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ABSTRACT

NEUROREHABILITATION OF THE HAND USING THE CYBERGRASP™ AND MIRROR IMAGE

**by
Amy Boos**

In recent years, researchers have explored the use of a mirror image as a means of rehabilitation for individuals suffering from hemiparesis. Through neuroimaging and functional testing, neurological improvement has been demonstrated in those that engage in mirror therapy. Bilateral training, or simultaneous movement of both sides of the body, has also been studied as a treatment method to improve function after cerebral vascular accident. The development of robotic systems to assist movement of the human body has played a major role in the fabrication of bilateral training devices.

In this experiment, the CyberGrasp™ robotic exoskeleton was used to assist the paretic hand in simultaneous bilateral movement in three subjects more than 1 year post stroke. While the bilateral motion took place, the subject viewed a mirror image of their unaffected hand superimposed on their impaired hand.

Results at the end of 2 weeks showed no major change in active digit extension, but a noted decrease in the stretch reflex and clinically significant improvements on the Jebsen Test of Hand Function. The system resulted in no major side effects. In conclusion, robot-assisted bilateral training in conjunction with mirror therapy may be a helpful treatment in patients suffering from hemiparesis due to neurological impairment. The experiment conducted demonstrated the feasibility of the system to be used in further research.

**NEUROREHABILITATION OF THE HAND USING
THE CYBERGRASP™ AND MIRROR IMAGE**

**by
Amy Frances Boos**

**A Thesis
Submitted to the Faculty of
New Jersey Institute of Technology
in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Biomedical Engineering
Department of Biomedical Engineering**

May 2011

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APPROVAL PAGE

**NEUROREHABILITATION OF THE HAND USING
THE CYBERGRASP™ AND MIRROR IMAGE**

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Dedicated to those who wait endlessly for a cure, that they may find hope in my work.

ACKNOWLEDGMENT

I would like to acknowledge, first and foremost, my thesis advisors, Dr. Sergei Adamovich, whose support and guidance allowed me to develop and complete an exciting research project, and Dr. Richard Foulds, whose time and energy assisted me in selecting a thesis that I genuinely wanted to pursue. I would also like to thank Dr. Eugene Tunik, for his interest in my work, the use of his lab at UMDNJ, and for assisting in taking the project farther than I had originally imagined.

I would like to thank the National Institute of Child and Human Development, a branch of the National Institutes of Health who provided funding for the project.

Integral to the development and execution of this master's thesis project was Qinyin Qiu, whose many hours of work and knowledge of computer programming contributed significantly to its success. I would also like to thank Dr. Gerry Fluet for his invaluable advice and assistance with subject coordination. I would like to thank John Hoinowski, Hamid Bagce, Naphtaly Ehrenberg and Ian Lafond for their individual efforts as well. Finally, I would like to thank William Moore for his proofreading assistance and moral support.

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LIST OF TERMS

Bobath	Berta Bobath, a physiotherapist, and her husband Karel invented the Bobath technique, a rehabilitation approach specifically designed to improve motor control after neurological injury.
Hand Dynamometer	A rehabilitation assessment tool that measures force exerted by a person's grasp.
Goniometer	A tool that measures an angle, or range of motion. It is often used in rehabilitation prior to and following an intervention, to determine if the intervention has had an effect.
Tenodesis	The natural tendency of the fingers to flex when the wrist is extended, due to shortening of the flexor tendons.
CMC	Carpometacarpal joint, found at the base of the thumb.
MCP or MP	Metacarpophalangeal joint, the joint at the base of the finger.
PIP	Proximal interphalangeal joint, the middle joint of the finger.
DIP	Distal interphalangeal joint, the farthest distal joint of the finger.
Occupational Therapist	A rehabilitation professional who helps restore independence in clients with illness or disability, through the use of purposeful activity.

CHAPTER 1

INTRODUCTION

1.1 Objective

The objective of this master's thesis is to demonstrate the feasibility of using robotics in conjunction with observation of mirrored movement for the purpose of hand rehabilitation in stroke. Specifically, the CyberGrasp™ and CyberGlove® technology were used in an experiment involving three subjects with diagnosis of chronic cerebral vascular accident. Initial measurements and testing were done prior to engaging in the two-week experiment, and repeated immediately post-experiment. Range of motion and force data were collected and analyzed to determine any improvement in neurological function of each subject. Electromyographic (EMG) data were also collected from the digit flexor musculature to examine the existence and nature of the flexor stretch reflex.

1.2 Background Information

1.2.1 Mirror Therapy

For many decades, health professionals and researchers have been struggling to find optimal treatment for patients who have suffered a cerebral vascular accident, or stroke. Despite the best efforts of doctors and therapists, stroke is one of the most common causes of long-term disability in the United States. Although a small stroke may only cause minor symptoms, a stroke that affects a large portion of the brain can cause complete loss of motor function on one side of the body. A diverse range of

rehabilitation techniques have been employed over the years, with varying amounts of improvement in patients' motor function.

In recent years, a treatment known as “mirror therapy” has been studied and proposed as beneficial to patients with impaired motor function due to neurological injury. A researcher named Ramachandran first studied the effect of viewing a mirror-image on brain function with the goal of helping to reduce pain in arm amputees. Subjects viewed the movement of their unaffected upper extremity in a mirror held perpendicular to the midline of the body, while the injured arm was blocked from view. Results of this study showed a decrease in pain levels in this specialized population [1]. Further studies done in the 1990's with macaque monkeys showed an excitability in similar brain areas when a monkey watched a person perform a motor act, as when the monkey performed the act itself [2, 3].

Despite the rich amount of neuroimaging data that supports the existence of a mirror neuron system, direct evidence of the system is lacking and isolated mirror neurons have yet to be found. Meanwhile, researchers continue to explore the relationship between image observation and brain transformation, in the pursuit of concrete proof. Several research studies have been performed in the present decade that show a positive effect on recovery of motor function after stroke, especially when action observation is combined with execution of the observed movements [4-7]. The studies report activation in many different areas of the brain, although there continues to be some discrepancy between the authors as to the specific areas that control the mirror neuron system.

In 2007, a study was published in *NeuroImage* [4] which demonstrated the effect of “action observation therapy” on the reorganization of the brain, using functional MRI (fMRI) technology. Eight patients with moderate chronic motor deficits of the upper extremity watched video sequences of daily life hand and arm actions. After observing the video, the patients were asked to repeatedly perform the viewed action with their paretic upper limb. In contrast, patients in the control group were shown video containing sequences of geometric symbols, and then were asked to perform the same action with their affected arm. The Frenchay Arm Test (FAT), Wolf Motor Function Test and the Stroke Impact Scale (SIS) were used in evaluation of the clinical status of patients. The experimental group showed significant improvement in motor function after 4 weeks of treatment, even more improvement than that of the control group, according to scores on the FAT and SIS. This improvement lasted through testing at 8 weeks post treatment. Functional MRI measurements were taken before and after the treatment, during object manipulation with the affected extremity. A post treatment increase in activation could be identified in the non-affected hemisphere in the ventral premotor cortex, the SMA, insula and the superior temporal gyrus. The affected hemisphere also showed increased activation in the ventral premotor cortex, the supramarginal gyrus and the superior temporal gyrus. The findings suggested that the improvement in motor skill was associated with reactivation of a network in the brain, where motor representations of trained actions are known to be present. The authors also suggested that the inclusion of action observation in rehabilitation was more beneficial than physical training alone.

Although the 2007 NeuroImage study used patient observation of a video as opposed to observation of a mirror image, it supports the theory of the existence of a mirror neuron system in the brain. Smaller case studies have also been presented demonstrating positive effects of mirror therapy after neurological injury [8-11]. The functional improvement of stroke patients after treatment with mirror therapy has been further documented in randomized controlled trials focusing on motor recovery in different parts of the human body. These studies include a 2007 study done involving the lower extremity, a 2008 trial that focused on the hand, and a study published in the spring of 2009 involving the upper extremity as a whole.

In 2007, a randomized controlled trial was published that explored whether mirror therapy was beneficial for restoring motor function in the lower extremity of subacute stroke patients. The authors hypothesized, based on previous research, that visual feedback and motor imagery provided by a mirror would help restore proper cortical processing and, in turn, improve function in the lower extremity. In the experimental group, a mirror was placed between the legs and perpendicular to the subject's midline. The patients observed the reflection of the unaffected leg while flexing and extending the ankle. The control group performed the same physical movements, but the nonreflecting side of the mirror faced the unaffected leg. Outcome measures included the Brunnstrom stages, Modified Ashworth Scale (MAS), Functional Ambulation Categories (FAC), and the Functional Independence Measure (FIM) motor portion. The mirror group showed significantly more improvement at a six-month follow-up than the control group in the Brunnstrom stages and the FIM motor score. Neither MAS nor FAC showed significant differences between the groups. The authors proposed that mirror therapy combined with

conventional rehabilitation provides additional long-term benefit to patients' lower extremity motor recovery [5].

A randomized controlled trial on subjects with subacute stroke, which determined the effect of mirror therapy on hand function, became available in 2008. The experimental group received mirror therapy treatment in addition to standard rehabilitation, whereas the control group received the standard program only. Patients performed wrist and finger flexion and extension exercises with their unaffected arm, while viewing the image in a mirror. During the mirror therapy treatment, subjects were asked to attempt to perform the viewed movement with their affected side as they were viewing the motor image. Outcome was measured using the Brunnstrom stages, the Modified Ashworth Scale (MAS), and the self-care items of the Functional Independence Measure (FIM). After four weeks and at six-month follow up, hand functioning was shown to improve more for the mirror therapy group, according to the Brunnstrom stages and the self-care portion of the FIM. There were no differences found in the MAS score, a measure of spasticity. It is noted that none of the patients in this study had apraxia or neglect, as this was an exclusion criteria [6].

A third randomized controlled trial was published in late 2009, which attempted to determine the benefit of mirror therapy in patients with upper extremity hemiparesis due to stroke. In this study, the mirror therapy group performed upper extremity movement exercises with their unaffected arm while viewing the mirror image. As in the hand function study discussed above, the patients were instructed to simultaneously attempt to move their affected side to match the viewed image. There was no mirror placed at midline for the control group, rather, these patients were simply asked to try to

move their affected arm in a way that matched their unaffected arm. The seven upper limb scores of the Fugl-Meyer test, the Action Research Arm test, and the motor portion of the FIM were used to assess subjects before and after treatment. The mirror therapy group improved more on the Fugl-Meyer test than the control group, and also showed more improvement in the areas of surface sensibility and neglect. Finger motion improved the most in patients receiving mirror therapy who initially had no finger movement at all. As in previous studies, it was found that mirror therapy does not appear to affect spasticity [7].

The authors of the 2009 study proposed the idea that distal movement is organized more unilaterally, whereas proximal movement relies more on bihemispheric representations. This may explain why patients in the mirror therapy group did not show as much improvement in the more proximal areas of the arm. They discussed how movement observation may modulate cortical somatosensory representations by increasing the excitability of the primary somatosensory cortex. This could lead to an increase in discrimination ability after treatment. They suggested that observation of mirrored distal movements led to corticospinal excitability, which assisted motor recovery after stroke. Also discussed in this paper was the idea that the Precuneus Region, or area V6, may also play a role in the mirror neuron system. Area V6 is part of the neural network that supports the mental representation of the self [7].

As mirror therapy has only been studied in depth in the past decade, theories are still developing as to why and how it works. It is apparent after exploring the topic of mirror therapy that more research is needed in this area. The three previous studies discussed were randomized and controlled, but there was no neuroimaging done within

the study to further establish scientific proof of cortical reorganization. Most of the studies on mirror therapy that contain neuroimaging are not randomized and controlled. Because of the limited number of quality studies on mirror therapy, there is no agreement on aspects such as duration or intensity of training with this new therapeutic approach. Incorporating mirror therapy into the conventional program at the early stages of treatment and applying it for a long period might be even more beneficial to improving motor function than adding it afterwards. The question still remains if there is differential involvement of the ipsilateral and contralateral hemisphere during different phases of stroke recovery. Future studies may also wish to investigate the effectiveness of mirror therapy as a home treatment, as it is very simple and inexpensive for the participant.

1.2.2 Bilateral Arm Training

In the past, treatment of upper extremity hemiparesis focused on exercise and stretches of the affected arm only. In recent years an approach called Constraint-Induced Movement Therapy (CIMT) or Constraint-Induced Therapy (CIT) has supported and enhanced this unilateral focus, and is based on using only the affected arm in functional activities. When participating in this program, an individual must “restrain” their unaffected arm in a mitt or glove for 90% of their waking hours, which forces them to use their affected hand to perform selected activities [12-15]. Generally, these repetitive functional activities are practiced for 6 hours a day for a two week period. It is believed that repetitive practice of unilateral activities may lead to reorganization in the damaged hemisphere of the brain [16]. However, many patients with moderate to severe hemiparesis are limited in their ability to perform any functional activities with their

affected arm, thereby lowering their chances of qualifying for involvement in this treatment program.

Although many patients have shown success with CIT, an alternate view of rehabilitation of hemiparesis that has grown in popularity recently is Bilateral Arm Training (BAT) or bilateral movement therapy. The basis of this theory is that the ipsilateral side of the brain is recruited and facilitates neuroplasticity when both sides of the body are moving together in the same pattern. It is also speculated that a template exists that is generated by the undamaged hemisphere, which controls movement of both arms. BAT can be used by patients who do not have sufficient functional use of their affected upper extremity to qualify for and participate in CIT. Along with CIT, BAT is considered an evidence-based treatment by rehabilitation professionals. Current research efforts have focused on determining if one treatment method is more beneficial than the other, in order to establish a universal standard of care for the treatment of upper extremity hemiparesis.

Both CIT and BAT require focused participation of the patient in a variety of repetitive tasks. Both programs also incorporate task orientation and goal directedness [17, 18]. BAT programs have taken on different forms, such as robot-assisted training, practice of functional tasks (bilateral isokinematic training) and rhythmic auditory cuing (bilateral motor priming), [19-27]. Rhythmic auditory cuing was suggested by Thaut et al [28], based on findings that showed significantly improved kinematic measures in individuals with chronic stroke that participated in a rhythmic condition as compared to a discrete (non-rhythmic) condition. There is fMRI evidence that stronger activity occurs in the contralateral sensorimotor cortex during rhythmic movement, as compared to

discrete movement [29]. Therefore, some experiments involving BAT have used auditory cues, such as the beat of a metronome, to cue the subjects to initiate movement [26].

A study done in Taiwan in 2010 [30] compared the effects of BAT with a control intervention. Subjects received either a BAT program or the control intervention for two hours, five days a week for three weeks. The BAT group practiced repetitively lifting two cups, stacking two checkers, picking up beans, folding towels, turning screws, manipulating coins and watering plants (using both hands to hold a sprinkler can). The control group received standard occupational therapy treatment, which incorporated neurodevelopmental techniques, education on compensatory strategies and weight bearing through the affected arm. This group also focused on upper extremity use, trunk-arm control and practice of fine motor tasks. The BAT group showed improved temporal and spatial efficiency after the training, in both unilateral and bilateral tasks. They also showed reduced motor impairment and less online error correction during the bilateral task. These findings showed support for the use of BAT to improve motor control and motor function in the upper limb, as compared to a control intervention.

