ABSTRACT

GHASSEMI, MOHAMMAD. Design and Control of an Assistive Myoelectric Hand Exoskeleton. (Under the direction of Dr. Kamper).

Stroke is a leading cause of disability in the U.S. Hand impairment is a common consequence of stroke, potentially impacting all facets of life as the hands are the primary means of interacting with the world. Typically, therapy is the prescribed treatment after stroke. However, a majority of stroke survivors have limited recovery and, thus, chronic impairment. Assistive, rather than therapeutic, devices may help these individuals restore lost function and improve independence and engagement in society. Current assistive devices, however, typically fail to address the greatest barriers to successful use with stroke survivors. In the hand, weakness and incoordination arise from a seemingly paradoxical combination of limited voluntary activation of muscles and involuntary neuromuscular hyperexcitability. Thus, profound strength deficits caused by limited voluntary activation of muscle may be accompanied by substantial forces opposing the intended movement. Furthermore, stroke survivors may have difficulty creating the complex activation patterns needed to produce the fingertip forces for object manipulation. Thus, I developed a wearable, assistive hand exoskeleton, the BAC-Glove, to improve hand function in stroke survivors. This assistive device provides active flexion and extension assistance independently to each digit through push-pull cables running along the dorsal side of the hand. This arrangement keeps the palmar surface clear for object manipulation. User control of the BAC-Glove throughout performance of a task can be implemented by decoding electromyographic (EMG) signals. EMG control is customized to the capabilities of each user by examining the voluntary EMG workspace. In order to help train EMG control, I worked to develop a platform for “serious games” that users play by creating specific EMG patterns. In this platform, the EMG vector is mapped to cursor location on a computer screen. By manipulating EMG patterns, the user is able to control the cursor to play a set of games. Modulation of the target EMG patterns encourages exploration of different subspaces of the muscle activation workspace. The feasibility of using the BAC-Glove, in conjunction with the EMG-training platform, was evaluated in a pilot study with neurologically intact participants. Each participant completed 7 training sessions, four with the BAC-Glove and three with the EMG-controlled serious games. Participants were randomly assigned to one of two groups: the Intervention group received EMG training for the same muscles used to control the BAC-Glove, while the Control group received EMG training for more proximal arm muscles. Both groups were able to successfully manipulate the BAC-Glove to perform tasks and both showed significant improvement in control after training. No statistically significant differences, however, were seen between the groups. The BAC-Glove was effective in assisting task performance; future, larger trials with stroke survivors seem warranted.

Design and Control of an Assistive Myoelectric Hand Exoskeleton

by
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DEDICATION

This dissertation is dedicated to my family.

Thank you for your love and patience.

BIOGRAPHY

Mohammad Ghassemi was born in Tehran, Iran. Mohammad completed his schoolwork at Shahid Soltani Middle and High School (a branch of the National Organization for Development of Exceptional Talents) in Karaj. He attended the University of Tehran and received a Bachelor of Science degree in Electrical Engineering-Biomedical Engineering-Bioelectric in 2011. Mohammad attended graduate school at Sharif University of Technology and got his Master of Science in Biomedical Engineering-Bioelectric in 2014. He started his PhD studies at the Illinois Institute of Technology at Chicago under the supervision of Dr. Kamper and continued it from 2016 to 2021 at North Carolina State University.

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CHAPTER 1: INTRODUCTION

1.1 Stroke

Stroke entails the disruption of blood flow to the brain, potentially leading to permanent brain damage. Based on mechanism, two main categories of stroke exist: hemorrhagic and ischemic. Hemorrhagic stroke arises from blood vessel rupture that results in bleeding in the brain, while ischemic stroke is caused by blood vessel blockage restricting the flow of blood [1]. While hemorrhagic stroke damages the brain primarily by causing edema and compressing the brain tissue, ischemic stroke damages neurons mostly through deprivation of oxygen and waste accumulation.

As of 2016, there were 80.1 million stroke survivors in the world [2]. Roughly 17 million strokes occur yearly [2]. The lifetime risk of having a stroke for people 25 years and older is 25% [3]. This risk represents an increase from about 23% in 1990. The population of stroke survivors in the US is roughly 7 million, with 800,000 cases of stroke occurring annually [2]. This equates to one American experiencing a stroke every 40 seconds. Of these 800,000 individuals experiencing a stroke annually, 600,000 will have a first-time stroke [2].

According to the World Health Organization, stroke is the third-leading cause of lost life years and 15th-leading cause of years lived with disability. These rankings have increased from 5th and 19th, respectively, in 2000 [4]. The high incidence rate combined with the prevalence of significant impairment makes stroke the leading cause of major, long-term disability for Americans [2]. While the greatest part of recovery happens during the first 6 months after stroke, stroke survivors continue to recover up to 18 months after stroke [5]. Despite this recovery, 50% of older stroke survivors (onset of stroke at age of 65+) have chronic hemiparesis [6].

Stroke often has a devastating effect on the life of stroke survivors. Only about half of stroke survivors return to work by 6 to 12 months after stroke [7]. Stroke also adversely affects family relationships (marital and parent-child complications), sexual function, finances, and social/leisure activities of stroke survivors.

1.2 Chronic Hand Impairment after Stroke

While a variety of deficits may be produced by the stroke, hand impairment is one of the most common. It is a primary contributor to chronic disability following stroke due to the prominence of the hands in performing activities of daily living [8]. Hand impairment varies widely across stroke survivors, but often manifests in paresis, both in hand opening and in grasp creation [9], delayed initiation and release of grasp [10], poor control of the fingertip force direction [11], and diminished capacity to move digits independently. Paradoxically, stroke survivors simultaneously exhibit a reduced capacity to voluntarily activate the muscles of interest [12] and involuntary hyperexcitability, especially of flexor muscles [13]. Only 55% of stroke survivors will have full manual dexterity 18 months after the stroke [14]. Thus, many stroke survivors must rely on compensatory strategies, especially using the unimpaired hand, to perform self-care and other key tasks.

The ability to compensate for deficits, however, may be limited by the lower extremity impairment that typically accompanies upper extremity impairment in stroke [15]. The lower extremity deficits often mandate the use of mobility aids, such as canes, for standing and gait. These aids must be controlled with the non-paretic hand, thereby affecting the ability of stroke survivors to perform upper extremity tasks while standing or walking. As a result, a number of stroke survivors who could ambulate with assistance end up using wheelchairs in their homes. Extensive wheelchair use may lead to further complications, such as increased risk of depression, premature death, obesity, diabetes mellitus, hypertension, various cardiovascular diseases, osteoporosis, osteoarthritis, muscle and bone atrophy in the legs, and pressure sores [16-18].

1.3 Assistive Devices to Improve Hand Function

The primary treatment after stroke focuses on rehabilitation therapy and restoration of lost sensorimotor control. Unfortunately, despite extensive therapy efforts, recovery after stroke is often limited and, as noted, a majority of stroke survivors will live with chronic impairment. These stroke survivors with the greatest impairment are the ones with fewest treatment options and are typically excluded from research studies. Thus, assistive devices may prove beneficial for restoring function for stroke survivors. Improved functional capabilities achieved with an assistive device could improve the quality of life for stroke survivors and reduce reliance on a caretaker. Due to its functional importance, the hand is an especially important target for assistance.

Deficits are prevalent both in control of digit extension and flexion. In a recent study with 95 stroke survivors with chronic hand impairment, Barry et al. showed that participants produced only 31% of finger flexion torque compared to healthy people and 6% of participants could generate any net finger extension torque [19]. The amount of assistance needed is dependent on the task and can vary with time due to changing levels of coactivation. Thus, ideally, active assistance of both flexion and extension would be provided. An assistive device should also be wearable and portable to be usable on a daily basis and allow performance of daily activities to be beneficial to daily living of users.

A large number of devices have been developed for hand rehabilitation [20], but the majority were intended for therapeutic use, and many are not portable. Wearable gloves that provide assistance through passive elements, such as elastic bands and springs used in the

SaeboFlex and SaeboGlove (Saebo Inc., Charlotte, NC, US) have been created but these typically provide insufficient assistance for the stroke survivors with severe hand impairment [21], those most in need of assistance. HANDSOME, which can provide substantial extension assistance, is bulky and also does not support flexion [22]. Actuated devices have added weight and complexity but are able to vary assistance or resistance depending upon need. Depending on their ultimate goal, current assistive hand exoskeletons may actively assist finger flexion, finger extension, or both.

1.3.1 Active extension assistance

As finger extension is often relatively more impaired than finger flexion, some devices focus on active support of extension [23, 24]. These devices typically create extension by pulling on cables traversing the dorsal side of the digit. While these devices are designed to overcome a primary deficit of stroke survivors, the inability to extend the fingers and open the hand, they lack the capability to help create different grasps and to produce the grip forces to manipulate objects.

1.3.2 Active flexion assistance

While finger flexion force is typically spared to a greater extent than extension, substantial deficits are common. Some stroke survivors are unable to generate any meaningful voluntary flexion force [19]. Others have difficulty properly controlling flexion to grasp and manipulate objects; the misdirection of fingertip forces can cause objects to slip from the grasp [11]. A number of devices, such as pneumatic and hydraulic gloves [25-27], have been developed to provide active assistance of digit flexion. Another group of devices provides flexion assistance through cables running on palmar side of the hand [28, 29]. While this arrangement produces finger flexion, it may interfere with object grasp. In general, while a number of these devices provide some extension assistance through passive elements [30, 31], the level of assistance available is often insufficient due to the large and variable flexor coactivation. Additionally, a number of these devices do not actuate all digits, including the functionally important index finger, used in most of precision grasps [29].

1.3.3 Active assistance of both flexion and extension

Another category of wearable hand exoskeletons assists both flexion and extension of the fingers through cables running along both sides (palmar and dorsal) of the digit. Most of these devices, however, are unable to create enough extension force for stroke survivors [31, 32]. Additionally, the flexor cables are routed along the palmar surface of the hand, potentially interfering with touch and object manipulation [30-43]. The double-cable actuation necessary for pull-pull cable devices requires the use of more motors [36, 37, 39, 40] or a complex mechanism to actuate two opposing cables using one motor [32, 33, 38, 41-43]. Sometimes the latter mechanisms introduce cable slack that can decrease the responsiveness of the device [42, 43].

One design did route the cables from the dorsal side of the palm to the ventral side of the fingers at their base to keep the inside of the palm free [33]. However, sensation in the digits is more critical than that in the hand for object manipulation. Also, in this design the cable must undergo sharp changes in direction that increase cable friction, thereby dissipating the tension produced by the actuators and requiring the use of more powerful and heavier actuators.

Use of Bowden cables, which allows a more proximal location of the actuators (thereby reducing torque imposed on the elbow and shoulder) [36, 37, 41, 43], also introduces considerable friction. The stiffness of these Bowden cables resists the required curvature; this exerts an additional force on the distal part of the device that is perceived as an additional weight on the hand.

Many of these devices actuate a limited number of the fingers [31-33, 36, 37, 39, 40, 42] to reduce weight and complexity, thereby limiting the functional capability of the hand. Other designs couple the movement of multiple fingers, which prevents independent digit and may reduce overall grasp and extension forces, and impairs hand conforming to grasped objects [30, 34-37, 39, 40].

In order to overcome the identified limitations of aforementioned designs, other researchers have sought to actuate degrees-of-freedom (DOFs) in both flexion and extension with a single mechanism. This solution has two advantages compared to the previous devices: first, actuation from the dorsal side alone leaves the ventral side of the hand free to sense and interact with objects; second, mass and bulk are reduced because only one actuator is needed. Arata et al. developed a device using a novel actuation composed of three layers of sliding springs [44]. The mechanism consisted of four rigid guides that were fixed to the back of hand and to each finger segment. The guides were connected at the base using a flat spring. An actuated spring slides between these guides to bend the spring and the joints below them. The use of these flat springs, however, limits the yaw and roll movement of the fingers. Also, the thumb is not actuated, presumably due to its more challenging geometry. This device does not provide independent actuation for any of the fingers. Nycz et al. built upon this design by moving the actuator from the back of the hand to a small backpack using a Bowden cable, in order to reduce the weight of the glove on the hand [43]. The addition of Bowden cable, however, exerts some force on the shoulder and elbow, adding to the weight perceived by the users. Index and middle fingers were controlled together, as were the ring and middle fingers. The thumb remained unactuated.

Mano is a hand exoskeleton that utilizes push-pull cables to actuate all of the digits [45]. The actuators for this device are worn on the chest. Force transmission from the motors is achieved using Bowden cables, connected to the arm and hand at various points and terminating at the fingertips. This design leaves much of the hand unobstructed, thereby facilitating object manipulation, but the ring and little fingers are coupled. The use of Bowden cables introduces friction, and the Mano could only produce a limited maximum flexion fingertip force of 5N.

1.3.4 Proposed Assistive Device

Several key issues must be considered when designing hand exoskeletons for stroke survivors. The hand is a complex and versatile part of body, with 27 DOFs. Creating an exoskeleton that can independently actuate this high number of DOFs in such a limited space is a challenging task that would result in a device that would be too heavy and bulky to be functional. Judicious selection of which joints to actuate independently can reduce device mass while still providing the key finger movements used to perform most daily tasks [46]. Providing independent control of each digit, for example, permits creation of a variety of grasps and the fine adjustment of applied forces within a given grasp. Equally important is the selection of which joints to allow to move freely. Permitting voluntary abduction/adduction of the metacarpophalangeal joints, for example, can provide additional function without adding to the mass of the device.

An assistive device designed to help with activities of daily life should be wearable so users can employ it in their daily lives. Since the mass of a hand exoskeleton exerts considerable torque on the shoulder and elbow, the device should be lightweight to prevent arm fatigue. The other source of fatigue for users in the assistive devices is the unintended torques exerted by components such as Bowden cables. While Bowden cables can decrease the weight of the exoskeleton at the hand by moving the actuators proximally, the cables do have a stiffness that impose an additional moment at the joints that they span. Therefore Bowden cables induce a perceived load on the joints crossed and may limit their range of motion [47].

The function and versatility of the hand is not only due to its DOFs and movement, but also to its sensation. The palmar side of the hands, especially the fingertips, have a high concentration of touch receptors [48]. Hence, the hands convey an acute sense of touch; this sensation plays a vital role in performing different tasks [49]. Therefore, assistive devices should strive to minimize interference with touch perception and sensory feedback. Also, any obstruction of the ventral side of the hand adversely affects the ability to manipulate objects.

Assistive devices should ultimately compensate for the deficits of targeted users. In stroke survivors, finger extension is typically impaired to a greater extent than finger flexion, in part due to substantial involuntary finger flexion. While many assistive devices have been developed for the hand, most are not appropriate for stroke survivors due to the focus on generating grasp forces (flexion) rather than promoting finger extension. Substantial active extension assistance should be available to counteract unintended flexor activity.

The device developed for this dissertation seeks to address the design objectives stated above. The device actuates the digits in both directions by pushing and pulling a pair of flexible cables routed on the dorsal side of the digits inside a conduit formed by a combination of rigid and flexible guides. Thus, the ventral side of the hand and fingers are not blocked. The rigid guides increase the moment arm at each joint to amplify the joint torque produced by a given cable force. This design provides the fingers with substantial flexion and extension assistance. Also, the combination of rigid and flexible guides prevents hyper-flexion or hyper-extension from occurring at the finger joints.

1.4 Control of Assistive Devices

There are many approaches to control assistive devices. One method entails using other parts of the body to create the control signals, such as movement to activate switches [41, 50, 51]. Kudo et al. used an interesting control input based on sensing the elevation of the mandible using two sensors mounted on temple of the user [52]. Subjects would clench their jaw to switch the device between open and close. Other researchers used control of smartphone apps with the unimpaired hand [38] or voice [42]. Mano used a brain-machine control interface for device control [45]. These methods are not ideal, however, because they require another part of the body to provide the control input. In addition to potentially interfering with performance of other tasks, this arrangement places greater mental demands on the user.

Other control methods respond more to the environment than the user. Popov et al. used an infrared distance sensor to detect proximity of an object to the palmar side of the wrist to trigger grasp [33]. Unfortunately, this control method does not take into account the intention of the user. In other words, the user does not have the option to control the kind of grasp or the speed of grasp. Exerted force is limited to pre-programmed levels.

Some control schemes are able to use the paretic distal limb or its connection with the brain to manipulate a device. These approaches can be categorized into three groups: force interfacing, kinematic interfacing and neural interfacing. Force-interfaced devices incorporate a force sensor, such as a force sensitive resistor on the fingertip. Assisted opening or closing of the hand is determined by the value of the measured force [28, 53]. Moromugi et al. used force sensors to measure muscle stiffness, which is related to its activation, to control their device [54]. Nilsson et al. used tactile sensors at the fingertips and a force sensor in the palm to control their device [29]. Unfortunately, some severely impaired stroke survivors are not able to create a measurable force or may unintentionally create a net force in the wrong direction due to involuntary coactivation [19].

In kinematic interfacing, the control is based on the sensed motion of the hand. Some devices use tenodesis control to directly use wrist movement for device control (flexion for hand opening and extension for hand closing) [37, 39]. Some devices sense finger joint kinematics to determine intended movement [33, 53]. There are even cases of combining different methods. Park et al. developed several combination of EMG, finger pressure, and finger posture to control a device; users can select the preferred modes based on their abilities [53]. Like the force interfacing methods, however, these control schemes rely on some level of functionality which might not be present in stroke survivors.

Finally neural interfacing tries to acquire the control signals from the neural signals underlying the control of the limb. The advantage of neural interfacing is that it may better capture user intent than force or kinematics due to sampling multiple components which produce the observed outcome rather than just the outcome itself. Acquiring neural signals directly from the brain or nerves can be quite challenging. Muscles, in contrast, make excellent amplifiers of neural signals [55]. Surface electromyography (EMG) can thus be used to capture neural activation patterns of muscles close to the surface of the skin, such as key actuators of the distal upper extremity. EMG is usually a desirable neural interfacing option for its ease of preparation and the availability of recording sites. The most common EMG control used for assistive devices is mapping the activity of fingers extensors to opening the hand and the activity of fingers flexor to closing the hands [41, 44, 56]. This simple control may be difficult for stroke survivors to implement due to muscle coactivation. Other devices used multiple channels of EMG and pattern recognition to control the device. Pattern recognition methods have a tendency to fail in grasp recognition, however, due to the change of muscle activation patterns necessary to counter gravity for different arm postures.

While EMG provides a natural means of control in other clinical populations, such as individuals with limb loss, stroke survivors often have aberrant muscle activation patterns and difficulties in creating distinct muscle activation patterns [10, 13, 57, 58]. This impairment makes the use of an EMG-controlled assistive device challenging. In order to better implement EMG control of the hand exoskeleton, I developed a platform for training the different activation patterns used in EMG control of the device. While several studies described the use of EMG games to improve the control of prostheses [59-62], these games used simple patterns that may not be appropriate for stroke survivors. The platform developed here supports simultaneous training of up to 8 muscles to enable customization of training to the region of the muscle activation space that can be best explored by each user.

1.5 Dissertation Outline

This project involves efforts to address current limitations in the restoration of hand function in stroke survivors. To achieve this goal, an EMG-controlled hybrid hand exoskeleton designed specifically for stroke survivors was developed. Also, a platform was developed for training users to create and control specific muscle activation patterns. The assistive device and the training platform were used together in a longitudinal study with neurologically intact subjects to evaluate system performance and the effectiveness of the EMG-game platform in improving the control of the assistive device.

In Chapter 2, a training paradigm is presented for improving user control of an assistive device through practice of control of EMG patterns. Based on work from Ranganathan [63, 64], a novel platform was developed for playing serious games. The EMG activation vector was mapped to cursor location on a computer screen. By manipulating the EMG pattern, the user could move the cursor to play different games. This platform addresses limitations in EMG control experienced by stroke survivors and seeks to adopt focus on customized regions in the EMG workspace.

Chapter 3 discusses the development of a novel hybrid hand exoskeleton, the BAC-Glove. The BAC-Glove achieves independent actuation of each digit in both flexion and extension by pushing and pulling a pair of flexible cables running along the dorsal side of the digits. This design provides the fingers with substantial flexion and extension assistance while limiting obstruction of the palmar surface. Also, the combination of rigid and flexible guides prevents hyper-flexion or hyper-extension from occurring at the finger joints.

In Chapter 4, an experiment is presented that was designed to test the utility of the BAC-Glove and the potential for incorporating training with the EMG platform in order to enhance user control. Ten healthy participants underwent 3 sessions of EMG game training interspersed with 4 training sessions with the BAC-Glove. Half of the subjects performed the EMG training with the same distal muscles used to control the BAC-Glove, while a control group used proximal arm muscles with the EMG platform. Evaluations were performed at the end of the first and last sessions to examine user performance with the glove.

