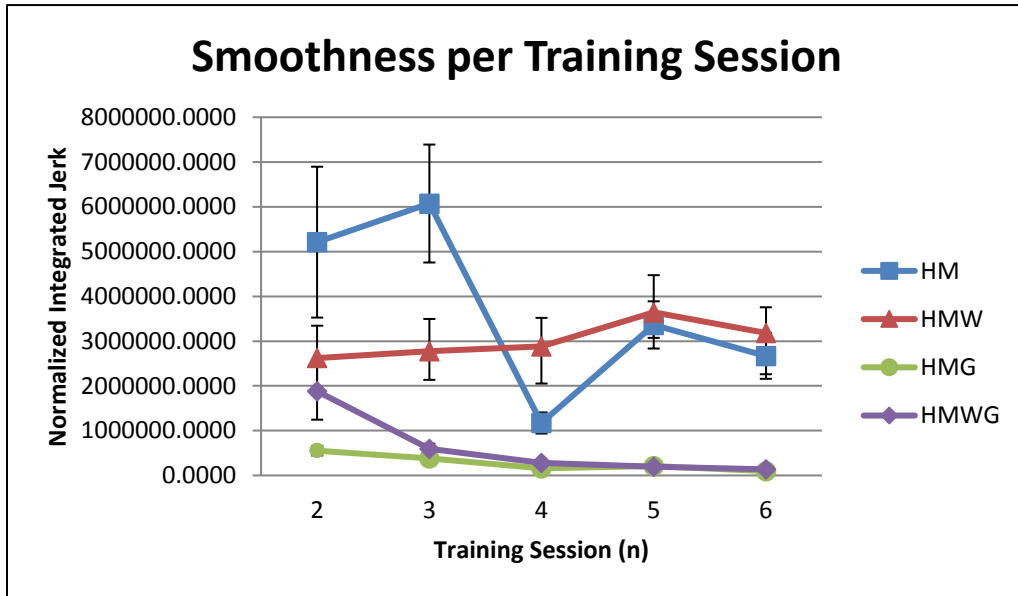
Figure 4.20 Smoothness calculated as NIJ for each experimental group for TS2 to TS6.

HMG group had significantly smoother trajectories than the HM control group (p=0.003) on TS2. The HMWG group trended towards significance compared to the HM control group (p=0.017) on TS2. There were no differences in smoothness between DOF groups on TS2. Training Session 3 resulted in significant differences between the HM control group and the experimental DOF. HMG and HMWG group had significantly smoother trajectories than the HM control group on TS3 (p<0.001). The HMW group trended towards significance compared to the HM control group (p=0.012). There were no differences in smoothness between DOF groups on TS3. Training Session 4 did not

result in statistically significant differences between the experimental DOF and the HM control group. Significant differences were observed between experimental DOF on TS4. The HMG and HMWG group had smoother trajectories compared to the HMW group (p<0.001). There was no statistical significance in smoothness between the experimental DOF and the HM control group for TS5. The HMG and HMWG trended towards significance compared to the HM control group (p=0.017, p=0.016). Observed effects that satisfied the desired confidence interval with α=0.0071 were reported between the DOF on TS5. The HMG and HMWG group had smoother trajectories compared to the HMW group (p<0.001). Significant observations were reported between the experimental DOF and the HM control group on TS6. The HMG and HMWG group had significantly smoother trajectories than the HM control group (p=0.002). Observed effects were reported between the DOF. The HMG and HMWG group had smoother trajectories compared to the HMW group (p<0.001). There were no effects observed between the HMG and the HMWG.

The HM control group experienced the greatest changes in smoothness as a result of cube variability, Figure 4.20. The greatest change in smoothness other than from TS1 to TS2 for the HM and HMW group during training occurs from TS3 to TS4. The HM control group has less smooth movements when the Medium cube is introduced in TS3 and then rapidly adapts to the change in cube size in TS4 with improved smoothness (Δ=4901449.21). The introduction of the Small cube opposes progressive improvement and results in an increase in NIJ from TS4 to TS5. Qualitative analysis indicates that the HM control group was affected by cube size variability the most based on the continuous flux in NIJ values. The HMW improved from TS1 to TS2 but experienced an almost

linear increase in NIJ values as training progressed. The HMG and HMWG produced smooth movement throughout training with continued improvement despite the cube size variability. Both groups were able to improve over the course of training.

A comparative analysis between training days was performed to examine significant changes in NIJ between training sessions to further support the qualitative analysis observed in Figure 4.20. A Friedman Test was performed to determine significance between repeated measures for each Training Session. Statistical significance between TS1 and TS4 was observed for the HM control group. The HM control group generated significantly smoother movements in TS4 compared to TS1 (p=0.003). These respective training sessions demonstrate a quantitative improvement in transport with the medium cube. While the HMW group did generate less smooth movements throughout training, statistical significance was observed between TS1 and TS4 (p=0.006). Smoother movements were observed for the HMG group during TS4 and TS6 compared to TS1 (p=0.001, p=0.011). The HMG group generated significantly smoother movements as training progressed despite the change in cube size. Similarly, the HMWG group was able to generate smoother movements as training progressed. The HMWG generated significantly smoother movements during TS6 compared to TS1 (p=0.002). The results suggest that there was significant difference between Training Sessions for the HMG and HMWG suggesting that the gripper groups were able to produce smoother movements in the subsequent sessions regardless of the cube size.
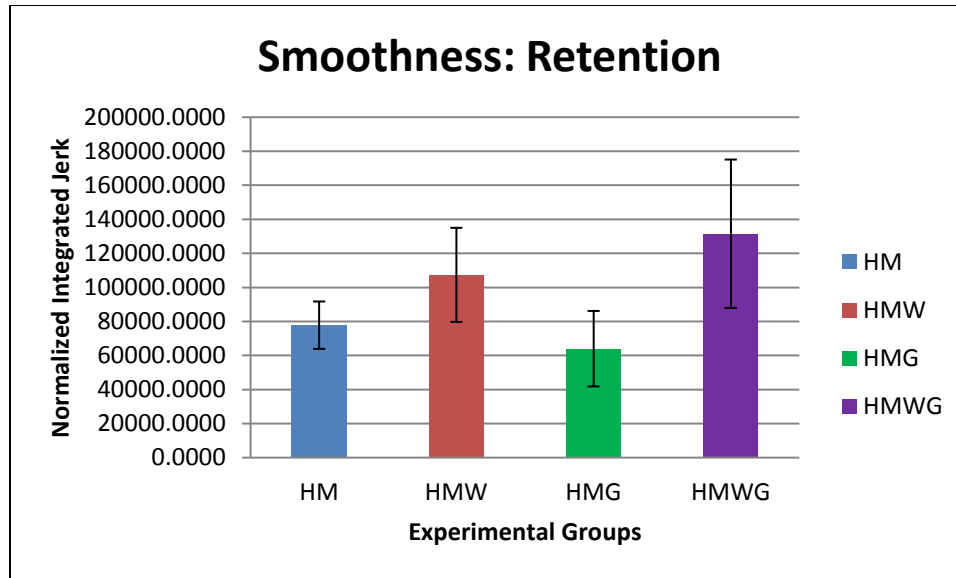
Figure 4.21 Smoothness as NIJ for each experimental group during retention task.

Upon completion of training, a follow up retention test was conducted to reassess training performance with the Big cube. Statistical calculations were performed to detect significant effects between experimental groups with an alpha value $\alpha=0.0071$. The NIJ values were in violation of the Shapiro-Wilk Test for Normality. A Kruskal-Wallis Test was issued to determine significance amongst experimental groups. It was determined that there was no statistical significance observed for smoothness between groups during TSR. Despite the lack of significance between the experimental groups, qualitative analysis from Figure 4.21 indicates that the HMG group generated the smoothest movements during TSR. The HMWG group had the least smooth movements during TSR with the greatest inter-subject variability evident by the large SEM. It should be noted that despite the appearance of less smooth movements during TSR, the HMWG group continued to improve from TS6 to TSR (TS6=136851±29761.18, TSR=131538.98±43576.31). Despite the change in cube size during training, the HMWG group continued to improve upon the previous session in the Retention Task, Figure 4.20.

The data also suggests that regardless of the experimental group, repetitive training/practice contributed to smoother movements possibly due to a learning effect.

Table 4.2 Comparative Analysis for NIJ Values between TS1 and TSR

Smoothness		Mean	Std. Error	Percent Change
HM	TS1	2.39E+11	1.55E+11	
	TS6	2.67E+06	5.13E+05	
	TS7	7.78E+04	1.39E+04	3.07E+06
HMW	TS1	5.76E+10	3.25E+10	
	TS6	3.19E+06	9.70E+04	
	TS7	1.07E+05	2.76E+04	5.36E+05
HMG	TS1	7.38E+07	4.11E+07	
	TS6	9.70E+04	1.53E+04	
	TS7	6.40E+04	2.22E+04	1.15E+03
HMWG	TS1	3.69E+07	1.97E+07	
	TS6	1.37E+05	2.98E+04	
	TS7	1.32E+05	4.36E+04	2.80E+02

To determine the effects of training on the experimental groups, the retention test was administered after TS6 to compare three time periods over the course of training: initial, final, and retention. A non-parametric Friedman test was performed to assess significant changes in smoothness between the respective training sessions for the HMWG group as a repeated measure. A Bonferroni Post Hoc with alpha corrected to $\alpha=0.0167$ was used to assess significance in smoothness. The percent change for each experimental group recorded in Table 4.2 indicates that each group exhibited improvements in smoothness. Subjects in the HM group demonstrated improvements in trajectory smoothness after training ($p<0.001$). The HM control group exhibited a 3.07E+06% improvement from

TS1 to TSR. Subjects in the HMW group demonstrated an improvement in trajectory smoothness after training (p<0.001). The HMW group demonstrated a 5.36E+05% improvement from the initial training session to the retention task. Statistically significant effects were observed for the HMG group. Subjects in the HMG group demonstrated improvements in smoothness after training (p<0.001). There was a 1.15E+03 % decrease in smoothness from TS1 to TSR for the HMG group. Subjects in the HMWG group demonstrated an improvement in trajectory smoothness after training (p<0.001). The HMWG demonstrated the smallest percent change in improved trajectories with a change of 2.80E+02. Each group produced significantly smoother movements with less jerk and sub-movements during the final retention session (TS7) compared to TS1. Improvements in smoothness are characteristics of learned motor control and reflect the ability to produce smooth coordinated movements.

4.12   RSQ Results

In order to estimate direct planar movement for forward and return trajectories during transportation, the R-squared coefficient (RSQ) was determined. This statistical measure is based upon planar movement for the forward transport trajectory and the return trajectory. Directness is often measured as the amount of separation between a reference path and the actual path taken and can be represented as a ratio. With the RSQ value, the directness of excursions taken to and from the target can be measured and compared to a standardized value. The standardized value is a fitted regression that determines how well the trajectories generated by the user compare to the fitted regression line. It provides an estimate of the directness of the path taken from the virtual table to the designated target

and from the target back to the virtual table. The degree of separation calculated is based upon the variability between the forward transport trajectory and the return trajectory. The regression coefficient represents the percentage of the response variable variation explained by the linear model between the directional trajectories. Regression coefficient values closest to one represent increased directness with minimal variability between forward and return trajectories. Values closest to zero indicate that there was increased variability in transport trajectory between both forward and return trajectories. An ideal path taken from the virtual table to the designated target and back would minimize extraneous movements with decreased variability between the forward path and the return path. Essentially, an ideal trajectory would utilize the same forward and return path. Therefore, the RSQ values can indicate whether the experimental groups relied on direct forward and return trajectories.
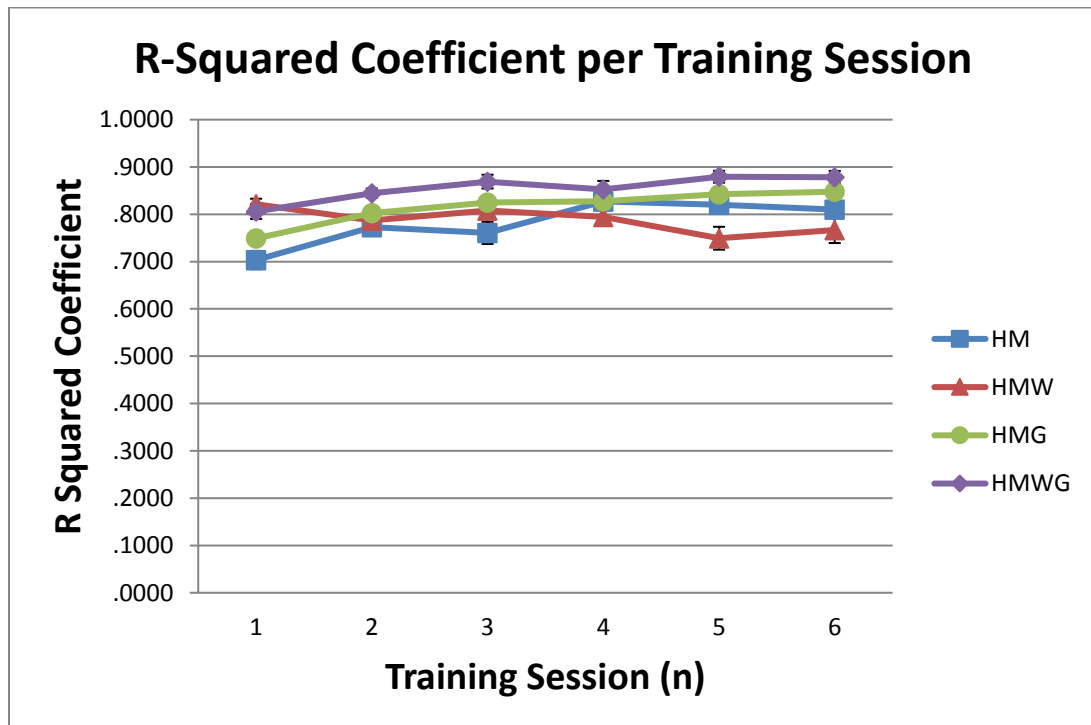
Figure 4.22 Average RSQ values for each experimental group per training session.

The two-way mixed ANOVA revealed that there was a significant interaction between Training Session and Degree of Freedom on RSQ as estimated with Greenhouse-Geisser method due to violation of Mauchly's test for Sphericity $F(8.641, 46.086) = 2.369$, $p = 0.029$. To assess the simple main effect between DOF significance between experimental DOF throughout the course of training, a Shapiro-Wilk Test of Normality was conducted. The data did not satisfy the Shapiro-Wilk Test and was evaluated using a Kruskal-Wallis Test with an alpha value of $\alpha = 0.0071$. A Bonferroni Post-Hoc analysis was conducted to determine the significant interaction between experimental groups. The RSQ values throughout training are depicted in Figure 4.22. Training Session 1 resulted in significant effects between experimental groups. HMWG group had higher RSQ values compared to the HM control group ($p < 0.001$). Significant differences were observed between experimental DOF. The HMW group also had greater RSQ values compared to the HMWG group on TS1 ($p < 0.001$). Similar effects were recorded on TS2. HMWG group had greater RSQ values compared to the HM control group on TS2 ($p < 0.001$). Differences were observed between DOF on TS2. The HMWG had greater RSQ values compared to the HMW group values. HMWG group had greater RSQ values compared to the HM control group on TS3 ($p < 0.001$). No differences were observed between experimental DOF on TS3. Significant differences in RSQ values between the HM control group and the HMWG group were detected on TS4 ($p < 0.001$). There was no significant difference in RSQ values between the HM control group and the experimental DOF on TS5. Observations were reported between experimental DOF on TS5. The HMG and HMWG group had significantly higher RSQ values than the HMW Group ($p < 0.001$). Significant effects were documented for TS6.

The HMWG group trended towards significance on TS6 (p=0.007). There was statistical significance between experimental DOF on TS6. HMWG had higher RSQ values compared to the HMW (p<0.001).

Trends for each experimental group are documented in Figure 4.22. The HM control group exhibited a step-like increase in RSQ values over the course of training. This step response indicates that the HM control group took longer to adapt to the change in cube size and adjust transportation mechanics. While there were no significant effects detected between the HMW group and the HM control group, the HM control group observed greater RSQ values than the HMW group from TS4 to TS6. This indicates that the HMW group deviated from direct paths during the transport with the Small cube and experienced greater trajectory variability with decreased directness. The HMG had the second greatest set of RSQ values for each session other than TS1 and TS4 compared to the experimental DOF. Similar RSQ values were recorded for the HMG group and the HM control group. The HMWG group maintained the greatest RSQ values throughout training compared to the other experimental groups. The HMWG group steadily improved throughout the course of training from TS1 to TS6. The results suggest that the HMWG increased directness with the use of similar pathways generated along the initial and final positions in both directions. Despite the lack of significance, the HMG group also utilized direct pathways for forward and return trajectories based upon the high RSQ values. The results suggest that gripper groups were able to reduce variability between forward and return trajectories throughout training, while the combination of the wrist and gripper contributed to greater RSQ values. The lack of a gripper in the HMW group illustrates that there was greater variability in the trajectory pathways when the wrist

component was used alone. The decrease in RSQ value suggests that the HMW group had greater variability between the forward and return trajectories. This factor suggests that the trajectory pathways generated were influenced by the DOF present and had greater stability when the wrist and gripper were utilized together.

To observe the effects between training sessions, a comparative analysis was performed for each experimental DOF. Normality was assessed using a Shapiro-Wilk Test. The data was in violation of the Shapiro-Wilk Test and was evaluated using the non-parametric Friedman Test for repeated measures. A Bonferroni adjustment was performed by SPSS to protect significance for multiple comparisons with an alpha value of $\alpha=0.05$. There was no statistical significance observed for RSQ values between training sessions for the HM control group, HMW group, or HMW group. Significance was observed for the HMWG group. Higher RSQ coefficients were observed for TS5 compared to TS1 for the HMWG group (p=0.035). Training Session 6 had the greatest improvement compared to Training Session 1 for the HMWG group.

Qualitatively, the HMW group exhibited a decrease in performance, which could be attributed to the decrease in cube size. The results suggest that the gripper group was able to continually improve transport mechanics over the course of training, evident by the approximately liner increase in Figure 4.22. The HMWG had significantly higher RSQ values for TS5 than TS1. The observations between sessions suggest that each experimental group, other than the HMW group, was able to improve upon initial performances and generate direct trajectories with minimal variation in forward and return trajectories, which suggests that each group learned to utilize similar pathways.

A retention test was conducted to determine the overall level of improvement upon completion of training. The data was assessed using a Kruskal-Wallis Test due to violation of the Shapiro-Wilk Test for Normality. Significance was assessed at $\alpha=0.0071$ to protect significance. The RSQ values for the retention test are recorded in Figure 4.23. There was no significant difference in RSQ values between the HM control group and the experimental DOF. Observations were reported between DOF. The HMWG group had significantly higher RSQ values than the HMW group ($p<0.001$). There were no effects observed between the HMG group and the HMWG group at the reported significance level ($p=0.032$).
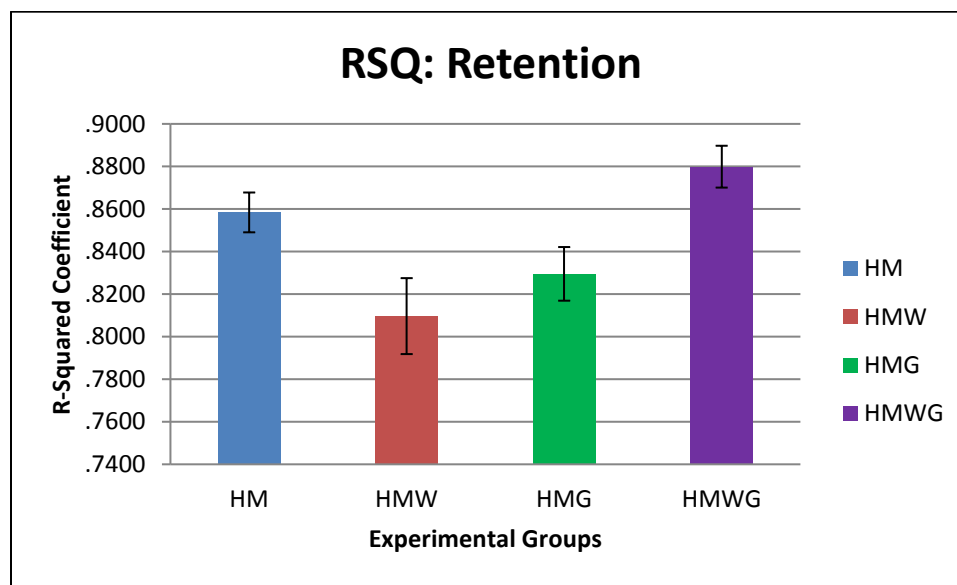
Figure 4.23 Average RSQ values recorded during the retention test for each group.
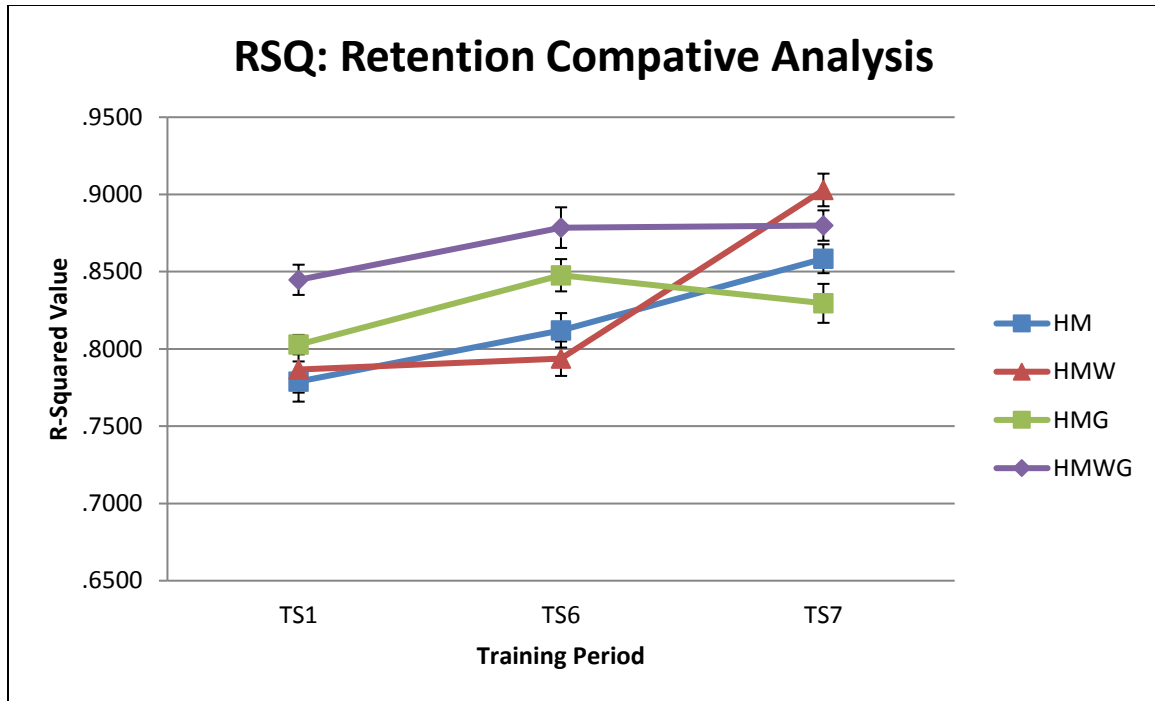
Figure 4.24 Comparative analysis for RSQ retention values between TS1, TS6, and TS7.

