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A novel approach to increase upper extremity active range of motion for individuals with duchenne muscular dystrophy using admittance control

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ABSTRACT

A NOVEL APPROACH TO INCREASE UPPER EXTREMITY ACTIVE RANGE OF MOTION FOR INDIVIDUALS WITH DUCHENNE MUSCULAR DYSTROPHY USING ADMITTANCE CONTROL

by
Madeline Corrigan

Duchenne muscular dystrophy (DMD), a neuromuscular disease with a prevalence of 1 in 3,500-5,000 male births, results in progressive muscle weakness causing loss of independence and imposing the demands of costly and intrusive assistive support and personal care for daily living tasks. Upper extremity function begins to decline while ambulation is still possible and gradually progresses with time, playing a prominent role in loss of independence. Importantly, upper extremity functional limitations exist despite residual muscle strength that is insufficient to lift the arms against gravity. Presently, there exist a number of commercially available assistive devices aimed at augmenting upper extremity functional deficit; however, these devices have been largely unsuccessful in delivering the independence they seek to provide. Passive orthoses, the most common of these commercially available assistive devices, are limited to those in the earlier stages of functional loss because of the imperfect gravity compensation, requirement of sufficient muscle strength to overcome the inertia of the device, and inability to accommodate loss of strength over time. The objective of this project is to overcome the limitations of currently available upper extremity assistive devices for individuals with DMD by using admittance control. Admittance control is an inherently safe and intuitive robotic control paradigm that maps the user's applied force to the motion of a robot. It is hypothesized that a motorized arm support utilizing the admittance control paradigm will

provide individuals with DMD an intuitive and effective means of increasing upper extremity AROM and independence through the use of their residual muscle strength.

The results of this project demonstrate that individuals with DMD who have limited or nonexistent upper extremity function retain residual muscle strength sufficient to generate voluntary movement when the arms are supported against gravity. Furthermore, the results show that admittance control allows for the use of this residual strength to increase the AROM of individuals with DMD to a greater degree than a commercially available passive arm support and provide increased independence in the performance of user-defined priority tasks compared to unsupported movements. The results also show that over one year there is no significant decrease in the AROM provided by the admittance control robot, indicating the viability of an admittance control motorized arm support to provide sustainable improvements in upper extremity function in the presence of progressive muscle loss. Finally, two prototypes are presented that demonstrate a novel approach to upper extremity exoskeleton design. The phase 1 prototype establishes the successful implementation of admittance control as the control paradigm for fully motorizing all degrees of freedom (DOF) of a commercially available passive arm support. The phase 2 prototype demonstrates a modular approach intended to accommodate changes in upper extremity function over time through the successful implementation of one motorized DOF of a commercially available passive arm support while keeping the other DOFs passive. The work presented herein is a comprehensive investigation to establish the benefits of admittance control to increase upper extremity AROM and improve independence for individuals with DMD with the intention of allowing these individuals to maintain optimal quality of life.

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by
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APPROVAL PAGE

A NOVEL APPROACH TO INCREASE UPPER EXTREMITY ACTIVE RANGE OF MOTION FOR INDIVIDUALS WITH DUCHENNE MUSCULAR DYSTROPHY USING ADMITTANCE CONTROL

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In memory of
Patrick Coggins and Cullen Connolly.
The time and energy you devoted to this research will change lives.
You have already certainly changed mine.

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CHAPTER 1

INTRODUCTION

1.1 Motivation

Progressive muscle weakness characteristic of Duchenne muscular dystrophy (DMD) results in loss of upper extremity function and reduction of independence in activities of daily living over time. For individuals with DMD, maintaining optimal quality of life depends largely on the preservation of self-sufficiency. It follows that an assistive device that can augment lost upper extremity function by providing increase voluntary movement has the potential to improve quality of life for these individuals. However, current commercially available upper extremity assistive devices fail to deliver the independence they seek to provide. Establishing the feasibility of using an admittance control robot to allow very small muscle forces to control upper extremity movements has the potential to significantly advance the field of upper extremity assistive devices for individuals with DMD. Even more, fabricating an upper extremity arm support that utilizes the benefits of admittance control has the potential to increase independence and overall quality of life for individuals with DMD.

1.2 Objective

The objective of this project is to overcome the limitations of currently available upper extremity assistive devices for individuals with DMD by using admittance control. Admittance control is an inherently safe and intuitive robotic control paradigm that maps the user's applied force to the motion of a robot. The use of admittance control provides

a means to balance the arm against gravity more precisely, minimize friction, and reduce inertia, thereby decreasing the overall force required by the user to generate a movement compared to that required by a passive arm support. It is hypothesized that a motorized arm support utilizing the admittance control paradigm will provide individuals with DMD an intuitive and effective means of increasing upper extremity AROM through the use of their residual muscle strength.

1.3 Specific Aims and Hypotheses

1.3.1 Specific Aim 1

Specific Aim 1: Validate the anecdotally reported observations of residual upper extremity muscle strength of individuals with DMD who have limited or nonexistent upper extremity function. The increase in upper extremity AROM of individuals with DMD when the arms are supported in the water compared to unsupported movements is a widely accepted clinical observation and a principle that is utilized in the design of passive orthoses; however, it has yet to be validated or quantified in a research setting. The objective of this aim is to validate the anecdotally reported observations that individuals with DMD who have limited or nonexistent upper extremity function have residual muscle strength sufficient to generate voluntary movement when the arms are supported against gravity.

Sub Aim 1.1: Investigate the degree of change in upper extremity AROM of an individual with DMD when the arms are supported against gravity compared to unsupported movements in a case study. The objective of this sub-aim is to quantify the degree of change in upper extremity AROM of shoulder and elbow movements while the

arms are supported against gravity in the water compared to when the arms are not supported. It is hypothesized that the AROM of shoulder and elbow movements will be greater when the arms are supported against gravity in the water compared to when the arms are not supported.

Sub Aim 1.2: Investigate the degree of upper extremity AROM of an individual with DMD when the arms are supported against gravity compared to unsupported movements in a longitudinal case study. The objective of this sub-aim is to track the changes in upper extremity AROM when the arms are supported in water over the course of 19 months, beginning during ambulation and continuing after ambulation is lost, compared to the upper extremity AROM while unsupported. It is hypothesized that prior to loss of ambulation water-supported and unsupported AROM will be similar; and, the unsupported AROM will decrease over time at a faster rate than water-supported AROM. Furthermore, it is hypothesized that there will be a larger difference between unsupported and water-supported AROM after ambulation is lost.

1.3.2 Specific Aim 2

Specific Aim 2: Examine the feasibility of using an admittance control motorized arm support to increase the upper extremity AROM of individuals with DMD to a greater degree than that provided by a passive arm support. Current commercially available arm supports provide increased AROM for individuals with DMD by providing support against gravity and reducing friction. However, these devices are limited by their inexact gravity compensation and their inability to reduce inertia. The HapticMASTER, a 3 degrees of freedom (DOF) admittance control robot, provides more exact gravity compensation while minimizing friction and reducing inertia. The objective of this aim is

to examine the upper extremity AROM provided by the HapticMASTER robot compared to the Armon Edero, a commercially available passive arm support, in a single session and in a longitudinal study.

Sub Aim 2.1: Investigate the degree of upper extremity AROM associated with the use of an admittance control motorized arm support compared to that associated with the use of a passive arm support by individuals with DMD. The objective of this sub-aim is to quantify the upper extremity AROM for a standardized set of movements while the arms are supported by the HapticMASTER admittance control robot compared to while the arms are supported by the Armon Edero commercially available passive arm support. It is hypothesized that the upper extremity AROM of individuals with DMD will be greater when supported by the HapticMASTER robot compared to the Armon Edero.

Sub-Aim 2.2: Investigate the degree of upper extremity AROM associated with the use of an admittance control motorized arm support compared to that associated with the use of a passive arm support by individuals with DMD in a longitudinal study. The objective of this sub-aim is to track the changes in upper extremity AROM when the arms are supported by the HapticMASTER in three sessions over the course of one year and compare that to the upper extremity AROM while supported by the Armon Edero over the same period of time. It is hypothesized that Armon Edero supported AROM will decrease over time at a faster rate than HapticMASTER supported AROM.

1.3.3 Specific Aim 3

Specific Aim 3: Examine the feasibility of using an admittance control motorized arm support to increase independence in activities of daily living for individuals with DMD. The success of an upper extremity assistive device relies heavily on the ability of the

device to meet needs defined by the user. The objective of this aim is to examine the feasibility of using an admittance control motorized arm support to provide an increase in independence in activities of daily living specified by each user based on their individual needs compared to the performance of the same activities while unsupported.

Sub Aim 3.1: Identify the upper extremity priority tasks of individuals with DMD who have limited upper extremity function. The objective of this sub-aim is to identify user-defined upper extremity priority tasks based on tasks that individuals with DMD cannot perform or have difficulty performing independently due to upper extremity functional deficits and would consider most important to be able to perform while using an upper extremity assistive device. It is hypothesized that upper extremity priority tasks of individuals with DMD will include activities of daily living relating to eating, drinking, personal care, and hygiene and hobbies specific to each individual's interests.

