THE EFFECT OF THE MYOMO ROBOTIC ORTHOSIS ON REACH PERFORMANCE AFTER STROKE

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Stroke affects 795,000 people yearly. Close to 85 percent of stroke survivors experience some degree of stroke-related upper extremity impairment due to spastic paresis (Nakayama, Jorgenson, Pedersen, Raaschou, & Olsen, 1994). Residual upper extremity impairments are associated with increased burden of care (Skidmore, Rogers, Chandler, & Holm, 2006) and decreased ability to garner gainful employment (Desrosiers et al., 2006). Current best evidence supports the use of a task-oriented practice regimen for the treatment of upper extremity impairment; however, many people have insufficient motor control to participate. It was the goal of this study to investigate the effect of the Myomo robotic upper extremity orthosis, a device that facilitates participation in a task-oriented practice regimen, on reach kinematic performance.

Specifically, we examined two research questions:

Question 1. What is the immediate effect of the Myomo orthosis on kinematic performance of reach? We predicted that before training, temporal (movement efficiency) and spatial characteristics (angular displacement, movement error, and acceleration cycles) of kinematic performance would be better with the Myomo orthosis than without the device.

Question 2. What is the training effect of the Myomo orthosis plus training kinematic performance? We predicted that temporal (movement efficiency) and spatial characteristics (angular displacement, movement error, and acceleration cycles) of kinematic performance without the Myomo orthosis would be better after 16 training sessions.

Findings suggest that the immediate effect of the Myomo orthosis on reaching performance (question 1) appears to be more attenuated than the training effect of the Myomo orthosis (question 2).All 6 participants demonstrated improvements in movement efficiency for one or more of three reaching targets. Five of the 6 participants demonstrated improvements in one or more of the spatial characteristics of kinematic performance. Effect size calculations suggest that the magnitude of the training effect was greatest for movement efficiency and angular displacement (medium effect size) and the least for movement error and acceleration cycles (small effect size).

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INTRODUCTION

Every 40 seconds someone in the United States has a stroke, resulting in more than 795,000 strokes annually (American Heart Association, 2012). Given the prevalence of stroke, it is not surprising that stroke is the leading cause of long-term disability in the United States. Direct and indirect costs associated with stroke-related disability were $38.6 billion in 2009 (Go et al., 2013). One major contributor to stroke-related disability is upper extremity impairment due to spastic paresis, occurring in approximately 85 percent of stroke survivors (Nakayama, Jorgenson, Pedersen, Raaschou, & Olsen, 1994). Residual upper extremity impairments are associated with increased burden of care (Skidmore, Rogers, Chandler, & Holm, 2006) and decreased ability to garner gainful employment (Desrosiers et al., 2006). Thus, interventions designed to reduce residual upper extremity impairment are likely to have a large impact on stroke-related disability.

Current best evidence suggests that task-oriented practice is the most effective intervention to reduce the impairment associated with upper extremity spastic paresis (Dobkin, 2005). Task-oriented practice requires individuals to perform functional upper extremity tasks with high repetition, otherwise referred to as massed practice (Morris & Taub, 2006). However individuals with severe upper extremity spastic paresis, particularly those with impaired motor planning, are often unable to participate in a task-oriented practice regimen due to the severity of their impairments (Barker, Brauer, & Carson, 2008). In addition, individuals with limited or absent distal function are frequently excluded from task-oriented practice programs because they

cannot independently perform the recommended tasks. Often these individuals are limited to interventions that address basic care of the upper extremity, including palliative interventions such as self-range of motion and stretching (O'Sullivan, 2006). Thus interventions that address the needs of these individuals, and allow them to participate in task-oriented practice programs have the potential to cause substantial clinical change.

One intervention that shows promise for individuals with severe upper extremity spastic paresis is the Myomo orthosis. The Myomo orthosis is a robot-powered, electromyography (EMG)-driven device designed to address impairments in reach after stroke. The device is lightweight, wearable, and can be used to perform variety of static and dynamic tasks including unimanual and bimanual tasks such as reaching, lifting objects, and progressive exercise (Stein, Narendran, McBean, Kreb, & Hughes, 2007).

Preliminary laboratory results suggest that the Myomo orthosis may significantly reduce upper extremity spasticity, improve motor planning and reverse progressive weakness, particularly in participants with limited distal function (Stein et al., 2007). Individuals with severe upper extremity spastic paresis who used the Myomo orthosis were able to participate in a variety of tasks including unimanual and bimanual reaching, manipulation and progressive strengthening. Furthermore, users of the Myomo orthosis demonstrated clinically meaningful improvements in upper extremity Fugl-Meyer Assessment scores (Stein et al., 2007). While these initial case studies have reported promising results, it is unclear whether these findings can be reproduced in a clinical setting.

This dissertation examines the current state of science addressing the recovery of upper extremity function after stroke, and examines a new robotic intervention designed to improve upper extremity function after stroke.

1.0 UPPER EXTREMITY FUNCTION: OUR CURRENT UNDERSTANDING

Given the importance of addressing upper extremity impairments after stroke it is essential to understand the components upper extremity function, current methods of measuring upper extremity function, and current methods of intervention to address upper extremity function after stroke. The following paragraphs address each of these topics in order.

1.1 UPPER EXTREMITY FUNCTION: COMPONENTS

Grossly, upper extremity function can be divided into three distinct but inter-related components: reach, grasp, and manipulation (Shumway-Cook & Woollacott, 2007). Together these three components combine to provide a person with a useful or "functional" upper extremity. Stroke frequently causes impairment in one or more of these components, often causing profound changes in upper extremity function. Among these components, reach is considered to be foundational, because the inability to reach precludes the ability to grasp or manipulate objects (Shumway-Cook & Woollacott, 2007). For this reason, rehabilitation designed to facilitate optimal upper extremity function, frequently focuses first on reach.

1.1.1 Reach: a critical component of upper extremity function

Reach involves complex interactions between visual, somatosensory and motor systems working in coordination to accurately position the hand in space in proximity to any given target. As such, reach is a multifaceted foundational upper extremity skill that is critical to the performance of daily tasks such as dressing, shaving, eating or driving (Shumway-Cook & Woollacott, 2007).

1.1.2 Reach following stroke

Stroke alters motor control, and thus alters the ability to reach. Several authors have examined differences in reach between individuals who have and have not sustained stroke, and reported these findings. In essence, reach after stroke is characterized by poor inter-joint coordination as demonstrated by gross execution of elbow flexion and shoulder horizontal abduction compared to reach without stroke (Cirstea, Ptito, & Levin, 2006; Wu, Chen, Tang, Lin, & Huang, 2007). In addition, individuals with severe reach impairment after stroke demonstrate difficulty moving the elbow from flexion to extension and coordinating this movement with shoulder movement (Wu et al., 2007).

Kinematic patterns of reach following stroke demonstrate a uniform abnormal pattern when compared to healthy participants in two ways. First, reach exhibits smaller amounts of movement at the shoulder, elbow, and wrist with increased compensatory trunk movement and reduced reach accuracy. Secondly, individuals following stroke exhibit decreased speed of hand movement with multiple starts and stops (Cirstea et al., 2006; Thielman, Dean, & Gentile, 2004; Wu et al., 2007). This is in contrast to the smooth speed of movement in individuals without stroke.

1.2 UPPER EXTREMITY FUNCTION: ASSESSMENT METHODS

Since upper extremity reach is a critical component of upper extremity function, a variety of clinical and research tools and techniques have been developed to measure impairments in reach. Grossly, we can group these various methods into two categories: clinical and kinematic measures.

1.2.1 Description of clinical measures

Clinical measures assess reach through a series of laboratory-based or activity-based tasks. For example, the Fugl-Meyer Assessment contains a series of laboratory-based tasks that require individuals to move through a variety of active motions without a functionally relevant goal (e.g., placing their arm on a box). In contrast, the Chedoke Arm and Hand Activity Inventory (CAHAI) contain a series of activity-based tasks that require individuals to use the upper extremity to perform functionally relevant tasks (e.g., brushing their hair). In both cases, clinical assessments of reach provide the clinician and researcher with valuable clinical observations, but are limited in their ability to detect minute changes in the quality or quantity of reach (Culmer, Levesley, Mon-Williams, & Williams, 2009)

1.2.2 Description of kinematic measures

Kinematic measures quantify reach using a tracking system (video, magnetic, or light) that records the position of the limb and body in space in static and dynamic conditions. Analysis of the recorded data produces a precise characterization of movement including movement

efficiency, angular displacement, movement error, and acceleration cycles. Table 1 provides descriptions of kinematic variables relevant to reach. Thus kinematic measures allow clinicians and researchers to measure minute changes in the quality, quantity and skill during reaching tasks (Winter, 1990).

1.2.3 Use of clinical and kinematic measures in stroke research

To further examine the current state-of-the-art methods for measuring reach after stroke, we completed a focused review of the peer-reviewed literature published between January 1999 and December 2012. We began with a thorough search of electronic databases (Cochrane Database of Systematic Reviews, MEDLINE, and CINAHL) using the following search terms: stroke, rehabilitation, reach, upper extremity, arm, task-oriented practice, task practice, repetitive task practice, robotics, robot, and device. In addition, we gleaned additional articles from published systematic reviews and consultation with experts. These searches yielded 525 primary articles. We narrowed our search by reviewing abstracts and selecting articles that examined interventions for reach impairment after stroke, and examined some component of task-oriented practice, device-assisted intervention or robotic intervention for reach impairment after stroke. We excluded articles based on the following criteria: 1) reach was not a primary or secondary outcome of the study, 2) reach was only measured as an indicator of balance, and 3) data represented a single case study report. Figure 1 provides a description of this process and the delimitation of articles. After examining each abstract for these criteria 30 primary articles were selected for the review. A summary of these articles is provided in Appendix A.

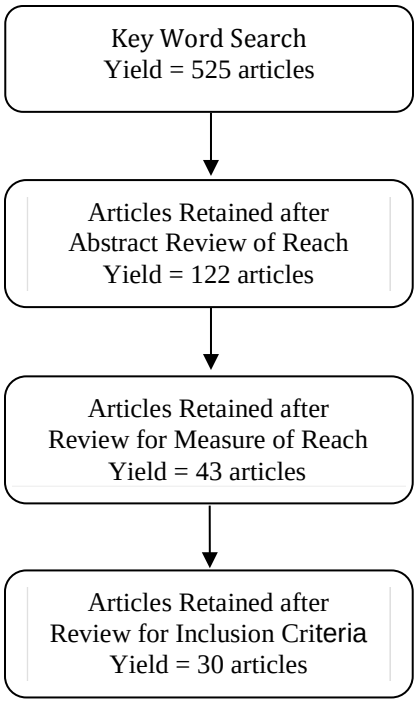


Figure 1: Delimitation of Articles for Literature Review

1.2.3.1 Use of clinical measures

Within these 30 articles, 10 different clinical measures of upper extremity reach were used. Among these clinical measures, the most common measure was the upper extremity component of the Fugl-Meyer Assessment, which was used in 17 of the reviewed studies. The second most common measure was the Wolf Motor Function Test used in 4 studies.

The Fugl-Meyer Assessment is a laboratory-based clinical measure that has long been the gold standard for upper extremity assessment following stroke. First published in 1975, the Fugl-Meyer Assessment assesses the stage of motor recovery, patterned after Signe Brunnstrom's 7 stages (Fugl-Meyer, Jaasko, Leyman, Olsson, & Steglind, 1975). Fifty items yield a total score ranging from 100 (no motor impairment) to 0 (complete hemiparesis). Several studies have suggested that the Fugl-Meyer Assessment has adequate validity and reliability (Duncan, Propst,

& Nelson, 1983). However, more recent reports have suggested that newer measures may be more inclusive and thorough without suffering from the ceiling effect present within the Fugl-Meyer Assessment. It has also been suggested that the Fugl-Meyer Assessment is missing key components such as hand dexterity and the use of the extremities during a functional task, items which are predictive of a more complete stroke recovery (Gladstone, Danells, & Black, 2002).

The Wolf Motor Function Testassesses upper extremity function (reach, grasp and manipulation) through a series of seventeen laboratory based tasks (Morris, Uswatte, Crago, Cook, & Taub, 2001). Items are scored on two scales, functional performance and time. Scores for functional performance are from 0 (does not attempt) to 5 (normal), yielding a total score of 75 (no motor impairment) to 0 (severe motor impairment). The Wolf Motor Function Test has adequate validity and reliability, and has been used as the primary outcome measure in many of the constraint-induced movement therapy trials (Morris, Uswatte, Crago, Cook & Taub 2001). One limitation reported in the literature is that the inclusion of the timed component in scoring causes a floor effect with more severe stroke survivors.

The Chedoke Arm and Hand Action Inventory, is a newer clinical measure designed to address some of the shortcomings of the previous measures. Unlike the Fugl-Meyer Assessment and the Wolf Motor Function Test, the Chedoke Arm and Hand Action Inventory uses activity-based tasks to assess reach in the context of everyday functional activities. Published in 2004, the Chedoke Arm and Hand Action Inventory has 4 validated versions (13 item, 11 item, 9 item, and 7 item versions; Barreca, Stratford, Masters, Lambert & Griffiths 2006). Nonetheless, the 13 item version is the only version with demonstrated reliability (Barreca et al., 2004). Because the

Chedoke Arm and Hand Action Inventory measures the level of assistance for the items, not just pass / fail, it does not suffer from the floor effect present in the Fugl-Meyer Assessment and the Wolf Motor Function Test, specifically when measuring more impaired patients.

1.2.3.2 Use of kinematic measures

Compared to the variety of clinical measures used in the reviewed studies, there was less variability in the kinematic measures used to quantify change in upper extremity reach. Among the reviewed studies (Appendix A), 9 studies used kinematic measures. Of these 9 studies, all measured one or more of the following 4 variables: movement efficiency, angular displacement, movement error, and acceleration cycles. Table 1 provides a description of each of these variables. Together these measures have been used to characterize reach impairment and quantify treatment effects following stroke.

Table 1. Definitions of Kinematic Variables

Variable	Type	Description
Movement efficiency	Temporal	Total time to complete one reaching task from movement initiation to target contact
Angular displacements	Spatial	Displacement of line segments defining the elbow
Movement error	Spatial	Degree in which the path to target varies from the optimal, or most efficient path
Acceleration cycles	Temporal /Spatial	Changes in direction along velocity curve (displacement/time) during the task

1.3 UPPER EXTREMITY FUNCTION: INTERVENTION METHODS

Given the importance of reach for upper extremity function, interventions that address reach impairment have the potential to significantly impact upper extremity recovery following stroke. Using the same 30 studies, we examined the current state of the science for interventions addressing reach impairment. Based on our review of these 30 studies, there are 3 classes of interventions currently being used to address upper extremity reach impairment following stroke. These classes are: task-oriented practice, non-robotic devices, and robotic devices.

1.3.1 Task-oriented practice

A growing body of evidence demonstrates that task-oriented practice is one of the most effective interventions for reducing reach impairment and promoting upper extremity recovery following stroke (Kwakkel, 2008;). Task-oriented practice is a term that encompasses a broad variety of interventions including constraint-induced therapy and repetitive task practice (Birkenmeier, Prager, & Lang, 2010) (Wolf et al, 2006). Key elements of task-oriented practice are high repetition of motor task practice and shaping (Rensink, Schuurmans, Lindeman, & Hafsteinsdottier, 2009). High repetition usually involves concentrated motor task practice throughout the day (i.e., massed practice). Shaping involves grading motor task practice complexity according to the patient's abilities and improvements over time.

A recent Cochrane review suggests that task-oriented practice is superior to other interventions (e.g., strength training, usual rehabilitation care exercises) for the reduction of upper extremity impairment following stroke (French et al., 2010).These reductions have been reported among participants who previously were thought to be outside the window of benefit from traditional therapies because they were 6 months or more after stroke (Kunkel, Kopp, Muller, Villringer, & Taub, 1999).Not only has task-oriented practice been associated with reductions in upper extremity impairment, but has also been associated with changes in cortical motor representation and activation patterns of the brain (Wittenberg et al., 2003).

Despite the promise of task-oriented practice, there are many considerations that affect the indication for and implementation of task-oriented practice. First, task-oriented practice requires that individuals have a certain level of upper extremity function in order to be able to participate in and benefit from the intervention (Kunkel et al., 1999). For example, in order to be considered a candidate for a constraint induced therapy protocol, a patient must exhibit 20 degrees of finger flexion, components of upper extremity function many individuals with severe spasticity do not have. In fact, many persons with the inability to activate the hand are relegated to self-range of motion and muscle tone regulation exercises (O'Sullivan, 2006).

Second, task-oriented practice requires a high-intensity of practice to yield results (Morris & Taub, 2006). These levels of practice are difficult to reproduce in clinical settings, requiring structured home exercise programs to augment existing clinical practice. This is problematic because many individuals require the assistance of a skilled therapist to assist in the completion a task-oriented practice regimen and may not have access to these.

Thus, task-oriented practice is an effective intervention for reach impairment following stroke for selected individuals. Specifically, individuals with a mild to moderate reach impairment, who have some hand functions, and who have the ability to carry-over intense practice programs at home without assistance are likely good candidates for task-oriented practice. However, for those with severe reach impairment (i.e., are unable to reach, grasp or manipulate without assistance or who require assistance to carry through with home practice programs), standard task-oriented practice programs may not be as effective.

In response to these limitations, researchers have proposed a number of new technologies to serve as adjunctive therapies to task-oriented practice (Brewer, McDowell, & Worthen-Chaudhari, 2007).We have grouped these technologies into two groups: non-robotic devices and robotic devices.

1.3.2 Non-robotic devices

Non-robotic training devices typically consist of an external structure that the hemiparetic arm is affixed to and applies external force (elastic bands, mechanical advantage, or sound limb) to increase the ease or amount of hand and arm motion. These devices are designed to be used in concert with task-oriented practice, assisting reaching in individuals with more severely impaired function. Among the reviewed studies, 5 examined non-robotic devices as an intervention to address reach impairment.

The Bilateral Arm Training with Rhythmic Auditory Cueing (BATRAC) System. The BATRAC System was developed at Johns Hopkins University as a device that uses bilateral movement with auditory cueing to facilitate repetitive motion. This device consists of 2 T-bars that the patient either grasps with both hands or is assisted in grasp with strapping. The patient is

then asked to move the arms reciprocally forward and back along a fixed path oriented in the transverse plane perpendicular to the patient. In addition the device uses auditory cues to cue the patient and help improve feedback (Whitall, McCombe, Silver, & Macko, 2000).

The BATRAC has been examined in 2 studies. Whitall et al. (2000) demonstrated statistically significant improvements in upper extremity Fugl-Meyer Assessment scores after a 6-week intervention in chronic stroke survivors. When compared to a standard care condition, Luft and McCombe (2004) demonstrated no significant differences in function, as defined by upper extremity FMA scores following a 6-week BATRAC intervention between the two conditions. Nonetheless, Luft & McCombe did report significant increases in pre- and post-central gyrus activation in the BATRAC condition compared to the standard care condition (Luft et al., 2004).

The Sensorimotor Active Rehabilitation Trainer (SMART Arm). Developed by the University of Queensland, the SMART Arm is designed to treat the impairment associated with forward reach. The SMART Arm consists of a customizable thermoplastic splint that slides along an elevated linear track. Pulleys unload the limb as it slides along the track, and patients observe their reaching distance via a video display. If the patient is unable to meet a preset goal, the SMART Arm provides electrical stimulation to the triceps muscle.

Only one selected study examined the Smart Arm. Barker and colleagues reported significant improvements in Motor Assessment Score (MAS), reaching force and reaching distance when using the SMART arm trainer with or without electrical stimulation, compared to standard practice (Barker, Brauer, & Carson, 2008).

The REHA Slide. Developed by researchers from Charite University of Medicine, Berlin, the REHA Slide is designed to assist patients with severe reaching impairment and give them the ability to participate in massed practice reaching activities. The design of the REHA Slide resembles a rolling pin on a track. The participant grasps both ends of the pin and is able to use the less involved arm to move the hemiparetic arm through reaching exercises with three degrees of freedom (Hesse, Werner, Pohl, Mehrholz, Puzich, & Krebs 2008). Visual feedback is also provided via a computer monitor.

Initial case series studies using the REHA Slide reported marked improvements in upper extremity FMA and strength (Hesse et al., 2007). However, a later randomized controlled trial demonstrated no significant differences between the experimental group (REHA Slide plus standard care), and the control group (standard care plus electrical stimulation; Hesse et al., 2008).

Therapy Assistant Wilmington Robotic Exoskeleton (WREX). The WREX was initially developed at the Pediatric Engineering Research Lab in collaboration with Drexel University as an orthosis to assist children with muscular dystrophy (Rahman, Sample, Seliktar, Alexander, & Scavina, 2000). A gravity-compensating passive arm orthosis, the WREX was later adapted for use with adults with hemiparesis. The WREX consists of a stationary exoskeleton designed to un-weight the hemiparetic arm to promote increased upper extremity reaching. Un-weighted is achieved by a series of elastic bands.

The WREX has been examined in one study. Iwamuro and colleagues reported significant improvements in reach kinematics and reduced EMG activity in bicep and triceps muscles when compared to reaching without the WREX (Iwamuro, Cruz, Connelly, Fischer, & Kamper, 2008).

1.3.3 Robotic training devices

Among the reviewed studies, 7 examined robotic training devices as an intervention method for individuals with reach impairment after stroke. Similar to non-robotic devices, robotic devices function in such a way as to reduce the amount of strength, movement or motor control needed to participate in reaching tasks. In contrast to non-robotic devices, participation in reaching tasks is accomplished through one of several control mechanisms such as computer-controlled motor - driven robotic arms or complex pulley systems. Among the reviewed studies, 7 unique robotic devices were described.

