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Development and evaluation of a hand exoskeleton for neurorehabilitation post stroke

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ABSTRACT

DEVELOPMENT AND EVALUATION OF A HAND EXOSKELETON FOR NEUROREHABILITATION POST STROKE

by
Ashley Joyce Mont

Stroke affects approximately 800,000 people in the United States each year, and due to its chronic effects, it is one of the leading causes of disability. Many individuals with stroke suffer the loss of motor function in their paretic upper extremity, and longitudinal studies show that 30 – 66% of individuals with hemiplegia fail to regain arm function six months post stroke. After a stroke, the brain undergoes neuroplasticity which will promote recovery of function. Investigators and clinicians are trying to develop rehabilitation interventions that can be designed to promote neuroplasticity, enhancing the recovery outcomes of therapy.

For individuals with all levels of impairment, robot-mediated therapy can assist with repetitive movements at a high dosage which is a crucial component of recovery. These control paradigms can be passive, moving an individual's limb through a preprogrammed trajectory, or active, requiring the individual to provide an intentional movement prior to receiving assistance from the robot. Another method that is used for enhancing neuroplasticity is priming. Motor priming preceding therapeutic interventions such as task-specific training may enhance the effects of the intervention facilitating better recovery. An exoskeleton is developed during this project that has the capabilities to perform motor priming with individuals with stroke.

The NJIT Gripper is designed as a low-cost lightweight, easy-to-use robotic exoskeleton that assists with flexion and extension of the fingers or opening and closing of the hand. For individuals with stroke, extending the fingers to open the hand is often a challenging task. Evaluations with healthy individuals and individuals with stroke demonstrate that the exoskeleton is well tolerated. The control schemes of the NJIT Gripper allow it to be used to provide movement-based motor priming in the form of stretching for individuals with stroke. The objective of this pilot study is to determine which method of stretching is the most effective. Individuals with chronic stroke participate in movement-based motor priming for 30 minutes of stretching the hand muscles, and kinematic and neurophysiological outcome measures are evaluated.

The NJIT Gripper is designed to be used in combination with the Home based Virtual Rehabilitation System (HoVRS) previously developed by our laboratory. To establish perceived acceptance, a usability study was performed, and HoVRS is evaluated by individuals with chronic stroke as well as physical and occupational therapists.

Finally, the NJIT Gripper is used in conjunction with HoVRS for a case study with one participant. The participant attends nine in-person training sessions where they receive 30 minutes of movement-based priming as well as therapeutic game play. The participant uses HoVRS at home unsupervised for two additional months. Clinical and kinematic outcomes are evaluated and demonstrate that even at ~6 years post stroke, the individual was able to make improvements.

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by
Ashley Joyce Mont

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"He who does not risk will never drink champagne."

- Russian Proverb

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LIST OF DEFINITIONS

Admittance Control	A control method that controls the position of a robot based on external force and torque.
Cerebrovascular accident (CVA)	The sudden death of brain cells due to lack of oxygen when the blood flow to the brain is impaired by blockage or rupture of an artery to the brain. A CVA is also referred to as a stroke.
Movement-based priming	Any type of continuous movement that may augment the effect of subsequent primary therapy.
Priming	Nonconscious process associated with learning where exposure to a stimulus alters the response of another stimulus.
Transcranial Magnetic Stimulation (TMS)	A non-invasive form of brain stimulation in which a changing magnetic field is used to cause an electric current at a specific area of the brain.

CHAPTER 1

INTRODUCTION

1.1 Significance of the Problem

Cerebrovascular accident (CVA) or Stroke affects approximately 800,000 people in the United States each year, and due to its chronic effects, it is one of the leading causes of serious disability (Virani et al., 2021). Many patients suffer the chronic loss of motor function in their paretic upper extremity compared to the recovery of motor function in their lower limbs. Longitudinal studies show that 30 – 66% of individuals with hemiplegia fail to regain arm function six months post stroke, while only 5 to 20% regain full recovery (Kwakkel et al., 2008). Current clinical service models do not prioritize the upper limb, as a greater emphasis is placed on retraining gait early in rehabilitation to increase patient mobility. In addition to this, the upper limb is more complex as movement requires multi-joint coordination (Aprile et al., 2014). The current standard of care for individuals with upper limb impairment due to stroke is highly repetitive task-oriented training.

After a stroke, the brain undergoes neuroplasticity, defined as "the ability of the nervous system to respond to intrinsic or extrinsic stimuli by reorganizing its structure, function and connections" (Cramer et al., 2011). In some cases, injury to a specific motor network can cause spontaneous intra-hemispheric changes, such as shifts in representational mappings. For example, a hand area that was damaged may shift dorsally to the shoulder region increasing hand function. One approach to investigating the changes in synaptic plasticity in humans is by applying noninvasive brain stimulation, such as transcranial magnetic stimulation (TMS). TMS can stimulate underlying neuronal populations via the corticospinal pathway, which results in a motor response in the contralateral hand muscle known as a motor-evoked potential (MEP) when applied over the hand region of the primary motor cortex (Dickins et al., 2017). These neuroplastic changes are dependent on experience and learning, which can be facilitated during rehabilitation (Carey et al., 2019). This change can occur in the days, weeks, months, and years post stroke. The central question remains: How can rehabilitation interventions be designed to promote neuroplasticity?

Robot-mediated therapy can be used for individuals with all levels of impairment because robots are programmed to provide customized levels of assistance depending on an individual's needs. For example, some robotic control schemes move a user's passive arm through a preprogrammed trajectory of movement for continuous movement therapy or passive hand stretching. Other control paradigms utilize the user's intention for active participation through admittance control, impedance control, or triggering methods based on force or muscle activity (Caimmi et al., 2021; Huang et al., 2018). These robotic systems are often integrated with virtual reality to create more engaging training sessions, while simultaneously providing a high dosage and many repetitions (Alves et al., 2022).

Another method to enhance the effects of neurorehabilitation training is motor priming. It has been suggested that motor priming preceding therapeutic interventions such as task-specific training may enhance the effects of the training session (Stoykov et al., 2017; Stoykov & Madhavan, 2015). In addition to assisting with task-oriented training, robots can be used to perform movement-based priming. There are few robotic exoskeletons specific to the hand in the literature that have multimodal control systems that allow for methods of priming, passive control, active control, and the incorporation of haptics in a virtual reality system.

1.2 Investigation Overview

The overall goal of this project was to develop a robotic exoskeleton for the hand with varying levels of assistance to maximize the effects of therapy to increase the potential for motor recovery. The device must allow for movement-based priming and assistance during training, as this robot will be incorporated into the Home based Virtual Rehabilitation System (HoVRS) intervention previously developed by our group (Qiu et al., 2020).

1.3 Specific Aims

Aim I. Develop a hand exoskeleton that can be synchronized with an individual's intention to move for the rehabilitation of the upper limb in individuals with stroke.

Aim II. Investigate the effects of movement-based priming with robotics in individuals with stroke on physiological and kinematic measures.

Aim III. Evaluate the usability of the Home based Virtual Rehabilitation System with therapists and individuals with stroke.

Aim IV. Test the feasibility of priming prior to intense upper arm and hand training on kinematic and functional outcome measures in individuals with stroke.

1.4 Hypotheses

Primary Hypothesis (Aim I): It is hypothesized that individuals with chronic stroke will tolerate the device with no adverse effects.

Secondary Hypothesis (Aim 1): The Leap Motion Controller will accurately track the hand while using the NJIT Gripper.

Primary Hypothesis (Aim II): It is hypothesized that the priming method will increase corticospinal tract excitability in addition to increasing grip and pinch strength, active range of motion, and motor control in the hands of individuals with stroke.

Primary Hypothesis (Aim III): It is hypothesized that the Home based Virtual Rehabilitation system will score in the acceptable range for usability with individuals with stroke.

Primary Hypothesis (Aim IV): It is hypothesized that all individuals participating in the study will see significant improvements in kinematic and clinical outcome measures.

CHAPTER 2

BACKGROUND

2.1 Cerebrovascular Accident

Cerebrovascular accident (CVA) or stroke affects approximately 800,000 people in the United States annually, and it is approximated that 7.6 million Americans self-report that they have experienced a stroke (Tsao et al., 2022). CVA occurs when a blood vessel carrying oxygen to the brain becomes occluded or bursts. Ischemic stroke, which makes up roughly 87% of strokes, occurs when a clot blocks the flow of blood to the brain (Figure 2.1). A hemorrhagic stroke occurs when a blood vessel ruptures, preventing blood flow to the brain. In either scenario, the deprivation of oxygen causes damage to the brain tissue, and there can be significant impairments to that part of the body under the control of that specific neuronal location. For example, if the lesion is in the motor cortex, there will be paresis or impairment of the motor system affecting the contralateral side. Sensory, motor, and cognitive impairment, as well as a diminished capacity to perform self-care and participate in social and communal activities, are all possible effects of a stroke. While most of the recovery is expected to occur in the first few weeks after a stroke, individuals with a stroke may progress on functional skills months later (Laver et al., 2017).

Activities of daily living (ADLs) are activities that are performed on a daily basis to maintain health and well-being. For example, eating and drinking, moving about, going to the bathroom, personal hygiene, dressing, and grooming are examples of ADL. When a stroke alters the motor pathways, the capacity to perform ADLs may be affected (Legg et al., 2017). Many stroke survivors, 24 – 75% (Miller et al., 2010), have long-term disabilities requiring assistance, decreasing their independence and quality of life.

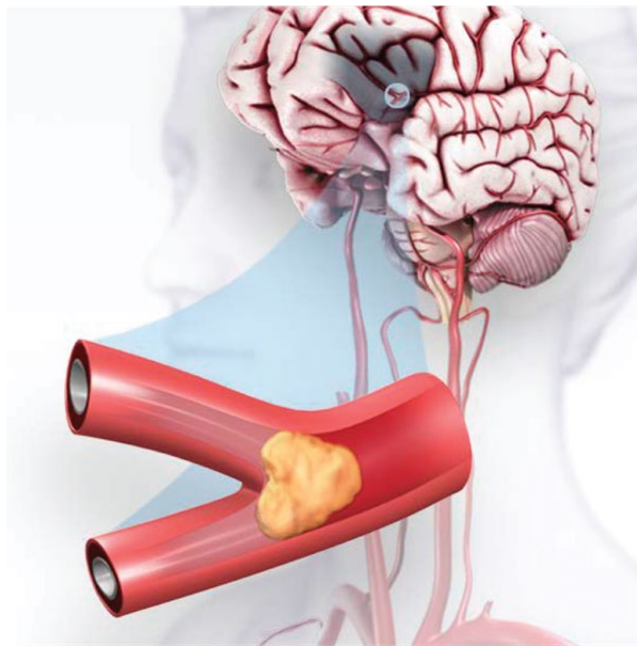

Figure 2.1 Schematic representation of ischemic stroke.

Source: American Stroke Association "About Stroke" https://www.stroke.org/en/about-stroke, accessed February 8, 2022

2.2 Standard of Care

The current standard of care for rehabilitation of the upper limb post stroke is highly repetitive task-oriented training based on the principle that a high number of repetitions of a specific task will stimulate motor learning and, therefore motor recovery (Langhorne et al., 2011). Through repetition, long term potentiation occurs as the connections between neurons are strengthened resulting in motor learning (Veerbeek et al., 2014). Ideally, in therapy, the specific task to be repeated would be one that could be translated into an activity of daily living (Langhorne et al., 1996; Muratori et al., 2013; Tomić et al., 2017). This principle has been extensively studied in Constraint Induced Movement Therapy, in which an individual's unaffected hand is constrained in a sling or glove and is prompted to complete repetitive tasks using only their affected limb. These studies have shown promising improvements in motor function in subacute and chronic stroke, even up to one year post training (Blanton & Wolf, 1999; Takebayashi et al., 2015; Taub et al., 1993).

Some individuals with moderate to severe impairment cannot participate in highly repetitive task-oriented training because they cannot produce enough flexion or extension movement at the wrist or fingers (Claflin et al., 2015). For these individuals, a physical therapist may need to physically assist the individual in completing the task, which is both labor-intensive to the physical therapist and can potentially decrease the intensity of training optimal for better therapeutic outcomes (Nef et al., 2007). Assistance from a physical therapist would require the individual to have access to a therapy clinic, transportation to and from in the clinic, access to home health therapists, and/or the ability to cover the cost or remaining cost through insurance. There is a need for easily accessible therapy that can deliver the appropriate dosage to the individual. Robot-mediated therapy can be used as a tool by therapists to provide highly repetitive movements in the clinic (Mehrholz et al., 2015; Wu et al., 2016). With recent technological advances, patients can now reach therapists through telerehabilitation, increasing access to therapy.

2.3 Robot Mediated Therapy and Virtual Reality Systems

Robot-mediated therapy has been shown to increase the motor function of the upper limb of individuals with stroke. Rehabilitation robots are designed to provide varying levels of assistance depending on the type of therapy they will be used for. One robotic device, The HapticMaster, has been studied extensively in systems designed for upper limb rehabilitation as it provides assistance for movement and haptic or tactile feedback (Van Der Linde et al., 2002). Some designs include the GENTLE/S system, the ACT 4-D rehabilitation robot, and the NJIT Robot-Assisted Virtual Rehabilitation (NJIT-RAVR) system (Loureiro et al., 2014; Merians et al., 2020; Qiu et al., 2009; Stienen et al., 2011). This device is controlled using an admittance control paradigm in which the user applies a force, and this is translated into a movement intention moving the user to the intended position, therefore, requiring the user to actively participate in the movement. This intention-based assistance is critical because active participation is important in motor recovery. Another benefit to an admittance control scheme is that even severely impaired individuals can interact with this system and participate in a training they otherwise may not have been able to do as small forces can be detected. The HapticMaster has been integrated with virtual reality games to engage users and incorporate sensory feedback. Motor learning can further be enhanced through the use of sensory, visual, and auditory feedback (Muratori et al., 2013). Another benefit is that these systems have adjustable parameters to change the level of user involvement. For example, for an individual with the ability to partially open their hand, a force threshold can be set so that the robot will only assist when needed. This allows for movement based on the user's intent while providing some assistance. Although these systems have promising results, many of these admittance-controlled robots that can incorporate haptics are designed for the arm, not specifically the hand, therefore there is a need to design an admittance controlled robot specific to the hand.

Another method that can be implemented is one where the robot moves through a preprogrammed trajectory and requires no active participation by the user therefore the active robot passively controls the user. This method has been used for continuous passive movement (CPM) therapy as well as stretching. While this method is effective for stretching, these mechanisms require no active participation by the user. Such devices can be combined with simulations that require participation by the user. For example, the CyberGrasp (CyberGlove Systems LLC, San Jose, CA) is a commercially available hand exoskeleton that has been used extensively in our laboratory in combination with gaming simulations (Adamovich et al., 2009; Boos et al., 2011; Fluet et al., 2012; Merians et al., 2011; Patel et al., 2019). This cable-driven design allows for extension assistance for each finger providing approximately 12 N of force. One study combined this with a virtual reality piano simulation to train finger individuation (Adamovich et al., 2009). The CyberGrasp allowed movement of the active finger only by providing flexion resistance to the inactive fingers. This control scheme has also been used for stretching the hand muscles as a method to reduce spasticity or prime the motor system.

In a study investigating spasticity, individuals with stroke would perform twenty minutes of stretching twice per day with a passive device that would stretch the wrist. After three weeks of stretching six days per week, a significant reduction in spasticity was observed, however, there were no changes in functional outcome measures (Jung et al., 2011). Triandafilou et al. (2011) developed a cable-driven hand exoskeleton called the eXtension Glove (X-Glove) that was used for passive range of motion stretching of a user's fingers in addition to assistance during active movement training (Fischer et al., 2016; Triandafilou & Kamper, 2014; Triandafilou et al., 2011). In one study, repetitive stretching was performed prior to an active training mode in which the glove provided constant extension assistance so that the user could complete flexion tasks as long as they could generate enough force to overcome the force required to keep the finger extended. Although no changes in spasticity were observed, there were significant changes in functional outcome measures and impairment measures, suggesting that the stretching may have facilitated the effects of the subsequent training (Triandafilou & Kamper, 2014). These studies indicate that although robotic-assisted stretching may or may not affect spasticity, an underlying effect may be enhancing the effects of repetitive task training. One possible mechanism preparing the brain for training could be movement-based motor priming.

2.4 Priming of the Motor Cortex

Priming refers to a "nonconscious process associated with learning where exposure to a stimulus alters the response of another stimulus" (Stoykov et al., 2017). It has been proposed that this type of implicit learning increases the excitability of the affected motor system and promotes plastic reorganization in response to a subsequent task. This method of priming the motor system has been gaining popularity in rehabilitation interventions through various forms such as stimulation-based sensory priming, movement-based priming, pharmacology-based priming, and motor imagery and action observation. For rehabilitation purposes, the goal is that priming will prepare the sensorimotor system, enhancing the effects of a training paradigm (Pomeroy et al., 2011; Stoykov & Madhavan, 2015). Movement-based priming, defined as "any type of continuous movement that may augment the effect of subsequent primary therapy," is one method of priming that has been investigated for neurorehabilitation (Stoykov & Madhavan, 2015). This continuous movement can be either active or passive at a single joint. Further, this movement can be of the same modality as the training, as the movements are the same. It is important to note that movement-based priming differs from task-oriented training in that the movement is neither skill -based nor-based nor goal-directed. Robotics can be used to provide the continuous movement of the impaired hand for individuals with stroke if they cannot complete the movements on their own. In a study comparing the effects of bilateral and unilateral priming prior to a task-specific training in individuals with stroke, Stoykov and Corcos observed improvements on both the Chedoke Arm and Hand Activity Inventory and the Fugl-Meyer Test of Upper Extremity Function for both the bilateral and unilateral group (Stoykov & Corcos, 2013). These results suggest that unilateral priming may be an effective way to prime the motor cortex to enhance the maximum benefits of repetitive task-oriented training.

2.5 Conclusion

This project is unique in that the robotic device has been programmed with passive and admittance control modes that allow for unilateral priming and assistance during training. Previous laboratory based, short term studies have shown that passive stretching prior to active task training is beneficial. *This project is innovative in that the robot will be used to stretch the hand prior to intensive therapy using the Home based Virtual Rehabilitation System (HoVRS) previously developed by our group (Qiu et al., 2020)*. The use of admittance control for stretching is also innovative as it allows for intention driven movement. The stretching devices that have been explored in the literature, move an individual's limb through a preprogrammed trajectory while they are relaxed, therefore there is not active participation by the individual. The intention of movement will enhance the effect of stretching.

Few studies in the literature have investigated stretching of the hand prior to an intense training session, so the effects are unclear. While stretching with subsequent active training has been investigated for the ankle (Waldman et al., 2013), to our knowledge, only one other group has looked specifically at unilateral hand stretching with task training with individuals with stroke (Fischer et al., 2016). They found that scores on the Upper Extremity Fugl Meyer Assessment, Chedoke Arm and Hand Activity Inventory, and Grip Strength continued to be significantly different than baseline measures even at 1 month post training. This demonstrated continued improvement after the 15-week training study ended. The authors state that it is possible that "some improvements may have occurred even without the intervention, especially as the subjects were in the subacute phase of recovery" (Fischer et al., 2016). Our design will allow us to investigate stretching as a priming method before training with our HoVRS system.

Further, in the literature, there is some controversy about whether intense task-oriented hand and arm training improves motor function post stroke. One reason for this discrepancy is differences in dosage or the amount and frequency of training (Lang et al., 2015). Many of the studies were laboratory-based, limiting the dosage as it is logistically challenging to perform a long-term training study. The nature of HoVRS allows for increased dosage. The robotic device allows us to investigate the longitudinal effects of active training with priming.

CHAPTER 3

DESIGN OF NJIT GRIPPER

3.1 Design and Fabrication

The NJIT Gripper was designed with the following specifications: lightweight, low cost, and customizable sizing. The primary function is to assist with flexion and extension of the fingers/hand. The design consists of a smart servo motor (Robotis, Lake Forest, CA), a 3 DOF force sensor (OnRobot, Denmark), custom-designed gears, and various 3D printed components. The overall weight of the device is approximately .158kg. The gears were custom designed using Creo Parametric AutoCAD software and manufactured using acetal homopolymer resin using laser cutting techniques. Creo Parametric AutoCAD software was used to designed and prototype the components to be 3D printed. The parts were printed with a carbon fiber-reinforced nylon called Onyx on the Mark Two 3D printer (Markforged, Watertown, MA). This material was chosen for its high strength yet low weight.

The finger and thumb components connect through a gearing system, with the movement driven by the motor horn. The first iteration of the design included only the index finger and thumb (Figure 3.1). This design was expanded to include the index, middle, ring, and pinky fingers in the second iteration. The index, middle, ring, and pinky are placed on the finger bar, and the thumb is placed in the respective ring (Figure 3.2). The force sensor is connected to the finger bar to obtain the forces generated by the fingers. The base component was designed using 3D scanning technology. Using the Sense 3D Scanner (3D Systems, Inc., USA), the dorsum of an average-sized hand was scanned. This scan was then imported into the Creo Parametric AutoCAD software, which allowed the part to be designed along the trajectory of the dorsum, ensuring a comfortable fit on the user's hand. For further customization, the placement of the finger bar can be adjusted depending on the length of the user's fingers. Additionally, the thumb ring can be adjusted to fit the proper placement of the thumb.