Sub Aim 3.2: Evaluate the use of an admittance control motorized arm support to increase independence in the performance of upper extremity priority tasks for individuals with DMD. Users will be asked to perform their priority tasks while their dominant arm is unsupported and again while the dominant arm is supported by the HapticMASTER robot. The objective of this sub-aim is for users to evaluate these experiences in order to determine whether the use of an admittance control motorized arm support will allow for improvements in independence while performing priority tasks. It is hypothesized that the use of an admittance control motorized arm support will allow for an increase in independence of priority tasks compared to when the arms are unsupported.

1.3.4 Specific Aim 4

Specific Aim 4: Design a prototype of an admittance control motorized arm support. The HapticMASTER robot, used to test admittance control in aims 2 and 3, is an expensive, large, non-portable means of providing increased AROM for individuals with DMD, and is limited to only 3 translational DOFs. For these reasons, the HapticMASTER is a research robot that can be used to test the benefits of admittance control in a laboratory setting but would not be practical as an assistive device for activities of daily living in the home and community. The objective of this aim is to build a prototype demonstrating the ability to fabricate an admittance control motorized arm support for the purpose of being used by individuals with DMD in the home and community.

Sub Aim 4.1: Design a fully motorized, multi-DOF proof-of-concept prototype of an admittance motorized arm support. The objective of this sub aim is to fabricate a fully functional, multi-DOF motorized arm support that operates under the admittance control paradigm.

Sub Aim 4.2: Design a modular admittance control arm support. The objective of this sub aim is to fabricate a fully functional arm support that implements admittance control modularly in a single DOF while other DOFs remain passive.

CHAPTER 2

BACKGROUND

2.1 Duchenne Muscular Dystrophy (DMD)

Muscular dystrophy is a group of disorders that greatly limit an individual's ability to use their muscles. Duchenne muscular dystrophy (DMD), the most common type of muscular dystrophy, is an X-linked recessive neuromuscular disorder with an incidence of 1 in 3,500-5,000 male births [1]. It is characterized by near or total lack of the protein dystrophin, which provides structural stability to the dystrophin-associated protein complex in the cell membrane of muscle cells [2, 3]. The absence of dystrophin in the muscle cell membrane results in the five mechanisms of DMD pathophysiology, which are: the mechanical weakening of the sarcolemma (the cell membrane of a muscle cell), inappropriate Ca2+ influx (which is involved in skeletal muscle contraction), aberrant cell signaling, increased oxidative stress, and recurrent muscle ischemia (restricted blood supply) [4]. These mechanisms directly result in the progressive weakening of skeletal, respiratory, and cardiac muscles causing decreased independence and shortened life expectancy [3].

The onset of muscle weakness in children with DMD characteristically occurs before 5 years of age. This is soon followed by gait difficulty and an eventual loss of ambulation occurring most often during the teenage years. At this time, individuals with DMD are fully dependent on a wheelchair. Chronic respiratory failure develops in the advanced stages of the disease and death occurs, on average, at the age of 25 [2, 5]. Figure 2.1 shows the results of an investigation by Kohler et al. demonstrating the change

in physical disability with age in 29 patients with DMD. The results clearly demonstrate that DMD presents progressive limitations in activities of daily living and dependence on personal care and technical aids as a result of progressive muscle loss [5].

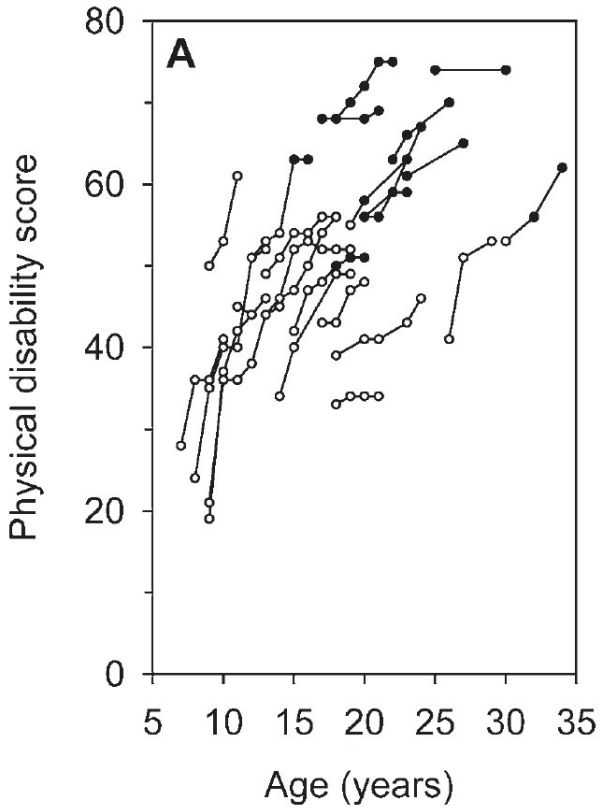

Figure 2.1 Disability scores of 29 individuals with DMD obtained from a longitudinal study demonstrating a progressive decrease in independence. Higher physical disability scores reflect greater dependence on personal and technical aids and limitations in activities of daily living.

Source: [5]

The administration of mechanical ventilation is commonplace when patients begin to exhibit respiratory failure. Its application is responsible for increasing the median survival rate for individuals with DMD beyond 25 years. Even more, noninvasive ventilation and mechanically assisted coughing have been shown to

significantly prolong survival [6]. Other treatments, such as steroids for muscle and cardiac function, slow the progression and increase the life expectancy of individuals with DMD. There are also a number of experimental drug therapies being developed and tested including Eteplirsen, an exon skipping drug that received accelerated approval from the US Food and Drug Administration in September 2016. Eteplirsen also aims to slow the progression of DMD and extend life expectancy [1]. However, despite the advancements in steroid treatments, respiratory aids, and drug therapies, there remains no cure for DMD [2, 3, 7]. These therapies that slow progression and increase life expectancy result in a significant portion of the population of individuals with DMD living with a strong dependency on personal and technical care and support.

2.2 Upper Extremity Functional Loss in DMD

Upper extremity functional assessment studies show progressive upper extremity weakness in individuals with DMD. The onset of upper extremity weakness occurs during ambulation and gradually increases with time in a proximal to distal gradient. A study by Jung et al. aimed to correlate the progressive upper extremity functional loss in individuals with DMD with age. The study involved the evaluation of upper extremity function using the Brooke scale. The Brooke scale consists of ratings between 1 and 6, with 1 reflecting full upper extremity functionality and 6 representing no useful function of the upper extremities. Table 2.1 shows the grading for the Brooke scale. Figure 2.2 shows a plot of the Brooke scale scores from 90 individuals with DMD collected in up to three separate sessions plotted versus age. The results of this study demonstrate a linear decrease in upper extremity function in individuals with DMD with age [2, 7, 8].

Table 2.1 Grading for the Brooke Scale for Upper Extremity Function

Grade	Functional Description
1	Starting with arms at the sides, the patient can abduct the arms in a full circle until they touch the head
2	Can raise arms above head only by flexing the elbow (shortening the circumference of the movement) or using accessory muscles
3	Cannot raise hands above head, but can raise an 8-oz glass of water to the mouth
4	Can raise hands to the mouth, but cannot raise an 8-oz glass of water to the mouth
5	Cannot raise hands to the mouth, but can use hands to hold a pen or pick up pennies from the table
6	Cannot raise hands to the mouth and has no useful function of hands

Source: [2]

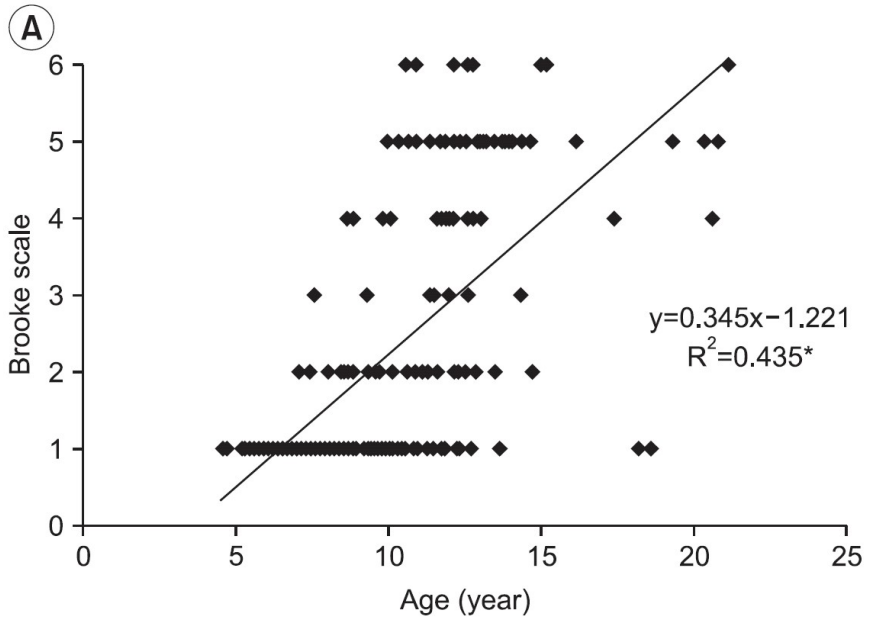

Figure 2.2 The Brooke scale score of individuals with DMD plotted versus age.