1.3.3.1 Description of robotic devices and the evidence

The following paragraphs provide a description of each of these 7 devices, and the evidence examining these devices.

The MIT Manus. Sold commercially as the InMotion2, the MIT Manus is a haptic upper extremity robotic device designed to assist patients with reach impairment. The Manus is composed of a multi-axial industrial robotic arm, a haptic feedback system, and a patient interface. The MIT Manus aids the participant by guiding the impaired extremity toward a computer-generated target on a video screen. The MIT Manus varies the resistance to challenge the patient or in the case when the participant cannot assist, guides the arm passively to the target (Aisen, Krebs, Hogan, McDowell, & Volpe, 1997).

Six studies have reported significant within group reductions in impairment in chronic stroke survivors (Aisen et al., 1997; Daly et al., 2005; Fasoli, Krebs, Stein, Frontera, & Hogan, 2003; Krebs et al., 2008; Macclellan et al., 2005; Volpe et al., 2008).Of the three studies that have compared the MIT Manus to a separate intervention (e.g. MIT Manus vs. standard care)

(Aisen et al., 1997; Daly et al, 2005; Volpe et al., 2008) only one study reported significant improvement in upper extremity Fugl-Meyer Assessment scores when using the MIT Manus compared to a sham intervention (Aisen et al., 1997).

Mirror Image Movement Enabler (MIME). Another robotic system designed to assist stroke patients with reach is the MIME. Similar to the Manus in design, the MIME is comprised of not one, but two industrial robotic multi-axial arms to which the user straps his/her arms via a grip style interface. The MIME is unique in that it emphasizes bilateral movements rather unilateral and allows participants to reach toward real objects. Similar to the Manus, the MIME has different modes whereby it can guide passively or actively assist the hemiparetic limb to the target (Lum, Burgar, Shor, Majmundar, & Van der Loos, 2002).

Two studies investigated the MIME with chronic stroke survivors and reported significant improvement in reach as measured using kinematic measures of velocity and displacement for the group using the MIME (Lum, Burgar, & Shor, 2004; Lum et al., 2002). In a study of 30 sub-acute stroke participants, Lum et al., (2006) reported significant proximal FMA scores compared to standard care, though these differences did not persist at the 6-month follow up.

Neurorehabilitation Robot (*NeReBot).* Another new technology, intended to reduce the upper extremity impairment following a stroke, is the NeReBot. This robotic device attaches to the users arm via a series of suspension wires and a rigid orthosis effectively acting as an un-weighting system for the arm (Masiero, Celia, Rosati, & Armani, 2007). The NeReBot can be programmed to perform repetitive movements within the patient's available range of motion as well as provide varied levels of assist. Feedback is provided both auditorally and visually

(haptic) throughout the exercise regimen. The NeReBot has been shown to improve proximal FMA and MRC strength in the bicep and deltoid when compared to standard care (Masiero et al., 2007).

GENTLE System. The GENTLE system is made up multi-axial robotic and a haptic visual computer feedback system. The user's wrist is attached to the device via a free motion gimbal located on the wrist. This system is unique in that it utilizes un-weighting of the hemiparetic arm to improve free motion. Similar to the MIT Manus or MIME, the GENTLE system operates in passive, assistive, and resistive modes. One study reported improved Motor Assessment Scores and Modified Ashworth scores during the GENTLE intervention period compared to sling suspension only (Coote, Murphy, Harwin, & Stokes, 2008).

The Assisted Rehabilitation and Measurement Guide (ARM). The ARM is another robotic system designed to aid reaching practice. The ARM consists of a linear track to which the participant's hand and forearm are attached via a splint interface. The linear track can be adjusted to any orientation; however the participant is constrained to a linear reaching path. Computer controlled drive motors provide either resistance or assist during the reaching task with haptic feedback provided by a video monitor that shows the users progress toward a target(Kahn, Zygman, Rymer, & Reinkensmeyer, 2006).One study examined the ARM, comparing the ARM to conventional reach training program by (Kahn et al., 2006).There were no significant differences between groups.

TheRobotic rehabilitation system for the upper limb motion therapy (REHABOB). The REHABOB consists of two industrial robots that together are able to provide ROM as the shoulder and elbow (Fazekas, Horvath, & Toth, 2006). This system was designed primarily to

supplement passive range of motion exercises. In a RCT of individuals with chronic stroke, no significant differences in upper extremity and self-care skills were detected between the REHABOB and standard care interventions (Fazekas, Horvath, Tronai, & Toth, 2007).

My Own Motion E100 (Myomo). The Myomo orthosis is an externally powered EMG guided wearable upper extremity robotic orthosis. EMG guidance of the motor unit is provided by an electrode placed either over the biceps or triceps muscle belly. Motor output, and thus elbow movement, is proportional in velocity and distance to the intensity of the EMG signal. Elbow extension (or flexion if the EMG is placed on the triceps) is achieved thru a passive spring assist, though this can only be activated by inhibiting the agonist muscle (Stein et al., 2007).Following a 6 week upper extremity intervention, 6 chronic stroke survivors demonstrated clinically important improvements in upper extremity FMA scores and decreases in Modified Ashworth Scores at the elbow and wrist (Stein et al., 2007).

In order to more clearly compare and contrast the similarities and differences of the 7 robotic upper extremity devices, it is useful to discuss them based on three clinically important properties: portability, control mechanisms, and training. Refer to Table 2 for a summary of robotic device characteristics.

Table 2. Summary of Robotic Devices Characteristics

Device	Portability	Activation Mechanism	Training Protocol	Feedback Mechanism
MIT Manus	Room bound	Active Assist/ Passive	Task-oriented practice	Haptic
MIME	Room bound	Active Assist/ Passive	Task-oriented practice	Visual Observation
ARM guide	Room bound	Active Assist/ Passive	Task-oriented practice	Haptic
NeReBot	Clinic portable	Active Assist/ Passive	Task-oriented practice	Haptic & Auditory
GENTLE System	Room Bound	Active Assist/ Passive	Task-oriented practice	Haptic
REHABOB	Room Bound	Passive	Range of Motion	None
Myomo	Wearable	EMG / Active assistive	Task-oriented practice	Visual Observation

1.3.3.2 Portability of robotic devices

Examining the portability of devices is useful in that it helps to identify the clinical setting and activities that best match each device. Furthermore, portability is related to the size and cost of devices. Examining these robotic devices together, they can be grossly divided into three categories by portability: room-bound, clinic portable and wearable devices.

Room-bound devices. The InMotion2 (commercial variant of the MIT MANUS), the MIME, REHABOB, and the GENTLE/s systems are examples of room-bound upper extremity robotic devices. In order to use the MANUS or MIME, patients sit stationary and are strapped to a multi-axis robotic arm. Similarly, the upper extremity is suspended by the GENTLE system. All three robotic systems provide variable levels of assistance depending on the level of weakness and ability. In patients with extremely limited upper extremity use, these devices revert to a guided passive mode and the limb is moved through therapist-selected patterns. Unique to the MIME, bilateral upper extremity tasks are possible or the device can be used in unilateral mode. With both devices the user is limited to a static position and therapy is based around reaching and targeting tasks. Because of the size and type of device, none of these devices can be easily incorporated into functional tasks.

Clinic portability. The NeReBot was from inception designed to be a clinic portable robotic intervention. The NeReBot is housed on a wheeled frame that can be moved between treatment areas. Despite the advantages of portability compared to the room-bound devices such as the MANUS, the NeReBot clinical application is similarly limited by cost and a fixed treatment environment.

Wearable devices. Currently there is only on commercially available wearable robotic upper extremity device, the Myomo e100. This device is a wearable exoskeleton that allows users to participate in functional reaching tasks in a variety of environments as well as assist in routine functional tasks such as sit to stand. In addition, due to its size the Myomo orthosis can be used in the home, unlike the other upper extremity robotic devices.

1.3.3.3 Activation mechanism of robotic devices

Another way to differentiate between robotic devices is by the activation method. Robotic devices utilize three primary activation mechanisms. They are passive, active assistive, and EMG activation. Devices such as the MANUS, MIME, ARM guide and NeReBot can operate in either passive or active assistive mode (Brewer et al., 2007).Active assistive mode requires the patient to actively move the limb toward the goal before the system will assist the limb. This approach requires that users have volitional active motion of the upper extremity prior to being able to use the device. In the absence of active movement, these devices degrade to a passive guiding mode where the limb is passively moved through range of motion to variety of computer generated or user defined points. Therefore, these devices are best suited for use with individuals following stroke with active shoulder motion. Alternatively, the Myomo orthosis uses an EMG sensor to detect to and respond to sub-motor levels of muscular activity, thus allowing the user to actively flex and extend the elbow even during the very early stages of recovery following a stroke, or when other robotic devices would provide only passive motion. EMG activation may allow stroke survivors to begin a task-oriented practice earlier and minimize upper extremity impairment (Stein et al., 2007).

1.3.3.4 Training with robotic devices

Of the 7 devices reviewed, 6 used massed practice training protocols and 1(the REHABOB) used passive range and proprioceptive input. Though the training mechanisms are similar, differences in the type of practice, environment and context are marked. With all of the room-bound robotic devices, much of the training is limited to routine arm movements along predetermined paths. Reaching is toward either toward a computer-generated 2-dimensional target on a video screen or generic target such as a ball. Furthermore, because the devices are

room-bound, or clinic portable, in the case of the NeReBot, all training takes place either in the context of the lab, or therapy clinic. None of the devices, with the exception of the Myomo e100, provides for clients to train in the context of daily activities and to use the upper extremity in the context of function such as transfers, sit to stand, and sitting balance.

1.3.3.5 Feedback mechanism

Of the devices reviewed, two primary feedback mechanisms exist, haptic and direct visual observation. Haptic feedback, such as is used with the MIT MANUS, consists of a computer monitor that displays a representation of the users arm as well as the digital target and progress toward it. In the case of the Myomo orthosis and MIME, feedback is provided by direct visual observation of the user's arm and its progress toward, or interaction with, the target.

1.4 SUMMARY

Impairment of upper extremity reach after stroke is common and associated with significant disability. Task-oriented practice is the intervention of choice for reducing upper extremity impairment. However, stroke survivors must possess some active range of motion to engage in task-oriented practice regimens. Several devices, mechanical and robotic, have been developed to facilitate use of the hemi-paretic extremity for participation in task-oriented practice regimens. However, only the Myomo e100 is portable, relatively inexpensive, and able to be used in a variety of settings, including the home. Also, unlike the other devices, the Myomo orthosis is able to detect and amplify sub-motor activity thus allowing earlier active motion. For this reason, we propose the following study to examine the clinical benefit of the Myomo orthosis.

2.0 SPECIFIC AIMS

While the Myomo orthosis has shown promise in early feasibility studies, the clinical effects of the Myomo orthosis on reach have yet to be rigorously studied. One widely accepted method for evaluating the effect of interventions on reach is the assessment of kinematic performance. Assessment of kinematic performance provides accurate quantitative measures of reaching performance including movement efficiency, angular displacement, movement error, and acceleration cycles (Schmidt & Lee, 1999). The overall aim of this study was to examine the effect of the Myomo orthosis on kinematic performance of the upper extremity. More specifically, we examined two research questions that investigated the immediate effect of the Myomo orthosis and the training effect of the Myomo orthosis plus therapy (Figure 2).

*Question 1.*What is the immediate effect of the Myomo orthosis on kinematic performance of reach? We predicted that before training, temporal (movement efficiency) and spatial characteristics (angular displacement, movement error, and acceleration cycles) of kinematic performance would be better with the Myomo orthosis than without the device.

*Question 2.*What is the training effect of the Myomo orthosis plus training kinematic performance? We predicted that temporal (movement efficiency) and spatial characteristics (angular displacement, movement error, and acceleration cycles) of kinematic performance without the Myomo orthosis would be better after 16 training sessions.

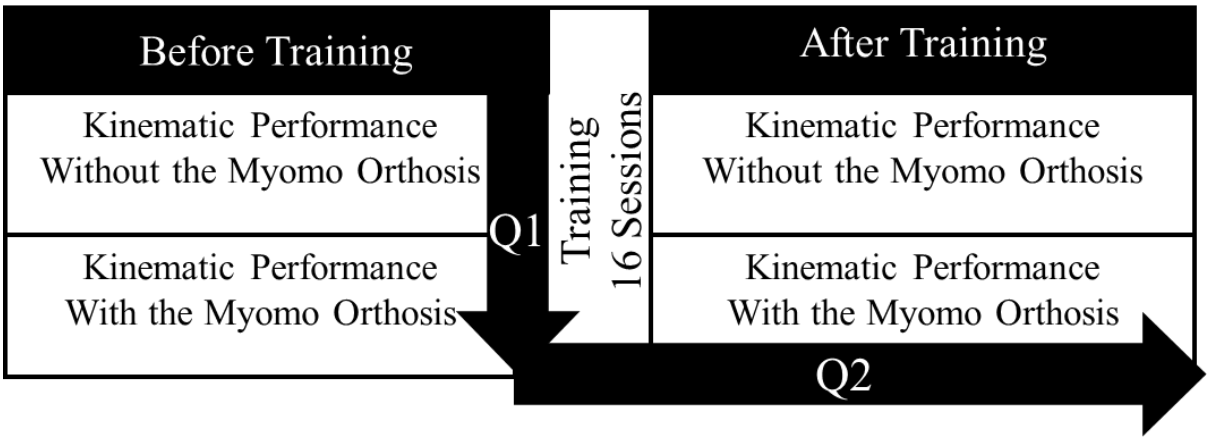


Figure 2. Overview of Planned Contrasts

3.0 RESEARCH METHODS

3.1 PARTICIPANT RECRUITMENT

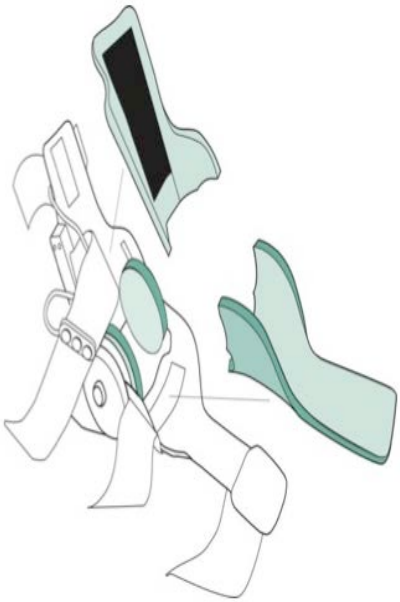
Participants were recruited from UPMC Rehabilitation Institute and through local stroke support groups. All study procedures were approved by the University of Pittsburgh and HealthSouth Institutional Review Boards.

All participants had a history of stroke for at least 3 months that resulted in upper extremity spastic hemiparesis. In addition all participants were able to follow three step commands with 80 percent success or greater and demonstrated the ability to recruit EMG activity in the biceps sufficient to activate the Myomo orthosis. Individuals were excluded if they had shoulder pain as defined by a Visual Analog Scale score of 5 or greater; contractures that limited full elbow extension; or skin lesions on the hemiparetic upper extremity. Individuals who were unable to tolerate the testing position were also excluded.

3.2 INTERVENTION

The Myomo orthosis is an FDA Class II externally powered EMG-guided upper extremity orthosis (Figure 3). The weight of the wearable portion of the unit is one pound 11 ounces. The motor unit was geared and capable generating torque equal to 14 Newton meters. EMG guidance

of the motor unit was derived from an electrode placed either on the biceps or triceps muscle but not both simultaneously. The input EMG signal is smoothed and filtered using a high bandwidth filter technique. Output from the motor is proportional in velocity to the input EMG signal. Extension or flexion of the elbow was achieved by an adjustable passive aid that works opposite of the muscle used to provide EMG control but was only active when agonist EMG is below pre -set value. Amplification of participants' existing motion, though weak, allowed participants with absent or severely limited active elbow motion to move through full range of motion in a controlled proportional fashion (see Figure 3).



Phase I: Familiarize participant with function of Myomo; Don/doff, customize fit, pad and adjust for comfort; Calibrate and determine optimum gain and spring settings; Routine elbow flexion/ extension;

Phase II: Basic upper extremity exercise with the Myomo; Vary patient position and adjust gain as appropriate; High repetition of elbow flexion / extension in different positions;

Phase III: Incorporate the Myomo into gross functional tasks such as transition from sit to stand, as a support during a reaching activity, guiding a wheeled walker;

Phase IV: Use Myomo during bimanual tasks such as lifting and moving a laundry basket, and pushing/ pulling objects.

Figure 3. Myomo Orthosis and Intervention Phases

The intervention program was based in part on a protocol that has previously been piloted at a local rehabilitation hospital. Additional input into the development and validation of the intervention program was provided by experts within the University of Pittsburgh's Department of Occupational Therapy. Participants were scheduled to complete 16 training sessions over a 4-week period. Each session lasted approximately 1 hour. The protocol consisted of 4 phases with each phase progressively more difficult than the previous phase (Figure 3).All participants began at Phase 1 and proceed until they achieved the highest phase that matched their ability level. Phase progression was determined by achievement of select goal activities within the phase (see Appendix B for expanded description of the intervention program).Meeting the achievement criteria, 6 of 8 tasks with 75 percent success for example, allowed the participant to progress to the next phase. Not all participants achieved all phases.

3.3 INSTRUMENTATION

3.3.1 Descriptive measures

Descriptive measures were administered to describe the sample. Following informed consent, age, chronicity, type of stroke, side, and pre-intervention function was obtained through participant interview. During the intervention phase, researchers kept a log indicating total time of Myomo orthosis use, phase of intervention program, and the settings and calibration of the Myomo orthosis. In addition participants were asked to report the start of or change in medications or interventions addressing spasticity (i.e., Botox injections).

3.3.2 Clinical measures

Clinical measures were administered to describe the clinical characteristics of the sample. The Modified Ashworth Scale (MAS) was used to measure resistance to passive stretch in the affected elbow, wrist, fingers and thumb. The MAS is a valid and reliable tool that is the clinical standard for measuring changes in muscle tone after stroke (Bohannon & Smith, 1987).Upper extremity function was evaluated using the Chedoke Arm and Hand Activity Inventory (CAHAI).The CAHAI measures upper extremity function in the context of routine daily tasks. The CAHAI has both high inter-rater reliability and validity and is sensitive to clinically important change (Barreca, Stratford, Lambert, Masters, & Streiner, 2005).A 10-centimeter Visual Analog Scale (VAS) was used to measure participants' levels of pain. The VAS has been shown to be valid and reliable measure of musculoskeletal pain (Katz, 1999).

3.3.3 Kinematic performance measures

Kinematic performance measures were used to test study hypotheses. One temporal and three spatial characteristics of reach were derived from the data collected using the motion analysis equipment. These variables were movement efficiency, angular displacement, movement error, and acceleration cycles. A detailed manual that describes the laboratory set-up and data collection methods is available from the first author.

3.3.3.1 Temporal characteristics

Movement efficiency was defined by the total time the participant took to reach from the starting position to each target and back to the starting position.

3.3.3.2 Spatial characteristics

Angular displacement was defined as the angle between the two vectors that define the arm and forearm. Angular displacements represent the elbow range of motion during the reaching task. Movement error was the degree from which the path to the target varies from the optimum path, as indicated by the area of the distance between the hand and the optimum path, in three-dimensional space throughout the reaching task. Finally, acceleration cycles were measured by the change in velocity direction over a defined threshold level during the reaching task. A smooth reaching movement with fewer changes in velocity direction and decreased movement error is commonly associated with a more skilled or practiced movement.

Prior to beginning the Myomo intervention, all kinematic performance data were collected using the NaturalPoint three-dimensional motion analysis system (OptiTrack system, Corvallis, OR). NaturalPoint is a three-dimensional passive infrared video based motion analysis system. This system is capable or resolving motion in Cartesian space with an error less than 1.0 millimeter. Calibration was completed, both statically and dynamically, prior to each participant evaluation using standardized static and dynamic references. All data were collected and analyzed at 120 Hertz.

Twelve cameras were placed around the participant to obtain multiple views to construct the 3D motion (Figure 4). Reflective spheres (5 millimeter) array were used to identify all targets and motion vectors of interest (Figure 4).

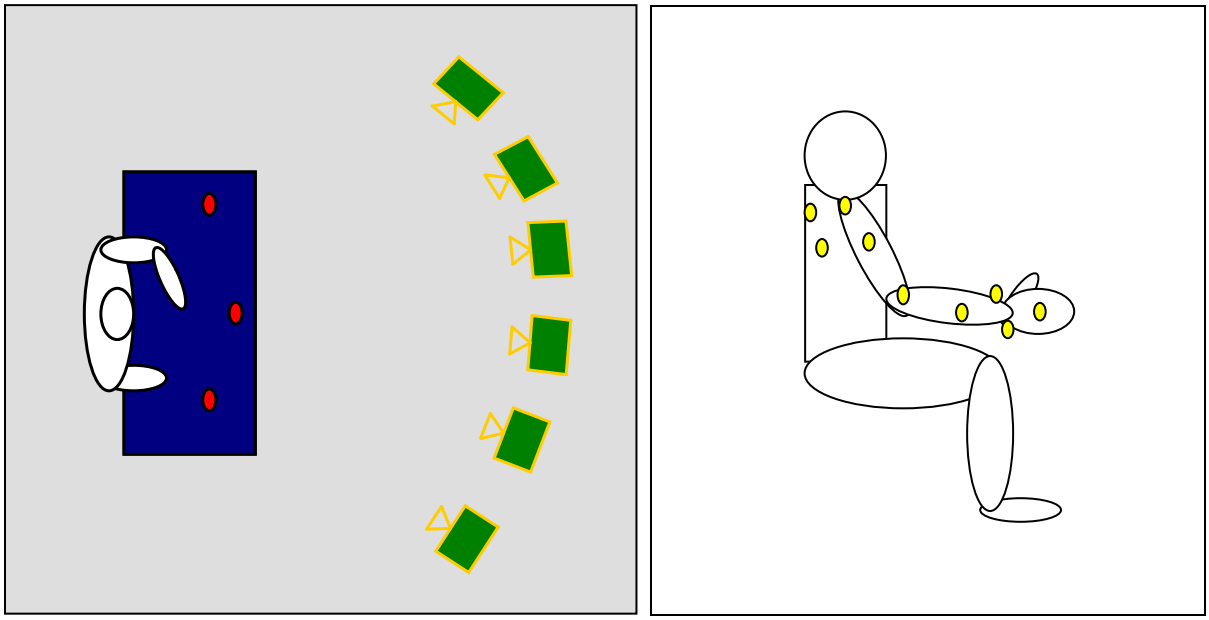


Figure 4. Camera and Marker Arrangement

3.4 PROCEDURES

The principal investigator contacted individuals interested in the study to discuss the study and answer any questions. Once informed consent was obtained, participants were screened for inclusion and exclusion criteria. If participants met criteria, they completed a clinical evaluation comprised of descriptive and clinical measures. The principal investigator, who is trained in administering and scoring each of these measures, administered all measures.