Finally, Chapter 5 discusses the lessons learned from the experiment and the development of the BAC-Glove and EMG platform. Recommendations are provided for improving grasp and generating thumb abduction-adduction assistance, as well as decreasing the size and weight of the assistive device. Future directions are discussed for use of the BAC-Glove and for improving incorporation of the EMG game platform.

CHAPTER 2: EMG GAME

M. Ghassemi et al., "Development of an EMG-controlled serious game for rehabilitation,"

IEEE TNSRE

2.1 Introduction

Much of the motor impairment seen after stroke results from aberrant muscle activation. Difficulties range from trouble with fully activating muscles [65] to deactivating them once excited [10]. Excessive coactivation of muscle pairs or groups commonly results in unintended movement direction (e.g., hand closing when trying to open [13]). This coactivation can be exacerbated by repeated attempts to perform a task [57], or by simultaneous activation of other muscle groups such as in the proximal arm [66] or the legs [67]. Furthermore, stroke survivors often exhibit reduced capacity to modulate the level of activation of a given muscle with the task [68] and diminished capability to create distinct activation patterns appropriate for specific tasks [69]. In essence, if one considers the space formed by all potential activation patterns of a group of muscles, the region of that space actually accessible by stroke survivors is drastically reduced [58]. This repertoire of muscle activation deficits affects EMG control schemes as well, impairing control of orthotics and prosthetics. This highlights a critical need for rehabilitation strategies and assistive technologies targeted directly at improving the repertoire of muscle coordination.

Efforts to directly address muscle activation patterns for rehabilitative training, however, have been relatively rare. Unlike motion or force, muscle activity may be difficult to sense in the clinic. While a number of researchers have employed electromyographically (EMG) triggered neuromuscular electrical stimulation [70-72], these approaches typically emphasize the amplification of existing muscle activation patterns rather than attempting to improve movement repertoire by reorganizing existing activation patterns or eliciting novel ones. In fact, typical approaches for EMG-triggered therapy use signals from the non-paretic limb [73] to initiate electrical stimulation (or to drive an exoskeleton), rather than employing signals from the impaired limb.

One method for directly training muscle activation patterns entails mapping them directly to a readily visible output, such as a cursor on a computer screen. This has been done for body-machine interface techniques, including for explorations of motor control [74, 75]. One study used EMG control of a cursor to train reduction in muscle coactivation after stroke [76]. Activations of individual muscles were mapped to cursor movement on the computer screen. For stroke survivors, biceps activation controlled cursor movement in the x-direction and anterior deltoid contraction controlled movement in the y-direction. Training consisted of creating independent activation of each muscle to move the cursor to one of two targets. As a result, participants learned to reduce coactivation of these muscles. While this technique showed promise, training was limited to two muscles, each in isolation, and subjects noted a desire for a more engaging interface.

To address these issues, we developed a new platform for therapy and assistive device training, targeting muscle activation patterns. As we were interested in patterns involving multiple muscles concurrently, we created a mapping scheme involving principal components to project the n-dimensional EMG space (up to 8 muscles) onto the two-dimensional space of the screen. Thus, the user can manipulate cursor location by generating activation patterns defined across multiple muscles. By controlling the mapping between activation patterns and cursor movement, we aim to guide exploration of the activation workspace. To address issues with engagement and encourage exploration of the activation workspace, we created custom exercises, or serious games. Additionally, to facilitate use in those with greater impairment, we developed both a unilateral mode, in which EMG signals from one arm drive the cursor, and a bilateral mode in which a weighted sum of signals from both arms control the cursor location.

To assess system performance, we conducted a pilot study with neurologically intact individuals, half of whom used the bilateral mode and half of whom used the unilateral mode. Based on prior work on learning in body-machine interfaces [77, 78], we hypothesized that EMG control of the cursor would improve across multiple sessions with continued practice. We further expected that users would alter their preferred activation patterns to better align with the mapping between EMG and cursor position.

2.2 System Design

2.2.1 System development

The intent of the system is to encourage exploration of the muscle activation workspace. The user must manipulate EMG signals to control the position of a cursor on the computer screen in order to play serious games.

2.2.2 Selecting target vectors

Two EMG patterns are mapped to the x- and y-axes, respectively, of the computer screen. These target vectors may be selected in a variety of ways. First, they can be entered directly into a custom graphical user interface (GUI) created using the MATLAB GUI environment. Second, the vectors can be read from a file specified through the GUI. Third, to shape the tasks to the capabilities of the user, they can be derived from the user's current activation workspace. For this third approach, the GUI cues the user to perform a brief (1-minute) initial calibration phase in which a variety of muscle activation patterns are created to span the voluntary workspace (Figure 2.1). Principal components (PCs) are calculated from the eigenvectors of the covariance matrix for this data set. From the GUI, the user or therapist is able to select which two PCs will serve as the target vectors, aligned with the two axes of the computer screen. The choice of PCs can be used to encourage exploration of the workspace and to maintain an appropriate level of challenge (e.g., increasing challenge by starting with the two PCs which explain most of the variance in the EMG data set and then progressing to PCs which explain less of the variance). Additionally, the PCs for one limb can be used as the target PCs for the other limb, as might be advantageous for stroke therapy.

Once the target vectors (hereafter generically referred to as PCs) are chosen, they are then used to select the region of the muscle activation space to be explored. The two selected PCs define a hyperplane within the activation workspace (Figure 2.2). This region can be represented

Figure 2.1. Calibration gestures. Examples of some of the hand gestures subjects were cued to perform in order to encourage exploration of the muscle activation workspace.

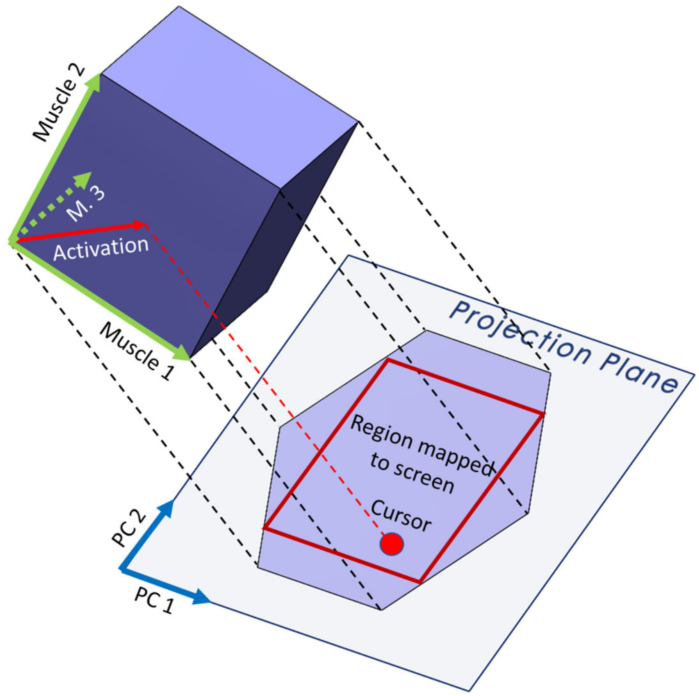

Figure 2.2. Mapping between muscle activation vector and screen. Cursor position is calculated by projection the muscle activation vector onto the projection plane formed by the target PCs.

in two-space as movement along a PC_i-axis and a PC_j –axis. The area within this PC_i-PC_j plane to be used for therapeutic practice can then be demarcated through a custom GUI (Figure 2.3). On the GUI, the therapist selects the desired activation range for each muscle (maximum range of 0%-100%). This forms a hypercube of the allowable activation space. This hypercube is then projected onto the PC-PC plane, thereby creating a polygon within this plane. The therapist then defines the portion of the PC-PC plane to be used by drawing a rectangle within the polygon (Figure 2.3). The larger the side of the rectangle, the greater the activation range of the corresponding PC needed to move the computer cursor fully across the screen.

2.2.3 Mapping EMG to cursor location

Muscle activation is estimated in real-time from filtered EMG signals. At each time point, the vector of normalized EMG activations (each component ranging between 0 and 1) is projected onto the hyperplane formed by the two orthogonal target PC vectors. The location within the hyperplane is then mapped to the corresponding location on the computer screen and the cursor is moved to this position.

For bilateral use, EMG signals in both limbs are used to control a single cursor. A variable relative weighting is applied to the EMG vectors from each extremity to compute the

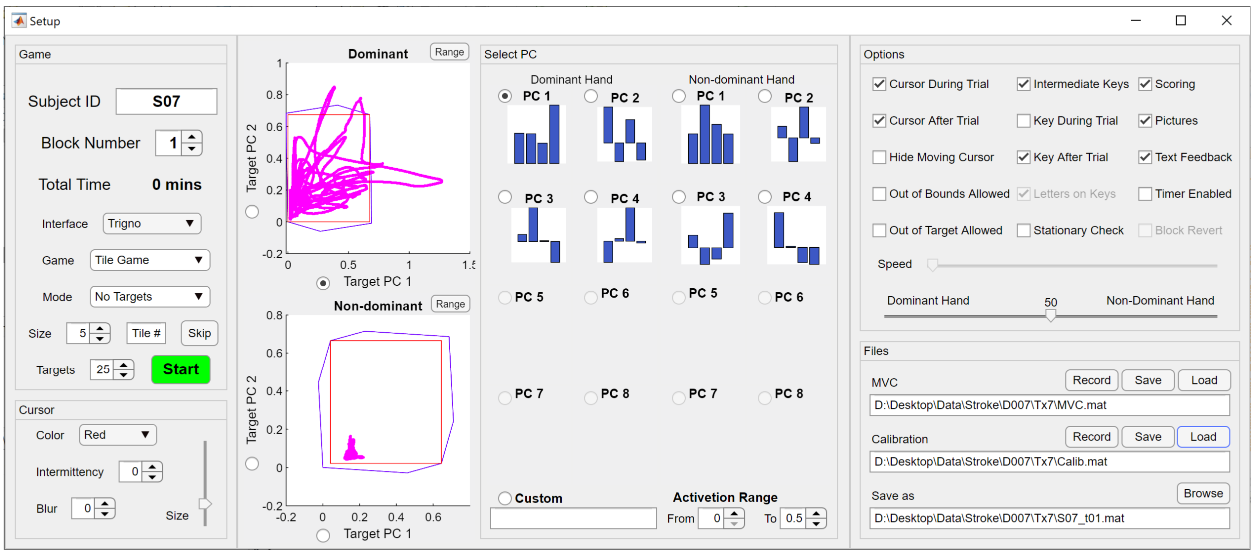

Figure 2.3. Graphical user interface. *Left Pane.* The therapist can select the hardware, game, and game related settings here, as well as control the cursor options. *Center Pane.* Radio buttons in the middle allow selection of target vectors for mapping EMG to the computer screen, either from PCs or from a file or the keyboard. Middle graphs display the PCs computed from the calibration data for the dominant (top) and non-dominant (bottom) hands. Left graphs display the achieved exploration (magenta) within the projection of the hyperplane defined by the selection of the chosen PCs. The polygon (blue outline) shows the projection of the hypercube representing the allowable activation range of each muscle. Through the GUI, one can size the rectangle (red outline) to select the area of the PC-PC plane to be mapped to the computer screen. Slider bar in middle right controls relative weighting of EMG signals for bilateral control. *Right Pane.* This pane has the options of the games and the save and load bottoms for calibration and game data files.

final vector, ultimately used to control the cursor. For example, initially 100% of the weight could be applied to one limb and then gradually over time (either within a session or over several sessions) the weight could be shifted toward the other limb. The weighting is easily adjusted through a slider bar located on the GUI (Figure 2.3). This training paradigm could be helpful for stroke therapy, wherein initial control of the cursor is dominated by the less impaired arm; as performance improves, cursor control gradually shifts to the more impaired limb.

2.2.4 Training Environments

Different training environments were created in Simulink to encourage exploration of the activation workspace. The underlying structure for most of these exercises is a square grid, formed by segmenting the computer screen into an n x n array of square tiles (default for most exercises is 5 x 5). If more or fewer elements are desired, the therapist can change the dimension of the array through the main GUI, which controls selection of exercise type and parameters.

The user manipulates his or her EMG patterns to move the cursor around the tiles. The outer border of the tiles changes color from its default white to cue the user when muscle activation patterns are being created that fall outside of the specified ranges. Whenever one or more muscles is or are activated beyond the range specified (see *Selecting target vectors*), all of the borders turn magenta, indicating that the subjects should relax their muscles. Alternatively, if muscle activation level falls below the minimum threshold, the borders all turn yellow to prompt the user to increase muscle activation. Should the user produce an EMG vector that would drive the cursor outside the array of tiles on the screen, the crossed border turns red.

Five serious games, or exercises, were created to increase engagement and guide exploration. *Picture Reveal* involves moving the cursor to different tiles by providing an appropriate EMG pattern (Figure 2.4a). The visual display provides continuous feedback of the current location of the cursor in relation to the location of each tile. Once the cursor stays on a tile for 0.1s, the tile disappears to reveal part of a picture beneath. By moving to different tiles, the user is able to reveal more of the picture and is free to choose the order of the revealed tiles. *Targeted Picture Reveal* increases the level of difficult by forcing the user to reveal the tiles in a specified order chosen at random by the computer (Figure 2.4b). The target tile turns green to indicate which tile can be revealed. Once the user successfully moves the cursor to the targeted tile and reveals the part of picture behind it, a new target tile, not previously targeted, is then randomly chosen and turned green to continue the game. The exercise continues until all of the picture is revealed.

In the *Maze* exercise, based upon a game written in MATLAB by Rodney Meyer [79], the user must control the cursor in order to find a path through the maze (Figure 2.4c). The cursor cannot move through the walls of the maze, so the user must modify their activation patterns to maneuver the cursor around the walls. Visual feedback of the path chosen is provided by marking the current tile location of the cursor with a red diamond and previously occupied tiles with yellow diamonds. To decrease the difficulty of the exercise, we implemented an option to prevent the cursor from inadvertently losing progress. With this option, a wall is introduced after every correct step of the cursor to prevent movement away from the target (Figure 2.4d). As the user improves, this bumper option can be removed. Additionally, a different maze with a unique solution path is created each time the exercise is called.

The goal of the *Coin Collector* exercise, based on the Asteroids game written by Héctor Corte in MATLAB [80], is to collect stationary coins which appear on the screen by moving the cursor (represented as a spaceship) to the coin without striking moving asteroids (Figure 2.4e).

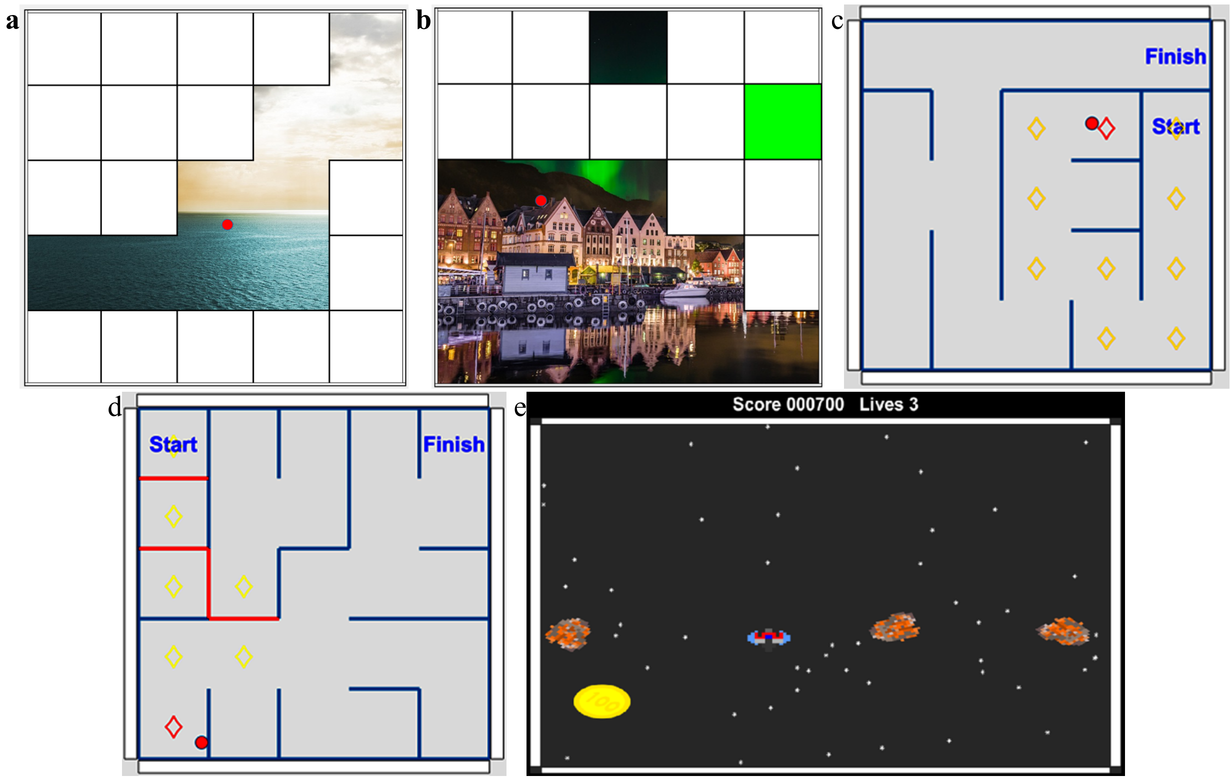

Figure 2.4. Original Serious Games. a) *Picture Reveal* exercise. Moving the cursor into the white square causes the square to disappear, revealing part of the hidden picture. b) In *Targeted Picture Reveal* exercise, the user must erase each square in an indicated order (indicated by the active square turning green). c) In *Maze* exercise, the user enters the maze by moving the cursor which moves freely in the game board to the start square. After that the walls will become active and the user should move the cursor through the maze to the finish square. d) In *Maze* exercise with blocks, red walls block the cursor from going back from the correct path. e) In the *Coin Collector* exercise, the user tries to gather the coins while avoiding the asteroids.

Points are awarded for each coin collected. Challenge is maintained by increasing the number and average speed of asteroids as the user collects more coins.

Explore exercise encourages thorough exploration of the muscle activation space by displaying the extent to which the participant accesses the 4-dimensional EMG space (Figure

2.5a). In this game, the activations of the first two muscles control the position of the cursor in the left grid and the activations of the other two muscles control the position of the cursor in the right grid. The color of the tile in the left grid indicates the extent to which the activation region represented by that tile has been explored within the tiles in the right grid. In this way, the 4-dimensional activation space can be represented on the two-dimensional screen.

Wheel Painting is a game designed to replicate the proposed controller for the BAC-Glove. The left side of the screen is the control part and the right side is the wheel that is controlled by the user. For each target a target sector with a random color and angle is displayed and the wheel is black and set at angle zero. The game has two modes, color selecting and wheel rotating modes. The color selecting mode is selected right after a target appears (Figure 2.5b). The user should select the matching color on the right side of the screen by moving the cursor to its sector and keep it close to the sector's border for one second. If a wrong color is selected the game gives wrong color warning for 5 seconds. After selecting the right color, game enters the wheel rotation mode. In this mode the user can rotate the wheel in the Open and Close directions by moving the cursor to the corresponding sectors (Figure 2.5c). The speed of the wheel's rotation will be relative to the distance of the cursor from the down-left side border of the rotation sectors. If the cursor moves to the red hashed area and stayed there for 1 second, the game returns to the color selection mode and the user should reselect the correct color. When the wheel blade matches the target sector and stays so for three seconds, the target is reached, a new target is displayed, and the game returns to the color selection mode.