Source: [2]

The impact of loss of upper extremity function in individuals with DMD is further emphasized by the decline in reachable surface area as the muscles atrophy over time. Figure 2.3 shows a three dimensional plot of the reachable surface area, a measure of

active range of motion (AROM) using the reachable surface evaluation [9], of a non-ambulatory individual with DMD compared to the reachable surface area of an individual without DMD. The plots demonstrate the upper extremity functional deficit experienced by individuals with DMD [9].

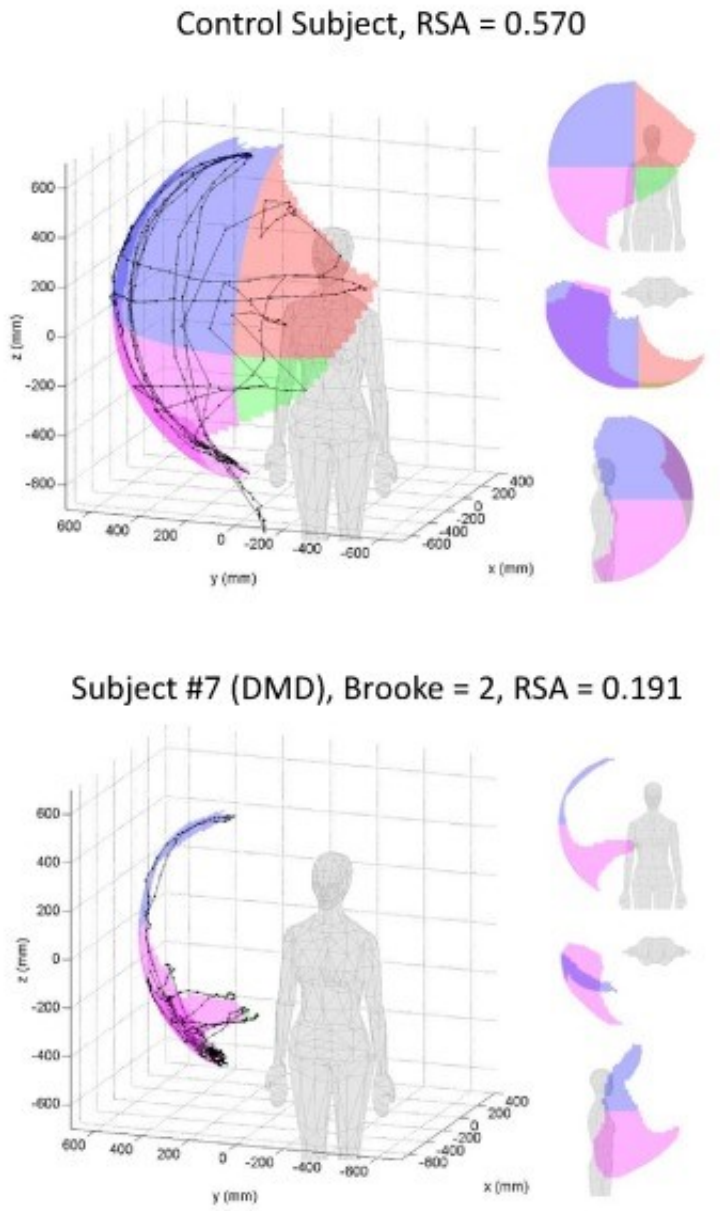

Figure 2.3 Results of the upper extremity reachable workspace evaluation of an individual with DMD (bottom) and control subject (top).

Source: [9]

The loss of upper extremity muscle strength and AROM in individuals with DMD is especially detrimental to self-sufficiency because of the correlation between upper extremity function and independently performing activities of daily living. Furthermore, a number of studies note that upper extremity function deserves more attention in rehabilitation and research because of its association with independence for individuals with DMD [3]. The importance of independence lies not only in providing self-sufficiency and improved quality of life, but also boasts the advantage of significantly decreasing the financial burden associated with personal care required for those with limited independence [10, 11]. These points underscore the need for assistive technology that can lessen the impact of limited and continually decreasing upper extremity function on independence, finances, and quality of life.

Loss of upper extremity function in individuals with DMD is not only due to muscle weakness resulting from the disease itself. Additional contributing factors to the loss of upper extremity function in individuals with DMD are disuse atrophy and the development of contractures. Disuse atrophy is the secondary deterioration of muscle strength that results from a person's actual performance despite a greater potential capacity. Because loss of muscle strength leads to a more sedentary lifestyle, especially for those who are non-ambulatory and cannot lift their arms against gravity, disuse atrophy accelerates functional loss. Even more, decreased activity leads to increased fat mass, making movements more difficult under the added weight, and further exacerbating the problem of progressive loss of strength due to disuse. It is widely accepted among clinicians that the regular use of residual muscle strength through sub-

maximal exercise has the potential to lessen or prevent disuse atrophy in individuals with DMD [12, 13].

An additional secondary complication resulting from the progressive loss of muscle strength and further contributing to loss of function is the development of contractures. Contractures are the loss of joint motion due to tightening of muscle, tendons, and ligaments. The result is a decrease in reachable workspace as the muscle can no longer stretch sufficiently to allow the joint to achieve its maximum angular range. Furthermore, the force generated by a muscle is a factor of the length at which the muscle contracts. Therefore, if a muscle is held in a shortened position, as is the case with contractures, it will be further weakened. Moreover, contractures cause discomfort, so it is typically recommended that preventing them not only allows for increased functionality but also improves postural symmetry and comfort while sitting. The development of contractures is correlated with the onset of wheelchair use and increases with time thereafter. Typical physical therapy interventions administered to individuals with DMD to prevent contractures include active, active-assisted, or passive stretching. However, these physical therapy interventions typically fall short as they require sufficient time and training and regular compliance by the individual [14-6].

In the presence of primary muscle weakness, any further secondary loss of muscle strength should be avoided at all costs [15]. Therefore, disuse atrophy and contractures should be prevented whenever possible. Unfortunately, there are a number of barriers that inhibit compliance with these recommendations including lack of time, feeling overwhelmed by prescribed exercise and stretches, limited access to physical therapy, and the unfamiliarity of some physical therapists with DMD. Consequently, despite these

recommendations, there often remains a lack of implementation of these measures to prevent the secondary deterioration of function [15, 16]. As a result, these secondary contributions accelerate functional loss, further emphasizing the need for assistive technology that can effectively provide increased upper extremity function.

2.3 Upper Extremity Assistive Devices for Individuals with DMD

Currently there exist a number of assistive devices aimed at augmenting upper extremity functional deficit for individuals with DMD. However, few of these devices are widely used by individuals with DMD and all have been largely unsuccessful in delivering the independence they seek to provide [17, 18]. Current state of the art upper extremity assistive devices for individuals with DMD fall into one of three categories: passive orthoses, active orthoses, and robotic manipulators.

2.3.1 Passive Orthoses

The Balanced Forearm Orthosis (BFO), also known as the mobile arm support, is a passive device, meaning that it is powered by the body. Developed in 1965, the BFO allows movement in the horizontal plane for individuals with weak musculature, such as individuals with DMD [19]. Enhanced version of the BFO have since been developed that support the arm against gravity using springs or rubber bands to allow for both horizontal and vertical movements. The Armon Edero by Armon Products and the X-Ar by Talem Technologies, shown in Figure 2.4, are two examples of commercially available passive arm supports. These devices support the arm against gravity by adjusting the length of a spring [20, 21]. Similarly, the Wilmington robotic exoskeleton (WREX) is a commercially available wheelchair mountable, passive arm orthosis that

balances the user's arm against gravity using rubber bands [22]. Gravity compensation allows individuals with DMD, who could not otherwise raise their arm against gravity, attain increased AROM. These non-powered devices are preferred to powered devices in many cases because they utilize the residual strength and natural control that is still present. However, passive arm supports are limited to those in the earlier stages of functional loss because of their imperfect gravity compensation. The springs or rubber bands utilized by passive arm supports provide the user support against gravity lifting the arm to a set-point resulting in a non-constant upward vertical force to counterbalance gravity. Therefore, lowering the arm against the force of the spring or rubber bands or raising the arm against gravity requires a substantial degree of muscle strength. As a result, these devices are limited to individuals with DMD who are in the early stages of functional loss because progressive muscle loss will eventually limit AROM to the horizontal plane. Additionally, passive arm supports reduce friction but still require sufficient strength from the user to overcome the inertia of their arm and the device in order to generate a movement. The friction and inertia opposing the user's movements are constant and cannot be adjusted as the user's muscle strength changes over time. So, the friction and inertia opposing the user's movements will eventually limit the AROM provided by the device as muscle strength decreases over time. These devices also require full functionality and strength of their hands and wrists for the user to be able to interact with their environment. And, if such functionality remains, any interaction the user has with their environment will cause the gravity compensation to become unbalanced, rendering the device useless [19, 23-26]. As a result, the use of passive arm

supports by individuals with DMD is limited due to their inability to significantly restore functionality for a sustained period of time.