The motion analysis testing was performed at the University of Pittsburgh Hand Motion Laboratory by personnel trained in operating the NaturalPoint kinematic motion analysis system. During motion analysis testing, participants were required to conduct 15 repetitions of reach to each of three targets for a total of 45 repetitions in two conditions: without and with the Myomo

Orthosis.. Participants then completed 16 one-hour interventions over 4 to 5 weeks. Upon competition of the intervention phase, participants completed their second motion analysis session, performing the same tasks under the same conditions in the same order (Figure 5).

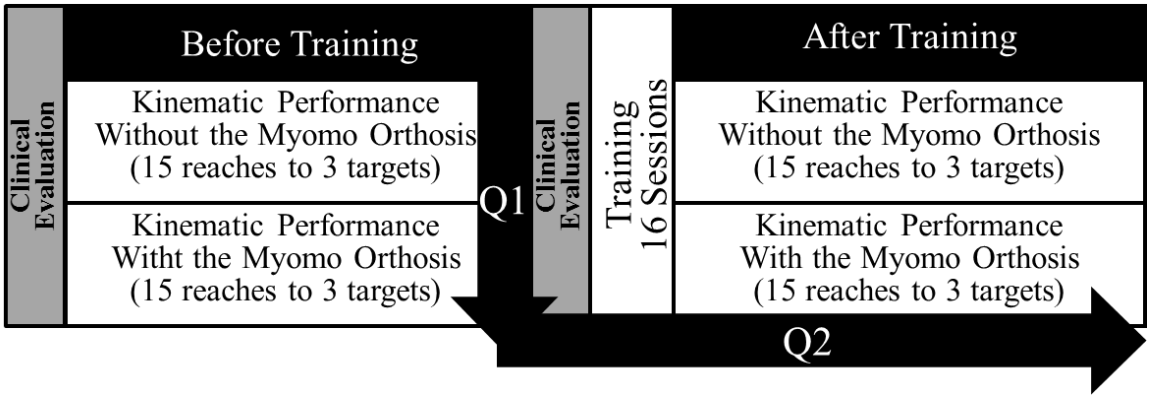


Figure 5. Research Procedures

3.5 DATA ANALYSIS

Motion analysis data were analyzed in two steps: pre-processing analyses and post-processing analyses. Together, these two steps produced the dependent variables that were analyzed using single participant design analysis methods. A manual with a detailed description of data processing methods is available from the first author.

3.5.1 Motion analysis pre-processing

Pre-processing was conducted using the Vicon Workstation software (Version 4.6, Los Angeles, CA).Each trial contained 15 repetitions of reaching to each of three targets. Pre-processing consists of several steps. First each trial is re-trajectorized (smoothed) using standard parameters

for the motion capture system. Then a computer model that represented the participant's scapula, humerus, forearm and hand was applied to re-trajectorized data points. Established guidelines were followed when correcting for the impact markers per the NaturalPoint manual (OptiTrack system, Corvallis, OR).

All of the kinematic variables under study required that each trial consisting of 45 reaches be partitioned into individual reach events to each target. This was done using the Vicon Workstation software. Each trial was opened and the sequence of reach task identified. Movement efficiency was defined as the difference in time (measured here in frame numbers 1/100 sec) from movement initiation to when the target was struck. Movement initiation was observed using a 5-frame trace function and visual inspection of the MET3 marker on the hand. When the participant began moving in the direction of the selected target, the first frame was movement initiation. The last frame was then recorded when the target was struck by the hand. Some participants were unable to reach all of the targets and in those cases the last frame was the point at which the MET3 marker was closest to the target marker. In addition to calculating movement efficiency, the time partitioned data were used to facilitate the post-processing analyses for angular displacement, movement error, and acceleration cycles.

Angular displacement of the elbow was measured using the Vicon Workstation software. Angular displacement of the elbow was calculated by subtracting the starting angle of the elbow from the elbow position when the participant struck the target. We calculated this measure using the Vicon Workstation software to determine the angle of the elbow at the reach initiation and subtracted the angle when the participant reached the target. Positive numbers indicate that the elbow was more extended at target hit. During the task participants demonstrated a variety of

compensatory and adaptive techniques to reach the target, which at times resulted in the elbow being more flexed when the target was hit then at reach initiation. This is represented by negative numbers in the results.

Movement error was calculated using the time partitioned movement segments used previously to calculate movement efficiency and a custom Matlab™ script developed by Doug Weber, Ph.D. The Matlab™ script calculated the average error based on a comparison of the optimal path (a straight line) of the hand marker to the target to the actual path. Results are reported as an average distance from the optimal path throughout the reach task.

Acceleration cycles were calculated using the graphing functions available within the Vicon software. For each trial the acceleration of the MET3 (hand) marker was graphed against time. Each time the hand marker changed acceleration greater than 50 millimeters per second we counted one cycle. We chose 50 mm/s as a threshold by evaluating the acceleration curves and comparing them to velocity time curves. At 50 mm/s we felt that it eliminated changes in acceleration that occurred at a frequency that was inconsistent with motor control and more likely was caused by the interaction between the hand and the reach surface.

3.5.2 Motion analysis post-processing

Post-processing was done using Vicon Workstation software and Matlab™ Version R2007a (Natick, MA 2012). Movement efficiency, angular displacement and acceleration cycles were calculated using Vicon Workstation software. Movement error was calculated using a custom Matlab™ script developed by Douglas Weber, PhD for this study.

3.5.3 Hypothesis testing

All data were analyzed using single participant design statistics recommended by Ottenbacher (1986) to test the study hypotheses. We began by examining all data for autocorrelation. If data were auto-correlated, we applied a transformation recommended by Ottenbacher (1986). If data were not auto-correlated, we proceeded with the single participant analyses. These tests evaluated individual participant changes over time and allowed for the evaluation of statistically significant changes between conditions.

For each of the two research questions, the four dependent variables of kinematic performance were analyzed using descriptive measures as well as the C-statistic. We decided *a priori* that for each outcome (movement efficiency, angular displacements, movement error and acceleration cycles), the C-statistic must be statistically significant (critical level $p < .05$) for one or more of the targets in order to reject the null hypothesis of no difference. Contrasts for hypotheses associated with questions 1 and 2 are illustrated in Figure 6.

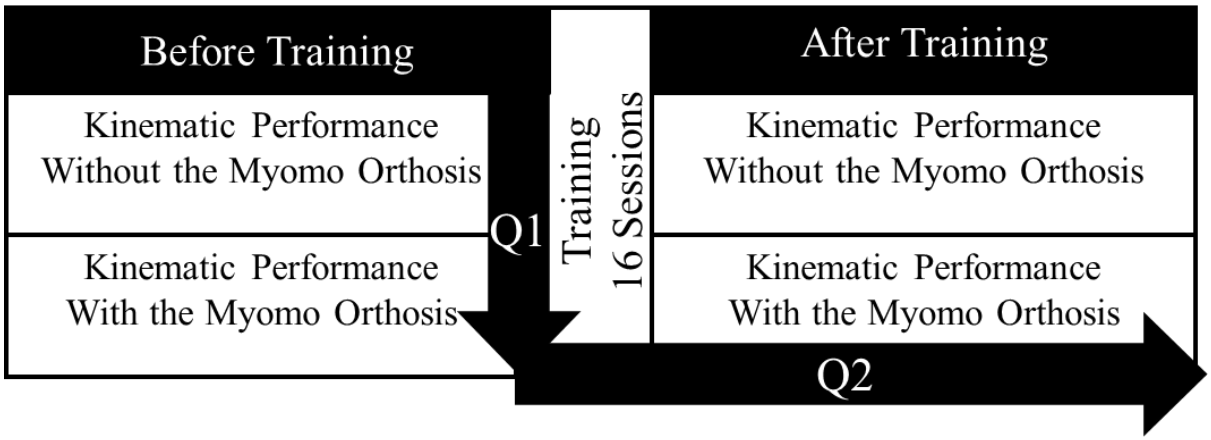


Figure 6. Hypothesis Tests

To better understand the overall training effect of the Myomo orthosis, we performed meta-analysis for each participant across all kinematic variables to one target. Target 3 (contralateral target) was selected because among the majority of participants, reach performance to this target improved for at least one of the kinematic variables. Cohen's *d* effect sizes were calculated for each kinematic variable (Lipsey and Wilson 2001), for each participant, comparing before and after intervention. Because the data collection methods and number of trials was consistent across all participants, no weighting or other transformations were required, thus the mean effect sizes reported are simple averages across all participants.

Additionally, using the statistical techniques described in Lipsey and Wilson (2001) we generated forest plots for variables of interest. For each participant we calculated an effect size (*r*), standard error, and confidence intervals.

4.0 RESULTS

4.1 PARTICIPANTS

A total of 20 participants were referred to the study. Of these 13 provided written informed consent and were screened. Of the 13 participants, all but two met inclusion and exclusion criteria and were referred on for initial clinical and kinematic testing. One participant was excluded due to exceeding the minimal motor criteria (i.e., not enough motor impairment) and one had an elbow contracture. Of the remaining 11 participants, three withdrew due to concerns with travel and scheduling. The Principal Investigator withdrew an additional participant due to inability to tolerate the testing position.

Seven participants began the intervention phase of the study and 6 completed the study (Figure 7). One participant (003) withdrew during intervention due to a new diagnosis of cancer. Participant characteristics are provided in Table 3.

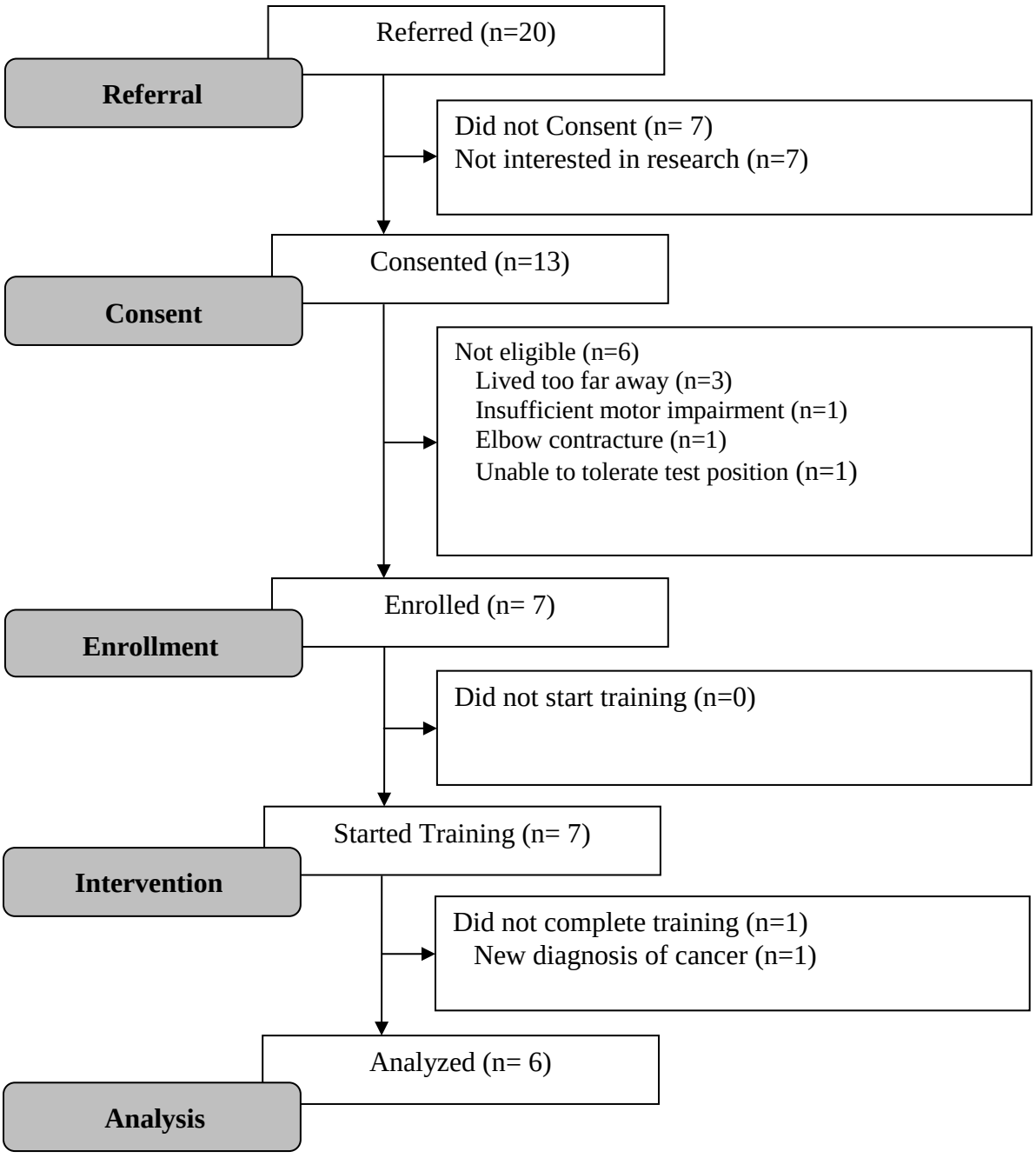


Figure 7. Study Flow Diagram

Table 3. Participant Characteristics

	001	003*	004	005	007	009	013
Age	49	76	49	47	55	68	62
Sex	M	M	F	M	M	F	M
Stroke onset (months)	84	24	12	144	12	72	12
Side affected	Left	Right	Right	Right	Right	Right	Right
Dominant side	No	Yes	Yes	Yes	Yes	Yes	Yes
CAHAI score	13	24	12	13	1	18	0
MAS Finger	2	1	2	3	3	2	3
MAS Wrist	1+	1	2	3	3	2	3
MAS Elbow	2	2	1	1+	2	1	3
MAS Shoulder	3	2	1+	2	2	1+	3
Visual Analog	4.6 cm	0 cm	1 cm	0 cm	0.1 cm	0.7 cm	0.1 cm

*Participant withdrew after starting training due to new diagnosis of cancer (not study related). CAHAI=Chedoke Arm and Hand Activity Inventory. MAS=Modified Ashworth Scale.

4.2 OUTCOMES: INTERVENTION PROGRESSION

All participants started the intervention in phase 1 and progressed through all phases based on stated achievement criteria. Figure 8 illustrates the number of intervention sessions per phase for each participant. Participant 001 spent the most time in phase 1 with 4 visits, and participant 009 spent the least time in phase 1, progressing out of phase 1 after one session. Though each participant varied in the amount of sessions spent in each phase, all participants progressed through all phases.

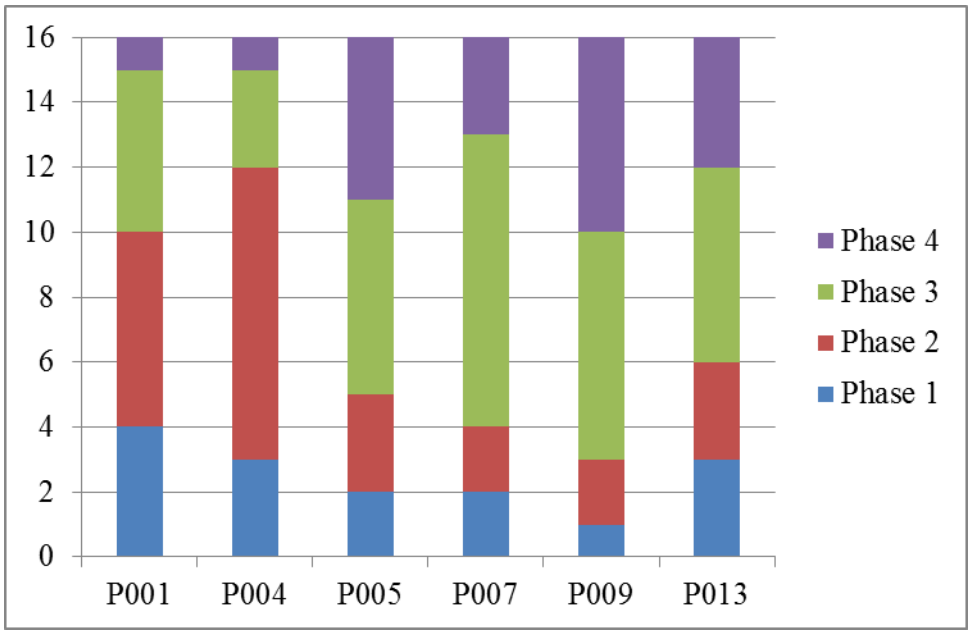


Figure 8. Number of Sessions in Each Intervention Phase by Participant

4.3 OUTCOMES: CLINICAL ASSESSMENT

We used the Chedoke Arm and Hand Activity Inventory (CAHAI) prior to and after 16 training sessions. Table 4 provides the total pre-test and post-test scores for each participant who completed training. Appendix C provides a complete table of item scores for each participant.

Table 4. Chedoke Arm and Hand Activity Inventory Scores

Participant	Pre-Test	Post-Test	Change
001	13	16	3
004	12	12	0
005	13	15	2
007	10	18	8
009	18	19	1
013	0	0	0

4.4 OUTCOMES: KINEMATIC ASSESSMENT

We plotted each variable with and without the Myomo orthosis, before and after training, for each participant separately (see Appendices D, E, F, and G).

4.4.1 Hypothesis 1: Immediate effect of Myomo on kinematic performance

To assess the immediate effect of the Myomo orthosis on kinematic performance, we examined temporal and spatial characteristics of kinematic performance before and after applying the Myomo orthosis (prior to training). Table 5 summarizes the significant findings for hypothesis 1 for each participant for each variable. For movement efficiency (temporal characteristic), we were able to reject the null hypothesis for 2 of 6 participants. For elbow angular displacement and movement error (spatial characteristics), we were able to reject the null hypothesis for 4 of 6 participants. For acceleration cycles (spatial characteristic), we were unable to reject the null hypothesis for any of the 6 participants.

Table 5. Hypothesis 1: Summary of Findings

Hypothesis 1: Individuals will demonstrate improvements in kinematic performance with the use of the Myomo orthosis prior to training.								
	Temporal Characteristic		**Spatial Characteristics**					
	Movement Efficiency		**Elbow Angular Displacement**		**Movement Error**		**Acceleration Cycles**	
Participant	**Targets***	**Result**	**Targets***	**Result**	**Targets***	**Result**	**Targets***	**Result**
001	1	Reject	1,3	Reject	1	Reject	No targets	
004	1	Reject	1,2	Reject	2,3	Reject	No targets	
005	No targets		No targets		No targets		No targets	
007	No targets		2	Reject	No targets		No targets	
009	No targets		3	Reject	1	Reject	No targets	
013	No targets		No targets		1	Reject	No targets	
Summary	**Reject 2/6**		**Reject 4/6**		**Reject 4/6**		**Reject 0/6**	

* Statistically significant targets only. 1=Ipsilateral, 2= Midline, 3=Contralateral

4.4.2 Hypothesis 2: Training effect of Myomo on kinematic performance

Table 6 summarizes the significant findings for hypothesis 2 for each participant for each variable. For movement efficiency (temporal characteristic), we were able to reject the null hypothesis for 6 of 6 participants. At follow up all participants demonstrated significant improvements to at least one target when comparing pre-test movement efficiency without the Myomo orthosis to the same post-test condition. For elbow angular displacement (spatial characteristic), we were able to reject the null hypothesis for 4 of 6 participants. For movement error and acceleration cycles (spatial characteristics), we were able to reject the null hypothesis for 3 of 6 participants.

Table 6. Hypothesis 2: Summary of Findings

Hypothesis 2: Individuals will demonstrate improvements in kinematic performance without the use of the Myomo orthosis after 16 sessions of training.								
	Temporal Characteristic		**Spatial Characteristics**					
	Movement Efficiency		**Elbow Angular Displacement**		**Movement Error**		**Acceleration Cycles**	
Participant	**Targets ***	**Result**	**Targets ***	**Result**	**Targets ***	**Result**	**Targets ***	**Result**
001	3	Reject	1,2,3	Reject	No targets		No targets	
004	2,3	Reject	1	Reject	1	Reject	2	Reject
005	2,3	Reject	1,2	Reject	3	Reject	2	Reject
007	3	Reject	No targets		No targets		3	Reject
009	1	Reject	1	Reject	1	Reject	No targets	
013	3	Reject	No targets		No targets		No targets	
Summary	**Reject 6/6**		**Reject 4/6**		**Reject 3/6**		**Reject 3/6**	

*Statistically significant targets only. 1=Ipsilateral, 2= Midline, 3=Contralateral.