A comparative analysis was conducted between the initial training session and the retention session. A non-parametric Friedman test was performed to assess significant changes in RSQ values between the respective training sessions for the HM control group as a repeated measure. A Bonferroni Post Hoc with alpha corrected to α=0.0167 was used to assess significance in RSQ values. The RSQ values for each time period can be observed in Figure 4.24. Statistically significant differences were observed for TS6 and TS7 compared to TS1 for the HM control group (p<0.001). The HM control group generated forward and return trajectories with less variability during TS6 and TS7 compared to TS1. There were no significant differences in RSQ values between TS6 and TS7. There were no significant differences observed for the HMW group in RSQ values between training sessions. Statistically significant differences were observed for TS6 and TS7 compared to TS1 for the HMG group (p<0.001). The HMG group generated forward and return trajectories with less variability during TS6 and TS7 compared to TS1. There

were no significant differences in RSQ values between TS6 and TS7. Statistically significant differences were observed for TS6 and TS7 compared to TS1 for the HMWG group (p<0.001). The HMWG group generated direct trajectories that utilized similar forward and return pathways during TS6 and TS7 compared to TS1. There were no significant differences in RSQ values between TS6 and TS7. An approximately linear fit or pathway would approach an RSQ value of 1.0, indicating identical forward and return paths. Each group was able to decrease the variability between the paths and improve throughout training. Groups with the wrist component were able to utilize greater local rotations to minimize the variability in forward and return trajectories. The RSQ values represent an estimate of distal directness with minimal compensated global movements from proximal components. Groups with the wrist component were able to utilize consistent pathways with decreased variability and less global movements.

4.13   Discussion

Functional biological movements of the upper extremity emerge in the stages of infancy where coordinated efforts between proximal and distal segments occur due to CNS maturation. Early reaching attempts are neither precise nor smooth in early infancy as they incorporate sporadic movements with limited functional coupling between proximal and distal components. The first change in reaching occurs by 2 months of age, which at time, infants make arm movements outside the innate extension synergy and they begin to extend their fingers and arm at the same time (Schneiberg et al. 2002). The timeline is consistent with the presence of motor development of infant grasping, which begins at about 3 months (Bethier and Keen 2006). The distinctive ability to coordinate effort

between proximal and distal components develops in combination with CNS maturation and with expansion of cognitive processes associated with the variability of movements during the observation of movement and development of new skills. Variability may represent an intermediate state in which the nervous system is in the process of organizing the coordinated control of a large number of degrees of freedom from a state of low organization to one of greater order and stability to master the excessive degrees of freedom (Bernstein 1967). The increased variability associated with skill development may reflect the system's attempt to search for optimal kinematic solutions during development and learning (Thelen and Smith 1994). Movements of coordinated effort may take longer to develop as synaptic connections between existing populations of neurons and are reinforced or eliminated according to pattern use (Sporns and Edleman 1993). This reinforcement contributes to innate and learned movement that grants the ability to associate coordination between multi-joint components in an end-effector manner to accomplish goal-oriented movement. Infants around the age of 2-3 months spend most of their waking time looking at their own hands and rely on proximal movements to keep their hand visible (White, 1964, Van der Meer 1997). Infant visual attention is directed towards reaching and grasping attempts during this period. Research on early visuo-motor development suggests that infants are particularly attracted by self-produced movements, especially by their reaching and grasping attempts (Giudice et al. 2008). Prehension grip between the thumb and forefinger does not emerge until 10 months (Gordon 1994). Precise grasping and manipulation of objects is dependent on the development and maturation of the corticospinal tract, somatosensory information, and other motor areas since poor force coordination in young children partially resemble

deficits in patients with motor impairments (Gordon 1994). Reaching and grasping tasks performed in infants have demonstrated smoother and straighter hand paths as the shoulder and elbow become more coordinated in infants around 3-5 months (Galloway 2002).The early stages of infancy represent a period where the maturation of the corticospinal pathways contributes to a greater degree of coordination between reach and grasp movements. These movements develop in a simultaneous manner that leads to characteristics of smoother and more direct movements based on exploratory mechanisms of efferent feedback and the emergence of optimal control strategies. Early CNS development of coordinated efforts represents an ideal control mechanism to perform coupled upper extremity movements in an efficient and concise manner with conscious intent to rely on distal movements.

While the CNS continues to develop and mature, coordinated efforts between proximal and distal components of the upper extremity are subject to the biomechanical redundancy imposed by the arm. This biomechanical redundancy provides limitless combinations to the configuration of the upper extremity even in the simplest case of a reach-point task. The kinematic redundancy of the whole limb and not only the distal segments would be exploited in building the appropriate hand configuration for a given object to provide the ability to reach, grasp, and manipulate. This observation suggests that the existence of a higher order coordination mechanism couples the different components of prehension (Jeannerod 1994). The redundancy of the system allows the motor cortex to select the relevant DOF to provide the best possible movement to accomplish the task with minimal cost. Such redundancy affords flexible and adaptable motor behavior, provided all the degrees of freedom can be coordinated together

(Todorov et al. 2002). Mechanical redundancy provides the ability to perform a motor task with the optimal DOF to conform to the internal planning and desired trajectory. The redundancy minimizes the total cost value and the arm assumes a configuration with the lowest cost at each position along the straight path (Cruse et al. 1993).

Following CNS damage due to lesion, compensatory or adaptive motor behavior spontaneously emerges as soon as an individual attempts to move based on the limited possibilities for the impaired individual to adapt the alignment of body parts in order to achieve desired movement (Ada 1994). Isolated training further reduces the availability of DOF and limits the number of functional movements. If the subject is able to plan the movement, robotic therapy can assist to achieve the final position by providing the necessary torque to the joint (Galloway 2002). The planning stage resolves the redundancy inherent in the musculoskeletal system by replacing the behavioral goal with a specified desired trajectory (Todorov et al. 2002). Robotic therapy may represent a solution to increase the capability of the upper extremity by restoring the redundant or necessary degrees of freedom to accomplish task-specific training. The biomechanical redundancy is used in an efficient manner to complete coordinated movements between proximal and distal components. Hemiparesis from stroke results in paralysis of the arm and hand, which can significantly reduce the functionality of the arm and limit the number of available joints to complete the biomechanical redundancy. While the body tries to optimize movement through intact cortical spinal pathways, rehabilitation should reflect more biomechanically natural movements generated with the assistance of robotic devices. Natural development of movement in infants occurs in a coordinated effort between arm and hand. Biomechanical redundancy permits multiple combinations of

movement due to the degrees of freedom of each joint. Rehabilitation that incorporates isolated training may provide movement that is not conducive or functional for activities of daily living and may compromise recovery. Therapeutic interventions should reflect the natural processes of development to restore function in a coordinated manner that optimizes movement and enhances recovery. This investigation was conducted to determine if increased distal degrees of freedom provide more biomechanically efficient movements and are more beneficial for training compared to proximal training alone or training with reduced distal degrees of freedom.

Transportation of an object depends on the ability to identify the object in space and generate a desired trajectory to complete the task successfully. The desired motor plan encompasses movements of the shoulder and elbow to facilitate movement of the hand towards the designated target. The fingers begin to shape during the time of transportation and are pre-shaped according to intrinsic properties of the object (size, shape, texture). Different degrees of rotation of the wrist and elbow are generated to allow the hand to complete the planned prehension due to the kinematic redundancy of the whole limb and not only the distal segments (Jeannerod 1994). The representation of the object to be grasped triggers specific motor patterns that relies on this kinematic redundancy to accomplish the prehension task to reach and grasp the object with relevant degrees of freedom. The specified motor configuration relies on environmental context to achieve an optimal solution where grasping performance relates to the type and orientation of the object (Magdalon et al. 2011). This kinematic redundancy provides an ideal geometry that contributes to direct modes of transport. Experimental results from Cruse et al. showed that the path for a comfortable movement between two points most

often approximates a straight line of the end effector in the workspace with increased degrees of freedom (1993). The arm is able to maintain a motor configuration that adapts to the environment to accomplish the task in a functional manner that affords the opportunity to minimize the cost at each position along the direct path.

Motor configurations of the upper extremity are salient to maintain appropriate kinematics with modes of efficient transport that maintain directness and smoothness. Movements that require a greater degree of coordination from increased degrees of freedom take longer to mature but provide an optimal configuration when developed. Evidence exists that trajectory straightness improves with age resulting in pathways with decreased curvature and increased straightness. Cruse et al. demonstrated that variability in endpoint trajectories was highest for younger groups (4-11 years) and decreased with age until adulthood (1993). Initial trajectories for grasping tasks are planned with the hand as the end effector within in spatial frames for reference. The persistence of a high variability in inter-joint coordination despite adult-like end point trajectories suggests that the system prioritizes movement smoothness (Cruse et al. 1993). The combination of the hand end-effector with task priority to preserve smoothness is essential in the coordination of the upper extremity and can be satisfied with kinematic redundancy or increased DOF coordination.

The effects of increased degrees of freedom were observed in this investigation. The kinematic redundancy of the upper extremity with maturated patterns from the CNS provides efficient movement that minimizes cost and optimizes efficiency with smooth and direct movements. In the simplest case, the HM control group represents proximal training with movement permitted by the shoulder joint. The HMWG group reflects a

system that relies on motor configurations to cooperate synergistically with both proximal and distal control. The HMG and the HMWG group maintained the highest levels of success over the course of training despite the change in cube size. The gripper becomes more valuable as the object size changes, which reflects the importance of hand preshaping in conjunction with proximal movement during prehension. While the HMG and HMWG were successful, the HMG group experienced significantly more errors over the course of training, whereas the HMW group was able to mitigate the number of errors. The HMW and HMWG group had significantly fewer errors compared to the HM control and the HMG. The wrist component is critical to stabilize the hand during prehension and affords local rotations to complete tasks in an effective and efficient manner. The efficiency rating (CSR) for the HMWG was greater than the HMG and HM experimental groups which suggests that the wrist maintains a critical role in stability. The HMWG allowed participants to prioritize directness and smoothness and contributed to significantly more direct pathways with less jerk compared to the HM, HMW, and HMG group based on TRL and NIJ values. The increased distal degrees of freedom allowed the participants to generate direct modes of transport to the target in a timely manner, as the HMWG also exhibited the fastest transport times (DCT) along with the HMG group. The DCT values for the HMG and HMWG group suggest that the gripper is salient to maintain appropriate timing for movements and can most likely be attributed to the haptic feedback provided by the device during grasp. The modular gripper also contributed to smoother movements and emphasizes that the increased degrees of freedom preserves smoothness with increased directness during the PPT. The HMWG had the highest RSQ values which indicates that participants with the combination of the

wrist and gripper generated movements with less variability between forward and return trajectories. The combination of the wrist and gripper provide a complimentary system that can reduce errors, enhance directness, preserve smoothness, and decrease transport variability. The biomechanical redundancy and the natural emergence of coordinated proximal and distal components of the upper extremity emphasize the importance of increased degrees of freedom at the distal end to preserve these features.

Functional movements with the appropriate degrees of freedom can be generated to enhance goal-oriented action or activities of daily living in individuals with stroke. While stroke may result in secondary complications that decrease the ability to coordinate effort due to muscle weakness or hemiparesis, robotic therapy may provide an intervention to facilitate the intended movement in a biological manner. Conventional robotic therapy relies on training proximal upper extremity movements; however, this rehabilitation paradigm has demonstrated a reduction in the available cortical space for distal components through the use of learned proximal movements. This may be problematic, as distal components of the upper extremity require a greater cortical representation compared to the cortical representation of proximal components (Merzenich et al. 1996). Training with both proximal and distal components may contribute to better remapping that provides adequate space for more distal movements. Early motor activity of the upper arm and shoulder may hinder recovery of hand function due to cortical competition facilitated through intensive motor activity (Adamovich et al. 2008). The wrist and gripper components may provide assistance to enhance distal movements and compliment more biologically natural movements to enhance functional gains in order to avoid the potential competition for cortical representation between

proximal and distal neural structures. Normal motor configurations rely on the redundancy of the upper extremity to minimize cost and enhance smoothness. The wrist and gripper components may present an opportunity to reduce compensation as reduced degrees of freedom can result in less direct modes of transport with increased time and jerk, evident by the HM control group. Even when the appropriate distal degrees of freedom are not present, the ability to perform efficient movements is compromised, as seen with the HMW group and HMG group with respect to DCT and TRL. To optimize the recovery process for individuals with stroke, therapeutic interventions should reflect biomechanically accurate systems to enhance recovery and facilitate meaningful movements. An investigation with reduced DOF in Chapter 5 will provide further evidence that advocate for more functional systems that incorporate proximal and distal degrees of freedom.

Virtual environments with assistive robotic intervention provide an ideal training setting that can adapt to patient progress and present an opportunity to be objectively manipulated to provide salient training paradigms. Training paradigms that incorporate training of the proximal and distal upper extremity have demonstrated greater efficacy than individualized training conventions. Adamovich et al. demonstrated that VE training with proximal and distal components resulted in improvements in inter-limb coordination and improved motor control based on decreased trajectory lengths, faster completion times, and smoother movements compared to isolated training alone (2008). After two weeks of intensive training with arm and hand together, eleven individuals with stroke were able to effectively control the limb during hand interaction with the target as demonstrated by improved proximal stability, smoothness and efficiency of the

movement path (Merians et al. 2010). Despite the difference in populations, stroke versus healthy, the results (decreased trajectory length, faster completion time, improved smoothness) are consistent with those obtained in this investigation for the HMWG group, which suggests that proximal and distal components when used together may provide a more biomechanically comprehensive mechanism to generate direct movements with efficient kinematic and kinetic properties.

A retention test was performed to assess the degree of learning between the initial stage of training and the retention phase. Each experimental group was able to improve over the course of training and demonstrated significant differences in metric assessments from TS1 to TSR. The Big cube was tested in both conditions to determine the overall degree of improvement. Each respective experimental group exhibited greater CSX, greater CER, shorter TRL, faster DCT, improved smoothness, and increased RSQ values. The virtual environment was rendered with high fidelity to provide a motivational setting for subjects to improve upon previous performance and simulate task specific events with a change in object size to prevent adaption and provide challenge. The results suggest motor learning and adaptation can occur in a virtual environment and is consistent with current research. The ability for able-bodied individuals to learn a relatively simple motor task in a virtual environment reflects another positive feature associated with the potential of improving motor performance in a virtual environment. Individuals with disability may benefit from extended training sessions in a virtual setting to improve motor performance. The degree to which motor coordination and performance can transfer to additional settings will be explored in Chapter 6.

4.14   Conclusion

Virtual reality settings that incorporate mechanisms to train both proximal and distal components may provide an advantageous component for rehabilitation that can enhance plasticity through repetitive and quantifiable training. Distal components like the wrist exoskeleton and modular gripper can provide the opportunity to perform local rotations at the wrist and present the opportunity to perform manipulation of virtual objects coupled with global movement of the upper arm. The combination of distal exoskeletons with proximally supported robots can provide more biomechanically accurate movements, similar to the redundancy (increased DOF) exhibited in the upper extremity. This mechanism of training may decrease competition between cortical remapping and provide a more physiologically appropriate mechanism to train similar to the natural ontogeny of coordinated movements. This investigation demonstrated that training with both proximal and distal devices can contribute to significantly efficient movements. Training the arm and hand together with increased DOF may provide greater improvement in individuals with stroke that seek to restore functional movement and increase independence.

CHAPTER 5

DEGREE OF FREEDOM ASSESSMENT POST TRAINING

5.1 Introduction

Pick and Place training incorporated six training sessions where the experimental groups were required to transport a virtual cube to the designated target. The experiment was designed to determine the effect of increased degrees of freedom during transport. Cube size was varied throughout training over the course of the six sessions. A follow up retention test was administered two weeks post training. Each group was required to transport the Big cube over the course of eight trials. Upon completion of the initial phase of the Retention Test, users were required to repeat the procedure without the initial degree of freedom. Users repeated the procedure with the Big cube without the benefit of the trained DOF. HMW subjects repeated the procedure without the wrist component. HMG users performed the task without the modular gripper. Members of the HMWG group completed the second phase of the retention task without the wrist and gripper components. Each experimental DOF group performed the second phase of the retention test in the same manner observed by the HM control group. The HM control group received an increase in DOF and performed the task with the wrist component to mimic the HMW group. The second phase of the retention test assessed the necessity of the added degrees of freedom and the benefit of each component. A comparative analysis was performed between the first phase of the retention task and the second phase of the retention task to assess statistical significance and evaluate performance.

5.2 Results

A comparative analysis for each experimental group was performed in order to determine the benefit of the DOF and establish the efficacy of the devices. Metrics used to quantify the contribution of the DOF include: Cube Success (CSX), Cube Error (CER), Cube Success Ratio (CSR), Trajectory Length (TRL), Delta Cube Time (DTC), smoothness (NIJ), and R-squared coefficient (RSQ). Each metric was recorded for each experimental group throughout the second phase of the retention test. It should be noted that each group will be referred to as the original trained group and evident comparisons will relate to the inclusion or exclusion of DOF.

5.3 Cube Success Results

Statistical analysis was performed to determine the significant effects between experimental groups with and without the DOF. A Shapiro-Wilk Test for Normality was used to check whether the sample from the population was normally distributed. The HM control group, HMW group, and HMWG were normally distributed and evaluated using and Independent Samples t-Test. The HMG group was not distributed normally and was assessed with a Mann-Whitney U Test. Each group was assessed at the significance level of alpha $\alpha=0.05$. Comparisons were made within groups between DOF conditions for the second phase retention test. Observations for each respective group with and without DOF are evident in Figure 5.1. There was no statistical significance in CSX when the HM group repeated the TSR with the wrist exoskeleton. Subjects in the HMW group had significantly greater CSX with the wrist exoskeleton compared to performance without the wrist exoskeleton in the second phase TSR ($p<0.001$). HMG group had significantly

greater CSX scores with the modular gripper compared to scores without the gripper (p<0.001). HMWG group had statistically greater CSX with the wrist and gripper compared to performance without the wrist and gripper during the second phase TSR (p<0.001).

Despite the lack of statistical significance for the HM control group, each experimental group scored significantly less cubes without the respective DOF. The HMWG was significantly affected by the lack of gripper and wrist and experienced a decrease in CSX score by 32.6% without the DOF components. The HMG group was equally impacted by the lack of DOF and had a 31.4% lower CSX score compared to performance with the modular gripper. The percent changes for each experimental group are recorded in Table 5.1. Figure 5.1 depicts that the greater the DOF the greater the percent change when the retention test was repeated without the DOF. CSX scores were higher for each experimental group when the DOF were present. The data suggests that the lack of a gripper contributed to a decrease in success, evident by the large percent change for the HMG and HMWG group.
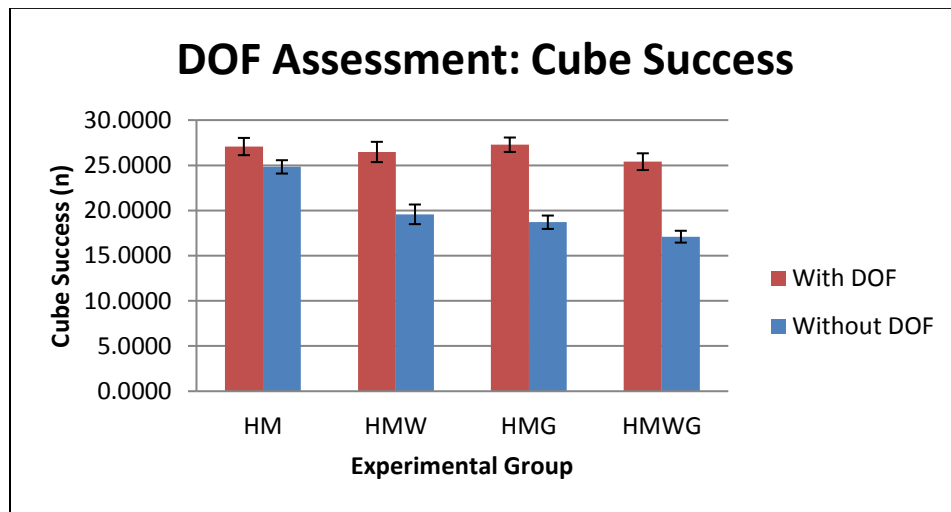
Figure 5.1 Average Cube Success for each group with and without respective DOF.

98

Table 5.1 Percent Change in Experimental Groups when DOF was Removed

DOF	HM	HMW	HMG	HMWG
Percent Change	-8.310249	-26.06232	-31.43905	-32.67717

5.4 Cube Error Results

Statistical differences in cube error were assessed to determine the effect of DOF. A Shapiro-Wilk Test for Normality was used to assess normality. The HM control group and HMWG group were normally distributed and evaluated using an Independent Samples t-Test. The HMW and HMG group were in violation of the Shapiro-Wilk Test and assessed with a Mann-Whitney U Test. A significance level of alpha $\alpha=0.05$ was used to determine significance in CER between DOF conditions. Figure 5.2 depicts the CER generated by each experimental group with and without the respective DOF. A significant effect with the wrist exoskeleton was observed when the HM control group repeated TSR with the wrist DOF. The wrist exoskeleton contributed to significantly less errors during TSR compared to task performance without the device for the HM control group ($p=0.016$). There was no statistical significance observed for the HMW group. While subjects had fewer errors with the wrist exoskeleton, there was no statistical significance between errors accumulated with the wrist exoskeleton and without ($p=0.91$). There was no statistical significance in CER for the HMG group when the subjects performed TSR without the added DOF. While subjects had fewer errors with the gripper, there was no statistical significance between errors accumulated with the gripper and without the gripper ($p=0.657$).

Significant effects were only observed for the HM group. The HM group had statistically significant CER values when the wrist exoskeleton was present. The HM control group generated significantly less errors with the wrist exoskeleton ($p=0.016$). Despite the lack of significance, each experimental group exhibited an increase in error when the respective DOF was absent. The HM control group had the greatest improvement in CER when TSR was performed with wrist component. The HM control group had 30.95% more CER when the wrist component was not present. Similar effects were observed for the HMW group. Although not significant, the HMW group had 21.6% more errors when the wrist component was excluded. The percent change for cube error is documented in Table 5.2. Qualitatively, the results depict improved performance when the DOF is present with less errors.
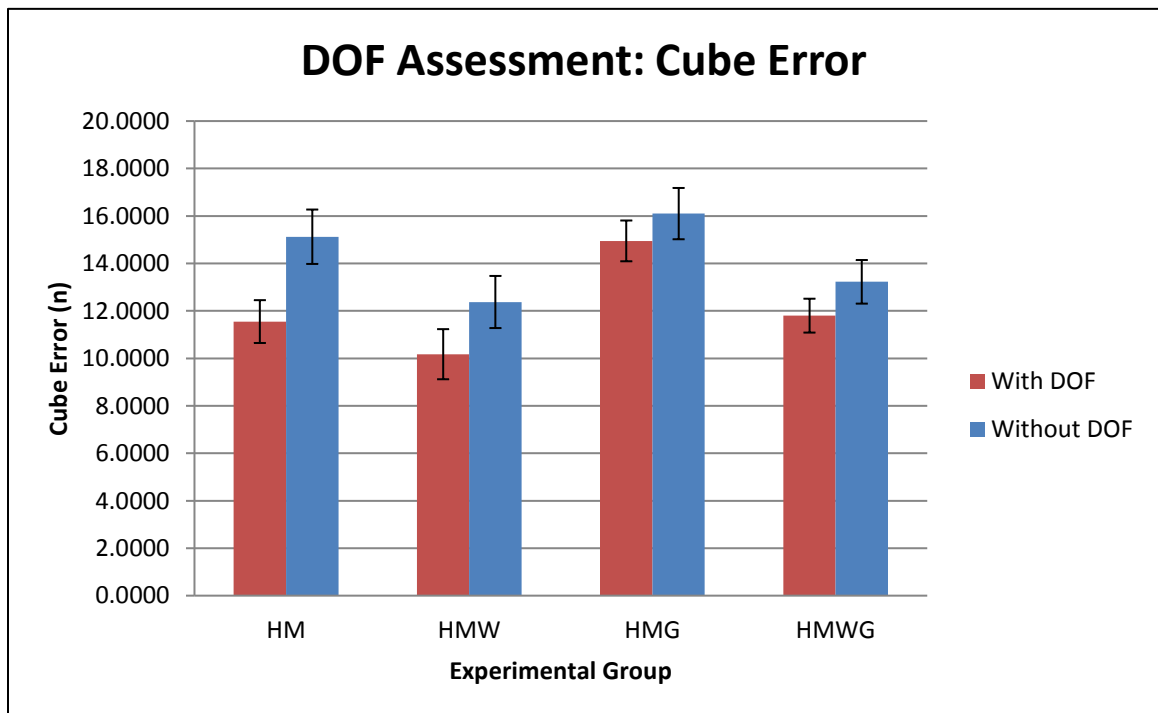
Figure 5.2 Average Cube Error for each group with and without respective DOF.