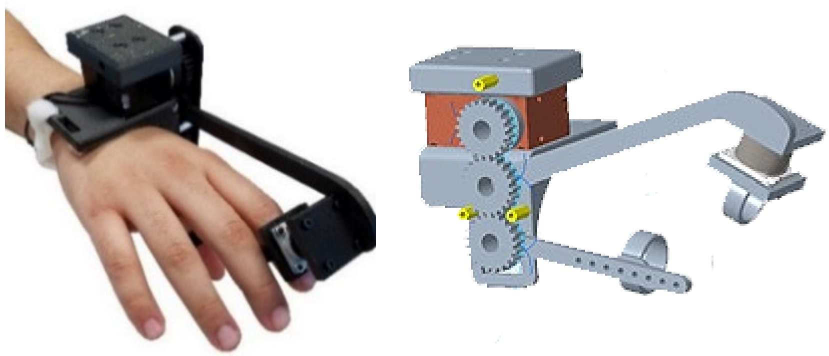

Figure 3.1 First iteration of NJIT Gripper. Left: Photo of NJIT Gripper on an individual's hand. Right: Creo Parametric Assembly File. This image shows the inside view of the gearing mechanism that moves the finger brackets.

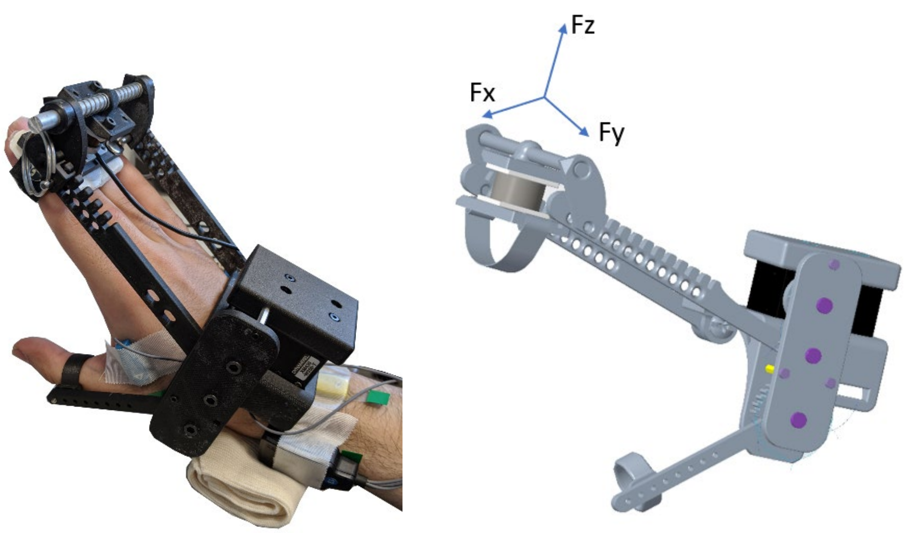

Figure 3.2 Second iteration of NJIT Gripper. Left: Photo of NJIT Gripper on an individual's hand. Right: Creo Parametric Assembly File. The force sensor is arranged so that the Z force is perpendicular to the surface of the fingers.

3.2 Control Schemes

Various control schemes are used for rehabilitation robots such as passive control or active control using admittance or impedance control (Babaiasl et al., 2016). The NJIT Gripper was programmed in MATLAB with two different control modes (passive and active). For use in the laboratory, these programs are synchronized with Electromyography (EMG) and Electroencephalography (EEG). The MATLAB codes that run the NJIT Gripper and data collection can be found here: https://github.com/ashley-montjohnson.

3.2.1 Passive Control

In passive control scheme, the robotic device will move the individual's limb through a preprogrammed trajectory of their range of motion. This occurs while the individual is at rest, so there is no active participation required (Babaiasl et al., 2016). This method is similar to continuous movement therapy that could be provided manually by a licensed physical or occupational therapist or through a device. There are a few rehabilitation robots that have been studied extensively in the literature that move the upper limb of individuals with stroke movement through a pre-programmed trajectory. These devices include the Mirror Image Motion Enabler (MIME), Bi- Manu-track, and the ARMin (Hesse et al., 2003; Lum et al., 2002; Nef et al., 2007; Staubli et al., 2009).

For the NJIT Gripper, the "Passive Mode," moves a user's fingers passively through a preprogrammed trajectory of the individual's range of motion. This occurs at a set speed and number of repetitions while the user is at rest. Additionally, the amount of rest time in extension and flexion positions can also be preprogrammed. The preprogrammed trajectory is the user's range of motion for extension and flexion while wearing the robot. These measures are taken before stretching to determine the extension and flexion limits for that particular session. Force, EMG, and motor position data are recorded during the stretching session. This control scheme allows for complete robotic control while the user can passively rest their hand during the movements.

3.2.2 Admittance Control

The second mode is called the "Admittance Control Mode," and this paradigm allows a user to apply force to generate movement of the robot to a specific location determined by the controller based on the user's intention. This method is implemented as an assistive control system that promotes the residual strength of the individual. There are two primary control paradigms used for human-robot interaction: impedance control and admittance control. Impedance control evaluates the error between the position and the starting point and computes the force or torque required to move to that position. Conversely, admittance control takes the force applied and calculates a relative displacement based on the virtual parameters set (Keemink et al., 2018; Topini et al., 2022). Admittance control is typically used for power amplification or load reduction. This mode can be used for individuals with varying levels of muscle weakness as the control parameters are easily adapted. For example, for an individual with severe impairment, constant assistance can be provided based on their intention, determined by the amount and direction of force applied to the sensor. Alternatively, for individuals who can generate some movement but may not be able to extend their fingers fully, a force threshold can be set so that when movement is initiated, and the threshold is reached, the robot will complete the movement by moving to a predetermined position. This paradigm allows for intention-driven movement and assistance as needed.

In this design, the user applies a force to the force sensor attached at the fingers and the controller will calculate a position based on Newton's second law of motion (Figure 3.3). This equation is described as F = m * a (F = force, m = mass, and a = acceleration). Depending on the force applied and the virtual mass set, it is possible to calculate the acceleration. Then the acceleration can be integrated twice to obtain the desired position for the robot to move to. This equation can be expanded to include damping in order to provide stabilization by reducing oscillations (Equation 3.1). The ordinary differential equation that is used to compute the acceleration of a robot (grey section of Figure 3.3) is defined as (x''(t)) based on the rate at which a small, frictionless virtual point mass (m) will accelerate under a user's applied force (F(x)) and specific damping (b) within a predefined duration (t).

$$x''(t) = \frac{F(x)}{m} - \frac{b * x(t)}{m} \tag{3.1}$$

The ordinary differential equation is calculated based on the force information that was read (Fz) and the current velocity (initial parameter). Inverse kinematics and conversions are calculated. These positions are checked against the limits of the user's preset range of motion limits. If the position is within the limits, the motor is given the command to write the goal position to the motor, ultimately moving the end effector. Control parameters for damping and mass can be altered in addition to force amplification or reduction to provide a user the appropriate level of assistance. The position and velocity values that were calculated from the last loop, become the new initial conditions for the ordinary differential equation for the next loop. This method allows for active participation from the user, while assisting with some movement. The mass (m) and damping (d) are tunable parameters that can be adjusted for an individual's needs.

The Admittance Control method has been adapted to include a force triggering limit to further assist with intentional movement. Within this method, the Admittance Control paradigm stays the same as in Figure 3.3; however, a force limit is set. To receive assistance, the individual must apply that amount of force, prompting the individual to participate to their maximum capability.

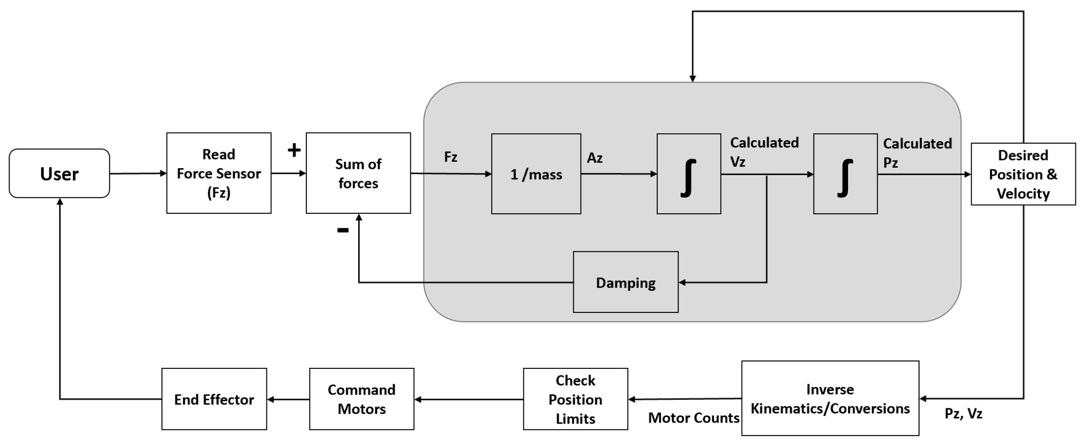

Figure 3.3 Diagram of Admittance Control loop.

We believe that the use of an admittance control paradigm will allow an individual to interact with the system and it will amplify the force that they are able to apply.

3.3 Modeling Evaluation of Admittance Control Loop

3.3.1 Introduction

A small study was performed to evaluate the admittance control loop with computer simulations used in the first iteration of the NJIT Gripper (Zhou et al., 2019; Zhou et al., 2020). This study aimed to model the NJIT Gripper interacting with a neuromuscular hand model to evaluate the effectiveness of the admittance control algorithm in providing different levels of assistance or resistance. By adjusting parameters such as mass and damping, it is possible to simulate these effects. The NJIT Gripper and a hand were modeled to demonstrate the interaction between the two. The NJIT gripper was modeled as an articulated rigid body with the base fixed to the hand, and the human musculoskeletal hand model was adapted from Lee et al (Lee et al., 2015) (Figure 3.4). This model included six finger muscles: extensor digitorum communis (EDC), extensor indicis (EI), flexor digitorum superficialis (FDS), flexor digitorum profundus (FDP), bipennate first dorsal interosseous (FDI) on the radial side and the ulnar side.

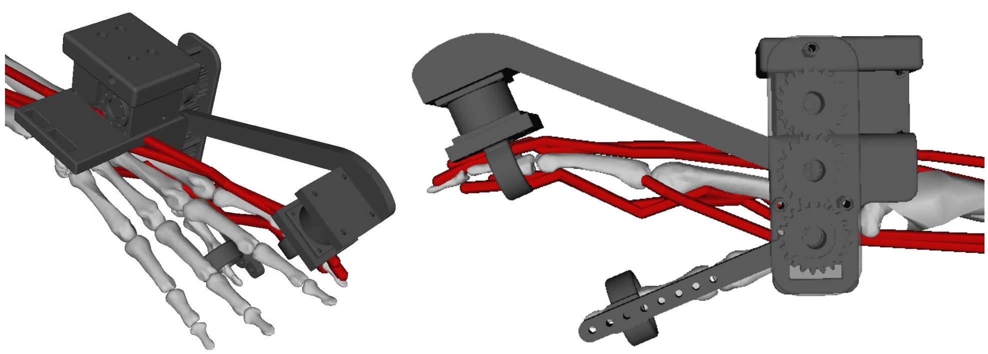

Figure 3.4 Assembled musculoskeletal model of the hand and the exoskeleton.

Source: Zhou, X., Mont, A., & Adamovich, S. (2020). Evaluation of a 1-DOF hand exoskeleton for neuromuscular rehabilitation. In 16th international symposium CMBBE and 4th conference on imaging and visualization. New York, NY: Springer.

3.3.2 Simulation Methods

The admittance control loop was evaluated with computer simulations of the NJIT Gripper's model interacting with the human hand's neuromuscular model. In the simulation, the admittance control paradigm works as described above. In the simulation, a proportional derivative (PD) controller was used to specify the desired joint torque to the motor (Equation 3.2).

$$\tau = k_p(\theta_d - \theta) - k_d\dot{\theta} \tag{3.2}$$

In this equation, k_p and k_d are tunable parameters, in which θ is the current angle, and $\dot{\theta}$ is the current angular velocity of the motor. This admittance control framework integrates the virtual end effector mass placed at the center of the index finger ring which is moved by the force applied by the index finger (Figure 3.5).

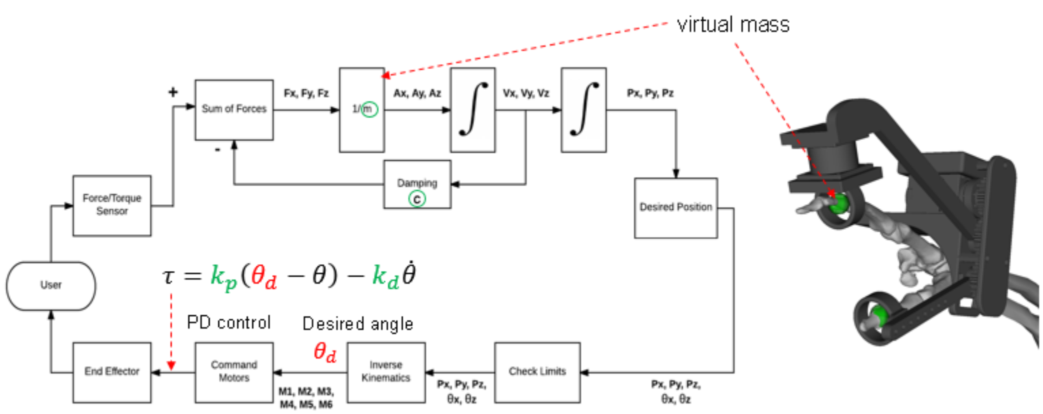

Figure 3.5 The designed admittance control framework. The parameters in green or circled in green are tunable control parameters.

Source: Zhou, X., Mont, A., & Adamovich, S. (2020). Evaluation of a 1-DOF hand exoskeleton for neuromuscular rehabilitation. In 16th international symposium CMBBE and 4th conference on imaging and visualization. New York, NY: Springer.

To model the interaction forces between the finger and the ring, a tri-directional spring – damper force element was used to mimic the contact between them. The tri-directional force element, which was inserted at the ring's center, predicts the directional changes in force due to the movement of the finger and the ring. In the initial start position, the points on the NJIT Gripper and the finger create a zero force. The force element was modeled using linear damped springs. The assumption that the lateral direction (YZ) stiffness is 20 times that of the X direction was made and this demonstrates resistance in the lateral direction and a softer resistance in the hand opening direction.

All simulations were performed using the musculoskeletal simulation code, CoBi-Dyn, developed by CFD Research Corporation (Huntsville, AL). A simulation framework similar to Zhou et al., which includes hybrid inverse dynamics (ID) and forward dynamics (FD), was implemented (Zhou et al., 2014). The finger movements were considered ID joints because the motions can be specified to track a motion that is input. The NJIT Gripper joints were classified as FD joints as their movements were controlled by the actuation forces and finger-ring interaction forces. At each step of the simulation, the framework predicted the joint torques for all finger joints and accelerations for the NJIT Gripper joints. These predicted joint torques become the desired torques that should be generated from the muscles around the joints. This prediction method aims to determine a muscle force combination that contributes to the desired joint torques as closely as possible. To overcome the redundancy of the muscles and large numbers of combinations, an optimization problem was used (Equation 3.3).

$$\sum_{i=1}^{n}\left(\frac{f_i}{f_i^{max}}\right)^p + w\boldsymbol{C}^{\boldsymbol{T}}\boldsymbol{C} \tag{3.3}$$

The force of the ith muscle is defined as f_i, and f_i^{max} was the maximum attainable muscle force at its current state. **C** was the difference vector between the desired joint moments and the moments generated by spanning muscles. The weighting factor was defined as w, and $\frac{f_i}{f_i^{max}}$ can be considered as the muscle activation for simplicity. For all of the simulations, p = 2 and w = 100 were utilized.

3.3.3 Experimental Methods

Experimental data was collected to calibrate the model parameters and validate the simulations. For this analysis, we collected data with the NJIT gripper under no torque control, meaning that the user had complete control of the robot. There was no control scheme implemented. A custom MATLAB script was used to collect data from the motor, tri axial load cell and EMG activity. Participants were seated comfortably so that they could rest their arms between sessions. EMG electrodes were placed on the FDI, EI, EDC, and FDS muscles of their right hand. The participant was then asked to wear the NJIT Gripper. Calibration of the NJIT Gripper was performed to zero the force sensor and set the rotational limits of the motor. These limits are set so that the fingers would not hyperextend. The participant was asked to complete 15 to 20 extension-flexion cycles in synchronization with a metronome set to the following speeds: 40 bpm, 50 bpm, 70 bpm, 100 bpm, and 150 bpm. The outcome measures were EMG, force, and position data. The position is determined by the rotation of the smart servo motor, and through the provided conversion factors, the joint angle can be calculated in radians. For the tri-axial load cell, we mainly looked at the perpendicular force (Z force), as this is the force aligned perpendicular to the surface of the index finger pad.

3.3.4 Experimental Results

A custom MATLAB script was used to process and analyze all session data for one participant. The sessions consisted of 15 – 20 extension and flexion sessions, and to further analyze this data, it had to be cycled into individual movements using peak detection of the motor position data. This data was resampled to 350 Hz and filtered with a 4th order lowpass Butterworth filter with a cutoff of 8Hz. This position data was converted from motor counts to angles so that the values could be evaluated. The force data were filtered with a 4th order lowpass Butterworth filter, with a cutoff of 10 Hz. The maximum extension force was calculated as well as the average maximum flexion force. Motor position and force data were resampled to 350 Hz. The motor position data were filtered with a 4th order lowpass Butterworth filter with a cutoff of 8Hz. The position data were be converted from motor counts to angles. The position, velocity, and force data were then cycled into individual time-synchronized cycles, and the average values were obtained.

The EMG data were filtered with a 4th order high pass Butterworth filter with a cutoff of 20 Hz, and a 4th order low pass Butterworth filtered with a cutoff of 500Hz. This data were resampled to 350 Hz, and rectified. For each muscle, the root mean square envelope was calculated using a sliding window of 30 samples, with an overlap of 29 samples. The maximum voluntary contraction was not obtained, so the root mean square (RMS) envelope was normalized to the maximum mean value of the FDI muscle.

For analysis with the simulation, we chose to further investigate the session with no torque at 40 bps. For this session, the first 50% of movement is flexion and the second half of the movement is extension. The results of that session are presented here. For an average of 20 cycles, the participant moved through a motor rotation angle of approximately 16 degrees within 1.5 seconds (Figure 3.6). The maximum force applied at the flexion phase of the cycle was approximately 1.2N, and at the peak of the extension phase, the user applied .5N (Figure 3.7). A faster velocity was observed during flexion, which would attribute to the greater force during that portion of the movement. Although a metronome was used, the movement speed varied between flexion and extension due to no constraint on the motor velocity. The activities of the flexors (FDI, FDS) and extensors (EI, ECD) were evaluated, and as expected, there was an onset of activation of the FDI during finger flexion and relaxation during the extension phase. Similarly, the EDC muscle shows an activation onset during extension and relaxation during flexion (Figure 3.8).

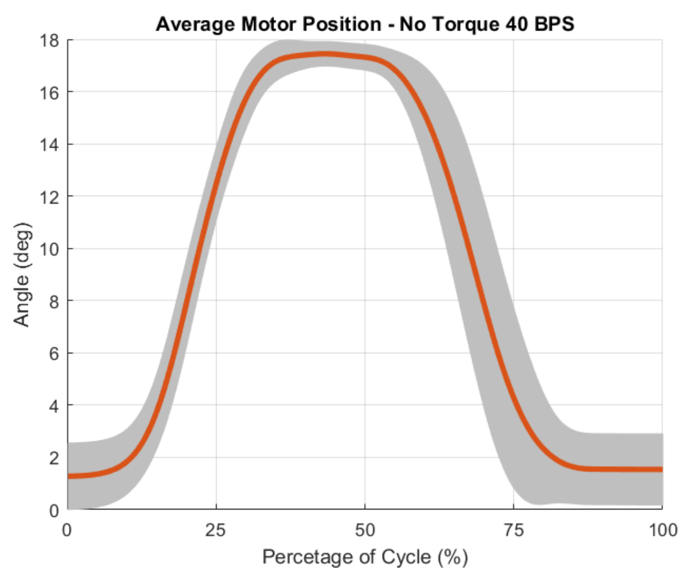

Figure 3.6 Average motor position of the exoskeleton during the flexion and extension cycles. The shaded area represents the standard deviation.

Source: Zhou, X., Mont, A., & Adamovich, S. (2020). Evaluation of a 1-DOF hand exoskeleton for neuromuscular rehabilitation. In 16th international symposium CMBBE and 4th conference on imaging and visualization. New York, NY: Springer.

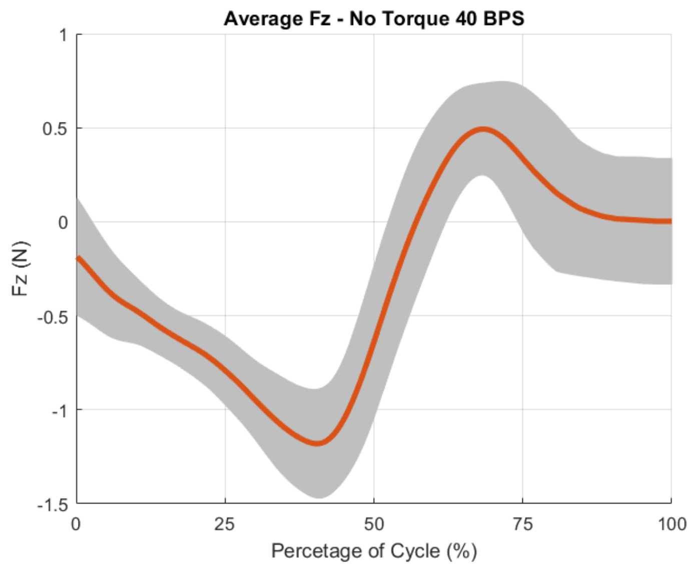

Figure 3.7 Average measured force from the tri-axial force sensor during the flexion and extension cycles with the shaded grey area representing the standard deviation. Fz is the direction perpendicular to the surface of the finger.