A study was published in March of 2011 [31] that compared the efficacy of dCIT (distributed Constraint Induced Therapy), BAT and a control treatment on upper extremity motor control and functional performance. Distributed CIT refers to CIT that is equal in amount to the original treatment protocol (60 total hours), but distributed over twice the number of days. 66 stroke patients were randomly placed into one of the three treatment groups. In post treatment measures, the BAT group showed a greater force generation at movement initiation during unilateral and bilateral tasks than the dCIT or

control group. However, the dCIT group had faster times on the Wolf Motor Function Test and higher functional ability scores when compared to the control group. Both the dCIT and the BAT groups showed smoother movement trajectories in unilateral and bilateral tasks.

Another very recent randomized controlled trial [32] tested the efficacy of bilateral arm training with rhythmic auditory cuing (BATRAC) against dose-matched therapeutic exercises (DMTEs) on upper extremity function in stroke survivors. A total of 111 unilateral stroke subjects were randomly selected to participate in six weeks of training with either BATRAC or DMTEs. The BATRAC group grasped a device with two T-bar handles and moved their arms simultaneously (in phase) and alternately (antiphase) to the sound of a metronome set at their preferred speed. The DMTE group performed exercises based on neurodevelopmental principles, including spine and scapular mobilization, weight bearing through the impaired arm and finger extension. Active movement was encouraged throughout the exercises in both treatment groups. Each group spent an equal amount of time in their respective programs. The two groups showed comparable improvements in upper extremity function that lasted four months post training. Functional MRI done following the training showed a significantly higher increase in brain activation in the BATRAC group, specifically in the ipsilesional precentral, anterior cingulate and postcentral gyri, supplementary motor area and contralesional superior frontal gyrus.

A functional magnetic resonance imaging study of BAT versus dCIT [33] showed varied results. Out of the six patients who were studied, one from each group showed large increases in bilateral hemisphere activation. Three out of four BAT group subjects

showed increased bilateral cerebellum activation during bilateral elbow movement. Two dCIT patients showed decreased cerebellar activation.

A systematic review of the impact of bilateral therapy on upper limb function after chronic stroke was done in 2010 [34]. Nine studies reported prior to 2008 were included in the review, three of which were randomized controlled trials, and six of which were cohort studies. A mechanical device was used as a means of providing bilateral arm training in eight of the studies. The authors concluded that “some evidence” exists that bilateral therapy improves upper extremity function in adults with chronic stroke, but stressed the need for more randomized controlled trials to support its clinical use.

A related area of research that has developed through the study of BAT is the question of whether there is a differential effect on proximal versus distal arm function. Cauraugh and Kim demonstrated that in mildly impaired subjects, bilateral training of the wrist was more beneficial for improving distal function than unilateral training [35]. A 2009 study of unilateral versus bilateral training [26] found that bilateral training may be more advantageous than unilateral training for improving proximal arm function. Although all of the subjects in this latter study demonstrated an increase in distal function, subjects showed more distal improvement with unilateral than bilateral training, as shown by the Wrist/Hand portion of the Motor Status Scale. Authors note, however, that this distal improvement can occur despite the focus of treatment being on whole-arm repetitive functional tasks. Another study done in 2004 also showed improvements in distal upper extremity function following a BAT program that targeted the proximal arm [36].

Despite the documented interest in distal improvement with BAT, there has been an absence of research done in the area of applying the bilateral arm training theory directly to hand and finger movement. One reason for the lack of studies on distal bilateral training may be the belief that proximal movement is based more on bihemispheric brain activation, whereas distal hand movement relies more on one side of the brain, as discussed in Section 1.2.1. It also may be due to the fact that distal neuromuscular function often is the last to show improvement during a patient's recovery from stroke. Simultaneous and repetitive bilateral movement of the fingers is normally very difficult for anything more than a mildly hemiparetic upper extremity. Spasticity, or increased muscle tone due to neurological injury, is also very common after stroke and can severely restrict functional hand movement. This makes bilateral hand movement activities more difficult as well. Many of the above mentioned research studies involving BAT mentioned use of a mechanical device to assist the affected upper extremity to move in synchrony with the unaffected arm. There has been some progress in development of robotic devices developed that assist in providing range of motion exercise to the hand, which will be discussed in the following subsection. At this time, however, there is no mechanical system that has been developed to efficiently apply BAT to finger movement. This is most likely due to the complex nature of the hand and finger movements that require assistance, as well as the large variety of anatomical differences in the human hand among subjects. The above-mentioned study of bilateral arm training involving the wrist joint showed that there may be promise in applying this treatment directly to the distal musculature of the hand.

1.2.3 Robots in Upper Extremity Neurorehabilitation

For the moderately to severely impaired stroke patient, early rehabilitation efforts generally focus on teaching compensatory strategies to enable the individual to return to the most independent life possible. Sometimes completely unable to use one half of their body, occupational and physical therapists teach them how to be more independent in daily living tasks such as feeding, dressing and bathing. Adapting to mobility through the use of the unaffected side of the body and an assistive device is encouraged to allow the person to walk again. This is true especially in the acute stages of recovery, where there is increasing focus on cost-reduction and reducing the length of the patient's hospital stay.

The large amount of time dedicated to repetitive functional task practice that has been shown to improve hemiparetic upper extremity function in research studies is not generally available to patients in the current model of rehabilitation administration. Even if it were obtainable, manually assisting a patient's affected arm to engage in hours of therapy is very labor-intensive for the therapist. Efforts have been made to improve the efficiency of administering range of motion exercise and repetitive task practice by means of an assistive mechanical device, or robot. It is hoped that, through development of cost-effective robotic devices, extensive neurorehabilitation in the recommended quantity will be less of a burden for therapists and more accessible to patients [37].

There has been significant progress in the development of robotic devices that assist upper extremity motion, with the goal of neurorehabilitation. Some devices have only been used for the purpose of research, yet others have become commercially available. The list includes: MIT-Manus, ARM Guide, MIME, HEXORR, HandSOME,

Armeo, Haptic Master, Myomo, ReoGo, 'Braccio di Ferro' (Iron arm), WREX, Bi-Manu-Track, Hand of Hope and Reha-Digit. This list is not all-inclusive, however, as there is continual progress in the development of new mechanical devices to assist with upper extremity therapy. Some of the robots are designed exclusively for mechanically assisting movement of the arm, while others incorporate electrical stimulation of the muscles of the arm and/or EMG-controlled components. Many of the devices integrate simple video games that the subject can view on a computer monitor, and engage in through control of the robotic arm. Figures 1.1 through 1.4 show examples of various robotic devices that have been developed for upper extremity neurorehabilitation.



Figure 1.1 A patient engaging in arm exercises in a virtual environment with the Armeo® robotic arm exoskeleton [38].



Figure 1.2 The Myomo e100 neuromotoric device incorporates EMG technology to improve elbow motion after stroke. After bicep or tricep surface electrodes detect even trace muscle contraction, a motor in the device assists with the individual's desired movement [39].

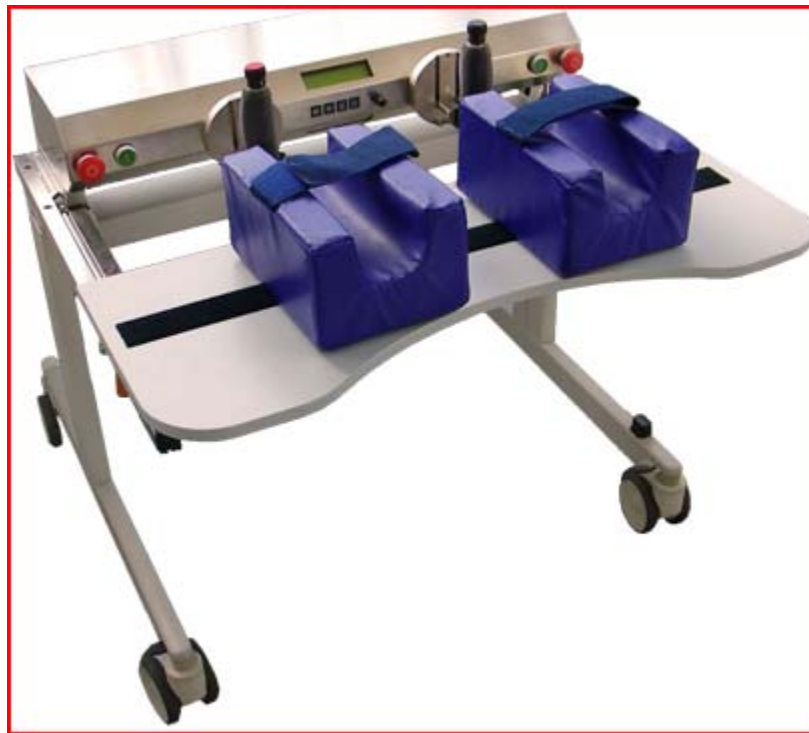


Figure 1.3 The BiManuTrack has passive, semiactive and active modes that provide passive and active exercise to the wrist and forearm, using the BAT approach [40].

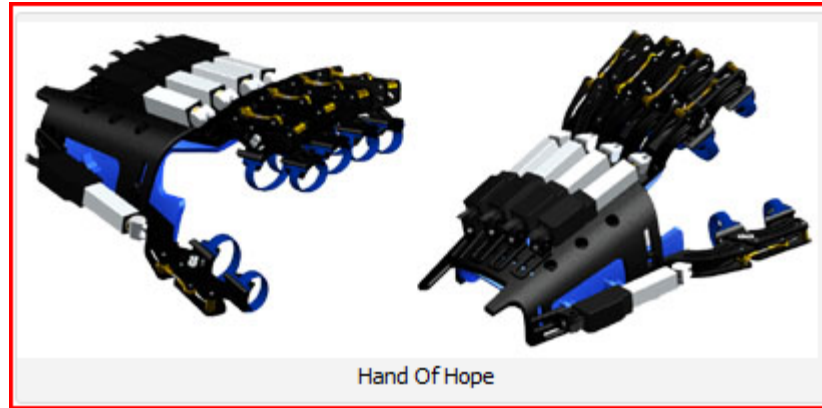


Figure 1.4 The Hand of Hope device combines EMG technology with a robotic exoskeleton to improve hemiparetic finger motion [41].

The MIT-Manus (Interactive Motion Technologies Inc, Cambridge, Massachusetts), a two-degrees-of-freedom robot developed in 1991 at Massachusetts Institute of Technology has undergone a large amount of clinical testing. The robot moves a patient's hand, thereby moving their shoulder and elbow in a horizontal plane. The MIT-Manus incorporates an impedance control mode, which attempts to replicate the assistance that a human therapist would give to their patient. Both acute and chronic stroke patients have shown significant clinical gains in upper extremity motor function with the use of this robot [42-46]. (Figure 1.5)

Early robotics research discovered the benefits of using robots for bilateral movement exercises, and found some advantages over unilateral movements [48, 49]. It was these early studies that helped to develop the theoretical explanation behind why using bilateral synchronous movement patterns within exercise sessions was beneficial [50]. Therefore, some devices, like the Mirror Image Movement Enabler (MIME), are equipped with both unilateral and bilateral modes (Figure 1.6). The bilateral mode of the

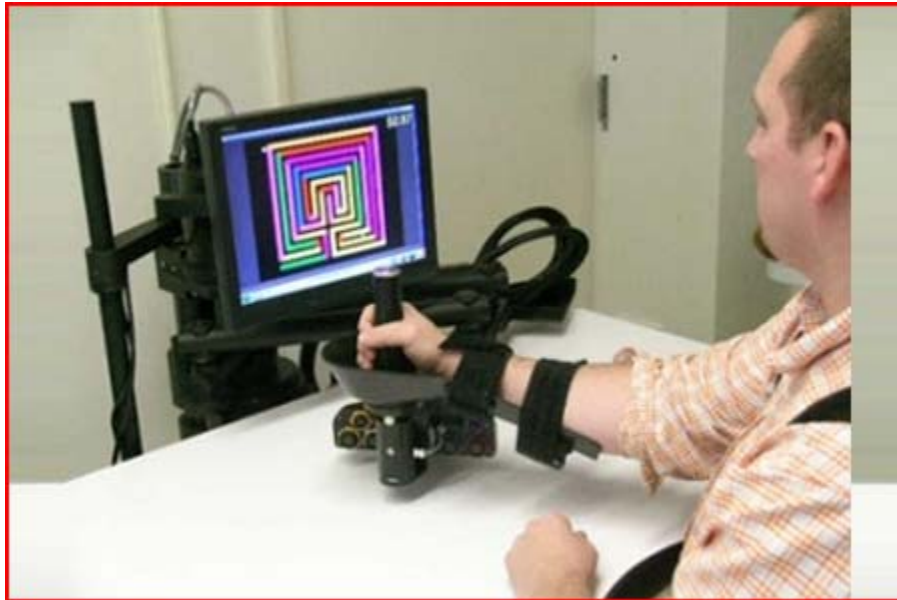


Figure 1.5 The MIT-Manus robot [47].

MIME incorporates a position digitizer, which measures the position of the unimpaired arm and sends the coordinates to the robot manipulator that is assisting the impaired arm to move. As a result, the impaired arm continuously moves with the unaffected arm's mirror image orientation and position. The MIME also has three other modes of operation: passive, active-assisted, and active-constrained. The passive mode simply moves the impaired arm, while the subject relaxes. In active-assist mode, the robot only assists the patient's movement after sensing volitional force from the subject. Active-constrained mode provides a "viscous resistance in the direction of the desired movement and spring-like restoring forces perpendicular to the movement direction" as the subject moved towards a target [37].

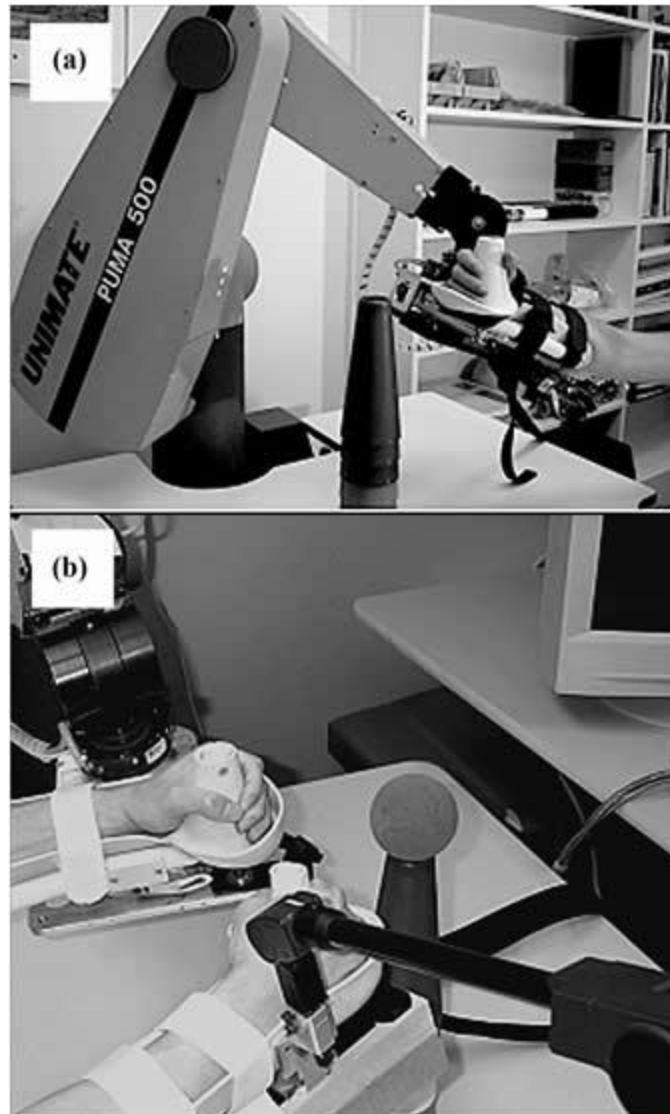


Figure 1.6 The Mirror Image Movement Enabler (MIME), in unilateral mode (a), and bilateral mode (b) [37].