To increase the accessibility of the game for users with visual issues, the cursor color and size are also adjustable through the main GUI. Additionally, the GUI provides feedback to the

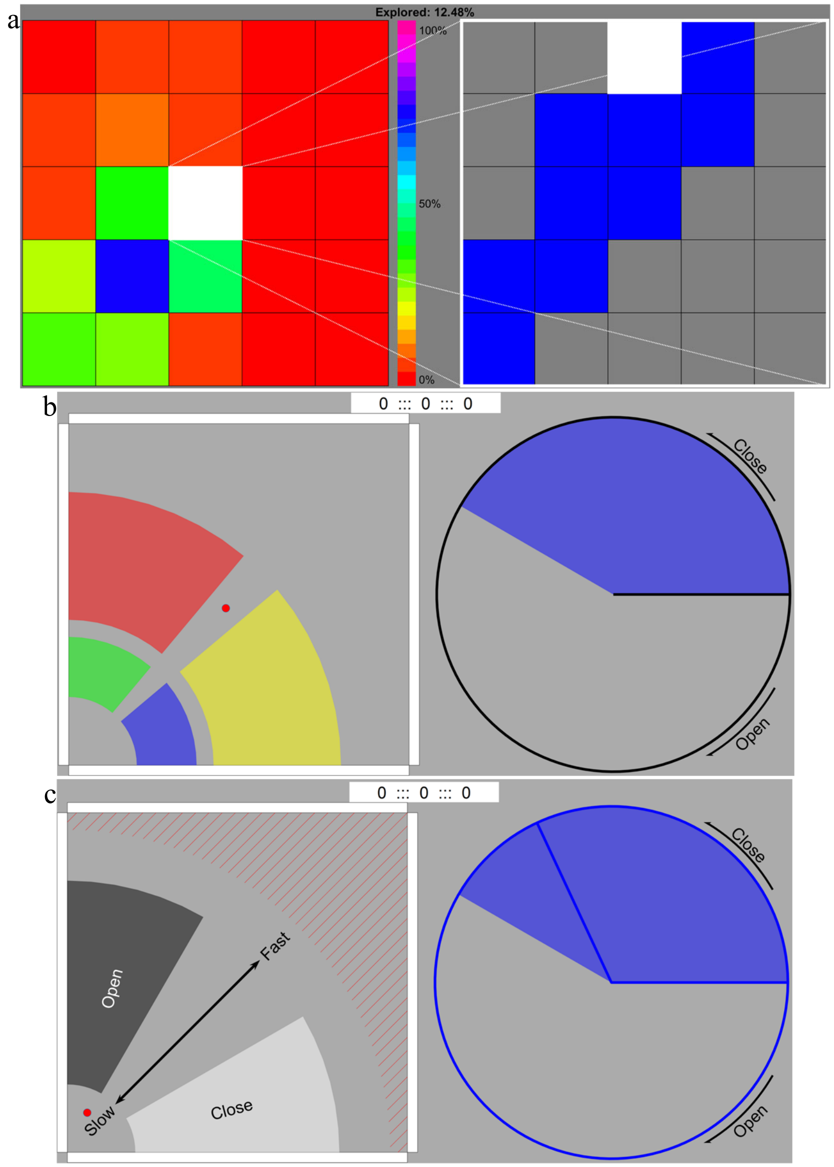

Figure 2.5. New Serious Games. a) In the *Volume Exploration*, activation for two muscles control the cursor location (white tile) on the left plane and activation for other two muscles control the cursor location on the right plane. The color represents the extent to which a certain activation region has been explored. b) In the *Wheel Painting* exercise, the user first selects the color shown on the right of the screen by moving the cursor to the color in the left side of the screen. c) After selecting the correct color, the user rotates the wheel on the right side of the screen to the displayed angle by moving the cursor to the "Open" and "Close" sectors on the left side of the screen.

therapist, by displaying the muscle activations being produced by the user, so that the therapist can guide the user as needed to alter their activation pattern.

2.2.5 Evaluations

All data from each session can be recorded. For example, system parameters can be saved to a file specified through the main GUI for future analysis or use in subsequent sessions. Duration of use, the exercise performed, specified exercise options, activation to computer screen mapping, and criteria of game play can be stored. These data provide information about system usage, difficulty of the game, and progress of the subject. Furthermore, all EMG data are recorded throughout each exercise for future analysis.

We included a test task in the system to assess EMG control of the cursor. This test task is similar to the *Targeted Picture Reveal* exercise in which the computer screen is divided into a 5 x 5 set of tiles without a picture to be revealed thus any target can be repeated multiple times. A total of four of these tiles, representing some of the most challenging movements, are used as targets: upper left, upper right, center, and bottom center (Figure 2.6). For the test, each of the four locations must be reached four times in a specified order. Target order for the 16 total targets is randomized. The system records the total time required to reach all targets.

2.3 Pilot study

2.3.1 Protocol

To assess system performance, we conducted a pilot study with healthy, neurologically intact adults. A total of 20 participants (7 Female/13 Male) were enrolled after providing informed consent in accordance with procedures specified by the Northwestern University Institutional Review Board, which oversaw the study. Mean age was 27 ± 5 years and ranged from 21-40 years. Participants were randomly assigned to one of two groups.

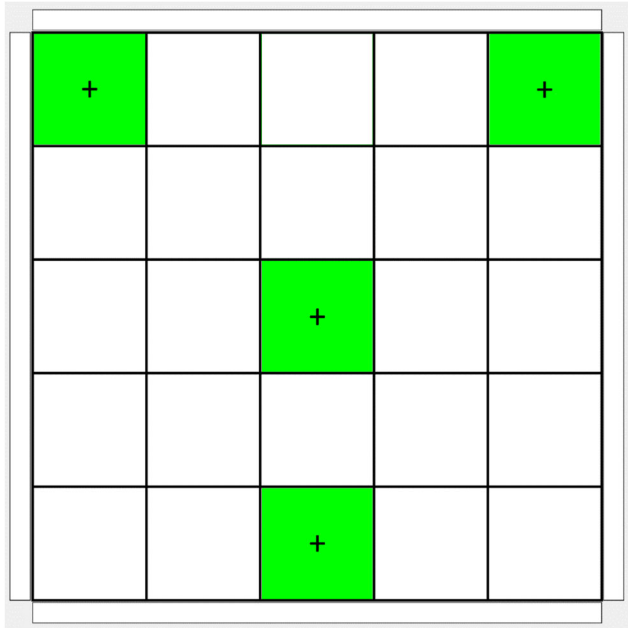

Figure 2.6. Targets in the Test evaluation. Target locations in the game board for the Test evaluation of cursor control. In the actual Test, only one target is illuminated at a time.

In order to simulate a potential therapy paradigm for stroke survivors, in this study the first two PCs from the dominant arm were used as the target vectors for the non-dominant arm. This mimics a scenario in which the activation patterns in the non-paretic arm are used as the target patterns for the paretic arm for stroke survivors

The Unilateral group used only their non-dominant arm to control the cursor location on the screen during the training game play. The Bilateral group used both arms to control the cursor. Cursor position was computed as a weighted sum of the cursor positions defined by the activation patterns in each limb:

$$CP = W_{DH} * CP_{DH} + (1 - W_{DH}) * CP_{NH}$$

where CP is cursor position, W_{DH} is the weighting coefficient of the dominant hand (ranging from 0 to 1), CP_{DH} is the cursor position calculated from the dominant hand EMG, and CP_{NH} is the cursor position calculated from non-dominant hand EMG.

The weighting coefficient W_{DH} was gradually adjusted by a member of the research team from full control by the dominant hand to full control by the non-dominant hand throughout the course of each session. The transition was gradual and uni-directional. As the user gained confidence in curser control, W_{DH} was decreased in 5% – 10% steps.

Four wrist and finger muscles were targeted in each limb. Thus, for the Unilateral group, four muscles in the non-dominant limb determined cursor location, while for the Bilateral group four muscles in each limb potentially impacted cursor location. EMG signals were recorded from extensor digitorum communis (EDC), flexor digitorum superficialis (FDS), extensor carpi ulnaris (ECU), and flexor carpi radialis (FCR) muscles in both arms using active, surface electrodes (Bagnoli, Delsys, Inc., Boston, MA). Electrode placement over these superficial muscles was guided by anatomical landmarks and palpation. The EMG signals were fed into the system for processing, as described in the previous session.

EMG signals were sampled at 1 kHz under control of the Simulink DAQ software. The raw EMG signals were band-pass filtered using a minimum order Butterworth filter with stopband frequencies of 20 and 450 Hz, passband frequencies of 35 and 435 Hz, and stopband attenuation of 20dB. To quantify EMG magnitude, the EMG signals were rectified and low-pass filtered using a minimum order Butterworth filter with bandpass frequency of 1.13 Hz and stopband frequency of 5 Hz. We selected filter parameters to create smooth cursor movement. The EMG envelope was subsequently normalized by the maximum envelope value for the corresponding muscle, as recorded during maximum voluntary contractions (MVCs) performed at the start of each session.

Each of the three training sessions began with a calibration phase. First, EMG signals were captured during MVC in order to normalize the signals. Subjects were asked to create specific gestures using MVC of each of the four muscles of interest. All sampled EMG data were subsequently normalized by the maximum values obtained during MVC contractions.

Next, participants were encouraged to fully explore the muscle activation workspace in order to find the target PCs. Each subject was shown the aforementioned series of gestures and movements (Figure 2.1) and was instructed to replicate them with up to 50% of MVC. The calibration EMG vectors, projected onto the plane mapped to the computer screen, were displayed along with the PCs. Calibration was repeated if necessary to ensure good coverage of the calibration plane.

PCs were computed for the EMG data from this Calibration phase to determine the target activation vectors. For both the Bilateral and Unilateral groups, the first two PCs (the ones explaining most of the variance) for the dominant hand data were employed as the target vectors mapped to the axes of the computer screen.

After completing the Calibration phase, the participant performed the Test with the system (Figure 2.6). The testing was followed by a Training phase in which the participant played a combination of *Tracking* and *Picture Reveal* exercises with the system. At the end of 30-45 minutes of game playing, the subject completed another Test. For both groups, all Tests were performed with the non-dominant hand only.

2.3.2 Analysis

Data from each of the 6 Tests performed over the three sessions were analyzed to examine the impact of training and group on test performance. Time to completion, EMG patterns employed, and cursor kinematics recorded during these phases were analyzed.

First, we wanted to examine whether practice with the system led to improved task performance. The time to complete each of the 6 Testing phases was assessed using a 3-way

(Session x Practice x Group) repeated measures analysis of variance (rmANOVA). The within-subject factors were Session (Day 1, Day 2, Day 3) and Practice (Pre-training, Post-training). The between-subject factor was training Group (Unilateral, Bilateral). The Greenhouse-Geisser correction was used when sphericity assumptions about the variance were violated.

Second, in order to examine potential changes in activation patterns produced by training, we examined EMG signals during the Test. We computed PCs for the EMG signals recorded from the non-dominant arm during each Test. The amount of variance accounted for (VAF) by the first two PCs was computed in order to determine whether these patterns were used more frequently after training. We conducted rmANOVA to examine any effects of Session, Practice, or Group. Furthermore, we compared the target hyperplane formed by the PCs of the dominant hand to the hyperplane created by the PCs from the non-dominant hand by computing the dihedral angle between them. We performed rmANOVA to examine potential effects of Session, Practice, or Group on this dihedral angle.

Finally, we evaluated control of cursor kinematics by computing the mean-squared jerk of cursor movement and the path length of the cursor between targets during each Test. Mean-squared jerk was computed through repeated differentiation and filtering of the original position data [81]. The lowpass filter had the same characteristic as the one used to calculate the activation signal. We computed actual path length between consecutive targets from the cursor displacement and then normalized this value by the Euclidean distance between the target locations (minimum path length is equal to 1). The path lengths were summed across all 16 targets to create a metric for path deviation. We employed rmANOVA to test for effects of Session, Practice, or Group on each of these outcome measures.

2.3.3 Results

All subjects participated in all three training sessions, held over a period of 3-14 days for each subject. Three subjects had incomplete data sets for one or more of the Tests, so their data were excluded from analyses. Data from two other subjects were excluded due to excessive noise in the EMG signals that precluded proper assessment. Data from the remaining 15 subjects (8 in the Unilateral group and 7 in the Bilateral group) were included in the statistical analyses. Sample cursor trajectories for Day 1 pre-training and Day 3 post-training Tests are shown in Figure 2.7. Participants substantially improved control of the cursor, which in turn led to reductions in the time needed to complete the Test. ANOVA results revealed that both Practice (Pre-training, Post training) and Session (Day 1, Day 2, Day 3) had significant effects on completion time ($F(1,13) = 62.730$, $p < 0.001$ and $F(2,26) = 8.358$, $p = 0.002$, respectively) across the two groups. Completion time decreased by a mean of 67% from the first trial on Day 1 to the last trial on Day 3 (Figure 2.8).

Figure 2.7. Participants substantially improved control of the cursor, which in turn led to reductions in the time needed to complete the Test. ANOVA results revealed that both Practice (Pre-training, Post training) and Session (Day 1, Day 2, Day 3) had significant effects on completion time ($F(1,13) = 62.730$, $p < 0.001$ and $F(2,26) = 8.358$, $p = 0.002$, respectively) across the two groups. Completion time decreased by a mean of 67% from the first trial on Day 1 to the last trial on Day 3 (Figure 2.8).

There were no significant differences in time to completion, however, between subject groups ($F(1,13) = 2.598$, $p = 0.131$). Both groups were able to manipulate muscle activation in the non-dominant limb to control the cursor despite the fact that the target activation plane was defined by the PCs from the dominant limb. The Unilateral group displayed slightly greater

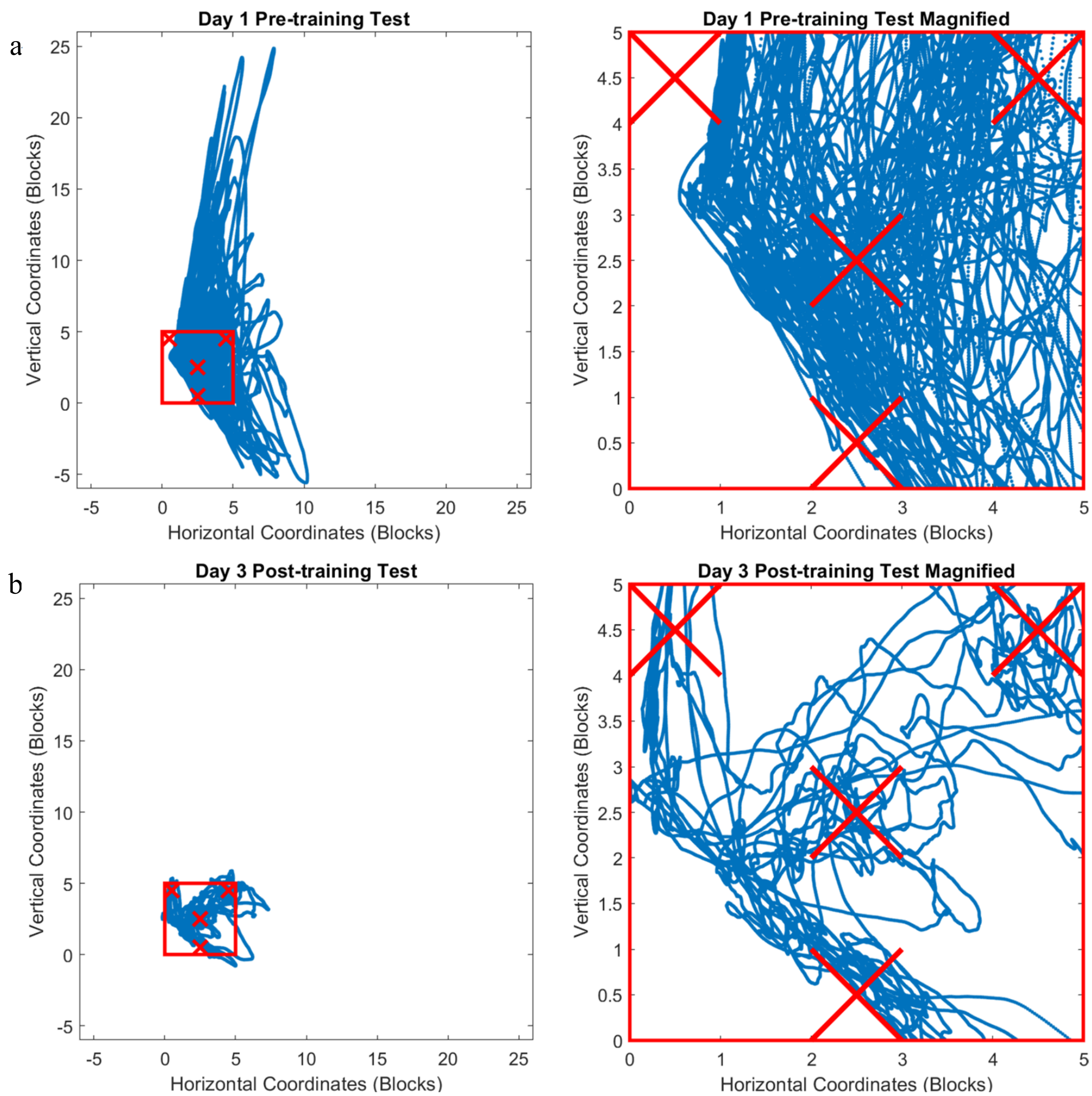

Figure 2.7. Test game cursor trajectories for a single subject. Blue trajectories represent the projected path of the cursor based on the activation patterns produced by a subject performing the Test evaluation shown in Figure 2.4. a) Day 1, Pre-Training and b) Day 3, Post-training. Red square (5 blocks x 5 blocks) indicates the extent of the computer screen (note that visual representation of cursor did not leave the screen during Test) while Xs indicate target locations. First column shows that trajectories traverse far outside the red square for the first Test game but stay largely within the square for the last Test game. The magnified view in the fight column shows that the subject was able to move more directly toward the targets during the final Test session.

improvement on Day 1 (non-significant), but the Bilateral group caught up by Day 2. No interactions were significant.

We anticipated that participants would adapt to favor specific activation patterns that would enhance completing the exercises and with training, more of the variance in EMG data would be explained by the first two PCs. However, neither Session nor Practice had a significant impact on VAF by PC1 ($F(2,26) = 0.148$, $p = 0.863$ for Session and $F(1,13) = 0.033$, $p = 0.859$ for Practice, see Figure 2.9). Furthermore, neither Session nor Practice significantly affected VAF by PC1 and PC2 together ($F(2,26) = 0.663$, $p = 0.523$ for Session and $F(1,13) = 0.004$, $p = 0.950$ for Practice, Greenhouse-Geisser correction). VAF by PC1 and PC2 actually slightly

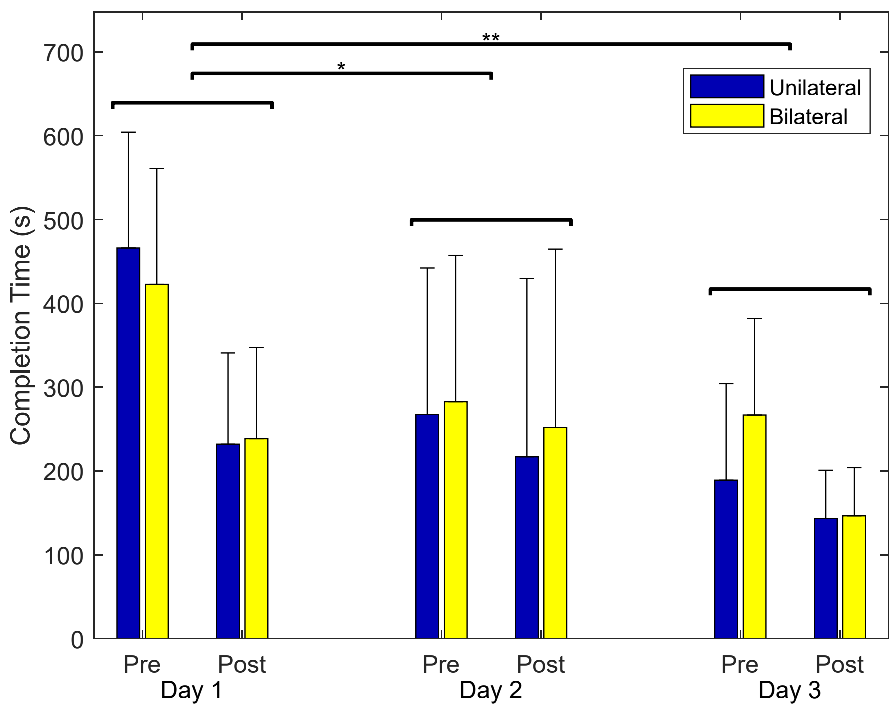

Figure 2.8. **Testing phase completion time.** Time required to complete the randomized, targeted Test sequence of 16 tiles before (Pre) and after training (Post) on each of the three sessions. Across both groups, completion time decreased significantly for both Session and Practice. There was no significant effect of Group.

decreased by an average of 1.3%, from 71.3% to 70.0%, over the three sessions. Subject group (Unilateral vs. Bilateral) did not impact VAF ($F(1,13) = 0.212$, $p > 0.612$ for VAF for PC1 and $F(1,13) = 0.040$, $p = 0.845$ for VAF for PC1 and PC2). All interactions were not significant.