Source: Zhou, X., Mont, A., & Adamovich, S. (2020). Evaluation of a 1-DOF hand exoskeleton for neuromuscular rehabilitation. In 16th international symposium CMBBE and 4th conference on imaging and visualization. New York, NY: Springer.

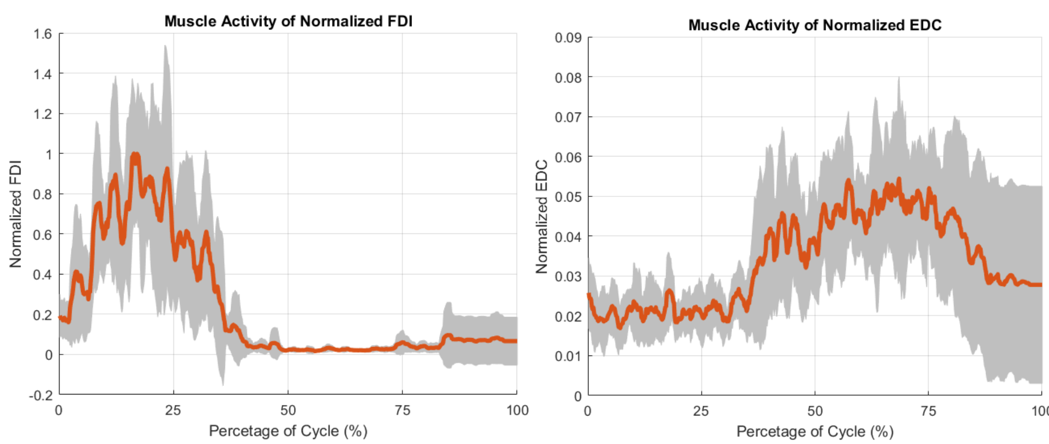

Figure 3.8 Average EMG envelope (normalized by the maximum value of FDI envelope) during the flexion and extension cycles, with the shaded grey area indicating the standard deviation.

Source: Zhou, X., Mont, A., & Adamovich, S. (2020). Evaluation of a 1-DOF hand exoskeleton for neuromuscular rehabilitation. In 16th international symposium CMBBE and 4th conference on imaging and visualization. New York, NY: Springer.

3.3.5 Simulation Results

Simulations were run for the NJIT Gripper in active modes, with the movement driven by the finger's flexion and extension cycles and torque control of the motor. Different combinations of the proportional gain and damping of the PD controller, end effector mass, and end effector damping coefficient was used. A range of values from .01 to 10 kg was used for the virtual end-effector mass (m). The damping coefficient (c) was set to .01 for all simulations.

During the simulations, the metacarpophalangeal (MCP) joint of the index finger tracks a flexion and extension movement, while the proximal interphalangeal (PIP) joint and the distal interphalangeal (DIP) joint are assumed to be stationary. The motions and torques were provided by the ID that was computed. The motion for the MCP joint was input, increasing from 0 to 25 degrees during flexion to the extension cycle within 1.5 seconds (Figure 3.9). The time was set to the same as found in the experimental sessions for movements at 40 bps. The angle of the motor rotation as computed by the FD was slightly less than 14 degrees, which is close to the experimental measure of 16 degrees. We attribute the difference in movement amplitude between the finger and the motor to the fact that the NJIT Gripper joints do not align 100% with anatomical joints.

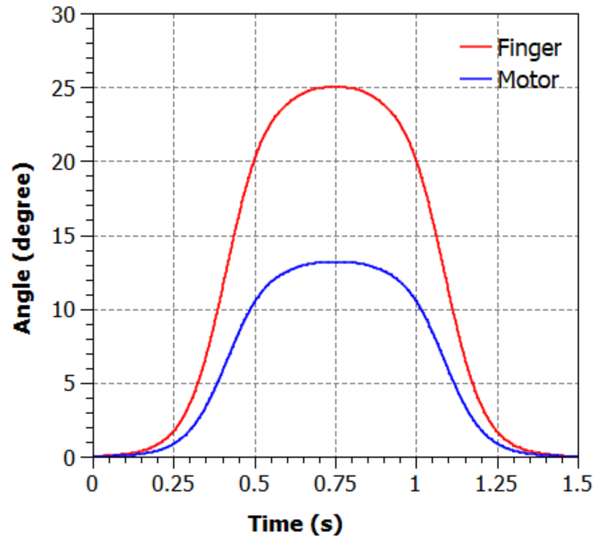

Figure 3.9 Angle of the index finger and motor rotation.

Source: Zhou, X., Mont, A., & Adamovich, S. (2020). Evaluation of a 1-DOF hand exoskeleton for neuromuscular rehabilitation. In 16th international symposium CMBBE and 4th conference on imaging and visualization. New York, NY: Springer.

The optimization routine made it possible to predict the muscle force and activation based on the computed joint torques during the input tracked motion. The interaction force was calculated based on passive control modes with various masses and proportional gains (Figure 3.10). For the passive control mode, the interaction forces were calculated to be 1.45N, which is within the measured experimental values.

We continued to evaluate different PD proportional gains (k_p = .1, 1, 2) at a mass of .1kg simulating an active control algorithm for 3 conditions. With an increase in proportional gain, the performance tends to increase, decreasing the interaction forces and once the gain of 2 is reached, the controller becomes unstable and oscillates. Similarly, when the virtual end-effector mass is set to .01kg, and k_p = .1, .5, 1, we observe oscillations at k_p = 1. Comparing the two controller parameters, the one that results in the smallest interaction force (~.52N) is when m = .01, and k_p = 1). These parameter settings would suggest that it would be easier for an individual to move through flexion and extension using the NJIT Gripper due to the decrease in force needed to provide movement assistance.

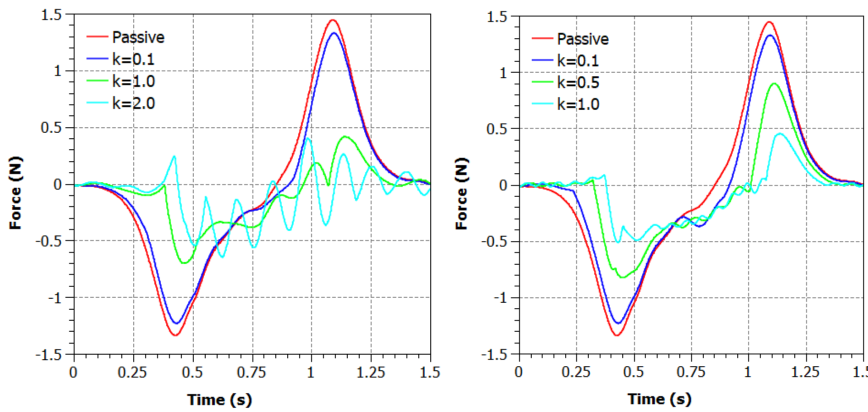

Figure 3.10 Predicted finger-ring interaction forces for different PD proportional gain (k_p or k in the figure); Left: m = 0.1; Right: m = 0.01.

Source: Zhou, X., Mont, A., & Adamovich, S. (2020). Evaluation of a 1-DOF hand exoskeleton for neuromuscular rehabilitation. In 16th international symposium CMBBE and 4th conference on imaging and visualization. New York, NY: Springer.

We further investigated the effects of adjusting the virtual end-effector mass, keeping the k_p = 1. By increasing the mass values from 1 to 10 (m = .01, .1, 1, 10), the assistive performance decreases and once m = 10, the NJIT Gripper actually provides a resistive force (Figure 3.11). The mass parameter that provided the most assistance was the smallest one (m =.01). By adjusting the mass parameters, the user can tune the level of assistance or resistance as desired.

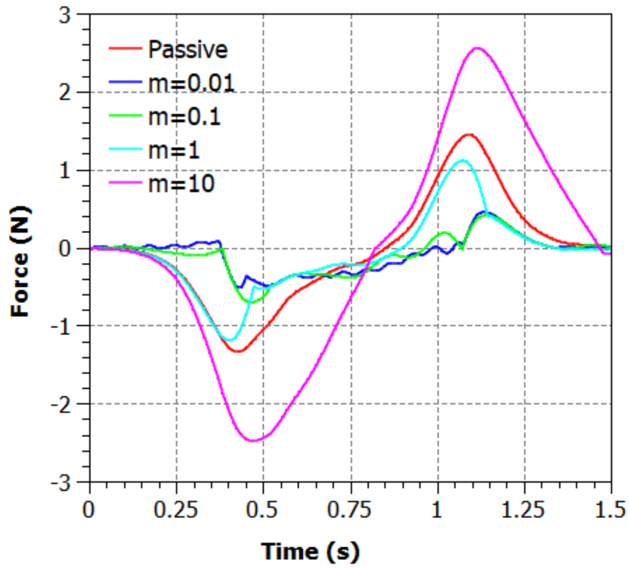

Figure 3.11 Predicted finger-ring interaction forces for different mass values. k_p = 1 for all masses.

Source: Zhou, X., Mont, A., & Adamovich, S. (2020). Evaluation of a 1-DOF hand exoskeleton for neuromuscular rehabilitation. In 16th international symposium CMBBE and 4th conference on imaging and visualization. New York, NY: Springer.

We compared the active motor torques for multiple controllers, three of which have m = 0.01 and gains k_p= 0.1, 0.5, 1, and the other with a large m = 10 and k_p= 1 (Figure 3.12). As k_p increases, the active motor torque increases and provides better assistance to the finger's flexion and extension cycle. This is evident from the reduction of interaction forces seen previously (Figure 3.10). For the large mass (m = 10), the active torque is similar in magnitude to the best assistive torque (m = $0.01, k = 1$) but in the reversed direction, indicating resistance instead of assistance. Additionally, the muscle activations of the flexors and extensors were evaluated for these four controllers. As expected, the flexors are active during the closing phase of the movement, while the extensors are active during the opening phase of the movement (Figure 3.12). For the three assistive controllers with m = 0.01, muscle activations of both muscle groups were reduced due to the decreased finger-ring interaction force. For the resistive controller (largest mass, m = 10), the muscle activations for both groups have increased when compared to the passive case (no active motor torque).

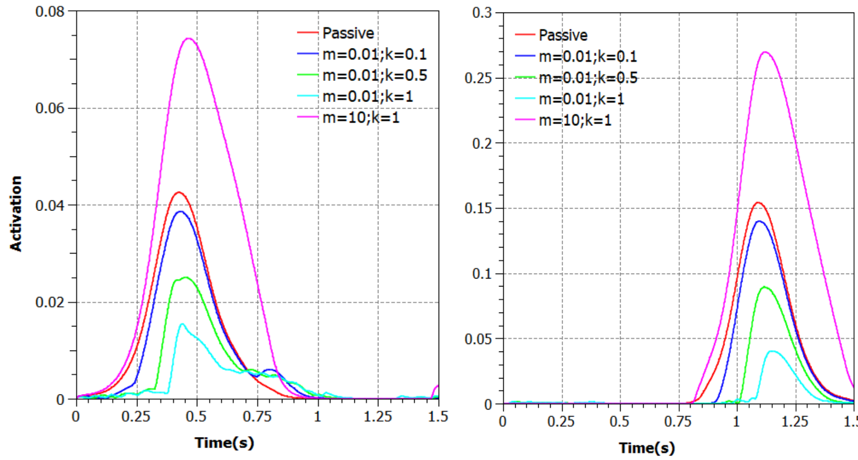

Figure 3.12 Predicted average muscle activations for different control modes and parameters. Left: flexors; Right: extensors.

Source: Zhou, X., Mont, A., & Adamovich, S. (2020). Evaluation of a 1-DOFhand exoskeleton for neuromuscular rehabilitation. In 16th international symposium CMBBE and 4th conference on imaging and visualization. New York, NY: Springer.

3.3.6 Discussion

When modeling the NJIT Gripper and its interaction with a musculoskeletal human hand model, we were able to evaluate the effectiveness of an admittance control method. The results demonstrated that the assistance provided by the motor reduces muscle activation significantly due to reduced interaction forces, making it easier for an individual with impairments to complete a movement that would otherwise be very difficult for them to complete without assistance as the virtual mass decreased, more assistance was provided, but the controller eventually became unstable and oscillatory. Although the admittance control paradigm is designed to provide assistance to the user, by increasing the mass, it is possible to results in resistance as well. In conclusion, modeling can help to predict the feasibility of the admittance control framework, guide the tuning of control parameters, and evaluate the exoskeleton's effectiveness for hand rehabilitation. Future work will include adding additional outcome measures to the experimental sessions to have more data to input into the model such as motion capture data of the fingers.

3.4 Conclusion

The successful design and development of the NJIT Gripper allow us to evaluate the effects of movement-based motor priming. The fabrication was completed and achieved all of the design requirements: lightweight, low cost, and customizable sizing. The three control paradigms were written and implemented for use with the NJIT Gripper. The modeling case study establishes that the admittance control paradigm is effective in providing assistance as needed by changing the parameters in the controller.

CHAPTER 4

EVALUATION OF NJIT GRIPPER WITH HEALTHY INDIVIDUALS AND INDIVIDUALS WITH STOKE

4.1 Introduction

Upon completing the design and fabrication of the NJIT Gripper and modeling the control paradigms, it was necessary to test the system with healthy individuals and individuals with stroke. This section is divided into two separate evaluations. The purpose of the first evaluation was to establish that the device is well tolerated and safe for individuals with chronic stroke. It was also necessary to determine whether or not the device could elicit muscle activity during its intended use of stretching for sensorimotor priming. During the feasibility testing, it was *hypothesized that individuals with chronic stroke would tolerate the device with no adverse effects*. The second evaluation was to determine whether or not the NJIT Gripper could be used with the motion capture system used by our laboratory for kinematic evaluation and gameplay for future integration. This evaluation was performed with healthy participants in order to get the most accurate results. It was hypothesized *that the Leap Motion Controller would accurately track the hand using the NJIT Gripper.*

4.2 Evaluation with Individuals with Stroke

4.2.1 Methods

Four individuals (2M, 2F) with chronic stroke participated in the evaluation of the NJIT Gripper. This group was balanced by gender and side of hemiplegia. The clinical and demographic descriptions of participants are in Table 4.1. All participants had moderate impairment levels as measured by the Upper Extremity Fugl-Meyer Assessment

(UEFMA). The UEFMA is an assessment scored on a scale of 0 – 66, with a higher score translating to less motor impairment. Individuals with scores between 0 – 20 were considered to have severe impairment, 21 – 50 moderate impairment, and 51 – 66 mild impairment (Velozo & Woodbury, 2011). The differences in gender, hand size, hemiplegic side, and impairment level created a diverse study population for feasibility evaluations.

Participants wore the NJIT Gripper on their hemiplegic hand for 30 minutes or 120 cycles of flexion and extension. They repeated this on two separate days to evaluate the passive and active (Admittance Control with Force Trigger) control paradigms. For the passive condition, participants were instructed to relax their impaired hand and arm and allow the NJIT Gripper to move their impaired hand through the preprogrammed trajectory. For the active condition, a force limit was set, and participants were instructed to attempt to extend their fingers; upon reaching the force limit, the NJIT Gripper would assist with the rest of their movement to extend the fingers. Their arms were placed either in an arm support or on a pillow in front of them on the table. Surface EMG was recorded using a 2 kHz Delsys Trigno system to measure the activity of the following muscles: extensor digitorum communis (EDC), extensor indicis (EI), flexor digitorum superficialis (FDS), and first dorsal interosseous (FDI). The following outcome measures were measured: pinch force, key pinch force, grasp force, and EMG during stretching. An increase in force measures might suggest that the stretching of the flexor muscles resulted in activation of the motor cortex. EMG activation during stretching might suggest a stretch reflex of the finger flexors.

Table 4.1. Demographic and Clinical Description of the Participants

Participant ID	Gender	Hemiplegic Side	UEFMA
S1	F	Left	40
S2	F	Right	36
S3	M	Right	48
S4	M	Left	48

4.2.2 Results

All participants could comfortably wear the NJIT Gripper and tolerate stretching of their hand for up to 30 minutes with no discomfort. Participants reported that 30 mins was a reasonable amount of time to stretch their hands. For the passive stretching condition, it is clear that the flexor muscles become active during stretching (Figure 4.1). This figure demonstrates two flexion and extension cycles. The hand is opening (extension) as the position of the motor changes from 0 to ~70 mm, and as the position decreases back to 0, the hand is closing (flexion). It is clear that during the extension phase, a stretch reflex has been elicited for the FDS muscle when the hand is fully extended.

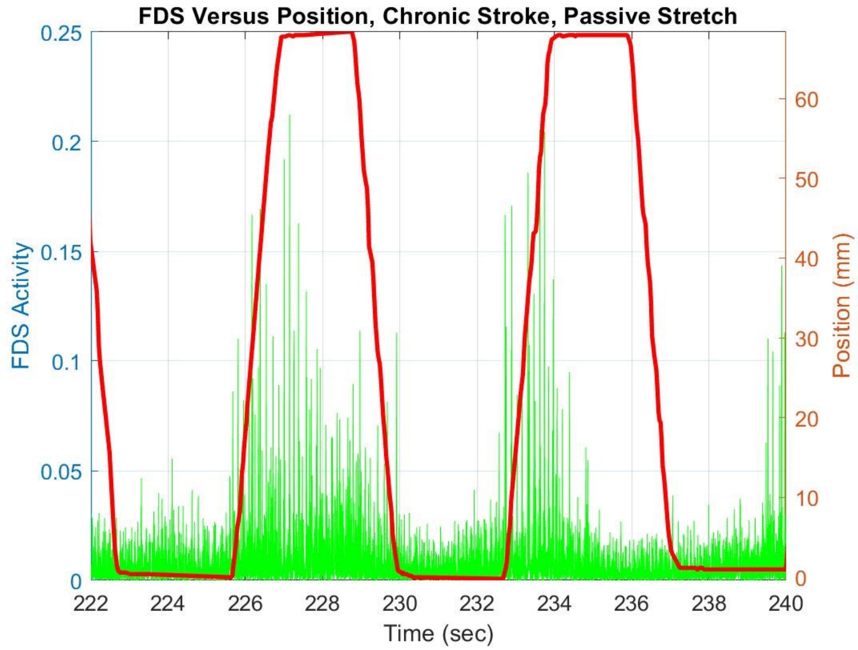

Figure 4.1 As the position increases from 0 – 70 mm, the hand is opening and in the extension phase of the movement. As the position decrease toward 0, the hand is closing and in the flexion phase of the movement. The FDS muscle is active when the hand is fully extended.

The active stretching with the force trigger was also evaluated to determine if it was working correctly and if individuals with stroke could interact even if they could only apply a small force. As shown in Figure 4.2, this individual had a force limit set to .1N. The hand opens as the position increases from 0 to ~26 mm, and the hand closes as the position reaches 0. The individual is applying a force as it moves from the negative direction toward .1N. Once the trigger threshold is reached, the NJIT Gripper starts to open the hand to the maximum position, which in this example is 26 mm. At the start of the movement, the finger extensor muscle (EDC) becomes active as the individual is attempting to extend their fingers. The FDI muscle becomes active during the maximum opening, due to the stretch reflex, and during the flexion phase of the movement.

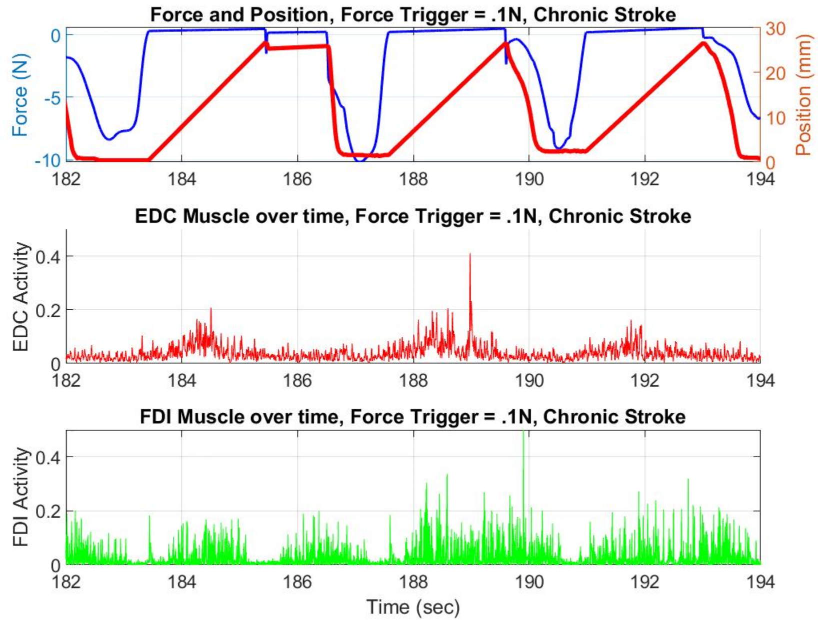

Figure 4.2 The individual with stroke, had a force limit of .1N. As the position changes from 0 to ~26 mm the hand is in extension, and when the position moves toward 0, the hand is in flexion. The EDC muscle activates during the extension phase of the movement, and the FDI muscle becomes active during the maximum stretch as well as during closing.