Table 5.2 Percent Change in CER without DOF for each Experimental Group

DOF	HM	HMW	HMG	HMWG
Percent Change	30.95238095	21.62162162	7.692307692	12.07627119

5.5 Cube Success Ratio Results

Cube Success Ratio values for each experimental group with and without relevant DOF were assessed. Statistical tests were performed to determine significant interactions between DOF conditions. Shapiro-Wilk Test for Normality was applied to identify normally distributed populations. Experimental groups that satisfied the Shapiro-Wilk Test included the HM control group , HMW group, and HMWG group. The HMG data was not normally distributed and was assessed using a Mann-Whitney U test. Each statistical test was evaluated using a significance level of alpha $\alpha=0.05$. The average CSR values are depicted in Figure 5.3. Significant differences were observed in CSR when the HM control group performed TSR with the wrist component. Significantly greater CSR was observed when the HM control group performed the TSR with the wrist component (p=0.011). The HMW group experienced significantly different CSR scores between DOF conditions. The wrist exoskeleton contributed to greater CSR compared to training without the wrist exoskeleton for the HMW group (p<0.001). The HMG group performance was greater when the modular gripper was present. HMG group had significantly greater CSR with the modular gripper (p<0.001). Significance was also observed for the HMWG group. HMWG group had significantly greater CSR with the gripper and wrist than without it (p=0.001).
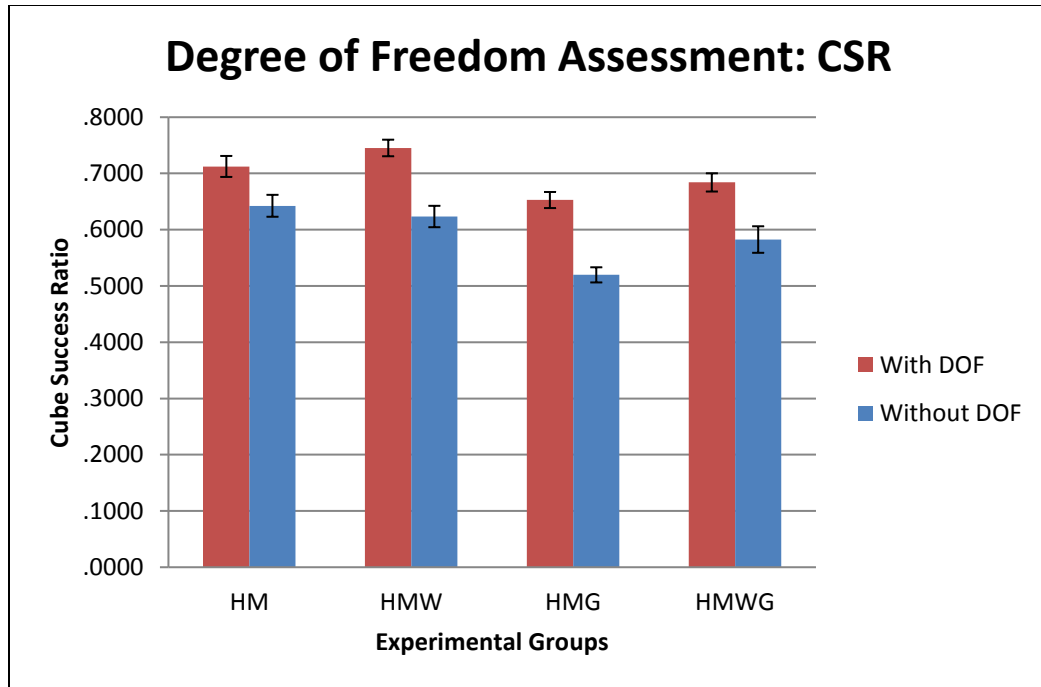
Figure 5.3 Average CSR for each group with and without respective DOF.

Experimental conditions without the DOF experienced significantly worse CSR scores. Each experimental DOF group had greater CSR scores when the respective DOF were present. Table 5.2 represents the percent change in CSR scores when the experimental groups performed TSR without the DOF. The HMG group had the greatest percent change in CSR when the gripper was not present (-20.34%). The results suggest that significantly greater CSR values were obtained in the presence of DOF.

Table 5.3 Percent Change in CSR without DOF for each Experimental Group

DOF	HM	HMW	HMG	HMWG
Percent Change	-9.818920332	-16.34737294	-20.37931132	-14.84755259

5.6 Trajectory Length Results

Trajectory length values were assessed to determine significant interactions between experimental conditions with and without DOF. Shapiro-Wilk Test for Normality was performed to determine applied statistical method. The HM control group and HMG satisfied the Shapiro-Wilk test for Normality and were evaluated using Independent Samples t-Test. The HMW and HMWG groups were in violation of the Shapiro-Wilk Test of Normality and were assessed with a Mann-Whitney U Test. Significance level of alpha $\alpha=0.05$ was applied to each statistical test. Figure 5.4 represents the average trajectory length for each experimental group in respective DOF condition. Significance was observed for the HM control group. The wrist exoskeleton resulted in significantly shorter trajectories compared to trajectories without the device for the HM control group (p=0.034). Subjects in the HMW group had statistically shorter trajectories when the wrist exoskeleton was present (p<0.001). No statistical significance in trajectory length was observed for the HMG group. Significance was detected between the DOF conditions for the HMWG group. Subjects had statistically shorter trajectories with the wrist and gripper compared to performance without the components (p<0.001).

Experimental conditions without the DOF resulted in significantly longer trajectories for every group except the HMG group. There was statistically significant evidence to suggest that the DOF contributed to shorter trajectories. The HMWG group experienced the greatest change in trajectory length when the DOF were not present. The HMWG group had a 19.16% increase in trajectory length with the absence of the DOF. The HMG group exhibited the smallest change in trajectory length with 3.74%. The results suggest that the added DOF improved transport based on the decreased trajectory

length. The HMWG group indicates that alternative pathways were utilized to compensate for the lack of DOF, resulting in longer trajectories. The lack of DOF contributed to different modes of transport that did not minimize the distance between the virtual table and the specified target and compensated for the lack of DOF. The compensated trajectories were significantly longer due to the lack of DOF for each case other than the HMG group.
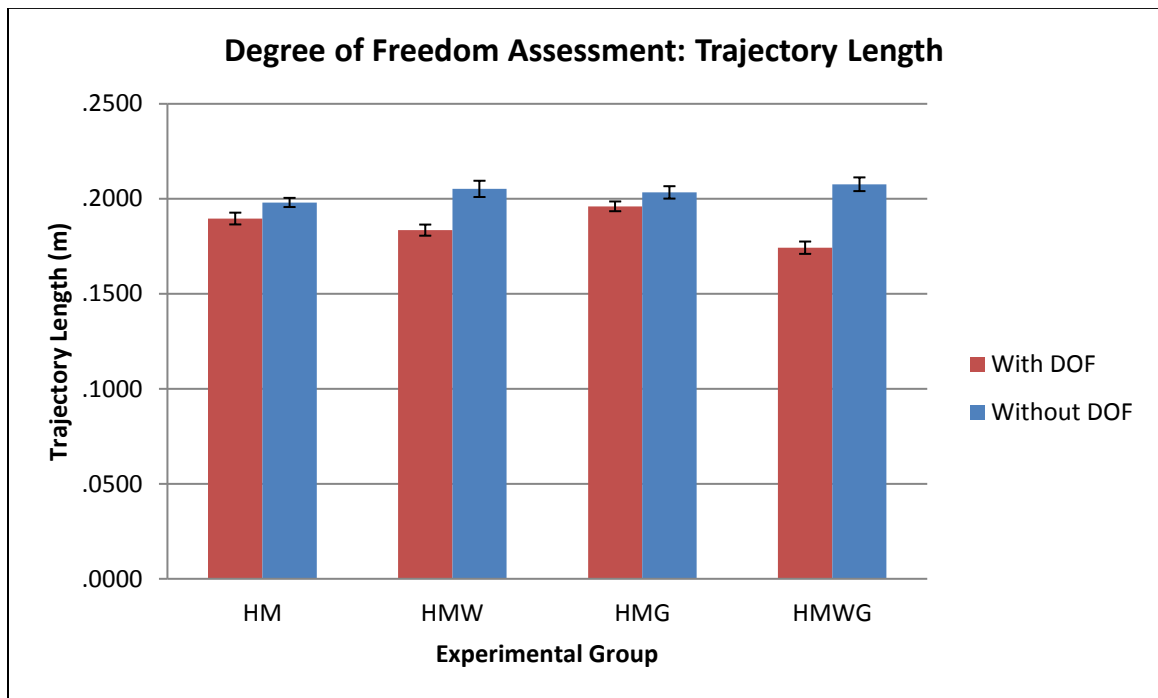
Figure 5.4 Average trajectory length for each group with and without respective DOF.

Table 5.4 Percent change in TRL without DOF for each Experimental Group

DOF	HM	HMW	HMG	HMWG
Percent Change	4.46557	11.8327	3.73884	19.1641

5.7 Delta Cube Time Results

Statistical analysis was performed to assess the significance between DTC values in each DOF condition. Shapiro-Wilk Test for Normality was performed to determine distribution normality. None of the experimental groups satisfied the Shapiro-Wilk Test for Normality. Each experimental DOF was assessed with a non-parametric test. A Mann-Whitney U Test was performed to determine significance between DOF conditions with a significance level of alpha $\alpha=0.05$. Figure 5.5 illustrates the average DCT scores for each experimental condition. Each group experienced significantly slower responses when the DOF were absent. The HM control group recorded significantly faster response times, indicated by the low DCT value when the wrist component was utilized (p=0.001). The HMW group experienced significantly faster response times, indicated by the low DCT value when the wrist component was utilized (p=0.001). The gripper contributed to significantly faster DCT for the HMG group compared to the condition without the DOF (p<0.001). The HMWG had significantly faster DCT values when the wrist and gripper components were used compared to the condition without the DOF (p<0.001).

The absence of additional DOF resulted in significantly slower response times for all experimental groups. The inclusion of the wrist component contributed to significantly lower DCT values for the HM Control group, Figure 5.5. The HMWG group experienced the greatest percent change when the DOF was excluded. The HMWG group was 72.2% slower without the DOF, Table 5.5. The HMG group also experienced a significant effect when the gripper was not present. HMG group performed 43.8% slower when the modular gripper was omitted in the experimental condition without DOF. The results suggest that the absence of DOF contributed to slower performance with increase DCT

values. The absence of both the wrist and gripper had the greatest effect on the HMWG group. Results recorded in Figure 5.5 and Table 5.5 suggest that the wrist in combination with the gripper had the greatest effect on transport times than the gripper or wrist alone since there was no statistical significance between DCT values between the respective experimental groups during the first phase of TSR.
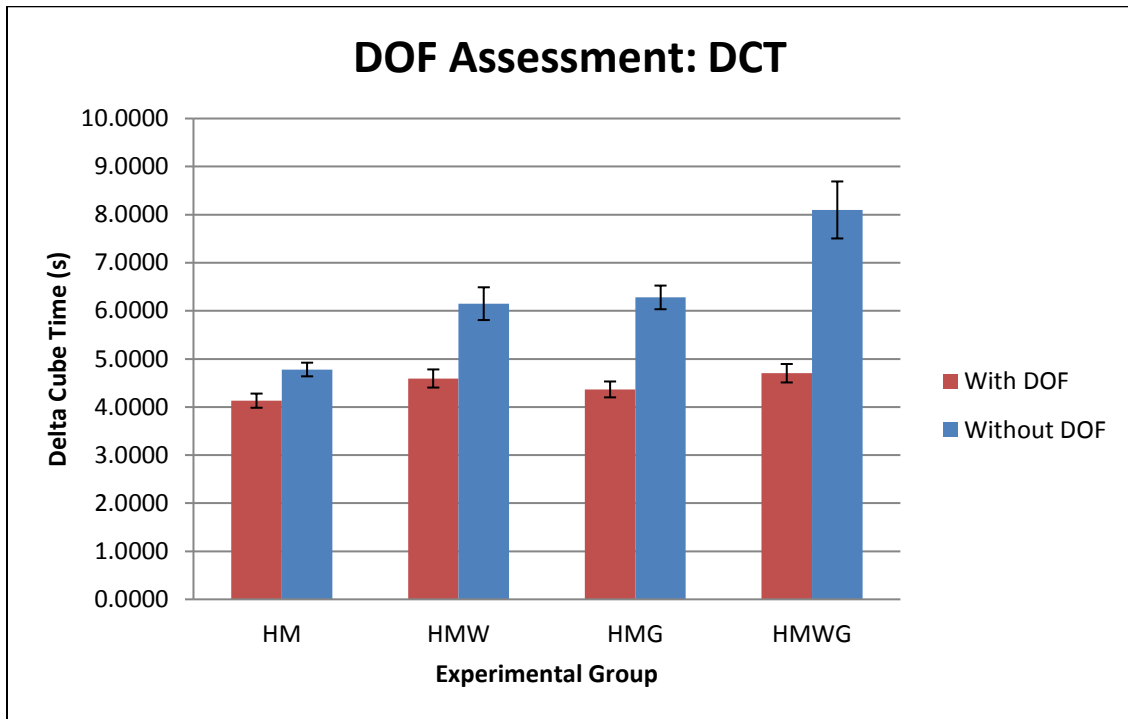
Figure 5.5 Average DCT values for each experimental group with and without DOF.

Table 5.5 Percent Change in DCT without DOF for each Experimental Group

DOF	HM	HMW	HMG	HMWG
Percent Change	15.69399559	33.87963034	43.82670519	72.20789961

5.8 Smoothness Results

To examine the statistical significance between smoothness values between the experimental conditions, a Shapiro-Wilk Test for Normality was first performed. The smoothness values, calculated as normalized integrated jerk for each experimental group, were in violation of the Shapiro-Wilk Test for Normality and assessed with a Mann-Whitney U Test. A significance level of alpha $\alpha=0.05$ was used to detect significant differences in smoothness values between experimental conditions with and without DOF. The HM control group experienced no significant difference in smoothness as NIJ between experimental conditions. The HMW group experienced significantly smoother movements when the wrist exoskeleton was utilized ($p=0.001$). The gripper contributed to significantly smoother movements for the HMG group ($p<0.001$). Movements without the gripper were less smooth. The HMWG group generated smoother movements with less sub-movements that minimized jerk when the wrist and gripper were used ($p<0.001$).

Significant changes were observed between experimental conditions when the DOF were absent. Transportation techniques resulted in less smooth movements with increased sub-movements without each respective DOF. Each experimental group generated significantly smoother movements in the presence of DOF. The percent changes are observed in Table 5.6. The HMWG group had the greatest significant change in NIJ values between experimental conditions. When the wrist and gripper components were removed, smoothness increased by 3325%. The HMG group experienced the second greatest change in smoothness when the gripper component was removed. Smoothness increased by 674.7% when the gripper was removed from the HMG group. The HM control group experienced less smooth trajectories when the wrist component

was used (Δ=-52.67%) but there was no significance between the experimental conditions. The results suggest that the combination of the wrist and gripper component had the greatest impact on smoothness based on the greatest percent change.
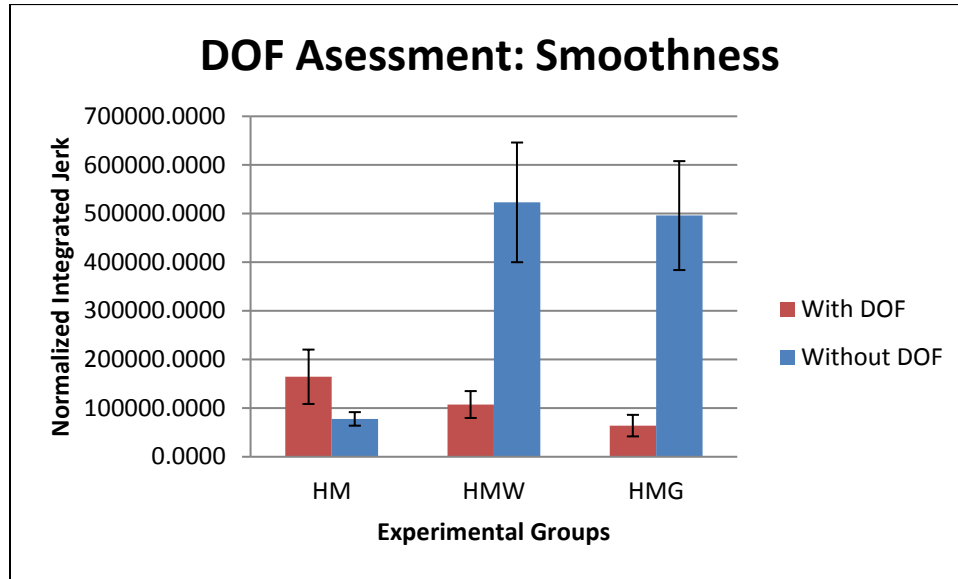
Figure 5.6 Average smoothness values calculated as normalized integrated jerk for each experimental condition. Units for normalized integrated jerk are dimensionless.
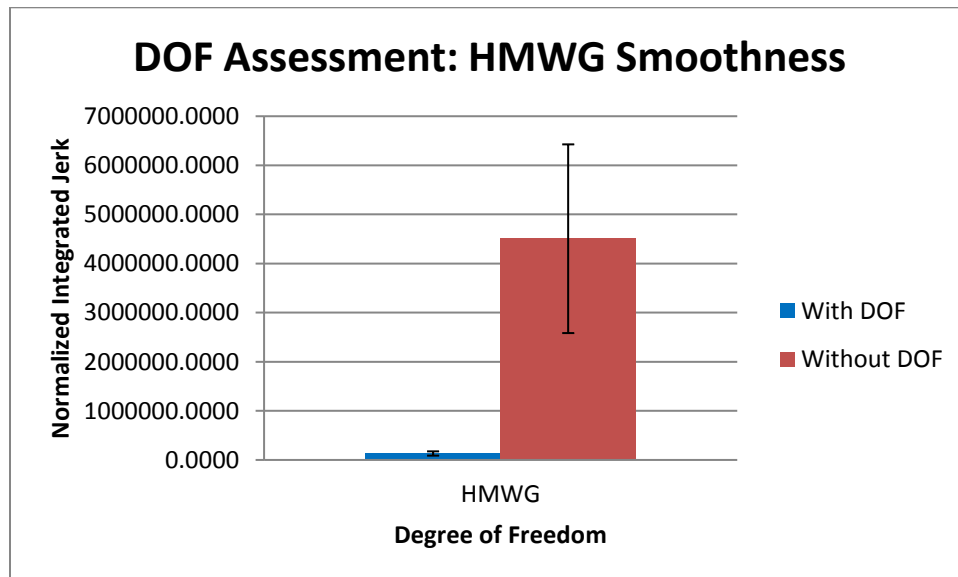
Figure 5.7 Average smoothness as NIJ for the HMWG group for each condition.

Table 5.6 Percent change in Smoothness between Experimental Conditions

DOF	HM	HMW	HMG	HMWG
Percent Change	-52.66998	+387.075	+674.704	+3325.31

5.9 RSQ Results

A comparative analysis was conducted to determine the statistical significance between RSQ values for each experimental DOF condition. Shapiro-Wilk Test for Normality revealed that the data was not normally distributed for the HM control group. A Mann-Whitney U Test was conducted and assessed at a significance level of alpha $\alpha=0.05$. All other experimental groups were evaluated with an Independent Samples t-Test with the same alpha value. The HM control group revealed that there was no statistical significance in RSQ values when the group used the wrist exoskeleton (p=0.996). There was no statistical significance between experimental conditions for the HMW group (p=0.202). The HMG group experienced significantly greater RSQ values in the presence of DOF (p<0.001). There was no statistical significance in RSQ values for the HMWG group between experimental conditions (p=.140).

Qualitative analysis of the RSQ values for each experimental condition indicates each experimental group recorded greater RSQ values in the presence of DOF, Figure 5.8. The HMG group exhibited statistically significant changes in RSQ values and exhibited the greatest change between conditions. The HMW group generated RSQ values that were 4.04% greater in the presence of DOF. The HMG group observed the greatest change in RSQ values in the absence of the modular gripper. The HMG group achieved RSQ values that were 10.8% lower without the gripper, Table 5.7. The results suggest that the HMW and HMG group utilized different pathways for the forward and

return trajectories when the DOF were not present. The greater RSQ values in the presence of DOF may indicate that similar pathways were observed for the forward and return trajectories. HMG group had statistically different RSQ values suggesting that there was greater variability in transport pathways without the DOF.
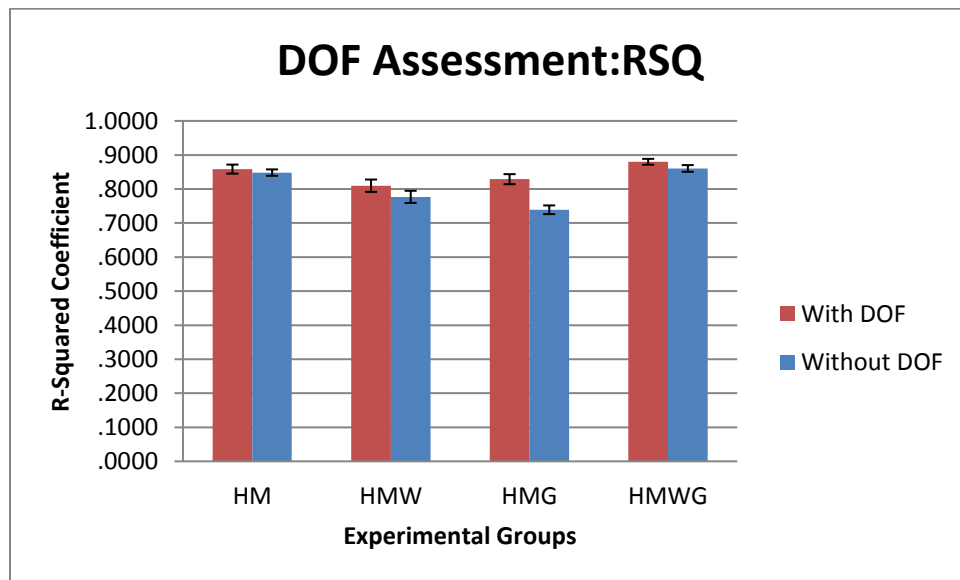
Figure 5.8 Average RSQ values for each experimental group in each DOF condition.

Table 5.7 Percent Change in RSQ Values between Experimental Conditions

DOF	HM	HMW	HMG	HMWG
Percent Change	1.185	4.04	10.8	2.21

5.10   Discussion

Functional movements of the upper extremity represent a coordinated effort between proximal and distal segments of the shoulder, elbow, wrist, and hand. The proximal segments position the upper extremity and orient the limb in a manner that creates an effective strategy for the distal components to manipulate the object. Neurological impairments due to lesions in the corticospinal tract or impairments that inhibit coordination between proximal and distal components of the upper extremity can contribute to slower and less accurate reaching movements (Kamper et al. 2002). Precise control of distal segments are disrupted following stroke and result in inaccurate and slow movements due to hemiparesis (Lang et al. 2005). Hemiparesis is often greatest in the distal muscles and least in proximal muscles of the upper extremity (Colebatch et al. 1989). Impairments to corticospinal tracts that result in hemiparesis can disrupt the nature of coordination between proximal and distal segments during reach and grasp movements. The decreased coordination can result from insufficient ability to move distal components and lead to diminished performance on activities of daily living.