We compared the actual PCs employed by the participants during the Tests with the target PCs by computing the dihedral angle between the hyperplanes formed by the respective sets of PCs (Figure 2.10). While these angles decreased slightly from the first to last Tests, changes were not significant. Neither Session ($F(2,26) = 1.816$, $p > 0.183$) nor Practice (($F(1,13) = 0.014$, $p > 0.909$) affected the angle, which maintained a value of roughly 40°. Group did not affect the angle between the planes, either.

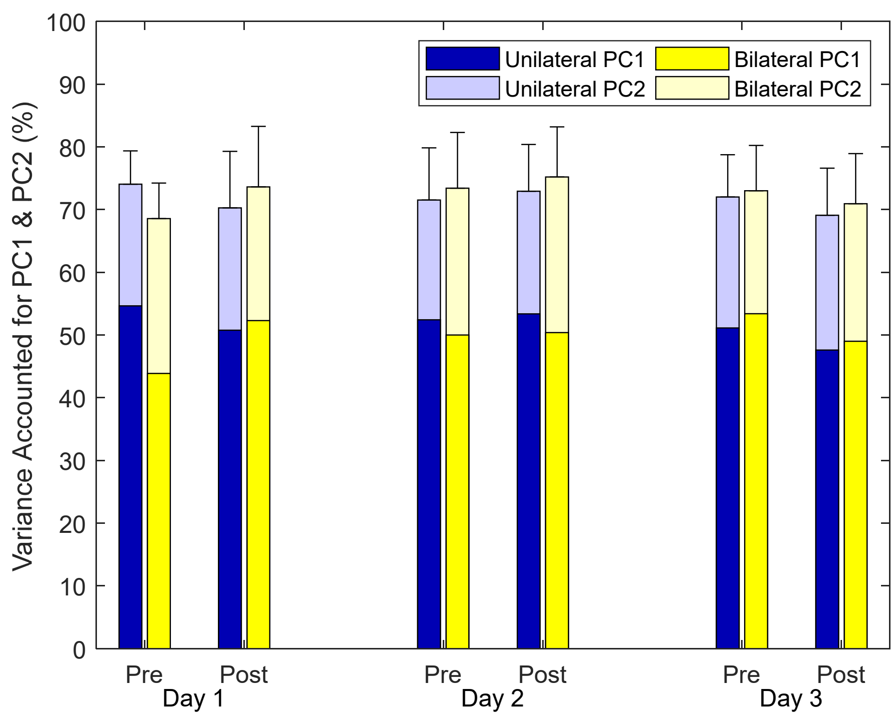

Figure 2.9. **Variance accounted for (VAF) by PCs.** Variance in EMG data recorded during the Test that was explained by PC1 (lower part of bar) and PC1 and PC2 together (full bar). No significant differences were seen across Group, Session, or Practice. Error bars represent one standard deviation of VAF for PC1 and PC2 together.

In contrast, participants exhibited substantially improved cursor kinematics. Total path length decreased by over 75% from the first (920.0) to last (221.3) Test (Figure 2.11). Both Practice and Session significantly affected path length ($F(1,13) = 30.538$, $p < 0.001$ and $F(2,26) = 8.070$, $p = 0.002$, respectively). There were also significant differences between subject groups ($F(1,13) = 5.996$, $p = 0.029$). The Unilateral group showed greater improvement in path length across the sessions, although path lengths for the final session were roughly equivalent for the Unilateral and Bilateral groups due to larger path lengths for the Unilateral group on Day 1 (Figure 2.11). None of the other interaction terms were significant.

Within a given Session, participants also exhibited a reduction in mean-squared jerk of the cursor (Figure 2.12). Across groups, Practice significantly affected mean-squared jerk, with a decrease of 9% ($F(1,13) = 62.6$, $p < 0.001$). There was a significant interaction between Session

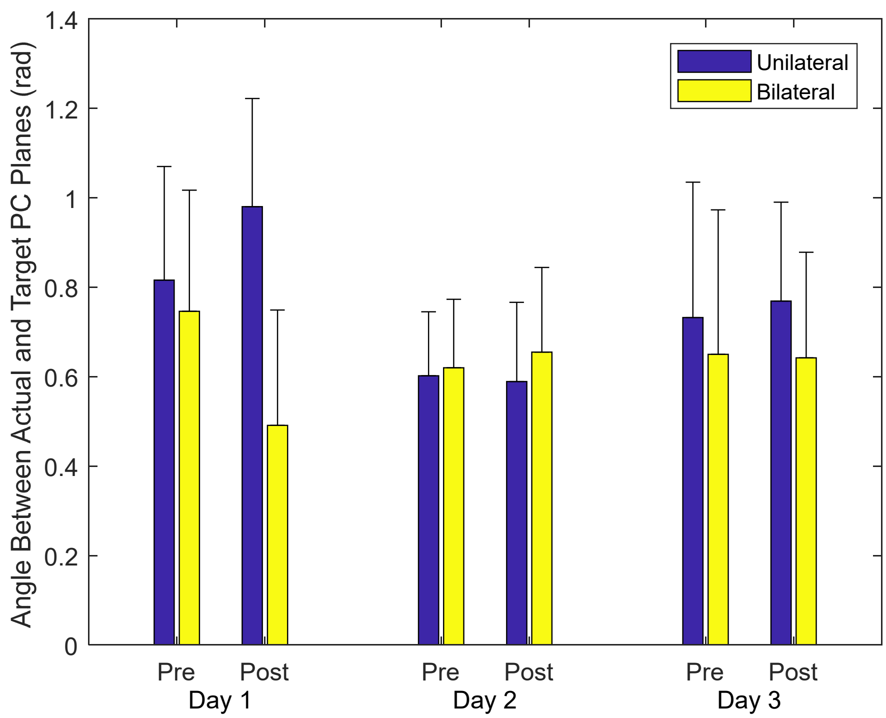

Figure 2.10. **Dihedral angle between actual and target PCs planes during the Tests.** No significant effects of Session, Practice, or Group were observed.

and Group (F(2,26) = 4.085, p = 0.029), but no other main effects or interactions had a significant effect on mean-squared jerk (p > 0.066).

2.4 Discussion

We have developed a system intended to facilitate training of multi-muscle activation patterns in stroke survivors and in other individuals with impairment arising from neurological damage. The system directly addresses primary mechanisms of impairment in stroke survivors, namely, diminished capacity to create unique activation patterns and to appropriately scale activation amplitude with task. Our system affords the flexibility to shape the training to the needs of the individual user through an intuitive graphical interface.

We successfully employed a version of the system with neurologically intact adults in a pilot study intended to examine feasibility. Participants trained with the system for 30-45

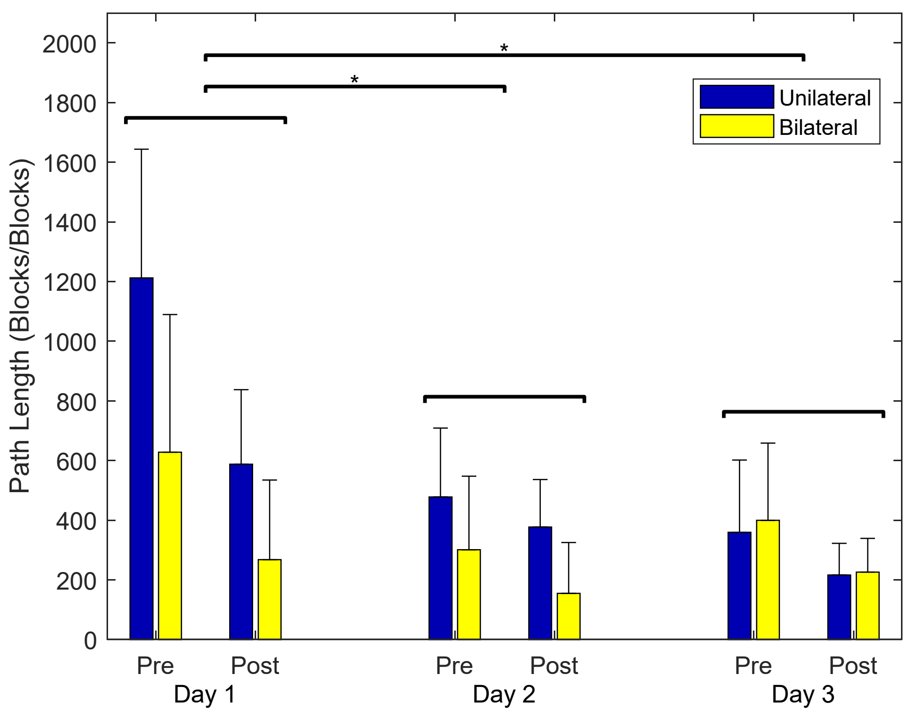

Figure 2.11. **Path length between targets for the cursor movement during the Tests.** Path length decreased significantly for both Session and Practice.

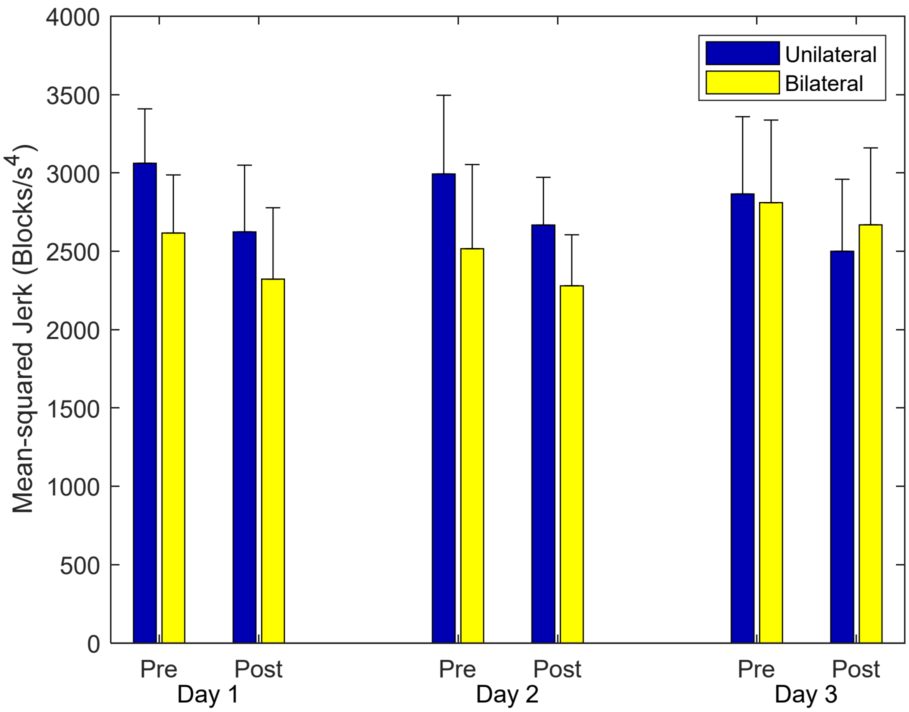

Figure 2.12. **Mean-squared jerk for the cursor movement during the Tests.** With training, subjects in both groups appeared to be able to create smoother movements, as indicated by the reduction in mean-squared jerk.

minutes on three separate days. In accordance with previous studies involving mapping of hand kinematics [63, 64] or EMG [82] to the cursor location, we observed significant improvement in cursor control both within a session and across sessions for both Unilateral and Bilateral groups. By the end of the first session, for example, subjects reduced the amount of time needed to complete the removal of the 16 targets by over 50%. These gains were largely maintained at the start of the second session, even though the mapping from EMG to cursor location could change with session. Overall, by the end of the third training session, subjects had reduced the time needed for Test completion by 67% (or roughly 281 seconds).

Improvement seemed to arise primarily from better control of existing activation patterns. Path length between targets was substantially reduced (by over 75%) following training. Within a session, mean-squared jerk of the cursor was significantly reduced as well. Subjects training unilaterally further displayed a reduction in mean-squared jerk across sessions. Thus, subjects seemed to improve the ability to control and scale the activation patterns needed to properly move the cursor.

Interestingly, participants did not appear to greatly alter the nature of their preferred EMG pattern, even as control of the cursor improved. The dihedral angle between the hyperplane formed by the target PCs and the hyperplane formed by the PCs from the actual EMG data did not change greatly within a session or across sessions despite substantial separation of the planes (separated by an angle of 40-45°).

This finding of using existing activation patterns to solve the task rather than reorganizing them is consistent with prior research [83], thereby indicating that the nervous system may have a preference for using habitual coordination patterns. However, these neurologically intact participants undoubtedly improved in their ability to modulate the relative activation of their patterns, as evidenced by the reduced path lengths. Such improvement in modulation would be very beneficial for stroke survivors who struggle to match muscle activation to task [68]. Additionally, stroke survivors may exhibit a greater propensity to shift activation patterns, especially in the acute and sub-acute phases. Should stroke survivors exhibit a reluctance to explore new patterns, we will add further motivation to change patterns, such as by adding noise to some of the signals [84] or by remapping the task so that the existing coordination patterns no longer result in motion of the cursor [63].

This training methodology holds several appealing features for stroke survivors. First and foremost, it addresses the primary impairment mechanisms for hand function after stroke: creation and modulation of appropriate muscle activation patterns. Fostering greater exploration of the workspace may lead to improved sensorimotor control. In a pilot study focused on fingertip force generation in stroke survivors, we observed that facilitating exploration of the three-dimensional workspace of isometric fingertip force led to improved normal force production for pinch [85]. Second, it encourages practice even when users are incapable of creating intentional finger movements or forces. EMG activation, even if insufficient or inappropriate to perform a physical hand task (like grasping an object), can still produce a functional outcome in the exercises within the interface. This provides the opportunity to reward even small changes in control, and encourage continued practice. Moreover, the difficulty of each exercise can readily be adapted to maintain the appropriate level of challenge [86] for each user.

Finally, the system supports both unilateral and bilateral modes of training. In this study, despite possible advantages for the bilateral mode due to target activation patterns being taken from the dominant limb, equally good improvement was seen in both groups of neurologically intact participants. We envision, however, that stroke survivors with severe hand impairment may benefit from the bilateral training mode, as control of the impaired upper limb may be insufficient to play the games [87]. In this case, contribution from less impaired upper limb would encourage game play and workspace exploration with the impaired upper limb by keeping the challenge at an appropriate level. The contribution from the non-paretic limb can gradually be weaned as the individual improves control of the paretic limb.

For this study, the first two PCs describing activation patterns in the dominant limb were used as target vectors for the non-dominant limb, simulating employment of the activation patterns of the non-paretic limb as targets for the paretic limb after stroke. Alternatively, other PCs (e.g. 3^{rd} and 4^{th}) from either limb could be used as target vectors for game play. In addition, while we chose to use PCs to represent the activation patterns, in part due to their orthogonality characteristics, other activation pattern representations (such as non-negative matrix factorization) could be employed. These would, however, require application of an appropriate transformation in order to map such non-orthogonal vectors to the orthogonal x- and y-axes on the screen.

A limitation of our pilot study is that it was conducted with neurologically intact subjects. Therefore, the extent to which the results generalize to stroke survivors is not known. However, as noted, there are several advantages to using this paradigm for stroke rehabilitation. Given that the current approach extends other EMG paradigms that have shown promise [76, 82], we are optimistic that training with this system will be therapeutically effective for stroke survivors. Future studies investigating this potential treatment technique with a patient population should be conducted.

CHAPTER 3: BAC-GLOVE

M. Ghassemi and D. Kamper, "A Hand Exoskeleton for Stroke Survivors' Activities of Daily Life," in *2021 43rd EMBC* and M. Ghassemi *et al.,* "Development of an integrated actuated hand orthosis and virtual reality system for home-based rehabilitation" in *2018 40th EMBC*

3.1 Introduction

Every 40 seconds, someone in the US experiences a stroke. This high incidence rate, combined with the prevalence of resulting significant impairment, makes stroke the leading cause of major, long-term disability for Americans [2]. While the stroke may produce a variety of deficits, hand impairment is common and is a primary contributor to chronic disability following stroke, due to the prominence of the hands in performing activities of daily living [8]. Despite current therapy efforts, 45% of stroke survivors will have limited manual dexterity 18 months after the stroke [14].

Thus, assistive devices may prove beneficial for restoring function for stroke survivors. Improved functional capabilities achieved with an assistive device could improve the quality of life for stroke survivors and reduce reliance on a caretaker. While a number of assistive devices have been developed for the hand, many focus on generating grasp forces (flexion) to help individuals with spinal cord injury [39, 42] or hand impairments [33, 45, 88]. While stroke survivors may exhibit weak grasp [12, 65], greater functional impairment arises from deficits in producing finger extension [13, 65] and object release [10]. Extensor weakness, arising from reduced voluntary excitation of extensor muscles [65], is compounded by involuntary, aberrant activation of finger flexor muscles. Thus, substantial extension assistance may be needed to achieve net extension. In a prior study of 95 stroke survivors with chronic hand impairment, over

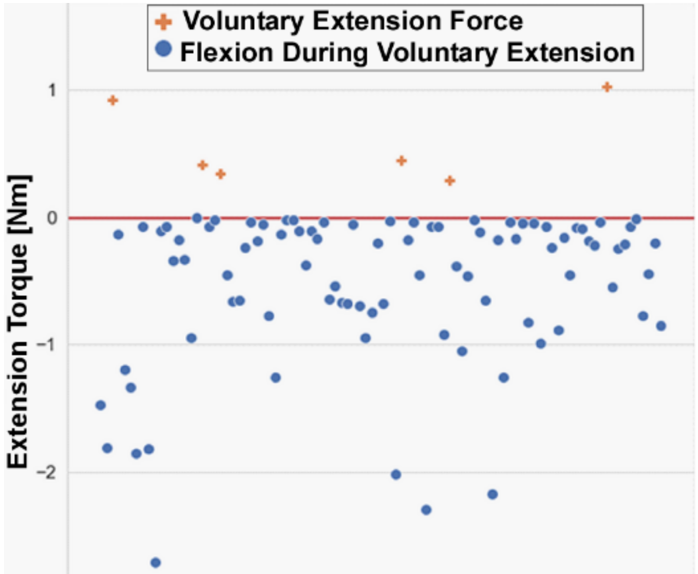

Figure 3.1. Extension deficits in stroke survivors. Attempts by stroke survivors to create isometric extension torque about the MCP joints typically resulted in net flexion torque; only 6 of the 95 subjects could generate a net extension torque [19].

75% of the participants produced a net finger flexion torque when trying to create a maximal finger extension torque (Figure 3.1) [19] and this torque could exceed 2 N-m.

A number of hand exoskeletons do provide assistance for flexion and extension, but many rely on passive extension, such as that produced by springs, that may be insufficient to generate finger extension for the stroke survivors most in need of an assistive device [31, 52]. Additionally, the lack of active extension force makes it difficult to assist in creating properly directed fingertip grip forces, which require contributions from both finger flexors and extensors. Other devices rely on actuators or cables on the palmar side of the hand that may interfere with object grasp or touch sensation. Current devices that actuate both flexion and extension from the palmar side are not portable [89] or restrict unactuated degrees of freedom (DOF) [44, 90].