Figure 2.4 The X-Ar passive arm support (top) and the Armon Edero passive arm support (bottom).

Source: [20, 21]

There have been devices that aim to overcome the limitation of mobile arm supports in which gravity compensation becomes unbalanced when the user picks up an object. Herder et al. developed a mobile arm support, pictured in Figure 2.5, that allows the user to initiate electronic adjustments to the gravity balancing force whenever they pick up an object [25]. Similarly, Daniel, et al. added an electronic component to the WREX, a passive device not originally designed to accommodate a varying load, that allows for dynamic gravity compensation [22]. These devices have been shown to successfully increase the upper extremity AROM of individuals with DMD, even in the

presence of a varying load. However, they require the user to adjust the gravity balancing force with switches or buttons whenever an object is picked up. This is cumbersome, non-intuitive, and requires the input of additional energy. In addition, these devices retain the limitations of other passive arm supports in that they require the user to have full hand and wrist function and remain limited to individuals in the earlier stages of functional loss [24, 27].

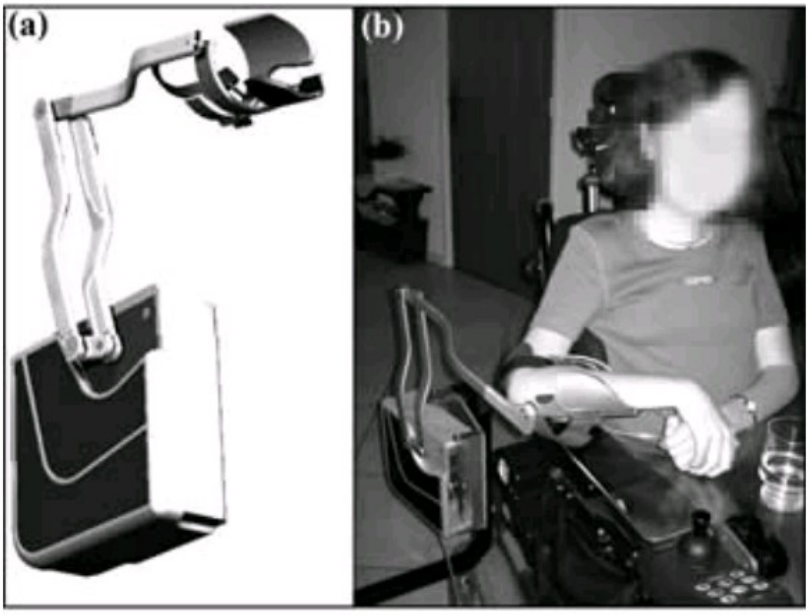

Figure 2.5 Prototype arm support developed by Herder et al. that allows electronic adjustment of the gravity balancing force.

Source: [25]

2.3.2 Active Orthoses

Active orthoses, also known as dynamic arm supports, are exoskeletons that support and direct the arm through the use of control inputs in order to perform activities of daily living. These devices, such as the ARMin pictured in Figure 2.6, a six DOF exoskeleton, have the potential to augment muscle capacity and allow increased joint range of motion

for individuals with DMD [28]. Additionally, if an orthosis is made available in the early stages of the disease, it has been suggested that the user will maintain a larger range of motion over the course of progression because of the prevention of contractures. Unfortunately, as is the case with passive orthoses, these devices require the user to have full use of their hand, wrist, and fingers for the device to allow independent performance of activities of daily living. Further limitations of exoskeletons include their large size, non-portability, substantial weight, power consumption, and the fact that functionality is generally overshadowed by the cumbersome nature of the devices and ultimate burden on the user. The position and orientation of most powered orthoses are controlled by switches or joysticks operated by the user's contralateral hand, head, or tongue. These control schemes are not intuitive because they involve mapping a one or two DOF control to a six DOF robot which will require operating modes and training. This results in significantly increased execution time for simple movements. Additionally, joysticks and switches are not well suited for individuals in the later stages of functional loss because they require the user to grasp the device for long periods of time which can result in fatigue [17, 19, 28-31].

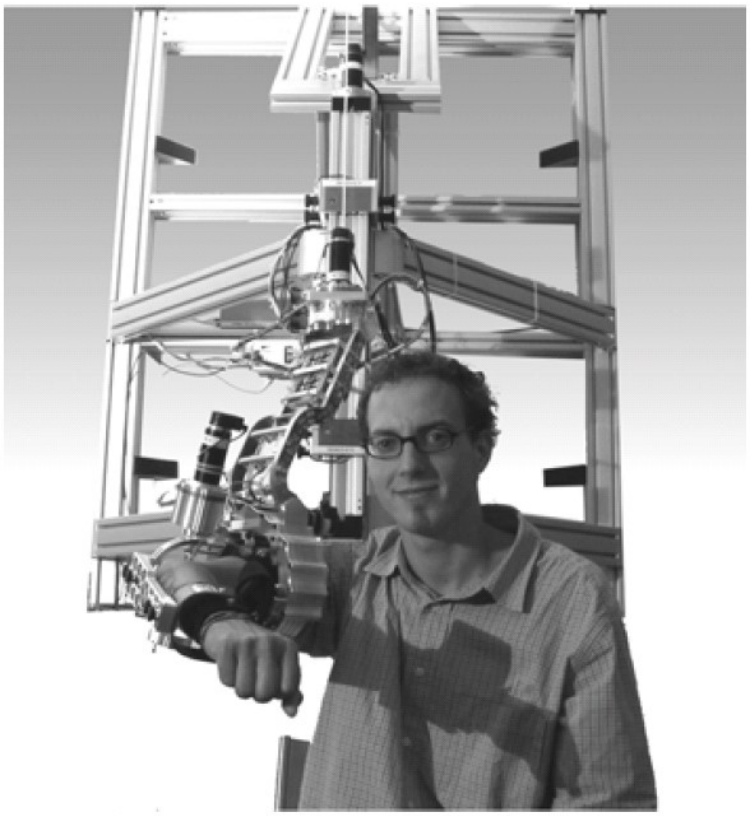

Figure 2.6 The ARMin active orthosis.

Source: [28]

2.3.3 Robotic Manipulators

Robotic manipulators perform tasks that require reaching and grasping to assist individuals with decreased arm strength, such as individuals with DMD, in order to allow independence in activities of daily living in the home, community, and employment settings. The intelligent Assistive Robotic Manipulator (iARM), commercially available from Exact Dyanmics, B.V. of The Netherlands, is a wheelchair mountable, six DOF assistive robot with a gripper that allows individuals with impaired arm function to perform a range of activities such as eating, drinking, brushing teeth, scratching, and even delicate tasks such as handling a DVD or USB stick, painting, and putting in earrings. The iARM, pictured in Figure 2.7, uses interfaces such as a keypad, joystick, or single

switch to allow the user to control its movement [32, 33]. The Teachmover manipulator from Microbot Inc., Mountain View, CA, is a similar wheelchair mountable assistive robot that has been commercially available for over 22 years. Similar to the iARM, it is powered with a 12-V wheelchair battery. The interface to the Teachmover manipulator is a multi-button touchpad. However, the interface can be changed based on the capabilities of the user, as was demonstrated in a study by Shramowiat et al., in which the interface was altered to use two toggle switches [34]. Similar studies performed by Bach et al. integrated both touch sensitive and toggle switch user interfaces for two six DOF robots with grippers: the Cobra RS2 manipulator by Cobra, Darmstadt, West Germany and the Microbot 453-H manipulator by Movemaster, Mountain View, CA [35]. All of these robotic manipulators have resulted in an improved initiative and sense of independence in activities of daily living and decreased dependence on personal care attendants for individuals with DMD. In addition, the cost of a robotic manipulator can be offset by the decrease in personal care costs [34, 35]. Even so, the progressive muscle weakness that is present in individuals with DMD impairs hand and wrist function that are essential for using button, joystick, and switch interfaces [36].

Figure 2.7 The intelligent Assistive Robot Manipulator (iARM).

Source: [33]

Fortunately, the majority of robotic manipulators allow for the integration of user-specific interfaces such as chin or head-position control, sip-and-puff switches, and voice control that eliminate the need for hand and wrist strength to control the device [34]. However, the development of user-specific interfaces to accommodate functional variations requires the time-consuming and costly work of a professional [34]. Furthermore, all of these control schemes are non-intuitive and therefore require operating modes and training [17]. The adequacy of a robotic manipulator is likely to be evaluated based on the time it takes to complete a task using the robot compared to time it takes a personal care attendant to perform the same task. To that point, it has been found that the majority of interfaces currently implemented with robotic manipulators require a significant amount of time to complete a task and frequently overshoot the

target, rendering them insufficient for frequent use for activities of daily living [17, 18, 34, 35].