Factors that lead to a reduction in degrees of freedom or inhibit effective use of inter-joint coordination such as immobilization of wrist or neurological impairments from hemiparesis due to stroke or cerebral palsy (CP) have demonstrated adverse effects in reach to grasp tasks. Immobilization of the wrist due to wrist splint lead to compensatory elbow movements with increase shoulder elevation (Mell et al. 2005). Muscle impairments due to the presence of spasticity in CP populations of children often lead to limitations in range of motion, timing accuracy, force production, and hand manipulation skills. Static splints that immobilize the wrist have demonstrate decreased muscle

activation, which over time may lead to disuse atrophy in the wrist muscles and overuse of more proximal muscles (Bulthaup et al. 1999). Individuals with CP wearing static splints had decreased muscle activation in the forearm muscles during grasp and recruited more proximal shoulder muscles, which suggest that prolonged use of static splints may lead to muscle atrophy of muscles that are more distal and increase activation in proximal muscles (Burtner et al. 2008). The inhibition of distal muscles has demonstrated increased recruitment of proximal muscles resulting in compensatory strategies for moment during reach to grasp activities. Accurate and smooth movements depend on precise control of shoulder and elbow movements coupled with distal segments to grasp and manipulate objects and transport efficiently for ADL. Damage to the corticospinal systems results in a reduced ability to selectively activate both proximal and distal muscle because precise control of the distal segments is more dependent on intact corticospinal system (Lang et al. 2004). These impairments can reduce the necessary degrees of freedom to complete the task and limit the active range of motion and the ability to coordinate efforts between joints, which can ultimately inhibit effective movements.

Not only can immobilization hinder physical performance and influence proximal and distal coordination, but it can result in plastic changes to cortical representations as well. Cast wearing and immobilization have demonstrated reduced hand use and impaired tactile acuity, associated with reduced activation of the respective finger representations in the somatosensory cortex (Lissek et al. 2009). Changes in cortical maps depend on use and activation in surrounding cortical areas. Enhanced repetitive performance or disuse due to immobilization or neurological impairments determine the plastic changes associated with cortical representations of movement or lack thereof. A reduction in the

cortical area density of the immobilized limb in the primary motor cortex was correlated with the duration of cast wearing (Liepert et al. 1995). Hemiparesis due to stroke can lead to less frequent use of the hemiparetic arm, which can reduce cortical areas associated with movement of the affected arm. Plastic changes evoked by nerve damage or central injuries are characterized by a confound of injury-dependent reorganization and those changes arising from changes in the amount of use (Lissek et al. 2009). Enlargements in cortical maps are associated with enhanced use, while two weeks of immobilization of the index finger resulted in significantly reduced hemodynamic response in the SI representation (Lissek et al. 2009). To drive positive plastic changes in cortical maps, repetitive movements and task practice should facilitate recovery to lesioned areas and enhance cortical reorganization.

The second component of the retention task was to observe the effects of reduced degrees of freedom on task performance to determine the overall benefit of distal degrees of freedom. The virtual task was performed without distal degrees of freedom to demonstrate the effects of movements generated by proximal movements alone, comparable to the original HM group. The reduction in the DOF is comparable to a simulation of neurological impairment or virtual immobilization where the number of effective degrees of freedom is reduced, especially at the distal end, as seen with hemiparesis after stroke. Purposeful movements of the upper extremity require precise control of both proximal and distal components. Each group that utilized distal degrees of freedom performed the PPT without the respective degree of freedom, while the HM group performed the task with the wrist component. In essence, the lack of degrees of freedom provides a constraint comparable to immobilization of the wrist and digits. Each

experimental group that performed the PPT without the wrist, gripper, or combination of components had significantly lower scores with the greatest changes observed in the HMG and HMWG group. The HM group had significantly greater success when the wrist component was introduced to the Pick and Place Task. The significant differences in decreased success were accompanied by longer trajectories for each group except the HMG group. The HMWG group had the largest increase in trajectory length (19.16%) indicating that the lack of wrist and gripper contributed to significantly longer trajectories that relied on greater proximal movements to compensate. Consistent with the literature, movements with reduced degrees of freedom were significantly less smooth and slower for all groups without DOF. An increase in time and decrease in movement speed were observed for hemiparetic individuals (Lang et al. 2005). In sum, the effect of adding a grasp component to a reaching task resulted in faster reaching in the healthy control group (Lang et al. 2005). The distal components contributed to significantly faster DCT when present for each group. Increased values of smoothness are a result of the increased time in combination with the longer movements and velocity, resulting in greater sub movements and variability from the initial position to the final target. Less variability in forward and return pathways was observed in the presence of the DOF for each experimental group. There was significantly less variability between forward and return trajectories in the presence of distal DOF as indicated by the significantly different RSQ values. The RSQ values reflect the efficacy in transport towards the target and the following return trajectory and relies on effective coordination between proximal and distal components to grasp and transport the virtual cube to the designated target. Mell et al. (2005) reported increase compensatory movements with increase proximal shoulder

elevation when the wrist component was immobilized. Investigations conducted with children with hemiplegic CP have demonstrated increased task duration, reduced peak-velocity, and increased variability (Coluccini et al. 2007). Timing and efficiency for transport is effected when distal DOF are compromised.

The added distal degrees of freedom demonstrated significant effects on performance as well as transport. Reduced degrees of freedom have demonstrated adverse effects when compared to movements completed with an increased level of DOF at the distal end. The HMWG group exhibited the greatest changes in CSX, TRL, DCT, and smoothness when the wrist and gripper were removed, which suggests that the combination of the wrist and gripper may be necessary to facilitate efficient transport for a reach to grasp exercise to maintain adequate timing (DCT) and velocity (smoothness) during direct (TRL) transport. The wrist component may be necessary to stabilize the manipulated object during the initial grasp since the errors were significantly greater for the HMW group and reinforces the necessity for local rotations for object manipulation. The greatest change in RSQ values occurred in the HMG group, which suggests that grasp alone may reflect the ability to accurately navigate forward and return pathways. These results suggest the benefits of distal degrees of freedom in the form of the wrist and gripper components may be necessary to facilitate efficient movements and enhance coordination while minimizing errors during transport. The HMWG group observed the greatest decline in performance and transport when the wrist and gripper were removed. In order to facilitate recovery in individuals with stroke, proximal and distal movements should be practiced together to increase cortical representations of the lesioned area. Immobilization and disuse can lead to adverse effects such as muscle atrophy and

reduced cortical representations. Based on the findings with respect to improved performance with distal degrees of freedom, especially with the use of the wrist and gripper components together, rehabilitation paradigms should reflect the need to increase cortical representations to facilitate recovery and restore function for activities of daily living through coordinated efforts of proximal and distal movements.

5.11 Conclusion

Functional use of the upper extremity in everyday activities requires efficient movements conducted in a timely and accurate manner. When distal components are reduced due to immobilization or hemiparesis, effective modes of transport are compromised in efficiency and timing. The results here indicate that distal components when used in conjunction with proximal components provide effective and meaningful movements. Rehabilitation paradigms that incorporate the use of proximal and distal training may strengthen the cortical representations and enhance plastic changes to facilitate greater recovery and contribute to meaningful movements that can be applied to ADL. Impairments to the distal portions of the upper extremity can result in secondary complications due to compensatory movements. To reduce the effect of compensatory movements and enhance excursions, the results suggest that training with proximal and distal degrees of freedom together may provide more accurate movements compared to excursions without distal components. Increased distal degrees of freedom may be beneficial for stroke rehabilitation to enhance cortical reorganization and prevent disuse.

CHAPTER 6

TRANSFERABILITY ASSESSMENT

6.1 Introduction

The introduction of virtual reality to rehabilitation can provide an immersive training environment that can provide an objective set of performance metrics to quantify repetitive training and accuracy of movements. Virtual reality environments provide an attractive method to localize and train particular skill sets in an immersive and interactive manner that can mimic real-world tasks. Repetitive training and exposure to VE can facilitate skill acquisition and better prepare the individual for real-world performance. The US National Aeronautics and Space Administration utilized complex virtual simulations to train astronauts in sequential tasks for a mission to repair the Hubble telescope (Loftin et al. 1995). Surgical skills can be practiced in a virtual environment to prepare surgical residents for complex operating procedures (Satava et al. 1992). Todorov et al. demonstrated that subjects that received virtual training performed significantly better than subjects who received comparable amount of real-task practice or coaching. Subjects that trained in the virtual environment experienced accelerated learning rates compared to the real-world controls. Virtual settings that employ augmented feedback have the potential to accelerate learning and skill acquisition, characteristics desirable for rehabilitation. Research suggests that virtual environments provide a controlled setting to monitor patient performance and enables modes of recovery that can benefit learning and improve basic daily living skills (Christiansens et al. 1998). Virtual environments

possess the ability to train a variety of complex motor tasks with the potential to augment real-world performance.

A new virtual task was created to assess skill transferability and the efficacy of learning in a virtual environment. Training in a virtual environment has demonstrated transferability to real-world tasks. To validate the transferability of skills acquired during the PPT, an unfamiliar environment with similar constraints was introduced to trained and untrained individuals. The unfamiliar virtual task referred to as the "Mailbox Task (MBT)" was devised to impose greater accuracy requirements than the Pick and Place Task. The mailbox test was evaluated to determine if learned movements could be transferred or generalized to untrained task movements. A reaching task was devised in which the subjects were required to extend their arm to grasp a block and then transport the block to a mailbox with a horizontal slot. The specified target required greater proximal movement with arm elevation and distal accuracy to insert the cube into the horizontal mailbox slot. Participants were required to pick up the virtual cube from a virtual table positioned in a spatially identical location as the PPT. Each experimental group was required to transport the virtual cube to a mailbox and insert the cube into the slot, Figure 6.1. Error detection features were implemented when the cube did not successfully reach the target slot. The cube was reset to the initial position when the cube was not successfully transferred and placed in the horizontal slot. Many training paradigms succeed in training one task but fail to achieve transfer to related functions. The Pick and Place training task demonstrates the ability to pick up and object and transfer it to a desired location. The Mailbox Task provides a similar objective for

transport with an increased difficulty based on the precision and elevation required to place the object in the horizontal slot.
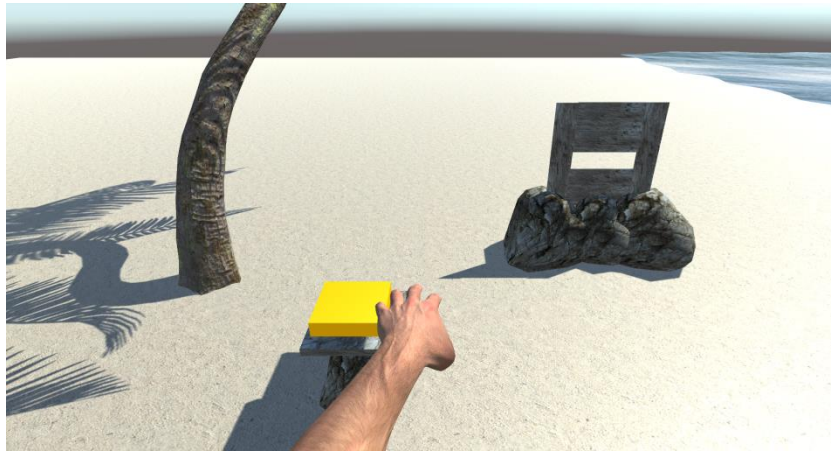
Figure 6.1 Mailbox test rendered in a different virtual environment with spatially identical initial positions and desired mailbox target with horizontal slot.

6.2 Methods

Healthy subjects with no visual or motor impairments that were right hand dominant and not exposed to previous training in the Pick and Place Task were recruited to participate in the study as the untrained control group. Subjects were seated in a comfortable chair in front of the haptic interface. An arm orthosis attached to the Haptic Master was used to support the left forearm of the subject. The left hand was placed in the wrist exoskeleton mounted to the end effector of the Haptic Master. A neutral hand position was maintained (no wrist flexion) to aid donning/doffing procedures. The grasping exoskeleton was applied to the left hand and securely fastened to provide precision pinch. Subjects were randomly assigned into one of four groups: Haptic Master control group (HM), Haptic Master with Gripper (HMG), Haptic Master with Wrist (HMW), and Haptic Master with Wrist and Gripper (HMWG).

Subjects from the PPT were recruited to participate in the MBT to serve as the trained group. Trained subjects were assigned to the originally trained group: HM, HMW, HMG, and HMWG group. Each experimental group participated in a single session of the unfamiliar MBT consisting of a practice trial and eight official trials. A single cube size was used to evaluate performance between the trained and untrained group. Subjects were instructed to transport the Big cube as many times as possible to the mailbox and insert the cube into the horizontal aperture within the 120s time interval.

To validate the efficacy of skill transferability, trained vs untrained control groups were assessed with the following metrics: Cube Success (CSX), Cube Error (CER), Cube Success Ratio (CSR), Trajectory Length (TRL), Delta Cube Time (DTC), smoothness (NIJ), and R-squared coefficient (RSQ). Comparative analyses for each metric were statistically evaluated to determine transferability of skill on an untrained task. Statistical methods were used to evaluate the respective DOF for each condition (trained vs untrained control).

6.3   Cube Success Results

Cube success for each experimental condition was recorded and compared between experimental groups. The cube success for each experimental group and respective training condition is summarized in Figure 6.2. Statistical analysis was performed to determine significant differences between trained and untrained experimental groups. A Shapiro-Wilk Test for Normality was conducted to assess population distribution. The experimental groups were in violation of the Shapiro-Wilk Test and evaluated with a non-parametric test. Each experimental DOF was assessed with a Mann-Whitney U test

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with a significance value of alpha $\alpha=0.05$ to compare trained and untrained conditions, respectively.
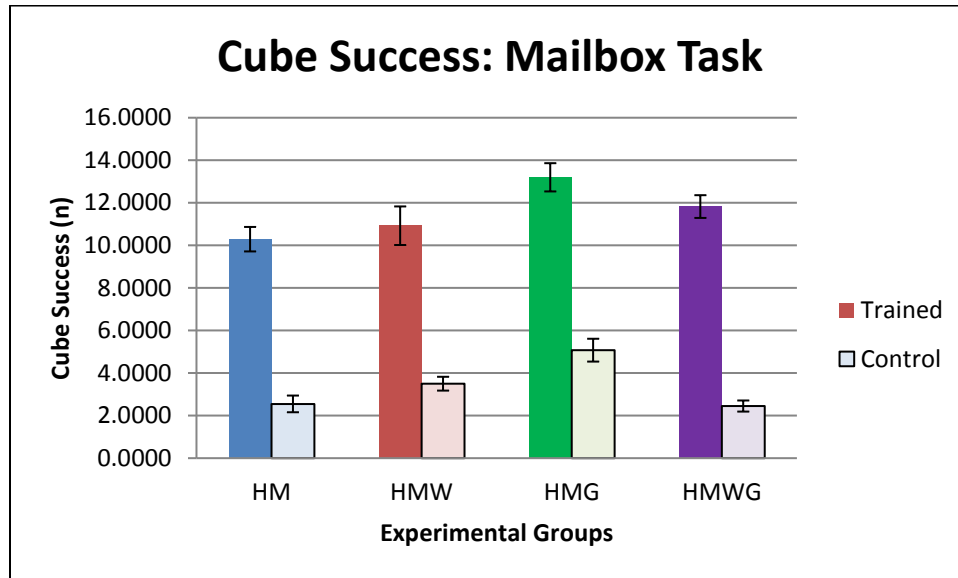
Figure 6.2 Average CSX for mailbox test for trained and untrained experimental groups.

Cube success for each trained group was statistically greater than the untrained control group. The trained HM group had statistically greater CSX than the untrained control ($p<0.001$). Training had a significant effect on CSX for the untrained MBT for the HM group. Significant effects were observed between the experimental conditions for the HMW group. Training had a statistically significant effect on CSX for the HMW group ($p<0.001$). The trained HMW had significantly greater scores than the untrained control group. Training had a significant effect on CSX for the HMG group. Subjects in the HMG group that received training performed significantly better than the untrained HMG group ($p<0.001$). The effects were also observed for the HMWG group. The trained HMWG group had statistically greater CSX scores compared to the untrained HMWG ($p<0.001$).

Each trained group had statistically greater CSX scores compared to the untrained control groups for each experimental DOF. The greatest change between trained and untrained DOF was observed between the HMWG groups. The trained HMWG group had scores 4.8 times greater than the untrained HMWG group (trained=10.29±0.576, untrained=2.55±0.392). The gain observed between trained and untrained CSX scores is recorded in Table 6.1. Each experimental group that received training demonstrated improvements in CSX scores with gains greater than 2.6. The results suggest that training had a statistically significant effect on CSX scores demonstrated by the improvements in trained CSX scores compared to untrained CSX scores.

Table 6.1 Calculated Gain for Trained vs. Untrained CSX Values

Experimental	HM	HMW	HMG	HMWG
Gain	4.04	3.12	2.60	4.83

6.4 Cube Error Results

Cube errors for each experimental condition were recorded and analyzed to determine significant effects between training conditions. Shapiro-Wilk Test for Normality revealed that the HM and HMW groups were not normally distributed, while the HMG and HMWG groups were normally distributed. A Mann-Whitney U Test was conducted for the non-normally distributed data, while an Independent Samples t-Test was used to assess the normally distributed data. Alpha values of $\alpha=0.05$ were maintained to assess significance. Cube error results are reported in Figure 6.3.

Statistically significant results were reported for cube error between experimental conditions. Training had a statistically significant effect on CER for the HM group. The trained HM group had significantly more errors than the untrained HM group ($p<0.001$).

No statistical significance was observed between the HMW groups. No effects were observed between the trained and untrained HMG group. Statistical significance was observed for the HMWG group that received training. The trained HMWG group had fewer errors than the untrained HMWG control group (p=0.001).
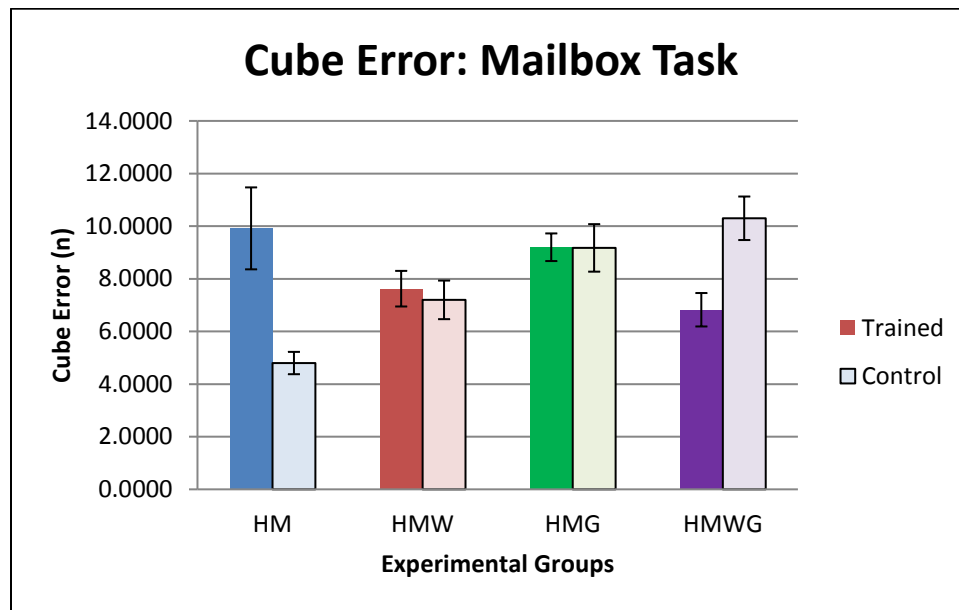
Figure 6.3 Average cube error for each experimental group and training condition.

Significance was observed for both trained and untrained cases. The HM trained group experienced significantly more errors while the trained HMWG group experienced significantly less errors. There was no statistical significance observed between the HMW and HMG experimental conditions. The results suggest that training with the wrist and gripper contributed to significantly less errors in the MB task based on the gain between trained and untrained HMWG groups and the trained experimental groups.

6.5 Cube Success Ratio Results

Cube success ratios for each experimental group were calculated and analyzed to determine statistical significance between trained and untrained conditions. A Shapiro-Wilk Test for Normality revealed that the HMW groups satisfied the requirements, while the HM, HMG, HMWG groups were in direct violation. The HMW group was evaluated with an Independent Samples t-Test, while the other experimental groups were evaluated with the non-parametric Mann-Whitney U Test. All significance levels were assessed at the alpha level, $\alpha=0.05$. The average CSR values are documented in Figure 6.4
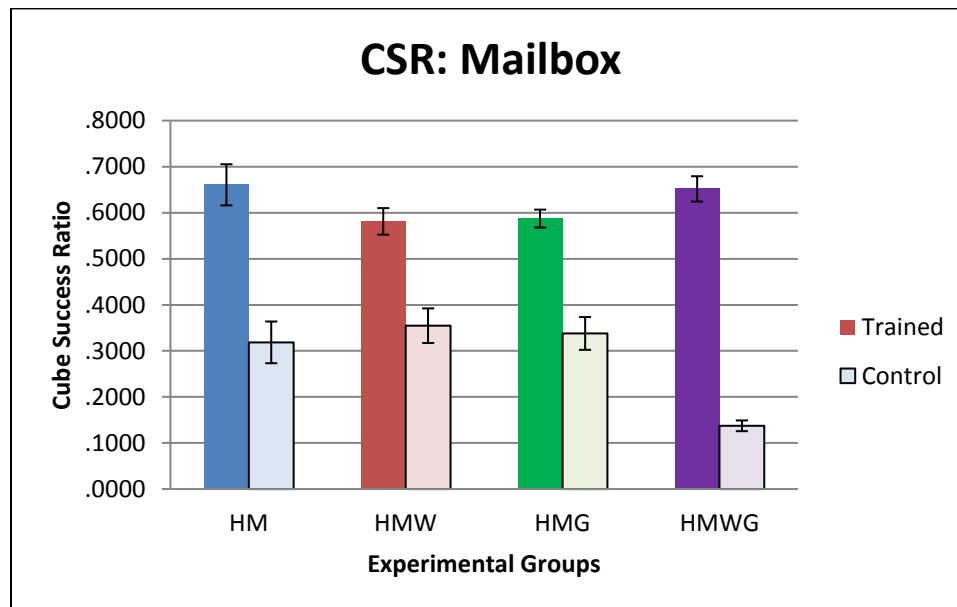
Figure 6.4 Average cube success ratio for each trained and untrained experimental group.

Training had a statistically significant effect on CSR ratios for each experimental group. HM subjects that received training had significantly greater CSR than the untrained HM group for the MBT ($p<0.001$). Statistically significant effects for HMW CSR were observed. HMW subjects that received training had significantly greater CSR than the untrained HMW group ($p<0.001$). Cube success ratios for the trained HMG

group were significantly greater than the untrained HMG group (p<0.001). Training had a statistically significant effect on CSR for the HMWG group (p<0.001). Subjects that received training had significantly greater CSR than the untrained HMWG group.