Statistical analysis of the force measurements was performed using R (R Core Team, 2022). A paired T-test was used to evaluate the Pre and Post time points for each isometric motor task (Pinch, Key Pinch, and Grasping). For the Pinch, as n = 4, the Shapiro Wilk test for normality resulted in the p = .4242, therefore, the distribution was not significantly different than normal. The mean for Pre was 9.48N (SD 5.97), and the mean for Post was 14.56N (SD 11.11). This was not a statistically significant difference (paired, samples t-test, t (3) = 1.4219, p = .2502). For the Key Pinch, as n = 4, the Shapiro Wilk test for normality resulted in the p = .2762, therefore, it was not significantly different from normal. The mean for Pre was 8.46N (SD 6.93), and the mean for Post was 13.11 N (SD 12.64). This was not a statistically significant difference (paired, samples t-test, t (3) = 1.017, p = .384). For the Grasping, as n = 4, the Shapiro Wilk test for resulted in p = .4902, therefore, the distribution was not significantly different than normal. The mean for Pre was 9.73N (SD 4.53), and the mean for Post was 11.38 N (SD 1.77). This was not a statistically significant difference (paired, samples t-test, t (3) = 1.5514, p = .2186).

Although the results were not statistically significant, for some participants their strength improved after stretching. The change in force for each of the outcome measures for all participants can be found in Table 4.2. The results that are in bold, demonstrate an increase in strength. For three of the four participants there is an increase greater than 2N for the grasp strength for the active condition. Two of the participants who were able to generate a higher grasp strength, were more severely impaired as measured by the UEMFA. We predict that the active stretching of the finger flexors, activated the motor cortex, enhancing muscle fiber activation and allowing the individuals to generate more force. The pinch and key pinch measures improved only for one participant, however the NJIT Gripper was not stretching any of the thumb muscles, so it was not expected to see a large increase for that measure.

Table 4.2 Changes in Strength Measures for Each Participant

Participant	UEFMA						
		Passive Condition			Active Condition		
		Δ Pinch (N)	Δ Key Pinch (N)	Δ Grasp Strength (N)	Δ Pinch (N)	Δ Key Pinch (N)	Δ Grasp Strength (N)
S1	40	-1.59	-1.01	-3.19	-5.86	-0.52	**2.15**
S2	36	-0.14	-1.41	-1.51	-1.92	.11	**2.43**
S3	48	**0.70**	**10.99**	**22.32**	-5.53	**5.28**	**3.64**
S4	48	-10.91	-1.93	-2.86	**13.32**	**8.48**	-6.01

4.2.3 Discussion

Study participants reported no adverse events or discomforts. The results establish that the NJIT Gripper was comfortable for different size hands and different impairment levels for a prolonged period of time. The NJIT Gripper can elicit a muscle response during stretching through the flexion and extension of the fingers for both the passive and active stretching paradigms. Although there were no significant changes in the force measures Pre to Post, there was an increase in strength for some participants. These results were similar to those observed for key pinch and grasp strength in two similar studies by Triandafilou et al. (Triandafilou & Kamper, 2014; Triandafilou et al., 2011).

4.3 Evaluation of Healthy Individuals

Upon establishing that the NJIT Gripper was well tolerated by individuals with stroke with varying levels of impairment and hand size, it was essential to establish that the NJIT Gripper could be used in conjunction with motion capture devices used by our laboratory to capture kinematic data. Kinematic data from motion capture systems could provide insight into the interaction between the NJIT Gripper and the fingers. In many of the studies performed by our laboratory, we use motion tracking to evaluate hand range of motion and the ability to regulate flexion and extension of the hand (Fluet et al., 2021; Merians et al., 2020; Qiu et al., 2020). In these studies, the Leap Motion Controller (LMC) (Ultraleap, United Kingdom) and the Optical Motion Capture System (Optitrack Prime 13 cameras, Optitrack, Corvallis, Oregon) were used. The optical motion capture system by Optitrack is considered the gold standard for motion capture and is used to validate many of the new technologies coming out on the market (Goreham et al., 2022; Guignard et al., 2021; Shuai et al., 2022; Wong et al., 2007). Alternatively, the LMC is an inexpensive and portable system for tracking, specifically the hand and fingers. It was imperative to compare the two systems and establish if the NJIT Gripper could be used simultaneously without disrupting the motion capture data.

The Optitrack Motion Capture System includes Prime 13 cameras which provide a 3D precision of .5mm at long ranges and .2mm at close range. In addition, the frame rate can be set as high as 240 frames per second. To control the motion capture system and collect data, the motion capture software Motive (NaturalPoint Inc., Corvallis, Oregon) was used. This software allows the user to calibrate the system and configure parameters for a specific need. In this setup, seven Prime 13 cameras were used. During data collection, the Motive software obtains 3D information through the reconstruction feature, which takes the multiple images of the 2D markers to obtain the 3D coordinates. This allows for the tracking of complex movements with positional accuracies of +/- .2mm and a latency of less than 9 ms. These system specs allow for precise tracking of joints during complex movements of the hand.

The Leap Motion Controller (LMC) is an infrared-based tracking device used to measure hand and finger gestures. The LMC provides a low-cost and marker-less alternative for hand tracking. The LMC consists of two cameras and three infrared LEDs, with the functional range extended approximately from 25 mm to 600 mm above the device, which provides a typical field view of ~150° (Ultraleap, 2017). The LMC uses an internal hand model and compares the sensor data to predict the position of each joint of the fingers and wrist, therefore, creating a three-dimensional representation as shown in Figures 4.1 and 4.2 (Ultraleap, 2015).

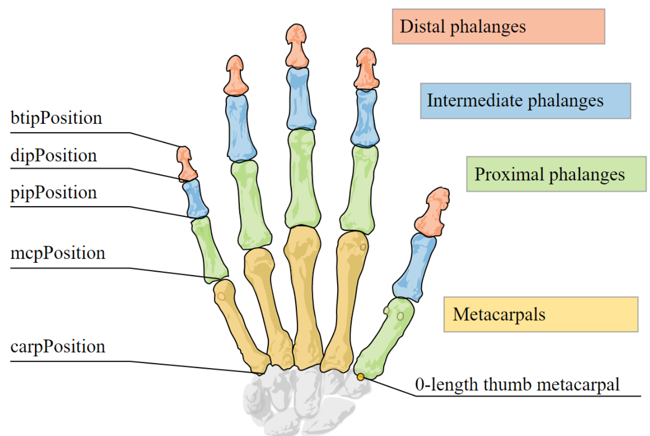

Figure 4.3 Example of each position of joints for the LMC tracking for each finger at the following joints: distal phalanges, intermediate phalanges, proximal phalanges, and metacarpals.

Source: Ultraleap. (2017) API Overview. Ultraleap. Retrieved on June 6, 2022, https://developer-archive.leapmotion.com/documentation/csharp/devguide/Leap_Overview.html

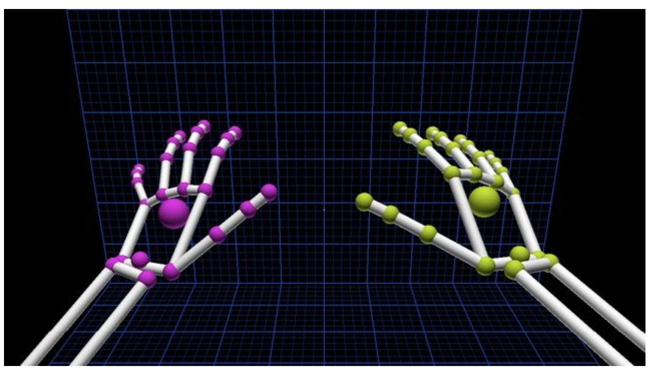

Figure 4.4 Skeleton Tracking visualization of the left and right hands.

Source: Ultraleap. (2015) Introducing the skeletal tracking model. Ultraleap. Retrieved on June 6, 2022, https://developer-archive.leapmotion.com/documentation/objc/devguide/Intro_Skeleton_API.html

In an evaluation by Weichert et al. (2013), it was found that for static movements, the LMC has a precision of .2mm, and for dynamic movements, it is 1.2mm (Weichert et al., 2013). However, it is essential to note that they were using an industrial robot to track the movements of a pen, not a human hand. The LMC has been used for engaging gaming applications for therapy of the hand across many different injuries/diseases such as

Orthopedic Injury, Stroke, Parkinson's Disease, and Multiple Sclerosis (Arora & Naqvi, 2022; Butt et al., 2017; Cuesta-Gómez et al., 2020; Qiu et al., 2020). While the LMC is appropriate for measuring gestures to allow for game interaction, few studies evaluate the measurements' precision using a human hand (Niechwiej-Szwedo et al., 2018; Smeragliuolo et al., 2016). These studies indicate that the LMC is accurate enough to provide clinically meaningful information for specific movements such as wrist flexion and extension in controlled environments. We evaluated the LMC with and without the gripper to assess the accuracy against the Optitrack Motion Capture System and the latency with and without the NJIT Gripper.

4.3.1 Methods

Healthy individuals participated in this study. A custom MATLAB script was written for data collection to allow for synchronization of data collection between the NJIT Gripper, EMG, Leap Motion Controller, and Optitrack motion capture system. The NJIT Gripper provided force data as well as motor position data. The LMC and Optitrack Motion Capture System tracked the movements of the fingers tips. Surface EMG was recorded using a 2 kHz Delsys Trigno system to measure the activity of the following muscles: extensor digitorum communis (EDC), extensor indicis (EI), flexor digitorum superficialis (FDS), and first dorsal interosseous (FDI). For the Optitrack Motion Capture System, 7 Prime 13 cameras were used. The system was calibrated in Motive software prior to use. The LMC does not have a calibration process when it is used for streaming data.

Participants were asked to place their arm in an arm support to standardize the position relative to the LMC and the Optitrack Motion Capture System to reduce the possibility of data being dropped due to movement outside the camera's field of view.

Active markers were placed on each fingertip, with additional markers on the tip of the thumb and thumb joints. EMG electrodes were placed on the FDI, EI, EDC, and FDS muscles. The participant was instructed to flex and extend their fingers approximately 20 times without the NJIT Gripper. This allowed for data collection from EMG, LMC, and Optitrack Motion Capture System to compare the two camera systems. Then the NJIT Gripper was placed on the individual's right hand, and they repeated the flexion and extension movements using the different control schemes (Passive, Active – Admittance Control, and Active – Admittance Control with Force Trigger).

4.3.2 Results

When evaluating the hand aperture as measured by the Optitrack Motion Capture System and the LMC without the gripper, there was an average error of ~5.80% (Figure 4.5). When the NJIT Gripper was added to the hand, the error increased to ~7.59% and we attribute this to the fact that the view of the fingers may have been slightly occluded by the NJIT Gripper (Figure 4.6).

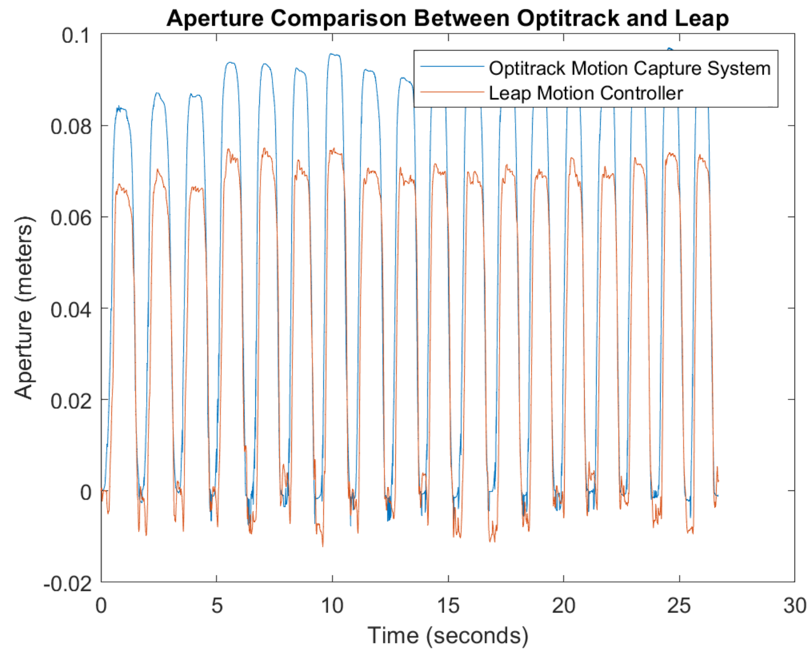

Figure 4.5 Aperture comparison between Optitrack Motion Capture System and Leap Motion Controller. The percent difference between the two systems is ~5.80%.

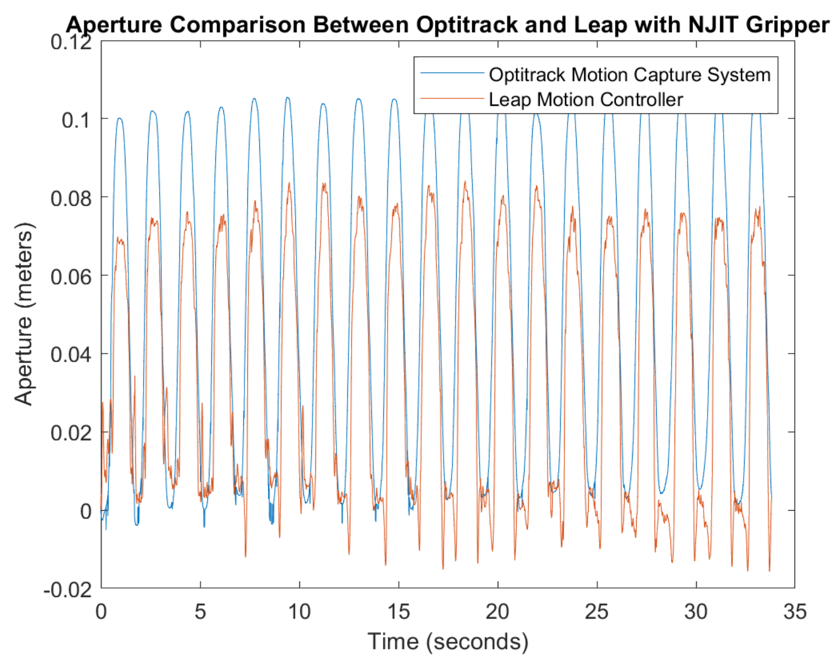

Figure 4.6 Aperture comparison between Optitrack Motion Capture System and Leap Motion Controller while the participant was wearing the NJIT Gripper. The percent difference between the two systems is ~7.59%.

In addition to evaluating the interaction with the motion capture systems, the force, position, and muscle activity were evaluated for the active control paradigms. For the first control paradigm, Admittance Control, the participant had complete control over the movement - with no force triggered assistance. The parameters were set so that the movement was easier, but the robot did not move the participant's hand. The hand was opening as the position increased from 0 to ~60 mm, and the hand was closing as the position went back to 0 (Figure 4.7). The force followed the same trend, as the force became more positive, the hand was opening. As the fingers started to extend, there was an activation of the extensor muscle (EDC), and as the fingers flexed, there was an activation of the flexor (FDS) muscle.

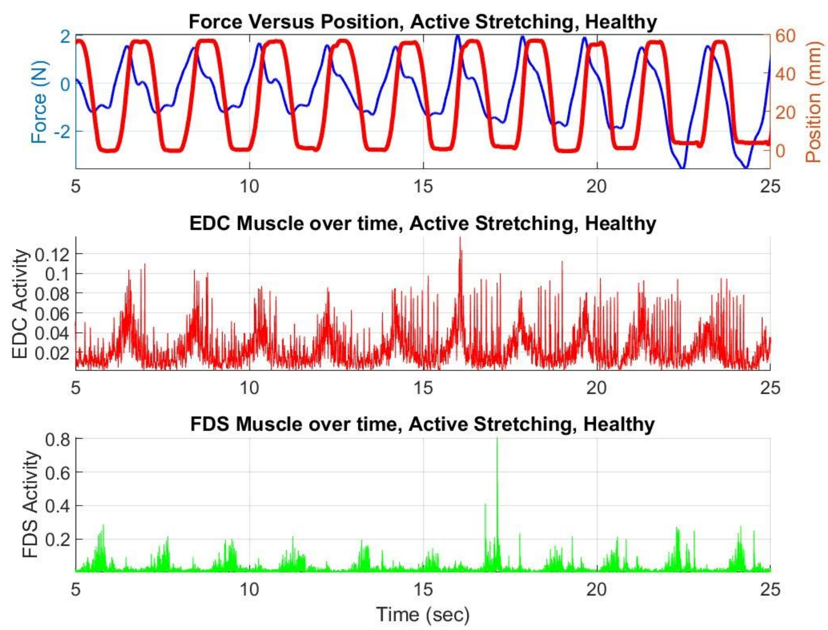

Figure 4.7 Healthy participant using the NJIT Gripper with Admittance Control.

During the force-triggered evaluation, the trigger limit was set to .5N. It is clear that once the limit was reached, the motor responded and started to open the hand to the maximum set position (Figure 4.8).

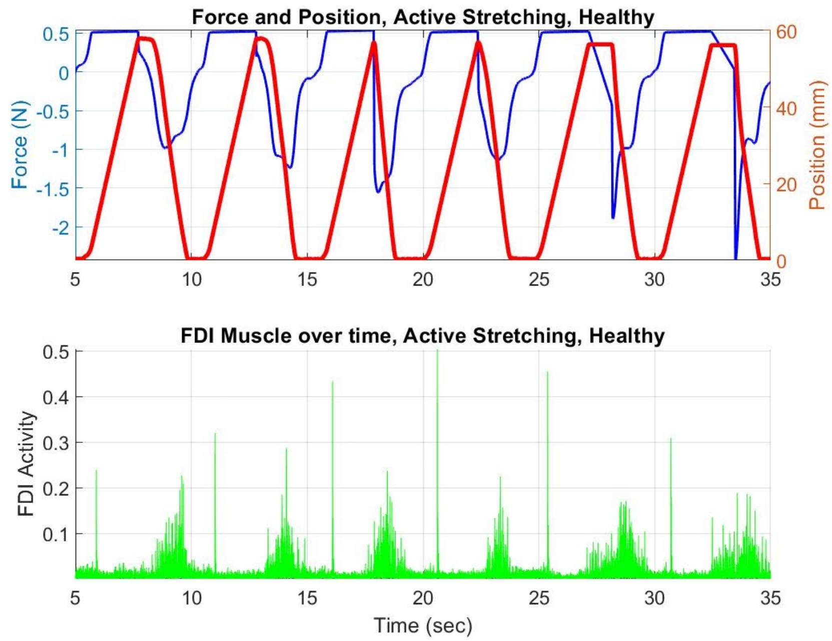

Figure 4.8 Healthy participant using the NJIT Gripper with Force Trigger = .5N

4.3.3 Discussion

While the LMC works well for the recognition of gestures, it falls short in the accuracy of flexion and extension of the fingers. In the setup that was used, there was a baseline error (~5.80%) between the Optitrack Motion Capture System and the LMC when the individual was not wearing the NJIT Gripper. These results are consistent with previous studies (Niechwiej-Szwedo et al., 2018; Smeragliuolo et al., 2016). Smeragliuolo et al., found that the hand posture that allowed the LMC to perform the greatest was when the hand was open. As the hand closed to a fist, this "posture made the LMC perform significantly worse than performing with an open hand." We were evaluating the flexion and extension of the fingers, so it is possible that the performance deteriorated for part of the movement. When the NJIT Gripper is on the hand, the aperture yields a higher error (~7.59%) when compared to the Optitrack Motion Capture System. Although the hand was visible throughout the trial, it is possible that the NJIT Gripper occluded joints on the fingers, and the LMC used the internal hand model to provide predictive tracking of those joints. The joints are reconstructed using this hand model, but because it is inside of the runtime library, we cannot assess the internal model to evaluate it for accuracy.

Another contributing factor to the error between the Optitrack Motion Capture System and the LMC measurements would be the interference of the Prime 13 cameras on the LMC. The LMC is very sensitive to light and reflection, and the Prime 13 cameras have a front-mounted status ring light that may have interfered with the ability to collect data. When the LMC is used for gameplay, no Prime 13 cameras are used, so this would not impact performance.

Additionally, it was observed that although the sampling rate of the LMC can be set up to 120 Hz, with time during data collection, this started to decrease. Multiple studies have demonstrated the inconsistency of the sampling rate of the LMC both between and within trials (de Souza et al., 2021; Guna et al., 2014; Niechwiej-Szwedo et al., 2018). This could lead to inconsistencies when determining the accuracy of the system.

The NJIT Gripper elicited muscle responses from healthy individuals in the active conditions. Further, it was demonstrated that the force triggering controls scheme works efficiently.

4.4 Conclusions

The NJIT Gripper was evaluated by individuals with chronic stroke and healthy individuals. The NJIT Gripper was well tolerated for individuals with stroke with no discomfort for various hand sizes and impairment levels. During the stretching, a muscle response was activated; therefore, we make the conclusion that the NJIT Gripper can be used for unilateral priming of the sensorimotor system. The NJIT Gripper was well tolerated by the healthy individuals who participated in evaluating the interactions between the NJIT Gripper, LMC, and Optitrack motion capture system. It was established that the LMC is not as accurate as the Optitrack Motion Capture System due to the nature of the internal human hand model and predictive capabilities of the LMC. When the NJIT Gripper was on the hand, the error increased slightly but still allowed for tracking. It is concluded that the LMC can be used for tracking during gameplay while wearing the NJIT Gripper, but it is less accurate if used for kinematic measurements as evaluations.