Despite all of the advancements and variety of approaches to augmenting upper extremity function, there remains no upper extremity assistive device that is widely accepted by individuals with DMD. Current prototypes and commercially available devices are largely unsuccessful in allowing the independence for activities of daily living that they seek to provide.

2.4 Antigravity Assistance to Increase AROM

The progressive loss of upper extremity strength in individuals with DMD eventually limits a person's ability to lift their arms against gravity causing movements to be limited to just the hand and wrist and eventually limited to just the fingers. Once an individual can no longer lift their arms against gravity their ability to independently perform actives of daily living is severely diminished. However, it is of great importance to note that though upper extremity movement is limited at this stage of functional loss, residual muscle strength does exist [4, 7].

The observation of remaining muscle strength following the loss of antigravity muscle strength is demonstrated in aquatic therapy for individuals with DMD. As the human body is immersed in water, water is displaced which results in the force of buoyancy. This force of buoyancy is opposite the force of gravity and therefore decreases joint loading forces on the joints that are immersed. It is a widely accepted qualitative assessment that individuals with DMD have an increased degree of freedom of movement when they are provided with antigravity assistance in the form of buoyancy.

Furthermore, multiple studies have anecdotally reported that the buoyancy of water enables independent initiation of movements for individuals with DMD that are less likely when the person is on land [37-40]. These observations have been the basis for assistive technology that can provide similar support against gravity to increase AROM. Passive orthotic devices for individuals with DMD provide assistance against gravity using springs or rubber bands. Despite the fact that these devices restore functionality to only a limited extent, they have been shown to allow those with limited antigravity strength significantly increased AROM [19, 23-26].

Once antigravity strength is lost, use of the arms for activities of daily living is hindered. Disuse of residual strength causes secondary disuse atrophy which hastens the deterioration of the upper extremity muscles. And, because the arms are no longer being utilized, the joints are no longer being moved regularly through their full range of motion which will ultimately lead to the development of contractures. As was previously mentioned, both disuse atrophy and contracture development will accelerate functional loss of the upper extremities. For this reason, when the arms can no longer be lifted against gravity, secondary disuse atrophy and contracture development become quintessential contributors to upper extremity functional loss [12-16]. Though exercise and active stretching are the best methods for preventing disuse atrophy and contractures, once an individual with DMD cannot lift their arms against gravity both exercise and active stretching are not possible [13, 19, 24-26].

A well designed assistive device will employ antigravity support as it provides a potential means for individuals with DMD to utilize their residual strength for increase independence in activities of daily living. Furthermore, a device that promotes the use of

residual muscle strength has the potential to reduce disuse atrophy and the development of contractures, introducing the potential of delaying functional loss to some degree with regular use of the device.

2.5 Admittance Control

Admittance control, though not routinely used in conventional robots, is a robotic control paradigm that maps the user's applied force to the motion of a robot using Equation 2.1. The acceleration of the robot (x''(t)) is determined by the rate at which a small, frictionless, virtual point mass (m) would accelerate under the user's applied force (F(x)) and specified damping (b) [41]. As a result, friction and inertia are minimized. The inertia of the small virtual point mass, which can be specified based on the capabilities of the user and adjusted as those capabilities change over time, and the specified damping are the only things opposing the user's movements. Therefore, the overall force required by the user to generate a movement is decreased compared to passive arm supports, as these devices only decrease friction and not inertia. Admittance control allows for proportional, compliant control because it mimics passivity which makes it inherently safe and intuitive. Additionally, it provides a means to introduce motorized antigravity assistance in order to increase the AROM of the user. Antigravity assistance is incorporated by including a vertical force equal and opposite to the force of gravity acting on the user's arm in the admittance control equation. This antigravity assistance is more precise than that provided by passive arm supports that use springs or rubber bands to support the arm as it is a constant upward force calibrated to the force of gravity acting on the user's arm [41, 42]. Because of the advantages of admittance control, it is well

suited for use by individuals with limited muscle strength as it allows for the use of residual muscle strength to intuitively control the motion of a powerful robot without the requirement of strength sufficient to overcome gravity and the friction and inertia of the robot. Also, any force encountered by an admittance control robot will not oppose the user's movements. Because an admittance control robot promotes the use of residual muscle strength and active stretching of the joints and muscles it may have the potential to reduce disuse atrophy and the development of contractures that further contribute to upper extremity functional loss.

$$x''(t) = \frac{F(x)}{m} - \frac{b * x'(t)}{m} \tag{2.1}$$

The HapticMASTER (Moog FCS Control Systems, The Netherlands) is a high-performance admittance control robot used in research studies to assess the effectiveness of admittance control and gravity compensation in rehabilitation. The HapticMASTER is a commercially available 3 DOF robot with low level inertial properties, allowing use by individuals with various levels of impairment [42, 43]. A study by Sukal et al. investigated upper extremity discoordination following hemiparetic stroke using the HapticMASTER as a tool to support the arms against gravity. The support provided against gravity and the minimization of inertia and friction allowed for use in rehabilitation with individuals post stroke as these individuals exhibit weakness and discoordination. The results from this study demonstrated a greater reachable workspace when the arm is fully supported against gravity using the HapticMASTER robot compared to unsupported or partially supported movements [43]. A similar study by Bastiaens et al. evaluated the AROM of individuals with multiple sclerosis with severe

arm dysfunction while supported by the HapticMASTER robot against gravity. Similarly, the results of this study demonstrated greater reachable workspace while supported by the HapticMASTER robot [44]. These studies demonstrate the usefulness of admittance control as a tool to allow individuals with limited upper extremity function increased AROM.

Lobo-Prat, et al. from the Flextension Foundation of the Netherlands Organization for Scientific Research has explored the use of admittance control for individuals with DMD. Feasibility studies have shown that an admittance control device allowed individuals with DMD to perform voluntary movements that they otherwise could not perform when unsupported [45]. However, the proposed device requires alignment between the motor axis and the elbow joint, a design in which misalignment can cause discomfort. Even more, the design requires increased complexity in the control system given the need to distinguish between the user's voluntary movements and gravity which is pose dependent. As a result, the authors state that a multi-DOF version of the device may be too cumbersome and not allow for gravity compensation. The authors also propose a combination system that involves force-based control and EMG for individuals with DMD [45].

CHAPTER 3

AIM 1: RESIDUAL UPPER EXTREMITY STRENGTH

3.1 Sub Aim 1.1 Methods

The objective of this sub aim was to quantify the degree of change in upper extremity AROM of an individual with DMD when the arms are supported against gravity compared to unsupported movements. The degree of voluntary movement was determined for shoulder and elbow movements while the arms were unsupported and while the arms were supported against gravity in water.

The subject for this sub aim was recruited though the Muscular Dystrophy Association. The subject was included in the study based on the following inclusion criteria: DMD diagnosis, cannot raise hands to mouth unassisted but has some residual hand function (Brooke Scale score of 5), regular participation in aquatic therapy (to ensure safety and comfort in the pool), and no presence of comorbidities affecting the upper extremities. The subject was instructed to perform five movements to the best of his ability: horizontal shoulder abduction and adduction while upright, shoulder abduction while supine, and elbow flexion and extension. Shoulder adduction while supine was not collected because the subject could not achieve the supine position for this movement while out of the water due to equipment restrictions preventing the movement from being conducted in the gravity-eliminated position. Each movement was performed with the left and right arms in two conditions: (1) outside a pool where the arms are unsupported and (2) in a pool while the arms are supported by the water. The AROM of each movement was recorded using a plastic universal goniometer with the AROM angle

measured in degrees from the start position to the end of voluntary movement. The AROM difference scores were calculated by subtracting the unsupported AROM angles from the water-supported AROM angles for each movement. The primary outcome measure for this study is the AROM angle of each of the five movements in the water and out of the water. The subject's body, with the exception of the arms, was supported as needed by an aquatic therapist while in the water. The portion of the study conducted in the water took place in an accessible, warm-water therapy pool. Figure 3.1 shows an example of the protocol with the subject.