Table 6.2 Calculated Gain for Trained vs. Untrained CSR Values

Experimental	HM	HMW	HMG	HMWG
Gain	2.07	1.64	1.73	4.75

Trained groups experienced significantly greater CSR compared to the untrained experimental groups. Table 6.2 depicts the calculated gain as a ratio between the trained and untrained CSR values. The trained HMWG had CSR scores that were 4.75 times greater than the respective untrained group (Trained=0.66±0.027, Untrained=0.1374±0.011). All other experimental groups achieved gain factors greater than 1.5. The results suggest that training had a significant effect on CSR values. The large gain observed between the experimental conditions for the HMWG and the low CSR values relative to the other untrained experimental groups suggests that subjects in the untrained HMWG group may benefit from extended periods of training. The results suggest that high CSR values can be attributed to greater success with less error and can potentially be a result of quick adaptation and application of learned skills from the PPT task.

6.6 Trajectory Length Results

A comparative analysis was conducted between trajectory length values to determine if training had an effect on transport efficiency. A Shapiro-Wilk Test for Normality determined that each group was non-normally distributed and required nonparametric statistical procedures. A Mann-Whitney U Test was conducted to assess significance between experimental conditions and evaluated with an alpha of α=0.05. The observed effects between respective experimental DOF trajectories for each training condition is depicted in Figure 6.5.
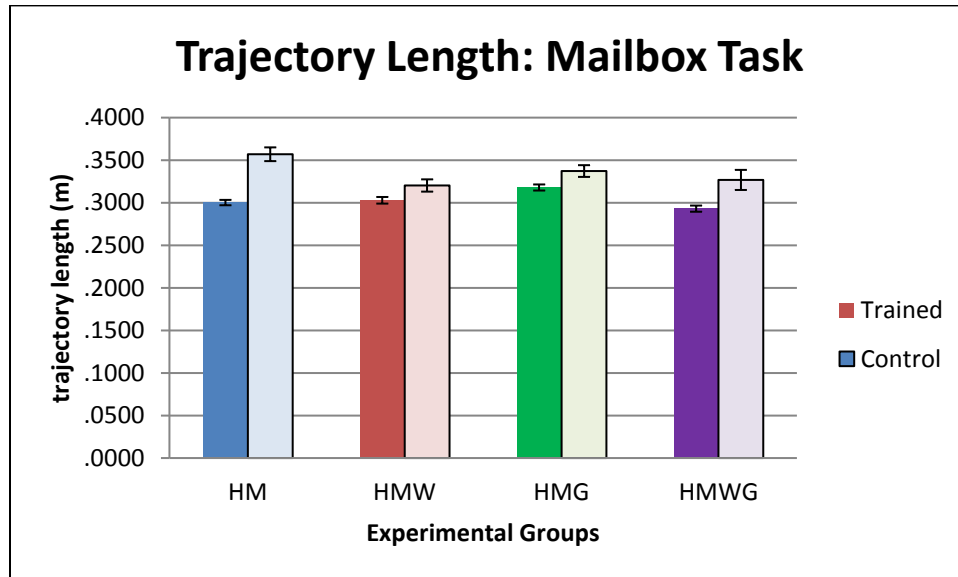
Figure 6.5 Average trajectory length for each trained and untrained experimental group.

Training had a statistically significant effect on trajectory lengths for each experimental DOF group. Subjects that received training demonstrated significantly shorter trajectories from the initial point to the virtual mailbox. The trained HM group had significantly shorter trajectories than the untrained HM group (p<0.001). Training had a statistically significant effect on trajectory length for the trained HMW group

(p<0.001). The trained HMG group reported significant effects between trajectory length values compared to the untrained HMG group (p=0.026). Similar effects were reported for the HMWG groups. The trained HMWG group generated excursions with shorter trajectories (p=0.001).

Table 6.3 Calculated Gain for Trajectory Lengths between Experimental Conditions

Experimental	HM	HMW	HMG	HMWG
Gain	1.19	1.06	1.06	1.11

Each experimental group that received training utilized direct pathways to transport the virtual cube from the initial position to the mailbox that minimized extraneous sub movements. The trained experimental groups had significantly shorter trajectories than the untrained experimental DOF. The untrained experimental groups exhibited longer trajectories evident by the gain reported in Table 6.3. The results suggest that training had a significant effect on trajectory lengths and that trained individuals utilized direct pathways to transport the cube to the mailbox. Over the course of training, the trained group exhibited a decrease in TRL values. The results suggest that the trained groups are able to adapt more quickly to the unfamiliar environment based on the more direct pathways compared to the pathways of the untrained control group.

6.7 Delta Cube Time Results

Statistical procedures were performed to assess significance between DCT values for trained and untrained experimental groups. A Shapiro-Wilk Test for Normality determined that each group was non-normally distributed. A Mann-Whitney U Test was conducted for each group to assess significance between experimental conditions and evaluated with an alpha of $\alpha=0.05$. The observed effects between respective experimental DOF trajectories for each training condition is depict in Figure 6.6.
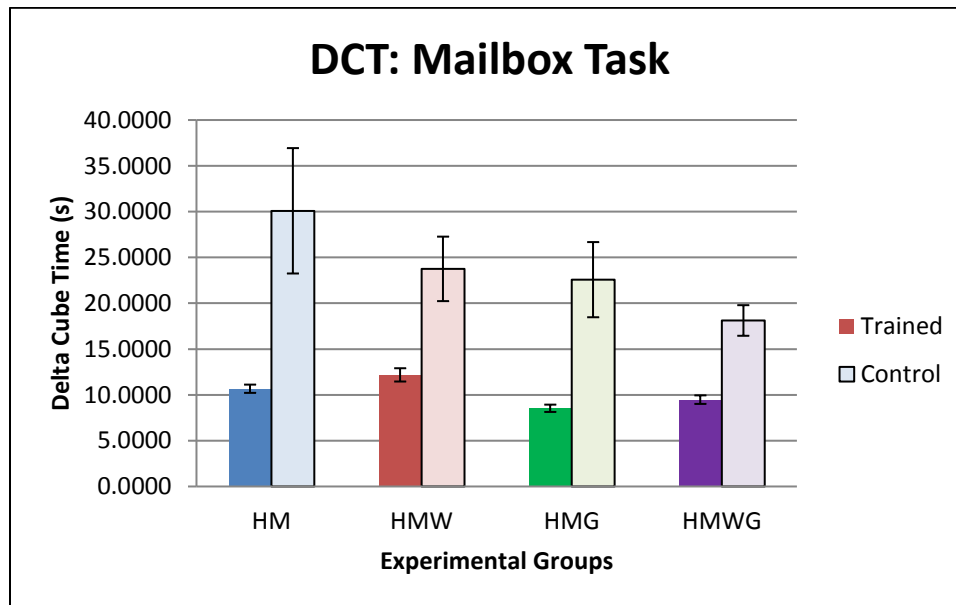
Figure 6.6 Average DCT values for each experimental group for each training condition.

Statistically significant results were observed between training conditions for each experimental group. Each trained group exhibited significantly lower DCT. Training had a statistically significant effect on DCT for the HM group. The trained HM group had significantly faster transport times (low DCT) compared to the untrained HM group ($p<0.001$). The trained HMW group reported faster transport times compared to the untrained HMW group ($p<0.001$). Similar effects were observed between the trained and untrained HMG group. The trained HMG group exhibited faster transport times than the

untrained HMG group (p<0.001). Training had a statistically significant effect on DCT for the HMG groups. HMWG subjects that received training had significantly greater response times indicated by the decreased DCT values compared to the untrained HMWG (p<0.001).

Training resulted in significantly faster transportation mechanics that minimized delays from the initial contact until the completion of the transport. Each experimental group exhibited significantly lower DCT scores compared to the respective untrained group. The greatest gain was observed between the trained and untrained HM group, Table 6.5. Each trained experimental group had significantly faster transport times that were nearly twice as fast as the untrained group. The results suggest that despite the new objective and unfamiliar environment, trained individuals were able to apply previous experience and skills to record faster times than the untrained controls.

Table 6.4 Calculated Gain for DCT between Trained and Untrained Groups

Experimental	HM	HMW	HMG	HMWG
Gain	2.82	1.95	2.65	1.91

6.8 Smoothness Results

Smoothness values were assessed to determine significant differences between trained and untrained experimental conditions. The smoothness values for each experimental group did not satisfy the Shapiro-Wilk Test for Normality. A Mann-Whitney U Test was conducted for each group to assess significance between experimental conditions and evaluated with an alpha of $\alpha=0.05$. The recorded smoothness for each experimental group for each respective training condition is illustrated in Figure 6.7.
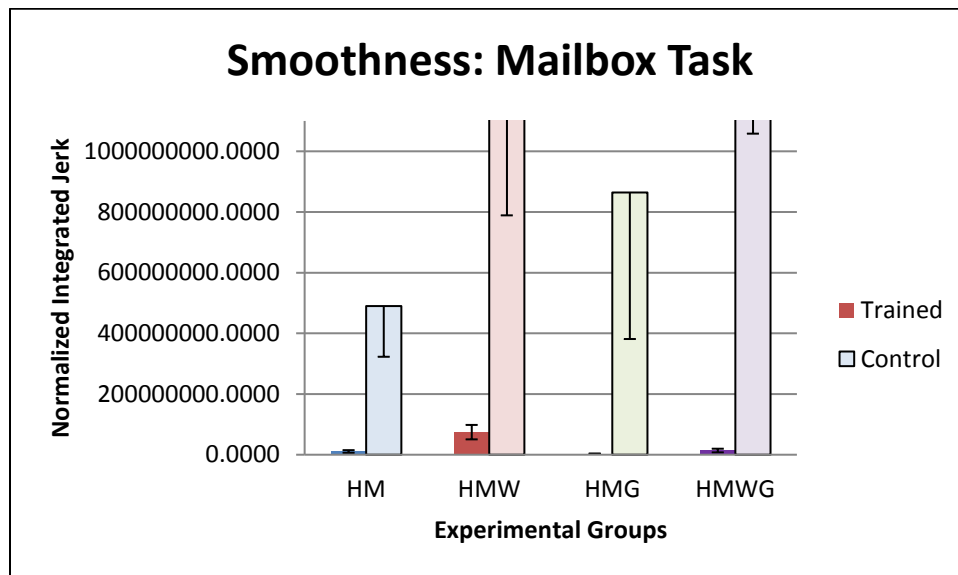
Figure 6.7 Average smoothness values for each experimental group for each condition.

Each group that received training had statistically smoother movements compared to the movements generated by the untrained controls. Subjects in the trained HM group demonstrated smoother movements compared to the untrained HM group ($p<0.001$). Statistically smoother movements were observed for the trained HMW group compared to the untrained HMW group ($p<0.001$). Training resulted in significantly smoother trajectories for the trained HMG group compared to the untrained HMG group ($p<0.001$).

The trained HMWG group produced smoother movements compared to the untrained HMWG group (p<0.001).

Table 6.5 Calculated Gain for Smoothness between Trained and Untrained Conditions

Experimental	HM	HMW	HMG	HMWG
Gain	46.32	20.26	289.23	124.97

Training resulted in statistically significant differences between smoothness values for the trained and untrained conditions (p<0.001). Each trained experimental group performed the task in a manner that minimized jerk and sub movements compared to the untrained experimental groups. The untrained HMG group experienced the greatest difference between training conditions. The calculated gain between each training condition is documented in Table 6.5. Untrained members of the HMG group exhibited trajectories that were 289.23 times less smooth than members that received training in the HMG group. Trained groups exhibited smoother movements with less sub movements compared to the less smooth movements generated by the untrained groups.

6.9 R-Squared Coefficient Results

A comparative analysis was conducted between RSQ values to determine if training had an effect on path directness. RSQ values were calculated to estimate the directness of the path taken from the virtual table to the mailbox and from the mailbox back to the virtual table. A Shapiro-Wilk Test for Normality determined that each group was non-normally distributed and required nonparametric statistical procedures. A Mann-Whitney U Test was conducted to assess significance between experimental conditions and evaluated with an alpha of $\alpha=0.05$. The observed effects between respective experimental DOF RSQ values for each training condition are evident in Figure 6.8.
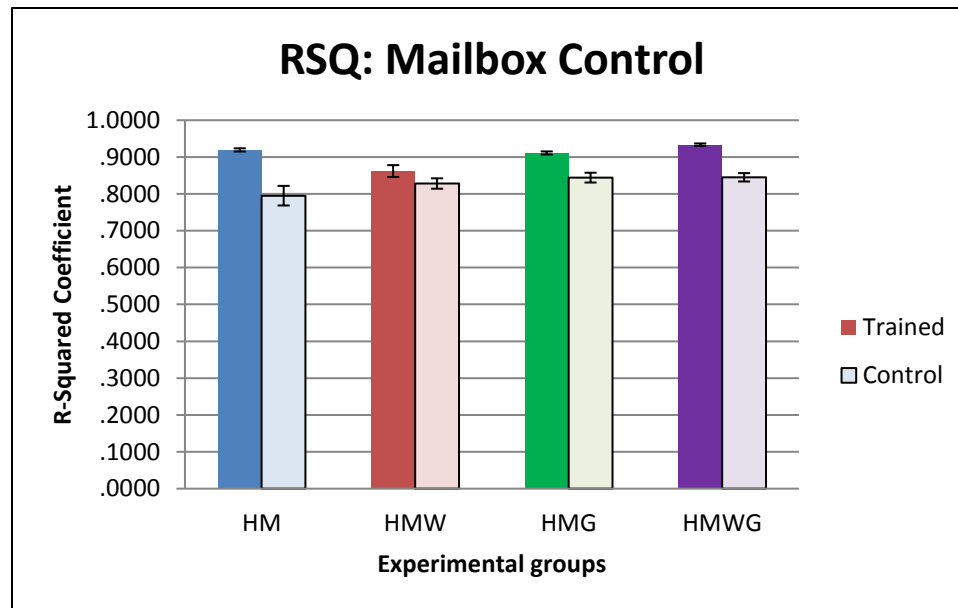
Figure 6.8 R-Squared coefficients for each experimental group in training condition.

Statistically significant differences were observed between training conditions for each experimental group. Subjects in the trained HM group demonstrated greater RSQ values compared to the untrained HM group ($p<0.001$). The trained HMW group had significantly greater RSQ values compared to the untrained HMW group ($p=0.025$).

Training resulted in better RSQ values for the HMG group compared to the untrained HMG group (p<0.001). Subjects in the HMWG group that received training demonstrated significantly greater RSQ values compared to the untrained HMWG group (p<0.001).

Table 6.6 Calculated Gain for RSQ Values between Trained and Untrained Group

Experimental	HM	HMW	HMG	HMWG
Gain	1.15	1.04	1.07	1.10

The trained groups demonstrated significantly greater RSQ values suggesting that the forward and return pathways utilized were more direct than the pathways observed by the untrained groups. The gain for each experimental group is depicted in Table 6.6. The trained HM group exhibited the greatest gain between trained and untrained conditions with RSQ values that were 1.15 times greater. The respective gains between the other experimental conditions revealed similar effects. The high RSQ values suggest that trained experimental groups utilized forward and return pathways with minimal variability compared to the untrained controls. Statistically significant differences in RSQ values were obtained between trained and untrained conditions suggesting that training contributed to improved RSQ values.

6.10   Mailbox Discussion

Transfer is defined as the application of knowledge, skills, and attitudes acquired during training to the environment in which they are normally used (Muchinsky 1991). To validate the effects of training and the ability to transfer skill between virtual environments, an alternative virtual environment was created to assess the skills of trained individuals with the non-dominant arm and hand. The MBT was devised to present trained individuals with an unfamiliar task with greater accuracy demands in a visually different VE with realistic physical elements and textures. The realistic visual elements such as the hand and environmental scenery were rendered to maintain high levels of fidelity to emulate real world settings. The level of fidelity must be high enough in each dimension for the behavior of interest to be exercised as it would in operational conditions to enhance skill transfer (Alexander et al. 2005). With respect to this study, transfer represents the ability for trained individuals to apply knowledge and skills previously learned in the PPT to the unfamiliar and untrained MBT in a manner that would result in improved performance compared to the untrained control groups for each experimental DOF. There is increasing evidence that suggests individuals with both cognitive and motor issues that train in VE can transfer skills practiced in VE to activities of daily living. Individuals with neurological impairments as well as able-bodied individuals have demonstrated positive transfer of skills between virtual simulations and real world practices.

The most important goal of virtual reality training is to increase the skill of the user regardless of neurological condition. Rehabilitation paradigms that utilize virtual training settings provide the patient with an opportunity to perform mass task practice

with goal-oriented objectives to better facilitate recovery. Brooks et al. conducted a study with a cognitively impaired individual to determine if a virtual representation of a real hospital setting could aid in hospital navigation. The individual was unable to navigate ten routes in the real hospital prior to virtual training. After three weeks of virtual training, the amnesia patient was able to transfer knowledge practiced in the VE and successfully navigate two routes in the hospital. Children with learning difficulties demonstrated faster times in supermarket navigation with VE simulations of the real market compared to controls who trained on an irrelevant VE (Brown et al. 1999). Todorov et al. (1997) conducted a battery of tests to determine the effects of motor skill transfer after training in a virtual environment. A table tennis stroke was practiced in a virtual environment with visual feedback to indicate the correct pathway and movements. Participants who trained in the virtual environment demonstrated better performance in the real world table tennis task than those that practiced in the real world alone. Seymour et al. (2002) assessed surgical skills with virtual laparoscopic training. Residents who trained on the MIST VR laparoscopic virtual trainer exhibited fewer errors and faster task completion times compared to conventional training group. Appropriate feedback conditions have also demonstrated positive effects on transfer between virtual and physical applications and can enhance the fidelity of the training environment. Physiological measurements on heart rate and skin conductance suggest that the incorporation of haptics can increase user presence and enhance interaction with the environment, which can lead to greater effects in transfer (Meehan et al. 2002). Direct haptic feedback has demonstrated improvements in error rates and force regulation (Richards et al. 1996). Virtual environments represent an attractive training method to

enhance skill acquisition and have demonstrated desirable transfer effects in real world activities.

Virtual training had a significant impact on MBT performance for the trained group compared to the untrained controls. Subjects who trained in the PPT environment demonstrated significantly greater CSX, improved CSR, decreased TRL, faster DCT, smoother trajectories, and improved RSQ values. Trained subjects were able to transport more cubes successfully in the new task compared to untrained individuals. Significant differences in cube error were observed between the HM groups and the HMWG groups. The trained HM group exhibited more errors compared to the untrained group. There was no statistical significance between the HMW groups and HMG reports. The HMWG had significantly less errors compared to the untrained control based on unfamiliarity with virtual training. The lack of statistical significance between CER may be a result of the greater accuracy demands required for successful transport and may rely on continued improvements and additional learning. Participants must place the cube in a horizontal slot that is approximately 1.5x greater than the virtual cube. There is a greater inherent risk of cube error when the cube is not accurately aligned with the horizontal slot of the mailbox. If the cube is not oriented in the proper manner, there is a greater chance of error accumulation. All trained experimental groups exhibited shorter trajectories during transport with faster times. Not only were movements faster and more direct, but the movements of the trained groups were significantly smoother compared to the untrained counterpart. Variability between forward and return trajectories was minimized in the trained group as indicated by the significantly greater RSQ values.

An untrained task was used to assess whether skills obtained in a virtual environment could be transferred to a virtual setting with similar context. The Muchinsky definition for transfer encompasses two distinct characteristics: knowledge and skills. Virtual training had a positive impact on performance in the Mailbox Task and contributed to significant effects between the trained and untrained groups. Participants that received training had knowledge of device performance, experience with virtual training, and were able to apply previously obtained skills to an unfamiliar task. Task performance was significantly better for trained individuals compared to untrained individuals. Trained subjects had significantly better performance compared to untrained controls which suggests an ability to adapt the previously learned strategy to a different task. Trained subjects repetitively practiced picking up virtual objects and transferring them to the designated target box in the PPT. The virtual platform that housed the virtual block for the MBT was in an identical location due to the workspace constraints of the Haptic Master. The virtual mailbox was positioned in a new location that was located away from the original target box and engaged new horizontal and vertical directional movements. Despite the redesign of the specified target with directional changes and greater accuracy constraints, trained individuals exhibited significantly faster times with greater success and trajectory mechanics than the control group. The data suggests that users transferred previous knowledge to pick up the virtual objects and deliver them to the new location. Training contributed to better task planning with more efficient modes of transport. Since the environment served as a fixed variable for both training groups with no prior exposure to MBT, the effect of training on performance was the only significantly different factor between groups. Holden et al. (1999) demonstrated that two

subjects with hemiparesis improved reaching ability in the real world following training in a VE on a similar task. Subjects were required to transport a virtual envelope to a virtual mailbox with a designated hand position. Virtual training has demonstrated positive transfer effects across populations with and without neurological impairments demonstrating functional gains in skill acquisition and application. The transferability of skills from a VE simulator to physical reality is essential for usability, especially when considering applications for rehabilitation.

6.11   Mailbox Conclusion

Virtual reality training paradigms represent an effective medium with which individuals with stroke can perform repetitive task practice to facilitate motor learning. The validity of virtual training and the ability to transfer skills between environments represents an objective and quantifiable approach for rehabilitation. The results observed in this investigation provide empirical evidence that supports skill transfer between independent virtual environments. Based on the observed metrics, training had a significant effect on performance compared to the untrained control group. Augmented environments can be created with enhanced immersion and haptic feedback to provide environments with greater fidelity. The effect of viewing mediums will be explored in the following chapter to discern the effects of viewing mediums on performance. The virtual reality investigation on the ability to transfer skills presented in this study demonstrated positive effects that knowledge and skills can be transferred between environments.

CHAPTER 7

VIRTUAL REALITY VIEWING ASSESSMENT

7.1 Introduction

There are two common mechanisms used to render virtual reality experiences: projection display and head mounted displays (HMD). Projection displays can provide a monoscopic planar representation of the virtual environment or 3D stereoscopic image with a wide field of view using stereoscopic glasses. HMD systems provide a panoramic view of the virtual environment that incorporates head-tracking and stereoscopic 3D rendering to simulate real world binocular experiences. Virtual reality systems that utilize HMD provide a more immersive viewing experience compared to the flat representation of a virtual scene (Connelly et al. 2005). Enhanced depth perception provided by the HMD can grant the user the sensation of presence, which is an essential component for immersion. Evidence suggests that the increased level of immersion in a VR system has demonstrated improvements in upper limb motor skill reacquisition (Henderson et al.). The sense of immersion provided by the VE may aid in visualization where activation of the brain areas following observation or motor imagery may thereby facilitate subsequent movement execution by directly matching the observed or imagined action onto the internal simulation of the action (Holper et al. 2010). Activities of daily living can be replicated in the immersive environment with appropriate feedback conditions. Haptic hand devices paired with the HMD can create a closed feedback loop where the user can interact and manipulate objects with force feedback.

To assess the differences between viewing experiences, a comparative analysis was conducted between two experimental DOF groups subject to immersive VR and projected VR. The investigation was conducted to determine if immersive VR with appropriate haptic feedback had more desirable effects on training than projected VR with haptic feedback. The HM and HMG group were assessed in two training conditions: immersive VR and projected VR. The Oculus Rift was used to provide the immersive virtual reality setting and an NEC DLP Projector was used to render the projected virtual environment. Each participant was untrained and required to perform the PPT in the respective experimental viewing condition.

7.2 Methods

Healthy subjects with no visual or motor impairments that are right hand dominant were recruited to participate in the study. Subjects were seated in a comfortable chair in front of the haptic interface. An arm orthosis attached to the Haptic Master was used to support the left forearm of the subject. The subject maintained a neutral hand position to aid donning/doffing procedures. The grasping exoskeleton was then applied to the left hand and securely fastened to provide precision pinch. Subjects were randomly assigned into one of four groups: Haptic Master with Projector (HMP), Haptic Master with Gripper and Projector (HMGP), Haptic Master with Oculus (HMO), and Haptic Master with Gripper and Oculus (HMGO). Subjects were instructed to transport a virtual cube in a virtual environment to a target location as many times as possible during 120s trial. Each subject

participated in a single session, where the session consisted of eight trials. Rest periods of 120s were applied in between trials.