CHAPTER 5

EFFECTS OF MOVEMENT-BASED PRIMING WITH ROBOTICS IN INDIVIDUALS WITH STROKE ON PHYSIOLOGICAL AND KINEMATIC MEASURES

5.1 Introduction

As the overall goal of this project was to develop a robotic exoskeleton to enhance the effects of task-oriented training through priming, it was imperative to evaluate the physiological and kinematic effects of these priming stimuli. Evidence supports that priming can induce increases in corticospinal excitability and promote neuroplasticity of the motor cortex, therefore enhancing the effects of task-specific training (Pomeroy et al., 2011; Stinear et al., 2008; Stoykov et al., 2020). Stoycov & Corcos (2013) observed that in individuals with chronic stroke, movement-based bilateral and unilateral priming of the affected hand before a training session led to increased functional outcome and kinematic measures, but physiological measures such as integrity of the corticospinal tract were not investigated (Stoykov & Corcos, 2013). Therefore, it is unknown if underlying physiological changes were an effect of priming. To explore different methods of priming in the form of stretching, one group has performed several studies with individuals with stroke (Fischer et al., 2016; Triandafilou & Kamper, 2014; Triandafilou et al., 2011). In an early study, repetitive stretching was compared with prolonged stretch and rest conditions in the hand muscles of individuals with chronic stroke. Although the results were not statistically significant in this study, repetitive stretching data suggested trends for improvement. The authors suggest that repetitive stretching seems more effective than prolonged stretching and rest, and one potential reason for this is that the afferent sensory stimuli are evoked by the repetitive stretch, which can result in elevated cortical excitability

(Triandafilou et al., 2011). A more recent study combined passive repetitive training with an active assist training paradigm. Participants in the subacute phase of stroke with substantial impairment participated in 15 sessions. The sessions included 30 minutes of repetitive passive stretching and 60 minutes of assisted active hand training using the robot to complete goal-oriented tasks. Various clinical performance and impairment measures were evaluated, but physiological measures investigating corticospinal excitability were not. Significant improvements were seen immediately after the last session and up to one month post training for some outcome measures. At one-month post-training, Fugl Meyer Upper Extremity Assessment and Chedoke Arm and Hand Activity Inventory were significantly improved from Pretest, which demonstrates improvements in both functional and impairment levels (Fischer et al., 2016). This suggests that this improvement might be from motor recovery and not simply compensation methods; however, as physiological measures of corticospinal excitability were not evaluated, it cannot be determined if priming had an effect on corticospinal excitability. These studies were performed with passive stretching of the hand, while the individual was at rest. Based on the evidence of intension-based movement, it was our belief that using intention-based stretching of the hand would enhance the effects seen with passive stretching (Hummelsheim et al., 1995; Miyai et al., 2002; Schaechter, 2004).

To fully understand whether motor priming is occurring as a result of stretching movement, it is imperative to probe the corticospinal tract, which can be achieved through the use of Transcranial Magnetic Stimulation (TMS) which measures the excitability in the form of Motor Evoked Potentials (MEPs) of muscles specific to the hand. It is predicted that priming will increase the corticospinal tract excitability, which will prepare the brain for motor learning through task-oriented training, but first, it has to be determined if the stretching paradigm provided by the NJIT Gripper can prime the motor cortex. *It is hypothesized that the priming method will increase corticospinal tract excitability in addition to increasing grip and pinch strength, active range of motion, and motor control in the hands of individuals with stroke.* The NJIT Gripper was used for the following conditions: passive stretching (Passive), admittance-controlled stretching (Active), and admittance-controlled stretching with added virtual reality-based visual feedback (ActiveVF). The Passive and Action conditions are both forms of movement-based priming, while the ActiveVF is movement-based priming with the addition of visual feedback from a virtual representation of the moving hemiparetic hand. The addition of visual feedback has been shown by our team to increase the excitability of the sensorimotor system as measured with fMRI and Transcranial Magnetic Stimulation (Saleh et al., 2014; Saleh et al., 2017; Yarossi et al., 2017). A within-subjects study was performed to evaluate the effectiveness of the three stretching conditions on priming the motor cortex and establish the most effective method of priming in individuals with chronic stroke.

5.2 Methods

5.2.1 Participants

This pilot study was approved by the Institutional Review Boards at the New Jersey Institute of Technology and the Kessler Foundation. Six individuals with chronic stroke (> 6 months) were recruited and enrolled in this study. Of the six individuals enrolled, four of these individuals completed the study. One participant withdrew from the study, and one additional participant was a screen fail as their Fugl Meyer Assessment of Motor Recovery (UEFMA) score was outside of the inclusion criteria. Their demographic and clinical information can be found in Table 5.1.

Table 5.1 Demographic and Clinical Information for Study Participants

Participant ID	Gender	Hemiplegic Side	UEFMA
NJHF01*	M	Left	49
NJHF02	F	Left	40
NJHF03	F	Right	36
NJHF04**	M	Left	64
NJHF05	M	Right	48
NJHF06	M	Left	48

* Participant withdrew, ** Participant was a screen fail due to UEFFMA > 50, see the inclusion criteria.

The inclusion criteria were the following: The participant 1) has sustained a stroke with weakness on only one side of their body. If there has been a stroke previously, there is no residual weakness, impaired range of motion, or spasticity from the previous stroke, 2) is between the ages of 18 and 95, 3) had the stroke at least 6 months prior, 4) has difficulty moving their weak arm but has enough shoulder, elbow, wrist, and hand movement to actively interact with the system, 5) have severe to mild impairments based on UEFMA score≥ 10/66 and ≤ 50/66, 6) have intact cutaneous sensation.

The exclusion criteria included the following: 1) severe increase in tone in their weak arm as determined by study staff, 2) cognitive problems making one unable to follow instructions or attend to the computer for at least 30 minutes, 3) visual problems or spatial neglect making one unable to interact with an entire twenty-four inch computer screen, 4) any other disabling condition (besides stroke) to the affected upper extremity that has caused residual weakness, impaired range of motion, or spasticity, 5) receptive aphasia, 6) not independent in functional activities/mobility prior to stroke, 7) severe arthritis that limits hand and arm movements, 8) has contractures in the upper limb, 9) pregnant women will be excluded from participation in the Transcranial Magnetic Stimulation (TMS) procedure because effects of TMS to an unborn fetus are unknown, 10) a metal implant may exclude from participation in the TMS procedure, 11) a history of prior surgery on the brain or spinal cord, will exclude from participation in the TMS procedure, 12) family history of seizures, 13) medications that lower seizure threshold.

Additionally, all participants were screened by the study Physician at the Kessler Foundation prior to enrolling in the study and participating in the TMS portion of the study. The approved TMS Physician Screen Form can be found in Appendix A.

5.2.2 Transcranial Magnetic Stimulation

Transcranial magnetic stimulation (TMS) is a technology that allows an investigator or clinician to non-invasively and painlessly modify neural activity in a small region of cortical tissue for a brief period of time (< 1 ms). Over the past decade, an increasing number of clinicians and researchers have used TMS in experimental settings to study the effects of various cognitive, perceptual, and motor processes on cortical excitability (Cowey & Walsh, 2001; Walsh & Cowey, 2000). TMS can be delivered in as "Single Pulse" where each pulse or pulse pair is separated by more than 1 second (< 1 Hz.). For the purposes of this study, single-pulse TMS was performed with each pulse separated by 4 seconds.

In this method, an electrical stimulus is delivered through the scalp to elicit a response in the muscle. TMS applied over the motor cortex, will elicit a twitch in the target muscle, and a Motor Evoked Potential (MEP) on electromyography (Klomjai et al., 2015). The MEP amplitude quantifies the corticospinal tract excitability, and an increase in MEP amplitude is interpreted as an increase in excitability (Bestmann & Krakauer, 2015). A simplified view of the mechanism of TMS can be seen in Figure 5.1.

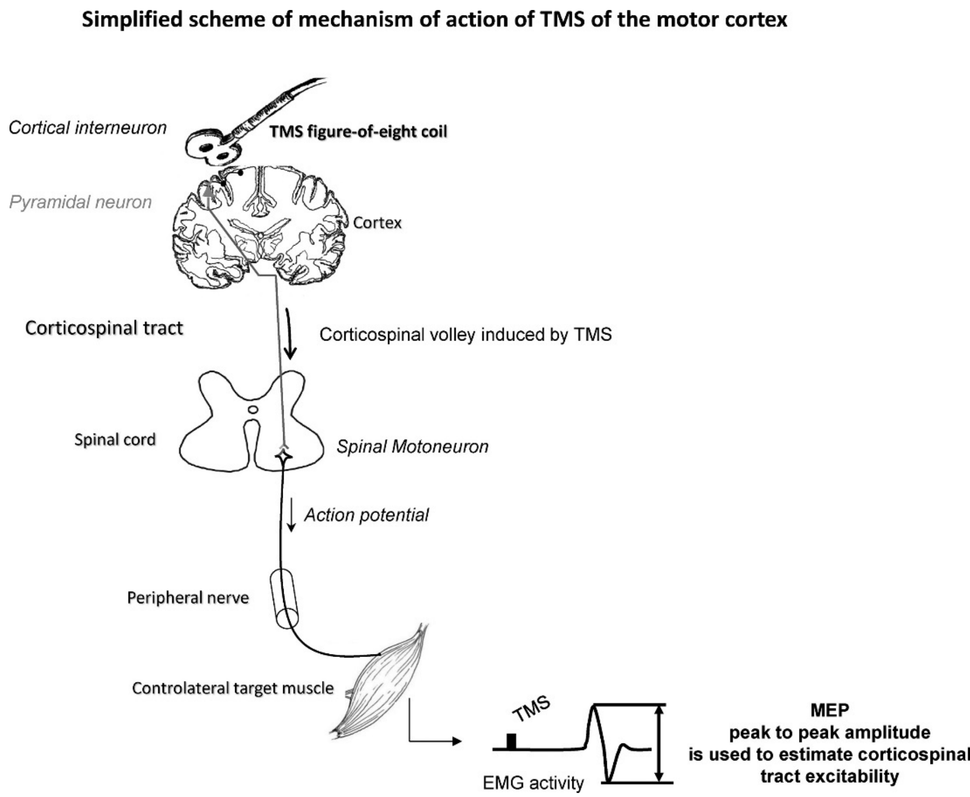

Figure 5.1 Schematic of TMS over motor cortex.

Source: Klomjai, W., Katz, R., & Lackmy-Vallée, A. (2015). Basic principles of transcranial magnetic stimulation (tms) and repetitive tms (rtms). Annals of Physical and Rehabilitation Medicine, 58(4), 208-213. https://doi.org/10.1016/j.rehab.2015.05.005

In this experiment, surface EMG was recorded using a 2 kHz Delsys Trigno system. EMG was collected from finger-hand muscles (first dorsal interosseous (FDI), extensor indicus longus (EI), flexor digitorum superficialis (FDS), and extensor digitorum communis (EDC)). Throughout the TMS procedure, participants were seated with their upper extremity comfortably placed on a pillow on top of a table in front of them. The TMS coil was held tangential to the scalp for all stimuli with the handle posterior 45° off the sagittal plane (Littmann et al., 2013). The hotspot for the contralateral FDI was first determined, and this was defined as the loci which produced the maximal motor evoked potential (MEP) in the FDI muscle. Following this, the resting motor threshold (RMT) was calculated as the minimum intensity required to elicit MEPs >50µV in the FDI muscle in

50% of six consecutive trials (Butler et al., 2005). Stimulation intensity was set to 120% of the determined RMT for stimulation (Bastani & Jaberzadeh, 2012; Christie et al., 2007). During the session, 20-25 stimuli are applied at each time point.

5.2.3 Experimental Protocol

Participants were asked to attend three sessions, separated by one week. During each session, the gripper was used with one method of control (Passive, Active, and ActiveVF). Outcome measures were performed before (Pre) and immediately after (Post) a 30-minute stretching session or 120 cycles of flexion/extension. To determine if and how long priming effects last, in addition to the Post timepoint, two additional time points are added: 30 minutes after stretching (Post 30) and 60 minutes after stretching (Post 60) (Figure 5.2).

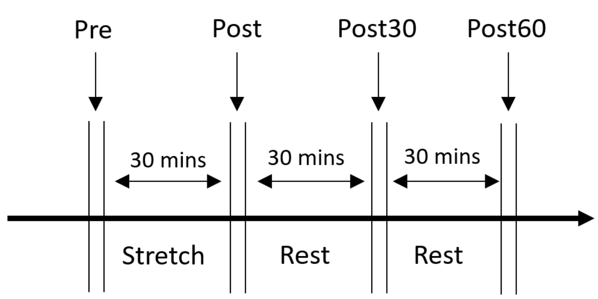

Figure 5.2 Timeline for protocol.

The primary outcome measure for this study was corticospinal excitability as measured by TMS. This stimulation is applied to the motor cortex area for the first dorsal interosseous (FDI) muscle to elicit a muscle response (MEP). The MEP amplitude is evaluated for 20-25 pulses of stimulation. The strength measures include Pinch Strength, Key Pinch Strength, and Grasping Strength, which are measured by a triaxial force sensor. The force sensor has 3D printed components that are attached to modify for each of the strength measures. The kinematic outcome measures are evaluated using the Leap Motion Controller and a custom Unity program. The range of motion for finger flexion/extension, wrist flexion/extension, and forearm pronation/supination were measured. In addition, participants were asked to use each of these movements to trace a sine wave to evaluate the tracing error to determine changes in motor control.

Upon completion of baseline tests, the NJIT Gripper was placed on the participant's impaired hand. Range of motion measures while wearing the NJIT Gripperwere recorded, serving as the limits of movement for the NJIT Gripper. Additionally, a force calibration was performed to remove any bias in the force sensor readings caused by the custom designed 3D printed components of the NJIT Gripper and the participant's fingers on the force sensor. Then the stretching intervention started, and the participant received either 30 minutes of stretching or 120 cycles of flexion or extension, whichever was achieved first. This stretching paradigm was adapted from Fischer et al. (2016) and Triandafilou et al (2011 and 2014) (Fischer et al., 2016; Triandafilou & Kamper, 2014; Triandafilou et al., 2011). Upon completion of the stretching, Post tests were immediately evaluated. The participant then had periods of rest between the Post30 and Post60 timepoints, where outcome measures were assessed again.

5.3 Results

A two-way repeated-measures ANOVA was performed to analyze the effect of Condition (Passive, Active, and ActiveVF) and Normalized Time (Post, Post30, and Post60) on the following outcome measures: Changes from baseline in Pinch Strength, Key Pinch Strength, Grasp Strength, Finger Flexion/Extension Range of Motion, Wrist Flexion/Extension Range of Motion, Forearm Pronation/Supination, Finger

Flexion/Extension Tracing Error, Wrist Flexion/Extension Tracing Error, Forearm Pronation/Supination Tracing Error, and MEP amplitude for FDI muscle. The Kolmogorov-Smirnov test for normality revealed that the following outcome measures were not normally distributed, and nonparametric tests were performed on these: changes from baseline in Pinch Strength, Grasp Strength, Forearm Pronation/Supination Range of Motion, and Wrist Flexion/Extension Tracing Error. Although the MEP amplitude for FDI muscle met the requirements for Normality Testing, it did not meet the requirements for Sphericity (Levene's Test), so a nonparametric test was performed.

The results of the two-way repeated-measures ANOVA (Table 5.2) showed no significant effects of Condition or Time on Key Pinch Strength, Finger Flexion/Extension Range of Motion, Wrist Flexion/Extension Range of Motion, Flexion/Extension Tracing Error, and Forearm Pronation/Supination Tracing Error.

Table 5.2 Results of Two-Way Repeated Measures ANOVA

Source	DF	Mean Square	F- Value	P-Value
Key Pinch Strength				
Participant	3	90.020	3.44	.033
Condition	2	8.319	.32	.731
Time	3	26.624	1.02	.377
Condition*Time	4	8.594	.33	.856
Error	24	24.203		
Finger Flexion/Extension Range of Motion	2	25.705	.34	.721
Participant	2	113.351	1.48	.266
Condition	2	4.043	.05	.949
Time	4	45.097	.59	.676
Condition*Time	12	76.439		
Error				
Wrist Flexion/Extension Range of Motion				
Participant	2	14.71	.14	.869
Condition	2	.277.29	2.69	.108
Time	2	106.5	1.03	.386
Condition*Time	4	326.78	3.17	.054
Error	12	103.16		
Finger Flexion/Extension Tracing Error				
Participant	2	249.132	13.66	.001
Condition	2	52.131	2.86	.104
Time	2	30.899	1.69	.232
Condition*Time	4	4.328	.24	.911
Error	10	18.235		
Forearm Pronation/Supination Tracing Error	2	4.618	.04	.960
Participant	2	21.812	.19	.828
Condition	2	52.317	.46	.641
Time	4	30.5	.27	.893
Condition*Time	13	113.719		
Error				

A Friedman Test was performed on the following outcome measures that did not meet the requirement for normality: Pinch Strength, Grasp Strength, Forearm Pronation/Supination Range of Motion, and Wrist Flexion/Extension Tracing Error. Since MEP amplitude for FDI muscle did not meet the requirements for Sphericity (Levene's Test), a Friedman Test was performed on this outcome measure as well. There were no significant time effects for any outcome measures (Table 5.3).

Table 5.3 Results of Friedman Test

Source	DF	Chi Square	P- Value
Pinch Strength			
Post	2	.50	.779
Post30	2	.50	.779
Post60	2	.50	.779
Grasp Strength			
Post	2	2.00	.368
Post30	2	2.00	.368
Post60	2	.50	.779
Forearm Pronation/Supination Range of Motion			
Post	2	2.00	.368
Post30	2	3.00	.223
Post60	2	2.00	.368
Wrist Flexion/Extension Tracing Error			
Post	2	.67	.717
Post30	2	3.00	.223
Post60	2	2.67	.264
MEP Amplitude FDI Muscle			
Post	2	3.00	.223
Post30	2	1.00	.607
Post60	2	1.00	.607

The individual values for MEP Amplitude for the two participants with reliable MEPs (NJHF05 and NJHF06) can be seen in Figure 5.3. These values were also normalized relative to baseline because the baseline values varied each day, therefore, a negative Post value represents a decrease from baseline.

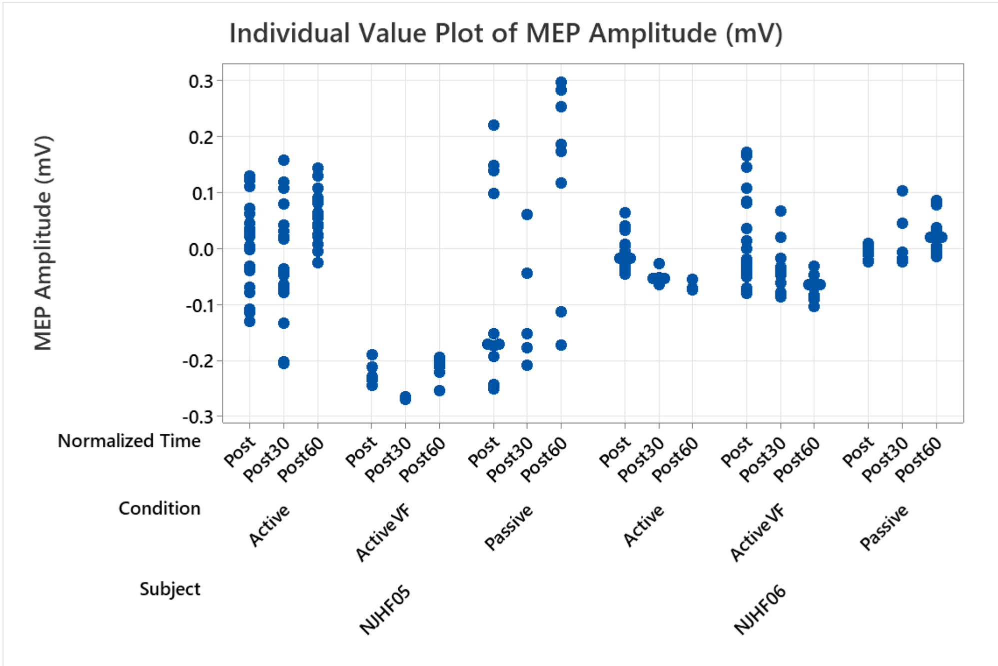

Figure 5.3 Individual value plot of MEP amplitude (FDI Muscle) for NJHF05 and NJHF06.

The Grasping Strength was used as a measure to evaluate fatigue between the active and passive sessions (Figure 5.4). For the Active Session, it is clear that the strength decreases immediately post stretching and returns to baseline at Post30 and Post60. However, we do not see the same trend during the passive stretching session.