We computed effect sizes to examine the magnitude of change for each participant across each variable (Table 7). Movement efficiency and angular displacement demonstrated the medium effect sizes (d=0.52 and d=0.51, respectively). Acceleration cycles were associated with the smallest effect sizes (d=0.21). Participant 007 demonstrated the largest mean effect size (d=0.68) compared to participant 001 with the smallest (d=0.12). Overall the mean effect size across all variables and participants was small (d=0.37).

Table 7. Effect Sizes: Kinematic Performance by Participant

	Temporal Characteristic	Spatial Characteristics			
Participant	Movement Efficiency	Angular Displacement	Movement Error	Acceleration Cycles	Mean Effect Size
001	0.22	0.61	-0.53	0.16	0.12
004	0.84	0.68	0.91	0.10	0.63
005	0.45	0.59	0.08	0.13	0.31
007	0.24	0.38	-0.04	0.12	0.17
009	0.79	0.69	0.88	0.35	0.68
013	0.56	0.09	0.07	0.39	0.28
Mean	0.52	0.51	0.22	0.21	0.37

Note. Effect sizes are Cohen's *d.*

We generated a forest plot examining the training effect of the Myomo orthosis on movement efficiency when reaching to target 3 (Figure 9). We selected this variable and this target because there were significant findings for all participants, and because the plot helped to contrast the differences in effect sizes reaching to the contralateral target. Effect sizes (*r*) ranged from a strong effect size, *r*=0.71 (participant 5) to a negligible effect size, *r*=0.019 (participant 2). The overall effect size was moderately strong (*r*=0.45; Lipsey & Wilson 2001).

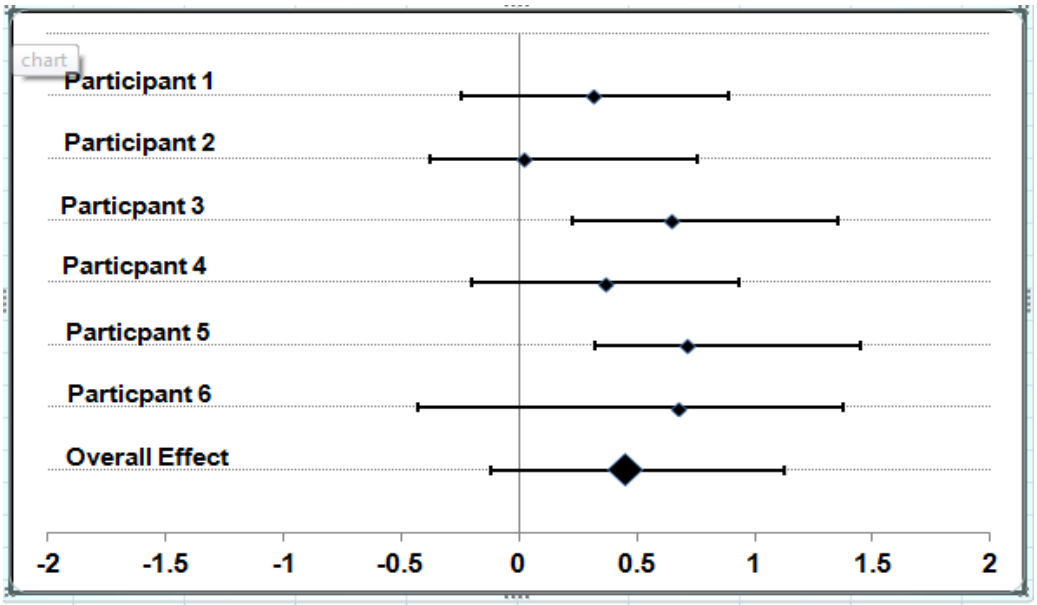


Figure 9. Forest Plot Movement Efficiency

Finally, we generated a forest plot examining the training effect of the Myomo orthosis on angular displacement of the elbow when reach to Target 1 (Figure 10). We selected this variable and this target because there were significant findings for all participants sans one, and because the plot helped to elucidate the variability among participants. Effect sizes (r) ranged from a strong effect size, r=0.69 (participant 2) to a modest effect size, r=0.14 (participant 6). The overall effect size was moderately strong (r=0.54; Lipsey & Wilson 2001).

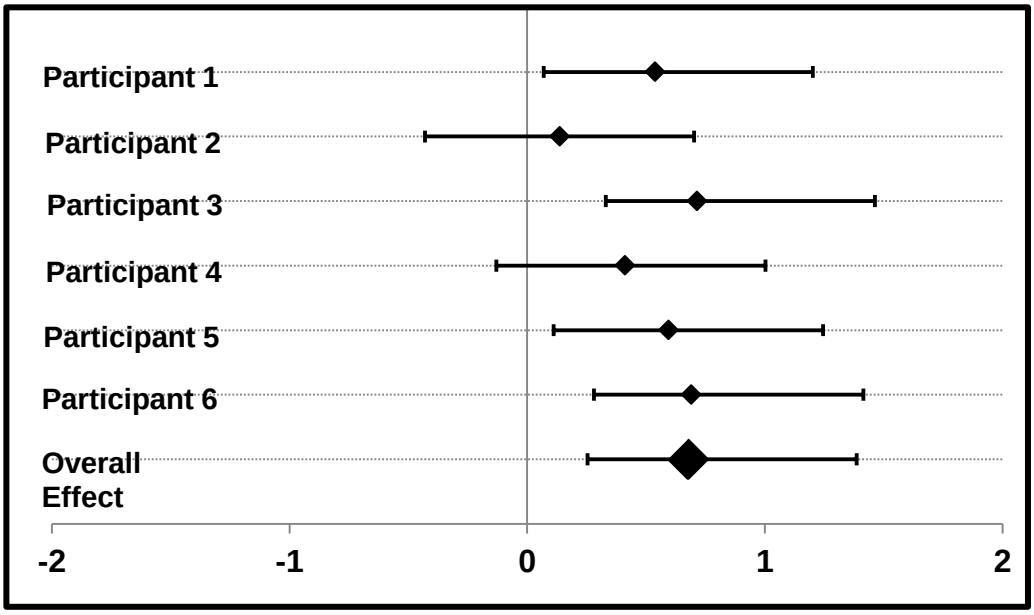


Figure 10. Forest Plot, Elbow Angular Displacement Improvements

5.0 DISCUSSION

We predicted that before training, the kinematic performance of movement efficiency, elbow angular displacement, movement error, and acceleration cycles would be better with the Myomo orthosis than without. This proved to be true for only 2 participants for movement efficiency (temporal characteristic), and 4 participants for elbow angular displacements and movement error (spatial characteristics).No participants demonstrated improvements in acceleration cycles. We also predicted that after 16 sessions of training with the Myomo orthosis, kinematic performance for each of the 4 variables would improve significantly. All 6 participants demonstrated improvements in movement efficiency for one or more targets. Five of the 6 participants demonstrated improvements in one or more of the spatial characteristics of kinematic performance. These findings suggest that the immediate effect of the Myomo orthosis on reaching performance (hypothesis 1) appears to be more attenuated than the training effect of the Myomo orthosis (hypothesis 2). Effect size calculations suggest that the magnitude of the training effect was greatest for movement efficiency and angular displacement (medium effect size) and the least for movement error and acceleration cycles (small effect size).

One of the benefits of multiple single subject design experiments using the same research paradigm is the opportunity to examine characteristics of individuals who demonstrated large and small responses to intervention. For example, individuals who had a little to no response to the intervention (low performers: 001, 007, 013) were characterized by high levels of spasticity,

as measured by the Modified Ashworth Scale. Though these participants did demonstrate statistically significant kinematic improvements, they each demonstrated a small magnitude of improvement, and consistently only with the contralateral target. We believe that this pattern is indicative of movements dominated by shoulder spasticity (i.e., shoulder internal rotation and horizontal adduction).These low performers demonstrated significant improvements on gross kinematic measures such as movement efficiency and elbow angular displacement, but not in more precise kinematic measures of skill such as movement error or acceleration cycles. Like the higher performers, these participants were able to progress through the staged intervention but generally required more time to reach phase IV and in general required a higher level of assistance from the Myomo device.

Given the sensitivity of kinematic measures of performance, it may not be surprising that all participants demonstrated some statistically significant improvements in reach performance. Perhaps a more interesting finding would be whether or not the participants demonstrated more meaningful clinical outcomes. All participants enrolled in this study were not able to participate in more traditional task-oriented practice regimens prior to the study, due to moderate to severe motor impairment. Furthermore, all participants were considered to have achieved all benefits from therapy (none were currently receiving therapy).Yet, despite these impairments, all participants (save one, due to unrelated medical issues) were able to participate in and to progress through a phased task-oriented practice program using the Myomo orthosis. It is worth noting that without the addition of the Myomo orthosis, participants would not have been able to engage in these treatment tasks.

Participants progressed through the four intervention phases at different rates but all participants were able to complete the tasks in each phase of the intervention. In the first phase, intervention consisted of simple flexion and extension of the elbow that required the participant to actively contract and relax the biceps muscle, a task that for some required multiple visits to achieve. Participants 001, 007, and 013 all required several visits to meet the achievement criteria to move out of Phase I, much of this time spent learning how to reduce co-contraction and selectively control the biceps muscle. Some participants, such as 009 progressed thru the first 3 phases of intervention within the first 3 visits and progressed to phase 4, where she had to complete more complex bimanual tasks in both triceps and biceps modes while others, notably 001 and 004 required 9 to 12 visits to reach the same intervention level of difficulty. Participants who progressed more slowly also, on average, required higher levels of assistance from the Myomo orthosis, indicating lower motor output. This is relevant and interesting in that it supports the idea that participants, even those with very low levels of upper extremity function can make measurable and clinically meaningful changes in upper extremity function.

These are the first findings examining the immediate and training effect of the Myomo orthosis among individuals with chronic upper extremity hemiparesis. As such they are useful in informing the design of future, more rigorous studies examining the use of robotic technologies to support upper extremity recover after stroke. Nonetheless, the implications of these findings must be discussed in terms of the limitations present within the current study. Limitations attributed to kinematic and clinical measurement, as well as limitations attributed to the device used in this study, are discussed in the following sections.

5.1 LIMITATIONS: KINEMATIC MEASURES

Elbow flexion and extension makes up only a portion of the mobility required to hit the targets in the three reaching conditions. The total movement of the hand to the target was comprised of varying degrees of trunk, shoulder, and elbow motions. During this study, no restraint was placed on the participant's trunk and as such compensatory motions made up portions of many reaching trials. Future studies should consider either restraining the trunk to provide a more clear understanding of the contribution of the elbow and shoulder or model the trunk to better quantify the compensatory behaviors.

5.2 LIMITATIONS: CLINICAL MEASURES

The Chedoke Arm and Hand Activity Inventory was not sensitive enough to detect the level and degree of change observed in the sample, as was detected through kinematic measures of reach. We believe there were several issues that contributed to this: First, learned nonuse appeared to affect the participant's ability to complete the CAHAI as indicated by 0 scores for one participant (013). This likely suggests that the participants had stopped using or incorporating their UE at any level in functional tasks. This was demonstrated by 0 scores through all 11 tasks for items for the pretest condition for one participant (013). A zero score indicates that the participant made no attempts or was unable to use the involved extremity in either a primary or stabilizing role.

Second, two participants (013, 004) demonstrated no difference in pre-test and post-test scores. However, these participants demonstrated significant differences for 3 or more of the kinematic measures. In addition, both participants progressed through the phased intervention program, demonstrating improvements in the execution of a task-oriented practice regimen.

These two issues illustrate an apparent disconnection between the significant kinematic changes observed and the absence of change in the CAHAI. One potential explanation is that the kinematic measures are highly sensitive to small incremental changes in reaching performance. Another potential explanation is that clinical measures, such as the CAHAI, may be insensitive to meaningful changes in severely impaired upper extremities, as in this study. We believe that the evidence may support the second explanation, as all of the participants were able to progress through the phased intervention. However, further work needs to examine the relationship between kinematic changes and meaningful functional changes.

5.3 LIMITATIONS: MYOMO E100

The device used in this study, the E100 is the first commercially available upper extremity EMG operated robotic device. As such, further development is required to improve the utility of the e100 in future research and clinical interventions. One limitation of the Myomo e100 is the inability of the device to detect EMG on the biceps or triceps simultaneously. This limitation means that the interventionist must work on flexion and extension in isolation or spend a considerable amount of intervention time removing the device and changing the sensor location. The tethered control box caused a second limitation imposed by the device. At times, the cord

was an obstruction or obstacle to completing some tasks such as standing and reaching. Finally, some participants had difficulty achieving optimal fit and experienced intermittent issues due to binding and / or difficulty with the electrodes not making contact with the skin.

Myomo has addressed some of these limitations through the development of next generation devices. The Mpower and Myopro both utilize simultaneous biceps and triceps sensors reducing down time and increasing flexibility and control options. In addition, the battery tether and controls and are now smaller and placed on the device. Both of the newer products address fit and electrode contact in different ways. The Mpower uses adhesive electrodes and the Myopro custom fit components to minimize fit and electrode contact issues as well as incorporates the improvements from the Mpower device.

5.4 FUTURE STUDIES

These data are useful in designing future phase I and II studies examining devices like the Myomo and their clinical applications. Future studies should investigate optimal measures for detecting clinically meaningful changes in reaching performance. Participants in this study demonstrated statistically significant improvements in kinematic performance but additional investigation examining the relationship between changes in kinematic performance and clinically meaningful changes in gross functional activities is warranted.

In addition, future studies should examine optimal dosing of training needed to achieve maximum results with the Myomo orthosis. The dosing in the current study was based on previous reports, but the optimal dosing is yet unclear. Furthermore, the threshold at which the Myomo orthosis is no longer required is yet to be determined. Although anecdotal, some

participants in the current study progressed beyond a point where the Myomo orthosis was beneficial. In some cases, the Myomo orthosis actually hindered reaching performance, particularly with respect to movement efficiency, as participants approached the end of the study. Further investigators quantifying observations that indicate discharge of the Myomo orthosis will be useful to assist clinical translation.

This study recruited only participants that were in the chronic phase of recovery. Based on the significant kinematic changes and the ability of these participants to perform a task-oriented practice regimen, we believe further investigation examining the best timing of the intervention is warranted. It is unclear whether initiation of training of this nature in the acute or sub-acute phases of recovery would yield improved upper extremity recovery over the long-term, or if early initiation would be well tolerated.

5.5 CONCLUSION

Primary findings were two-fold. First, following 16 training sessions with the Myomo upper extremity robotic orthosis, significant improvements in reach performance existed for all participants across measured kinematic variables. Second, participants were able to participate in and progress through a phase-based task-oriented practice regimen. Without this device, participants likely would not have been able to complete these activities. As a result of these findings, we believe that devices such as the Myomo upper extremity robotic orthosis offer promising new technology that enhances participation in therapy for individuals with severe

impairments following a stroke. Future studies should focus on better understanding the mechanism of change as well as evaluating the effectiveness of this and similar technological applications for reducing the impairment associated with long-term upper extremity impairment.

APPENDIX A

SUMMARY OF LITERATURE

Table 8. Summary of Literature

TASK-ORIENTED PRACTICE INTERVENTIONS				
Citation (Authors, Year)	*Intervention Characteristics*	*Sample Characteristics*	*Outcome Measures*	*Significant Findings*
Kwakkel (1999)	Protocol: 30 min. 5x week for 20 wks of Standard rehab + air splint restraint vs. Standard rehab + task specific training.	101 acute (14 days post) severely disabled (Barthel below 9 and unable to ambulate) stroke patients	Barthel; Functional Ambulation Categories; Action Research Arm Test (ARAT)	Task specific training group demonstrated more improvements (ARAT) at weeks 12, 20, and 26.
Langhammer (2000)	Protocol: 40 min. 5 days/week of either Bobath or motor control program for the duration of hospital stay.	61 acute stroke patients with first stroke onset randomized to two groups. Motor Control (task practice) =33 Bobath = 28	Motor Assessment Scale Sodring Motor Evaluation Barthel ADL index Nottingham Health Profile Number of hospital days Discharge disposition	Decreased # of hospital days in the Motor Control (MC) group compared to the Bobath group (BG). Improved Motor function in the MC group (Sodring Motor evaluation) Women in the MC group improved ADL vs. BG.
Dromerick, Edwards & Hahn (2000)	Protocol: 2hrs/day 5x week x2 weeks (20 hrs total)	23 acute stroke survivors randomized into CIT group vs. standard care (SC)	ARAT Barthel Index Pinch, grasp and gross motor Functional Independence Measure (FIM)	CIT group had greater ARAT scores. Secondary analysis: CIT also increased pinch, and self care FIM score compared to SC.

Table 8 (continued)

Citation (Authors, Year)	*Intervention Characteristics*	*Sample Characteristics*	*Outcome Measures*	*Significant Findings*
Winstein (2004)	Protocol: 1hour/day *5 days week/ 4 wks. (20 hrs total) for the Functional training (FT) and strength training (ST) group beyond the Standard Care (SC) group	64 acute stroke admissions stratified into severity groups by the Orpington Prognostic Scale (OPS) then randomized into FT, ST, and SC groups	Functional Test of the Hemi-paretic UE (FTHUE) Isometric torque Fugl-Meyer (FMA) UE Functional Independence Measure (FIM)	No differences in FTHUE. FT and ST improved FMA at 6 wks and FT improved compared to ST at follow up. Both FT and ST increased Isometric torque compared to SC at all measurement points. Greatest improvement in the less severe group.
Thielman (2004)	Protocol: 1hour/session, 3x week for 4 wks of either Task related training (TRT) or Progressive resistive exercise (PRE).	12 stroke survivors $\geq$ 6 months, matched using the motor assessment scale (MAS) and randomly assigned to Task practice vs. Progressive resistive exercise	Kinematic analysis Rivermead Motor Assessment (RMA) Motor Assessment Scale (MAS)	Hand paths straightened in low level TRT group. Low level TRT group demonstrated more trunk substitution during kinematic reaching task at post test. RMA increased in low group.
Blennerhassett & Dite (2004)	Protocol: Both groups received additional 1hr/5 days week/ 4 wks of either Task practice or Mobility training.	30 subjects (chronicity not stated) randomized into 2 groups Task Practice vs. Mobility training	Motor Assessment Scale (MAS); Jebsen Taylor Hand Function Test (JTHFT); Timed up and go; 6min walk test;	Both groups improved on the mobility measures TP group improved on the JTHFT and the MAS
Yen, Wang, Chen & Hong (2005)	Protocol: 2wk modified CIMT intervention	30 subjects from acute rehab hospital randomized into control (17) or CIMT (13)	Wolf Motor Function Test (WMFT)	CIMT group improved scores on 6 items within the WMFT compared to control group

Table 8 (continued)

Citation (Authors, Year)	*Intervention Characteristics*	*Sample Characteristics*	*Outcome Measures*	*Significant Findings*
Michaelsen, Dannenbaum, & Levin (2006)	Protocol: 3x wk*5 weeks, 1 hr each session. Both TR and C groups completed object related reach to grasp training in the home	30 chronic stroke survivors randomized to either Task specific training with trunk restraint (TR) or without © Participants were stratified by FMA level	Kinematic measures of reach, FMA TEMPA Box and Blocks	TR decreased UE impairment (FMA), TR had increased reach (elbow extension) Secondary analysis: TR groups' change in arm ability (TEMPA) was positively correlated with elbow extension while the C group was not.
Higgins, Salbach, Wood-Dauphinee, Richards, Cote & Mayo (2006)	Protocol: 90 minutes/session, 3x /week/6 weeks (18 total sessions). TOP group: tasks designed to improve fine and gross UE movement Control: walking tasks	91 ambulatory individuals within 1yr post stroke. Participants were randomly assigned to one groups and stratified in into high, medium and low impairment groups.	Box and block 9 hole peg TEMPA Stroke Rehabilitation Assessment of Movement	No significant differences between groups at post-test
DEVICE-ASSISTED INTERVENTIONS				
BATRAC TRAINER				
Whitall, McCombe – Waller, Silver, & Macko (2000)	Protocol: 20 min. of BATRAC 3 times/ week for 6 wks.	16 adults with chronic hemiparesis (6 months or greater)	(Pre/Post Intervention with retention test) Fugl-Meyer UE Motor Performance Test (FMA) Wolf Motor Function Test Purpose developed Use Questionnaire	Pre vs. Post and Pre vs. Retention FMA & WMFT, improved. The Use Questionnaire showed increased use between pre and post and pre and retention.

Table 8 (continued)

Citation (Authors, Year)	*Intervention Characteristics*	*Sample Characteristics*	*Outcome Measures*	*Significant Findings*
Luft, McCombe-Waller, Whitall, Forrester, Macko, Sorkin, Schulz, Goldberg, & Hanley (2004)	Protocol: 1hour/session, 3x/week for 6weeks for: 1) BATRAC training 2) Dose matched therapeutic exercise (DMTE)	21 adults with chronic hemiparesis (>34 months) randomly assigned into 2 groups BATRAC (9) DMTE (12)	Functional MRI (fMRI) FMA WMFT University of Maryland Arm Questionnaire for Stroke	BATRAC group had increased fMRI activation in the contralesional cerebrum and ipsilateral cerebellum. No significant between group functional differences.
SMART ARM				
Barker, Brauer, & Carson (2008)	Protocol: 1 hour/day, 3 days/week, 4 weeks; 1) SMART Arm, 2) SMART Arm + EMG-stimulation, & 3) No Treatment Control	33 adults with chronic hemiparesis (CVA) SMART Arm (n=13) SMART Arm+EMG-stimulation (n=10) No Treatment (n=10)	(Pre/Post Intervention/Week 12) Motor Assessment Scale (Item 6); Manual Muscle Testing (Triceps); Modified Ashworth Scale (MASS); Isometric Reaching Force; Reaching Distance;	Both SMART Arm groups, but not the control group, showed significant improvements all measures post intervention and at Week 12. Compared to the control group, both SMART Arm groups demonstrated greater improvements in Motor Assessment Score, MASS, Reaching Force and Reaching Distance.