Figure 7.1. *Left)* Immersive VR components include the modular gripper and Oculus Rift. *Middle)* Stereoscopic view of virtual task viewed through Oculus Rift. *Right)* Individual engaged in immersive experience with visual and haptic feedback provided by Oculus.

The virtual environment included a virtual arm, virtual cube, and virtual target. Arm movements were mapped to the virtual arm via the HM. The virtual hand aperture mimics the movement provided by the modular gripper. When the virtual hand grasps the virtual cube, the haptic interaction will prevent the gripper aperture from closing, providing the force feedback sensation. Once the cube is grasped, the subject transports the cube to the designated location and places it on the specified target. When the cube is successfully placed on the target, a new virtual cube appears at the origin of the workspace. If the subject does not grip the cube properly or apply enough force, the cube falls and resets to the initial position. Additionally, if the cube is not placed on the specified target, the cube resets and the user repeats the operation. Collisions between the

hand and object provide haptic feedback to the user. Feedback provides real-time information to the user, such as specified target, points scored, and time remaining. Each respective group received visual feedback from either a projector or HMD (Oculus Rift, California, USA). Performance in the virtual task was assessed based on the number of cubes successfully transported to the target, the number of cubes that did not reach the target, and the length of the path taken towards the target.

To determine the effects of immersion on training, each viewing condition was assessed with the following metrics: Cube Success (CSX), Cube Error (CER), Cube Success Ratio (CSR), Trajectory Length (TRL), Delta Cube Time (DTC), smoothness (NIJ), and R-squared coefficient (RSQ). Comparative analyses for each metric were statistically evaluated to determine the effect of the Oculus HMD compared to the projected display and assess whether immersive VR contributes to better performance. Statistical methods were used to evaluate the viewing conditions for each experimental group between respective viewing conditions.

7.3 Cube Success Results

A comparative analysis was conducted between cube success for each viewing condition and experimental group to determine if viewing condition had an effect on performance. A Shapiro-Wilk Test for Normality determined that each group was non-normally distributed and required nonparametric statistical procedures. A Kruskal-Wallis Test was conducted to assess significance between experimental conditions and evaluated with an alpha of $\alpha=0.0071$ to determine significance between all conditions and correct for

multiple comparisons. The observed effects between respective DOF for each viewing condition are presented in Figure 7.2.

There was no statistical significance observed between HM viewing conditions. No significant effects were reported between the HMP and HMO groups (p=0.874). There was no statistical significance observed between HMG viewing conditions. The HMGP and HMGO reported no significant differences between viewing conditions (p=0.054). Significant effects were observed between the HMP and HMGP group (p=0.001). Overall, there were no statistically significant differences reported between viewing conditions.
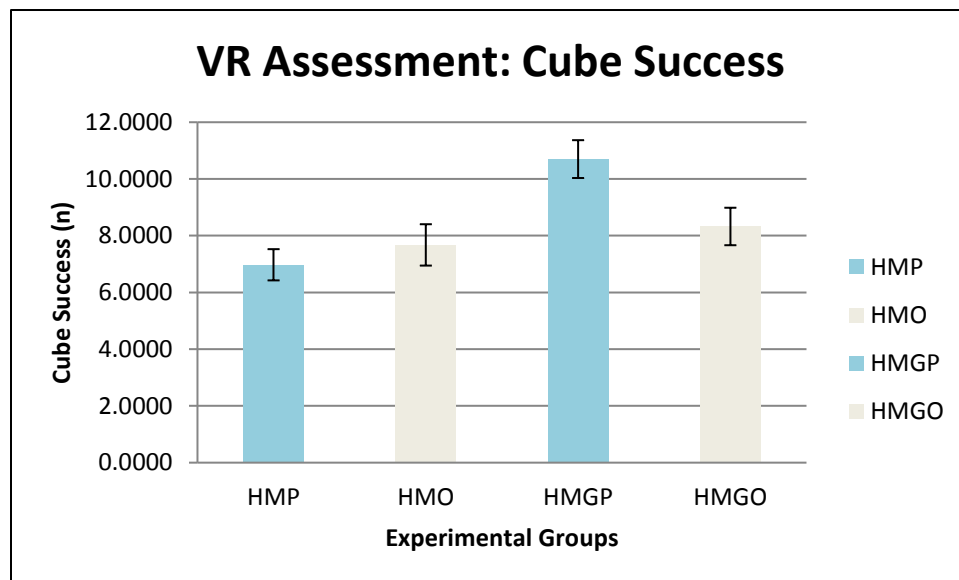
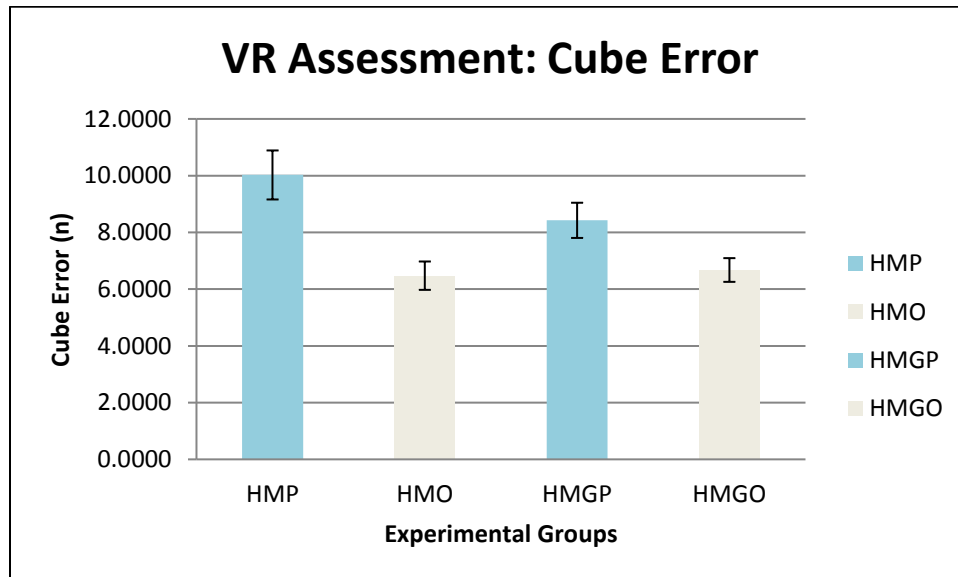**Figure 7.2** Average CSX for experimental groups in respective viewing conditions.

7.4 Cube Error Results

Statistical procedures were performed to assess significance between CER values for each experimental group in the respective viewing condition. A Shapiro-Wilk Test for Normality determined that the data was non-normally distributed. A Kruskal Wallis Test

was conducted to assess significance between experimental conditions and evaluated with an alpha of α=0.0071. The observed effects between respective viewing conditions for each experimental group are depicted in Figure 7.3.

Statistically significant results were observed between the HM viewing conditions. The HMP group had significantly more errors than the HMO group (p=0.001). The HMP group also had significantly more errors than the HMGO group (p=0.001). No significant differences were reported between the HMGP and HMGO. There were no significant differences between the HMO and HMGO. Despite the lack of statistical significance between the HMGP and HMGO, the results qualitatively suggest that the immersive VR with the Oculus may provide a viewing experience that reduces error. The observed CER for each experimental group with the Oculus exhibited fewer errors than the projector groups and was significantly less for the HMO group.

Figure 7.3 Average CER for experimental groups in respective viewing conditions.

7.5 Cube Success Ratio Results

A comparative analysis was conducted between CSR values to determine if viewing experience had an effect on performance. CSR values were calculated to estimate the performance efficiency for each experimental group in the respective viewing conditions. A Shapiro-Wilk Test for Normality determined that the data was non-normally distributed and required nonparametric statistical procedures. A Kruskal-Wallis Test was conducted to assess significance between experimental conditions and evaluated with an alpha of $\alpha=0.0071$. The observed effects between viewing conditions for each experimental group values are evident in Figure 7.4.
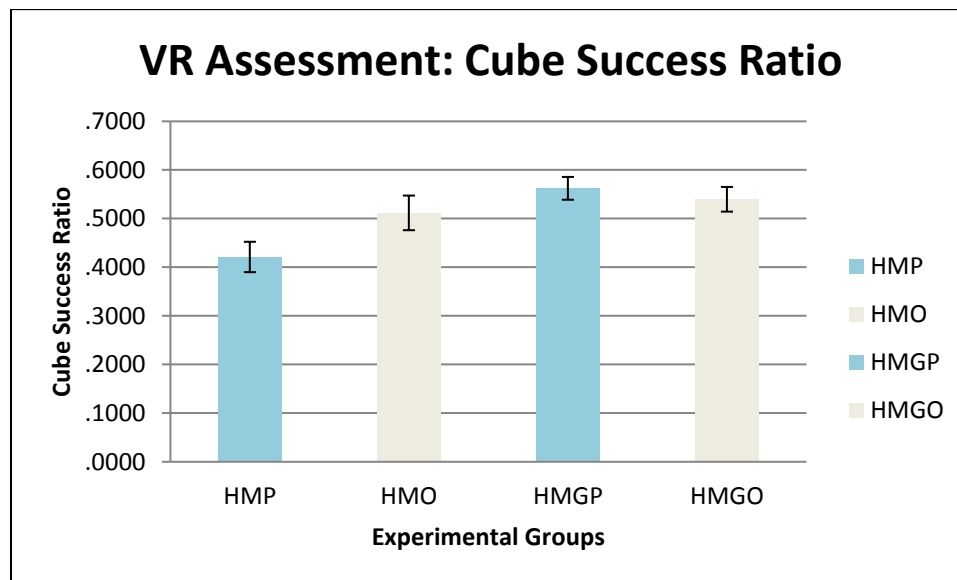

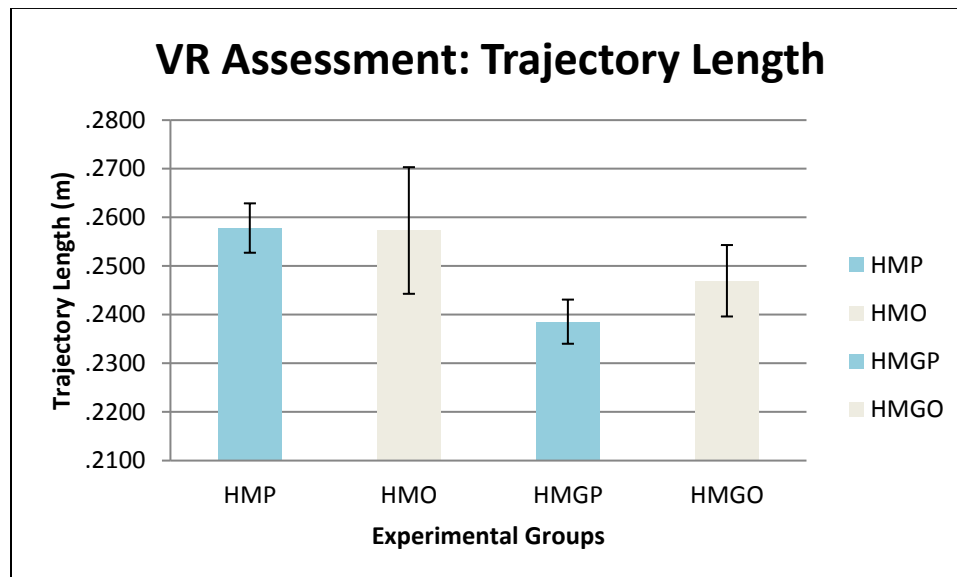**Figure 7.4** Average CSR for experimental groups in respective viewing conditions.

Statistical significance was not observed between either experimental group for each viewing condition. There was no statistical significance between Oculus and Projector groups. Significant differences in CSR values were observed between Projector groups. The HMGP had significantly greater CSR than the HMP (p=0.005).

7.6 Trajectory Length Results

Trajectory length values for each viewing condition were calculated and assessed with statistical procedures to determine if viewing conditions affected transport trajectories. The data was in violation of the Shapiro-Wilk Test for Normality and evaluated using non-parametric procedures. A Kruskal-Wallis Test was conducted to determine significance between experimental groups and evaluated with alpha $\alpha=0.0071$ to protect significance levels. The average trajectory lengths for each experimental group are illustrated in Figure 7.5. The Kruskal-Wallis test revealed that there was no statistical significance between experimental groups for either viewing condition.


Figure 7.5 Average trajectory lengths for each experimental group and viewing condition

7.7 Delta Cube Time Results

Statistical procedures were performed to assess significance between DCT values for each viewing condition and associated experimental group. A Shapiro-Wilk Test for Normaility determined that each group was non-normally distributed. A Kruskal-Wallis Test was conducted for each group to assess significance between viewing conditions and evaluated with an alpha of α=0.0071. The observed effects between DCT for each viewing condition group is depicted in Figure 7.6.

No statistical significance was observed between experimental groups for each viewing condition. The measured response time DCT between the HMP and HMO groups was not statistically different (p=0.917). There was no significant difference observed between the HMGP and HMGO group (p=0.976). Despite the lack of statistical significance, the data suggests that the HMG group performed faster evident by the low DCT values compared to the HM groups for both the Projector and Oculus group.
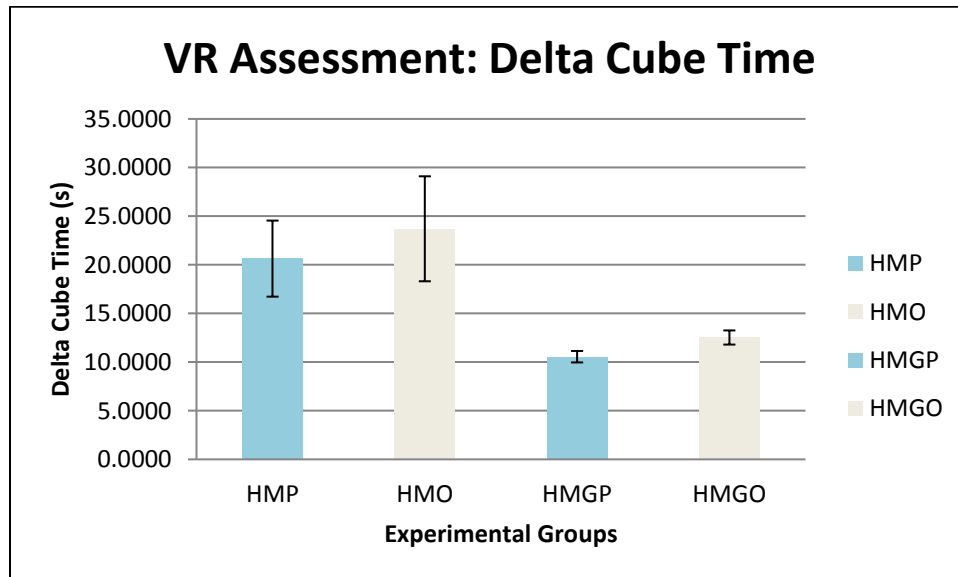

Figure 7.6 Average response time for each experimental group and viewing condition.

7.8 Smoothness Results

Smoothness values calculated as normalized integrated jerk were compared between experimental viewing conditions to assess statistical significance between conditions. A Shapiro-Wilk Test for Normality was performed prior to analysis to determine normality of distribution. The data was non-normally distributed and evaluated with a non-parametric test. The Kruskal-Wallis Test revealed that there were no significant differences observed between experimental groups at the significance level of alpha $\alpha=0.0071$. The smoothness values for the HM an HMG groups are observed in Figure 7.7 and Figure 7.8, respectively.

Despite the lack of statistical significance between the groups, the results qualitatively depict that movements with a projection display were smoother than movements performed in the immersive Oculus environment. The results suggest that the gripper contributed to smoother movements with respect to the HM group for both viewing conditions although no significance was observed between either DOF condition or viewing condition.
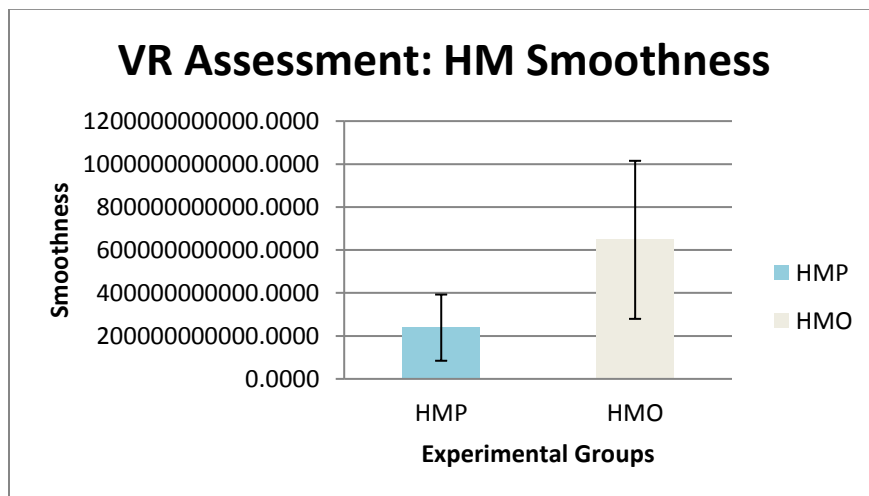
Figure 7.7 Average smoothness for HM group for each viewing condition.
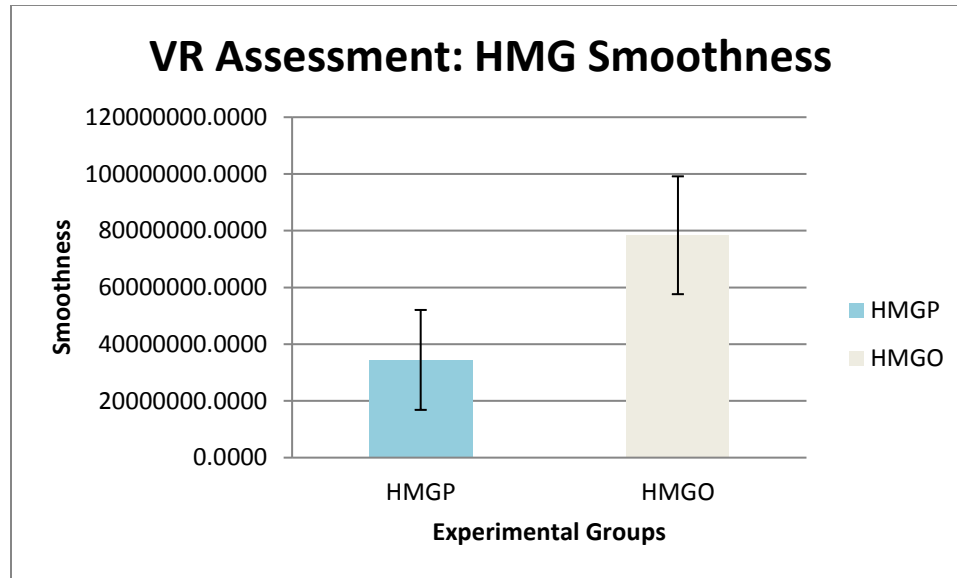
Figure 7.8 Average smoothness for HMG group for each viewing condition.

7.9 R-Squared Coefficient Results

R-squared coefficients were assessed to determine significant differences between experimental viewing conditions. The RSQ values for each experimental group did not satisfy the Shapiro-Wilk Test for Normality. A Kruskal-Wallis test was conducted to assess significance between experimental conditions and evaluated with an alpha of $\alpha=0.0071$ to protect significance levels. The recorded RSQ values for each experimental viewing group for each respective DOF condition are in Figure 7.9.
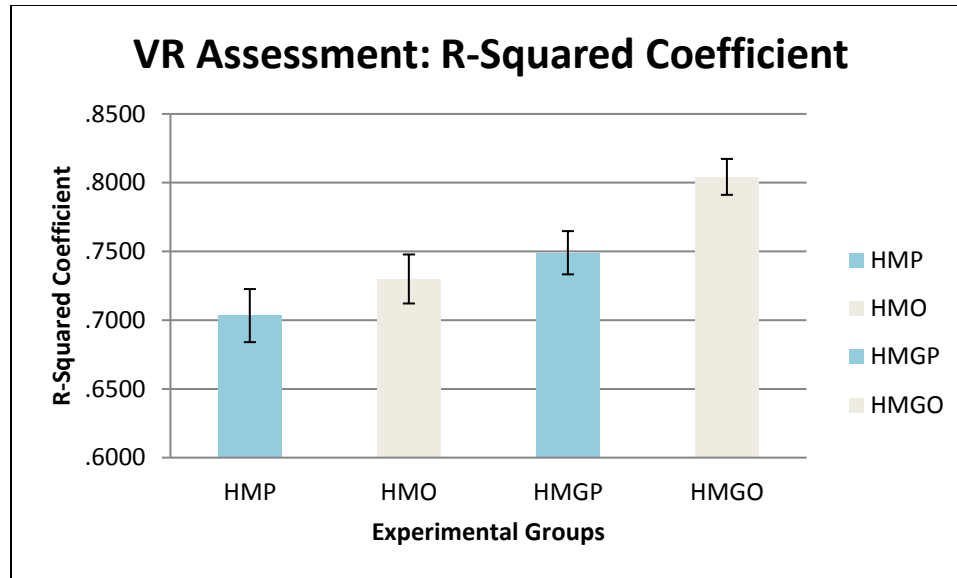
Figure 7.9 Average RSQ values for each viewing condition and experimental group

Statistical analysis revealed that there was no significant difference between the HMP and HMO viewing conditions. There were no significant effects observed between the HMGP and HMGO viewing conditions. Statistical significance was observed between the HMP and HMGO group. The HMGO had significantly greater RSQ values compared to the HMP group ($p<0.001$). Due to the Bonferroni Correction, there was no significance observed between the HMO and HMGO groups ($p=0.01$). The data qualitatively suggests that the Oculus condition observed greater RSQ values compared to the projected VR group. The addition of the gripper resulted in an increase in RSQ values compared to both HMP and HMO conditions. RSQ values were observed to be greater when the Oculus was used simultaneously with the gripper. The results suggest that the HMGO viewing condition had a significant effect compared to the HMP viewing condition.

7.10   VR Assessment Discussion

Advancements in interactive technologies have increased the appeal and potential of virtual reality applications. Physical interactions with the virtual environment through motion capture modalities such as the Microsoft Kinetic, LEAP Motion, and Wii-U provide users with a direct interface to coordinate movements between digital and physical environments in order to perform virtual actions and manipulate virtual objects. Viewing experiences such as immersive HMDs or non-immersive projections provide the visual interface with which the user can observe the translational effects between the digital and physical world. Henderson et al. (2007) found evidence that increased levels of immersion in a virtual reality system provide advantages in upper limb motor skill reacquisition. A preliminary investigation was conducted to determine if an immersive HMD viewing experience with haptic feedback increased subject performance compared to conventional non-immersive planar projection with haptic feedback.

The results indicated that there was no statistical difference between respective experimental groups for each viewing condition other than for CER. Significance was observed for the HM viewing conditions between the HMO and HMP with respect to CER. The HMO had significantly fewer errors compared to the HMP group. While there was no statistically significant difference between viewing conditions, the modular gripper did contribute to significantly greater CSX as observed between the HMP and HMGP groups. Significant differences in cube error were observed between DOF conditions and viewing conditions. The HMP group had significantly more errors than the HMGO group, suggesting that the combination of immersion and haptic feedback contributed to less error compared to the condition with less immersion and no haptic

feedback. Significance was observed between RSQ values for the HMP and HMGO groups, suggesting that the combination of the Oculus and gripper contributed to decreased variability between forward and return trajectories. The results suggest that the Oculus may contribute to less error and provide a perspective of the environment that is conducive for direct transport compared to non-immersive projected environments.