Of current debate is the appropriate recommended frequency to use robotic therapy with patients. It is generally assumed in neurological rehabilitation that “more is better”, but there has been some concern about patients losing mental focus on the activity with increased treatment time. This is an issue particularly during active-assist modes, when the robot assists in completion of the movement task despite decreased

effort on the part of the patient. With decreased concentration on the task at hand, some subjects show a diminished level of participation and effort. A new term has been coined amongst rehabilitation robotics researchers for this lower level of exertion displayed during robotic therapy. It is known as “slacking” [51].

Some research studies have also been done to determine if there is a difference between supervised and unsupervised treatment with robotics [52]. A future goal in the rehabilitation field is that this treatment will be available for patients to use in the home, without the need for constant supervision by an occupational or physical therapist.

1.2.4 The Stretch Reflex

The stretch reflex is defined as the contraction of a muscle in response to a stretch induced upon that muscle or an attached tendon. When muscle spindles (sensory receptors located within a muscle) increase in length in response to a mechanical stretch in the associated muscle, a message is sent to the spinal cord via Group Ia afferent neurons. A change in the rate of action potentials is recognized. Group IIa afferent neurons, also located in the muscle spindle, detect the velocity of this change in muscle length and also send this information to the spinal cord. Alpha motor neurons receive the Ia afferent signals monosynaptically and then transmit efferent impulses to the muscle fibers, which generate resistance to the stretch. Interneurons also transmit the Ia signal, which results in inhibition of the alpha motoneurons of the antagonist muscles, causing the opposing muscles to relax. Co-activation of gamma neurons assists in the stretch reflex by maintaining the length of the muscle spindle even during contraction of the muscle. The biological purpose of the stretch reflex is to prevent injury to the muscle/tendon as a result of being stretched beyond its normal range [53].

One example of the stretch reflex is the patellar reflex (Figure 1.7), commonly induced by a physician by tapping on the patellar ligament at the knee, just below the patellar bone. The muscle spindles trigger an impulse in the Ia afferent fibers of the femoral nerve which synapses at the L4 level of the spinal cord. The alpha motor neuron then transmits the activity to the quadriceps muscle of the thigh, causing it to contract while an inhibitory interneuron induces relaxation in the opposing hamstring muscle.

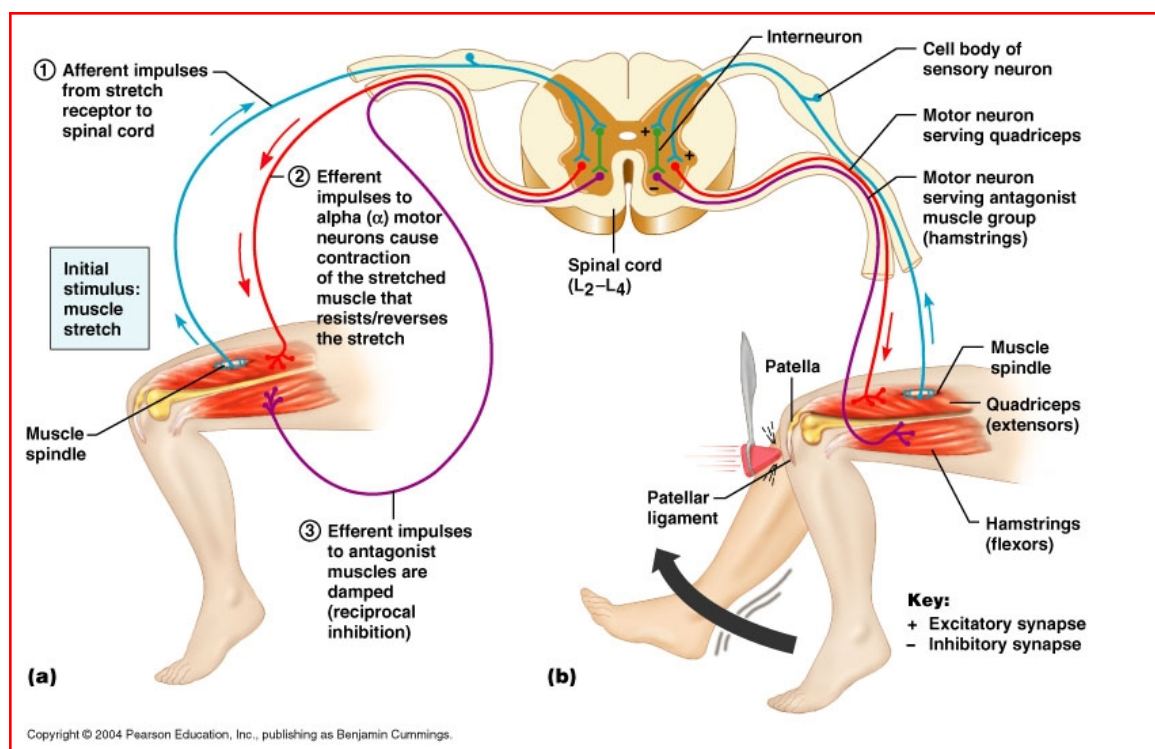


Figure 1.7 The Patellar Reflex, an example of a stretch reflex [54].

After neurological injury, the stretch reflex can become oversensitive, causing spastic hypertonus, or spasticity in the muscle. This condition can severely impair functional use in the arm and hand of a patient who has had a stroke. Range of motion

exercise, prolonged stretching via splinting and casting, along with medical therapy (for example, Botox injections) is sometimes required to improve the patient's quality of life.

Described as a velocity dependent reflex, the likelihood of activating the stretch reflex can be reduced by slowly stretching the affected segments in the opposite direction of the spastic muscle. It has been discovered that this can be done manually by a therapist or mechanically via a robotic device. A study done in 2007 involving the REHAROB Therapeutic System, which uses two industrial robotic arms to provide range of motion exercise to an individual's upper extremity, showed that the apparatus has potential to reduce spasticity following brain injury [55]. In this study, the control group received only Bobath-style neurodevelopmental treatment, while the experimental group received an additional 30 minutes of "robot-mediated therapy" on the same days. The REHAROB System provided passive shoulder and elbow range of motion exercise, as programmed by a physiotherapist. Results of the experiment showed a statistically significant change in the modified Ashworth scale for the shoulder adductors and elbow flexors, in the robotic group only. The goal of the REHAROB was unique in the robotics field in that it focused on performing repetitive range of motion exercises at a slower speed, with a constant velocity, and with the goal of not only improving range of motion, but decreasing spasticity in the upper extremity.

CHAPTER 2

CYBERGLOVE® AND CYBERGRASP™ TECHNOLOGY

2.1 CyberGlove®

The CyberGlove® is an instrument developed by Immersion Corporation which is used to measure the movement of the hand and fingers. Sensors imbedded inside the dorsal surface of the glove are positioned over or near the hand and finger joints. As long as the sensor completely covers the arc of the joint between adjacent bone segments, “the sensor will provide an output proportional to the angle between the bones, independent of where the sensor lies relative to the joint and the joint radius.” The CyberGlove® is designed to fit the average-sized hand [56]. (Figure 2.1.)



Figure 2.1 The CyberGlove® [56].

In the following experiment, the 18-sensor glove was used on the left (active) hand, and the 22-sensor glove was used on the right (impaired) hand. In the 18-sensor CyberGlove®, there are two “bend sensors” on each finger, two for the metacarpal phalangeal (MP) and interphalangeal (IP) joints of the thumb, and two for each MP and proximal interphalangeal (PIP) joint of the fingers. In the 22-sensor glove, there is one additional bend sensor per finger to measure motion at the distal interphalangeal (DIP)

joint. In the 18-sensor glove, the DIP joint angle of the four fingers is inferred from the PIP joint angle with the VirtualHand software. The VirtualHand© software is copyrighted and is provided only with the purchase of a CyberGlove®. Abduction sensors are located in-between the thumb and index, index and middle, middle and ring and ring and small fingers. The abduction sensors measure the amount of lateral movement of the finger in the plane of the palm. The thumb has an additional sensor that measures the amount of rotation across the palm towards the small finger. The small finger also has a sensor that measures how much the small finger rotates across the palm towards the thumb. There are two wrist position sensors, one to measure wrist pitch and one to measure wrist yaw [56].

The CyberGlove® Interface Unit (CGIU) contains amplification and digitization circuitry for the CyberGlove® and is connected to the computer via serial cable/ serial port [56].

2.2 CyberGrasp™

The Immersion Corporation developed a force-feedback option to be used in conjunction with the CyberGlove®, called the CyberGrasp™. The CyberGrasp™ is a lightweight (16 oz) exoskeleton that fits over the top of the CyberGlove® device and can provide force-feedback to the fingers. The device was designed to be used in virtual reality or to control end-effectors in telerobotic applications. The system provides a sense of size and shape of an object being manipulated in a virtual reality environment. The CyberGlove® Instrumentation Unit processes and communicates the data to the CyberGrasp™ Force Control Unit (FCU). Resistive feedback is provided to the fingers via a system of

“tendons” or cables that traverse the back of the hand and are affixed at the tip of each finger. The resistive feedback can be applied in the direction of digit extension only. The CyberGrasp™ is not able to provide resistance in the direction of digit flexion. Five separate actuators for each finger are housed in an “actuator enclosure”, separated from the exoskeleton by approximately 2 feet of cable. The CyberGrasp™ can provide a maximum of 12 Newtons of continuous force to each finger [57]. (Figure 2.2)

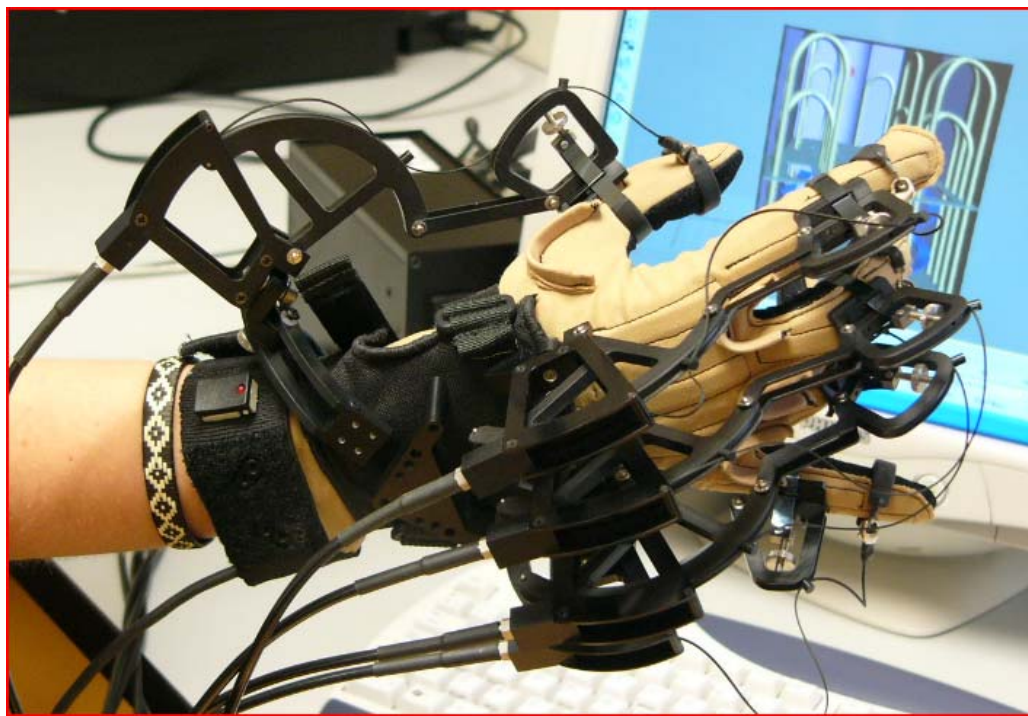


Figure 2.2 The CyberGrasp™ exoskeleton, worn over a CyberGlove® [58].

In this experiment, the CyberGrasp™ was used in a manner for which it was not originally designed. Initially created for the United States Navy for use in telerobotic applications, the CyberGrasp™ can be used for virtual reality simulation, manipulation of hazardous materials, and computer-aided design (CAD) [57]. In the following experiment, the CyberGrasp™ was used to assist movement of the fingers of a person

who has suffered a stroke and has decreased ability to open their hand as a result. Subjects in this experiment had flexor spasticity, ranging from mild to moderate, and the CyberGrasp™ was used in order to assist the affected hand to move in sync with the unaffected hand during bilateral movement training. Without robotic assistance, the subjects would not have been able to properly engage in simultaneous bilateral hand movement.

CHAPTER 3

EXPERIMENTAL PROCEDURE

3.1 Subject Selection

Subjects from a local hospital stroke support group were screened and selected based on appropriate movement patterns for the experiment. Specifically desired were subjects whose right upper extremity was affected by their stroke, due to the fact the CyberGrasp™ owned by the lab was designed only for the right hand. Ideally, the subject would be able to fully close their hand from an open position, but have no active digit extension. The CyberGrasp™ device would only be able to assist in digit extension, not digit flexion. If the subject was unable to close their affected hand, it would not be possible to have a mirrored movement pattern. Also desired were subjects that have slight flexor spasticity from their stroke. This allowed the examination of the presence of a flexor stretch reflex with the use of electromyography (EMG). It was preferred that the subjects did not have severe spasticity, as this would make it difficult to place the glove and exoskeleton on the impaired hand as well as position the affected hand behind the mirror. It was best for the subject to be able to extend the elbow to at least 90 degrees. The subjects needed to have good vision; right visual neglect was not allowed because the subject would not be able to properly visualize the mirror image on their right side. Reasonably good hearing was required as well, as the subject needed to be able to hear the directions “open” and “close”. Subjects also needed to have the ability to follow simple directions and have the ability to initiate movement in their affected arm.

Table 3.1 Study Participants

	<i>Subject 1</i>	<i>Subject 2</i>	<i>Subject 3</i>
Prior Hand Dominance	Right	Right	Right
Affected Hand	Right	Right	Right
Age (years)	58	54	76
Sex	Male	Male	Male
Years since stroke	8	8	1

Subject 1 previously worked as a Drywaller. He had six months of rehabilitation following his stroke consisting of physical, occupational and speech therapy. At the time of the study, he participated in exercises on his own at a gym. He was able to open the refrigerator, open bottles and wash dishes using his affected upper extremity.

Subject 2 was employed at a telecommunications corporation prior to his stroke. He received inpatient rehabilitation for 18 days followed by outpatient therapy for one month. With his impaired hand, he reported that he could open and close the refrigerator, and stabilize bottles to open them.