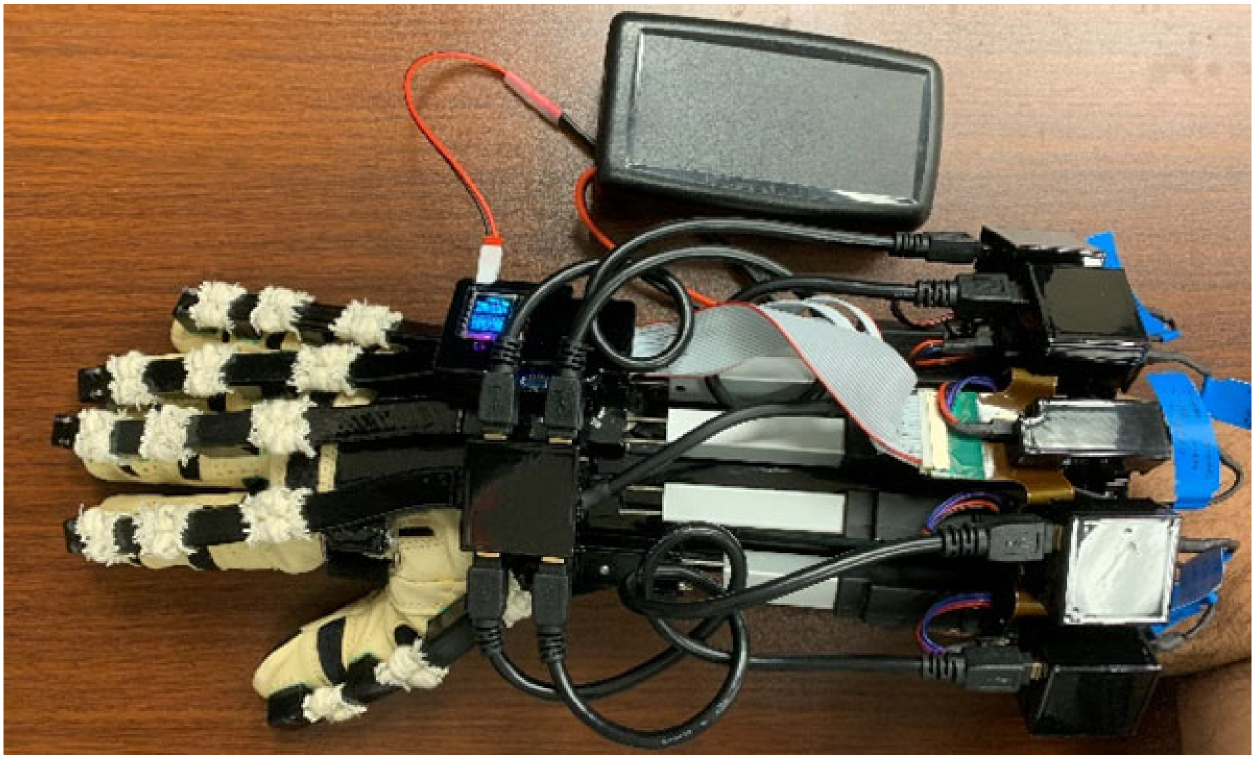

Figure 3.2. BAC-Glove. The device is self-contained on the arm, aside from the indicated battery pack.

To address the needs of stroke survivors, we sought to develop a soft-hard, hybrid hand exoskeleton that could actively assist both flexion and especially extension from the dorsal side of the hand while maintaining a relatively low profile and allowing movement of unassisted DOF. I describe the design and initial efforts to measure mechanical performance.

3.2 Design

3.2.1 Actuation

The device presented here moves fingers through bidirectionally actuated cables (BAC) (Figure 3.2). Using a single actuator for each digit, the BAC-Glove provides flexion and extension assistance by employing wire rope push-pull cables (Loos & Co, Pomfret, CT). These cables have sufficient flexibility to accommodate the full physiological range of motion of each joint while remaining stiff enough to propagate a pushing force to flex the digit. The cables run

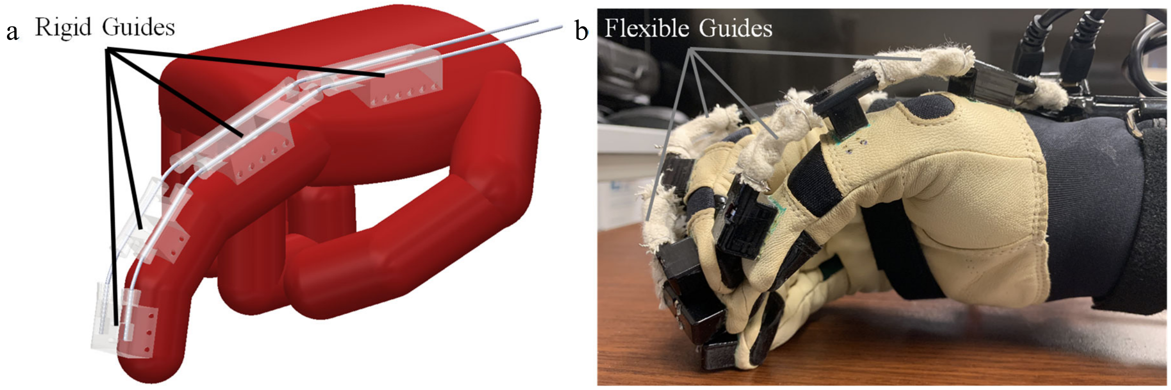

Figure 3.3. Rigid and flexible guides. a) Rigid guides direct the cables and their force. b) Flexible guides prevent from cable buckling.

through conduit located on the dorsal side of the digit (Figure 3.3a). Due to these rigid cable guides, designed in Solidworks (Dassault Systèmes SE, Vélizy-Villacoublay, France) and then 3D printed, the cables can both push the finger into flexion and pull the finger into extension. Two cables are used for each digit to increase lateral stability of the cable guides with respect to the finger. These rigid guides also serve other functions: 1) maintaining the desired joint moment arms, 2) preventing the cable from rubbing across the joint, and 3) preventing joint hyperextension during pulling. The printed cable guides were bonded to a lightweight leather glove (Bionic Glove Technology, Louisville, KY) to interface with the hand.

As the finger joints flex, a gap naturally forms between consecutive rigid cable guides. When pushing, this gap could result in buckling of the cable. To prevent this, deformable cotton sleeves reside between the guides (Figure 3.3b). The cotton sleeve strongly resists stretch, thereby preventing cable buckling during digit flexion, while imposing minimal impedance to compression during digit extension.

Each of the five cable pairs is translated using a linear actuator (L12 by Actuonix, Saanichton, BC, Canada) to enable independent control of each digit. In order to reduce the size

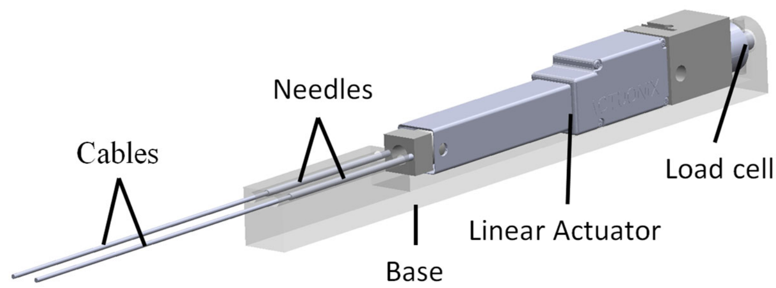

Figure 3.4. Actuator. Linear servomotor actuates the needles and the load cell measure the force applied to the cables.

and weight of the device, the shaft of the actuator was removed and replaced with steel needles that slide inside the shaft guide. The cables are connected to these needles (Figure 3.4). Each actuator is mounted on a 3D printed fixture mounted to a wrist splint. A load cell (L113B-30KG by Forsentek Co., Shenzhen, China) situated between the motor and the fixture measures the force exerted on the cables. The 3D-printed wrist splint maintains the wrist in a functional posture. We have observed that providing external wrist support alone can lead to increased maximal pinch force generation in stroke survivors, presumably by supporting the wrist extensors so that greater extrinsic finger flexor activation can be employed without causing the wrist to flex.

3.2.2 Controller

A custom controller board powered by a 32-bit microcontroller (PIC32 by Microchip Technology, Chandler, AZ, USA) drives the actuators and samples the signals measuring cable force and displacement (Figure 3.5). The PIC32 supports a variety of communication avenues (I2C, UART, SPI and CAN), which were used to interface with peripheral devices (see figure 3.6). The I2C port communicates with an LCD on the printed circuit board to provide feedback to the user. In the future, it could also be used to interface with IMU sensors that measure the orientation of the hand in space. The SPI peripheral is used to communicate with two 8-channel,

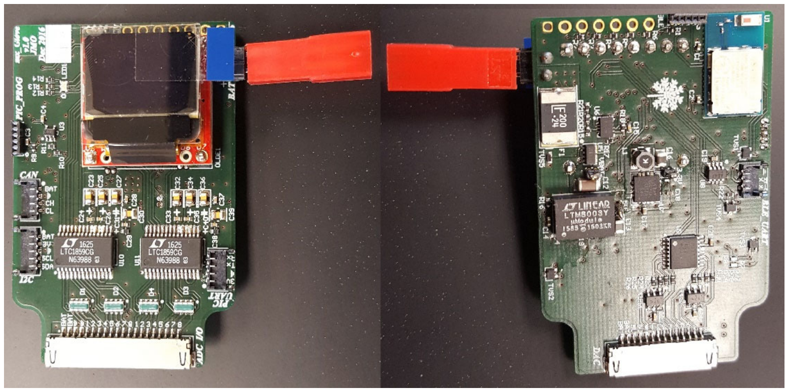

Figure 3.5. Controller Board. This board contains the microprocessor and other electronics required for control of the BAC-Glove.

16-bit analog-to-digital converters and with an 8-channel, 12-bit digital-to-analog converter. The CAN peripheral could also be used to communicate in real time with other boards, such as digital signal processing boards for more complicated electromyographic sampling and processing. The controller board also has a Bluetooth Low Energy (BLE) module BLE113 (by Silicon Labs, Austin, TX, USA), which communicates through UART with the PIC32; the BLE unit enables wireless communication between the BAC-Glove and computers or other devices.

Communication with the user can be achieved through a custom graphical user interface (GUI) (Figure 3.7) displayed on a computer or through an LCD screen on the device. We have

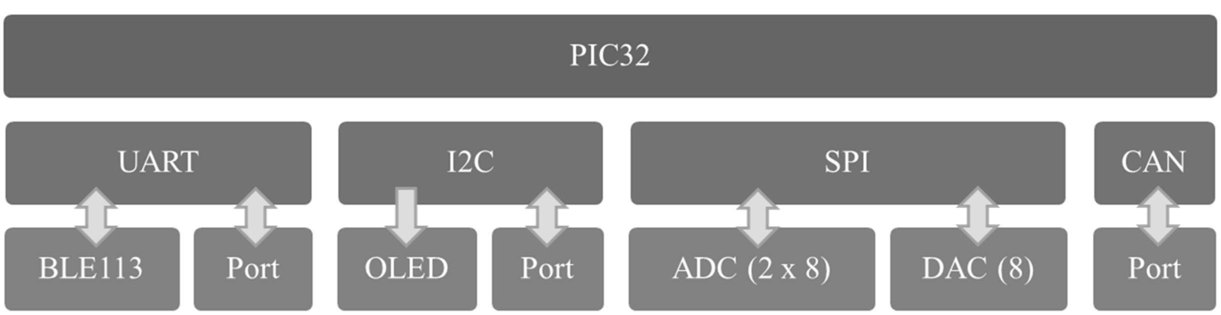

Figure 3.6. Diagram of the communication flow. Cartoon illustrates the modes of supported communication between the PIC32 and external devices.

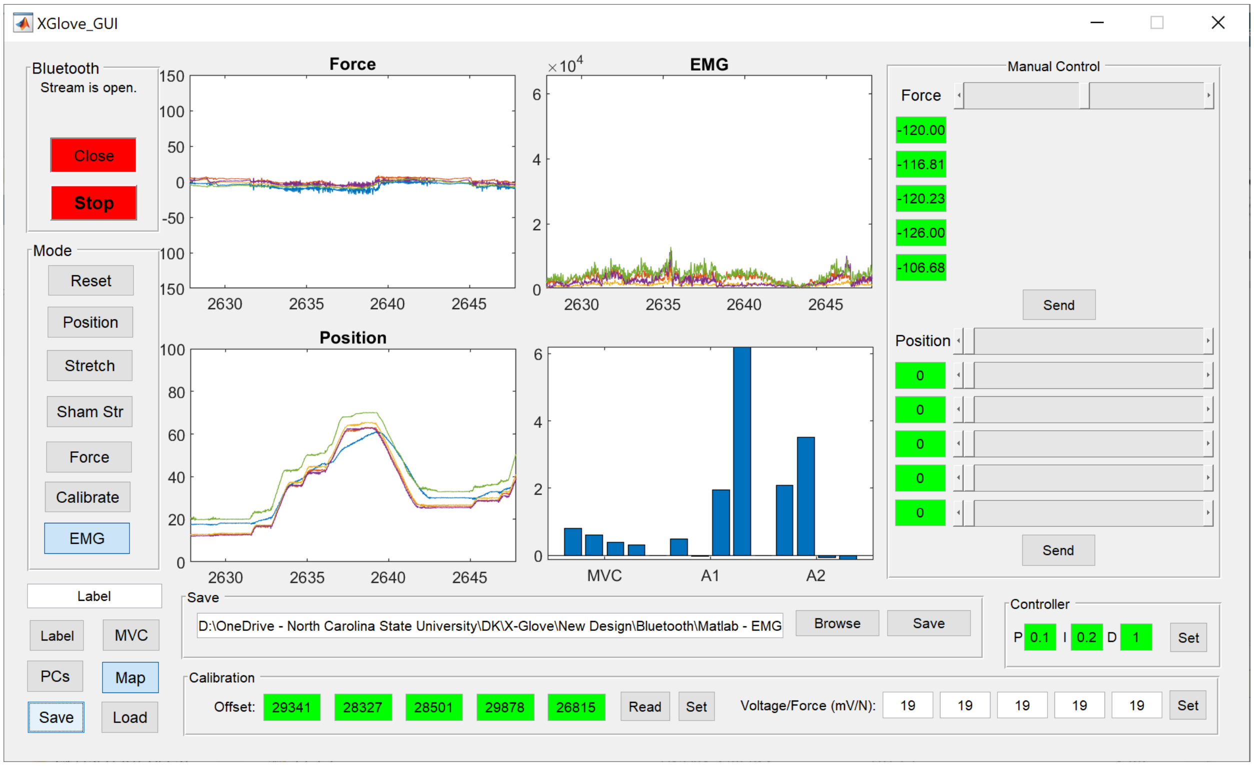

Figure 3.7. MATLAB GUI. This GUI provides an interface between the BAC-Glove and a computer to facilitate control and data storage. Control parameters for the BAC-Glove can be changed dynamically and data from the BAC-Glove can be displayed and stored on the computer.

created a custom graphic user interface (GUI) in MATLAB (MathWorks, Natick, MA, USA) to display data collected by the BAC-Glove and to set parameters for exoskeleton control. The microcontroller board on the BAC-Glove communicates wirelessly through the BLE module with the GUI to receive control inputs and store data. The controller firmware on the BAC-Glove samples actuator length from the motors and force from the load cells at 50 Hz. The firmware communicates with the BLE113 using BGApi protocol (Silicon Labs) in packet mode and sends sampled data over Bluetooth to the computer. On the computer side, a BLE dongle (BLE112D, Silicon Labs) is used to communicate with the PC. The dongle is controlled using BGApi protocol through serial USB connection. The GUI permits display and control of a number of

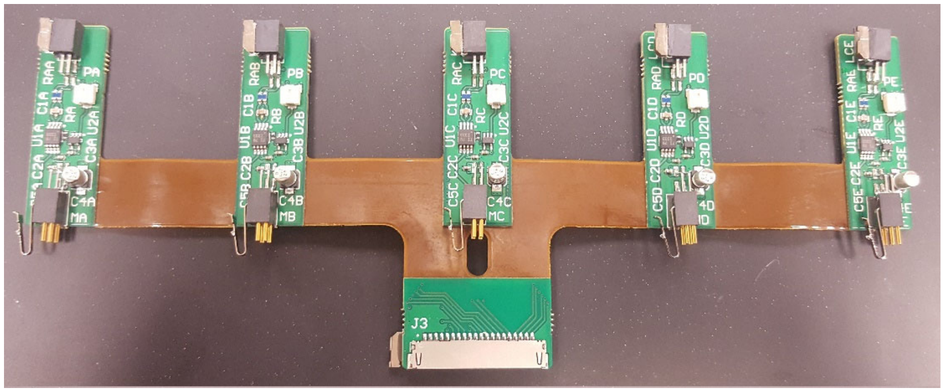

Figure 3.8. Break-out board. Printed circuit board connecting the motors and load cells with the input to/ output from the Controller Board. The finger-module (each of the 5 green identical boards) connects to the motor and the load cell for each digit and conditions the load cell output. The flexible board (brown film) is the flexible part of the board which connects the finger-modules and the connector module (green board with 20 pin connector) which connects to the controller board.

device settings. For example, the desired extension force to be maintained for assistance for each digit is shown and can be adjusted in real-time through the GUI.

The device can be operated in different modes depending on the goal of the user. The Stretch mode dynamically stretches finger muscles by rotating from specified flexion to extension limits for each digit. This stretching may provide at least temporary improvement in hand motor control [91]. The Force mode maintains a constant level of extension assistance for each digit. The assistance can be set manually or according to the measured force level required to passively rotate each digit into extension. In the EMG mode, the user directly controls glove movement through the creation of electromyographic (EMG) signals. Selection of mode and modification of parameters can be performed through an external device.

To improve signal quality and enhance robustness, the signal conditioning hardware was moved as close as possible to the load cells and motors. We designed a new set of printed circuit boards to interface with the load cells and motors (Figure 3.8). The breakout board is a low footprint flex-rigid board. A set of 5 small rigid boards provide amplification and conditioning of the signals from the load cell, as well as connections with the load cells and motors. These boards adhere to a bracket over the top of the motors, thus minimizing cable length. Ground planes beneath the circuits attenuate the electromagnetic noise from the motors. The wires connecting the rigid boards are contained within flexible boards which permit changes in separation between the boards to accommodate differently sized devices for differently sized hands. Two cables connect the controller and break-out boards.

3.2.3 EMG Control

EMG provides a natural means of controlling assistive devices. In the EMG mode, the user can control assistance provided by the BAC-Glove through creation of specific EMG signals. The raw EMG signals, acquired from passive electrodes, are processed with custom circuits on printed circuit boards that amplify, filter, and rectify each signal. The amplitudes of the resulting EMG envelopes are sampled by the PIC32.

As stroke survivors typically have difficulty creating specified muscle activation patterns, we have developed a paradigm for customizing control signals to the capabilities of the user. The voluntary muscle activation space of the user is characterized by having the user perform a variety of hand tasks (guided by images) while the EMG signals are recorded. Principal component (PC) analysis is then used to find the two PCs that explain the largest amount of variance in the EMG data set collected during this exploratory period. These two PCs are chosen to serve as the target vectors defining a hyperplane within the EMG workspace. EMG activation patterns are subsequently projected onto this hyperplane in real-time in order to control the glove

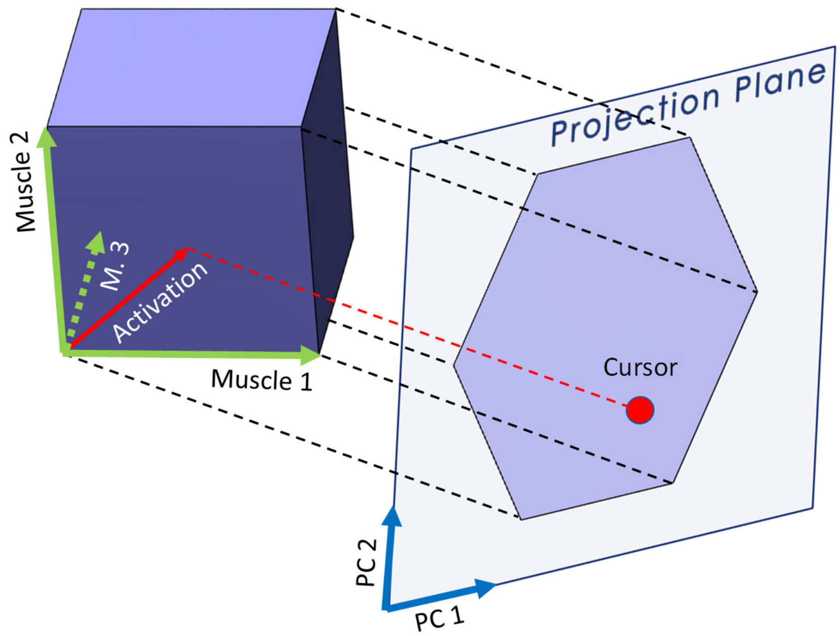

Figure 3.9. Mapping between muscle activation vector and cursor position. Cursor position is calculated by projection the muscle activation vector onto the projection plane formed by the target PCs.

(Figure 3.9). By moving within this hyperplane, the user can select a desired grasp and control the velocity at which the movement is performed.