Table 8 (continued)

Citation (Authors, Year)	*Intervention Characteristics*	*Sample Characteristics*	*Outcome Measures*	*Significant Findings*
REHA SLIDE				
Hesse, Werner, Pohl, Mehrholz, Puzich, & Krebs (2008)	Protocol: 20-30 minutes/session,5days/week for 6weeks Treatment A: standard Care + REHA SLIDE Treatment B: Standard care+ electrical stimulation	54 sub-acute (4-8wk post stroke) subjects with severe UE impairment (FMA <18)	(Multi-center RCT) UE Fugl-Meyer Box and Block test Medical Research Council Modified Ashworth Scale (MASS)	No significant differences were found between the electrical stimulation and REHA SLIDE group for any of the outcome measures.
THERAPY ASSISTANT WREX				
Iwamuro, Cruz, Connelly, Fisher, & Kamper (2008)	Repeated measures with 3 trials to reach to 12 objects both with and without the WREX. Use of WREX was randomized with at least 1 day between trials.	10 CVA subjects with chronic hemiparesis (>3mo) 2 to stage 3 on the Chedoke-McMaster Stroke Assessment scale for the arm	(Within-subjects repeated measures) Reaching Arm Kinematics (reach distance to target, peak velocity, peak velocity within the movement and mean jerk) Surface EMG of bicep, triceps and brachioradialis	In subjects using the WREX: Reach distance increased Peak velocity, Peak velocity within the movement and mean jerk decreased compared to without the WREX. Bicep and Anterior Deltoid EMG activity reduced in the WREX group
ROBOT-ASSISTED INTERVENTIONS				
MIT MANUS (Also known as Inmotion)				
Aisen, Krebs, Hogan, McDowell, & Volpe (1997)	Protocol: unknown MIT-Manus with Standard Practice vs. Sham Manus with standard practice	20 CVA subjects with acute hemiparesis from rehabilitation hospital	FMA Motor Status Score Motor Power Score (shoulder)	Significant decline in impairment in the experimental group compared to standard care.

Table 8 (continued)

Citation (Authors, Year)	*Intervention Characteristics*	*Sample Characteristics*	*Outcome Measures*	*Significant Findings*
Fasoli, Krebs, Stein, Frontera & Hogan (2003)	Protocol: Robotic therapy 3x/week for 6 weeks 1. Sensory- motor (if unable to move arm) 2. Progressive resistive (if able to reach) *Both groups used MIT MANUS	20 participants with chronic stroke 1-5 years post *Must have MPS between 2/4	Modified Ashworth Scale (MASS) Fugl-Meyer (FMA) Motor Status Scale (MSS) Medical Research Council motor power score (MPS)	Both groups improved in: FMA, MSS (shoulder, elbow, wrist and hand), MPS Secondary analysis of change found increased MSS (wrist and hand) for the progressive resistive group vs. sensory-motor
Daly, Hogan, Perepezko, Krebs, Rogers & Goyal (2005)	Protocol: 5hrs/day, 5days/week for 12 weeks. 1. 1.5 hrs/session of INMOTION reach training 2. 1.5 hrs/session of Functional electrical stimulation (FES)	12 participants with chronic stroke Must have 1/5 wrist ext and greater than a 10 on the upper limb coordination measure	Arm motor ability test (AMAT) FMA Kinematic measures recorded by Inmotion: 1. Accuracy 2. Smoothness	No significant differences between groups. Within groups: the INMOTION group showed improvement in AMAT, FMA & Kinematic measures of Accuracy & Smoothness
MacClellan, Bradham, Whitall, Volpe, Wilson, Ohlhoff, Meister, Hogan, Krebs & Bever (2005)	Protocol: Pre-post: 2 hours/day, 3days/week for 3 weeks (18 session's total) of goal directed reaching using the Inmotion Robot.	30 chronic (>6mo) stroke with Motor Power Score of 3or less Participants were stratified by FMA: <15 = severe FMA: 16 or < moderate	Motor Status Score (MSS) Wolf Motor Function Test (WMFT) FMA (UE)	Moderate group improvement in WMFT Severe group improvement in FMA, Motor power assessment, and WMFT. At 3mo follow up compared to post-treatment: Moderate group improved FMA and severe group improved WMFT.

Table 8 (continued)

Citation (Authors, Year)	*Intervention Characteristics*	*Sample Characteristics*	*Outcome Measures*	*Significant Findings*
Krebs, Mernoff, Fasoli, Hughes, Stein & Hogan (2008)	Protocol: 3x/week, 6 weeks Robotic assist functioned in three different modes A) no grasp B) grasp actual object C) grasp a virtual object	47 chronic stroke community dwelling individuals with a Medical rehab council power score(MPS) of 1 or greater sufficient cognition to participate	FMA Kinematic measures (results not published)	No significant difference between 3 modes Aggregate of 3 modes: FMA increased over time
Volpe, Lynch, Ferraro, Galgano, Hogan, & Krebs (2008)	Protocol: 1hr/session, 3x/week for 6 weeks. 1. Robotic training 2. Standard care	21 chronic stroke survivors with a FM score > 33.	FMA (Shoulder &elbow) FMA (Wrist & hand) Motor Power Scale MAS Stroke Impact Scale Action Research Arm Test (ARAT)	No differences between groups for all of the primary motor impairment measures.
Mirror-Image Movement Enabler (MIME)				
Lum, Burgar, Majmundar, Van der Loos & Shor (2002)	Protocol: 24 1hr. sessions over 2 months. 1)Robotic assisted shoulder and elbow movements 2)Traditional therapy(NDT)	24 chronic stroke participants (> 6mos)	Reach kinematics FMA reach displacement strength	The robotic group increased reach extent, & strength (on the device) & FM (proximal movement component)
Lum, Burgar & Shor (2004)	Protocol: 24 1hr. MIME sessions over 2 months. Intervention involved reaching to 8 targets in active constrained mode. Targets placed table top and shoulder level, forward, lateral and between.	13 chronic stroke participants (> 6mos) Mean FM score was 24	Work output and Kinematic measures of Velocity and reach distance (measured by MIME) EMG activation patterns	Increased work output Improved velocity of movement in high level, increase distance in low. Improved activation patterns in shoulder height reaching targets

Table 8 (continued)

Citation (Authors, Year)	*Intervention Characteristics*	*Sample Characteristics*	*Outcome Measures*	*Significant Findings*
Lum, Burgar, Van der Loos, Shor, Majmundar & Yap (2006)	Protocol: 1 hour/session, 15 sessions over 4 weeks. 4 groups: 1. MIME unilateral 2. MIME bilateral 3. MIME unilateral/bilateral 4. Standard care *6 month follow up	30 sub-acute stroke participants in 4 groups. (3 robotic + 1 standard care)	Modified Ashworth Scale (MASS) FMA (proximal and distal) Motor Status Score (MSS) Motor Power Functional Independence Measure (FIM) self care and transfers	In subjects in the bilateral/unilateral MIME group, FMA (proximal) improved. At the 6 month follow up no significant differences were reported.
NeReBot (NEuroREhabilitation robot)				
Masiero, Celia, Rosati, & Armani (2007)	Protocol: All participants received standard care (amount not reported) A) Standard care + NeReBot 20-30 min x2/day 5day/week, x5weeks. B) Standard care + sham NeReBot. *3 and 8 month follow up	35 acute stroke participants A) 17 B) 18	FMA (upper extremity) Medical research council motor power score (MPS) FIM MAS	NeReBot group showed greater improvement in FMA(proximal) and strength (MRC) in bicep and deltoid *Gains in FMA and deltoid strength were maintained at 3 and 8 months follow up.

Table 8 (continued)

GENTLE/s Robot-Mediated Therapy System				
Citation (Authors, Year)	*Intervention Characteristics*	*Sample Characteristics*	*Outcome Measures*	*Significant Findings*
Coote, Murphy, Harwin & Stokes (2008)	Protocol: 30 min of either GENTLE or Sling supported UE therapy 3x week. Duration of each phase not stated. Single subject design with multiple baselines (ABC or ACB) where A=baseline, B=GENTLE, C=Sling suspension GENTLE intervention compared to sling suspension only	20 subjects with varying time since stroke assigned to 2 groups of 10	ROM FMA Motor Assessment Scale (MC) MASS	Group 2 (ACB) had improved Motor Assessment Score during the GENTILE intervention period and decrease MAS in Group 1 during the GENTILE intervention period.
Assisted Rehabilitation and Measurement (ARM) Guide				
Kahn, Averbuch, Rymer, & Reinkensmeyer (2006)	Protocol: 45 minute/session, x24 sessions in an 8 wk period. 2 groups: 1) Robotic active assistive training using the ARM guide 2) Free reach training: unassisted reaching exercises	19 participants >1 year post Subjects were stratified by severity using the Chedoke-McMaster (CM) Stroke Assessment Scale	Biomechanical measures derived from ARM guide: 1. Reach distance 2. Reach speed 3. Stiffness 4. Straightness 5. Smoothness CM scale Ranchos Los Amigos Functional Test of Upper Extremity Function (FTHUE)	Both groups improved over time in Reach distance, speed, straightness and CM score. The Free reaching group showed smoother reach The Robotic group demonstrated improved scores on the RLA.

Table 8 (continued)

REHABOB (robotic rehabilitation system for upper limb motion therapy for the disabled) Therapeutic System				
Citation (Authors, Year)	*Intervention Characteristics*	*Sample Characteristics*	*Outcome Measures*	*Significant Findings*
Fazekas, Horvath, Troznai, & Toth (2007)	Protocol: RCT with 2 groups A. Bobath therapy only (30 minutes/ day, x20 days) B. Robotic therapy plus Bobath (Additional 30 minutes of REHABOB x20 days	30 participants with upper motor lesion secondary to head injury or stroke. Highly variable degree of acuity (1month – 87 months post injury)	Rivermead arm score MAS (shoulder) MAS (elbow) Fugl-Meyer (shoulder – elbow) ROM FIM self-care	No between group differences were present. Both groups showed improvement over time for most measures. The control (Bobath) group improved on FIM self care while the robotic group did not.
Bi-Manu-Track				
Hesse , Werner , Pohl , Rueckriem, Mehrholz, Lingnau (2005)	Protocol: Random assignment to two groups: A. Bi-Manu-Track B. Electrical Stim Both groups received standard care plus intervention: (20 minutes/day, 5days/week for 6 weeks (total of 30 sessions)	44 sub-acute participants with sub-acute stroke and severe (FM<18) paresis	FMA Secondary: Motor Power Score (MPS) MAS	FM improved in both groups over time but improved significantly more in the robotic group vs. electrical stimulation Similarly the MPS improved in both groups over time and improved in the robotic group vs. electrical stimulation
Myomo	**Myomo**	**Myomo**	**Myomo**	**Myomo**
Stein, Narendran, McBean, Krebs, & Hughes (2007)	Stein, Narendran, McBean, Krebs, & Hughes (2007)	Stein, Narendran, McBean, Krebs, & Hughes (2007)	Stein, Narendran, McBean, Krebs, & Hughes (2007)	Stein, Narendran, McBean, Krebs, & Hughes (2007)

APPENDIX B

INTERVENTION DOCUMENTATION AND FLOW SHEETS

Phase I

Goals: To properly fit, adjust and calibrate the Myomo to the participant

- Select appropriate size using guidelines from the Myomo handbook and certification course
  - Size_____
  - Side_____
  - Device number _____
- Adjust padding for comfort and free elbow motion
  - Notes on any additional padding or non-standard padding for comfort and fit _____
- Calibrate the Myomo on biceps with participant's arm in calibration position
  - Record resting calibration level _____
- Set spring and assistance levels to 1(spring) and 4 (assistance)
  - Adjust spring and assistance levels until smooth motion is achieved
  - Record starting settings _____
  - Begin Phase 1 activities listed below in the flow sheet
  - Record information in the data collection tool

Table 9. Phase I Flow Sheet

PHASE I : Phase Goal: Don, calibrate, and gain familiarity with device

Participant ID #_____Time in:_____Time out:_____

Activity	Visit #__	Visit #__
	Date___	Date___
	Warm up**	Warm up**
Warm up: Table top self-range of motion (2x10) for wrist, elbow and shoulder		
Seated weight-bearing through elbow; Seated weight-bearing through arm elbow extended		
Don and Calibrate Myomo(B)	Settings / Repetitions	Settings / Repetitions
Passively flex elbow; participant actively relaxes biceps, extending elbow full range (2x10)		
REST	4 min	4 min
Mid-range hand to chin with should internally rotated (2x10, rest between sets or until fatigued)		
REST	4 min	4 min
Full range hand to mouth with should internally rotated; Visualize bringing a french fry to mouth(2x10 or until fatigued)		
IF participant is able to complete full range elbow flexion with 75% success (3 out of 4 consecutive trials), progress to Phase II		

*(B) denotes Biceps, (T) triceps setup (P) = Participant**prior to putting on the Myomo

PHASE II

Table 10. Phase II Flow Sheet

Phase Goal: Initiate and gain proficiency with basic elbow flexion and extension motions in a variety of planes and positions

Participant ID #_____ Time in:_____Time out:_____

Activity	Visit #__	Visit #__
	Date___	Date___
	Warm up**	Warm up**
Warm up: table top self-range of motion (2x 10) for wrist, elbow and shoulder		
Seated weight-bearing through elbow; Seated weight-bearing through arm elbow extended		
Don and Calibrate Myomo(B)	Settings / Repetitions	Settings / Repetitions
Hand to chin with hand on beginning on opposite knee, flex and try to touch chin(2x10 or until fatigued)		
REST	3 min	3 min
Flex and extend elbow with shoulder in neutral orientation; Reach toward same shoulder;		
REST	3 min	3 min
Flex shoulder to ~45 degrees; Repeat above; Reach toward same side ear to adjust glasses;		
Flex shoulder to 90 degrees but not beyond;Simulate bringing back a ball to throw and then release;		
Change EMG to triceps and recalibrate	Settings / Reps	
(T) Resist elbow extension in partial range with shoulder in neutral (sit or stand)		

Table 10 (continued)

(T)Full range elbow extension (sit or stand)		
REST	3	3
(T) Elbow extension with shoulder flexed to 45 degrees		
(T) Elbow extension (dart throwing) with shoulder flexed to 90 degrees (standing), if no shoulder pain		
If able to complete 6 out of 8 tasks with 75 percent success progress to Phase III		

Phase III

Table 11. Phase III Flow Sheet

Phase Goals: Add occupation and function to established motions

Participant ID #_____ Time in:_____Time out:_____

Activity	Visit #__	Visit #__
	Date___	Date___
	Warm up**	Warm up**
Warm up: Table top self range of motion (2x 10) for wrist, elbow, and shoulder		
Seated weight-bearing through elbow; Seated weight-bearing through arm elbow extended;		
Don and Calibrate Myomo(B)	Settings / Repetitions	Settings / Repetitions
Warm up biceps in flexion and extension (2x10)		
Remove towels from elevated surface, flex elbow and place on table (B) or (T)sitting/standing		
Bilateral elbow flexion; Use a cane and flex and extend bilaterally (3x10) (B)	3 min	3 min
In standing, simulate dusting table top by flexing and extending elbow with internal rotation, cloth in hand		
REST	3 min	3 min
In standing, simulate dusting table top by flexing and extending elbow with shoulder internally rotated, cloth in hand		
REST		
Bilateral elbow flexion; Use a cane and flex and extend bilaterally (3x10)		
If participant is able to complete 6 out of 7 tasks with 75 percent success progress to Phase IV		

Phase IV

Table 12. Phase IV Flow Sheet

Phase Goals: Add increased complexity to bimanual tasks and motions

Participant ID #_____ Time in:_____Time out:_____

Activity	Visit #__	Visit #__
	Date___	Date___
	Warm up**	Warm up**
Warm up: Table top self range of motion (2x 10) for wrist, elbow and shoulder		
Seated weight-bearing through elbow; Seated weight-bearing through arm elbow extended;		
Don and Calibrate Myomo(B)	Settings / Repetitions	Settings / Repetitions
Warm up biceps in flexion and extension (2x10)		
Remove towels from elevated surface, flex elbow and place on table(B) or (T) in sitting/standing		
In standing, work on bilateral elbow flexion; Move laundry basket from low to high surface	3 min	3 min
In standing, simulate sanding block activity using table top by flexing and extending elbow; Increase movements away from midline to increase difficulty;		
REST	3 min	3 min
In sitting, complete unilateral and bilateral wheelchair propulsion (B) or (T) based on abilities		
REST		
Wheelchair pushups in sit-to-stand in (T) mode; Sets of 5 unless otherwise noted;		

APPENDIX C

CHEDOKE ARM AND HAND ACTIVITY INVENTORY SCORES

Table 13. Chedoke Arm and Hand Activity Inventory Scores

	001		004		005		007		009		013	
Item	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
1.	3	3	1	1	2	2	1	2	4	4	0	0
2.	1	2	1	1	1	1	0	1	1	1	0	0
3.	1	1	1	1	1	2	0	1	3	3	0	0
4.	1	2	1	1	1	2	0	1	2	2	0	0
5.	1	1	2	2	2	2	0	1	2	2	0	0
6.	1	1	1	1	1	1	0	1	1	2	0	0
7.	1	1	1	1	1	1	0	0	1	1	0	0
8.	1	1	1	1	1	1	0	2	1	1	0	0
9.	1	1	1	1	1	1	0	0	0	0	0	0
10.	1	1	1	1	1	1	0	1	2	2	0	0
11.	1	1	1	1	1	1	0	1	1	1	0	0
Total	13	15	12	12	13	15	1	11	18	19	0	0

APPENDIX D

MOVEMENT EFFICIENCY

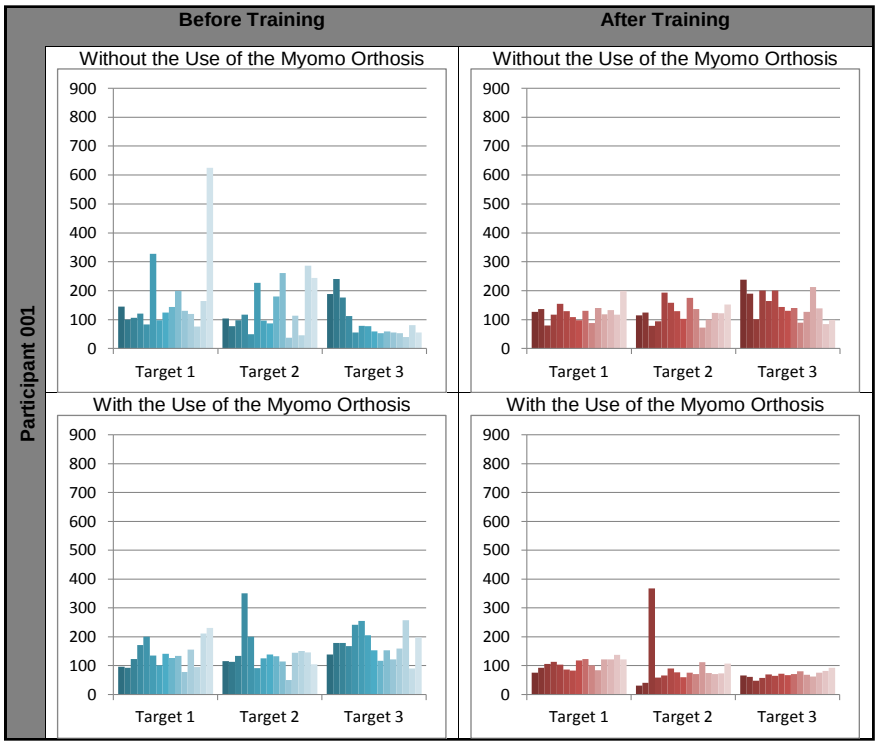


Figure 11. Movement Efficiency: Participant 001

Table 14. Movement Efficiency: Participant 001

Participant 001: Without Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
Ipsilateral	No	170.8	105.6	0.24	No
Middle	No	134.9	91.4	0.49	No
Contralateral	No	92.3	68.9	-3.48	Yes
Participant 001: With Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
Ipsilateral	No	139.2	125.3	-0.43	No
Middle	No	140.5	125.1	-0.86	No
Contralateral	No	174.3	150.7	-0.65	No
Participant 001: Before Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	170.9	139.2	4.92	Yes
Middle	No	134.2	140.5	-0.09	No
Contralateral	No	92.3	174.3	-2.83	Yes**
Participant 001: After Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	105.7	125.7	0.24	No
Middle	No	91.4	125.7	0.28	No
Contralateral	No	68.9	150.7	-2.96	Yes**