Subject 3 was self-employed prior to his stroke, working in the area of social work. He also received inpatient and outpatient rehabilitation, and had participated in many research studies prior to this experiment. He was able to squeeze a ball, pick up a small cup of fluid, brush his teeth, and operate a light switch with his impaired upper extremity. He also exercised regularly at the time of the study, including walking and jogging. Prior to the experiment, he reported that he was able to do two sets of ten push-ups.

3.2 Methods

The experiment was carried out in the New Jersey Institute of Technology's Motor Control and Rehabilitation Lab. Subjects were seated comfortably in a well-lit laboratory environment. A chair with armrests was selected that allowed a wooden platform to be placed and secured approximately at the level of the subject's diaphragm. Both arms were supported on this platform, and a mirror was placed in the subject's midline. The affected upper extremity was positioned on an individual basis to accommodate for different levels of spasticity and varied movement patterns. Optimal placement of the right upper extremity allowed for the actual hand to be blocked from the subject's view by the mirror and for the fingers to have as much range of motion as possible. It was important that the mirror was positioned in a way that the subject could clearly see the mirror image of their unaffected hand superimposed upon where their affected hand would be, without postural strain. The mirror position was adjusted differently for each subject and, if needed, for different days of the experiment with the same subject. It was desired that the subject be comfortable enough to perform the experiment for at least 30 minutes. Subjects were verbally instructed to attempt to actively open and close both of their hands, in synchrony with computer generated auditory commands "open" and "close," while focusing their visual attention on the mirror image of their unimpaired hand.

It was proposed that the effect of the mirror image on brain reorganization would be increased if the subject received simultaneous proprioceptive feedback that their affected hand was moving in the same way as the visualized image. This was done via

the use of the CyberGrasp™ exoskeleton, which assisted with impaired digit extension. CyberGloves® were placed on both of the subjects' hands, the 22-sensor glove on the

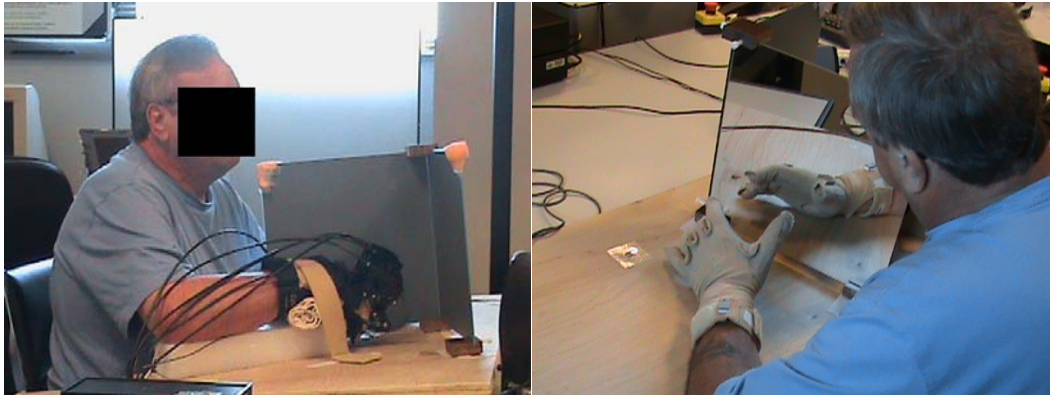


Figure 3.1 View of Subject 1 experimental set-up, from affected upper extremity side (left photo), and unaffected upper extremity side (right photo).

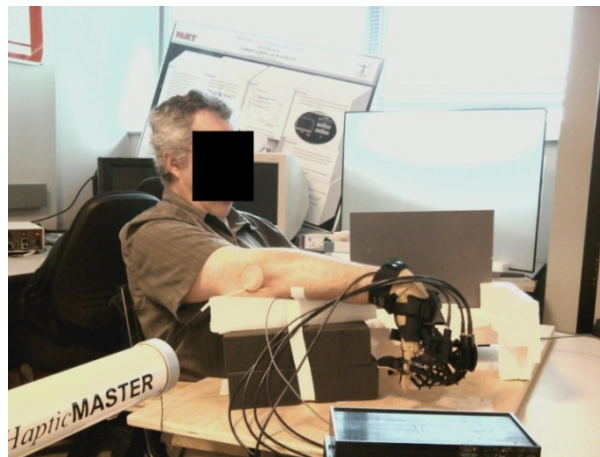


Figure 3.2 Subject 2 experimental set-up, affected upper extremity view.



Figure 3.3 Subject 3 experimental set-up, with both hands in “open” (left photo) and “close” (right photo) position.

right hand and the 18-sensor glove on the left hand. The CyberGrasp™ was placed on the right hand, on top of the CyberGlove®. The CyberGrasp™ was adjusted daily to fit the subject's hand securely. Speakers were placed on the table, near the wooden platform, and volume was adjusted so that the subject could easily hear the auditory cues.

Software from the CyberGrasp™ and the CyberGlove® were merged using C++, and a graphical user interface (GUI) was created (by Qinyin Qiu). This program allowed the extension force provided by the CyberGrasp™ to depend on the position of the subjects' hands. As stated previously, the maximum force that can be generated by the CyberGrasp™ is 12 Newtons per finger. A program was created (Appendix A.1) that generated force based on two variables. The first force variable, F_{diff} , depended on the difference in joint angle between the left and right hands.

$$F_{diff} = \text{glove diff} / 90 * \text{maximum assistive force} / 2 \quad (3.1)$$

In Equation 3.1, *glove diff* equals the difference between the average unimpaired finger flexion angle and the corresponding average impaired finger flexion angle and *maximum assistive force* is the largest assistive force necessary to fully extend finger during calibration. The second force variable, F_{alpha} , depended on only the joint angles in the “active” left hand.

$$F_{alpha} = \text{unimpaired finger actual angle} / 90 * \text{maximum assistive force} / 2 \quad (3.2)$$

In Equation 3.2, unimpaired finger actual angle equals the average unimpaired finger flexion and *maximum assistive force* is the largest assistive force necessary to fully extend finger during calibration. These two variables are combined to determine the assistive force provided by the CyberGrasp™, Fassist (Equation 3.3).

$$\text{Total assistive force (Fassist)} = F_{\text{diff}} + F_{\text{alpha}} \quad (3.3)$$

Various configuration files were used, depending on the length of time desired for each subject to engage in the experiment (Appendix B). Generally, subjects participated in 30 or 45 minute sessions, in which three to five minute movement time blocks were interspersed with one minute rest breaks. Subjects were also given the option to participate in two 30 minute sessions, with one five to ten minute rest break in between sessions. During the rest breaks, the subject remained seated, with all experimental equipment on their hands. They were allowed to look about the room and engage in conversation with the experimenters. They were also allowed to slightly adjust their arm and postural position for comfort. At the beginning and end of the 30 to 45 minute sessions, subjects were asked to try to move their hands simultaneously in the experimental set-up, without any assistive force from the CyberGrasp™. The glove joint position data from these “active” initial and final portions were used as an outcome measure to determine whether the subjects’ active movement improved after the session of robotic assistance.

Audio files were created and added in synchrony with the CyberGrasp™ force, so that when the word “open” was heard, the force from the CyberGrasp™ would turn on,

and when “close” was heard, the force from the CyberGrasp™ would turn off. The amount of time allotted to open and close both hands was selected on an individual basis, depending on the subject’s level of spasticity. Subjects with a higher level of spasticity demonstrated a slower response to the assistance provided by the CyberGrasp™, and therefore required a longer amount of time to attain the maximum amount of finger extension on their impaired hand. For example, one subject required a full 4 seconds for the CyberGrasp™ force to open his fingers into the maximum possible extended position. Also, some subjects required increased time to fully flex the fingers from an extended position. The shortest possible amount of time was selected, in order for the subject’s motion to as closely as possible resemble a rhythmic motion, as described above in Section 1.2.2. However, it was also desired to use the lowest possible force from the CyberGrasp™ to assist with finger extension, so as not to promote a stretch reflex in the finger flexors. The amount of force required to obtain maximum finger extension, as well as maximum finger flexion and maximum finger extension were calibrated prior to each session.

An electromyography surface electrode was placed at the muscle belly of the digit flexor musculature to determine active participation after the “close” command, and to examine the existence of a flexor stretch reflex after the “open” command. The Delsys Bagnoli EMG System four channel model was used to collect EMG data. The polycarbonate-housed sensor uses parallel-bar contacts made of pure silver, and has a curved enclosure geometry “designed to maximize skin contact and adhesion while minimizing the negative effects of sweat during vigorous activities” [59]. The receiving electrode sensors were aligned perpendicular to the muscle fibers at the center of the

muscle belly of the flexor digitorum superficialis. Data were collected at a rate of 1000 Hz with a gain factor of 1000. A grounding sensor was placed near the lateral epicondyle at the elbow. The EMG data collection was initiated through the MATLAB graphical user interface prior to the start of the “open” and “close” commands.

The experiment was conducted four days per week over the course of two weeks for each of the three subjects. Pre-experiment measures were completed on the first day, immediately prior to the first experimental session. Post-experiment data was collected approximately one hour after the final experimental session.

The experimental method was piloted with three female subjects prior to the actual experiment, two of which were healthy and one subject who had suffered a stroke and was in the laboratory for the purposes of participating in a separate experiment. The unhealthy pilot subject had right upper extremity movement impairments that were not as severe as the experimental subjects. The pilot subjects donned both right and left CyberGloves® and the CyberGrasp™ on the right hand, and the nature of the experiment was explained verbally to them. No mirror was used during this pilot study, therefore, the subjects had full view of both hands the entire time. EMG electrodes were not used in the pilot testing. The subjects participated in approximately 5 minutes of hand movement, viewing the words “OPEN” and “CLOSE” on a computer monitor, as visual cues. Auditory cues were added at a later time. Subjects were instructed to try to move both hands simultaneously, and also to try to move both hands differently from each other, to feel the changes in force from the CyberGrasp™. The three pilot subjects completed a pre-experiment questionnaire (Figure 3.4).

Did you feel any discomfort when the devices were placed on your hands?	YES	NO
Did you feel any discomfort during the experiment?	YES	NO
Did you understand the directions given before the experiment?	YES	NO
Were you able to easily follow the directions on the screen?	YES	NO
Did you have any trouble moving your hands in-sync with each other?	YES	NO
Comments: _____		

Figure 3.4 Pre-experiment questionnaire.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Pilot Results

All three of the pilot subjects reported no discomfort from the experiment. They said they understood the verbal directions given to them, were able to follow the directions on the computer screen, and had no trouble moving their hands in synchrony.

4.2 Experimental Results

The experiment was subsequently initiated with the full set-up described in the “Methods” section above. There were no special instructions given to the subjects in regard to activity or exercise outside of the laboratory, with the exception of Subject 2. The first day of the experiment, the experimenter noted difficulty fitting the subject’s affected hand into the CyberGlove® and CyberGrasp™ devices due to increased spasticity in the subject’s hand. Subject 2 was instructed to wear a resting-hand splint, which he already had at home, for approximately 1.5 hours prior to participating in the experiment. Use of the resting hand splint improved the ease of placing the CyberGlove® and CyberGrasp™ onto his affected hand at the beginning of each day.

Outcome measures for the experiment included the following: the Jebsen Test of Hand Function, the Ashworth Scale, the Chedoke McMaster Stroke Assessment Impairment Inventory Hand Stage, grip strength (measured by a hand dynamometer), and range of motion measures taken manually with a goniometer. Pre and posttest measurements and data collection were done by the primary investigator, who is also a

licensed and experienced Occupational Therapist. The investigator was not blinded to the study. Pre-experiment testing was done on the first day of the experiment, prior to participation in the bilateral mirror activity. Post-experiment measures were done on the last day of the experiment, following a rest break of approximately one hour.

The Jebsen Test of Hand Function is a clinical assessment tool that is used to assess an individual's hand function. There are seven subtests that reflect a range of functional movements of both upper extremities. Each section is scored based on the amount of time in which the subject completes the given task, with a 2-minute time limit. Level of disability can be interpreted depending on the amount of time it takes to complete the subtests. Interrater reliability has been established for the test, with the interclass coefficient ranging from 0.82 to 1.00 for the seven subtests. Test-retest reliability was studied and the Pearson product correlation ranged from 0.84 to 0.85. Correlations between the Jebsen Test of Hand Function and the Klein-Bell scale indicate that the Jebsen Test of Hand Function is reasonably valid.

Table 4.1 provides pre- and post-experiment scores from the Jebsen Test of Hand Function. In pre-testing, Subject 1 was unable to perform the Beans, Cards, Checkers or Heavy subtests with his impaired, previously dominant, upper extremity. He was able to pick up the two bottle caps in the Small subtest, but was not able to manipulate pennies or paper clips with his right hand. He was able to completely transfer four cans with his right arm in the Light subtest, but was unable to completely transfer the can which was closest to his body. During post-testing, Subject 1 showed improvement in the Light subtest, in that he was able to completely transfer all of the cans with his impaired side within the allotted time. His right-hand performance on all other post-subtests was

similar to pre-testing and he was unable to achieve a score on any other subtest besides the Light subtest.

Subject 2 was unable to perform any subtests with his impaired hand on pre-testing except for the Light subtest. He was able to completely transfer all of the cans on one trial within the two minute time limit. On post-testing, however, he was able to pick up transfer two bottle caps with his right hand within 45 seconds on all three trials of the Small subtest. He had been unable to transfer any objects on pre-testing. In the Beans post-test, he was able to pick up and transfer four beans with the spoon in his right hand,

Table 4.1 Jebsen Test of Hand Function Scores

	Subject 1		Subject 2		Subject 3	
	Pre	Post	Pre	Post	Pre	Post
Unimpaired (Left)						
Small	11	9	6	6	9	9
Beans	13	12	8	9	10	NT
Cards	5	6	3	3	5	5
Checkers	5	3	4	9	NT	4
Heavy	6	8	11	NT	NT	NT
Light	6	23	4	4	NT	NT
Impaired (Right)						
Small	120	120	120	120	120	120
Beans	120	120	120	120	NT	NT
Cards	NT	120	120	120	59	54
Checkers	120	120	120	120	120	59
Heavy	NT	NT	NT	NT	NT	NT
Light	120	37	115	120	NT	NT

Pre-experiment and post-experiment Jebsen Test of Hand Function average scores. Scores are given in seconds. NT = Not Tested

on the first trial. On the second post-test trial, he was able to pick up and transfer two beans. During pre-testing he was unable to pick up any beans with the impaired side. Following the experiment, Subject 2 was able to pick up and partially stack two checkers with his right hand, whereas in pre-testing he was unable to pick up any checkers with that hand. His right-handed performance in the other subtests was similar in pre- and post-testing.

As compared to before the experiment, Subject 3 showed a slight improvement in speed when flipping cards over with his right hand, in the Cards post-test. He was also able to complete three trials of the Checkers subtest with his impaired hand, which he was unable to do prior to the experiment.

The Ashworth Scale (Table 4.2) is a measure of the amount of spasticity in a joint. An examiner using the Ashworth Scale determines the amount of resistance in a joint when manually stretching the soft tissue, and then grades this resistance on a scale of one to five. In order to properly scale finger spasticity, the elbow is placed in as much extension as possible, and the forearm is placed in neutral. The fingers are placed into full flexion and then all fingers are extended at once to a position of maximum possible extension. The Ashworth Scale is one of the most universally recognized assessments of spasticity, although it has been subject to criticism due to its subjective nature. Brashear et. Al showed good interrater and intrarater reliability when using the Ashworth to assess wrist, finger and elbow spasticity [60].