For an initial application of the BAC-Glove, a set of distinct grasps were chosen for assistance by the BAC-Glove. These grasps were selected based on their relevance to performance of tasks daily life and to test the capabilities of the BAC-Glove. The four grasps were: 1) power grasp, 2) two-digit (palmar) pinch, 3) three-digit pinch, and 4) single-finger pointing and pressing. The user selects the grasp type by creating an EMG activation pattern corresponding to the desired sector of the control hyperplane. To facilitate learning this control, we developed a GUI (in MATLAB) that represents the projection of the current EMG activation pattern as a cursor on a screen and the grasp sectors as regions on the computer screen (Figure 3.10a). Once the cursor hovers in a sector for 1s, the controller switches to the grasp execution mode and moves the fingers to the base gesture for that grasp. In the visual representation, the

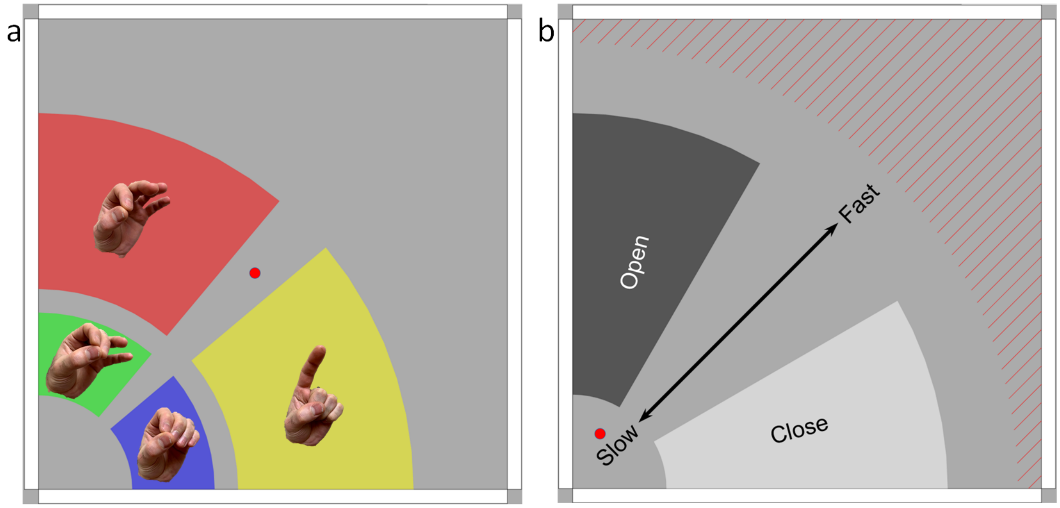

Figure 3.10. Control interface. a) User selects desired grasp in grasp selection mode and b) controls speed and direction of the grasp in grasp execution mode.

cursor must be moved to the "open" or "close" sector (Figure 3.10b). The distance of the cursor from the origin controls the speed of the opening or closing of the grasp and its direction. Activating all the muscles over a threshold triggers a return to the grasp selection mode.

3.3 Validation

3.3.1 Protocol

As an initial evaluation of the device, benchtop testing was performed in order to quantify the amount of flexion and extension assistance that the BAC-Glove could provide. With the hand of a human participant in the glove, the fingertip of the index finger was secured to a 6-axis load cells (SI-80-4, ATI Industrial Automation, Inc. Apex, NC). The wrist was fixed in neutral flexion/extension and ulnar/radial deviation by the splint of the BAC-Glove. Straps placed across the forearm resisted arm and hand translation while maintaining the forearm at 20° of pronation. In this posture, the elbow was flexed roughly 90°, while the shoulder was abducted about 70°. The participant was instructed to remain relaxed throughout the procedure.

Maximum isometric fingertip force applied by the BAC-Glove to the fingertip was measured at three different index and middle fingers postures, produced by 20%, 40%, and 60% of full cable extension. These postures corresponded roughly to joint postures of metacarpophalangeal (MCP) angle, proximal interphalangeal (PIP) angle, and distal interphalangeal angle (DIP) of: (10°, 5°, 10°), (20°, 15°, 20°), and (20°, 25°, 20°). This process was repeated for the middle finger.

Inverse kinetics was used to calculate the torque at the different joints of the finger from the recorded load cell data and the joint angles. To quantify the direction of the force created at the fingertip, the angle between the normal force vector (with respect to the long axis of the distal finger segment) and the fingertip force vector was calculated.

To measure grip and pinch forces created by the device, a dynamometer was positioned in the hand to measure force, while the glove created the desired grasp. The Hydraulic Hand Dynamometer (Jamar, Clifton, NJ) was used to measure peak grip force and a pinch gauge (B&L Engineering, Santa Ana, CA) recorded peak pinch force. Again, the participant was instructed to keep his hand relaxed inside the glove during the procedures.

3.3.2 Results

The desired and actual properties of the BAC-Glove are presented in Table 3.1. The desired forces for the 2-finger pinch and power grasp are the maximum values from the sample activities of daily living [92]. The desired value for the 3-finger pinch is the maximum force needed to do most of the daily activities using the comparable key-pinch [93]. The desired values for the range of motion are what is needed to do 90% of activities of daily living [94]. Desired extension and flexion torque are calculated to create a 5N extension and 10N flexion forces normally at the tip of index finger at joint posture of 20°, 15°, 20° (MCP, PIP, DIP).

Table 3.1. Actual and desired properties of the BAC-Glove.

Properties	Actual	Desired
Mass	850g (Hand: 165g; Forearm: 685g)	500g
Force (2-finger Pinch, 3-finger Pinch, Power Grasp)	5N, 10N, 20N	16N, 18N, 21N
Range of motion (MCP, PIP, DIP)	5°-40°, 0°-40°, 5°-35°	19°-71°, 23°-87°, 10°-64°
Speed of movement	6s	< 1s
Extension Joint Torque (MCP, PIP, DIP)	-0.86 (N-m), -0.55 (N-m), -0.46 (N-m)	-0.37 (N-m), -0.14 (N-m), -0.04 (N-m)
Flexion Joint Torque (MCP, PIP, DIP)	0.37 (N-m), 0.21 (N-m), 0.16 (N-m)	0.75 (N-m), 0.28 (N-m), 0.08 (N-m)

The BAC-Glove created substantial fingertip force in both flexion and extension for the two digits tested (Figures 3.11 and 3.12). Fingertip forces were similar across the index and middle fingers but varied with finger posture. Flexion force was greatest at the most extended posture (approaching 8 N), while extension force was greater at the flexed postures (reaching 12 N). The device generated extension or flexion torques across the MCP, PIP, and DIP joints simultaneously (Table 3.2). The computed MCP torques for extension exceeded 0.5 N-m across postures and reached 0.9 N-m. MCP flexion torque was greatest at the most extended posture (0.6 N-m) and decreased for the most flexed posture (0.2 N-m). Peak grip force created by the BAC-Glove was 20N. The device created 5N of force for 2-finger pinch and 10N of force for 3-finger pinch.

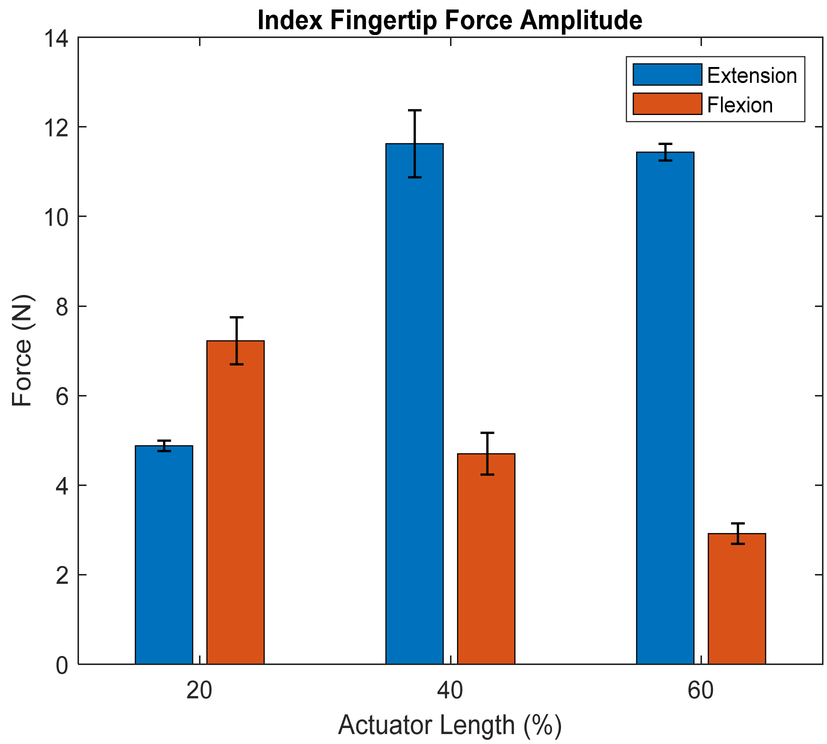

Figure 3.11. Index finger extension and flexion forces. The mean amplitude of the extension and flexion forces for index fingertip at different lengths of the actuator. Error bars indicate the standard deviation of the values.

Table 3.2. Fingertip force and torque values generate in the index finger.

Posture		**Joints Torque (N-m)**			**Force (N)**	
Actuator Length	***Direction***	***MCP***	***PIP***	***DIP***	***Amplitude***	***Direction***
20%	Extension	-0.52	-0.37	-0.31	4.88	45°
	Flexion	0.64	0.41	0.31	7.22	40°
40%	Extension	-0.86	-0.55	-0.46	11.63	37°
	Flexion	0.37	0.21	0.16	4.7	27°
60%	Extension	-0.75	-0.47	-0.45	11.44	41°
	Flexion	0.20	0.12	0.11	2.92	35°

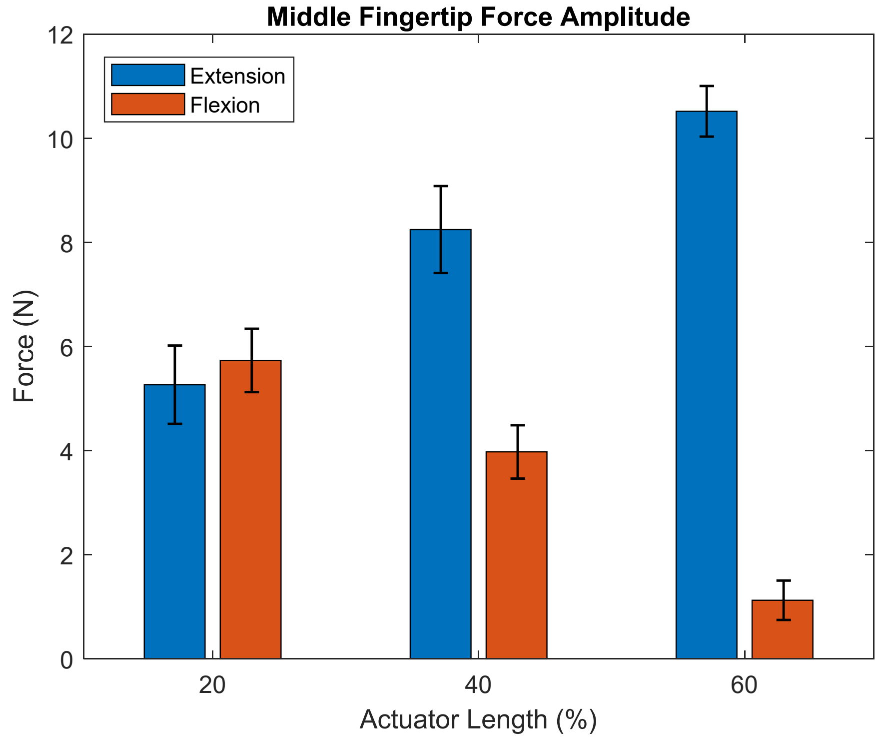

Figure 3.12. Middle finger extension and flexion forces. The mean amplitude of the extension and flexion forces for middle fingertip at different lengths of the actuator. Error bars indicate the standard deviation of the values.

3.4 Discussion

The BAC-Glove is an assistive device designed to address functional hand deficits particularly in stroke survivors. The device can actively assist both digit flexion and extension with a single actuator for each digit. Actuation and force transmission occurs entirely on the dorsal side of the hand, thereby freeing the palmar surface for object grasp and manipulation. All of the digits are actuated independently to provide more force and flexibility in executing different grasps. The device can operate in a number of different modes, including under EMG control. The EMG control scheme is designed with the limited muscle activation space of stroke survivors in mind, as it concentrates on the most accessible region of the muscle activation workspace for each user.

Bench testing confirmed that the BAC-Glove is capable of providing substantial finger extension assistance in addition to finger flexion assistance. The glove was able to generate up to 12 N of extension force in a single digit. This translated into more than 0.5 N-m at the MCP joint of the index finger across postures. These values are in the range of what might be required to overcome involuntary flexor activity during attempted finger extension [19]. The created flexion was smaller, although it did reach roughly 8N of fingertip flexion force and 0.6 N-m of MCP torque for the most extended posture tested. These values decreased for more flexed postures. The flexion force was directed more normally than many stroke survivors can achieve voluntarily [85] which is beneficial as the normal direction helps to keep objects from slipping out of the grasp. Having the BAC-Glove create less shear force in relation to normal force would improve grasping.

Flexion assistance decreased for more flexed postures. This could be due to the fact that as the actuators flex the fingers, they get closer to the end of their range of motion and have less room to move and flex. Thus, they have less capacity to overcome the stretch in the glove and deformation of the cables and create flexion force. The same thing is true in the case of finger extension and creation of extension force.

While force generation is ultimately limited by motor size, losses also occurred within the structure of the glove itself. Shear forces led to excessive stretch in the glove during actuated finger flexion. This also resulted in occasional twisting of the intermediate rigid cable guides, with a detrimental effect on the direction of the force applied on the fingers and the resulting torques, as well as on the peak fingertip flexion force that could be generated. In a future design this situation could be improved by increasing coupling between the user and the device through a glove with better fit and less compliance.

CHAPTER 4: EVALUATE BENEFITS OF EMG TRAINING FOR CONTROL OF BAC-GLOVE

4.1 Introduction

People who are over 25 years old have a 25% chance of having a stroke in their lifetime [3]. Stroke is a leading cause of serious and chronic disability in the US due to its high incidence probability and the prevalence of associated impairment [2]; one study reported that 45% of stroke survivors had limited manual dexterity 18 months after stroke [14], a time at which deficits are considered chronic. As the hands play vital roles in performing tasks of daily living, hand impairment can dramatically impact overall function [8]. Compensation with the opposite, nonparetic hand may not be feasible in many situations due to the necessity of controlling mobility aids, such as canes, with the paretic hand [15]. Additionally, many tasks require the use of both hands.

Therapy to recover lost sensorimotor control is the main treatment after stroke. Unfortunately, recovery may be limited, especially for those individuals who originally present with substantial hand impairment. Instead, assistive devices could be used to increase the functional capability of the paretic hand. Assistance with digit opening and closing would be beneficial, as stroke survivors exhibit substantial deficits both in finger flexion and extension [9]. The number of wearable devices capable of actively assisting both flexion and extension of each digit independently, however, is currently quite limited [20]. This unmet need led us to develop such a device, the BAC-Glove assistive hand exoskeleton [95].

The BAC-Glove can be controlled by the user through electromyographic (EMG) signals, one of the most natural and fully explored means of instituting user control [55]. As the muscle acts as a natural amplifier for neural signals, EMG signals require only relatively low amplification and yield a high signal-to-noise ratio. Discernible EMG signals may be present even when the user is unable to create any apparent movement or force.

Unfortunately, stroke survivors often have difficulty manipulating muscle activation patterns. Diminished capacity to fully activate muscles [65], delay in activating and relaxing the muscles [10], excessive coactivation of muscles [13], and limited modulation of muscle activity with task are prevalent [58]. These impairments can severely impede EMG control of an assistive device. Potentially, training the production of EMG signals could improve control of an EMG-driven device. A few studies describe the use of “serious” computer games to improve the EMG control of prosthetics [59-62], although these studies mainly focused on promoting simple activation of one or two muscles [60-62, 96]. Van Dijk et al. examined training muscle activation patterns in stroke survivors with simple games, but again the training was limited to a pair of muscles [59]. This independent control of muscles may be very challenging for stroke survivors. Instead, incorporating more muscles might actually facilitate control by opening access to regions of the EMG workspace that may be easier for the user to reach. In this manner, the control space can be customized to each user.

We developed a platform that promotes exploration of different activation patterns in stroke survivors. This platform consists of serious games that users can play by creating distinct muscle activation patterns that are then mapped to the cursor location on a screen. By controlling the cursor location through creation of EMG patterns, the user can play different games. Both neurologically intact individuals [97] and stroke survivors [98] were able to improve this cursor control after training with the system.

The goal of this pilot study was to examine the performance of the BAC-Glove in a longitudinal intervention and to determine if training EMG patterns with the serious games improved control of the BAC-Glove in neurologically intact adults. A control group performed the EMG training with upper-arm muscles while the intervention group trained with the same muscles used to control the BAC-Glove. We hypothesized that the group that the intervention group performs better in the control of the assistive device at the end of the training.

4.2 Methods

4.2.1 BAC-Glove

The BAC-Glove is an assistive device which is designed to address the special needs of stroke survivors, who exhibit deficits in both finger flexion and extension. Extension is especially impaired, due to limited ability to activate long finger extensor muscles [65] and excessive, involuntary coactivation of the long finger flexors [13, 65]. Thus, substantial extension assistance may be needed to overcome the unintended flexor activity in order to properly shape the hand for grasp, produce the desired finger placement and fingertip forces on the object, and facilitate object release [10]. The BAC-Glove can provide substantial extension assistance while also being able to assist digit flexion.

The BAC-Glove actuates each digit using two cables that are routed along the dorsal side of the digit (see figure 4.1). These push-pull cables are routed through rigid, 3D-printed guides that control cable position, prevent joint hyperextension, prevent cable rubbing across the joint, and maintain moment arms to create greater joint torque for a given cable force. The rigid guides naturally separate as a joint flexes. These gaps could allow the cable to buckle during the pushing used to create digit flexion. Soft, flexible guides comprised of cotton sleeves have been inserted between the rigid guides to prevent this from happening. The sleeves create negligible resistance to digit extension, while strongly resisting cable buckling during finger flexion.

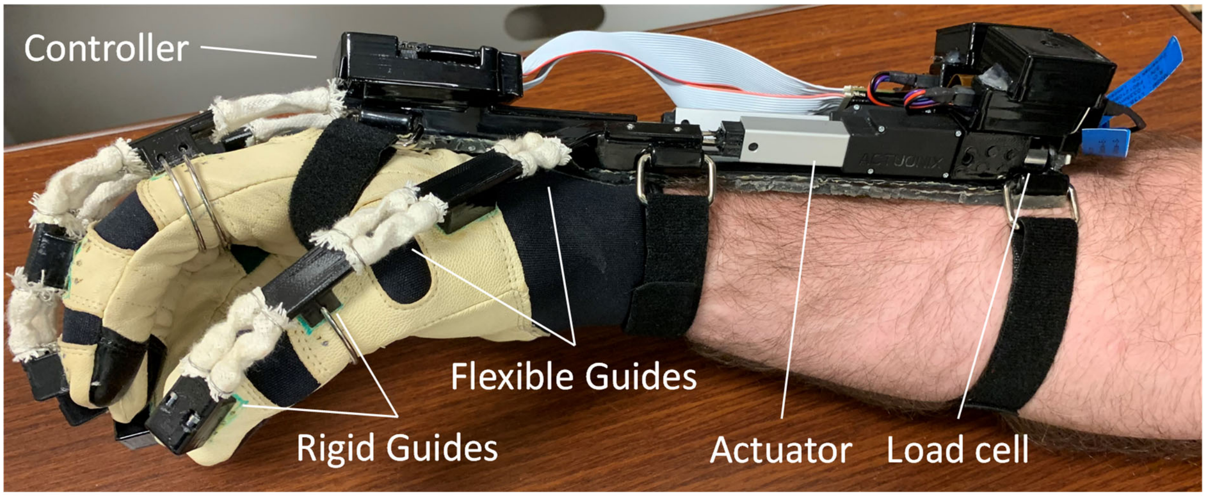

Figure 4.1. BAC-Glove. The BAC-Glove and its components.