Untrained subjects were recruited for a single session to test the effects of immersive VR with the Oculus Rift. Users may have benefited from extended training with multiple sessions to determine the impact of each viewing condition. Another possible explanation for the lack of significance may be due to the sample size. Each of the four experimental conditions utilized five participants to follow the original protocol of the PPT. For this particular investigation, the small sample size reduced statistical power and resulted in a decrease in significant changes between viewing conditions. Increasing the sample size would provide more statistical power to detect significant changes between viewing conditions. While no significant differences were detected between viewing conditions for the VR Assessment, an increase in sample size and extended exposure to training for each viewing condition may provide a more suitable experimental setup to detect significant changes between immersive VR and non-immersive VR displays. Just et al. (2014) reported that movement profiles in a virtual environment rendered with the Oculus resembled movements of reaching to a real target with longer deceleration components. The quality of the viewing environment may alter how movement is produced. Smoother and faster movements were generated in the projector group compared to Oculus group, although no significance was observed between the viewing conditions, these findings are consistent with previous studies.

Submaranian et al. (2011) reported that movements made with HMD viewing conditions were slower and less precise than movements made with a computer monitor in healthy controls. However, stroke subjects with moderate to severe hemiparesis actually performed faster in the virtual environment when viewed with the HMD (Submaranian et al. 2011). Each experimental condition relied on pointing to targets rather than a task oriented transport goal with haptic feedback. The goal of the present study was to propose a preliminary investigation to determine the effects of viewing mediums on task performance with haptic feedback as previous studies have relied on tasks that lack haptic feedback.

Despite the lack of significance between viewing conditions, each interface may provide unique benefits. Users reported an increased feeling of immersion with the Oculus and increased interaction with the haptics provided by the modular gripper. The human brain is highly optimized for reconstructing 3D scenes from images by exploring depth cues such as stereopsis, motion parallax, perspective, and occlusion (Bowman et al. 2007). HMD devices provide the ability to generate stereo images and head tracking to increase user interaction with the virtual environment through stereopsis and motion parallax (Bowman et al. 2007). Participants indicated that the virtual environment mimicked real world settings in terms of haptic sensation and stereoscopic rendering. Extended training sessions may reveal the added benefit of immersion on VR training. Additionally, games that require a greater sense of depth and rely on the stereoscopic capabilities of HMD may reveal the potential benefits of VR training with immersive displays like the Oculus Rift. The PPT task might not have relied on the extensive use of depth, as most of the targets and initial contact points were in the foreground. Games that

engage the user with varied distances and target locations may provide an environment with which the differences between planar projection and HMD can be assessed and determined.

Although the positive features associated with HMD such as stereopsis, motion parallax, and immersion may create favorable virtual experiences, certain limitations exist which favor conventional displays or projection, especially with concerns for applications for rehabilitation. Prolonged periods of HMD use have been known to create cyber sickness, associated with nausea, dizziness, and vomiting, visual problems like reduced binocular acuity and eye strain, and a higher incidence of disorientation compared to other display media like monitor or projector (Cobb et al. 1999). The weight of the HMD device could prove to be an issue in populations with disability and severe muscle weakness if worn for prolonged periods. The weight added by the HMD to the head changes head and neck posture which may cause an increase in the angle formed between eye level and the target leading to distance underestimation (Ooi et al. 2001). The weight of the device could alter joint kinematics and influence performance. The reduced field of view (FOV) presents another limitation of the HMD compared to projections. The normal FOV for a healthy adult with normal visual acuity spans 200 degrees horizontally and 120 degrees vertically compared to the 110 degree FOV of the Oculus Rift (Submaranian et al. 2011). HMD with restricted FOV of 30 degrees or less have contributed to underestimations in target distances. Naceri et al (2009) found that HMD movements resulted in misestimation of distances in VE. While the presented limitations may favor conventional media displays, the current limitations that may

determine HMD use concern the weight of the device and the potential phenomenon of cyber sickness, especially when considering applications for rehabilitation.

The underlying principals investigated in the viewing assessment may indicate that there is no increased benefit to training with an immersive stereoscopic display compared to standard projection. The task did not require extensive depth perception and a 2D planar representation might be sufficient for the designated virtual task. Unity 3D renders realistic environments in a visually 3D environment for primarily 2D representation. The game developing software relies on high fidelity textures with shadows to create realistic environments with the sense of depth perception. The perspective of translated objects decreases as the object is translated further away from view. The elements provided in Unity3D represent 2.5D, which may be sufficient when viewed with projection. The Oculus as an immersive HMD may not provide any additional benefit compared to the rendered elements in Unity3D other than the sense of immersion. The results of this study suggest that there is minimal statistical significance between viewing mediums and conventional projection may be a sufficient viewing medium.

7.11   VR Assessment Conclusion

This preliminary study was conducted to determine the effects of immersion with HMD compared to conventional projection display with and without haptic feedback conditions during a PPT task. Previous studies have relied on experimental procedures without task specific training with appropriate haptic feedback. Despite the lack of significance between the experimental viewing conditions, the data qualitatively suggests that the results between HMD and projection display may be in accordance with established research, that the HMD may not provide any increased benefit on task performance. Prolonged training sessions with a larger sample population may provide greater insight into the benefits of either viewing condition during training. However, Unity 3D graphics and rendered objects may be sufficient to render high fidelity environments with appropriate textures and shading to provide the sense of 2.5D with projection. While HMD devices can create immersive virtual environments that provide stereoscopic scenes to enhance depth perception and head tracking to create panoramic viewing experiences comparable to real world environments, conventional projection may be sufficient due to the lack of significance between viewing experiences and the HMD may not provide an increased benefit. Conventional display media can provide large FOV displays where the user can compare real world actions with virtual excursions. Rehabilitation applications should consider the potential benefits and disadvantages of each media display to create a suitable landscape for repetitive training paradigms and accommodate patient comfort.

CHAPTER 8

CLINICAL RELEVANCE: MODULAR GRIPPER ASSESSMENT

8.1 Introduction

An understanding of the contribution of underlying neuro-physiological principles on motor control after stroke may lead to the identification of suitable rehabilitation programs based on clinical evidence. The leading cause of disability after stroke is hemiparesis, which results in severe motor impairments that affect upper extremity control of arm and hand function. Some of the associated complications due to hemiparesis include muscle weakness, spasticity, contracture, and flaccid hemiparesis (Louse et al.2006). Spasticity is characterized by a velocity-dependent increase in tonic stretch reflexes with exaggerated tendon jerks, resulting in hyper-excitability of the stretch reflex (Lance 1980). When a muscle contracts reflexively due to spasticity, it will tend to remain in a shortened position. Extended periods in this shortened state can lead to a loss of sarcomeres, which can contribute to changes in muscle-tendon lengths and reduce range of motion (Louse et al. 2006). This reduced range of motion can affect joint mobility and is typically characterized as contracture. Contracture can lead to muscle weakness which decreases joint mobility and upper extremity function and can result in shortening of tissues, thereby reducing joint range of motion (Louse et al. 2006). Atrophy of type II muscle fibers have been documented in spastic patients resulting in paralysis or weakness that predispose the patients to rest the paretic limb in a comfortable position. The posture of the hemiparetic arm subjects elbow flexor muscles to immobilization in a

shortened position, conditions shown to produce muscle contracture in experimental animals (O'Dwyer et al. 1996).

Another complication typically associated with stroke involves the inability to perform voluntary muscle movements due to the emergence of synergy patterns. The early appearance of synergy patterns can lead to involuntary movements with minimal control and can result in abnormal movements with joint couplings. The synergy patterns between muscles are often uncoordinated and require extensive rehabilitation to synchronize the synergies to regain motor control. The appearance of synergy patterns and coordination between muscles facilitate the voluntary movements, which becomes stronger with occupational and physical therapy (Jensen 2015). The rehabilitation process aims to reduce spasticity, improve muscle weakness, strengthen the coordination between muscles, and reduce contracture.

The modular gripper was assessed in a clinical setting to determine the efficacy of an admittance controlled assistive device in individuals with stroke. The device was assessed across various stages of stroke ranging from two weeks to seven months post stroke. Under admittance control, the user senses only the inertia of the small virtual mass which can be very small compared to the inertia and load capabilities of the actual robot actuators. This makes it useful for individuals with significant muscle weakness to employ their residual motor control to effectively drive a powerful robot. Rehabilitation robots rely on interactive control systems that react to inputs from the subject. (Hu et al. 2011). Admittance control is an ideal control system that can reduce the virtual inertia of the system to facilitate movements in individuals with severe weakness. Validation of the

admittance control paradigm is a critical feature of this study to determine feasibility of interventions that incorporate the control system and its ability to augment movements.

8.2 Methods

Individuals who had suffered a stroke and had left hemiplegia were evaluated by a physical therapist to determine participation in the study. A physical therapist was present at all times and aided in donning the modular gripper on the left hand of each subject. Each subject was asked to perform a sequence of pinch movements without the gripper to determine overall function. Each subject was then asked to perform the pinch movements with the gripper. Full flexion and extension for the pinch movements were based on individual active range of motion. Subjects participated in a single session and were required to perform sequenced pinch movements over the course of two minutes for several trials. Adequate rest was applied in between each trial to decrease risk of fatigue. After completion of the task, the physical therapist removed the device from the user.

Detailed information about each participant was recorded which included: name, age, time post stroke, hemiplegia, and dominant hand. Information with respect to stroke was recorded to assess the effect of the gripper on various stages of stroke. Five individuals were recruited for the study ranging from two weeks to seven months post stroke. Subjects who exhibited more function with the gripper were asked to attempt additional tasks to further evaluate the modular gripper. The associated tasks included pinching a block and applying adequate force to maintain pinched position. Individuals who demonstrated increased function were asked to complete certain components of the

Action Research Arm Test (ARAT) ranging from transporting cubes of various size to cylinders of various diameter.

8.3   Results

Each participant was required to perform a series of sequenced pinch with and without the gripper. Instructions for the sequenced pinch were vocalized to the participant where each participant was required to "open" or extend the thumb and index finger and "close" or flex the thumb and index finger. Pinch movements for an able-bodied user were recorded as reference. The sequenced pinch activation and amplitude for the applied forces can be observed in Figure 8.1. Based on the orientation of the force sensor and the construct mount, positive forces indicate extension (open), while negative forces indicate flexion (close). The healthy subject data was used as a comparison to assess the respective movements for individuals with stroke.
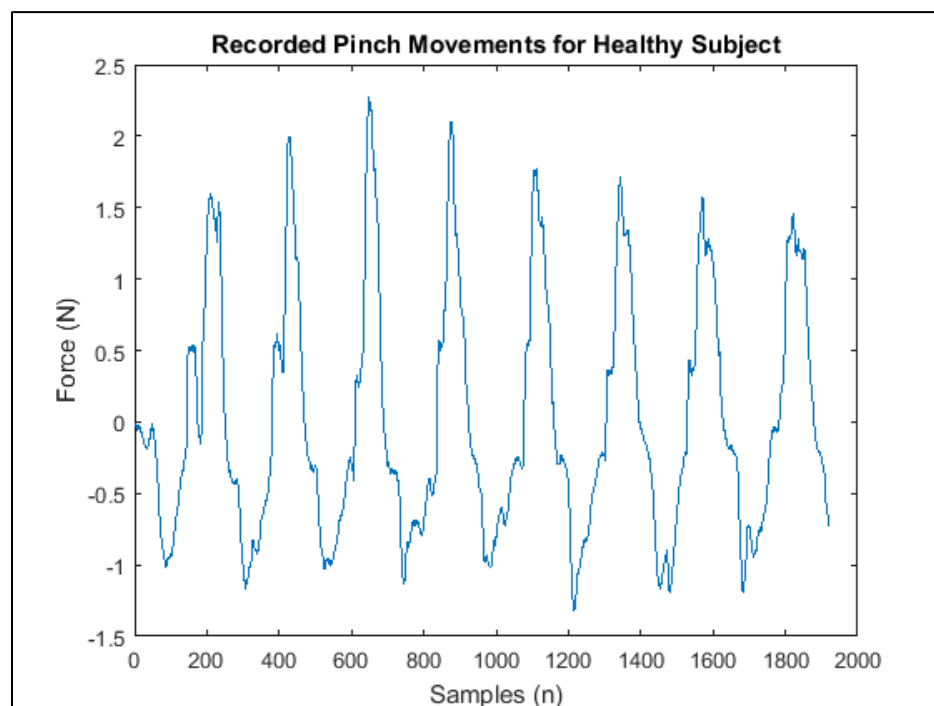
Figure 8.1 Sequenced pinch for healthy subject where positive forces indicate flexion and negative forces indicate extension. Forces are measured in Newtons (N).

Table 8.1 Stroke Population Demographics from Least Impaired to Most Impaired

Subject	Age	Stroke(Days)	Hemiplegia	Dominant	UEFMA(Hand)	UEFMA(Wrist)	Lay Description
CN	54	208	L	R	10	9	Weakness
LK	43	49	L	R	7	10	Weakness
EM	66	211	L	R	4	0	Synergy
FR	54	54	L	R	0	0	Semi-Flaccid
MC	62	62	L	R	0	0	Flaccid

Individuals with left hemiplegic stroke with an average age of 55.8±3.95 years, were recruited to participate in the modular gripper assessment. Four individuals were in the acute phase of stroke with one individual approximately two weeks post stroke. One participant was in the chronic phase of stroke and 208 days post stroke. All subjects were right hand dominant and the details for each participant are described in Table 8.1. Results for each participant are described separately based on variability between stages of recovery and associated secondary complications: weakness, spasticity, contracture, flaccidity, and synergy. Main observations and complications witnessed during the session are recorded in Table 8.1. Subjects are organized in hierarchical structure based on hand function from least impaired with greatest hand function to most impaired with least hand function. The results represent a comprehensive quantifiable analysis based on force profiles. Clinical assessments were performed to characterize hand function based on the Upper Extremity Fugl-Meyer Assessment (UEFMA) for both the hand and wrist. Additional observations with respect to type of impaired movement is also recorded in Table 8.1.

Subject CN exhibited significant hand swelling associated with severe hand weakness during the gripper assessment. CN was assessed without the gripper first to determine the overall level of hand function. Upon initial investigation, CN demonstrated compensatory hand movements during the Box and Blocks Test that resulted in zero successful transports. CN could not isolate movements with specific digits and performed whole hand grasp rather than isolated digit movement with the thumb and index finger. Thumb abduction was significantly used to assist in compensated pinch. Subject CN was unable to grasp and hold the standardized cube even with the compensated grip. The thumb was used to abduct the cube towards the index finger, where it resulted in slippage and a drop.

Upon completion of the initial assessment, the modular gripper was applied by a physical therapist to the left hand of subject CN. CN was asked to perform passive pinch movements with the device. Passive pinch movements were movements generated with the gripper without assistance. The passive pinch relied on volitional control of the user and was conducted to evaluate user force in order to estimate admittance control parameters. The response from the passive gripper is depicted in Figure 8.2. Subject CN applied excessive extension force with minimal flexion force. Despite the large flexion force, CN exhibited relatively little movement with the passive device and provided more force modulation with little movement. The data suggests that the large forces were generated to initiate the movement and additional motor recruitment compensated for the lack of movement.
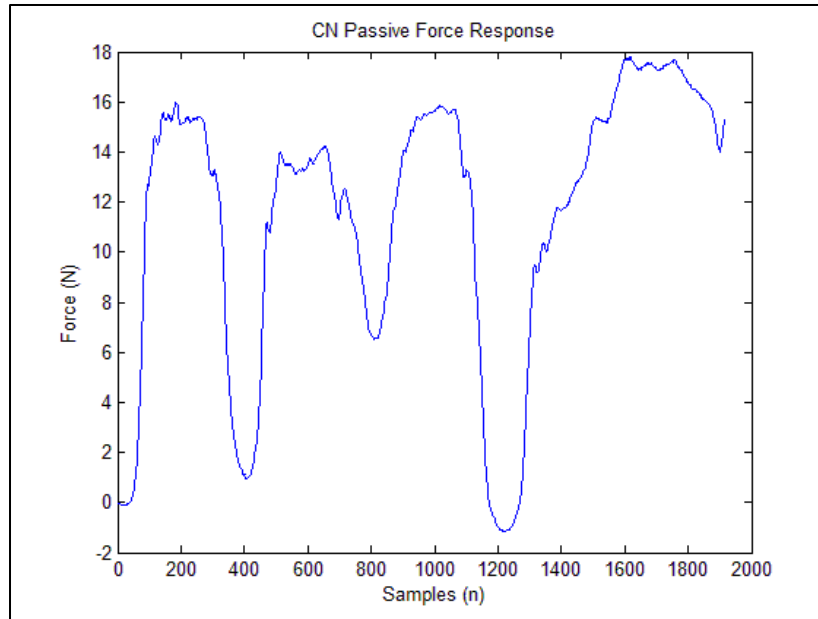
Figure 8.2 Subject CN passive pinch movement measured by the modular gripper.

Subject CN was able to perform the pinch movements under the assistance of the modular gripper. CN completed successful movements with the active gripper and was able to isolate digit movement with thumb and index finger control. The gripper corrected the compensated thumb abduction previously observed during the initial evaluation. The forces exhibited a drastic decrease when the digits performed the intended movements with assistance from the modular gripper compared to the passive momvenets, Figure 8.2 to Figure 8.3. Previously, subject CN was unable to grasp a block and hold it, evident in the Box and Blocks Test. With the modular gripper, the user was able to pinch the block and maintain the grip with assistance from the admittance control paradigm, Figure 8.4. With the modular gripper, CN was able to repeatedly perform the intended instructions and maintain contact with the block to prevent slippage.

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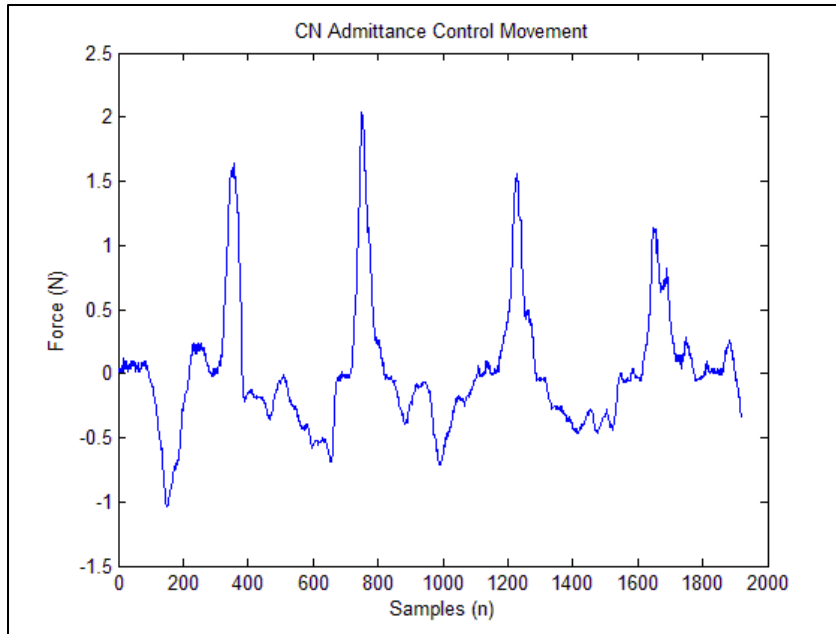
**Figure 8.3 S**ubject CN active pinch with assistance from modular gripper.

Figure 8.4 *Left)* Subject CN unable to grasp cube during Box and Blocks Test. *Right)* Subject CN with modular gripper assisting pinch movements and pinching block.

Subject LK exhibited hand weakness during the initial evaluation. The initial evaluation was performed with a standard cube to assess distal hand function. Subject LK was unable to isolate digit movement to pick up the cube in a flattened position and exhibited significant thumb weakness. Compensated movements were applied to drag the cube along the surface of the table until it was grasped. Subject LK had a tendency to perform complete grasp when attempting to perform isolate pinch movements. All fingers performed flexion when subject LK attempted to pinch the cube. Movements were comparable to key grasp rather than pinch tip.

Passive pinch tip movements were recorded with the modular gripper. Movements were comparable to pinch movements observed in the initial evaluation and are evident in Figure 8.5. Hand weakness was still present during the passive but the modular gripper corrected for compensated movements. Subject LK used custom constructed ring thimbles to accommodate for the smaller diameter digits. LK hand size was the smallest tested and the user required additional support to alleviate weight of device.
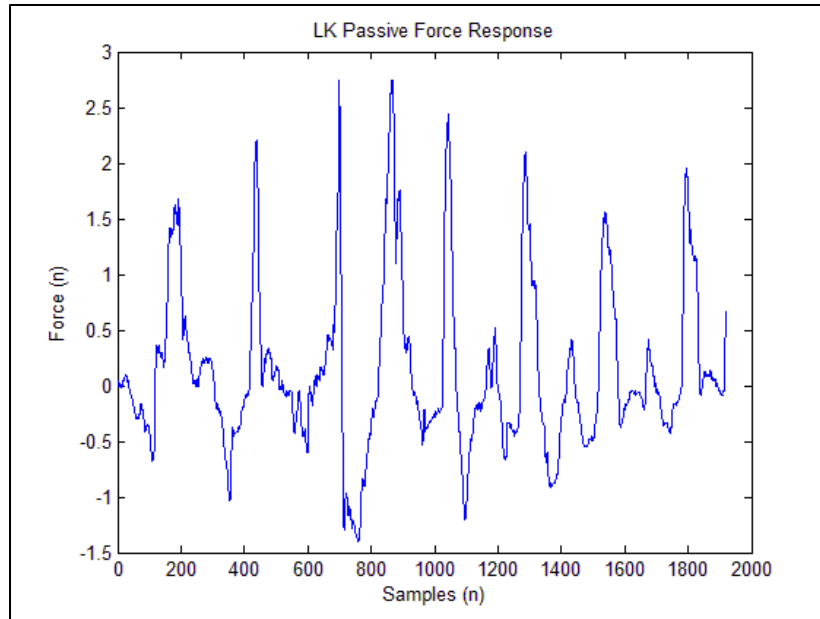
Figure 8.5 Subject LK passive pinch measured during pinch tip movement with gripper.
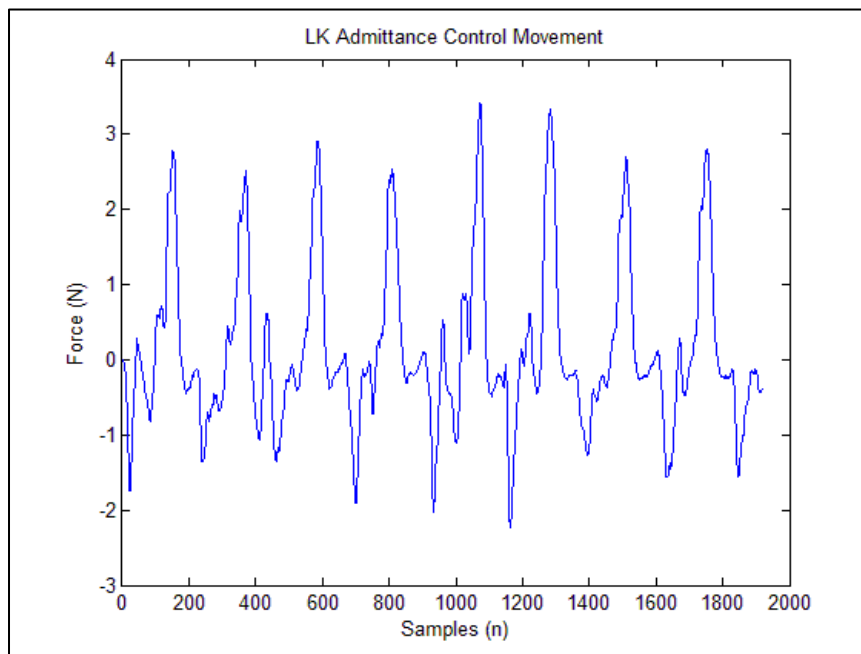
Figure 8.6 Subject LK pinch movements performed with admittance control.