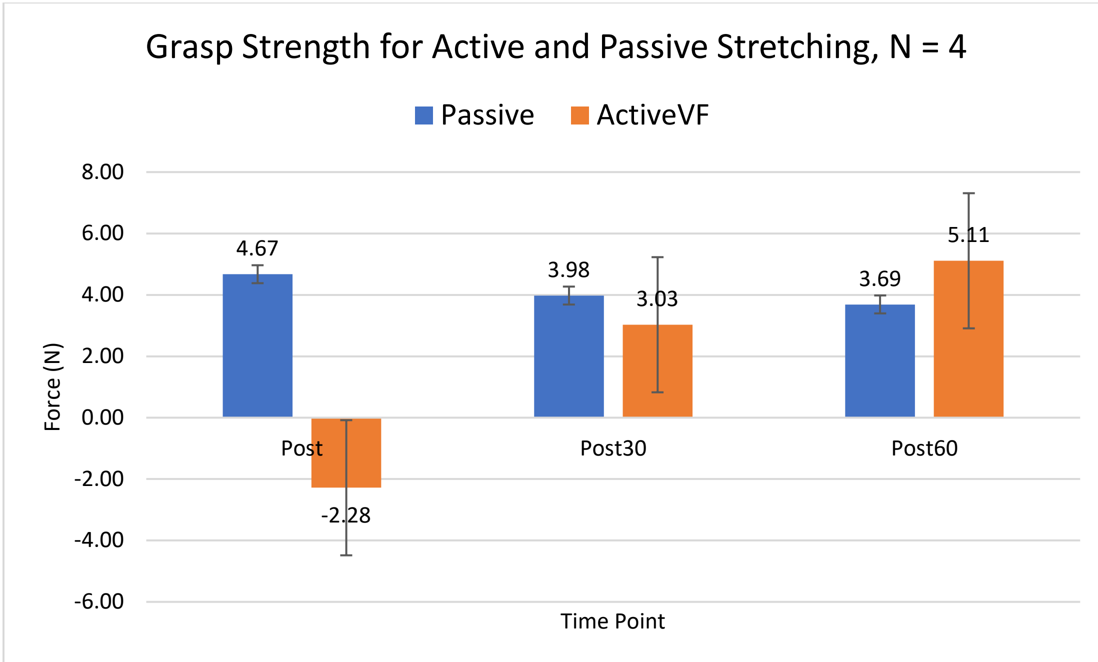

Figure 5.4 Comparison of Active versus Passive Stretching conditions on Grasping Strength across all time points. The force data shown here is the average of all participants (n = 4). For the active condition, the force decreases immediately post stretching, and returns to baseline levels by Post30. Error bars indicate standard error.

5.4 Discussion

Although the experimental sessions were relatively long, the protocol was well tolerated by all study participants. Participants were able to attend each of the three sessions on separate weeks. The kinematic, neurophysiological, and clinical outcome measures did not show any significant differences between the time points (Post, Post30, and Post 60) and/or condition (Passive, Active, ActiveVF); therefore, we cannot determine which condition had the most effect on these outcomes. Based on the results of the Pinch Strength, with the desired power level of 80% and an effect size of .75, six participants would be needed to fully evaluate the effects. For most outcome measures, n = 4, but for the corticospinal excitability, there was only an n of 2. Therefore, additional participants would be needed to determine if excitability was affected. Unfortunately, collecting MEP data from severely to mildly impaired participants was very difficult. Since the NJIT Gripper is designed for those with more severe impairments, the inclusion criteria were specific for individuals with severe to mild impairment as measured by the UEFMA. The more impaired participants either had no apparent motor evoked potentials or their MEPs were too inconsistent to measure reliably. This occurred in NJHF01 (prior to dropping out), NJHF02, and NJHF03. This is an inherent risk of working with individuals with more severe impairments, as the neuromotor pathways may be more damaged as a result of the stroke.

One way to expand the pool of participants would be to broaden the clinical tests for the inclusion criteria. Participant NJHF04, was a screen fail due to his high score of 64/66 on the UEFMA. His impairments were more specific to his hand and not reflected in this score as his proximal movement was almost normal. With the UEFMA there are ceiling effects, and even a score of 66/66 does not translate to fully recovered. He may have benefited from the movement-based priming; however, he was excluded from the study. In the future, it might be better to include the Upper Extremity Fugl Meyer Assessment Hand and Wrist Subscore as the inclusion criteria to be more inclusive of those with distal impairments.

One apparent trend, based on changes in Grasping Strength was that participants were fatigued after the active stretching sessions. For all 4 participants, the Grasping Strength decreased immediately after stretching but returned to baseline after resting 30 minutes post stretching. It is plausible that active stretching would fatigue the muscles while the individuals are actively attempting to extend their fingers. The design of the control scheme with a force limit requires participants to interact as much as possible to extend their fingers. Some participants even mentioned feeling fatigued immediately after the active sessions. This effect was not seen with the passive condition because participants were told to relax their arm as much as possible and allow the NJIT Gripper to open and close their hands.

5.5 Conclusion

The protocol for this pilot study was well tolerated by all participants with chronic stroke. Although it was not possible to recruit enough participants with reliable MEPs to evaluate which condition would have the most significant effect on corticospinal excitability, a few trends emerged. Participants did experience some fatigue after the priming sessions, where they were actively involved in extending their fingers. This information is beneficial when designing a longitudinal study that will include priming with 30 minutes of therapeutic gameplay, as individuals with stroke may not be able to do 30 minutes of stretching followed by 30+ minutes of gameplay.

CHAPTER 6

USABILITY STUDY OF HOME BASED VIRTUAL REHABILITATION SYSTEM

6.1 Introduction

As the NJIT Gripper will be used with the HoVRS system, it was necessary to determine the baseline usability of the HoVRS system prior to adding in the additional technology. We needed to establish usability in this aim prior to using the NJIT Gripper with HoVRS with individuals with stroke. *It was hypothesized that the Home based Virtual Rehabilitation system would score in the acceptable range for usability with individuals with stroke*.

6.2 Background on Home based Virtual Rehabilitation System

The Home based Virtual Rehabilitation System (HoVRS) was developed by researchers at the New Jersey Institute of Technology and Rutgers University to expand access to quality rehabilitation of the hand and arm post stroke (Qiu et al., 2020). In the United States, for in-patient stroke care, therapy for the hand and arm only lasts about 2 to 3 weeks. As outpatients, individuals are typically only seen by therapists 2 to 3 times per week. This rehabilitation volume falls short of what is needed to restore normal hand function. Further, socioeconomic factors such as cost, geographic location, lack of motivation, and transportation create challenges for many individuals preventing them from receiving the amount of rehabilitation they need to recover (Rimmer et al., 2008). Although in the absence of therapists, individuals with stroke are prescribed exercises to perform at home, it has been found that unsupervised home exercise adherence is low (Miller et al., 2017).

Several studies have shown that therapy in the form of video games or virtual reality increases adherence to the rehabilitation plan (Standen et al., 2015; Wittmann et al., 2016). HoVRS was designed to be used by an individual in their home over a period of time to achieve the necessary volume of exercise to elicit recovery while engaging the individual to continue their regimen.

HoVRS is made up of four elements: 1) a commercially available infrared camera designed to capture finger movements, 2) engaging games designed to train the fingers, wrist, and arm, 3) software that monitors and archives data, and 4) a secure wireless data connector to collect data in real-time. The secure channel also allows for video communication between a clinician and an individual with stroke for evaluations as well as troubleshooting assistance if needed. The games are designed to exercise specific therapeutic movements such as: finger individuation, finger flexion/extension, wrist flexion/extension, and forearm pronation/supination. Images of these games and their descriptions can be found in Appendix B.

Our group evaluated HoVRS in two separate studies with promising results. In one study, 15 individuals with chronic stroke were instructed to use the system every weekday for 12 weeks (Qiu et al., 2020). Participants, on average, adhered to the regimen by playing an average of 13.5 hours out of the suggested 15 hours over 12 weeks. Additionally, the group average change in Upper Extremity Fugl Meyer Assessment (UEFMA) increased by 5.2 points, which is higher than the minimally clinically important difference of 4.25.

Another study demonstrated that adherence to the regimen was higher than traditional home exercises (Fluet et al., 2019). The 11 participants performed over 400 unsupervised sessions in their homes with no adverse events. The changes in UEFMA and

Box and Blocks Test (BBT) were statistically significant pre to post, suggesting that the training had an effect on improving function.

6.3 Design of Arm Support for HoVRS

Previous (unpublished) work performed by NJIT and Rutgers University determined the best vertical hand location relative to the infrared motion caption camera for optimal performance. To evaluate this, hands of various sizes and impairment levels were positioned above the LMC at different heights, and data was collected. Kinematic tests were performed, and it was determined that the position that provided the most accurate and reliable position and orientation results was 20 cm above the LMC. Before starting the usability study, an arm support was designed based on these specifications.

The arm support was developed to standardize the positioning of the arm in relation to the LMC. Previous iterations were designed using wooden columns and a wooden base. These iterations were effective for supporting the arm against gravity and allowing for movement, however, we wanted to streamline the manufacturing process. The finalized arm support was designed in Creo Parametric 6.0 software and 3D printed using Onyx, a carbon fiber-reinforced nylon material. This provided a lightweight, yet robust solution to support the arm against gravity and still allow for movement of the hand, wrist, and arm. Two different components were used to support the arm. The first component is a convex shape that allows for the following movements: wrist flexion/extension and forearm pronation/supination. It does not allow for horizontal movements as it keeps the arm in a stable position. For games requiring horizontal movement, a second component with a flat top has been created that allows for the following movements: horizontal movements, wrist flexion/extension, and forearm pronation/supination. These components can be easily changed depending on the individual's level of impairment or what movements are required for the game. These components rest on the columns attached to the base and are designed so that someone with an impaired arm could swap the parts without difficulty. The CAD drawing of the arm support is shown in Figures 6.1 and 6.2.

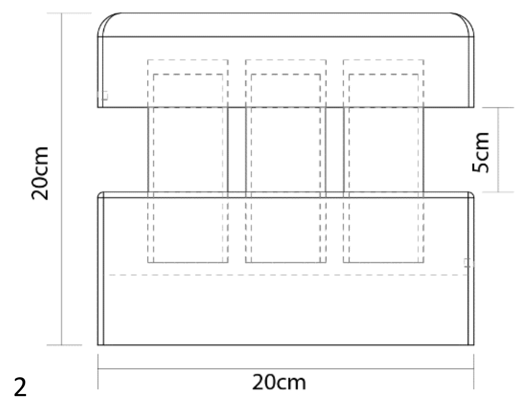

Figure 6.1 CAD Drawing of Arm Support with a flat top.

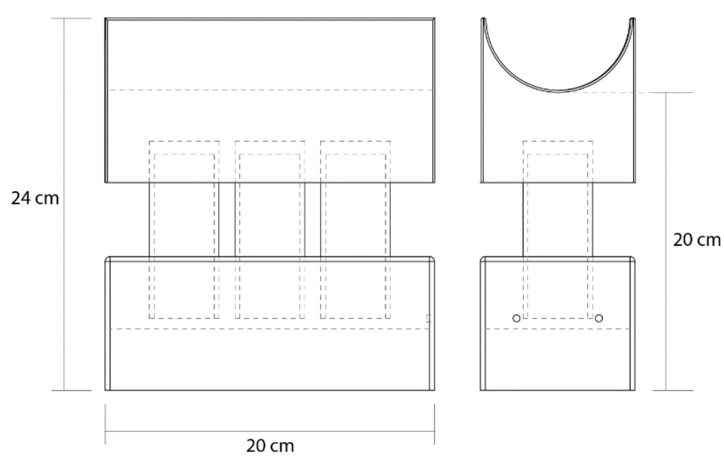

Figure 6.2 CAD Drawing of Arm Support with a convex top.

6.4 Usability Study Methods

For this study, eight licensed therapists and eight individuals with chronic stroke (> 6 months post stroke) were enrolled. The inclusion criteria for therapists were 1) between the ages of 25 and 70 and 2) licensed physical or occupational therapist. For individuals with stroke, the inclusion criteria were 1) between the ages of 20 and 80, and 2) enough shoulder, elbow, wrist, and hand movement to actively interact with the video exergames. The exclusion criteria included the following: 1) severe arm weakness, 2) severe increase in tone, 3) difficulty following instructions or paying attention to computer video exergames for at least 10 minutes, and 4) visual problems that make it difficult for them to interact with an entire computer screen.

The therapists participated in four sessions, and the individuals with stroke participated in three. During the first session, therapists were given training on how to use the web portal, including signing in, creating/adding a patient, choosing a rehabilitation plan, and selecting exergames to prescribe. The rehabilitation plan includes selecting the percentage of the following focus areas: range of motion, coordination, and motor control. These focus areas correspond to specific movement goals of the exergames.

Therapists were also trained to use the system launcher, which allows video conferencing with the individual with stroke. They were trained to calibrate the system and perform remote kinematic assessments. Three exergames focusing on hand, wrist, and shoulder movements were demonstrated so that the therapists could play the exergames first to understand the rehabilitation goals of each game. Finally, they reviewed the progress reports and gave feedback on what they felt was necessary to display in real-time and how they would like to see data shown.

During Session 2, the therapist and individual with stroke were seated in the same room which allowed therapists to help the individual with stroke set up the physical system, which includes a laptop, infrared motion capture camera, arm support, and video conferencing camera (Figure 6.3).

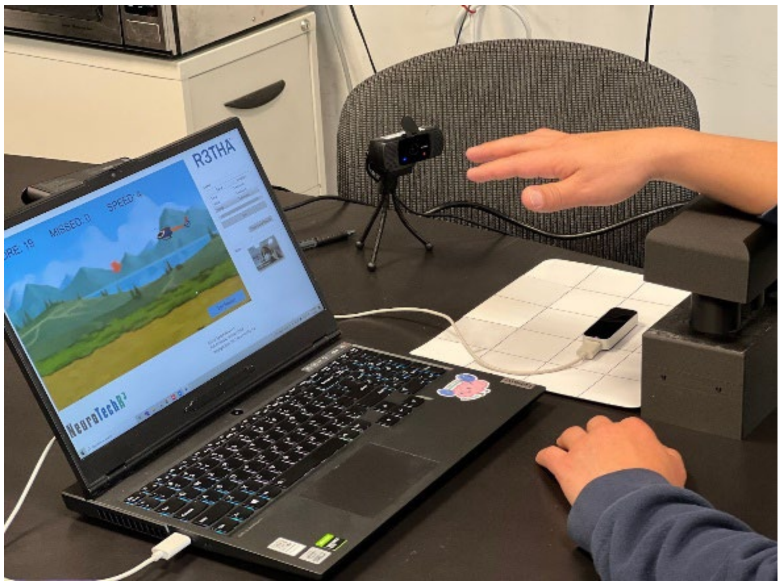

Figure 6.3 HoVRS system set up includes laptop, infrared motion capture camera, arm support, and video conferencing camera.

Source: Mont A., Qiu Q., Cronce, A., Adamovich, S., & Eriksson, M. (2022). Usability assessment of R3THA, a comprehensive rehabilitation tool for hand and arm. Rehabilitation Engineering and Assistive Technology Society of North America 2022 Conference Virtual.

The therapists controlled the individual with stroke's system launcher via a remote desktop application. They then guided the individual with stroke through the calibration, the remote kinematic assessments, and finally, three exergames. During Sessions 3 and 4, the therapist and individual with stroke were seated in separate rooms to simulate the remote nature of the system. They communicated via video conferencing software which allowed them to see each other. The therapist also saw the individual with stroke's hand and arm during the session to ensure that they were performing the correct movements to avoid compensatory movements. They repeated the same steps as Session 2. After completing Session 4, both participants completed a System Usability Survey (SUS).

The individual analysis for each participant's SUS score was performed, and then the median and mean values for the two groups were evaluated. The ten statements on the survey alternate between positive and negative, and each item's contribution (between 0 – 4) must be calculated. The ten statements can be scored from 1 (Strongly Disagree) to 5 (Strongly Agree). Statements can be seen in Table 5.1. For items 1, 3, 5, 7, and 9, the score contribution is the scale position minus 1. For items 2, 4, 6, 8, and 10, the contribution is 5 minus the scale position. Each item's score contributions are then summed and multiplied by 2.5 to achieve the final score, which ranges from 0 – 100 (Brooke, 1996). A higher score is associated with greater usability. We performed three separate SUS calculations based on data from 1) all the participants, 2) only therapists, and 3) only individuals with stroke.

6.5 Results

This survey score demonstrates the overall perceived usability of the system. It is widely accepted that a score of 68 or more means that the device is considered acceptable to use (Lewis, 2018). In this usability study, HoVRS was rated high. The survey score from all participants was 81.8, for only therapists, it was 83, and the score for only individuals with stroke was 80, which all correspond to a system with good usability (Mont A. et al., 2022). We performed further analysis to see the score contribution of individual items for the three groups (Table 6.1).

Table 6.1 System Usability Survey Score Contribution of Individual Items

SUS Analysis Item Statements are scored from 1 (Strongly Disagree) to 5 (Strongly Agree)	**Total Score**	**Therapist Score**	**Stroke Score**
I think that I would like to use this system frequently	4	3	3
I found the system unnecessarily complex	4	4	4
I thought the system was easy to use	3	4	2
I think that I would need the support of a technical person tobe able to use this system	3	3	3
I found the various functions in this system were well integrated	3	3	3
I thought there was too much inconsistency in this system	3	4	3
I would imagine that most people would learn to use this system very quickly	3	3	2
I found the system very cumbersome to use	3	4	3
I felt very confident using the system	3	3	3
I needed to learn a lot of things before I could get going with this system	3	4	3

Source: Mont A., Qiu Q., Cronce, A., Adamovich, S., & Eriksson, M. (2022). Usability assessment of R3THA, a comprehensive rehabilitation tool for hand and arm. Rehabilitation Engineering and Assistive Technology Society of North America 2022 Conference, Virtual.

6.6 Discussion

Overall, the perceived usability of HoVRS as scored by therapists and individuals with chronic stroke was high as each group scored the system over 80. Although the score was high, this does not translate to acceptance in the field by clinicians (Bangor et al., 2008). Therefore, future studies with NeuroTechR3 will be performed in the outpatient clinic to assess the system's usefulness in a less controlled environment.

To further investigate improvements that could be made to the system based on user responses, individual analysis items that fell below a score of 3 were deemed as areas for improvement for the next prototype iteration. Two individuals with stroke scored the following prompts a 2: “I thought the system was easy to use” and “I would imagine that most people would learn to use this system very quickly.” It is important to note that the improvements made to the web portal and launcher were designed with a focus on the therapist’s point of view. These participants with stroke were more severely impaired, and it was difficult for them to interact with the physical system, especially the optional arm support. Some games require the use of the arm support while others do not. Investigations will be performed to evaluate the system's ergonomics because the positioning of the arm support on the table and the individual’s height plays a significant role in comfort.

Two other similar remote hand and arm rehabilitation systems for individuals post stroke used the SUS as an evaluation (Nijenhuis et al., 2015; Rozevink et al., 2021). In these studies, these systems were placed in the homes of individuals with stroke, and the individuals played rehabilitation games for six weeks. The MERLIN system scored 77, and the SCRIPT Program scored 69. HoVRS scored higher on the SUS compared to both systems. We anticipate that the trend will continue when we perform longitudinal studies with HoVRS.

6.7 Conclusions

It is clear that the HoVRS system, in its current development state, was found to be acceptable for use by individuals with stroke and therapists. Compared with other systems in the literature, HoVRS scored higher on the SUS, meaning that there is a higher level of acceptance of the system. Though this was a smaller duration of use, it is anticipated that this trend would continue. This study established the acceptability of the HoVRS system on its own. The next step was to combine HoVRS with the NJIT Gripper.

CHAPTER 7

FEASIBILITY OF PRIMING PRIOR TO INTENSE UPPER ARM AND HAND TRAINING ON KINEMATIC AND FUNCTIONAL OUTCOME MEASURES IN INDIVIDUALS WITH STROKE

7.1 Introduction

This study was designed to be a pilot study investigating the effects of the addition of unilateral movement-based priming into the current protocol using the HoVRS system in the homes of individuals with stroke.

7.2 Methods

Individuals with chronic stroke (> 6 months) were recruited for this study. The inclusion criteria were the following: 1) between the ages of 25 to 80 years old, 2) experienced a unilateral right or left side stroke, 3) no hemi-spatial neglect or severe proprioceptive loss, 4) UEFMA between 9 and 58 / 66. The exclusion criteria were the following: 1) severe arm weakness limiting movement needed to interact with games, 2) severe increase in tone in the weak arm, 3) difficulty following instructions or attending to a computer screen for at least 10 minutes, 4) visual problems that make it difficult to interact with an entire computer screen. To date, one participant has completed this training study, and their Demographic and Clinical information is found in Table 7.1. This participant had moderate impairment measured on Upper Extremity Fugl Meyer Assessment (UEFMA) (Velozo & Woodbury, 2011).

Table 7.1 Demographic and Clinical Information for Participant

Participant ID	Gender	Hemiplegic Side	UEFMA	Time Since Stroke (days)	Age	Dominant Hand
S1	Female	Right	40	1930	67	Right

The training study protocol can be found in Figure 7.1. For this training study, individuals were asked to come to the laboratory to participate in 9 sessions consisting of 30 minutes or 120 cycles of active stretching with the NJIT Gripper, followed by gameplay using the HoVRS system. These sessions occurred 3x per week for the first three weeks. The participants were given a HoVRS system to continue gameplay while at home without stretching. Upon completing the nine sessions of in-person training, the individual continued to use the HoVRS system only (no NJIT Gripper) at home for two additional months (Weeks 4 -11). During these two months, the participant met with the study team virtually every two weeks (Weeks 6, 8, and 10) to see if the participant was having an issue that needed troubleshooting, recalibration, and evaluation of the difficulty levels. Outcome measures were evaluated prior to starting the training study (Pre), upon completion of the lab-based training sessions (Mid), and upon completion of the two additional months using HoVRS at home (Post).

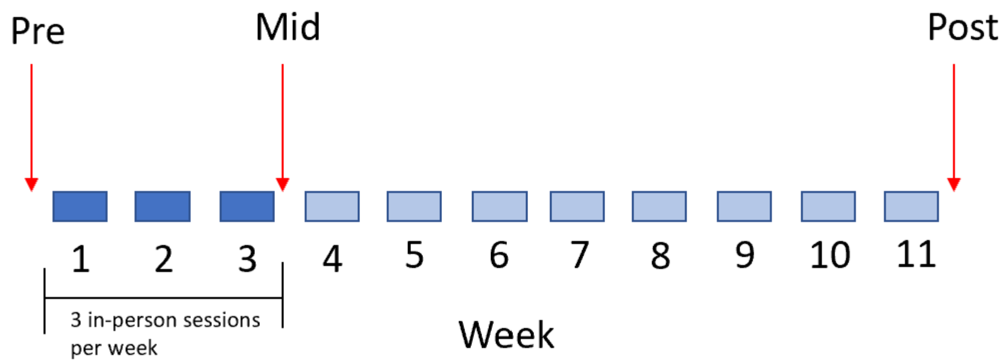

Figure 7.1 Study Protocol. Participants came to the laboratory for 9 in person training sessions - 3x per week for the first week. The participants used the HoVRS system only in their homes for weeks 4 – 11, with video conference check-ins during Week 6, 8 and 10.