Among its operational modes, the BAC-Glove can be controlled through EMG signals created by the user. The control is customized by first determining the region of the EMG workspace that can be best accessed by the user. EMG activity of the targeted muscles is recorded over a short calibration period during which the user creates a variety of activation patterns. Principal components (PCs) are then fit to these data. The first two PCs, the ones associated with most of the variance in the EMG signals, are then used as the target PCs for control; subsequent EMG activation vectors are mapped to the plane formed by the two PCs. Control consists of two steps. In the first step (grasp selection mode), user can select a grasp by creating activation patterns corresponding to the region of the EMG space associated with a particular grasp. In the second step (grasp execution mode), the user can open and close the selected grasp through manipulation of the projection of the EMG pattern within this plane. This control process can be visualized by the positioning of a cursor on a screen (see figure 4.2). The target PCs are aligned with the x- and y-axes of the screen and the cursor represents the projection of the EMG vector onto this plane. The further the cursor is from the left-bottom

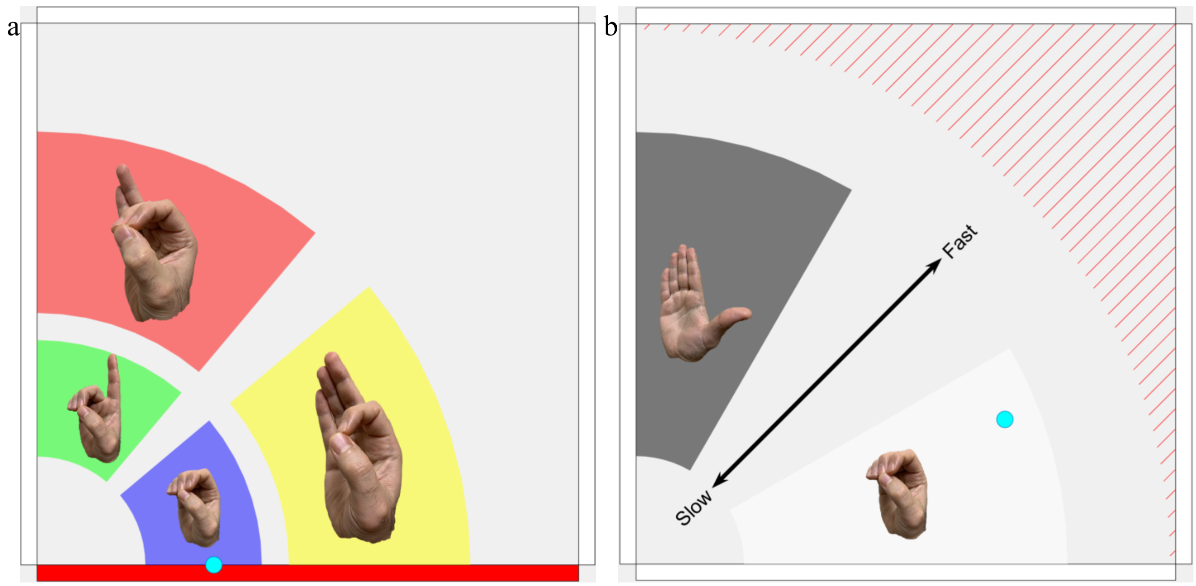

Figure 4.2. Control Interface. Holding the cursor in the desired region selects the corresponding grasp (a). Holding the cursor on the posture moves the fingers in the direction of that posture (b).

corner of the screen (figure 4.2b), the faster the glove moves in the selected direction. The user can return to the grasp selection mode to select another grasp by holding the cursor in the red hashed area for 2 seconds.

4.2.2 EMG Game

The EMG Game is a platform for serious games that we developed to help stroke survivors explore their muscle activation space. In this game, two muscle activation patterns are mapped to the x- and y-axes on the screen, as previously described. The two muscle activation patterns form a plane and at any moment the muscle activation vector is projected onto this plane to determine the cursor location on the screen.

The games that the players played in this experiment are *Picture Reveal*, *Asteroids*, and *Maze*. In the *Picture Reveal* game, the screen is divided into N x N white tiles that conceal a picture behind them. The player can reveal part of the picture behind these tiles by moving the cursor to the desired tile and keeping the cursor within that tile for a specified length of time. The game is played in two modes: simple mode (figure 4.3a) in which any tile can be revealed and targeted mode (figure 4.3b) in which only a highlighted tile can be revealed. In the *Asteroids* game (figure 4.3c), the cursor is replaced by a spaceship and player needs to move the spaceship on the screen to collect coins that appear at random screen locations. In the *Maze* game (figure 4.3d), the player needs to move the cursor through a maze from start to finish. This game has an

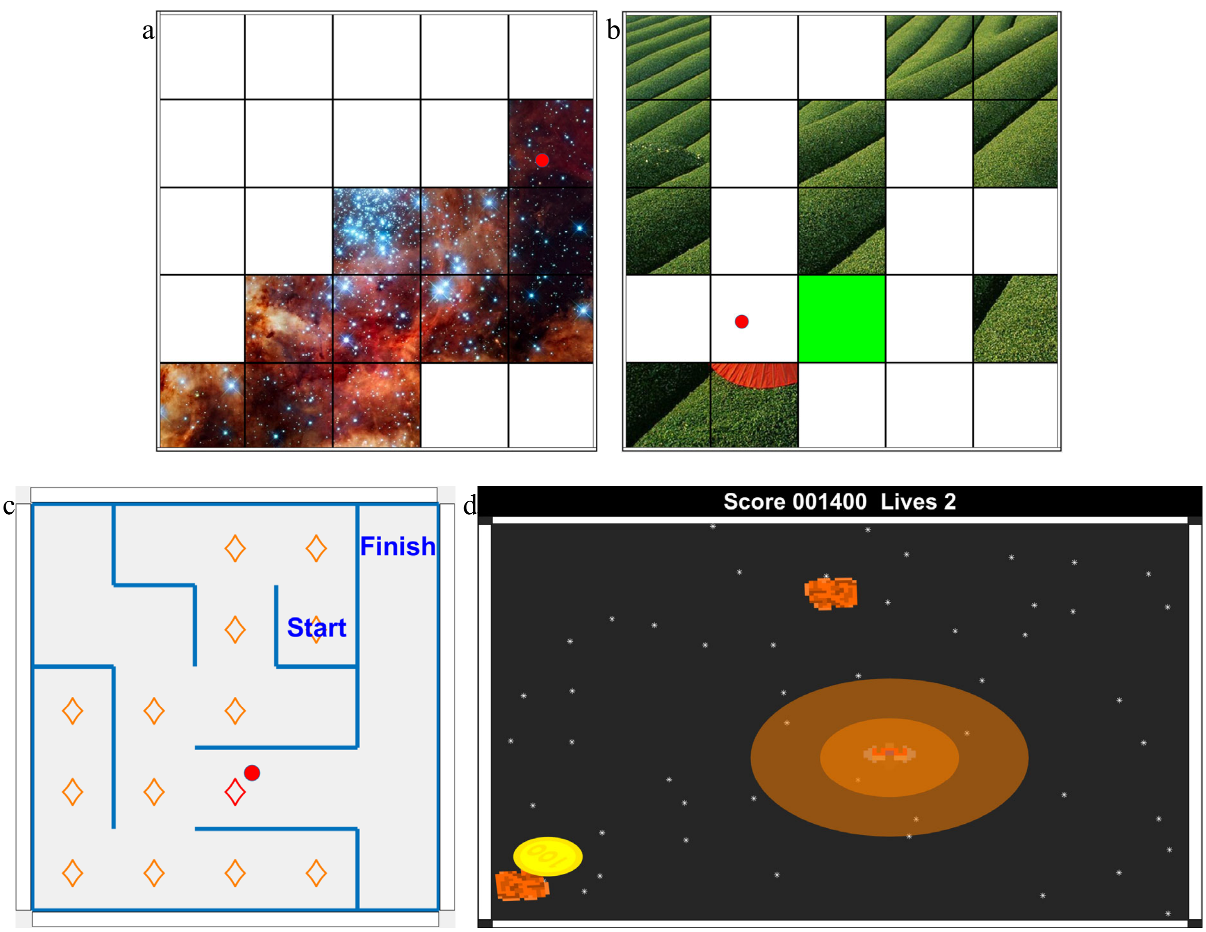

Figure 4.3. EMG Games. Picture reveal - moving the cursor around reveals the picture (a) or moving the cursor to the highlighted tile reveals the picture behind it (b). Maze - the cursor should be moved from start to finish through the maze (c). Asteroids - the spaceship should collect the coins avoiding the asteroids (d).

easy mode in which new walls are added dynamically once progress is made to prevent the cursor from being inadvertently moved in the wrong direction and subsequently losing progress.

4.3 Protocol

A group of 14 neurologically intact subjects (5 Female/9 Male) with no known orthopedic impairments that would limit finger movement, were enrolled in a longitudinal trial. The subjects provided informed consent in accordance with procedures specified by the North Carolina State University Institutional Review Board which supervised the study. The subjects completed the short version of the Edinburgh handedness inventory [99, 100] to verify that they were right-handed.

Participants completed a set of two evaluation sessions and 7 training sessions in the laboratory over 2-4 weeks. They received 4 sessions of training with the BAC-Glove and 3 sessions of training with the EMG-controlled game. Subjects were randomized to one of two groups: intervention and control. The intervention group used the activation patterns from four muscles distal muscles located in the forearm - extensor digitorum communis (EDC), flexor digitorum superficialis (FDS), extensor carpi ulnaris (ECU), and flexor carpi ulnaris (FCU) - both for the EMG-controlled game and the BAC-glove. The control group used different (proximal arm) muscles - biceps, triceps, posterior deltoid, and anterior deltoid - for control of the EMG game while using EDC, FDS, ECU, and FCU to control the BAC-Glove. In this manner, we were able to examine whether training with the serious games improved control of the assistive hand exoskeleton.

4.3.1 Training

Each session lasted roughly 60 minutes with 45 minutes of training to emulate a typical clinical session with a therapist. The first, third, fifth, and seventh sessions involved BAC-Glove training and second, fourth, and sixth sessions involved training with the EMG-controlled games.

In each BAC-Glove training session, subjects wore the BAC-Glove on their right (dominant) hand. Electrodes were placed over EDC, FDS, ECU, and FCU. Participants were guided to create a maximum voluntary contraction (MVC) for each muscle. These MVC values were used to normalize all subsequent EMG signals. They then completed a 5-minute calibration session during which they were guided to create a variety of muscle contractions; the target PCs were obtained from this data set. For the rest of the session, participants performed a variety of grasp-and-release tasks with BAC-Glove. The training included playing two games, stacking cups (Audioec Inc, Monroe, NY) and Buildzi (Tenzi, Greenwich, CT), that required the grasp and release of cups and blocks using different grasps (see figure 4.4). During training, the generated EMG pattern and the corresponding state of the BAC-Glove were displayed on a

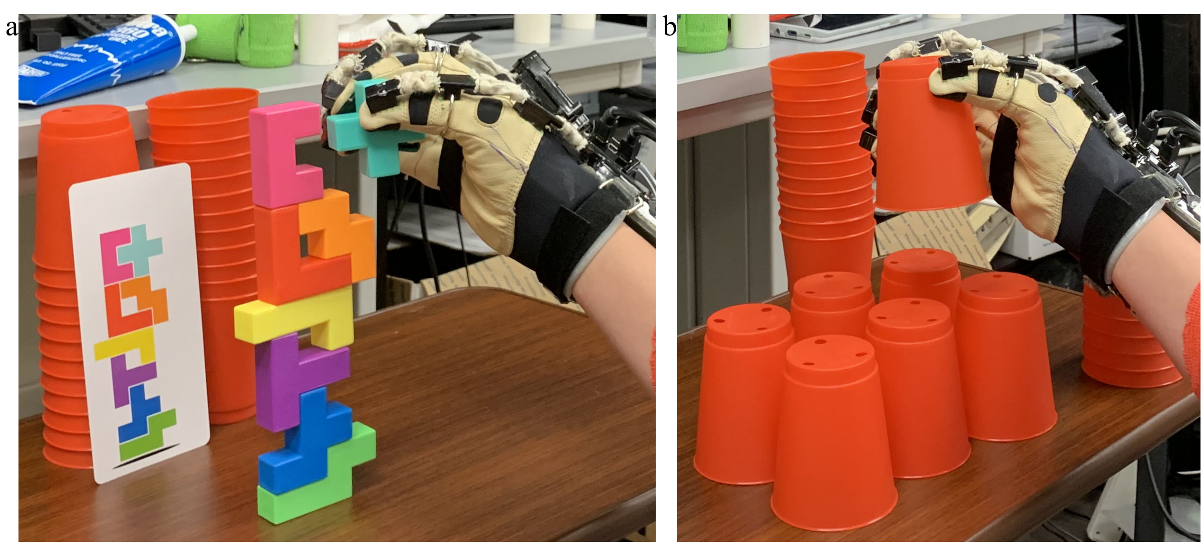

Figure 4.4. BAC-Glove training session. During the training session the subjects played BUILDZI (a) or cup game (b).

computer screen as visual feedback. During the first BAC-Glove training session, participants were instructed on the basics of controlling the device by producing EMG signals in order to select and execute different grasps.

Three EMG-game training sessions were interleaved with the BAC-Glove training sessions (see figure 4.5). Control and intervention groups had equal exposure to EMG training during these sessions but used different sets of muscles to control the cursor. While the intervention group utilized the same muscles to control the cursor for the serious games as used to control the BAC-Glove, the control group used upper limb muscles to play the serious computer games. In this manner, the control group also focused on the right upper-extremity during the session but did not practice creating the EMG patterns needed to control the BAC-glove. For these sessions, the first two PCs fit to the EMG data collected during a calibration phase were selected as the target activation patterns defining the x- and y-axes of the computer screen. Participants then played a variety of games by controlling the location of the cursor on the computer screen. Game difficulty was adjusted as the subject progressed in order to maintain the appropriate level of challenge. Difficulty could be adjusted by increasing tile number for the *Picture Reveal* games, increasing the size or removing blocking walls for the *Maze* game, and increasing asteroids as the score increased for the *Asteroids* game.

Figure 4.5. Pilot study sessions. Four BAC-Glove training sessions are interleaved with three EMG game training sessions. Pre and post evaluations are held after first and last BAC-Glove training

4.3.2 Evaluation

Evaluation sessions were held after the first and last training sessions. Participants performed all the subtests of the Action Research Arm Test (ARAT) [101] and the Box and Block test (BBT) [102] while wearing the BAC-Glove. They also performed a timed test in which they were required to select each grasp sequentially two times (total of 8 grasps). The sequence of the grasps was randomized.

4.4 Analysis

First, we examined control of the BAC-Glove and how this control changed with training. To compare hand dexterity with the device before and after the training, we used the score and time of the ARAT test, the number of blocks moved in the BBT, and the time required to complete the specified sequence of grasp selection. We examined whether EMG training had an effect on hand dexterity and glove control using the glove by examining outcome measures 2-way repeated measure analysis of variance (rm-MANOVA) with Group (intervention and control) and Session (initial and final). Finding of significance led to post-hoc rm-ANOVA analysis for individual outcome measures.

To determine whether performance in the EMG-controlled serious games changed during the study, we used the data from a 5 x 5 *Targeted Picture Reveal* exercise from each session. The average time to achieve a target and the average cursor path length to achieve targets normalized by the minimum distance were used to evaluate the proficiency of the subject in the EMG game. These variables were examined using a two factor (Group and Session) rm-MANOVA. There were three levels for the Session factor for (first, second, and third EMG training sessions) and two levels for Group (intervention and control).

4.5 Results

From the 14 enrolled subjects, 10 completed the full study. Of the four subjects who did not complete the study, one dropped out due to scheduling conflicts while the other three completed the study but experienced technical problems during data recording that precluded inclusion of their data in the final analysis. The data from the remaining 10 subjects (equally distributed between the two groups) was statistically analyzed. The two groups were well matched in terms of age and gender (table 4.1).

Table 4.1. Demographics of qualified participants

	Total	**Intervention**	**Control**
Gender (Female/Male)	4/6	2/3	2/3
Age (years)	29±6	30±4	29±7
Age Range (years)	23-40	25-36	23-40
Laterality Quotient (LQ)	76±18	68±21	84±10
LQ Range	50-100	50-100	67-92

The repeated measure MANOVA for the evaluation data revealed that Session had a significant effect ($F(4,5) = 7.445$, $p = 0.025$) on outcomes. Subsequent analysis of an rm-ANOVA for the ARAT score showed that participants significantly improved from the initial to the final evaluation session ($F(1,8) = 8$, $p = 0.022$). Improvements were seen in both groups (Intervention: $\Delta 1 \pm 1$, Control: $\Delta 3 \pm 3$) (figure 4.6). Session also had a significant impact on ARAT completion time ($F(1,8) = 5.86$, $p = 0.042$), with the Intervention group reducing completion time by -76 ± 65.2 s and the Control group decreasing completion time by -40.6 ± 85.7 s (figure 4.7). Similarly, across groups, performance on the BBT improved ($F(1,8) = 6.23$, p

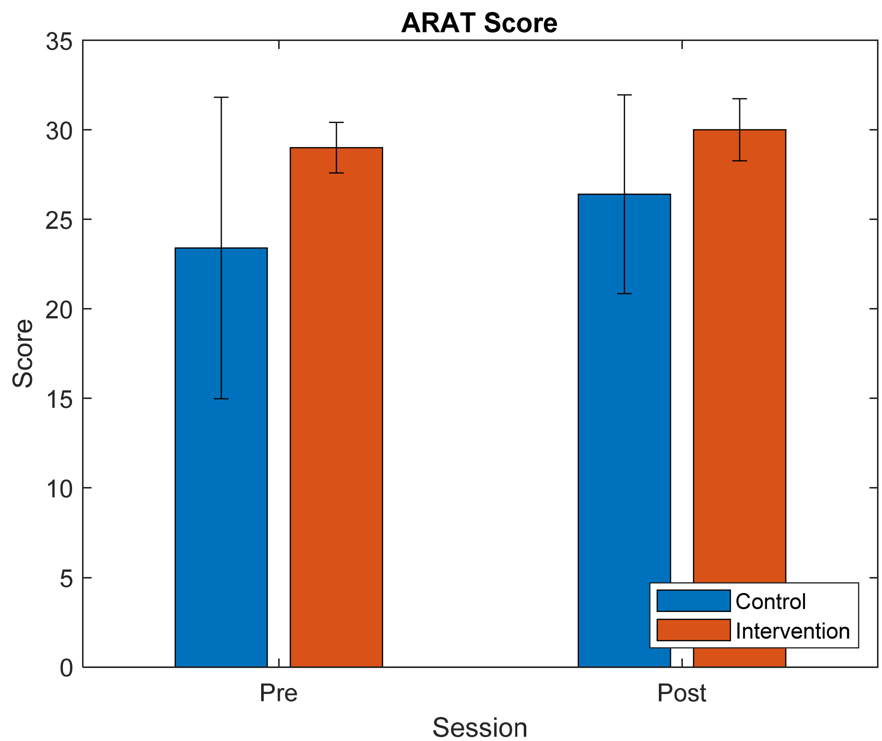

Figure 4.6. ARAT Score. Subjects improved their ARAT score but there was no significant difference between the groups. The error bars are standard deviation.

= 0.037), with the Intervention group able to transfer 1.8 ± 2.7 more blocks and the Control groups able to transfer 1.8 ± 1.8 more blocks (figure 4.8). Across these outcome measures, the Session-Group interaction was not significant ($p > 0.2$). The time needed to complete the grasp selection test decreased across all participants ($F(1,8) = 8.39$, $p = 0.02$), but to a different extent for each group as indicated by a significant Session-Group interaction ($F(1,8) = 5.80$, $p = 0.043$). The decrease was -8.6 ± 11.1 s for the Intervention group and -93.6 ± 78.1 s for the Control group) (figure 4.9).

For the outcome measures for the EMG-controlled games (average time and average path length), the MANOVA results showed that neither Session ($F(4,30) = 1.476$, $p = 0.234$) nor Session-Group interaction ($F(4,30) = 1.026$, $p = 0.41$) had a significant effect on these outcomes

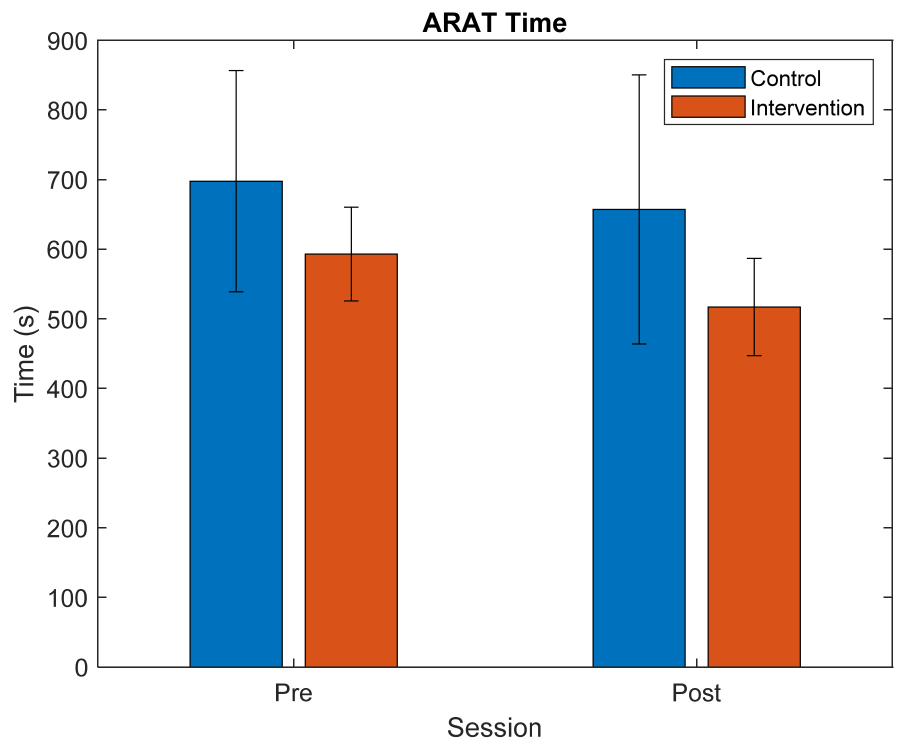

Figure 4.7. ARAT Time. Subjects decreased their ARAT time but there was no significant difference between the groups. The error bars are standard deviation.