The Chedoke McMaster Stroke Assessment (Chedoke Assessment) is another neurological assessment that can be used to determine level of disability with the stroke population. Its reliability and validity has been proven in research studies [61].

Table 4.2 The Ashworth Scale

1.	No increase in muscle tone.
2.	Slight increase in tone giving a “catch” when affected part is moved in flexion or extension.
3.	More marked increase in tone but affected part is easily flexed.
4.	Considerable increase in tone; passive movement difficult.
5.	Affected part is rigid in flexion or extension.

Source: B Ashworth, “Preliminary trial of carisprodal in multiple sclerosis,” *Practitioner*, vol. 192, 1964, pp. 540-542.

In this experiment, only the Hand Stage of the Impairment Inventory of the Chedoke Assessment was used. There is also an Activity Inventory portion of the Chedoke Assessment which consists of a Gross Motor Function Index and a Walking Index. The Activity Inventory was not used in this experiment, as gross motor skills and walking ability were not expected to change from the experimental activities.

Pre- and post-test measures of grip strength, Ashworth Scale Stage and Chedoke McMaster Stroke Assessment Hand Stage for the three subjects are given in Table 4.3. It should be noted that Subject 2 showed improvement in Chedoke Stage, moving from a 2 to a 3. This was due to improved active wrist extension, which the patient did not have prior to the experiment. This subject showed maximal finger movement, both passive and active, when positioned in wrist flexion, elbow extension and approximately 80 degrees of shoulder flexion. When positioned in a similar fashion to the other subjects, his passive finger extension was limited, even with a maximal force from the CyberGrasp™ exoskeleton. Therefore, he was positioned in this alternative way for the duration of the experiment. It is possible that the subject engaged in some form of

tenodesis motion in order to actively close his hand, thereby improving the strength of the wrist extensor musculature. When observing the subject during the experiment and watching video taken of his movement however, he maintains his wrist at approximately 70 degrees of wrist flexion, disproving this supposition.

Table 4.3 Grip Strength, Ashworth Scale and Chedoke Assessment Stages

	Subject 1		Subject 2		Subject 3	
	Pre	Post	Pre	Post	Pre	Post
Grip Strength, Left (unimpaired)	91	86	100	105	78	72
Grip Strength, Right (impaired)	44	43	11	10	22	19
Ashworth Stage	3	3	3	3	1	1
Chedoke Stage	3	3	2	3	4	4

Pre-experiment and post-experiment measures of bilateral grip strength (as measured by a dynamometer, average of 3 measures is shown), Ashworth Scale Stage, and Chedoke McMaster Stroke Assessment Hand Stage, for all three subjects.

It is also noted that, with the exception of Subject 2's left hand, bilateral grip strength decreased in all three subjects. This may be due to muscle fatigue as the post-test measures were done on the same day as the last session of the experiment.

Other outcome measures for the experiment are the range of motion data collected by the CyberGlove® technology, force data measures provided by the CyberGrasp™, and EMG data. Figure 4.1 illustrates the master-slave relationship of the experimental system. It indicates that the force from the CyberGrasp™ increases as the joint angle differences from the gloves increase, as anticipated. This relationship allowed bilateral synchronous movement of the subjects' two hands.

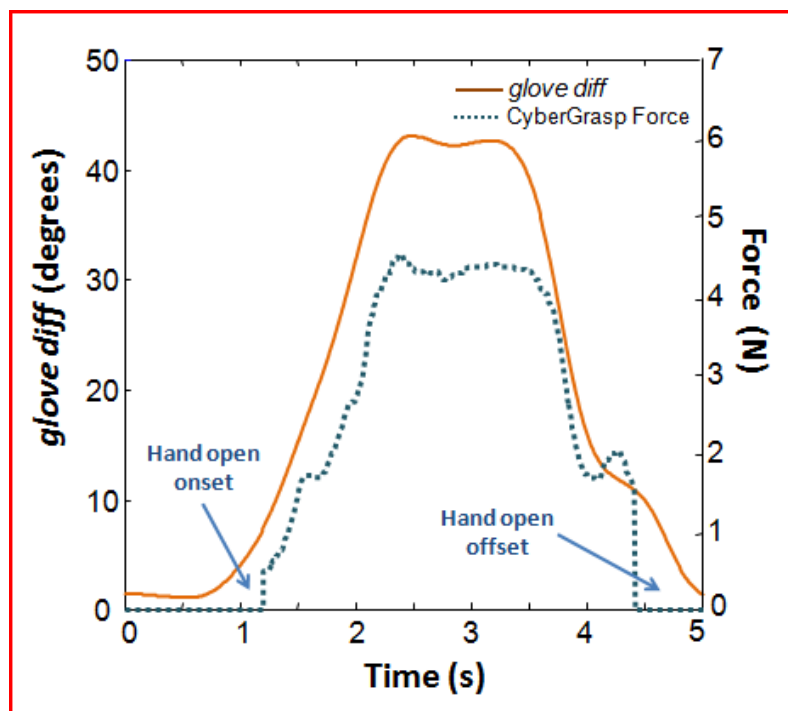


Figure 4.1 This graph illustrates the functionality of the system, in that as the difference in joint angle between the two hands (*glove diff*) increases during a subject's attempt to open both hands, the Force provided by the Cybergrasp™ increases to assist the impaired fingers to fully extend. *Glove diff* and Force return to zero when both hands arrive at full extension. Joint angle data from the index finger of each hand of Subject 1 was used in this graph.

There was some wear and tear on the CyberGrasp™ during the experiment, as some subjects required a large amount of repetitive force to be exerted in order to assist the fingers into a fully extended position. One of the cables that provided the assistive force broke, and required repair. There was also some noted wear on the CyberGloves®, especially the glove required for the subjects impaired hand. In order to don the glove over the hand with increased spasticity, it sometimes required pulling and stretching the material in ways not intended by the manufacturer.

For certain subjects, the finger loops of the CyberGrasp™ did not fit properly. At times, the distal finger loop for the thumb was not attached during the experiment, as it

was too small. Larger finger loops delivered by the manufacturer were also a poor fit for one subject. It should be noted that there is no way to record the fit position of the CyberGrasp™ for each individual, so the fit was re-adjusted daily for all three subjects. Therefore, there may have been some variability in the force line of pull or the amount of pressure of the CyberGrasp™ device on the CyberGlove® sensors from day to day. This variability in fit could cause small changes in joint angle measurements.

The following graphs (Figure 4.2 through Figure 4.4) illustrate the changes in joint angle of one finger of each subject, on days when an initial active trial and a final active trial were successfully recorded. The finger that was analyzed graphically was chosen by the experimenter based on video analysis. The finger that appeared to demonstrate the most active movement for each subject was analyzed. Joint angle closer to zero represents a joint position closer to the maximum calibrated extension. A higher joint angle value represents a greater degree of joint flexion.

As shown in the graphs below, there appeared to be no consistent pattern of change in average joint angle of one finger within or across subjects, when comparing the initial and final active trials of individual 30 minute sessions. The graphs that show the most change from flexed to extended finger position appear to be from Subject 2, Day 4 and Day 8; and from Subject 3, the first 30 minute session of Day 8. When analyzing this data, it is difficult to make any kind of statement in regards to the ability of the set-up to reduce spasticity in the impaired hand.

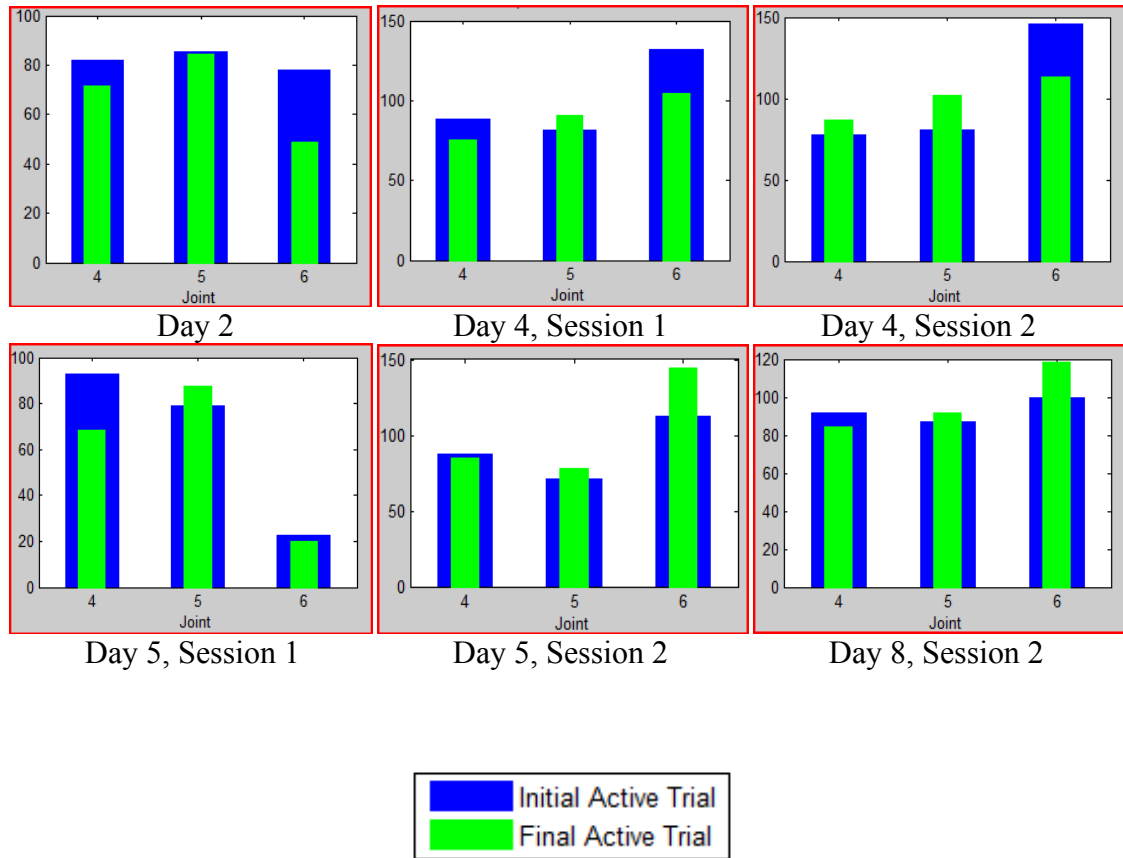


Figure 4.2 Average index finger joint angle for Subject 1, at sequential days of the experiment. The x-axis identifies the joint of the index finger, 4 being the MP, 5 the PIP and 6 the DIP joint. The joint angle (in degrees) is represented by the y-axis. A joint angle of zero represents maximum joint extension, and the number increases in value as joint angle flexion increases. Session 1 indicates the first 30 minute session, Session 2 the second 30 minute session.

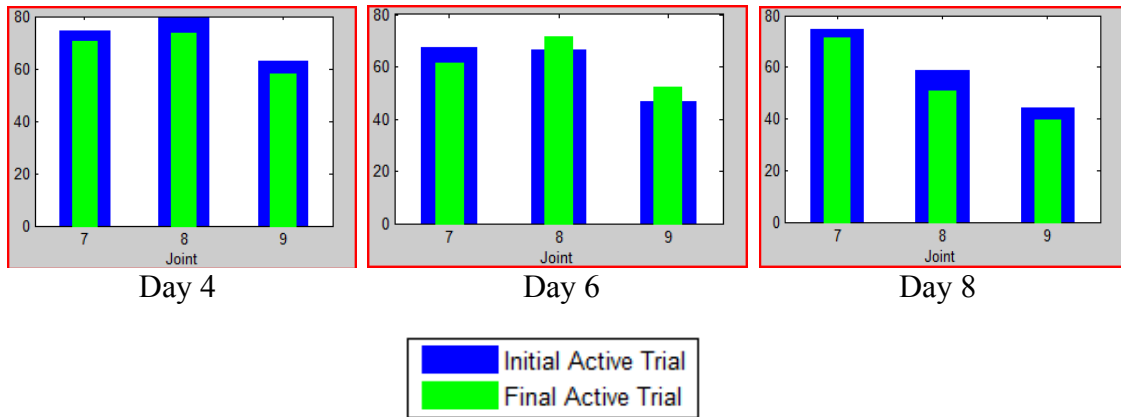


Figure 4.3 Average middle finger joint angle for Subject 2, at sequential days of the experiment. The x-axis identifies the joint of the middle finger, 7 being the MP, 8 being the PIP and 9 the DIP joint. The joint angle (in degrees) is represented by the y-axis. A joint angle of zero represents maximum joint extension, and the number increases in value as joint angle flexion increases.

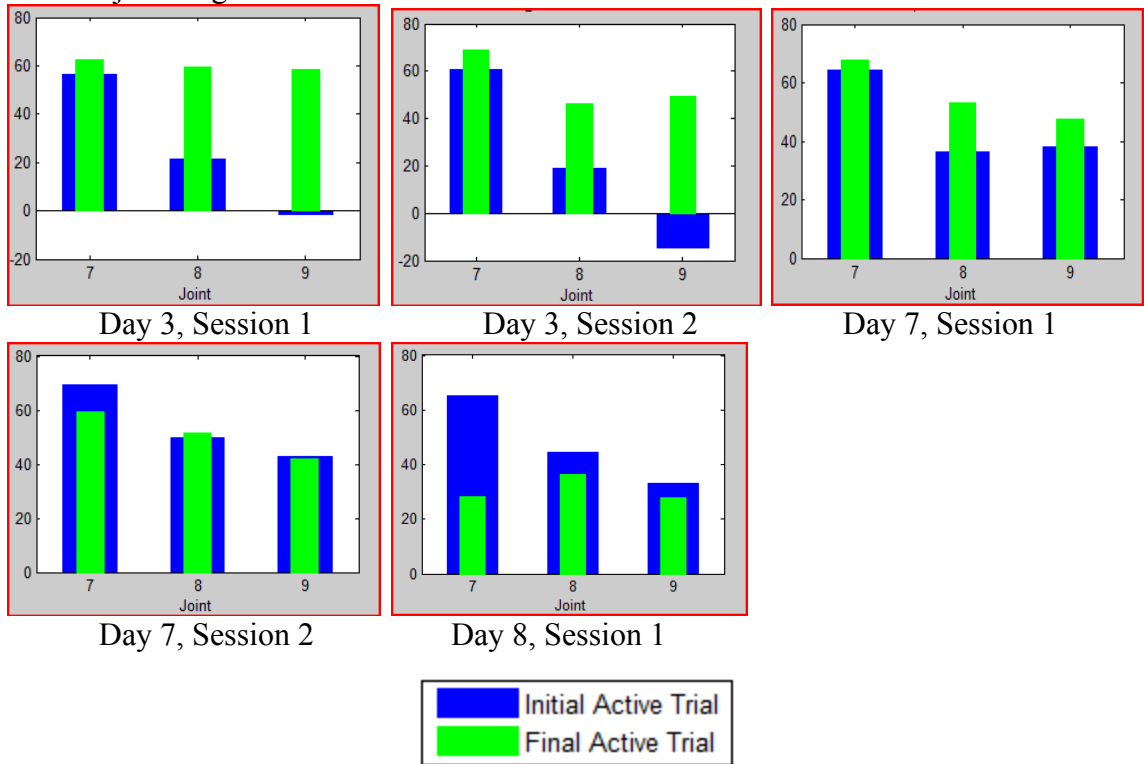


Figure 4.4 Average middle finger joint angle for Subject 3, at sequential days of the experiment. The x-axis identifies the joint of the middle finger, 7 being the MP, 8 being the PIP and 9 the DIP joint. The joint angle (in degrees) is represented by the y-axis. A joint angle of zero represents maximum joint extension, and the number increases in value as joint angle flexion increases. Session 1 indicates the first 30 minute session, Session 2 the second 30 minute session.