The Leap Motion Controller was used with a custom-written program in Unity to perform kinematic measurements. The kinematic outcome measures were Finger Flexion/Extension Range of Motion, Wrist Flexion/Extension Range of Motion, Forearm Pronation/Supination, Finger Flexion/Extension Tracing Error, Wrist Flexion/Extension Tracing Error, and Forearm Pronation/Supination Tracing Error (Methods from Qiu et al., (2020)).

A licensed physical therapist evaluated the clinical outcome measures, and they included: 1) Fugl Meyer Assessment Upper Extremity (UEFMA), which evaluates and measures recovery in post-stroke hemiplegic individuals, 2) Box and Blocks Test (BBT) which assesses unilateral gross manual dexterity, and 3) Action Research Arm Test (ARAT) which assess upper limb function using observational methods.

The duration of time that participants played each game and how often they played each game were also analyzed. Participants were asked to complete the System Usability Survey, which demonstrates the overall perceived usability of the system.

The games the participant was assigned to play along with the corresponding therapeutic movement can be found in Table 7.2.

Table 7.2 HoVRS Game and Corresponding Movements

Game	**Movement(s)**
Breakout	Forearm Pronation/Supination
Car	Finger Flexion/Extension and Forearm Pronation/Supination
Pitch (Fly)	Wrist Flexion/Extension
Finger (Fly)	Finger Flexion/Extension
Maze	Full arm movements

7.3 Results

The outcome measures were evaluated at baseline after the nine in-person stretching+ gameplay ended and after two additional months of HoVRS only. It is important to note that the Pre and Mid testing timepoints were performed earlier in the day compared to the Post time point due to scheduling conflicts. The participant mentioned that she had an active morning, and she was using her hand. She also stated that on certain days her hand feels more stiff, and this was one of those days. The kinematic data includes range of motion data as well as root mean square error during tracing controlled by hand, and arm movements. The range of motion for finger flexion/extension, flexion/extension of the wrist, and pronation/supination of the forearm were evaluated (Figure 7.2). We attribute the decrease below the baseline values for Finger Flexion/Extension due to the stiffness the participant was experiencing that day in addition to the later time of tests.

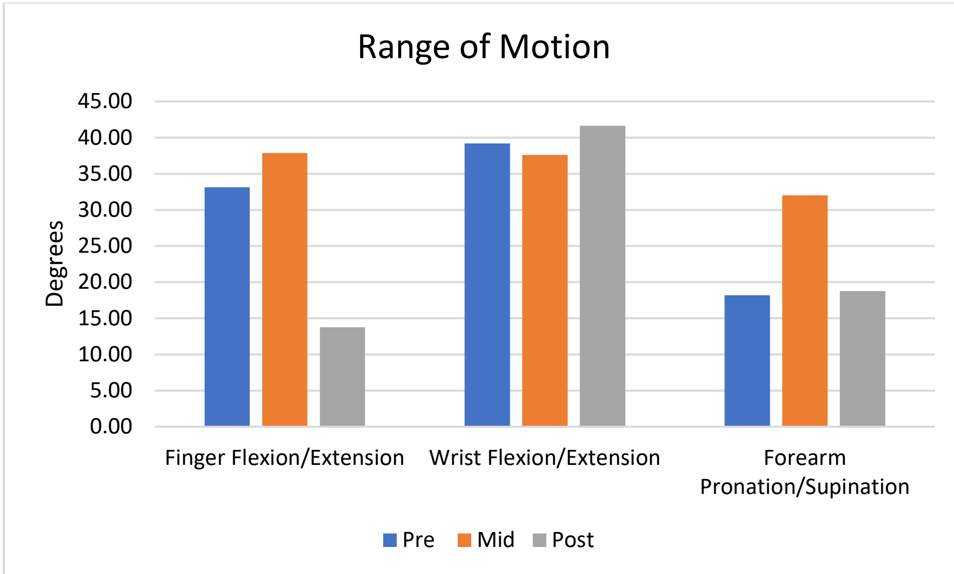

Figure 7.2 Range of Motion for finger flexion/extension, wrist flexion/extension, and forearm pronation/supination.

To evaluate the tracing of the sine wave, the root mean square error was calculated (Figure 7.3). For the Post test, the participant's hand was very stiff on this particular day and their fingers had minimal movement, and while the LMC could pick up the range of motion, the movement was not large enough to provide a trace on the screen. Therefore, there is no data for that session. The Wrist Flexion/Extension error decreased over time.

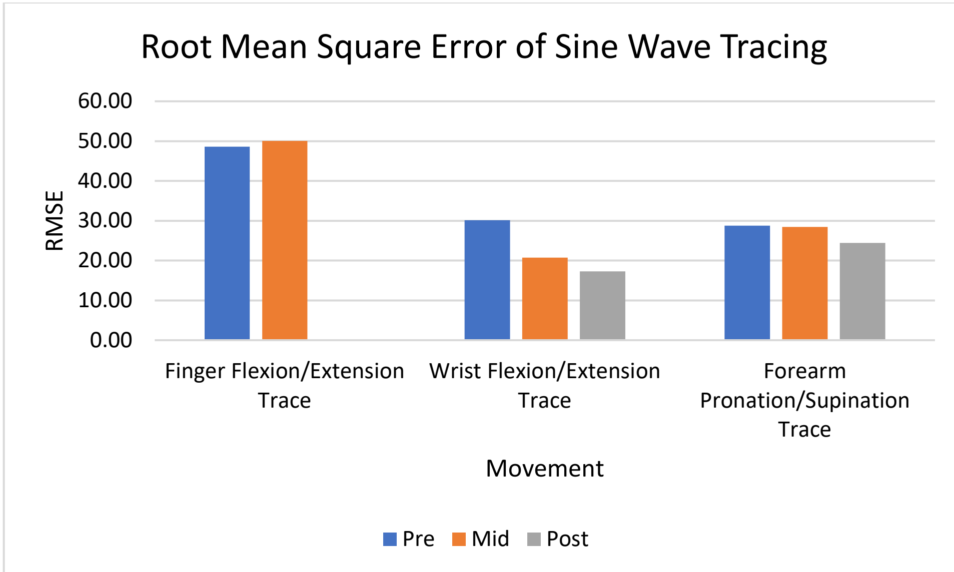

Figure 7.3 Tracing error for finger flexion/extension, wrist flexion/extension, and forearm pronation/supination.

The clinical outcome measures were evaluated at each time point and are displayed in Table 7.3. For this case study, we wanted to compare the clinical outcomes of this participant to the group averages of the participants in the ongoing HoVRS study that does not include movement-based priming. These results can be seen in Table 7.4. At baseline, the participant was within range for the UEFMA, but the BBT and ARAT scores were lower. The goal of the inclusion of the NJIT Gripper into HoVRS is to be more inclusive of individuals with more severe impairment. A subset of HoVRS participants were evaluated and compared with the participant in this study (Table 7.5).

Table 7.3 Clinical Outcome Measures

Clinical Outcome Measure	Pre	Mid	Post
UEFMA	40	39	43
BBT	6	13	5
ARAT	12	14	15

Table 7.4 Group Average of Clinical Outcomes of HoVRS Study Without Priming, n = 28

Clinical Outcome Measures	Baseline	Post
UEFMA	41.53	47.95
BBT	15	18.84
ARAT	26.16	30.63

Table 7.5 Subset of HoVRS Participants Matched by Age and Time Post Stroke to S1.

Participant	Age	Gender	Time Post Stroke	Δ UEFMA	Δ BBT	Δ ARAT
S1	67	F	6 years	3	-1	3
HoVRS 1	65	F	1.2 years	7	5	7
HoVRS 2	63	F	1 year	7	1	0
HoVRS 3	74	M	7 years	5	0	11
HoVRS 4	45	M	5 years	5	5	11

The changes in EUFMA, which evaluates and measures recovery in post-stroke hemiplegic individuals, can be seen in Figure 7.4. The changes in BBT, which assesses unilateral gross manual dexterity, can be seen in Figure 7.5. This assessment was completed for both impaired and unimpaired hands (Figure 7.6). The ARAT score, which is an assessment of upper limb function, can be seen in Figure 7.7.

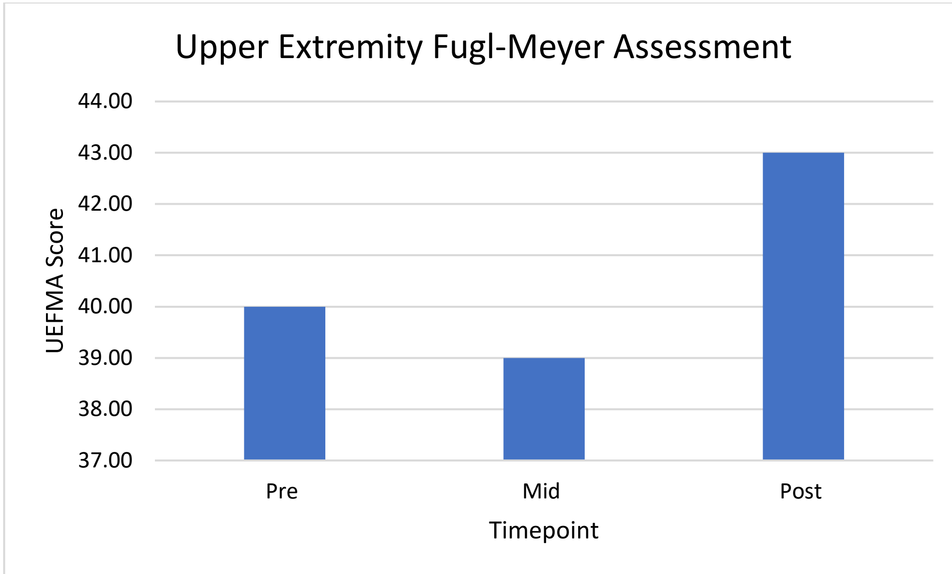

Figure 7.4 Upper Extremity Fugl-Meyer Assessment Score over time.

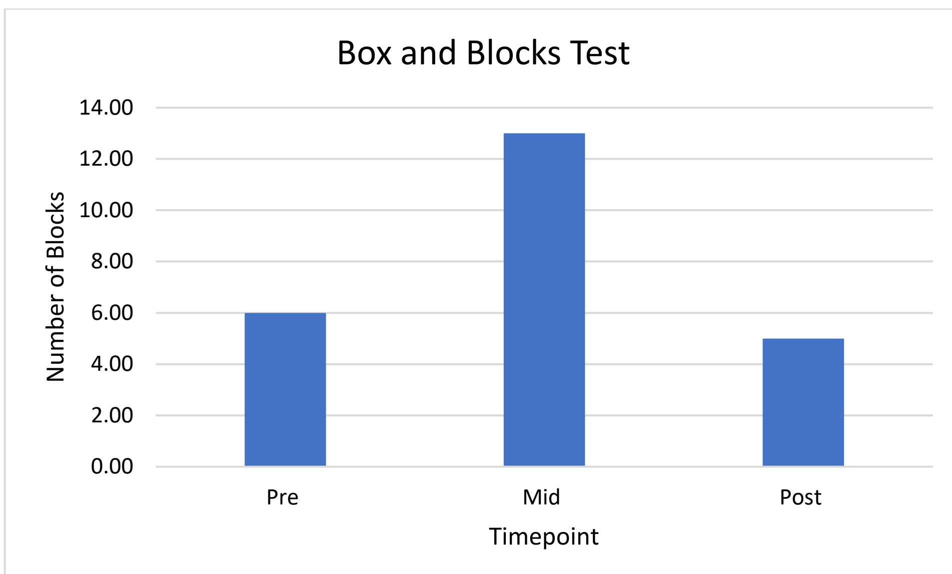

Figure 7.5 Box and Blocks Test score over time. This test is evaluated by the number of blocks the participant is able to pick up in 1 minute.

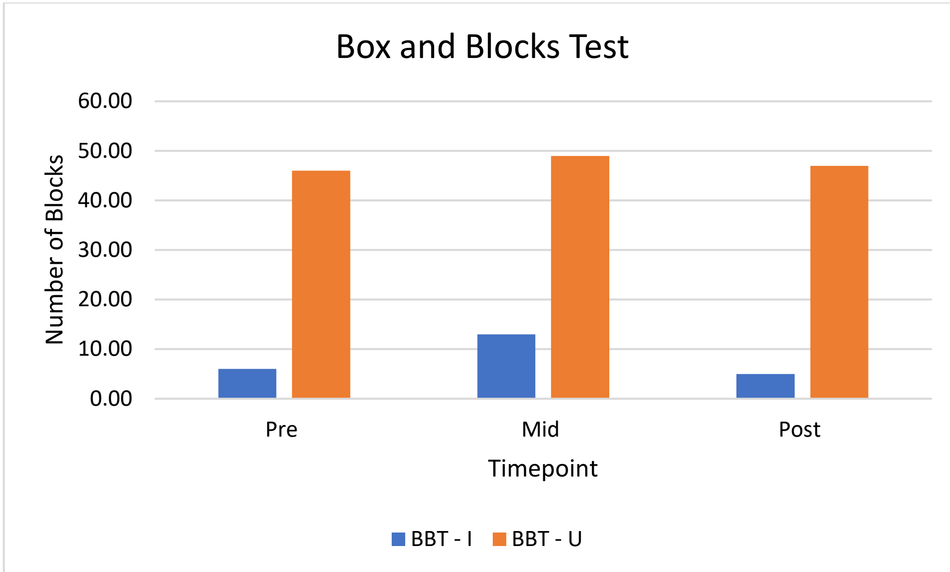

Figure 7.6 Box and Blocks Test score over time for impaired hand (blue) and unimpaired hand (orange).

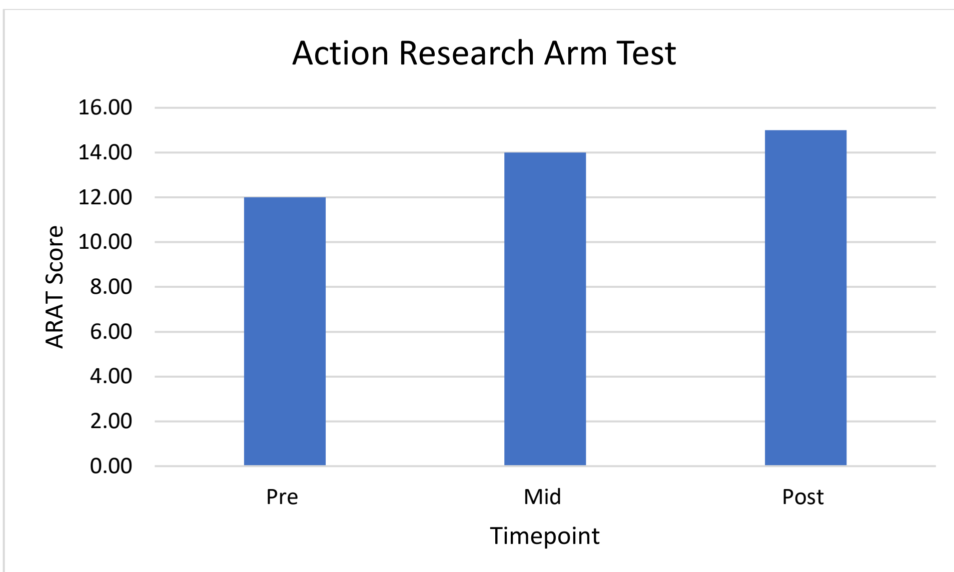

Figure 7.7 Action Research Arm Test score over time.

The participant played HoVRS games post stretching during the nine visits to the laboratory and was instructed to play the HoVRS games at home on the days that they were not training. Upon completion of the in-person training, the participant continued to play the HoVRS games unsupervised at home. The total gameplay duration for each game can be seen in Figure 7.8. The participant played a total of 756 minutes during the 11-week study. In Figure 7.9, the duration of gameplay each week is broken down by the period of time each game was played.

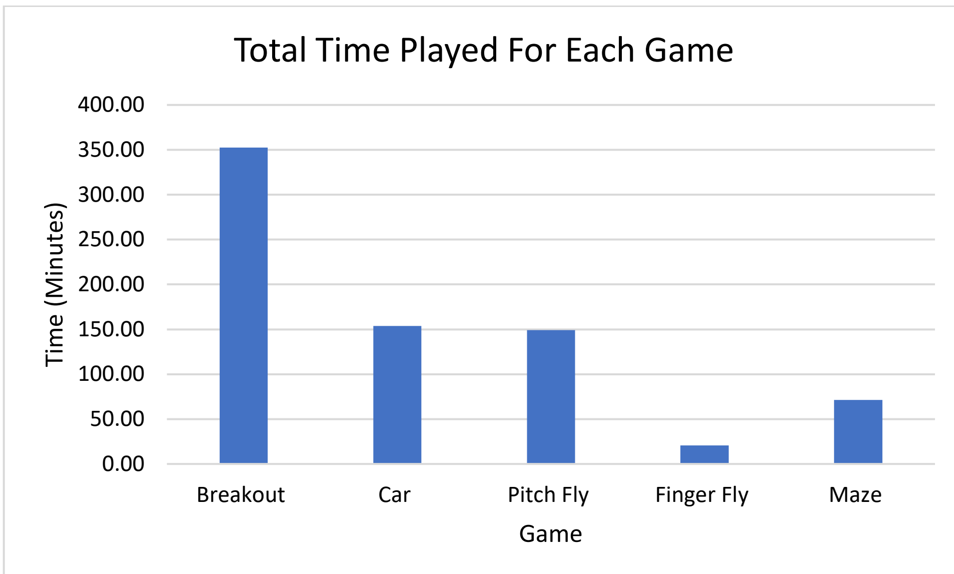

Figure 7.8 Total time played in minutes for each game for the total duration of the study.

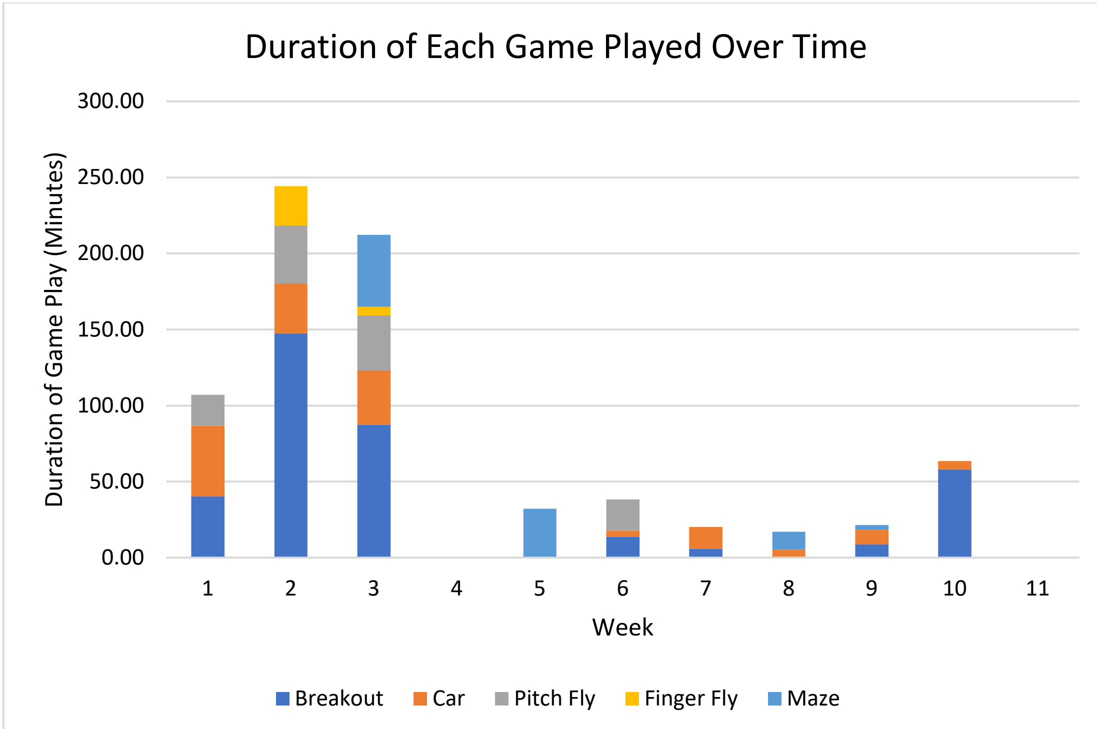

Figure 7.9 Duration of gameplay for each game over the 11-week study. The majority of the gameplay occurs during the in-person training during Weeks 1-3**.**

The results of the System Usability Survey can be found in Table 7.5. The ten statements can be scaled from 1 (Strongly Disagree) to 5 (Strongly Agree) and are calculated as follows: for items 1, 3, 5, 7, and 9, the score contribution is the scale position minus 1 and for items 2, 4, 6, 8, and 10, the contribution is 5 minus the scale position. Each item's score contributions are then summed and multiplied by 2.5 to achieve the final score, ranging from 0 – to 100 (Brooke, 1996). A higher score is associated with greater usability. The score for both time points was 85.