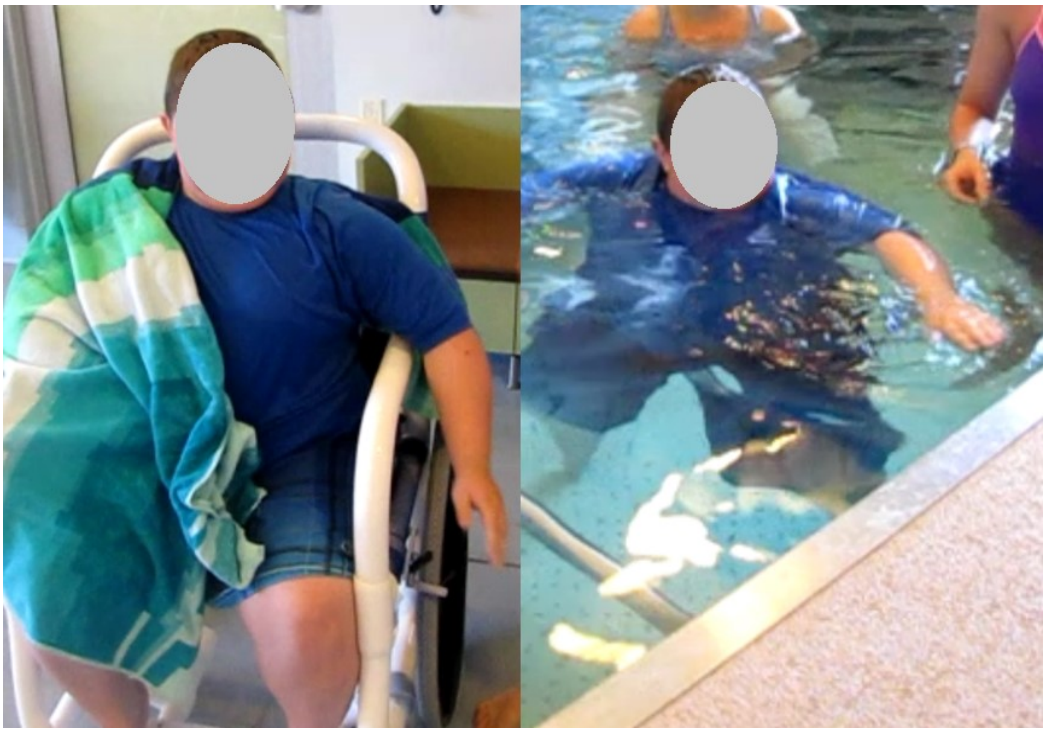

Figure 3.1 A subject with DMD performing the upright horizontal adduction movement with the left arm out of the water (left) and in the water (right).

3.2 Sub Aim 1.1 Expected Results

Due to the progressive nature of DMD and the requirement of sufficient muscle strength to lift the arm against gravity, it is expected that all AROM angles will be larger for the movements executed while the arms are supported against gravity in the water compared to unsupported movements.

3.3 Sub Aim 1.1 Results

Table 3.1 shows the unsupported AROM angles, the AROM angles in the water, and the difference scores for one subject with DMD for the left and right arms. The water-supported AROM was larger for all 5 movements for the left and the right arm compared to unsupported movements. The left arm had a mean increase in AROM of 35 degrees for water-supported movements compared to unsupported movements. The right arm had a mean increase in AROM of 49.7 degrees for water-supported movements compared to unsupported movements. Horizontal elbow flexion and horizontal elbow extension had the smallest increase in AROM for water-supported movements compared to unsupported movements for the left and right arm. Horizontal abduction had the largest increase in AROM for water-supported movements compared to unsupported movements for the left and right arm.

Table 3.1 Unsupported and Water-Supported AROM Results

Movement	AROM Out of Water		AROM In Water		Difference Scores	
	Left	**Right**	**Left**	**Right**	**Left**	**Right**
Horizontal Abduction	36.0°	11.0°	91.0°	98.5°	55.0°	87.5°
Horizontal Adduction	21.5°	36.0°	70.5°	89.0°	49.0°	53.0°
Abduction	35.0°	40.0°	72.5°	96.0°	37.5°	56.0°
Horizontal Elbow Flexion	70.5°	50.0°	89.0°	88.0°	18.5°	38.0°
Horizontal Elbow Extension	86.0°	87.0°	101.0°	101.0°	15.0°	14.0°

3.4 Sub Aim 1.1 Discussion

The results from this case study support the hypothesis that individuals with DMD have increased AROM when the arms are supported against gravity. This indicates that individuals with DMD who have limited or nonexistent upper extremity function while unsupported retain the ability to generate voluntary movement with their upper extremities when supported against gravity because of residual strength that is insufficient to lift the arms against gravity.

The shoulder movements (horizontal abduction, horizontal adduction, and abduction) had larger AROM difference scores compared to elbow movements (horizontal elbow flexion and horizontal elbow extension). This can be explained by the fact that loss of upper extremity function in individuals with DMD typically progresses in a proximal to distal gradient. Therefore, unsupported shoulder AROM is limited more significantly prior to loss of unsupported elbow AROM. It would follow that, given the presence of limited shoulder AROM while unsupported, the elbows will retain a greater

degree of function and therefore have AROM closer in value to the water-supported elbow movements.

This aim was a case study and included only one subject. Because of the small population of individuals with DMD and the limited number of these individuals who currently participate in aquatic therapy or are willing to participate in a single aquatic session, the availability of subjects for such a large scale study of this nature is limited. If a future study were conducted with additional subjects, the researchers could also measure passive range of motion (PROM) to be used as a measure of "maximum attainable range". Doing so could allow researchers to normalize the AROM measures to the PROM of each subject, allowing for a primary outcome measure of percentage of maximum AROM instead of measurements in degrees that can be used to more easily compare between subjects without the consideration of differences in contractures.

3.5 Sub Aim 1.2 Methods

The objective of this sub aim was to quantify the degree of change in upper extremity AROM of an individual with DMD when the arms are supported against gravity compared to unsupported movements in a longitudinal study. The degree of voluntary movement was determined for shoulder and elbow movements while the arms were unsupported and while the arms were supported against gravity in water in four sessions over the course of 19 months.

The subject for this sub aim was recruited though the Cerebral Palsy of North Jersey (CPNJ) Horizon School. The subject was included in the study based on the following inclusion criteria: DMD diagnosis, late ambulatory stage at study enrollment

(ability to walk, difficulty climbing stairs and getting up from the floor), regular participation in aquatic therapy (to ensure safety and comfort in the pool), and no presence of comorbidities affecting the upper extremities. The subjects was instructed to perform six movements to the best of his ability: horizontal shoulder abduction and adduction while upright, shoulder abduction and adduction while supine, and elbow flexion and extension. Each movement was performed in two conditions: (1) outside a pool where the arms are unsupported and (2) in a pool where the left and right arms are supported by the water. The AROM of each movement was recorded using a plastic universal goniometer with the AROM angle measured in degrees from the start position to the end of voluntary movement. The AROM difference scores were calculated by subtracting the unsupported AROM angles from the water-supported AROM angles for each movement. The primary outcome measure for this study is the AROM angle of each of the six movements in the water and out of the water. The data collection procedure was repeated at four sessions over the course of 19 months: 0 months, 5 months, 11 months, and 19 months. The subject's body, with the exception of the arms, was supported as needed during the later sessions by an aquatic therapist while in the water. The portion of the study conducted in the water took place in an accessible, warm-water therapy pool. Figure 3.2 shows an example of the protocol with the subject performing the supine shoulder abduction movements in and out of the water.

AROM difference scores were computed for each session by subtracting the out of water AROM angle from the in water AROM angle for each movement.