Analysis was also done to determine, not simply the average change in joint angle, but more specifically the average change in finger extension range. This was determined through the assistance of a publicly available MATLAB peak detection code, which aided in calculating the range of motion from maximum joint flexion to maximum joint extension. Results are as follows, in Tables 4.4 through 4.9. Occasional technical difficulties with running the computer programs prevented collection of a complete data set.

Trial 0 and Trial 10 were trials in which the CyberGrasp™ force was turned off, and the recorded joint motion was due to only active movement initiated by the subject's own muscle activity. Subjects 1 and 2 both show a slight increase in active extension, when comparing Trial 0 with Trial 10, with an average increase of approximately 3% and 5% respectively at the analyzed joints. However, data from Subject 3 showed a decrease in average active extension of about 5% at the analyzed joint when comparing the first and last active trials. Subject 2 shows an improvement in active extension over the 8 days of the experiment in Trial 0, going from 6.63 on Day 1 to 16.32 on Day 8. This pattern was not consistent across subjects.

Trial 2 and Trial 8 were robot-assisted trials. This data is shown to demonstrate the effectiveness of the robot on improving joint extension as intended. It is noted that Subject 1 required less force to demonstrate approximately the same amount of extension on Day 4 as compared with Day 3 (Table 4.5). This could indicate some type of physiological adaptation to the system, such as a decrease in the stretch reflex with use, or a decrease in spasticity in the finger flexors over time. This pattern is not found in Subjects 2 and 3.

Table 4.4 Average Active Joint Extension, Subject 1

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Ave±SD
Average Extension Trial 0	32.14	10.73	ND	7.69	13.04	6.50	25.28	7.35	14.7±10.0
Average Extension Trial 10	35.68	18.79	14.44	12.28	20.45	ND	ND	13.89	19.3±8.63

Average active index MP joint extension (in degrees) for **Subject 1** during Trial 0 and Trial 10. In these trials, there was no assistance provided by the CyberGrasp™. Trial 0 is the first un-assisted trial of one 30-minute session, and Trial 10 is the last un-assisted trial from the same session. ND=No Data.

Table 4.5 Average Robot-Assisted Joint Extension and Force Data, Subject 1

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Ave±SD
Average Extension Trial 2	ND	99.95	81.18	81.42	ND	90.95	22.84	81.30	76.3±27.2
Average Extension Trial 8	ND	93.52	86.74	85.74	ND	92.05	102.42	80.48	90.16±7.6
Average Force Trial 2	3.951	3.392	2.696	2.569	2.599	2.693	3.529	2.98	3.05±0.514
Average Force Trial 8	4.414	2.550	3.153	2.657	2.927	3.248	3.436	2.748	3.14±0.598

Average index MP joint extension (in degrees) for **Subject 1** during Trial 2 and Trial 8, and associated force (in Newtons) provided by the CyberGrasp™. Trial 2 is the first robot-assisted trial of one 30-minute session, and Trial 8 is the last robot-assisted trial from the same session. ND=No Data.

Table 4.6 Average Active Joint Extension, Subject 2

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Ave±SD
Average Extension Trial 0	6.63	ND	8.58	10.76	11.77	14.33	ND	16.32	11.4±3.58
Average Extension Trial 10	ND	ND	ND	19.36	ND	20.18	ND	22.66	20.7±1.72

Average active middle finger MP joint extension (in degrees) for **Subject 2** during Trial 0 and Trial 10. In these trials, there was no assistance provided by the CyberGrasp™. Trial 0 is the first un-assisted trial of one 30-minute session, and Trial 10 is the last un-assisted trial from the same session. ND=No Data.

Table 4.7 Average Robot-Assisted Joint Extension and Force Data, Subject 2

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Ave±SD
Average Extension Trial 2	35.05	ND	71.61	67.08	101.92	56.12	ND	64.74	66.1±21.8
Average Extension Trial 8	46.78	ND	77.12	71.02	110.47	68.60	ND	64.48	73.1±21.0
Average Force Trial 2	1.063	ND	1.515	1.541	1.583	1.330	ND	1.533	1.43±0.199
Average Force Trial 8	1.111	ND	1.668	1.470	1.563	1.328	ND	1.316	1.41±0.199

Average middle finger MP joint extension (in degrees) for **Subject 2** during Trial 2 and Trial 8, and associated force (in Newtons) provided by the CyberGrasp™. Trial 2 is the first robot-assisted trial of one 30-minute session, and Trial 8 is the last robot-assisted trial from the same session. ND=No Data.

Table 4.8 Average Joint Extension and Force Data, Subject 3

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Ave±SD
Average Extension Trial 0	ND	40.10	ND	ND	11.39	8.74	8.34	ND	17.1±15.4
Average Extension Trial 10	ND	ND	9.03	ND	ND	ND	7.58	ND	8.31±1.03

Average active middle finger MP joint extension (in degrees) for **Subject 3** during Trial 0 and Trial 10. In these trials, there was no assistance provided by the CyberGrasp™. Trial 0 is the first un-assisted trial of one 30-minute session, and Trial 10 is the last un-assisted trial from the same session. ND=No Data.

Table 4.9 Average Robot-Assisted Joint Extension and Force Data, Subject 3

	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Ave±SD
Average Extension Trial 2	ND	53.67	35.23	60.34	80.64	86.21	92.34	82.11	70.1±20.8
Average Extension Trial 8	ND	7.85	54.07	66.71	ND	82.34	88.71	87.81	69.6±30.9
Average Force Trial 2	ND	1.567	1.454	1.438	ND	1.510	1.459	1.452	1.48±0.049
Average Force Trial 8	ND	1.306	1.518	1.501	ND	1.488	1.379	1.436	1.44±0.082

Average middle finger MP joint extension (in degrees) for **Subject 3** during Trial 2 and Trial 8, and associated force (in Newtons) provided by the CyberGrasp™. Trial 2 is the first robot-assisted trial of one 30-minute session, and Trial 8 is the last robot-assisted trial from the same session. ND=No Data.

Electromyographic analysis was done for Subjects 1 and 2. A clear and consistent EMG signal was not detected from Subject 3, despite multiple attempts. This was thought to be due to skin movement and associated movement of the EMG electrode away from the muscle belly of the flexor digitorum superficialis. Figure 4.5 shows an analysis of selected EMG data that may indicate a decrease in the stretch reflex of

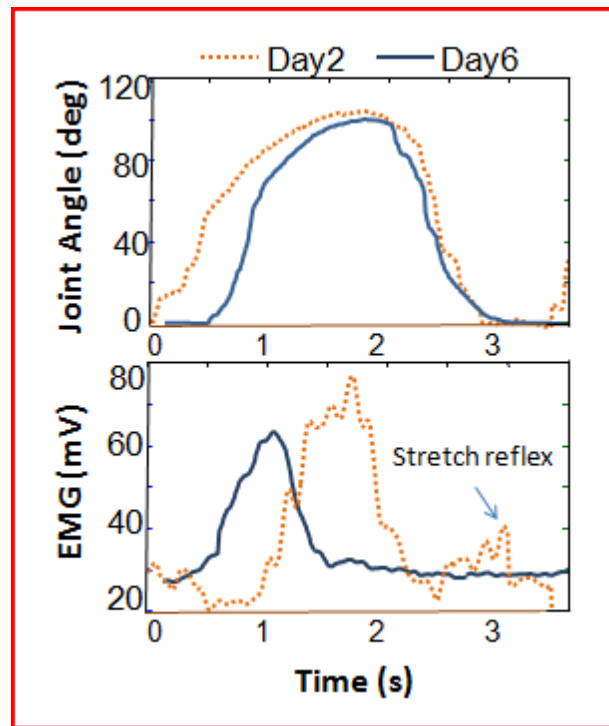


Figure 4.5 Joint angle and EMG responses collected from Subject 1. The top panel shows MP joint angle of the impaired index finger during opening and closing of the hand (average of 20 cycles). The finger starts in full extension, closes actively, and finally is extended passively by the CyberGrasp™. The bottom panel shows mean EMG response to the movement in the top panel. Day 2 response (dotted line) shows strong muscle activity during active flexion movement and a secondary burst in response to passive lengthening. On Day 6 (blue line) there is no second burst at the time of passive lengthening.

Subject 1 in the later days of the experiment (Day 6), as compared to the earlier days (Day 2). Early in the experiment, this graph shows a large spike in finger flexor muscle

activity as the impaired joint angle increases in degrees (increases in flexion) and a second smaller spike in muscle activity prior to the joint angle returning to zero degrees (full extension). In the later days of the experiment, this second spike disappears. This indicates that there is no increase in flexor digitorum superficialis muscle activity when the CyberGrasp™ is applying an extension force to the tissues on Day 6. It can be assumed that the second spike on Day 2 is due to the stretch reflex of the finger flexors as a result of the CyberGrasp™ force. It is proposed that over time, Subject 1 showed a physiological adaptation to the experimental system that caused a reduction in the stretch reflex. On Day 1, Subject 1 also appeared to demonstrate a whole-arm tremor in addition to a stretch reflex response to the CyberGrasp™ force, which declined significantly by Day 2. These physiological adaptations made by Subject 1 deserve further research. There was no clear pattern of this nature found with Subjects 2 and 3.

CHAPTER 5

CONCLUSIONS

This experiment was designed to determine if bilateral arm training could be applied to the distal musculature of the hand in conjunction with mirror image therapy, with the goal of improving hemiparesis after cerebral vascular accident. It was unique, in that most published studies done in the field have applied BAT to the more proximal areas of the arm. It was successful in maintaining the master-slave relationship between the two hands throughout an eight-day experiment, for three different subjects with varied movement patterns. All three subjects were able to view the image of their unimpaired hand for the necessary duration. The subjects reported no discomfort from wearing the robotic equipment, and the only side effect from the activity was mild muscle fatigue.

One disadvantage of the study is that there are two confounding variables, the bilateral arm training and the mirror image therapy individually. It would be a difficult task to find a large enough subject pool with the necessary movement patterns to create a control group. If more subjects were appropriate, it would have been helpful to have one group of subjects that performed only the BAT, with no mirror, and one group that participated in only the mirror therapy part of the experiment, with no robotic devices. An experiment of longer duration would, of course, also be preferred.

Although the CyberGlove® and CyberGrasp™ equipment served the requirements of the experiment, it would be ideal to have only one device on the right hand, which combined the requirements of measuring joint angle and providing assistive force. Also, the best robotic device for this experiment would be one that assists

with not only the motion of extending the fingers, but one that also assists with the motion of finger flexion. This would enable subjects with even less active range of motion in their fingers to be able to participate in the study.

It was noted that, at times, some subjects displayed decreased attention to actively moving their impaired hand. This “slacking” could be decreased by increasing visual or auditory stimulation in some way, to assist the subjects in actively engaging in the activity. Decreased attention to the activity or lower levels of motivation would most likely increase in an experiment of longer duration.

The Jebsen Test of Hand Function, used as an outcome measure, proved to be too difficult for many of the subjects to participate in with their impaired upper extremity. It would have been beneficial to choose a functional assessment tool that requires a lower level of upper extremity coordination, so that small improvements could be more easily compared quantitatively.

Some studies done in the area of mirror therapy have shown improvement in stroke patients with distal sensory impairments. Although none of the subjects used in this study reported any sensory deficits, this is a possible contraindication to the set-up that was used in the experiment. The Cybergrasp loops are tightened in such a way that may cause reduced circulation, especially when used for a prolonged period of time.

In summary, studies done in the past decade show that mirror therapy may be beneficial for patients with hemiparesis after cerebral vascular accident when combined with a conventional rehabilitation program. Scientists, patients and their caregivers alike, anticipate that further research will help determine the scientific and physiological explanation of how and why it works. This experiment combined mirror therapy with

non-invasive robotic assistance to the impaired arm, in order to facilitate synchronous bilateral movement, which has also been shown in research studies to improve upper extremity function after stroke. The experiment was successful in that all three subjects showed some type of improvement, and there were no major side effects from the activity. It is hoped that further studies of this nature will explore the benefits of various combinations of stroke treatments to reduce the disability created by upper extremity hemiparesis.

APPENDIX A

MATLAB PROCESSING AND ANALYSIS CODES

A.1 Conversion of Raw Data Files

When analyzing one day of data files at a time, this code converts the raw kinematics data from all trials into actual joint angle data.

```
%This code converts the raw kinematics data from all trials into actual
%joint angle data, when pointed to one day of data at a time.
%At the end, you can choose which data you want to compare.
%
%Amy Boos NJIT 9/2010

OpenCallib=GloveCalibration(1,:);
CloseCallib=GloveCalibration(2,:);
Diff=CloseCallib-OpenCallib;
OneDegree=Diff/90;

for (i=1:15)
    RCGdata0(:,i)=RCGdata0(:,i);
    CalculationA=RCGdata0(:,i)-OpenCallib(i+15);
    ConvertedAngleR0(:,i)=CalculationA/OneDegree(i+15); %this gives you
    %a matrix, ConvertedAngleRight, which contains all the right hand joint
    %ROM in trial 0.
end
for (i=1:15)
    RCGdata01(:,i)=RCGdata1(:,i);
    CalculationA=RCGdata01(:,i)-OpenCallib(i+15);
    ConvertedAngleR1(:,i)=CalculationA/OneDegree(i+15); %trial 1.
end
for (i=1:15)
    RCGdata02(:,i)=RCGdata2(:,i);
    CalculationA=RCGdata02(:,i)-OpenCallib(i+15);
    ConvertedAngleR2(:,i)=CalculationA/OneDegree(i+15); %trial 2.
end
for (i=1:15)
    RCGdata03(:,i)=RCGdata3(:,i);
    CalculationA=RCGdata03(:,i)-OpenCallib(i+15);
    ConvertedAngleR3(:,i)=CalculationA/OneDegree(i+15); %trial 3.
end
for (i=1:15)
    RCGdata04(:,i)=RCGdata4(:,i);
    CalculationA=RCGdata04(:,i)-OpenCallib(i+15);
    ConvertedAngleR4(:,i)=CalculationA/OneDegree(i+15); %trial 4.
end
for (i=1:15)
    RCGdata05(:,i)=RCGdata5(:,i);
    CalculationA=RCGdata05(:,i)-OpenCallib(i+15);
    ConvertedAngleR5(:,i)=CalculationA/OneDegree(i+15); %trial 5.
```

```

end
for (i=1:15)
    RCGdata06(:,i)=RCGdata6(:,i);
    CalculationA=RCGdata06(:,i)-OpenCallib(i+15);
    ConvertedAngleR6(:,i)=CalculationA/OneDegree(i+15); %trial 6.
end
for (i=1:15)
    RCGdata07(:,i)=RCGdata7(:,i);
    CalculationA=RCGdata07(:,i)-OpenCallib(i+15);
    ConvertedAngleR7(:,i)=CalculationA/OneDegree(i+15); %trial 7.
end
for (i=1:15)
    RCGdata08(:,i)=RCGdata8(:,i);
    CalculationA=RCGdata08(:,i)-OpenCallib(i+15);
    ConvertedAngleR8(:,i)=CalculationA/OneDegree(i+15); %trial 8.
end
for (i=1:15)
    RCGdata09(:,i)=RCGdata9(:,i);
    CalculationA=RCGdata09(:,i)-OpenCallib(i+15);
    ConvertedAngleR9(:,i)=CalculationA/OneDegree(i+15); %trial 9.
end
for (i=1:15)
    RCGdata10(:,i)=RCGdata10(:,i);
    CalculationB=RCGdata10(:,i)-OpenCallib(i+15);
    ConvertedAngleR10(:,i)=CalculationB/OneDegree(i+15); %trial 10.
end

plot(ConvertedAngleR0(:,8),'b')%plots the right middle finger PIP joint
%angle for trial zero, in blue.
hold on
% plot(ConvertedAngleR1(:,8),'b')
% plot(ConvertedAngleR2(:,8),'b')
% plot(ConvertedAngleR3(:,8),'b')
% plot(ConvertedAngleR4(:,8),'b')
% plot(ConvertedAngleR5(:,8),'b')
% plot(ConvertedAngleR6(:,8),'b')
% plot(ConvertedAngleR7(:,8),'b')
% plot(ConvertedAngleR8(:,8),'b')
% plot(ConvertedAngleR9(:,8),'b')
plot(ConvertedAngleR10(:,8),'g')%plots the right middle finger PIP
joint angle for trial 10, in green.

title('Subject Three, Day 8_1: Initial Vs. Final Active Trials')
xlabel('Samples')
ylabel('Middle PIP joint angle')
legend('Initial Active Trial','Final Active
Trial','Location','SouthEast')