Table 7.6 System Usability Survey Scores

SUS Analysis Item Statements are scored from 1 (Strongly Disagree) to 5 (Strongly Agree)	**Mid**	**Post**
I think that I would like to use this system frequently	5	5
I found the system unnecessarily complex	1	1
I thought the system was easy to use	5	5
I think that I would need the support of a technical person to be able to use this system	**4**	**3**
I found the various functions in this system were well integrated	4	4
I thought there was too much inconsistency in this system	**1**	**2**
I would imagine that most people would learn to use this system very quickly	4	4
I found the system very cumbersome to use	4	1
I felt very confident using the system	4	4
I needed to learn a lot of things before I could get going with this system	1	1

7.4 Discussion

For this case study, the kinematic data demonstrate that the participant had an increased range of motion for wrist flexion/extension. In addition, the root mean square error for tracing for the wrist flexion/extension movement demonstrates an improvement change of 12.84 from Pre to Post. The participant stated that she felt the system had the most effect on her wrist and thought the improvements translated to her everyday tasks. For the forearm pronation/supination range of motion, there was a large increase from Pre to Post with a difference of 13.84 degrees. During the in-person training, the games that the participant played the most, Breakout and Car, primarily focused on pronation and supination of the forearm. This improvement disappears after the Mid time point, as does the amount of gameplay when the participant was unsupervised (Weeks 4 – 11).

The change in score for the UEFMA did not change by more than the minimal detectable change (MDC) of 5.2 points. Although the score improved by 3 points, it was not higher than the MDC, and therefore it can be determined that the participant's level of impairment stayed the same through the 11 weeks of the study (Wagner et al., 2008). For the BBT between Pre and Mid, for the impaired hand, this was improved by 7 blocks which is higher than the MDC of 5.5 blocks (Chen et al., 2009). This effect did not last at the Post time point, and the score decreased by 8 blocks. When the data is normalized between the impaired and unimpaired hand, the number of blocks between the Mid and Post time point is 6, which is still larger than the MDC. This trend follows the decrease in gameplay after in-person training ends. For the Action Research Arm Test, the participant continued to improve at each time point, and the change between Pre and Post was 3 points which is the MDC for this evaluation (Simpson & Eng, 2013). This improvement did not meet the Minimally Clinically Important Difference (MCID) of 5.7 points (van der Lee et al., 2001). However, there was a positive trend for improvement. This measure continued to improve, even as gameplay duration decreased.

The duration of participation was similar when comparing this participant to the group averages for the HoVRS study without priming. These participants used the system exclusively at home for 12 weeks, but this study slightly differed in that it consisted of three weeks of training with an additional eight weeks of HoVRS unsupervised. The baseline measure for UEFMA is similar between this participant and the HoVRS group, but the BBT and ARAT scores are much lower, demonstrating that the upper limb function and unilateral gross manual dexterity are more impaired. The BBT improvement from Pre to Mid (7 blocks) is greater than the HoVRS group (3.84 blocks), which might suggest that the priming through stretching for only 3 weeks may have affected the gross manual dexterity. This participant did meet the MDC, while the HoVRS group average did not. The 3-point increase on the ARAT score follows the same trend as the HoVRS group (4.5 point increase), even though the participant started at a much lower score. This reflects that the system was able to induce a detectable change in a more severely impaired participant. To further investigate, we also evaluated a subset of HoVRS participants that were close in age, time post stroke, and impairment level to S1, and the trends for improvement were similar (Table 7.5). For this subset, the average impairment level as measured by UEFMA was 37. The average BBT score was 5.75 and the average ARAT score was 17.25. These clinical baseline levels were similar to S1. For the BBT, the change for S1 from baseline to the Mid point, of 7 blocks was higher than this subset of HoVRS participants. The gains made by S1 in UEFMA and ARAT follow the same trend, but they are not as significant.

Clinical results are similar to those in Aguiliera-Rubio et al. (Aguilera-Rubio et al., 2022). In this study, individuals with chronic stroke participated in a study using the Leap Motion Controller and virtual reality games designed for similar shoulder, wrist, elbow, and finger movements. Participants received two 60-minute sessions for eight weeks, with 30 minutes of traditional therapy and 30 minutes of virtual reality gameplay. Their group (n = 10) average demonstrated a 2-point increase in ARAT, and a BBT improvement of 6.5 blocks, which is similar to this case study.

From the game duration data, it is clear that the participant played the game more during the weeks of in-person training (Weeks 1-3). The participant would perform 30 minutes or 120 cycles of flexion/extension of the fingers with the NJIT Gripper and then participate in gameplay. During each of these weeks, there were over 100 minutes of gameplay. When the participant was using the HoVRS system only unsupervised, the amount of gameplay dropped to ~32 minutes per week during the weeks played. The participant did not participate in any gameplay during Week 4 and Week 11 due to starting a new job in Week 4 and a family emergency during Week 11. Perhaps there would have been a stronger trend from Pre to Post for the clinical outcome measures had the participant kept to the same amount of gameplay as during Weeks 1-3.

The total amount of gameplay was 756 minutes or 12.6 hours. The game that the participant played the most was Breakout which focused on pronation/supination of the forearm. The second most played game was the Car game which focused on finger flexion/extension and pronation/supination of the forearm. The participant reported that she felt the most improvement in her wrist rotation and lifting, which correlates to the active movements she performed the most.

The participant was asked to complete a System Usability Survey at the Mid and Post time points. For the Mid time point, the participant was instructed to evaluate the NJIT Gripper + HoVRS system, and for the Post time point, they were only evaluating the HoVRS system. Both surveys scored an 85, demonstrating high acceptability of the system. There were changes to only two statements. On the Post survey, the participant rated the following statement at a lower score "I think that I would need the support of a technical person tobe able to use this system." This means that she disagreed with that statement more than she previously did, suggesting she felt less likely to need the support of a technical person to use the system. The statement score that improved was "I thought there was too much inconsistency in this system," meaning that she slightly agreed that there was inconsistency in the system. The participant stated that she felt the calibrations were "off" some days due to how stiff her hand was that particular day, and as a result, some of the game settings were not appropriate. The system was not recalibrated each day; it was only recalibrated every two weeks during the video session. These inconsistencies that the participant felt could be resolved if there was an easier way for the participant to recalibrate the system on their own.

7.5 Conclusion

The participant attended 100% of the in-person priming and gameplay sessions demonstrating high adherence. The three times a week for three weeks paradigm was well tolerated by the participant, as she did not report any soreness or discomfort. The participant did see improvements in the range of motion for wrist flexion/extension and control over those movements. There were trends for improvement on the UEFMA as well as the ARAT even though the participant used the system less during the weeks after the in-person sessions ended. This suggests that the protocol would be reasonable if performed for a more extensive study. Future work could include the participant using the NJIT Gripper unsupervised with the HoVRS system for a fully independent rehabilitation plan.

CHAPTER 8

SUMMARY AND CONCLUSION

8.1 Clinical Relevance

Robotic exoskeletons can be useful for clinicians treating individuals with stroke or other neuromuscular disorders. However, many are too expensive for the traditional clinic to purchase. Exoskeletons like the NJIT Gripper could be used in the clinic to provide methods of motor priming prior to a therapy session, as this project has established that it is low cost, easy to use, and well tolerated by individuals with moderate impairment due to stroke. The participants in these studies were not intimidated by the technology and felt that this could be adopted into their therapeutic routines if given the opportunity. This perception of high usability was reflected in the scores of the System Usability Survey for both the HoVRS system and HoVRS with priming.

The case study reflected trends for clinical improvement, especially during the time that the participant was attending the in-person visits. This demonstrates that even at ~6 years post stroke, the individual could make functional improvements when sticking to a therapeutic regimen. Although the participant played the games less once the in-person sessions ended, they continued to make gains even from the decreased amount of gameplay. If this participant could continue to use the system regularly in their home, it is possible that they would make more clinically significant gains.

It is also possible that this device could be used in research studies to provide assistance during hand training sessions in the clinic. For example, in our current clinical trial that takes place at the inpatient hospital, the CyberGrasp robot is used for more severely impaired participants to allow them to participate in training (Merians et al., 2020). The CyberGrasp moves the individuals' fingers while they are relaxed, the NJIT Gripper would provide the added benefit of active participation.

8.2 Limitations

The limitation that had the largest impact on this work, especially in the studies described in Chapters 5, 6, and 7, was the COVID-19 pandemic which began in March 2020. This not only impacted the ability to conduct studies, but it severely impacted recruitment. The research laboratories and rehabilitation hospital were shut down for many months, only to open and shut back down with local outbreaks in New Jersey, forcing all human research studies to halt completely. Even when the laboratory and rehabilitation hospital was open, there were several delays due to staff and participant quarantines. The most significant impact was on participant recruitment. Although appropriate safety precautions were put in place by the New Jersey Institute of Technology and the Kessler Foundation, participants were afraid to participate in person for fear of contracting the virus. Padala et al., (2020) investigated this issue of perceptions of safety with current study participants and their caregivers and found that "even though informants felt that the medical center was prepared to handle the pandemic, only half the participants preferred the in-person visit" (Padala et al., 2020). Of the individuals that were contacted for recruitment in the study in Chapter 5, only 30% were interested in enrolling in the study, and the other 70% cited concerns about COVID-19. Even though all safety protocols were in place, those with disabilities were unwilling to put themselves at undue risk by participating in clinical research studies in person. The difficulties associated with recruiting during a pandemic is the main reason for the low number of participants.

Another limitation specific to the study described in Chapter 5 was the use of Transcranial Magnetic Stimulation as the primary outcome measure. We were only able to measure reliable motor evoked potentials in two participants, which is an inherent risk of working with severely to mildly impaired individuals with chronic stroke. We are seeing this trend in our other ongoing studies that utilize TMS. In the future, it may be beneficial to evaluate the priming conditions with individuals with mild impairment to see if they have more reliable MEPs. We are also investigating other methods such as EEG to noninvasively evaluate the brain.

8.3 Future Work

In order to fully integrate the NJIT Gripper into a home system, slight modifications would need to be made to the design. A motor with higher stall torque would be used for those with larger hands or more spasticity. The motor that was chosen in the current design was a balance between size, weight and performance as it was necessary to fit on the back of the hand. Further investigation into smaller and stronger motors on the market would be done. Additionally, a graphical user interface would be created to allow for self calibration of the device. In the current state, the engineer or therapists would need to perform the calibrations, however, this could be programmed to allow a caregiver or the individual with stroke the capability to do it.

Future work will also expand the game library to include games that allow interaction with the NJIT Gripper to provide haptic feedback. The admittance control scheme of the NJIT Gripper has been converted from MATLAB to C# and was integrated into one game that provides haptic feedback, however, it has not yet been evaluated with individuals with stroke. This would allow individuals with more severe impairment to play the HoVRS games as it will provide the assistance, they need to perform the intended therapeutic movement. A laboratory-based study would be sufficient to determine the feasibility of playing 30 minutes of games with the NJIT Gripper on the hand prior to placing the NJIT Gripper in the homes of individuals with stroke.

By performing a longitudinal study that compares the effect of HoVRS+Movement-Based Priming with HoVRS only for three months we could determine if there is an added benefit to priming. The case study demonstrated that the participant made the most gains when performing active stretching three times a week. Therefore, it is hypothesized that continued use would result in continued improvements. This study will allow investigators to determine if there is a benefit to using movement-based priming in combination with the home system and how long the effect may last.

APPENDIX A

KESSLER FOUNDATION TMS SCREENING FORM

Figures A.1 to A.2 show the Approved TMS Physician Screening form.

R-1131-20 **Effects of Motor Cortex Priming on Hand and Arm Function Post Stroke**
Screening Visit   Subject ID _ _ _ _   Date _ _/_ _/_ _ _ _

	TMS physician screen form	YES	NO
1.	Have you ever had a seizure	☐	☐
2.	Family history of epilepsy (first degree biological relative with diagnosis of epilepsy)	☐	☐
3.	Aneurysm clips or coils	☐	☐
4.	Cardiac pacemaker or wires	☐	☐
5.	Internal cardioverter defibrillator	☐	☐
6.	Carotid or cerebral stents	☐	☐
7.	deep brain stimulators	☐	☐
8.	Metallic devices implanted in your head	☐	☐
9.	Dental implants	☐	☐
10.	Cochlear implants / ear implants	☐	☐
11.	Cerebrospinal (CSF) shunt	☐	☐
12.	Eye implants	☐	☐
13.	Cardiac stents, filters or metallic valves	☐	☐
14.	Tattoo	☐	☐
15.	Vagus nerve stimulator (VNS)	☐	☐
16.	Blood vessel coil	☐	☐
17.	Shrapnel, bullets, pellets, BB's or other metal fragments	☐	☐
18.	Wearable cardioverter defibrillator	☐	☐
19.	Implanted insulin pump	☐	☐
20.	Programmable shunt or valve	☐	☐
21.	Hearing aid	☐	☐
22.	Cervical fixation devices	☐	☐
23.	Surgical clips, staples, or sutures	☐	☐
24.	VeriChip microstransponder	☐	☐
25.	Wearable monitor (e.g. heart monitor)	☐	☐

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Figure A.1 Kessler Foundation TMS Physician Screening Form.

Screening Visit Subject ID _ _ _ _ Date __/__/____

26.	Bone growth stimulator	☐	☐
27.	Wearable infusion pump	☐	☐
28.	Radioactive seeds	☐	☐
29.	Portable glucose monitor	☐	☐
30.	Tracheostomy	☐	☐
31.	Medication patch / nicotine patch	☐	☐
32.	Other implanted metal or device if yes, please specify:	☐	☐
33.	Damaged scalp due to trauma or surgery, skull defects,	☐	☐
34.	Are you pregnant?	☐	☐
35.	Significant medical problems such as hypertension, diabetes mellitus, pulmonary or airway disease, heart failure, coronary artery disease, or any other related condition	☐	☐
36.	Have you ever been a machinist, welder or metal worker?	☐	☐
37.	Have you ever had a facial injury from metal and/or metal removed from your eyes?	☐	☐

Is participant cleared to participate in TMS portion of the study? yes ☐ no ☐

Physician name and signature ______________________

Date __/__/____

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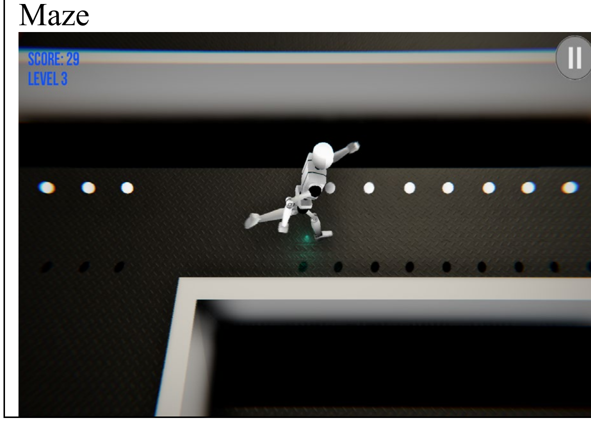
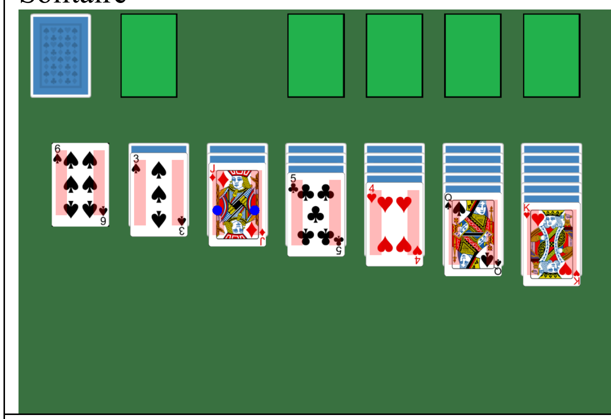
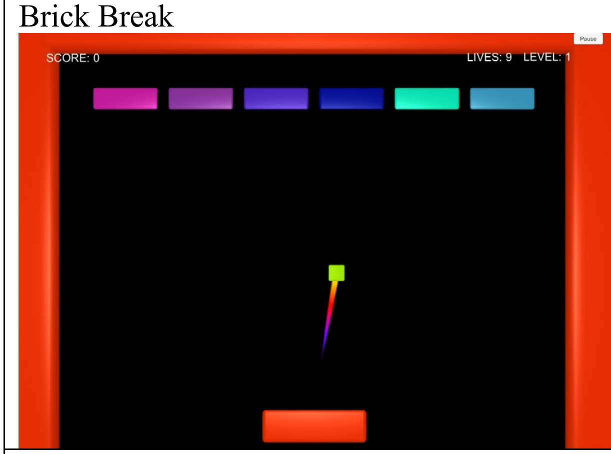
Figure A.2 Kessler Foundation TMS Physician Screening Form Continued.

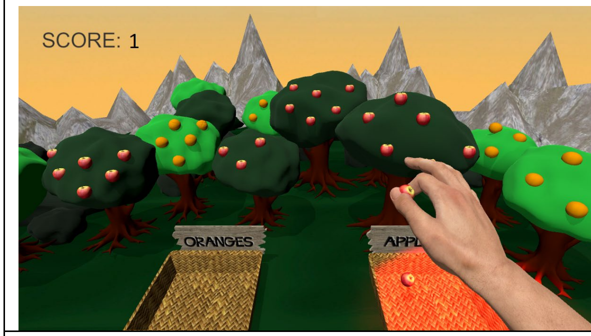
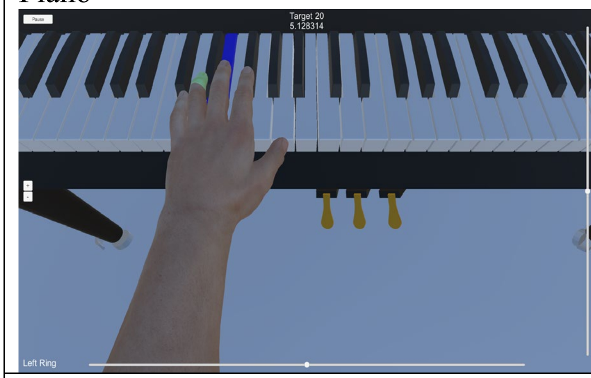
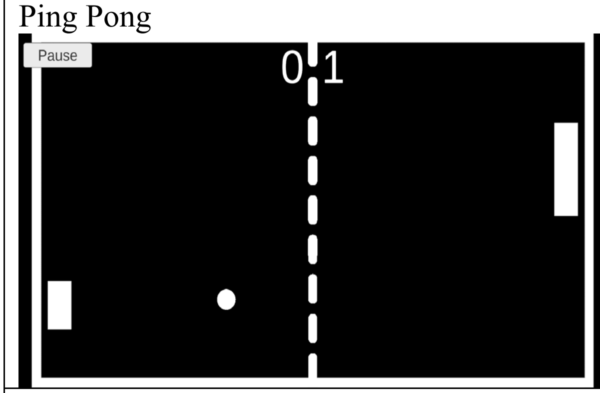
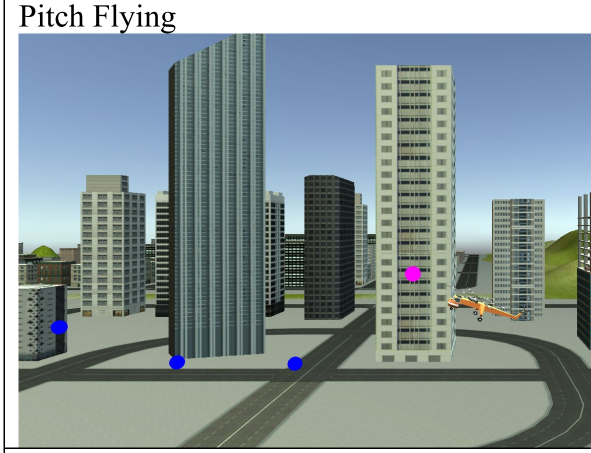
APPENDIX B

HOME BASED VIRTUAL REHABILITATION SYSTEM GAMES

Table B.1 HoVRS Library of Games with Descriptions

Game	Description	Movement
Car 	Player controls the speed of the car by opening and closing their hand. Pronation/supination changes lanes to avoid obstacles and collect coins.	Hand opening, pronation/supination
Finger Flying 	Player controls pitch of the helicopter to reach targets by opening and closing their hand.	Hand opening
Maze 	Direction of the running character is controlled by horizontal plane reaching.	Arm movement in the horizontal plane

3d Flying (Arm) 	Player controls the roll, pitch, and yaw of the helicopter with wrist movements.	Arm movement to control the helicopter position. Wrist extension/flexion, radial/ulnar deviation, pronation/supination to rotate the plane.
Solitaire 	Player controls the mouse movement by moving their arm in the vertical plane and pinches to select and release cards.	Arm movement in the vertical plane, index/thumb pinch
Brick Break 	Player moves their wrist to control paddle movement in order to hit the ball and knock down blocks.	Radial/ulnar deviation
Fruit Catch 	Player moves their arm to control basket movement and practices pronation/supination to catch fruit and drop them in the basket.	Arm movement in the horizontal plane, pronation/supination

Fruit Pick 	Player moves their arm to move within proximity of fruit trees and pinches their index and thumb to grab the fruit.	Arm movement, index/thumb pinch
Piano 	Player practices finger individuation of the selected finger to hit the highlighted piano key.	Finger individuation
Ping Pong 	Player controls the paddle to prevent the ball from passing and tries to score against the PC (or a local opponent)	Wrist extension flexion or arm raising
Pitch Flying 	Player controls a helicopter. They control the rotation and vertical position based on wrist extension/flexion to collect the objects on screen.	Wrist extension flexion
Bowling	Player controls a virtual hand. They open the	Hand opening

	hand to move the ball forward towards the pins.	

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