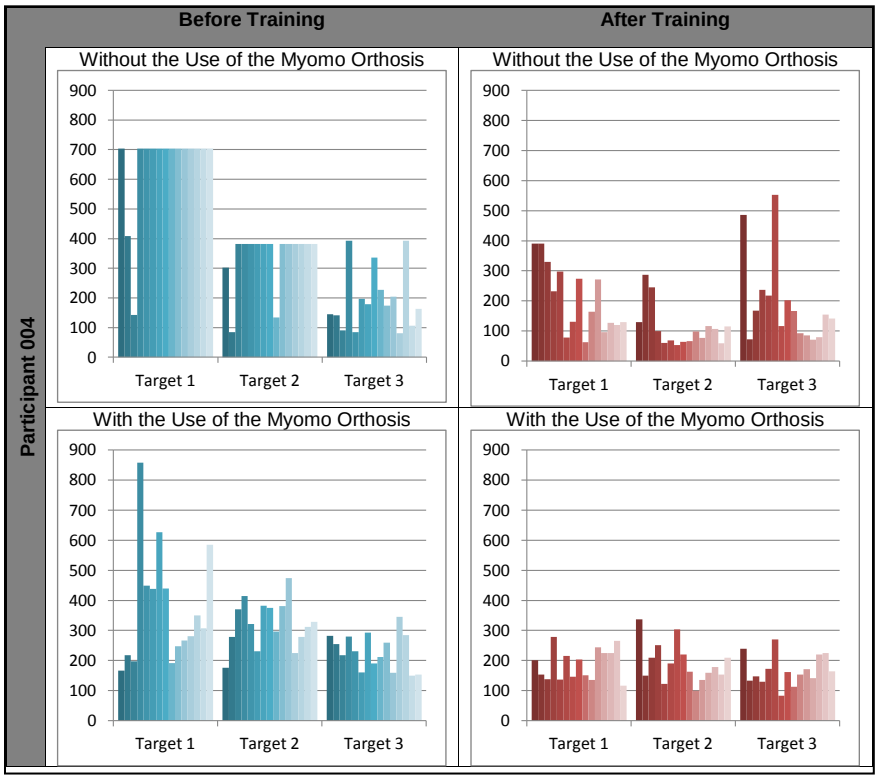


Figure 12. Movement Efficiency: Participant 004

Table 15. Movement Efficiency: Participant 004

Participant 004: Without Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
Ipsilateral	No	646.0	206.3	-3.33	Yes
Middle	No	340.3	109.8	-2.80	Yes
Contralateral	No	194.3	189.5	0.81	No
Participant 004: With Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
Ipsilateral	No	374.8	188.9	-1.69	Yes
Middle	No	322.9	192.3	-2.32	Yes
Contralateral	No	231.5	168.3	-0.61	No
Participant 004: Before Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	646.0	374.8	-2.20	Yes
Middle	No	340.3	322.9	-0.26	No
Contralateral	No	194.3	231.5	1.32	No
Participant 004: After Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	206.3	188.9	-0.68	No
Middle	No	109.8	192.3	-2.28	Yes
Contralateral	No	189.5	168.3	0.19	No

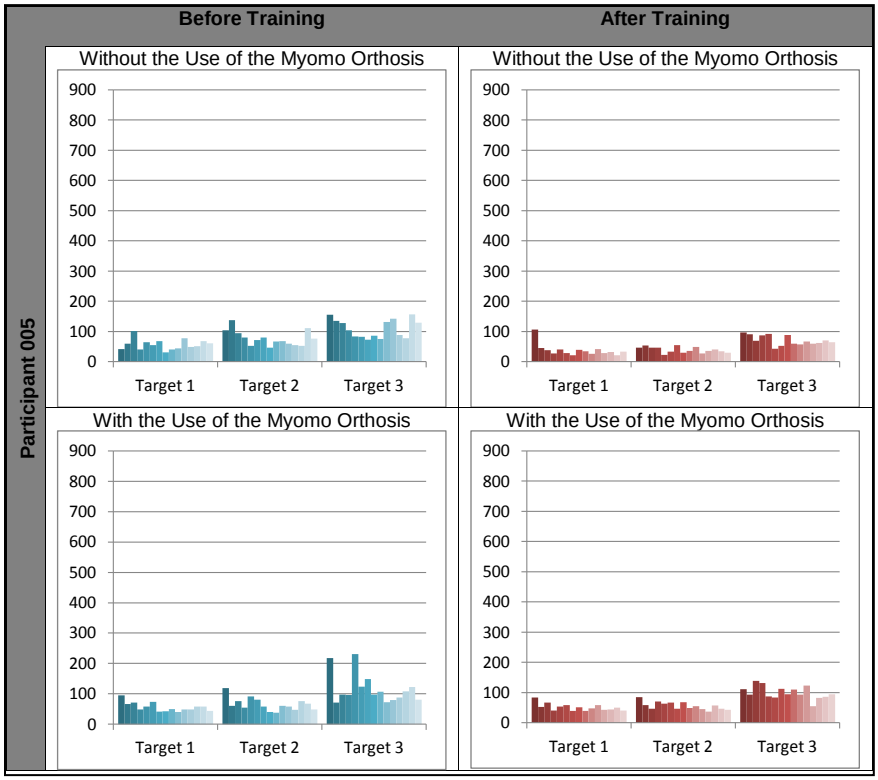


Figure 13. Movement Efficiency: Participant 005

Table 16. Movement Efficiency: Participant 005

Participant 005: Without Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
Ipsilateral	No	57.0	37.5	-1.28	No
Middle	No	77.0	39.1	-2.07	Yes
Contralateral	No	109.9	70.8	-2.51	Yes
Participant 005: With Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
Ipsilateral	No	56.20	51.20	-0.87	No
Middle	No	65.20	55.80	-1.12	No
Contralateral	No	116.10	99.70	-0.55	No
Participant 005: Before Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	57.0	56.2	-0.41	No
Middle	No	77.0	65.2	-1.33	No
Contralateral	No	109.9	116.1	-0.61	No
Participant 005: After Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	37.5	51.20	-1.16	No
Middle	No	39.1	55.80	-1.82	Yes
Contralateral	No	70.8	99.70	-1.80	Yes

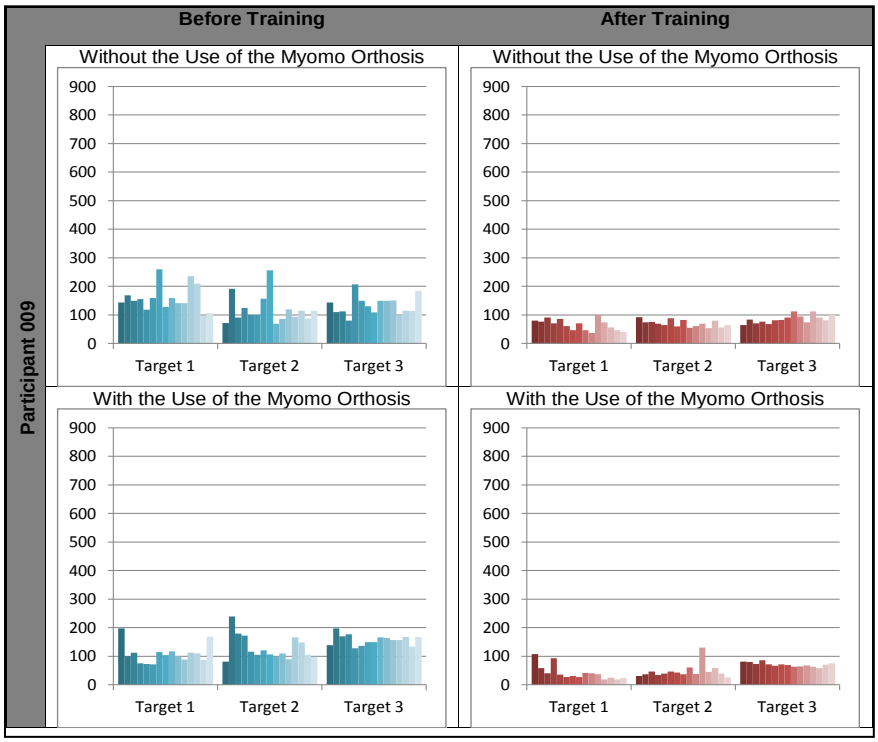


Figure 14. Movement Efficiency: Participant 009

Table 17. Movement Efficiency: Participant 009

Participant 009: Without Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
Ipsilateral	No	158.2	65.5	-2.73	Yes
Middle	No	118.5	69.6	-0.92	No
Contralateral	No	133.9	85.6	-1.24	No
Participant 009: With Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
Ipsilateral	No	109.1	41.8	-2.90	Yes
Middle	No	129.1	47.4	-2.53	Yes
Contralateral	No	157.3	70.9	-3.56	Yes
Participant 009: Before Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	158.2	109.1	-1.60	No
Middle	No	118.5	129.1	-0.11	No
Contralateral	No	133.9	157.3	-0.60	No
Participant 009: After Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	65.5	41.8	-1.87	Yes
Middle	No	69.6	47.4	-0.22	No
Contralateral	No	85.6	70.9	-1.92	Yes

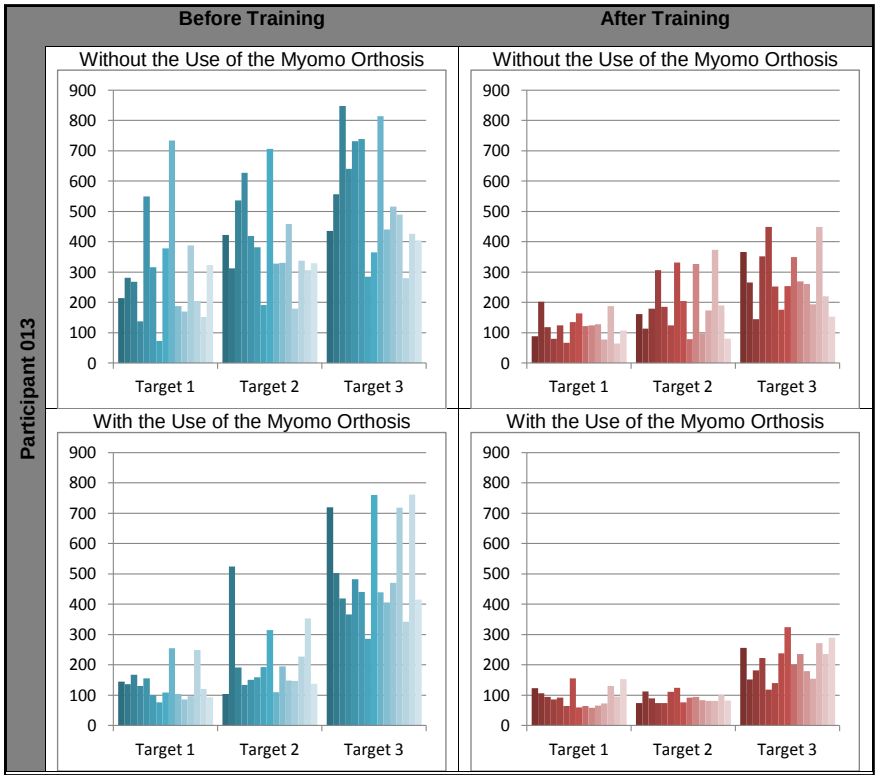


Figure 15. Movement Efficiency: Participant 013

Table 18. Movement Efficiency: Participant 013

Participant 013: Without Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
Ipsilateral	No	291.9	119.4	-1.10	No
Middle	No	391.3	195.3	-0.98	No
Contralateral	No	531.7	277.1	-1.90	Yes
Participant 013: With Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
Ipsilateral	No	135.0	95.0	-0.41	No
Middle	No	205.9	90.2	-0.87	No
Contralateral	No	502.2	277.1	-2.06	Yes
Participant 013: Before Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	291.8	135.0	-0.69	No
Middle	No	391.3	205.9	-0.77	No
Contralateral	No	531.7	502.2	0.17	No
Participant 013: After Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	119.4	95.0	0.44	No
Middle	No	195.3	90.2	-0.88	No
Contralateral	No	277.1	213.5	-0.53	No

APPENDIX E

ELBOW ANGULAR DISPLACEMENT

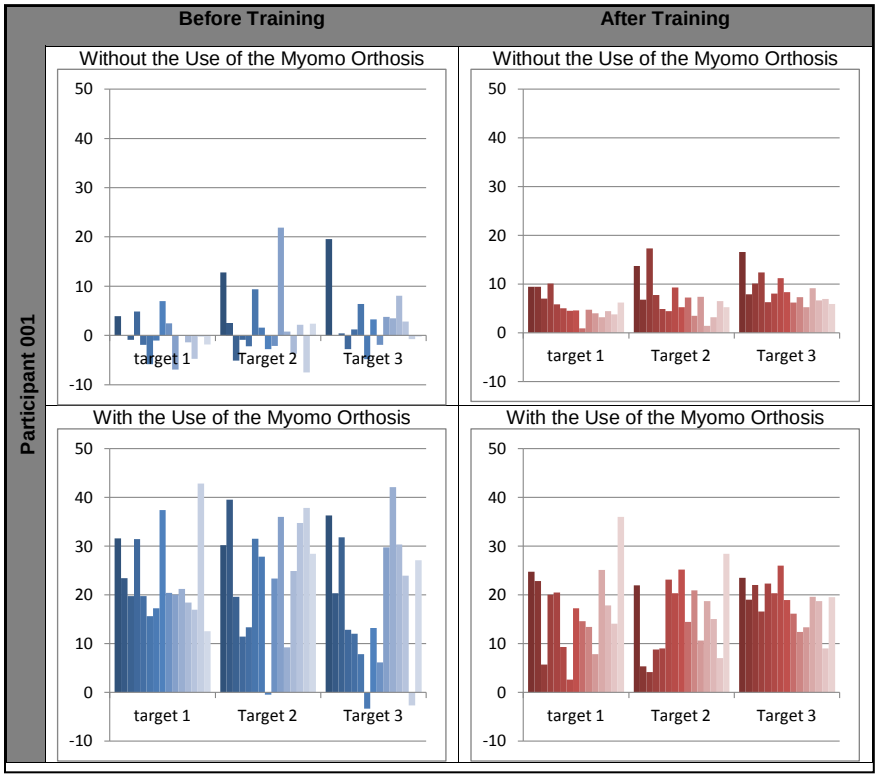


Figure 16. Elbow Angular Displacement: Participant 001

Table 19. Elbow Angular Displacement: Participant 001

Participant 001: Without Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
Ipsilateral	No	-0.43	5.53	-1.94	Yes
Middle	No	1.95	6.91	-0.46	Yes
Contralateral	No	2.58	8.53	-1.26	Yes
Participant 001: With Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
Ipsilateral	No	23.21	16.77	0.30	No
Middle	No	24.47	15.51	-0.99	No
Contralateral	No	19.15	18.48	-1.27	No
Participant 001: Before Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	-0.43	23.21	-2.93	Yes
Middle	No	1.95	24.47	-0.27	No
Contralateral	No	2.58	19.15	-2.33	Yes
Participant 001: After Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	5.53	16.77	-1.59	No
Middle	No	6.91	15.51	-1.55	No
Contralateral	No	8.53	18.48	-2.96	Yes

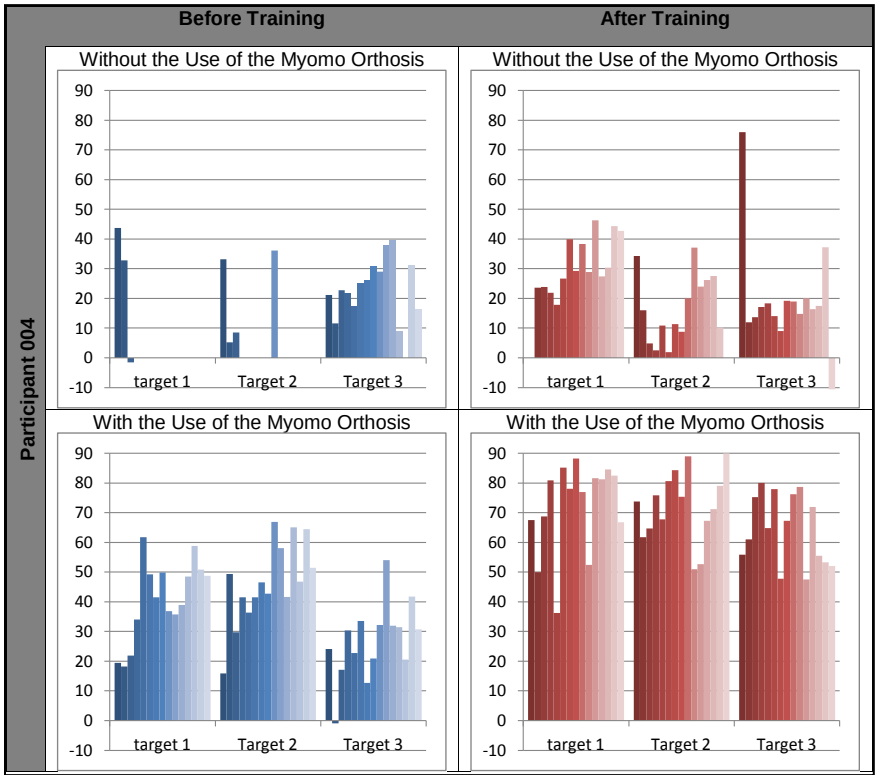


Figure 17. Elbow Angular Displacement: Participant 004

Table 20. Elbow Angular Displacement: Participant 004

Participant 004: Without Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
Ipsilateral	No	5.00	29.42	-3.35	Yes
Middle	No	5.53	15.71	-1.35	No
Contralateral	No	22.63	17.72	2.17	Yes**
Participant 004: With Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
Ipsilateral	No	40.94	72.10	-2.68	Yes
Middle	No	46.53	72.56	-2.40	Yes
Contralateral	No	26.87	64.33	-3.02	Yes
Participant 004: Before Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	5.00	40.94	-3.73	Yes
Middle	No	5.53	46.53	-3.18	Yes
Contralateral	No	22.63	26.87	-0.86	No
Participant 004: After Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	29.42	72.10	-2.65	Yes
Middle	No	15.71	72.56	-1.35	No
Contralateral	No	17.72	64.33	2.16	Yes**

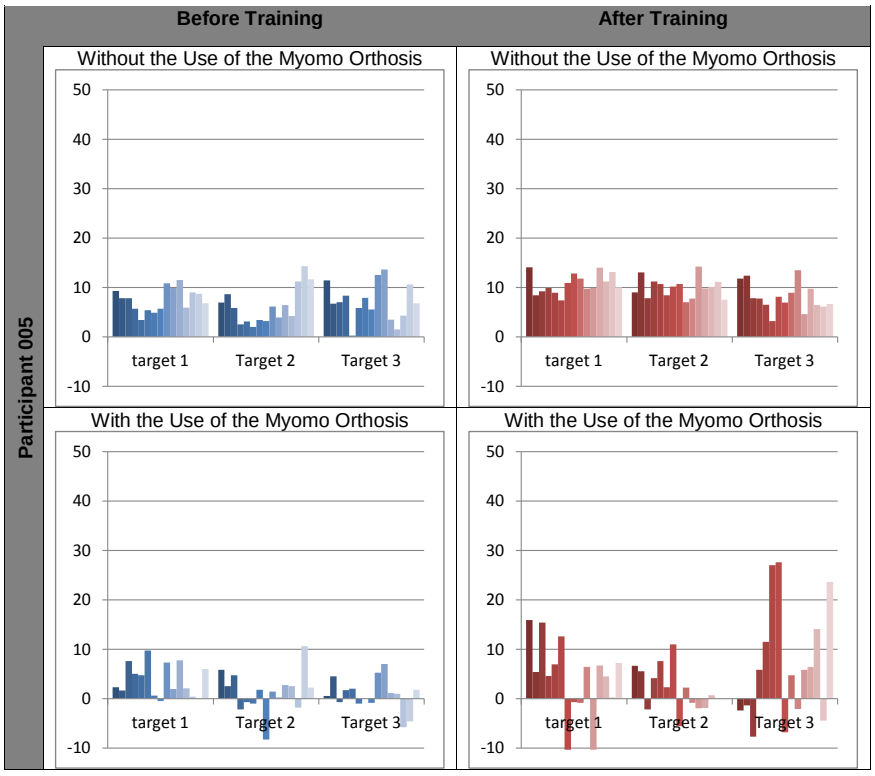


Figure 18. Elbow Angular Displacement: Participant 005

Table 21. Elbow Angular Displacement: Participant 005

Participant 005: Without Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
Ipsilateral	No	7.51	10.75	-1.83	Yes
Middle	No	6.21	9.98	-2.54	Yes
Contralateral	No	7.04	8.01	-0.52	No
Participant 005: With Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
Ipsilateral	No	3.77	0.59	0.35	No
Middle	No	1.36	1.82	0.26	No
Contralateral	No	0.79	6.77	-0.66	No
Participant 005: Before Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	7.51	3.77	-1.36	No
Middle	No	6.21	1.36	-1.71	Yes**
Contralateral	No	7.04	0.79	-2.03	Yes**
Participant 005: After Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	10.75	0.59	-0.21	No
Middle	No	9.98	1.82	-2.12	Yes**
Contralateral	No	8.01	6.77	-0.71	No

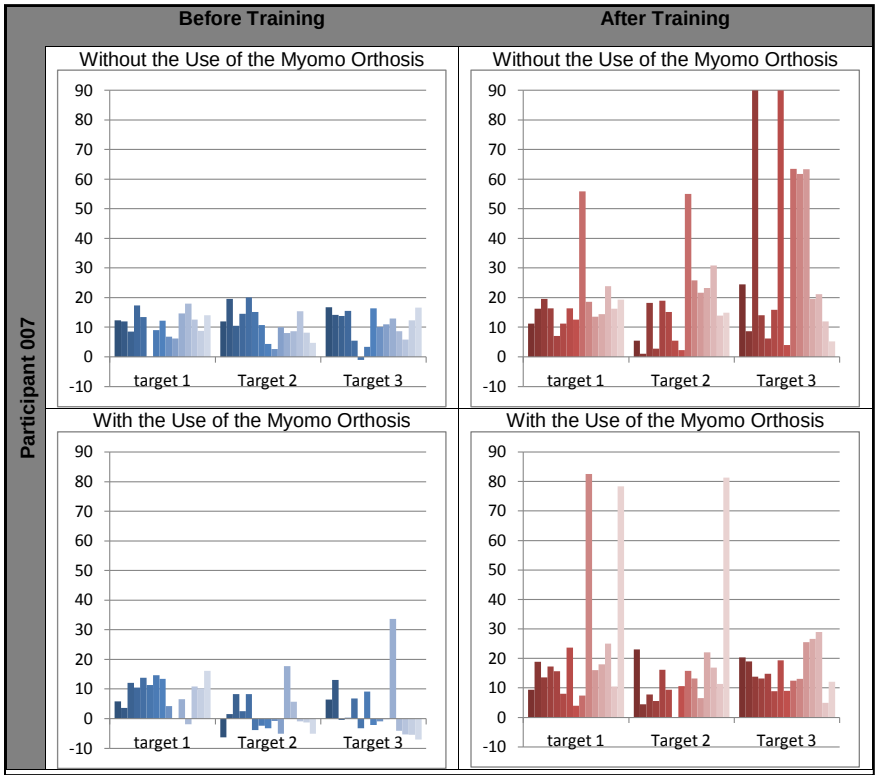


Figure 19. Elbow Angular Displacement: Participant 007

Table 22. Elbow Angular Displacement: Participant 007

Participant 007: Without Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
Ipsilateral	No	11.05	18.17	-0.55	No
Middle	No	10.95	16.98	-0.86	No
Contralateral	No	10.78	34.31	-0.26	No
Participant 007: With Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
Ipsilateral	No	8.75	23.21	1.38	No
Middle	No	1.00	16.26	3.35	Yes
Contralateral	No	2.71	16.13	-1.18	No
Participant 007: Before Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	11.05	8.75	-1.07	No
Middle	No	10.95	1.00	-1.99	Yes
Contralateral	No	10.78	2.71	-0.31	No
Participant 007: After Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	18.17	23.21	0.82	No
Middle	No	16.98	16.26	0.26	No
Contralateral	No	34.31	16.13	0.14	No