```

A.2 Peak Detection

This publically available MATLAB function was used to assist in calculating joint extension range of motion as well as analyze EMG data.

```
function [maxtab, mintab]=peakdet(v, delta)
%PEAKDET Detect peaks in a vector
% [MAXTAB, MINTAB] = PEAKDET(V, DELTA) finds the local
% maxima and minima ("peaks") in the vector V.
% A point is considered a maximum peak if it has the maximal
% value, and was preceded (to the left) by a value lower by
% DELTA. MAXTAB and MINTAB consists of two columns. Column 1
% contains indices in V, and column 2 the found values.
% Eli Billauer, 3.4.05 (Explicitly not copyrighted).
% This function is released to the public domain; Any use is allowed.

maxtab = [];
mintab = [];

v = v(:); % Just in case this wasn't a proper vector

if (length(delta(:))>1
    error('Input argument DELTA must be a scalar');
end

if delta <= 0
    error('Input argument DELTA must be positive');
end

mn = Inf; mx = -Inf;
mnpos = NaN; mxpos = NaN;

lookformax = 1;

for i=1:length(v)
    this = v(i);
    if this > mx, mx = this; mxpos = i; end
    if this < mn, mn = this; mnpos = i; end

    if lookformax
        if this < mx-delta
            maxtab = [maxtab ; mxpos mx];
            mn = this; mnpos = i;
            lookformax = 0;
        end
    else
        if this > mn+delta
            mintab = [mintab ; mnpos mn];
            mx = this; mxpos = i;
            lookformax = 1;
        end
    end
end
end
```

A.3 Calculation of Joint Range of Motion

This MATLAB code calculates and plots the joint extension range of motion of a given joint for a given trial, one subject at a time. It allows multiple days to be calculated simultaneously.

```
%Qinyin Qiu  NJIT 3/2010

clear all
figure
colorin=['r','g','b','k','y','m','ks','k'];
for day = 3
    directory = ['F:\THESIS\AmyKinematicsdatasubjectone\day'
num2str(day) '\RCGdata0.txt'];
    %to do all sesssions, use a * instead of zero.
    files = ls(directory);

    % load calibration file
    Califile = ['F:\THESIS\AmyKinematicsdatasubjectone\day'
num2str(day) '\GloveCalibration.txt'];
    if (exist(Califile))
        Cali = load(Califile);

    end

    if (size(files,1))
        for i=1:size(files,1)
            filename = ['F:\THESIS\AmyKinematicsdatasubjectone\day'
num2str(day) '\ ' files(i,:)]
            X=load(filename);

            %
            filenameL =
['G:\AmyBilateral\AmyKinematicsdata\subject3\day' num2str(day)
'\LCGdata0.txt']
            %
            XL=load(filename);

            % butter filter
            [b,a]=butter(2,1/100);
            Y=filtfilt(b,a,X);

            %
            YL=filtfilt(b,a,XL);

            %
            plot(Y);

            X_Cali_deg = BilaterCalibration(Y, Cali,1); % right hand
            %
            XL_Cali_deg = BilaterCalibration(XL, Cali,2); % left hand
            %
            peak_MaxVal= max(X_Cali_deg(2000:end,4));
            peak_MinVal = min(X_Cali_deg(2000:end,4));
            temp = peak_MaxVal-peak_MinVal;
```



```

4, which is [maxtab, mintab]=peakdet(X_Cali_deg(:,4), 5);%uses column
%the MP joint of the index finger.
% hold off
plot(X_Cali_deg(:,4),colorin(day));
hold on
plot(maxtab(:,1),maxtab(:,2),'r*');
plot(mintab(:,1),mintab(:,2),'g*');
%
range_size = min(size(maxtab,1),size(mintab,1));
range = zeros(1,range_size);
for j = 1:range_size
    range(j) = maxtab(j,2) -mintab(j,2);
end

range_mean(day) = mean(range)

clear range;
clear X_Cali_deg
clear X
clear Y
clear maxtab;
clear mintab;
end
end
end
Title('Subject One, Trial Zero, Days Four through Eight')
ylabel('Index MP Joint ROM'), xlabel('Samples')
legend('Location','SouthEast')

% plot(range_mean);
%
% fname1=['C:\Documents and
Settings\Administrator\Desktop\AmyBilateral\AmyKinematicsdata\subject3\
FingerRange_MCP.txt'];
% save(fname1, 'range_mean', '-ASCII');

```

A.4 Force Analysis

To analyze the force that was applied to each finger by the CyberGrasp™ at various times in the experiment, this code was written in MATLAB.

```
%FORCE: ONE DAY AT A TIME
%This code looks at the first assisted session and the last assisted
%session and compares the force required to extend an individual
%finger. You can choose which finger you want to look at by
%uncommenting that line. The plot shows the difference in force that
%the cybergrasp applied to the finger.
%
%Amy Boos NJIT 10/2010

% Thumbforce2=GRASPdata2(:,1)+GRASPdata2(:,2);
% Indexforce2=GRASPdata2(:,3)+GRASPdata2(:,4);
% Middleforce2=GRASPdata2(:,5)+GRASPdata2(:,6);
% Ringforce2=GRASPdata2(:,7)+GRASPdata2(:,8);
% Pinkyforce2=GRASPdata2(:,9)+GRASPdata2(:,10);

% Thumbforce8=GRASPdata8(:,1)+GRASPdata8(:,2);
% Indexforce8=GRASPdata8(:,3)+GRASPdata8(:,4);
% Middleforce8=GRASPdata8(:,5)+GRASPdata8(:,6);
% Ringforce8=GRASPdata8(:,7)+GRASPdata8(:,8);
% Pinkyforce8=GRASPdata8(:,9)+GRASPdata8(:,10);

Middleforce2act=Middleforce2*12;%mulitplied by 12N to get actual force
Middleforce8act=Middleforce8*12;

plot(Middleforce2act,'b')
hold on
plot(Middleforce8act,'g')
title('Subject One, Day 1: Daily Change in Required Force')%can modify
subject #, Day #, description
xlabel('Samples')
ylabel('Force on Index Finger (N)')%can modify specific digit being
analyzed
legend('Initial Assisted Trial', 'Final Assisted Trial')
```

A.5 EMG Analysis

This code was used to analyze EMG data, to assist in determining the effect of the experiment on the stretch reflex.

```
%Qinyin Qiu  NJIT  2/2010

plot(data)
plot(data(:,3));
hold on
plot(1000*data(:,4), 'r')

data=data(1:17182,:);

for i=1:2:10
    dataNew(:,i)=data(:,i)-mean(data(:,i));
    dataNew2(:,i)=dataNew(:,i)-min(dataNew(:,i));
end

dataNew(:,2)= data(:,2);
dataNew(:,4)= data(:,4);
dataNew(:,6)= data(:,6);
dataNew(:,8)= data(:,8);
dataNew(:,10)= data(:,10);

%=====
[maxtab, mintab]=peakdet(dataNew(:,3), 20)
plot(dataNew(:,3));
hold on
plot(maxtab(:,1),maxtab(:,2), 'r*');
plot(mintab(:,1),mintab(:,2), 'g*');
plot(dataNew(:,4)*1000, 'r');

dataAcum=zeros(2000,2);
for j=1:2:(floor(size(maxtab,1)/2)-1)
    for m=1:(maxtab(j+2,1)-maxtab(j,1))
        dataAcum(m,1)=dataAcum(m,1)+dataNew((maxtab(j,1)+m-1),3);
        dataAcum(m,2)=dataAcum(m,2)+dataNew((maxtab(j,1)+m-1),4);
    end
end
for a=1:size(dataAcum,1)
    dataFinal(a,1) = 2*dataAcum(a,1)/j;
    dataFinal(a,2) = 2*dataAcum(a,2)/j;
end
figure
plot(dataFinal(:,1))
hold on
plot(dataFinal(:,2)*1000, 'r')
title('day8');

%=====
[maxtab1, mintab1]=peakdet(dataNew(:,5), 20)
figure
```

```

plot(dataNew(:,5));
hold on
plot(maxtab1(:,1),maxtab1(:,2),'r*');
plot(mintab1(:,1),mintab1(:,2),'g*');
plot(dataNew(:,6)*1000,'r');

dataAcum1=zeros(2000,2);
% for k=1:(floor(size(maxtab1,1)/2)-1)
for k=1:2:11
    for n=1:(maxtab1(k+1,1)-maxtab1(k,1))
        dataAcum1(n,1)=dataAcum1(n,1)+dataNew((mintab1(k,1)+n-1),5);
        dataAcum1(n,2)=dataAcum1(n,2)+dataNew((mintab1(k,1)+n-1),6);
    end
end
figure
for b=1:size(dataAcum1,1)
    dataFinal1(b,1) = dataAcum1(b,1)/5;
    dataFinal1(b,2) = dataAcum1(b,2)/5;
end
plot(dataFinal1(:,1))
hold on
plot(dataFinal1(:,2)*1000,'r')
title('day2');

%=====
[maxtab2, mintab2]=peakdet(dataNew(:,1), 20);
figure
plot(dataNew(:,1));
hold on
plot(maxtab2(:,1),maxtab2(:,2),'r*');
plot(mintab2(:,1),mintab2(:,2),'g*');
plot(dataNew(:,2)*1000,'r');

dataAcum2=zeros(2000,2);
for q=1:(floor(size(maxtab2,1)/2)-2)
    for w=1:(maxtab2(q+1,1)-maxtab2(q,1))
        dataAcum2(w,1)=dataAcum2(w,1)+dataNew((maxtab2(q,1)+w-1),1);
        dataAcum2(w,2)=dataAcum2(w,2)+dataNew((maxtab2(q,1)+w-1),2);
    end
end
figure
for c=1:size(dataAcum2,1)
    dataFinal2(c,1) = dataAcum2(c,1)/q;
    dataFinal2(c,2) = dataAcum2(c,2)/q;
end
plot(dataFinal2(:,1))
hold on
plot(dataFinal2(:,2)*1000,'r')
title('day1');
%=====

```

```

[maxtab3, mintab3]=peakdet(dataNew(:,7), 20);
figure
plot(dataNew(:,7));
hold on
plot(maxtab3(:,1),maxtab3(:,2), 'r*');
plot(mintab3(:,1),mintab3(:,2), 'g*');
plot(dataNew(:,8)*1000, 'r');

dataAcum3=zeros(2000,2);
for g=1:2:(floor(size(maxtab3,1)/2)-2)
    for h=1:(maxtab3(g+2,1)-maxtab3(g,1))
        dataAcum3(h,1)=dataAcum3(h,1)+dataNew((maxtab3(g,1)+h-1),7);
        dataAcum3(h,2)=dataAcum3(h,2)+dataNew((maxtab3(g,1)+h-1),8);

    end
end
figure
for v=1:size(dataAcum3,1)
    dataFinal3(v,1) = 2*dataAcum3(v,1)/g;
    dataFinal3(v,2) = 2*dataAcum3(v,2)/g;
end
plot(dataFinal3(:,1))
hold on
plot(dataFinal3(:,2)*1000, 'r')
title('day4');

%=====
[maxtab4, mintab4]=peakdet(dataNew(:,9), 20);
figure
plot(dataNew(:,9));
hold on
plot(maxtab4(:,1),maxtab4(:,2), 'r*');
plot(mintab4(:,1),mintab4(:,2), 'g*');
plot(dataNew(:,10), 'r');

dataAcum4=zeros(2000,2);
for g=1:2:(floor(size(maxtab4,1)/2)-2)
    for h=1:(maxtab4(g+2,1)-maxtab4(g,1))
        dataAcum4(h,1)=dataAcum4(h,1)+dataNew((maxtab4(g,1)+h-1),9);
        dataAcum4(h,2)=dataAcum4(h,2)+dataNew((maxtab4(g,1)+h-1),10);

    end
end
figure
for v=1:size(dataAcum4,1)
    dataFinal4(v,1) = 2*dataAcum4(v,1)/g;
    dataFinal4(v,2) = 2*dataAcum4(v,2)/g;
end
plot(dataFinal4(:,1))
hold on
plot(dataFinal4(:,2), 'r')
title('day6');

%=====
figure
subplot(2,1,1)

```

```

plot(dataFinal(:,1), 'LineWidth', 2);
hold on
plot(dataFinal(:,2)*1000, 'r-.', 'LineWidth', 2)
axis([0 1000 -60 60])
subplot(2,1,2)
plot(dataFinal1(:,1), 'b', 'LineWidth', 2)
hold on
plot(dataFinal1(:,2)*1000, 'r-.', 'LineWidth', 2)
axis([0 1000 -60 60])

figure
plot(dataFinal2(:,1), 'y', 'LineWidth', 2)
hold on
plot(dataFinal2(:,2)*1000, 'm-.', 'LineWidth', 2)

clear dataAcum
clear dataAcum1
clear dataAcum2
clear dataAcum3
clear dataAcum4
clear dataFinal
clear dataFinal1
clear dataFinal2
clear dataFinal3
clear dataFinal4
clear maxtab
clear maxtab1
clear maxtab2
clear maxtab3
clear maxtab4
clear mintab
clear mintab1
clear mintab2
clear mintab3
clear mintab4

figure
plot(dataFinal(:,1));
hold on
plot(dataFinal2(:,1), 'r');

plot(dataFinal(:,2)*1000-100);
plot(dataFinal2(:,2)*1000-100, 'r');

```

APPENDIX B

CONFIGURATION FILE EXAMPLE

Example of a 31 minute configuration file. “A” represents the CyberGrasp force being turned off while the subject is opening and closing their hands, “B” represents the force being turned on while the subject is opening and closing their hands, and R represents “rest”; the force being turned off and the subject is not performing any hand movements.