Participants in both groups did tend to reduce their average time to reach a target (Intervention: -11.9 ± 11.6, Control: -4.5 ± 4.9) (figure 4.10) and their average path length per target (Intervention: -43.7 ± 44.6, Control: -2 ± 20) (figure 4.11) between the first and third sessions, but these changes were not significant.

4.6 Discussion

The BAC-Glove proved to be effective for use with object grasp and release as the participants were able to play games and complete hand function tests. The device could be employed under user control to manipulate a variety of objects, form objects of daily life used in the ARAT test to the pieces used in games. The BAC-Glove exhibited robustness across 40 one-hour sessions of continuous use, thereby demonstrating potential for daily use.

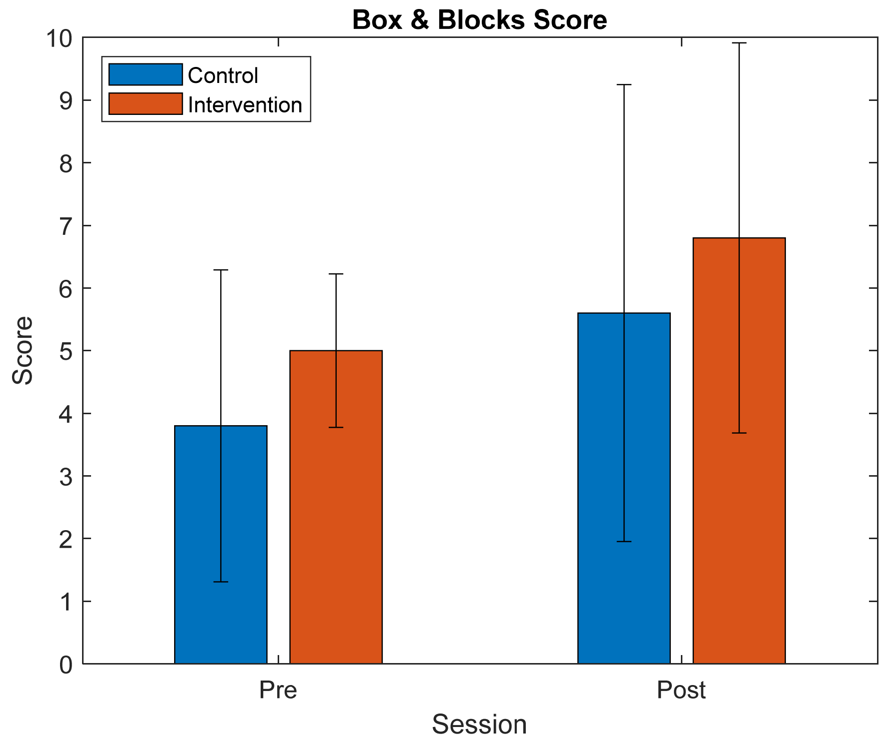

Figure 4.8. Box and Blocks Score. Participants improved their BBT score with no significant effect of the groups. The error bars are standard deviation.

Across participants, improvement in EMG-control of the BAC-Glove was observed across all outcome measures – ARAT score and time, number of blocks moved in the BBT, and the time to sequentially activate each grasp. By the final session, some subjects were able to reach maximum achievable scores on the ARAT while using the BAC-Glove. This suggests that subjects were able to learn to better control the device, although the device control was not intuitive. It is important to note that the controller was designed to use the muscle activation plane in which the ultimate users (stroke survivors) could easily control their EMG patterns. Thus, the target muscle activation patterns did not necessarily correspond to those typically used to produce the intended hand movements. Nevertheless, the subjects were able to control the glove after one training session and improved their control with further practice.

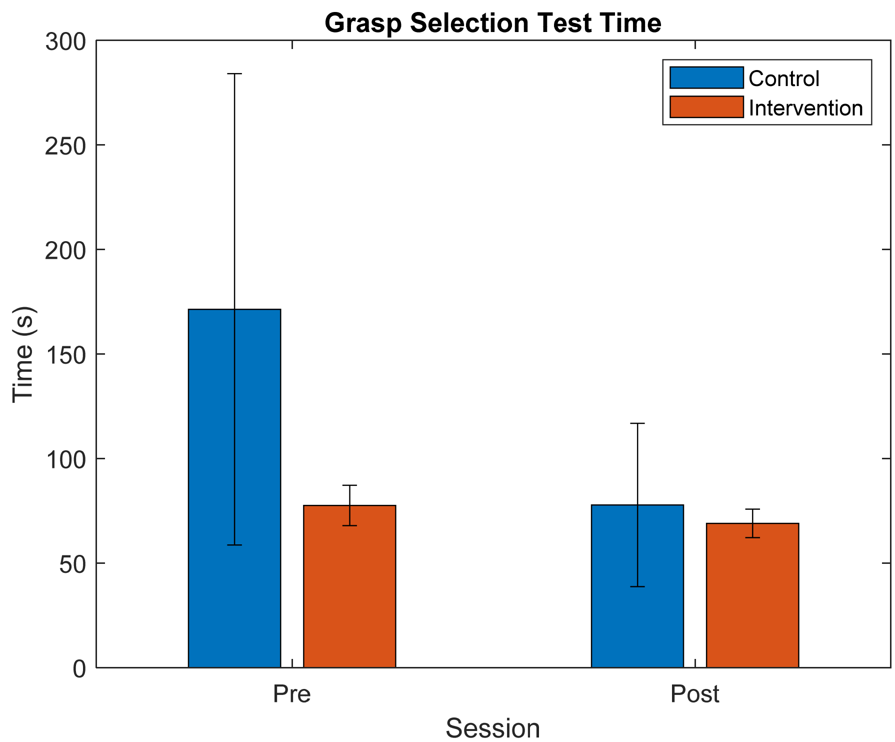

Figure 4.9. Grasp Selection Time. Participants reduced their grasp selection test time significantly and there was a significant session-group interaction. The error bars denote one standard deviation.

Contrary to our hypothesis, we observed a statistically significant difference in the change of outcome measure between groups only for the selection time for grasp, where the Control group showed a greater decrease. This difference appears to have been driven largely by the very long selection time for two of the subjects of the Control group at the initial evaluation. At the final evaluation, the selection times for the two groups were very similar. In part, the lack of Session x Group interaction effects for the other outcome measures may be due to the relatively small sample size for each group. Additionally, we observed a ceiling effect for the ARAT score. The current BAC-glove lacks the range of motion to pick up small objects, such as the 6mm ball bearing. Therefore, the maximum achievable score for the ARAT test is 31 and

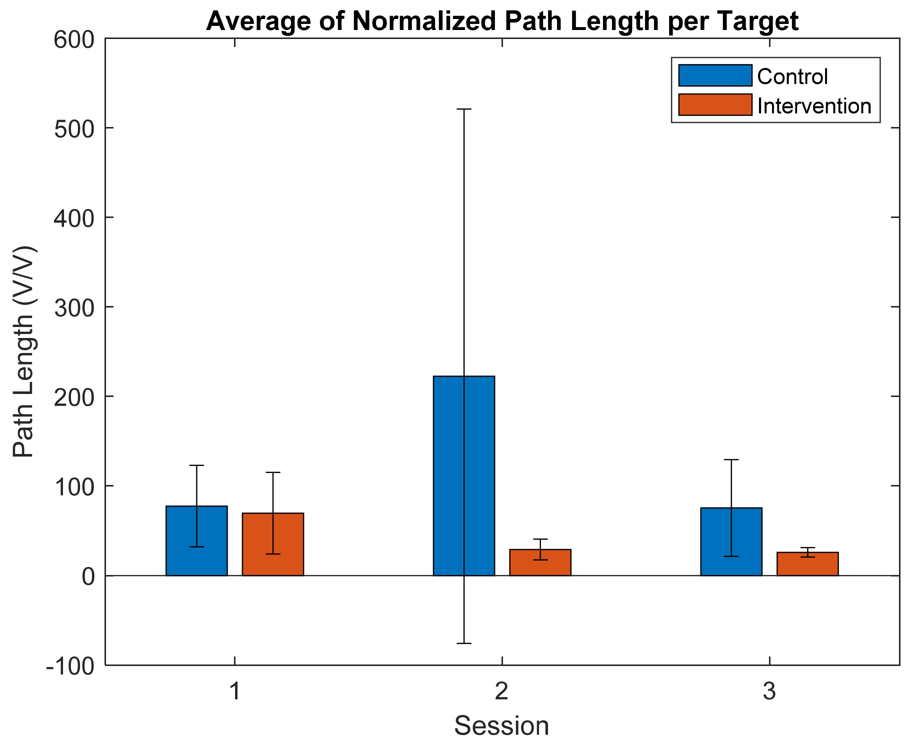

Figure 4.10. Average Normalized Path Length. There was no significant difference across Group or Session. The error bars denote one standard deviation.

three participants from intervention group and one from control group got this maximum achievable score.

The lack of statistical difference in change in outcomes between groups may also be partly attributable to the limited number of sessions with the EMG-controlled serious games. While a previous study [97] reported a significant decrease in time and path length for reaching specified tiles after three sessions with the platform, we did not observe significant improvement in these outcomes after 3 sessions in this study. This disparity may have resulted from the small number of subjects examined. The Intervention group did show a consistent downward trend for path-length and time across sessions, while the Control group did not. This apparent difference could be because of the different muscles used in the Control group, or because the Intervention

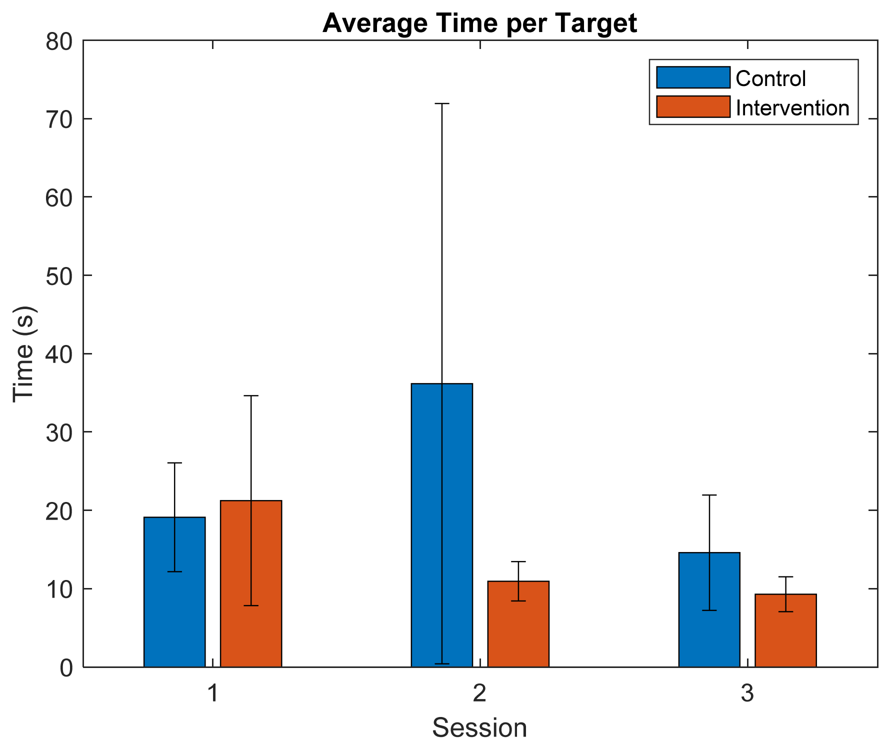

Figure 4.11. Average Time per Target. Average time per target decreased more for the Intervention group than the Control group. The error bars denote one standard deviation.

group was using the same muscles for the BAC-Glove sessions. More training sessions may have led to greater improvement in EMG cursor control, potentially translating to the BAC-Glove performance improvement. It also should be noted that in the EMG game the users were free to select their arm and hand posture throughout the session, while in the BAC-glove sessions the arm and hand postures were dictated by the task. This difference may have limited carryover from the EMG game to the BAC-Glove. Alternatively, training with the EMG platform may not have translated well to control of the BAC-Glove.

One of the limitations of this study was use of neurologically intact subjects. In addition, as a pilot study, it included a rather small number of participants. Additionally, while subjects were frequently reminded not to overpower the motors to move the glove, they still may have opened or closed the exoskeleton unintentionally. Overall, these preliminary results seem to justify a larger future study with stroke survivors.

In summary, the BAC-Glove showed promise in providing hand assistance to perform functional tasks as a completely portable device. The primary complications arose from the fit of the glove to the hand; slack in the glove could result in unintended movement of the glove and cable guides with respect to the hand rather than digit movement. The EMG-control paradigm proved feasible and improved with training. While trends for improved performance for the EMG games were observed, these were not statistically significant and did not necessarily translate to control of the BAC-Glove. Using the EMG training platform to directly practice the EMG control scheme of the BAC-Glove or using the platform before beginning with the BAC-Glove may provide a more direct benefit.

CHAPTER 5: CONCLUSION AND FUTURE WORK

5.1 Conclusion

In this dissertation, I introduced the EMG-controlled serious games and the BAC-Glove, assistive technologies designed to improve function in stroke survivors. The EMG-controlled games are designed to promote exploration of the muscle activation workspace and control of specific activation patterns. The EMG vector is mapped to a plane defined by target EMG patterns. This plane is then mapped to a computer screen such that the user can control movement of a cursor on the screen by manipulating their muscle activation pattern. The BAC-Glove is an assistive hand exoskeleton designed specifically for stroke survivors. The exoskeleton can provide digit flexion assistance independently for each finger and the thumb. along with the digit extension assistance so greatly needed by stroke survivors. Actuation occurs by pushing or pulling cables traversing the dorsal side of the fingers, an arrangement that leaves the palmar side of the hand free to interact with objects and minimizes interference with the touch sensation that is so important for grasping. Although the BAC-Glove covers the palmar side of the hand, the thin leather covering these areas has a limited adverse effect on touch sensation, especially compared to the other devices that route tendons and conduits on the palmar side of the hand. The BAC-Glove can be driven directly by the user through EMG control.

For the platform of EMG-controlled games, the system was first validated with neurologically intact subjects with no hand impairment. The results demonstrated that cursor control improved with training, thereby enabling subjects to complete the test game in a shorter time. The path-length of the cursor from one target to another decreased, verifying that users improved the ability to manipulate activation patterns to properly move the cursor. This improvement was retained from session to session, which is promising for producing long-term effects. Further studies have subsequently been performed with stroke survivors, both with severe and moderate hand impairment. These participants have also been able to use the system successfully, even when they could not produce any voluntary finger extension.

The BAC-glove design was focused on the needs of stroke survivors. The push-pull cables traverse through a series of rigid and flexible guides that maintain joint moment arms, prevent joint hypermobility, and direct the cable pathway. Benchtop testing revealed that the exoskeleton could create considerable extension assistance, including joint torques on the order of those needed to counteract involuntary flexion torques produced by the user. Achieved flexion forces and torques were smaller than expected due to imperfect coupling between the exoskeleton and the hand. Excessive slack in the glove sometimes led to twisting of the exoskeletal structure rather than movement of the digit. This could be improved through better glove design or through a design that eliminates the glove altogether.

I conducted an experiment to explore the benefits of muscle activation pattern training on control of the BAC-Glove. A group of neurologically intact participants performed BAC-Glove training, interspersed with EMG training targeted either at the forearm muscles controlling the BAC-Glove (intervention group) or upper arm muscles (control group). The results showed that participants from both groups, especially the intervention group, improved their control of the BAC-Glove.

5.2 Future work

The EMG-controlled serious games can be further improved in a variety of ways. First, cursor movement is jittery despite the aggressive filtering using a low-pass filter with a cut-off frequency of 0.1Hz. In my opinion, the cursor position can be further smoothed using moving average or any other signal smoothing method.

Also, more games should be added to the platform. Games playable with a cursor, such as Minesweeper, are perfect for this goal. Additionally, the current tile game could be modified to include letters such that users can be asked to spell certain words or perform word searches. Games relying on directional keys are playable in the same manner as the Maze game, with the cursor moved to activate different directional keys. However, in the current version of the Maze game, the subject playing the maze can become confused as cursor movement on the screen is limited by the walls. The cursor location corresponding to their actual activation pattern may be far removed from the shown cursor position. I suggest that a ghost cursor be added to the game, so that subjects would be aware of their actual activation pattern. This cue would help subjects to better correct their muscle activation pattern to move the real cursor through the maze.

The BAC-Glove would benefit from a better interface with the hand. While the glove is soft and maintains the shape of the hand exoskeleton, it proved to be overly compliant. This allowed twisting of the cable guides and the cables, especially during flexion assistance. Instead of using an actual glove, the entire exoskeletal structure could be 3D-printed as a single unit that could be donned entirely from the dorsal side of the hand [103]. This design has the advantages of facilitating donning (as the stereotypically flexed hand does not have to be opened) and completely freeing the palmar side of the hand. Softer plastic can be used to connect consecutive cable guides and line the parts of the device that come in contact with skin. Harder plastic will be used for the rest of the device. The design of this structure could be improved by creating retaining clips, connecting to the digits (figure 5.1), that are separate from the cable guide structure. In this manner, the clips could first be pressed onto the fingers. Securing the cable guides to the clips would subsequently lock the clips in place, thereby securing them to the fingers. Alternatively, the cable guides could be secured to the finger using a ring. In either case,

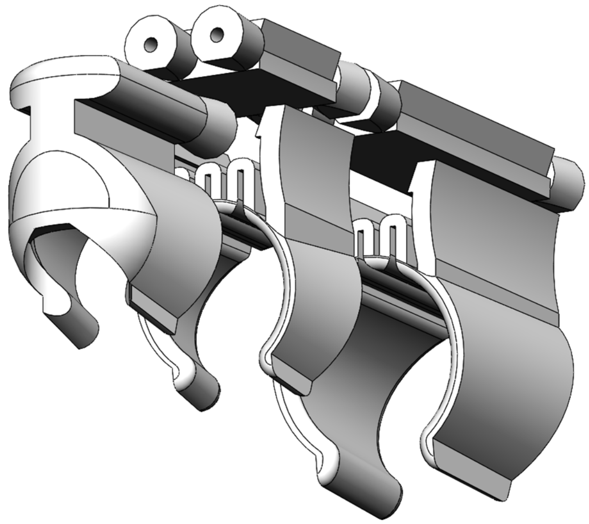

Figure 5.1. Digit part of the proposed 3D printed glove. The clips latch on the digit and the actuator locks them in place.

a compromise between frictional coupling and comfort between the device and hand would have to be achieved.

The weight and bulk of the BAC-Glove should be reduced. This could be achieved by a change in actuator. We used linear actuators connected to the cables through needles. This arrangement could be replaced with miniature rotational motors that connect with the cables through pinion gears, although fabrication of custom gears would be required. This arrangement would enable reductions on the length and weight of the forearm splint and in the bulk of the device.

The functionality of the BAC-Glove could also be enhanced by independently actuating the abduction/adduction DOF of both the MCP and CMC joints of the thumb. Right now, the thumb is adducted when it is extended and abducted when it is flexed. If we actuate the two cables of the thumb independently, we can control the abduction/adduction independently. This would add to the weight of the glove by requiring an additional motor, but would increase its function tremendously.

The main potential of the muscle activation pattern training may prove to be in preparing the users of an assistive device. The EMG game has flexibility for keeping an appropriate challenge level for users with different levels of capability. This could be beneficial for novices who might find use of the assistive device frustrating. On the other hand, controlling an assistive device at different hand postures, which affects the muscle activation patterns required, is different from playing a game while keeping the hand at a user-preferred posture. Thus I suggest exploration of the use of the muscle activation training as a precursor of the assistive device training. The other option would be to have the subjects play the game with different hand postures during the EMG training session.

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