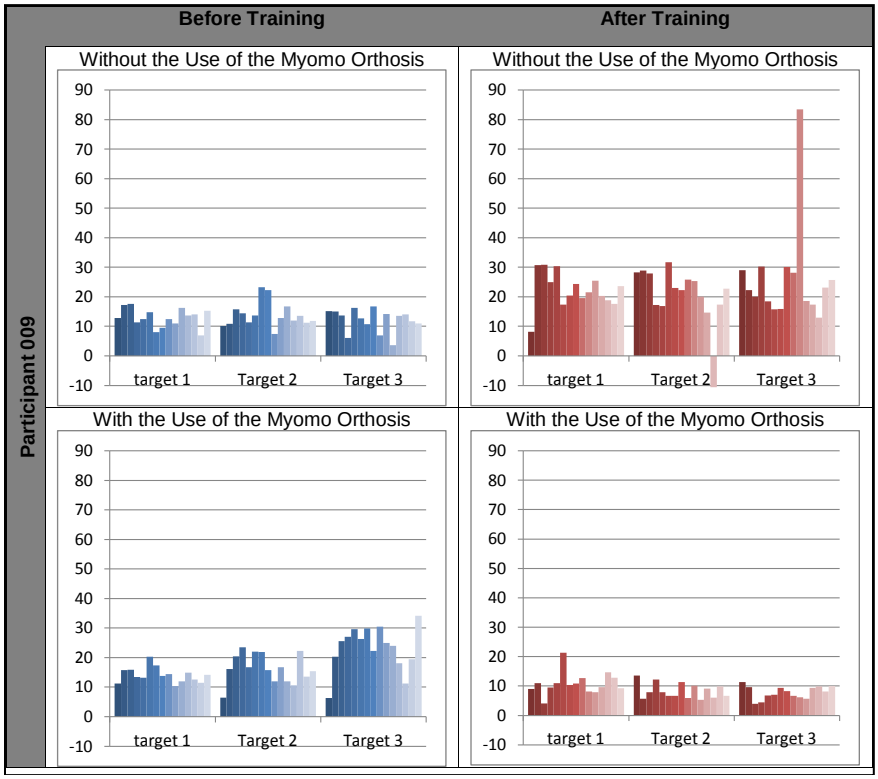


Figure 20. Elbow Angular Displacement: Participant 009

Table 23. Elbow Angular Displacement: Participant 009

Participant 009: Without Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
Ipsilateral	No	12.89	22.26	-2.19	Yes
Middle	No	13.81	16.88	-0.34	No
Contralateral	No	12.08	26.07	-0.89	No
Participant 009: With Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
Ipsilateral	No	14.2	10.81	-1.04	No
Middle	No	16.35	8.33	-2.39	Yes**
Contralateral	No	23.29	7.79	-3.07	Yes**
Participant 009: Before Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	12.89	14.2	-0.51	No
Middle	No	13.81	16.35	-1.02	No
Contralateral	No	12.08	23.29	-2.26	Yes
Participant 009: After Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	22.26	10.81	-2.57	Yes**
Middle	No	16.88	8.33	-0.45	No
Contralateral	No	26.07	7.79	-1.48	No

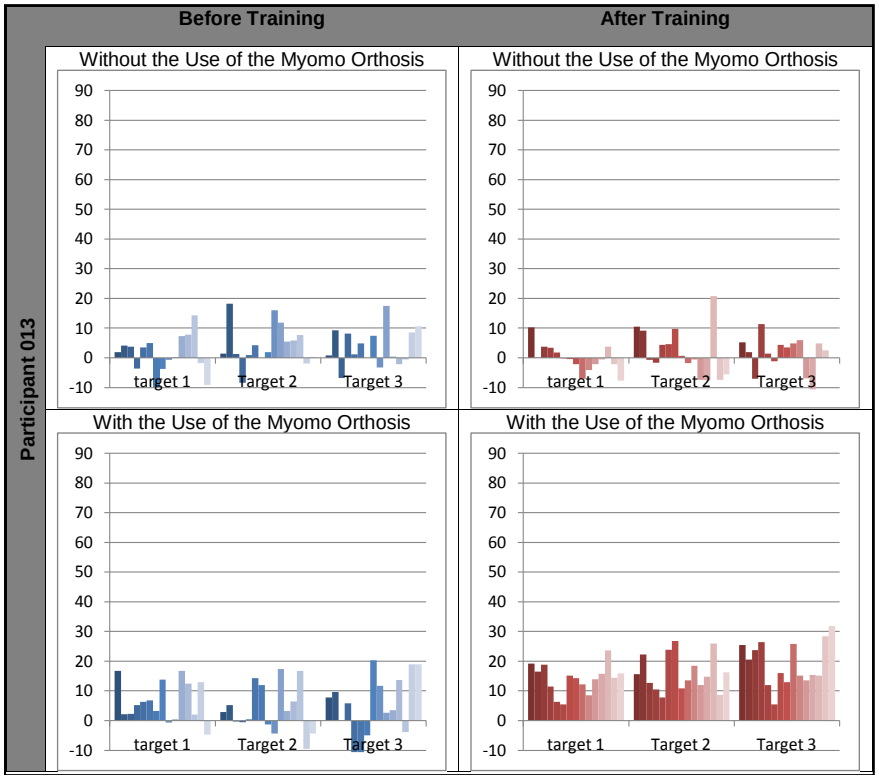


Figure 21. Elbow Angular Displacement: Participant 013

Table 24. Elbow Angular Displacement: Participant 013

Participant 013: Without Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
Ipsilateral	No	1.28	-0.23	-0.56	No
Middle	No	4.30	1.82	0.04	No
Contralateral	No	10.60	1.34	0.96	No
Participant 013: With Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
Ipsilateral	No	6.38	14.01	-0.59	No
Middle	No	3.88	15.99	-1.22	No
Contralateral	No	5.13	19.19	-2.28	Yes
Participant 013: Before Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	1.28	6.38	-0.41	No
Middle	No	4.30	3.88	-0.08	No
Contralateral	No	10.60	5.13	-0.23	No
Participant 013: After Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	-0.23	14.01	-3.45	Yes
Middle	No	1.82	15.99	-1.78	Yes
Contralateral	No	1.34	19.19	-2.64	Yes

APPENDIX F

MOVEMENT ERROR

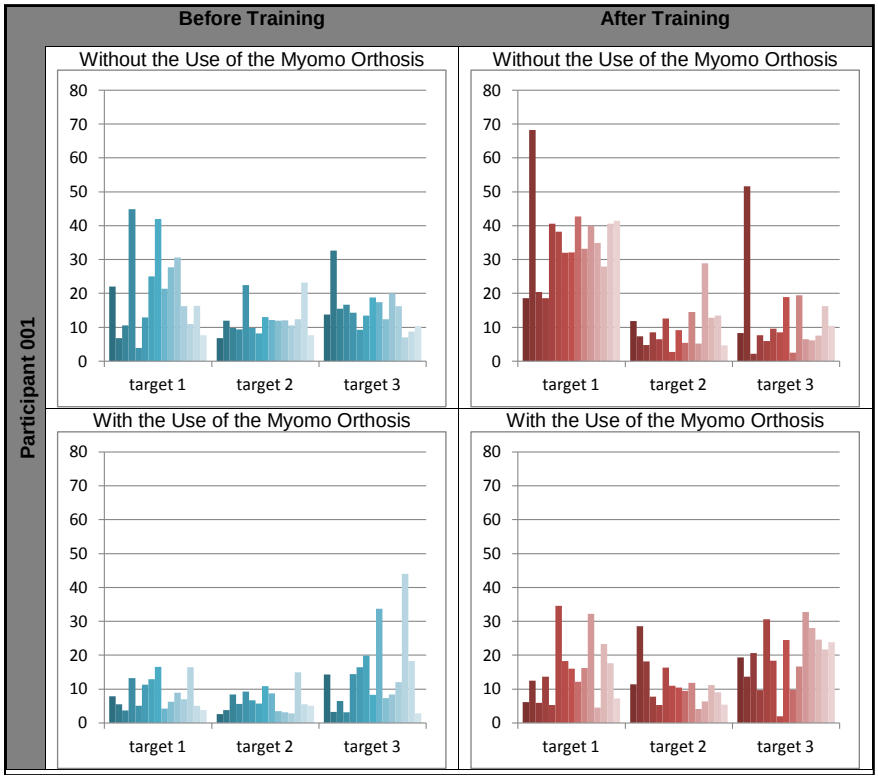


Figure 22. Movement Error: Participant 001

Table 25. Movement Error: Participant 001

Participant 001: Without Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
Ipsilateral	No	19.93	35.33	-0.50	No
Middle	No	12.08	9.88	0.66	No
Contralateral	No	15.10	12.09	0.76	No
Participant 001: With Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
1	No	8.52	15.07	-0.10	No
2	No	6.44	11.10	-1.33	No
3	No	14.19	19.74	0.01	No
Participant 001: Before Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	19.93	8.52	-0.98	No
Middle	No	12.08	6.44	-2.96	Yes
Contralateral	No	15.10	14.19	-0.04	No
Participant 001: After Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	35.33	15.07	-1.19	No
Middle	No	9.88	11.10	-0.14	No
Contralateral	No	12.09	19.74	0.48	No

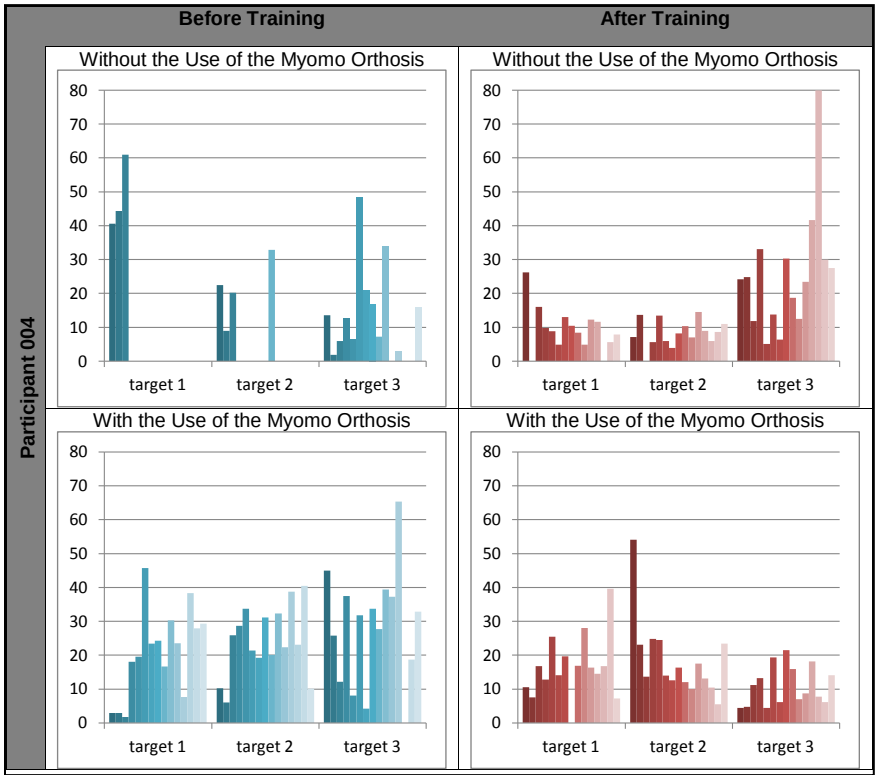


Figure 23. Movement Error: Participant 004

Table 26. Movement Error: Participant 004

Participant 004: Without Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
Ipsilateral	No	48.63	9.33	-3.76	Yes
Middle	No	9.39	8.29	-0.48	No
Contralateral	No	12.42	25.86	-1.28	No
Participant 004: With Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
1	No	20.84	16.42	-0.53	No
2	No	24.24	18.35	-0.36	No
3	No	27.96	10.86	0.27	No
Participant 004: Before Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	48.63	20.84	-2.88	Yes
Middle	No	9.39	24.24	-2.03	Yes
Contralateral	No	12.42	27.96	-0.42	No
Participant 001: After Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	9.33	16.42	0.22	No
Middle	No	8.29	18.35	-2.28	Yes
Contralateral	No	25.86	10.86	-1.64	Yes

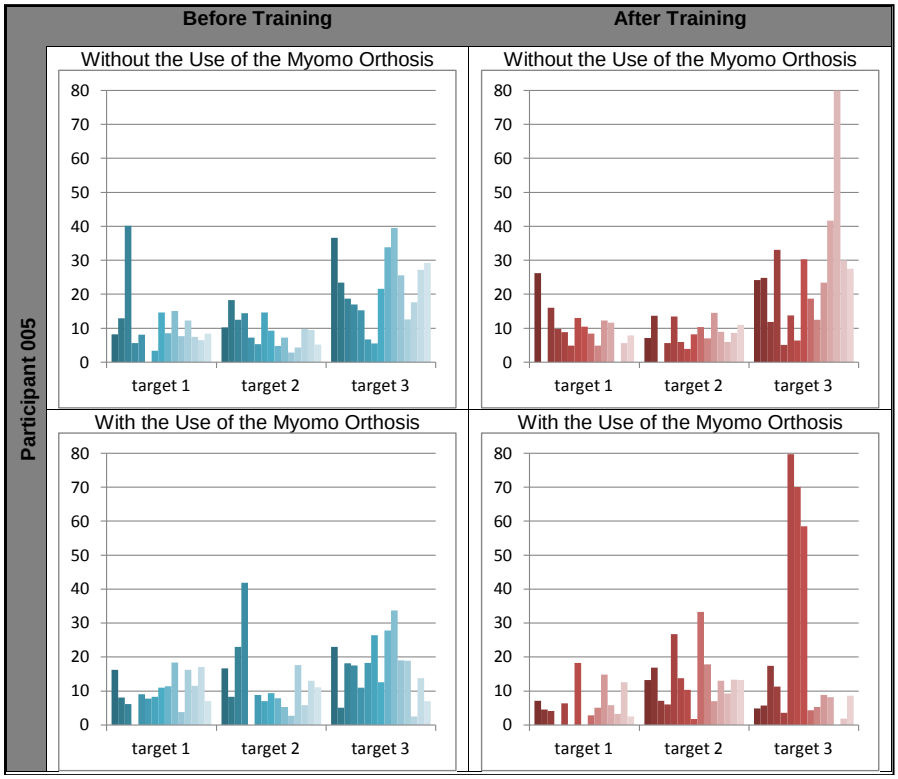


Figure 24. Movement Error: Participant 005

Table 27. Movement Error: Participant 005

Participant 005: Without Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
Ipsilateral	No	10.58	9.33	0.26	No
Middle	No	9.03	8.29	0.33	No
Contralateral	No	22.02	25.85	-2.04	Yes
Participant 005: With Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
1	No	10.01	5.81	0.55	No
2	No	11.90	13.52	-0.33	No
3	No	16.98	19.22	1.87	Yes**
Participant 005: Before Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	10.58	10.01	0.06	No
Middle	No	9.03	11.90	-0.28	No
Contralateral	No	22.02	16.98	-1.07	No
Participant 005: After Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	9.33	5.81	1.58	No
Middle	No	8.29	13.52	0.20	No
Contralateral	No	25.85	19.22	-1.85	Yes

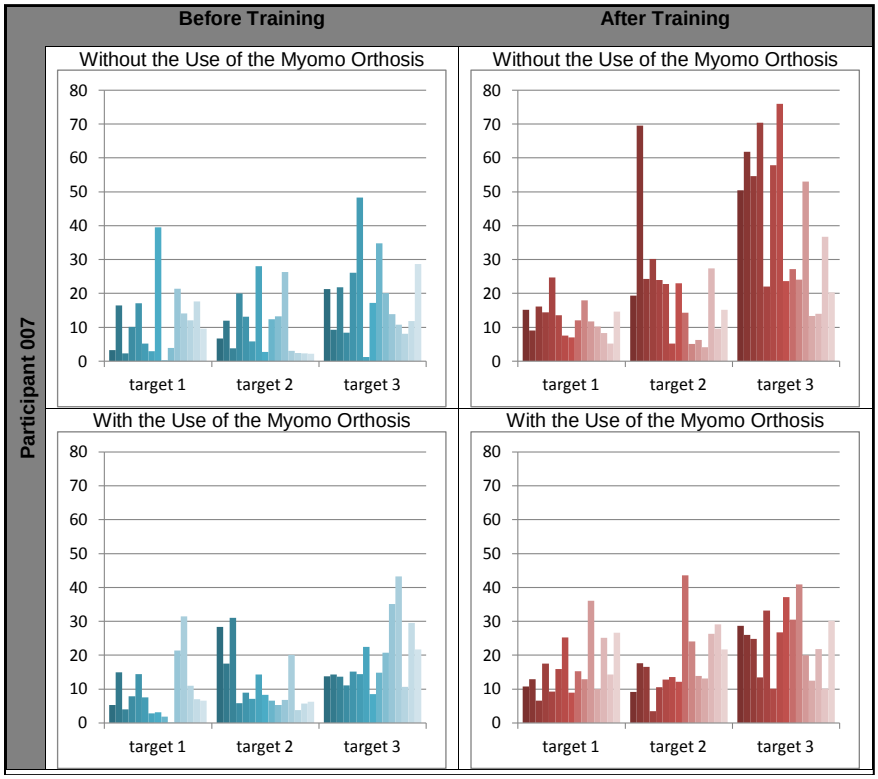


Figure 25. Movement Error: Participant 007

Table 28. Movement Error: Participant 007

Participant 007: With Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
Ipsilateral	No	11.71	12.49	1.17	No
Middle	No	10.25	20.00	-0.75	No
Contralateral	No	18.78	40.35	-1.43	No
Participant 007: With Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
Ipsilateral	No	9.29	16.49	-0.52	No
Middle	No	11.72	17.84	-2.99	Yes**
Contralateral	No	19.29	24.42	-0.82	No
Participant 007: Before Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	11.71	9.29	0.34	No
Middle	No	10.25	11.72	-0.24	No
Contralateral	No	18.78	19.29	0.07	No
Participant 007: After Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	12.49	16.49	0.33	No
Middle	No	20.00	17.84	-0.76	No
Contralateral	No	40.35	24.42	-1.17	No

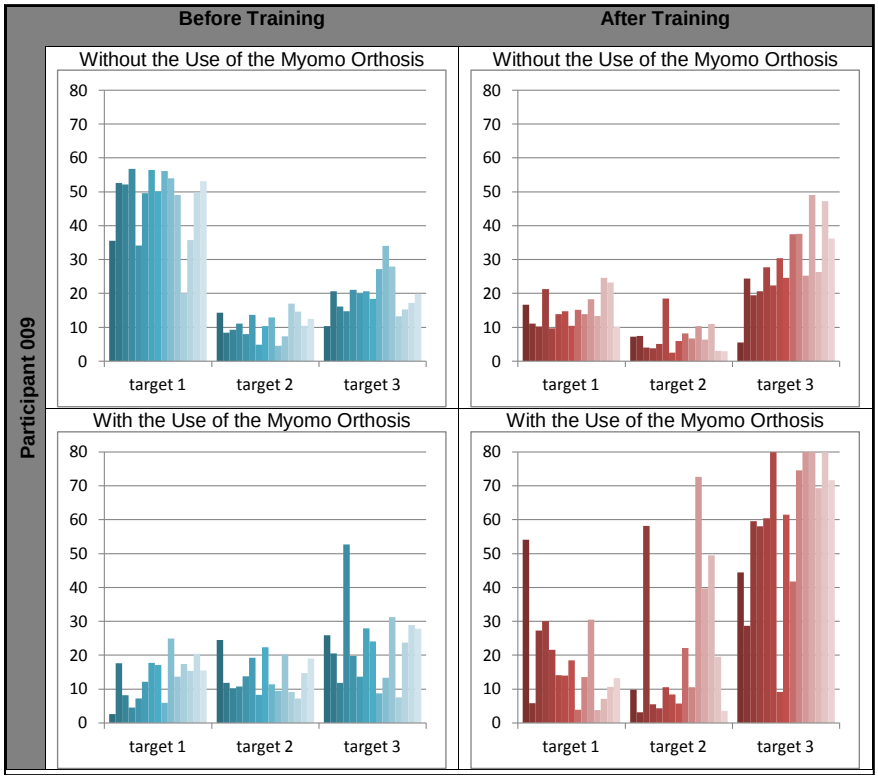


Figure 26. Movement Error: Participant 009

Table 29. Movement Error: Participant 009

Participant 009: Without Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
Ipsilateral	No	47.02	15.11	-3.13	Yes
Middle	No	10.61	6.87	0.09	No
Contralateral	No	19.77	28.92	-1.69	Yes**
Participant 009: With Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
Ipsilateral	No	13.35	17.89	0.25	No
Middle	No	14.14	21.55	-0.51	No
Contralateral	No	22.51	64.60	-2.42	Yes**
Participant 009: Before Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	47.02	13.35	-3.35	Yes
Middle	No	10.61	14.14	-0.11	No
Contralateral	No	19.77	22.51	0.57	No
Participant 009: After Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	15.11	17.89	-0.51	No
Middle	No	6.87	21.55	-1.07	No
Contralateral	No	28.92	64.60	-1.97	Yes**