A:3;
R:1;
B:5;
R:1;
B:5;
R:1;
B:5;
R:1;
B:5;
R:1;
A:3.

REFERENCES

1. V.S. Ramachandran and D. Rogers-Ramachandran, "Synaesthesia in phantom limbs induced with mirrors," *Proc. R. Soc. Lond. B. Biol. Sci.*, vol. 263, 1996, pp. 377-86.
2. M. Fabbri-Destro and G. Rizzolatti, "Mirror neurons and mirror systems in monkeys and humans," *Physiology*, vol. 23, 2008, pp. 171-79.
3. G. Rizzolatti and L. Craighero, "The mirror-neuron system," *Annual Review Neuroscience*, vol. 27, 2004, pp. 169-92.
4. D. Ertelt et al, "Action observation has a positive impact on rehabilitation of motor deficits after stroke," *NeuroImage*, vol. 36, 2007, pp. 165-72.
5. S. S□tbeyaz and G. Yavuzer, "Mirror therapy enhances lower-extremity motor recovery and motor functioning after stroke: a randomized controlled trial," *Arch. of Phy. Medicine and Rehabilitation*, vol. 88, 2007, pp. 555-59.
6. G. Yavuzer et al, "Mirror therapy improves hand function in subacute stroke: a randomized controlled trial," *Arch. Phys. Medicine and Rehabilitation*, vol. 89, 2008, pp. 393-8.
7. C. Dohle C et al, "Mirror therapy promotes recovery from severe hemiparesis: a randomized controlled trial," *Neurorehabilitation and Neural Repair*, vol. 23, 2009, pp. 209-16.
8. E.L. Altschuler, S.B. Wisdom, and L. Stone, "Rehabilitation of hemiparesis after stroke with a mirror," *Lancet*, vol. 353, pp. 2035–2036.
9. J.A. Stevens and M.E. Stoykov, "Using motor imagery in the rehabilitation of hemiparesis," *Arch. Phys. Medicine and Rehabilitation*, vol. 84, 2003, pp. 1090–1092.
10. J.A. Stevens and M.E. Stoykov, "Simulation of bilateral movement training through mirror reflection: a case report demonstrating an occupational therapy technique for hemiparesis," *Top. Stroke Rehabilitation*, vol 11, 2004, pp. 59–66.
11. K. Sathian, A.I. Greenspan and S.L. Wolf, "Doing it with mirrors: a case study of a novel approach to neurorehabilitation," *Neurorehabilitation and Neural Repair*, vol. 14, 2000, pp. 73–76.
12. E. Taub, G. Uswatte and T. Elbert, "New treatments in neurorehabilitation founded on basic research," *Nat. Rev. Neurosci.*, vol. 3, 2002, pp. 228-236.
13. S.L. Wolf, C.J. Winstein, J.P. Miller, et al, "Effect of constraint-induced movement therapy on upper extremity function 3 to 9 months after stroke: the EXCITE randomized clinical trial," *JAMA*, vol. 296, 2006, pp. 2095-2104.
14. E. Taub, G. Uswatte, and D.M. Morris, "Improved motor recovery after stroke and massive cortical reorganization following constraint-induced movement therapy," *Phys. Med. Rehabil. Clin. N. Am.*, vol. 14, 2003, pp. S77-S91.

15. E. Taub, G. Uswatte, and R. Pidikiti, "Constraint-induced movement therapy: a new family of techniques with broad application to physical rehabilitation- a clinical review," *J. Rehabilitation Res. Dev.*, vol. 36, 1999, pp. 237-251.
16. Y. Dong, C.J. Winstein, R. Albistegui-DuBois, and B.H. Dobkin, "Evolution of FMRI activation in the perilesional primary motor cortex and cerebellum with rehabilitation training-related motor gains after stroke: a pilot study," *Neurorehabilitation and Neural Repair*, vol. 21, 2007, pp. 412-428.
17. J. Whitall, "Stroke rehabilitation research: time to answer more specific questions?," *Neurorehabilitation and Neural Repair*, vol. 18, 2004, pp. 3-8.
18. L. Oujamaa, I. Relave, J. Froger, D. Mottet, and J.Y. Pelissier, "Rehabilitation of arm function after stroke: literature review," *Ann. Phys. Rehabilitation Medicine*, vol. 21, 2007, pp. 412-428.
19. S. Hesse, C. Werner, M. Pohl, S. Rueckriem, J. Mehrholz, and M.L. Lingnau, "Computerized arm training improves the motor control of the severely affected arm after stroke: a single-blinded randomized trial in two centers," *Stroke*, vol. 36, 2005, pp. 1960-1966.
20. S. Waller McCombe, W. Liu, and J. Whitall, "Temporal and spatial control following bilateral versus unilateral training," *Human Movement Science*, vol. 27, 2008, pp. 749-758.
21. J. Whitall, S. Waller McCombe, K.H. Silver, and R.F. Macko, "Repetitive bilateral arm training with rhythmic auditory cueing improves motor function in chronic hemiparetic stroke," *Stroke*, vol. 31, 2000, pp. 2390-2395.
22. G.N. Lewis and W.D. Byblow, "Neurophysiological and behavioural adaptations to a bilateral training intervention in individuals following stroke," *Clinical Rehabilitation*, vol. 18, 2004, pp. 48-59.
23. J.H. Morris, F. van Wijck, S. Joice, S.A. Ogston, I. Cole, and R.S. MacWalter, "A comparison of bilateral and unilateral upper-limb task training in early poststroke rehabilitation: a randomized controlled trial," *Arch. Phys. Med. Rehabilitation*, vol. 89, 2008, pp. 1237-1245.
24. E. Tijs and T.A. Matyas, "Bilateral training does not facilitate performance of copying tasks in poststroke hemiplegia," *Neurorehabilitation and Neural Repair*, vol. 20, 2006, pp. 473-483.
25. M.H. Mudie and T.A. Matyas, "Responses of the densely hemiplegic upper extremity to bilateral training," *Neurorehabilitation and Neural Repair*, vol. 15, 2001, pp. 129-140.
26. M.E. Stoykov, G.N. Lewis, and D.M. Corcos, "Comparison of bilateral and unilateral training for upper extremity hemiparesis in stroke," *Neurorehabilitation and Neural Repair*, vol. 23, 2009, pp. 945-953.

27. J.J. Summers, F.A. Kagerer, M.I. Garry, C.Y. Hiraga, A. Loftus, and J.H. Cauraugh, "Bilateral and unilateral movement training on upper limb function in chronic stroke patients: a TMS study," *J. Neuro. Sci.*, vol. 252, 2007, pp. 76-82.
28. M.H. Thaut, G.P. Kenyon, C.P. Hurt, G.C. McIntosh, and V. Heomberg, "Kinematic optimization of spatiotemporal patterns in paretic arm training with stroke patients," *Neuropsychologia*, vol. 40, 2002, pp. 1073-1081.
29. S. Schaal, D. Sternad, R. Osu, and M. Kawato, "Rhythmic arm movement is not discrete," *Nat. Neuroscience*, vol. 7, 2004, pp. 1136-1143.
30. K.C. Lin, Y.A. Chen, C.L. Chen, C.Y. Wu, and Y.F. Chang, "The effects of bilateral arm training on motor control and functional performance in chronic stroke: a randomized controlled study," *Neurorehabilitation and Neural Repair*, vol. 24, 2010, pp. 42-51.
31. W. Ching-yi, C. Li-ling, L. Keh-chung, C. Hsieh-ching and T. Pei-kwei, "Randomized Trial of Distributed Constraint-Induced Therapy Versus Bilateral Arm Training for the Rehabilitation of Upper-Limb Motor Control and Function After Stroke," *Neurorehabilitation and Neural Repair*, vol. 25, 2011, pp. 130-139.
32. J. Whitall, S.M. Waller, J.D. Sorkin, L.W. Forrester, R.F. Macko, D.F. Hanley, A.P. Goldberg, and A. Luft, "Bilateral and unilateral arm training improve motor function through differing neuroplastic mechanisms: a single-blinded randomized controlled trial," *Neurorehabilitation and Neural Repair*, vol. 25, 2011, pp. 118-129.
33. C.Y. Wu, Y.W. Hsieh, K.C. Lin, L.L. Chuang, H.L. Liu, C.L. Chen, K.H. Lin, and Y.Y. Wai, "Brain reorganization after bilateral arm training and distributed constraint-induced therapy in stroke patients: a preliminary functional magnetic resonance imaging study," *Chang Gung Medical Journal*, vol. 33, 2010, pp. 628-38.
34. C.P. Latimer, J. Keeling, B. Lin, M. Henderson, and L.A. Hale, "The impact of bilateral therapy on upper limb function after chronic stroke: a systematic review," *Disabil. Rehabil.*, vol. 32, 2010, pp. 1221-31.
35. J.H. Cauraugh and S. Kim, "Two coupled motor recovery protocols are better than one: electromyogram-triggered neuromuscular stimulation and bilateral movements," *Stroke*, vol. 33, 2002, pp. 1589-1594.
36. S. Waller McCombe and J. Whitall, "Fine motor control in adults with and without chronic hemiparesis: baseline comparison to nondisabled adults and effects of bilateral arm training," *Arch. Phys. Med. Rehabil.*, vol. 85, 2004, pp. 1076-1083.
37. P.S. Lum, C.G. Burgar, M. Van der Loos, P.C. Shor, M. Majmundar, and R. Yap, "MIME robotic device for upper-limb neurorehabilitation in subacute stroke patients: A follow-up study," *Journal of Rehab. Research & Devel.*, vol. 43, 2006, pp. 631-642.

38. M. Snyder, "Springing Back to Life: From AVM Stroke to Homecoming Queen in 330 days with the Armeo®Spring," Jan. 2010; <http://www.therapytimes.com/content=0002J84C487EB484408040441>
39. S. Scheible, "Myomo System Can Help More Stroke Patients," March 2011; <http://blogs.wickedlocal.com/goodage/2011/03/15/myomo-system-can-help-more-stroke-patients/#axzz1JLoeflWD>
40. "Bi Manu Track: Rehabilitation of the Wrist," 2011; <http://www.rehatechnologies.eu/en/produkte/bi-manu-track/>
41. "New EMG-Controlled Hand Rehabilitation Robot," Nov. 2010; <http://www.hometelemed.com/2010/new-emg-controlled-hand-rehabilitation-robot/>
42. B.T. Volpe, M. Ferraro, D. Lynch, P. Christos, J. Krol, C. Trudell, H.I. Krebs, and N. Hogan, "Robotics and other devices in the treatment of patients recovering from stroke," *Curr. Atheroscler. Rep.*, vol. 6, 2004, pp. 314-19.
43. B.T. Volpe, H.I. Krebs, and N. Hogan, "Robot-aided sensorimotor training in stroke rehabilitation," *Adv. Neurol.*, vol. 92, 2003, pp. 429-33.
44. M. Ferraro, J.J. Palazzolo, J. Krol, H.I. Krebs, N. Hogan, and B.T. Volpe, "Robot-aided sensorimotor arm training improves outcome in patients with chronic stroke," *Neurology*, vol. 61, 2003, pp. 1604-7.
45. J. Stein, H.I. Krebs, W.R. Frontera, S.E. Fasoli, R. Hughes, and N. Hogan, "Comparison of two techniques of robot-aided upper limb exercise training after stroke," *Am. J. Phys. Med. Rehabil.*, vol. 83, 2004, pp. 720-28.
46. S.E. Fasoli, H.I. Krebs, J. Stein, W.R. Frontera, and N. Hogan, "Effects of robotic therapy on motor impairment and recovery in chronic stroke," *Arch. Phys. Med. Rehabil.*, vol. 84, 2003, pp. 477-82.
47. "MIT-Manus: Robot Assisted Therapy may help Stroke Patients Regain Function," April 2010; <http://www.techshout.com/science/2010/17/mit-manus-robot-assisted-therapy-may-help-stroke-patients-regain-function/>.
48. P.S. Lum, S.L. Lehman, and D.J. Reinkensmeyer, "The bimanual lifting rehabilitator: an adaptive machine for therapy of stroke patients," *IEEE Trans. Rehabil. Eng.*, vol. 3, 1995, pp. 166-74.
49. P.S. Lum, D.J. Reinkensmeyer, S.L. Lehman, "Robotic assist devices for bimanual physical therapy: preliminary experiments," *IEEE Trans. Rehabil. Eng.*, vol. 1, 1993, pp. 185-91.
50. C.G. Burgar, P.S. Lum, P.C. Shor, and M. Van der Loos, "Development of robots for rehabilitation therapy: The Palo Alto VA/Stanford experience," *J. Rehabil. Res. Dev.*, vol. 37, 2000, pp. 663-73.
51. L. Marchal-Crespo and D.J. Reinkensmeyer, "Review of control strategies for robotic movement training after neurologic injury," *Journal of NeuroEngineering and Rehabilitation*, vol. 6, 2009, pp. 1-34.

52. M.J. Johnson, Y. Shakya, E. Strachota, and S.I. Ahamed, "Low-cost monitoring of patients during unsupervised robot/computer assisted motivating stroke rehabilitation," *Biomed. Tech. (Berl)*, vol. 56, 2011, pp. 5-9.
53. A. Brashear and E. Elovic, *Spasticity Diagnosis and Management*, Demos Medical, 2011, p.17-31.
54. "Exam 4 Review: Chapter 13: Proprioception and Types of Reflexes,"
<http://apbrwww5.apsu.edu/thompsonj/Anatomy%20&%20Physiology/2010/2010%20Exam%20Reviews/Exam%204%20Review/CH%2013%20Proprioception%20and%20Types%20of%20Reflexes>.
55. G. Fazekas, M. Horvath, T. Troznai, and A. Toth, "Robot-Mediated Upper Limb Physiotherapy for Patients with Spastic Hemiparesis: A Preliminary Study," *J. Rehabil. Med.*, vol. 39, 2007, pp. 580-582.
56. *CyberGlove® Reference Manual v1.0*, Virtual Technologies, Inc, Palo Alto, C.A., 1991-1998.
57. *CyberGrasp™ User's Guide v1.2*, Immersion Corporation, San Jose C.A., 2000-2003.
58. "CyberGlove® Lets Us Manipulate Digital Objects Physically," Oct. 2010;
<http://www.trendbird.biz/2994>.
59. Delsys® Bagnoli™ EMG System Users Guide, Delsys Incorporated, 2009.
60. A. Brashear, R. Zafonte, and M. Corcoran et al., "Inter- and intrarater reliability of the Ashworth Scale and the Disability Assessment Scale in patients with upper-limb poststroke spasticity," *Arch. Phys. Med. Rehabil*, vol. 83, 2002, pp. 1349-1354.
61. C. Gowland, P. Stratford, and M. Ward, et al., "Measuring physical impairment and disability with the Chedoke-McMaster Stroke Assessment," *Stroke*, vol. 24, 1993, pp. 58-63.