Upon completion of the initial evaluations with and without the passive device, the admittance control paradigm was evaluated to determine overall benefit of the active gripper. With the active modular gripper, subject LK was able to perform pinch movements comparable to pinch tip, rather than the key grip movements observed during the hand assessment, Figure 8.6. The modular gripper constrained the thumb and aided joint posture during the pinch task to provide pinch tip. Subject LK was able to pick up the cube from the table with the modular gripper when the cube was upright. Compensated movements were applied with the gripper when the cube was presented flush against the table. Performance with a cylindrical object (medical tape roll) was assessed after the cube trials. Passively, subject LK was unable to perform complete grasp to securely fix the grip aperture to maintain adequate contact with the cylindrical tape. Qualitative observations with the gripper revealed that subject LK was able to grip the cylindrical object more securely and lift it in both the horizontal and longitudinal position. It appeared the gripper had greater benefit when the cylindrical objects were grasped in a longitudinal position with the diameter of the object parallel to the table. This position allowed subject LK to secure the object in the hand with all digits and transport it to the physical therapist.
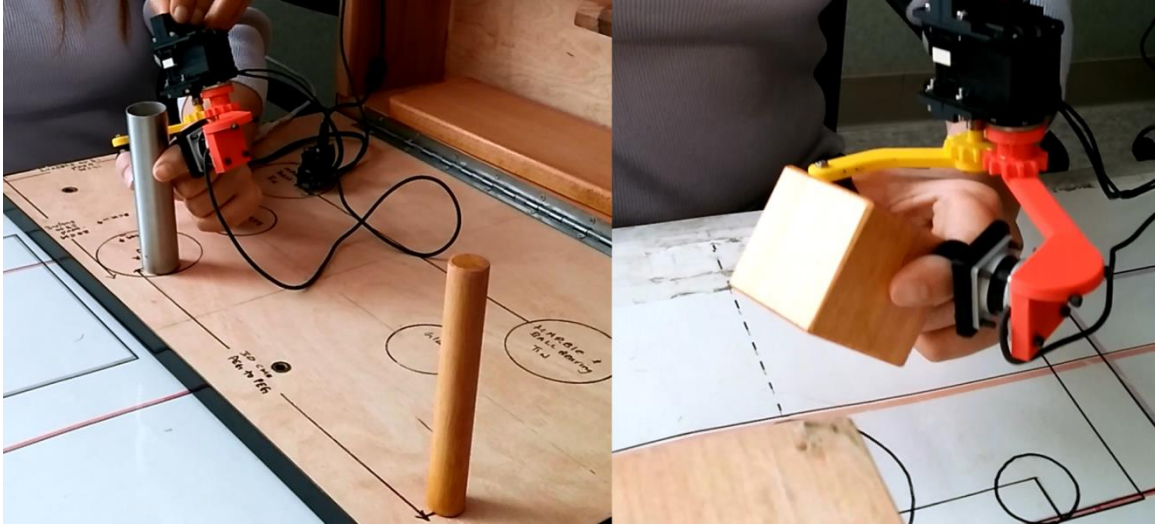
Figure 8.7 Components of the ARAT Test. *Left)* Large diameter cylindrical diameter rod. *Right)* Medium cube transported with modular gripper from table to top of box.

Components of the Action Research Arm Test were used to evaluate hand function and determine benefit with modular gripper. The ARAT test is a clinical measure used to assess specific changes in limb function for individuals with hemiparesis. It utilizes objects of different sizes, weight, and shapes to introduce task specific-goal oriented movements to assess upper extremity function. Subject LK performed the ARAT test with two cylindrical rods of varying diameter and several sized blocks. Subject LK was unable to transport the large diameter rod from the initial peg to

the final peg with a pinch grip. Subject relied on compensated cylindrical grasp rather than isolated pinch grip without the gripper. When the gripper was applied, subject LK was able to isolate pinch movement and secure the large diameter rod between the index and thumb. The next ARAT task was to transport a cylindrical rod with a smaller diameter. A lateral pinch grip was applied to secure the smaller cylindrical rod during transport without the gripper. Subject LK was able to perform the intended pinch movement with the device but experienced difficulty during transport from the weight of

the device due to fatigue. The final task was to transport a medium sized cube from the table to the top of the ARAT box. Qualitative evaluation from the physical therapist indicated that the benefit of the modular gripper was evident during transport of the medium cube. The modular gripper allowed the subject to fix the aperture around the cube to secure it during transport from the table to the top of the box. Observed forces during the grasp and transport are documented in Figure 8.8.
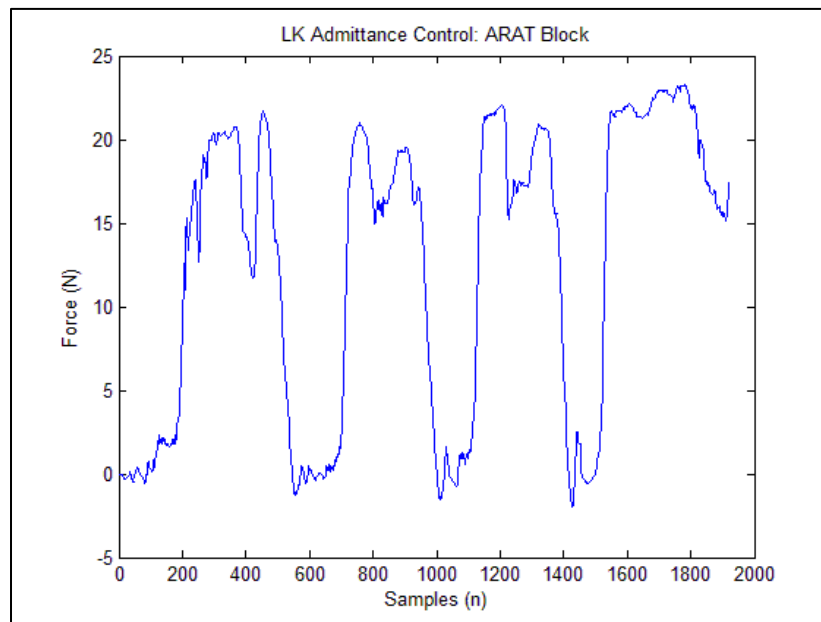

Figure 8.8 Subject LK ARAT block forces performed with admittance control.

Subject EM exhibited significant hand swelling and heavy contractures during the gripper assessment. The physical therapist massaged the hand of subject EM prior to the initial evaluations. Despite the massage, subject EM still exhibited contractures. During the initial evaluation, subject EM was asked to perform the pinch task without the gripper. Subject EM maintained a tensed position with the entire hand closed in a fist. The contractures contributed to a resistance in movement during the passive evaluation. The physical therapist performed additional treatment after the evaluation before the

passive gripper evaluation. The physical therapist aided in donning the gripper on the left hand of subject EM. The passive force was measured and recorded in Figure 8.9. The figure reveals low amplitude forces without the characteristics for flexion and extension. Subject EM was unable to complete flexion or extension during the passive evaluation due to the presence of contractures. The admittance control parameters were tuned to accommodate the presence of contractures with a mass of m=0.001 kg with damping β=1.0 Ns/m and gain A=6.0. The subject used custom ring gimbals to accommodate the hand size and swelling. The admittance control response can be observed in Figure 8.10. Subject EM was unable to perform movements and exhibited frequent oscillations. EM was able to generate slight movements for flexion, Figure 8.10. The oscillations were a result of the low mass and high gain with minimal damping and the large rings. The large rings were actually displaced by the gap between the finger and the index thimble ring. The space evident between the finger and ring allowed the gripper to oscillate based on the forces provided during collision with the finger. To reduce the oscillations, the damping could be increased or the space between the finger and the ring could be minimized. Throughout the session, medical tape was applied to the index finger to maximize contact between the finger and thimble ring. The medical tape reduced the oscillations, but the subject was still unable to perform the intended movements. The intensity of the contractures prevented the subject from relaxing the digits and resulted in minimal movement.
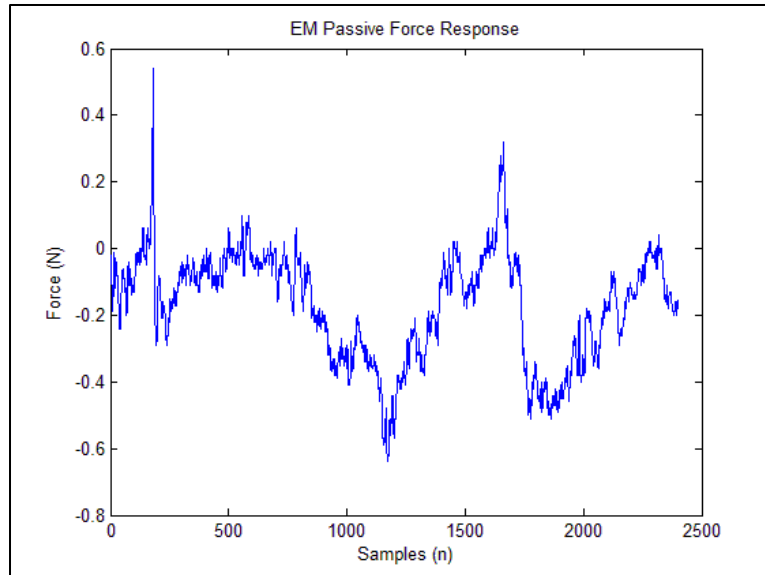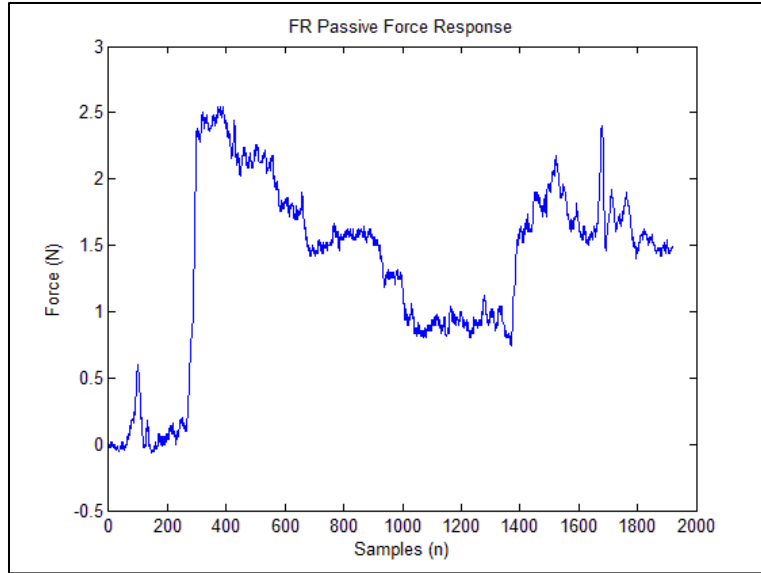
**Figure 8.9** Subject EM passive pinch measured with gripper.
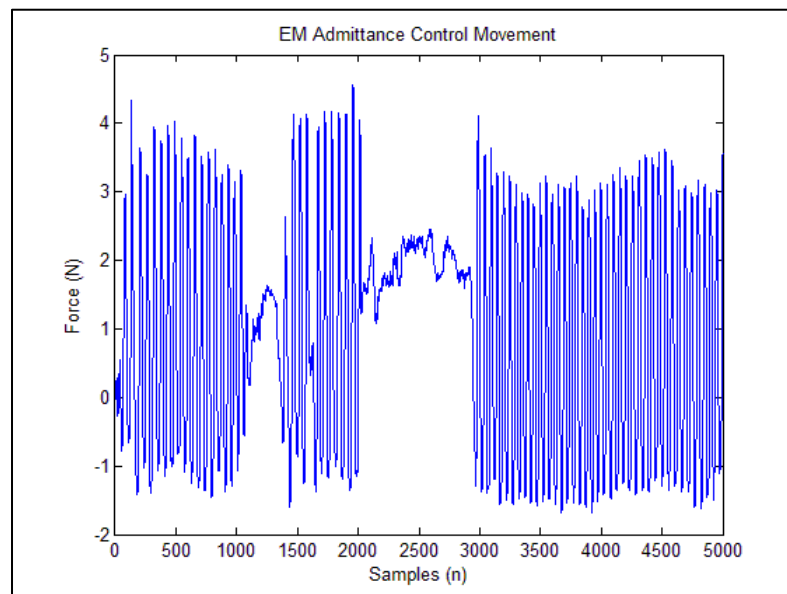
Figure 8.10 Subject EM with modular gripper operating under admittance control

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Subject FR was unable to perform the flexion or extension movements and exhibited hand flaccidity. Subject FR performed the initial evaluation in a compensated manner using the unaffected hand to assist the hemiparetic hand. When the gripper was applied for passive force evaluation, subject FR exhibited joint coupling where shoulder movement was present during pinch flexion. The passive force response is illustrated in Figure 8.11. The forces generated by subject FR represent the inability to directly modulate or scale the force based on the degradation of the step response. It is an all or nothing response when movement occurs. Despite the initial passive attempt and flaccidity observed in the initial evaluation, the subject was able to perform individual movements over the course of the session. As training progressed, subject FR was able to perform flexion movements with slight extension movements, although the extension was less prevalent. Based on the flaccidity present at the initial evaluation, the admittance control parameters were tuned to accommodate for weakness. The admittance control parameters were tuned to accommodate flaccidity with a mass of m=0.001 kg with damping β=1.0 Ns/m and gain A=10.0. Subject FR experienced similar oscillations due to relatively low damping coefficient. As training progressed, subject FR was able to generate enough force to perform a flexion and extension movement observed in Figure 8.12. During the training, subject FR reported that despite not generating the movements repeatedly, the feeling of "electricity" was present in his arm. This suggests that training with the modular gripper may have enhanced perception of the descending motor signal.

Figure 8.11 Subject FR passive pinch measured with gripper.
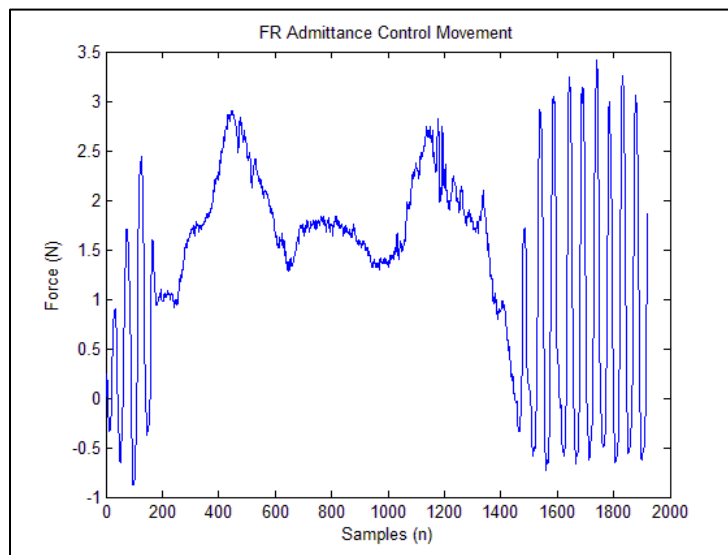
Figure 8.12 Subject FR with gripper operating under admittance control.

Subject MC was tested two weeks post stroke and exhibited complete flaccidity with unresponsive movements. During the initial evaluation, the subject was unable to perform any distal movements including flexion and extension of the digits. The force response from the passive gripper evaluation is depicted in Figure 8.13. The force profile indicates that the subject was unable to generate any force movements. The admittance control parameters were adjusted to accommodate for flaccidity and amplify subtle movements, but the inability to modulate force resulted in no volitional movement. Oscillations were observed as the gain was increased in order to attempt to initiate movement. The similarities in force profiles can be observed in Figure 8.13.
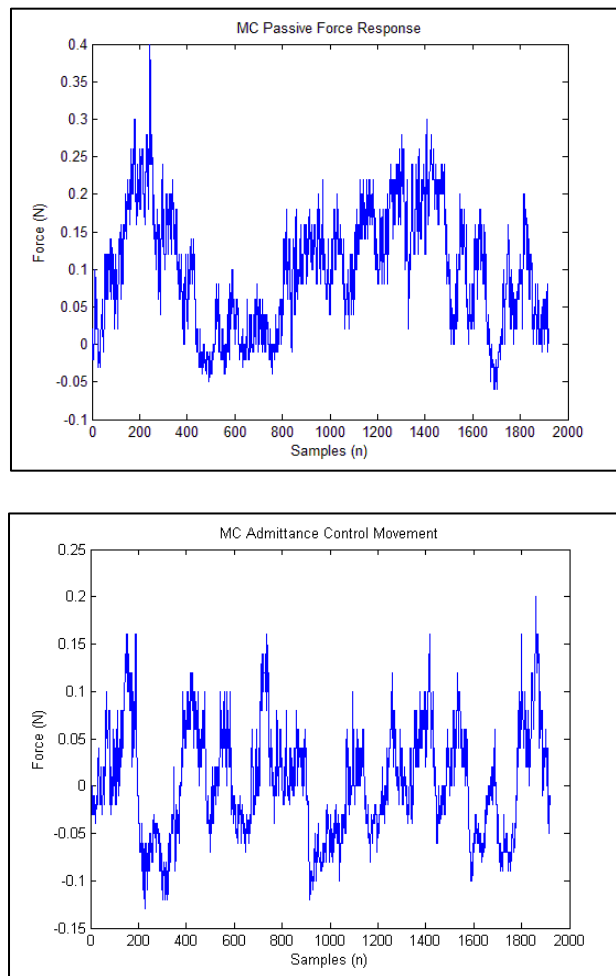
Figure 8.13 Subject MC force profile during passive pinch (*top*) and active pinch (*bottom*).

8.4 Discussion

The modular gripper assessment was conducted in a clinical setting to determine if individuals recovering from stroke could improve hemiparetic hand function and benefit from robotic assistance with the modular gripper. The modular gripper utilizes admittance control to scale the virtual mass of the object and reduce the inertia of the system. This effect allows individuals with muscle weakness to drive the modular gripper with minimal force. The feasibility study was conducted to observe the effects of the gripper in various stages of stroke. Based on the qualitative investigation throughout task performance and the quantitative forces observed, it appears that individuals in the later stages of stroke would be suitable candidates for robotic therapy with the modular gripper. The ideal feature essential for control of the modular gripper or any admittance controlled device is the ability to provide directional force. Individuals who possess the ability to modulate force despite hemiparesis and weakness have the potential to benefit from training with such a device. The clinical investigation revealed that subjects that lack the ability to modulate force or exhibit flaccidity would benefit from additional rehabilitation until the ability to modulate force is present. The flaccidity observed in this investigation was due to the early stages of stroke (2 weeks post) where subject MC had not experienced significant training and had just begun the rehabilitation process. Subjects CN and LK exhibited the ability to modulate force and were able to successfully use the gripper to flex and extend the thumb and index finger to grasp objects with less compensated techniques previously observed during the initial evaluation. Subject CN was unable to complete the Box and Block Test during the initial evaluation to assess hand function. With the gripper, subject CN was able to repeatedly pick up the block,

maintain contact, and transport it to the physical therapist. Subject LK exhibited a decrease in compensated movements and improvement in digit flexion and extension with the device. With the gripper, subject LK was able to grasp various objects with isolated movements during the ARAT task. Each subject that exhibited the ability to modulate force was able to use the modular gripper to transport various objects without the degree of compensation previously observed in the initial evaluation.

Not only does flaccidity present a great challenge but contractures are also another issue that prevents fine motor control. The pronounced contractures exhibited by subject EM illuminated the difficulty to overcome the increased muscle tone and joint torque. The increased muscle tone decreased the ability to modulate force and required a greater torque to engage the desired pinch movement. The contracted muscles and synergies represent a challenge to overcome before the descending motor command can be parsed or isolated to modulate force and produce the desired motor command. Despite the contractures, the individual reported that he was able to move his thumb at the end of the session, a task he was previously unable to do. Contracture and spasticity present a great challenge in the rehabilitation process. Individuals may benefit from the modular gripper as the presence of contracture and spasticity subside.

8.5 Conclusion

The clinical investigation revealed that great variability in recovery is present in stroke rehabilitation due to the secondary complications: flaccidity, muscle weakness, spasticity, and contracture. Despite the variability between time post stroke and associated conditions, it is evident that individuals that possess the ability to apply directional force even with weakness can benefit from admittance controlled devices. Individuals in the early stages of rehabilitation would benefit from extended periods of conventional rehabilitation to restore the ability to modulate force. The modular gripper could be used in conjunction with traditional interventions if contracture and spasticity could be reduced as long as the individual possesses the ability to modulate force. The modular gripper can adapt to patient performance throughout the course of rehabilitation to assist or resist movements to enhance paretic hand function. The modular gripper represents a potential rehabilitation device that can assist in repetitive training to engage and motivate patients. The device relies on volitional control of the user and can amplify user intended movement with the aims to induce repetitive training to enhance paretic hand function and facilitate recovery.

CHAPTER 9

SUMMARY

9.1 Concluding Remarks

Virtual reality settings may provide a motivating environment that encourage repetitive training and can facilitate motor learning. The initial findings from these investigations suggest that proximal and distal components when used together provide appropriate degrees of freedom that contribute to more efficient movements. The HMWG group demonstrated significantly improved performance compared to the HM control group and the other experimental DOF groups. When the distal components were eliminated to simulate immobilization or loss of DOF, excursions were significantly affected and exhibited compensated mechanisms to adapt to the loss of biomechanical function. Alternative pathways were utilized to compensate for the lack of DOF, resulting in longer trajectories and reduced performance. The lack of DOF contributed to different modes of transport that did not minimize cost or optimize modes of biomechanical transport. The results suggest that training with the wrist and gripper to facilitate proximal and distal training together may provide a more effective strategy to rehabilitate lost function with biomechanically accurate, assisted movements.

While the participants were able-bodied, there is strong evidence to suggest that proximal and distal components when used together can enhance motor learning and improve efficacy of transport in both trained and untrained environments. Trained subjects demonstrated the ability to transfer skills acquired in one virtual setting and applied it to an unfamiliar task. The transferability of skills from a VE simulator to

physical reality is essential for usability, especially when considering applications for rehabilitation. Training contributed to better planning with more efficient modes of transport. Trained subjects experienced significantly greater modes of transport despite the unfamiliar environment compared to the untrained control group. Virtual reality applications that incorporate task specific training with proximal and distal components have the potential to transfer to activities of daily living, which is critical for rehabilitation of individuals with stroke that require extensive rehabilitation. The opportunity to rehabilitate in a virtual setting introduces the potential to disseminate the technology and apply it in a home based setting, where users will have access to the technology necessary to facilitate recovery and enhance biological motion.

Virtual environments that incorporate stereoscopic viewing mediums through the use of HMD may provide an increase in immersion which could enhance subject performance. A virtual environment that provides greater use of the stereoscopic effects and incorporates elements of greater depth may reveal the potential benefits of virtual training paradigms with HMDs. Prolonged training sessions with a larger sample population may provide greater insight into the benefits of either viewing condition during training. Stereoscopic virtual reality settings should exploit the ability to create games that rely on the sense of depth to provide a greater understanding of the impact of viewing mediums between conventional displays and rapidly immerging HMD technology. However, based on the results of this investigation, there does not appear to be an increased benefit from HMD.

Individuals with stroke may benefit from training with the admittance controlled exoskeleton in a virtual environment. The feasibility study demonstrated that individuals

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with stroke that have the ability to modulate force may benefit from therapeutic interventions that incorporate similar devices. Individuals with stroke that exhibit the ability to modulate force even in the presence of weakness may benefit from proximal and distal training due to the nature of biomechanically accurate movements and the kinematic redundancy of the upper arm. Proximal and distal training with admittance controlled exoskeletons in a virtual environment may provide more natural movements to enhance recovery and decrease competition between proximal and distal cortical representations. Future rehabilitation paradigms may benefit from the volitional activation of user intent in conjunction with proximal and distal control of the upper extremity to generate greater functional outcomes through the use of more salient training in a virtual environment.

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