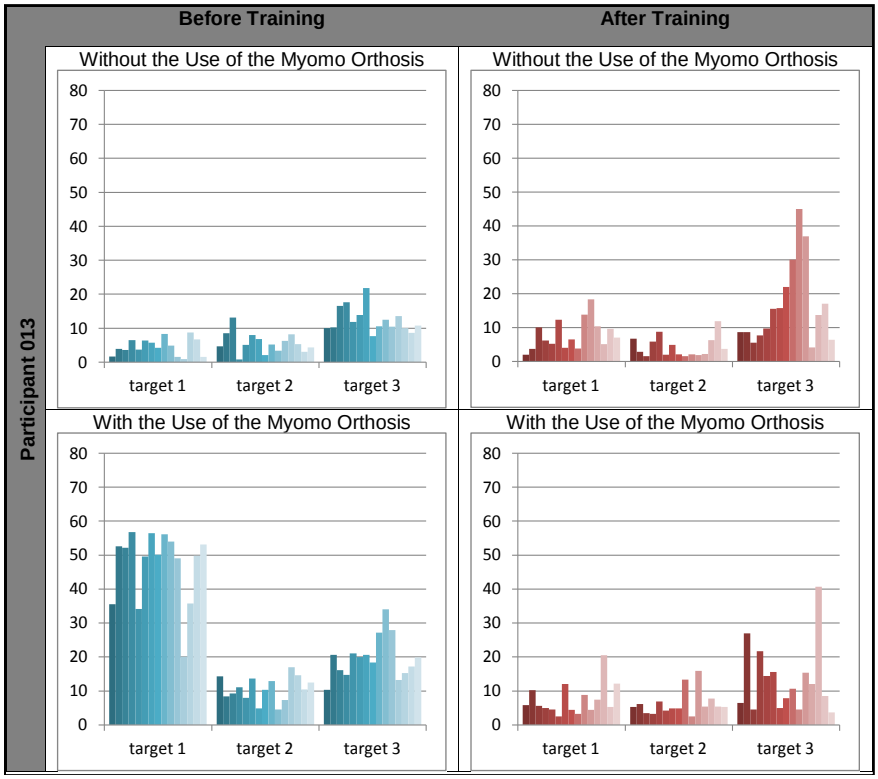


Figure 27. Movement Error: Participant 013

Table 30. Movement Error: Participant 013

Participant 013: Without Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
Ipsilateral	No	8.74	7.92	-0.86	No
Middle	No	6.31	4.33	-0.05	No
Contralateral	No	10.35	16.50	-1.74	Yes**
Participant 013: With Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
Ipsilateral	No	4.55	7.46	0.21	No
Middle	No	5.65	6.31	1.04	No
Contralateral	No	12.40	13.20	0.96	No
Participant 013: Before Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	8.74	4.55	-3.35	No
Middle	No	6.31	5.65	-0.11	Yes
Contralateral	No	10.35	12.40	0.57	No
Participant 013: After Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	7.92	7.46	-0.51	No
Middle	No	4.33	6.31	-1.07	No
Contralateral	No	16.50	13.20	-1.97	Yes

APPENDIX G

ACCELERATION CYCLES

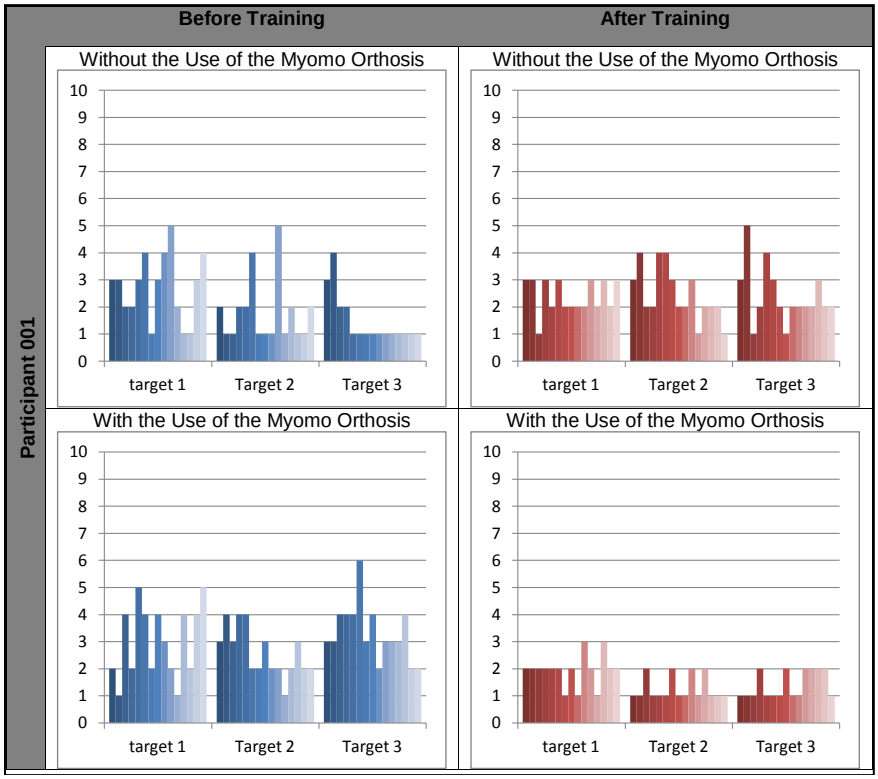


Figure 28. Acceleration Cycles: Participant 001

Table 31. Acceleration Cycles: Participant 001

Participant 001: Before Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	2.73	3.00	-0.11	No
Middle	No	1.80	2.60	-2.96	Yes**
Contralateral	No	1.47	3.33	-2.87	Yes**
Participant 001: After Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	2.40	1.93	1.46	No
Middle	No	2.46	1.26	-1.83	Yes
Contralateral	No	2.40	1.40	-0.97	No
Participant 001: Without Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
Ipsilateral	No	2.73	2.40	-0.13	No
Middle	No	1.80	2.46	-2.47	Yes**
Contralateral	No	1.47	2.40	-2.69	Yes**
Participant 001: With Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
1	No	3.00	1.93	-0.34	No
2	No	2.60	1.26	-0.19	No
3	No	3.33	1.40	-1.65	Yes

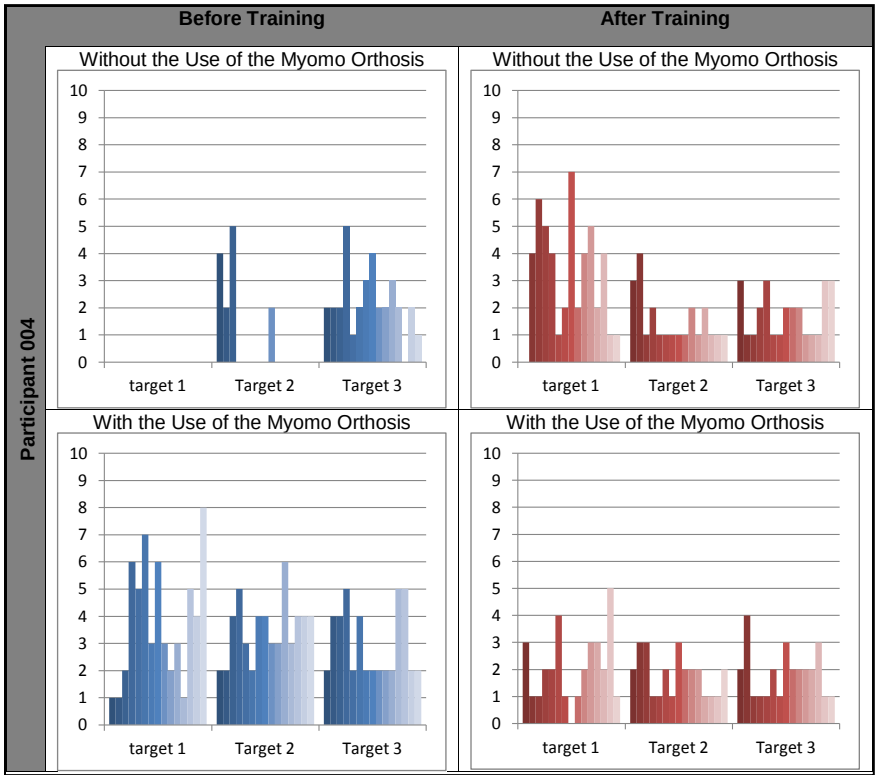


Figure 29. Acceleration Cycles: Participant 004

Table 32. Acceleration Cycles: Participant 004

Participant 004: Without Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
Ipsilateral	No	No trials	3.43	-3.19	No trials
Middle	No	3.25	1.53	-1.94	Yes
Contralateral	No	2.35	1.80	0.03	No
Participant 004: With Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
1	No	3.80	2.21	-1.15	No
2	No	3.53	1.80	-1.92	Yes
3	No	3.00	1.87	-1.04	No
Participant 004: Before Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	No trials	3.80	-2.96	No trials
Middle	No	3.25	3.53	-3.02	No
Contralateral	No	2.35	3.00	-0.45	No
Participant 004: After Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	3.43	2.21	-0.62	No
Middle	No	1.53	1.80	1.63	No
Contralateral	No	1.80	1.87	0.34	No

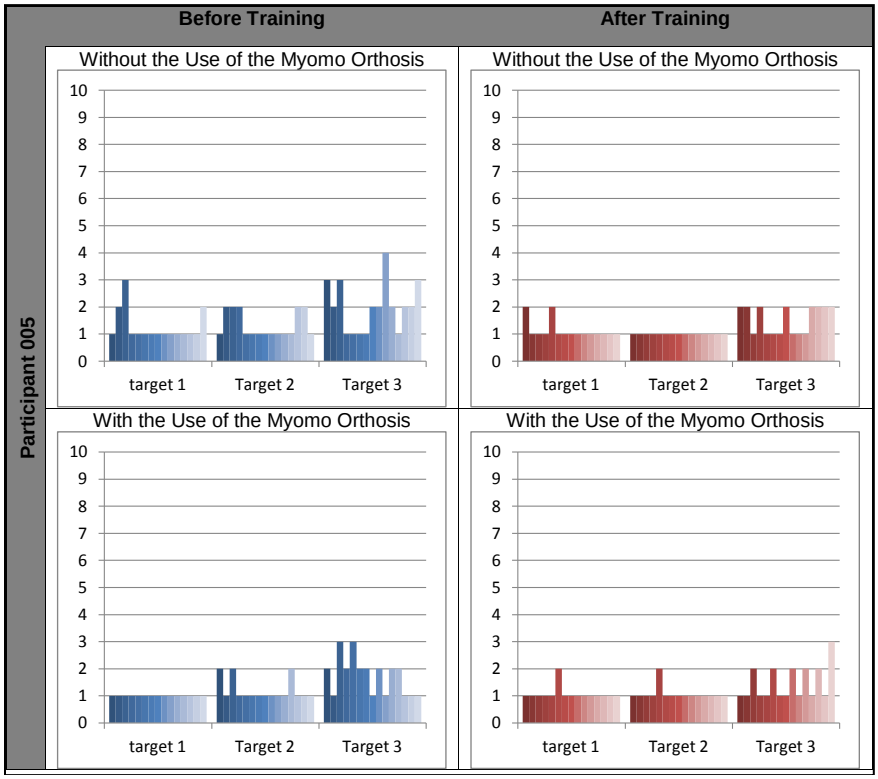


Figure 30. Acceleration Cycles: Participant 005

Table 33. Acceleration Cycles: Participant 005

Participant 005: Without Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
Ipsilateral	No	1.27	1.13	-1.08	No
Middle	No	1.33	1.00	-2.15	Yes
Contralateral	No	2.00	1.53	-1.16	No
Participant 005: With Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
1	No	1.00	1.07	0.15	No
2	No	1.20	1.07	0.06	No
3	No	1.73	1.47	0.84	No
Participant 005: Before Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	1.27	1.00	-1.50	No
Middle	No	1.33	1.20	-0.93	No
Contralateral	No	2.00	1.73	-0.04	No
Participant 005: After Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	1.13	1.07	0.48	No
Middle	No	1.00	1.07	0.15	No
Contralateral	No	1.53	1.47	0.56	No

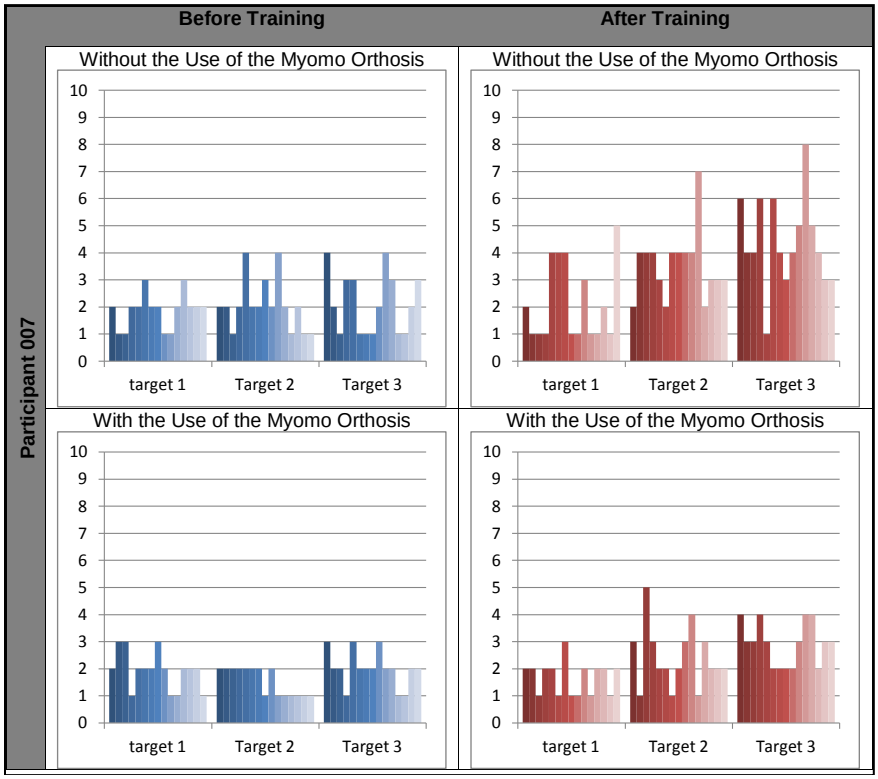


Figure 31. Acceleration Cycles: Participant 007

Table 34. Accerlation Cycles: Participant 007

Participant 007: Without Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
Ipsilateral	No	1.87	2.13	-0.07	No
Middle	No	2.06	3.53	-1.33	No
Contralateral	No	2.13	4.40	-1.87	Yes
Participant 007: With Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
1	No	1.93	1.67	0.40	No
2	No	1.53	2.40	-0.30	No
3	No	2.00	2.93	-1.61	No
Participant 007: Before Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	1.87	1.93	-0.88	No
Middle	No	2.06	1.53	-1.07	No
Contralateral	No	2.13	2.00	-0.54	No
Participant 007: After Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	2.13	1.67	0.52	No
Middle	No	3.53	2.40	-0.42	No
Contralateral	No	4.40	2.93	-0.76	No

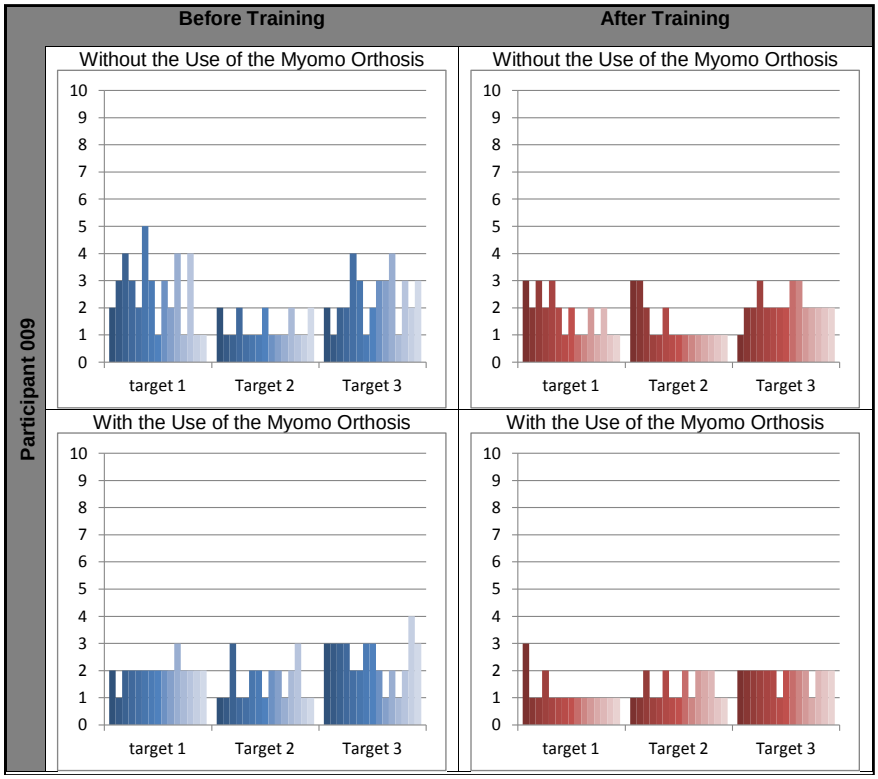


Figure 32. Acceleration Cycles: Participant 009

Table 35. Acceleration Cycles: Participant 009

Participant 009: Without Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
Ipsilateral	No	2.60	1.80	1.36	No
Middle	No	1.33	1.40	-1.67	No
Contralateral	No	2.40	2.13	0.28	No
Participant 009 With Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
1	No	2.00	1.20	-2.05	Yes
2	No	1.60	1.40	0.65	No
3	No	2.47	1.86	-1.67	Yes
Participant 009: Before Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	2.60	2.00	0.61	No
Middle	No	1.33	1.60	0.86	No
Contralateral	No	2.40	2.47	-0.37	No
Participant 009: After Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	1.80	1.20	-1.16	No
Middle	No	1.40	1.40	-1.14	No
Contralateral	No	2.13	1.86	-0.69	No

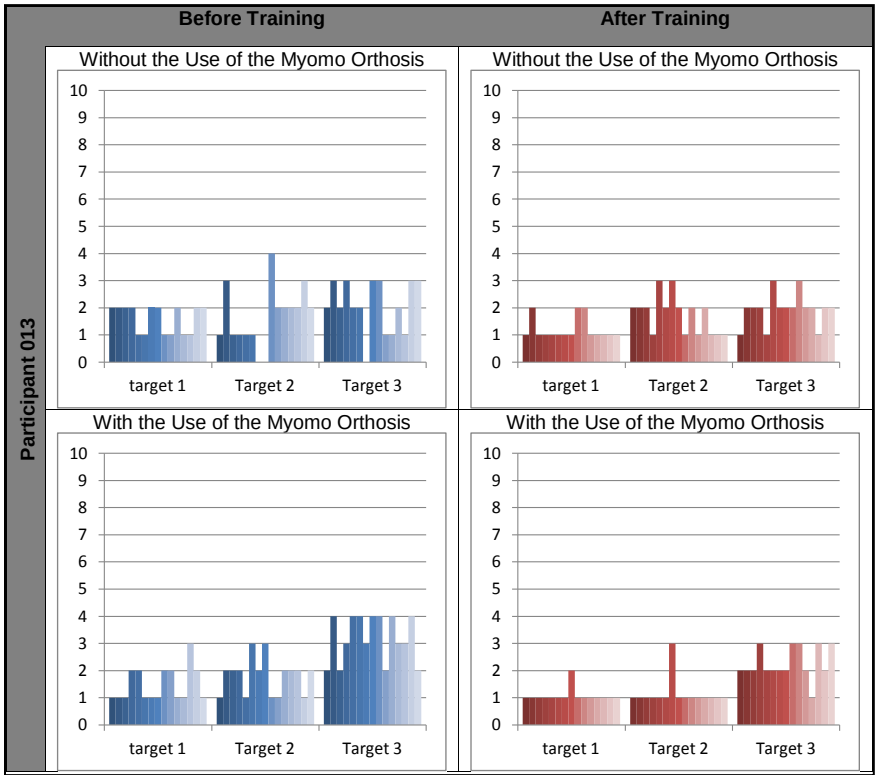


Figure 33. Acceleration Cycles: Participant 013

Table 36. Acceleration Cycles: Participant 013

Participant 013: Without Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
Ipsilateral	No	1.60	1.47	-0.91	No
Middle	No	1.79	1.80	-0.32	No
Contralateral	No	2.24	3.20	0.66	No
Participant 013: With Use of Myomo					
Target	Auto-Correlation	Pre Mean Value	Post Mean Value	Z-Score	*P*<.05
1	No	1.20	1.06	-0.96	No
2	No	1.73	1.13	-0.39	No
3	No	1.93	2.27	-0.63	No
Participant 013: Before Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	1.60	1.47	-0.33	No
Middle	No	1.79	1.80	-0.07	No
Contralateral	No	2.24	3.20	-0.84	No
Participant 013: After Training					
Target	Auto-Correlation	Mean Value Without Myomo	Mean Value With Myomo	Z-Score	*P*<.05
Ipsilateral	No	1.20	1.06	-0.54	No
Middle	No	1.73	1.13	-0.69	No
Contralateral	No	1.93	2.27	0.90	No

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