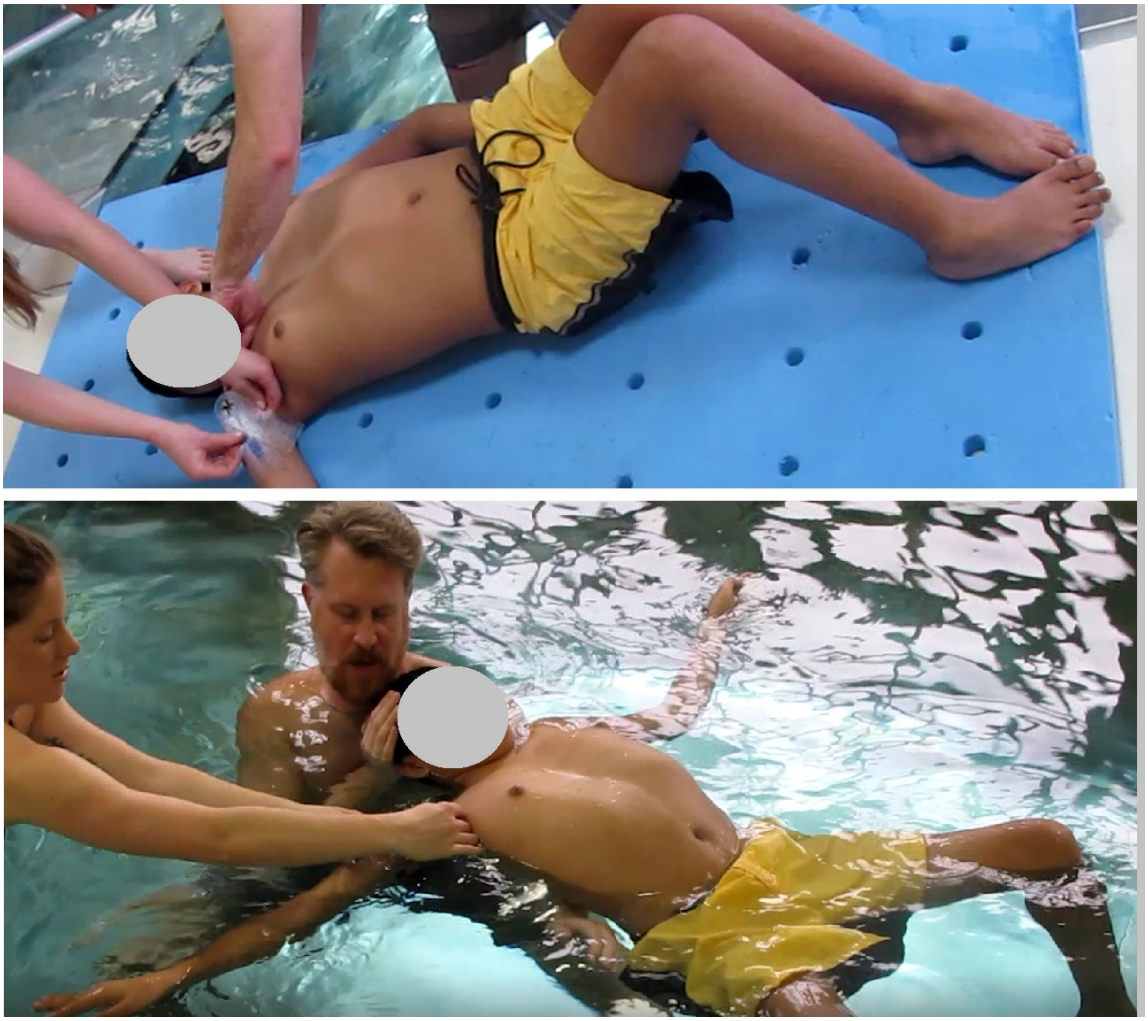

Figure 3.2 A subject with DMD performing the supine shoulder abduction movement with the right arm out of the water (top) and in the water (bottom).

3.6 Sub Aim 1.2 Expected Results

Due to the progressive nature of DMD and the progressive loss of upper extremity function that continues after ambulation is lost, it is expected that AROM angles will be similar in the first session, with unsupported AROM movements decreasing at a faster rate in subsequent sessions compared to water-supported AROM. Accordingly, AROM difference scores are expected to increase with time for each movement.

3.7 Sub Aim 1.2 Results

Figure 3.3 shows the unsupported and water-supported AROM angles for the right arm at 0 months, 5 months, 11 months, and 19 months for one subject with DMD compared to average joint ranges of motion for individuals with no disability according to [46]. Figure 3.4 shows the same results for the left arm for the same subject. The subject was late ambulatory at the first and the second session (0 months and 5 months), and nonambulatory at the final two sessions (11 and 19 months).

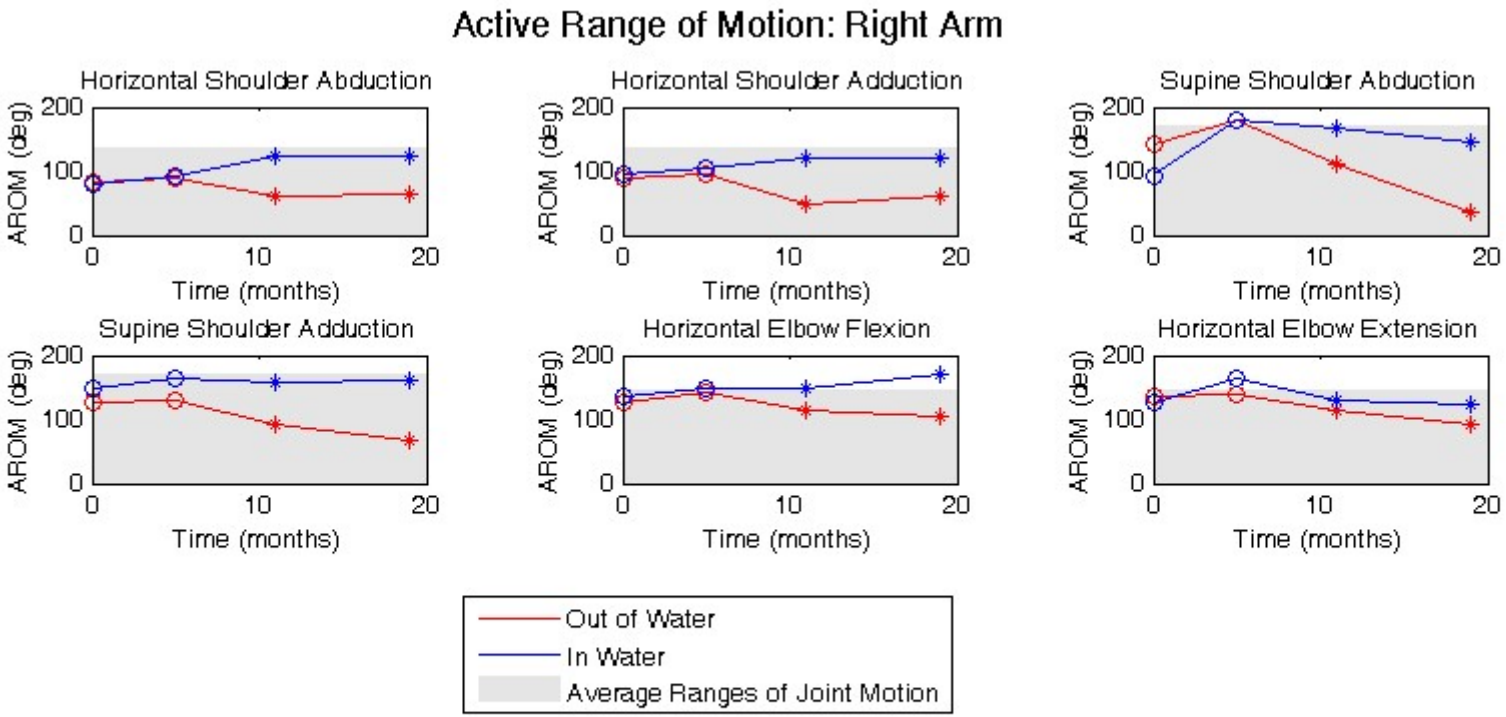

Figure 3.3 AROM results for the right arm from one subject with DMD while out of the water (red) and in the water (blue) over the course of 19 months (4 sessions) compared to average ranges of joint motion (gray). Circles denote data collection sessions that occurred while the subject was late ambulatory and asterisks denote data collection sessions that occurred while the subject was nonambulatory.

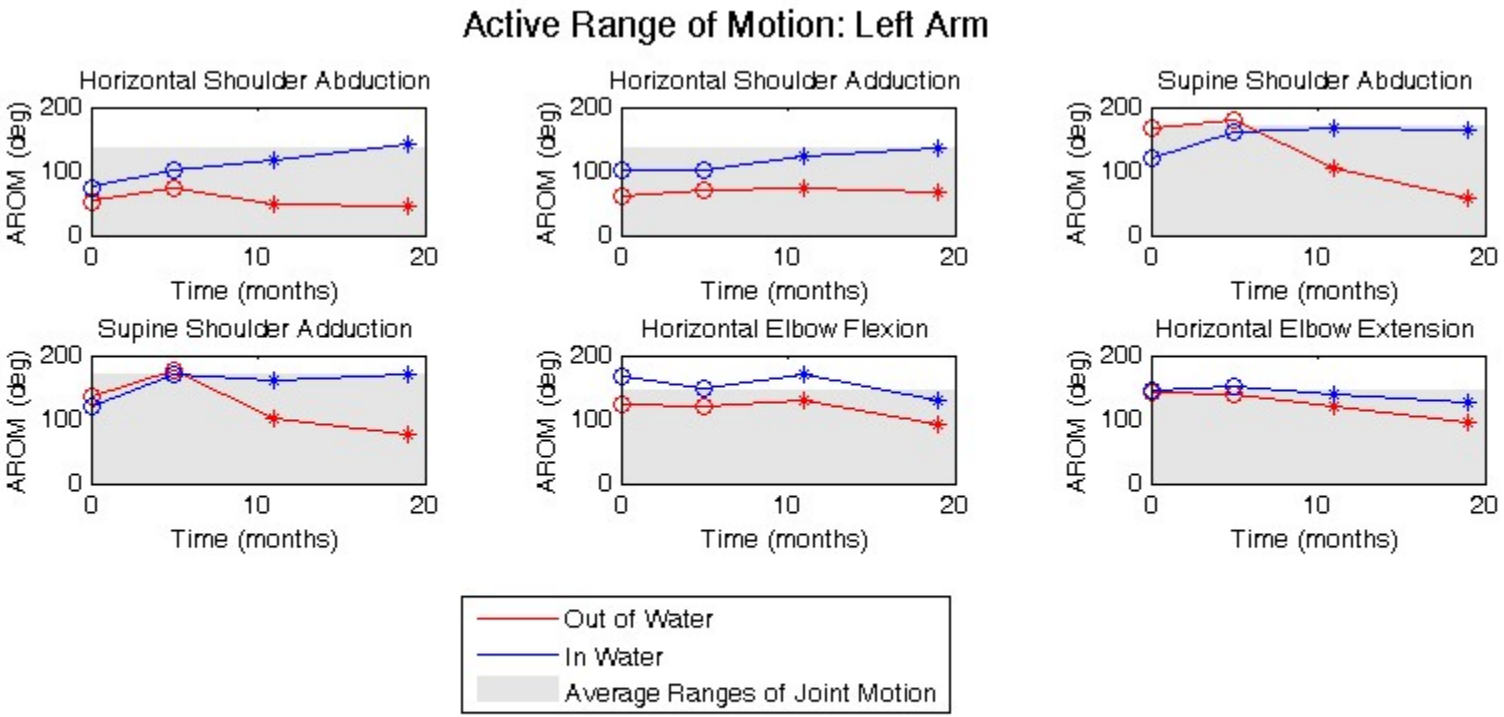

Figure 3.4 AROM results for the left arm from one subject with DMD while out of the water (red) and in the water (blue) over the course of 19 months (4 sessions) compared to average ranges of joint motion (gray). Circles denote data collection sessions that occurred while the subject was late ambulatory and asterisks denote data collection sessions that occurred while the subject was nonambulatory.

Figure 3.5 shows the AROM difference scores for the right arm for each of the 6 movements at 0 months, 5 months, 11 months, and 19 months for one subject with DMD. Figure 3.6 shows the same result for the left arm for the same subject.

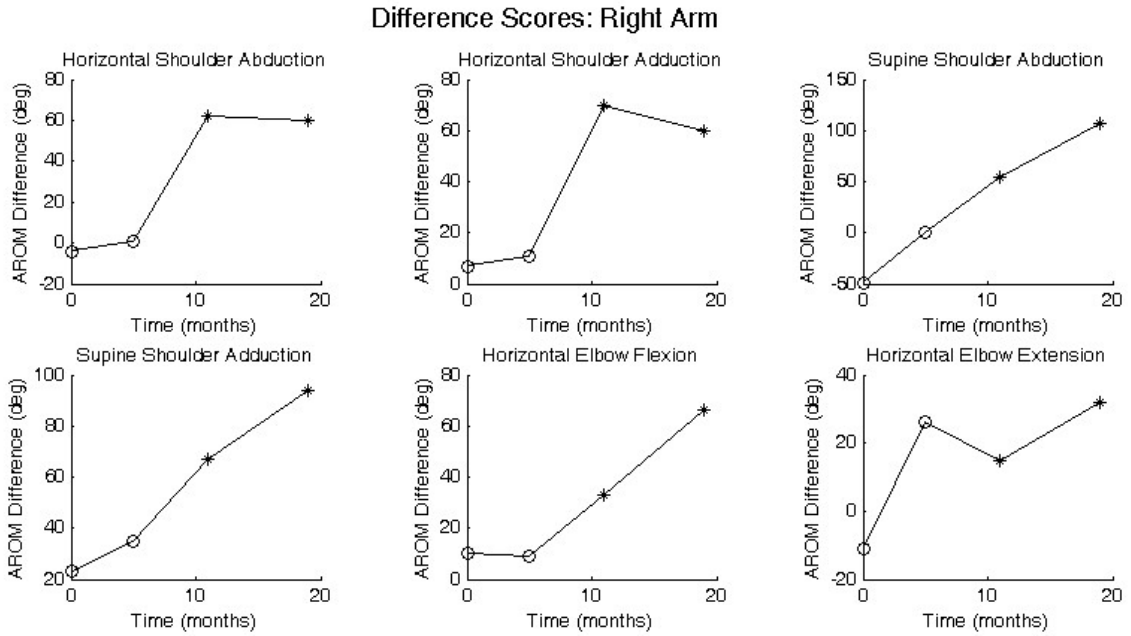

Figure 3.5 AROM difference scores (in water AROM minus out of water AROM) for the right arm from one subject with DMD over the course of 19 months (4 sessions). Circles denote data collection sessions that occurred while the subject was late ambulatory and asterisks denote data collection sessions that occurred while the subject was nonambulatory.

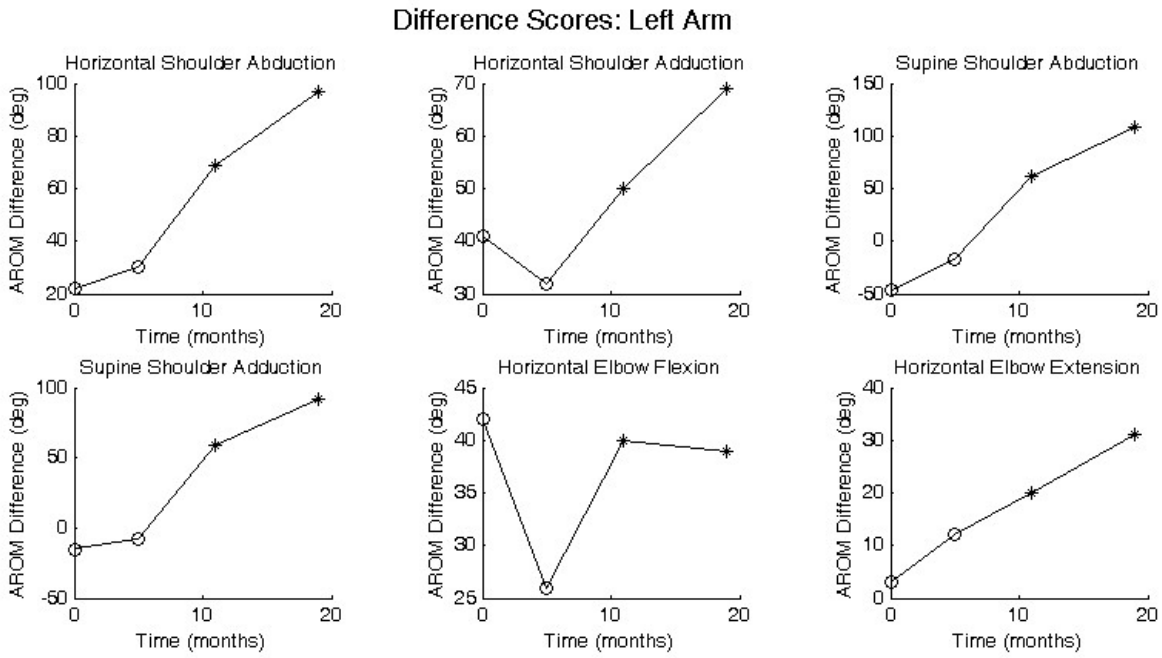

Figure 3.6 AROM difference scores (in water AROM minus out of water AROM) for the left arm from one subject with DMD over the course of 19 months (4 sessions). Circles denote data collection sessions that occurred while the subject was late ambulatory and asterisks denote data collection sessions that occurred while the subject was nonambulatory.

3.8 Sub Aim 1.2 Discussion

The results of this longitudinal case study support the hypothesis that individuals with DMD have increased AROM when the arms are supported against gravity, a pattern that is maintained over time in the presence of progressive muscle loss. This indicates that individuals with DMD who lose the ability to generate unsupported voluntary movements over time retain enough residual muscle strength to allow for voluntary movements when supported against gravity.

Overall, AROM difference scores (water-supported AROM minus unsupported AROM) followed a trend of increasing over time. Furthermore, the AROM difference scores for shoulder movements (horizontal shoulder abduction, horizontal shoulder

adduction, supine shoulder abduction, and supine shoulder adduction) were larger when the subject was nonambulatory compared to when the subject was ambulatory. In other words, the water-supported AROM values for shoulder movements were larger than unsupported movements when the subject was nonambulatory. However, when the subject was still ambulatory, the water-supported AROM values were larger than unsupported movements for some cases (right arm supine shoulder adduction and left arm horizontal shoulder abduction and adduction); smaller than unsupported movements in some cases (right arm supine shoulder abduction and left arm supine shoulder abduction); and close to the same as unsupported movements for the remaining cases (right arm horizontal shoulder abduction and adduction, and left arm supine shoulder adduction). In other words, the water-supported AROM values for shoulder movements did not follow a trend, but were roughly the same for a number of shoulder movements compared to unsupported movements when the subject was still ambulatory. As expected, these results indicate loss of upper extremity strength over time. Even more, these results indicate that loss of upper extremity strength that allows an individual with DMD to generate movements against gravity decreases with time more notably after ambulation is lost. It follows that support against gravity to augment upper extremity AROM could be a valuable intervention to allow for increased independence after ambulation is lost and could become increasingly important as upper extremity strength continues to decrease over time.

The AROM difference scores for horizontal elbow extension for the left arm and horizontal elbow flexion for the right arm follow similar patterns to upper extremity AROM differences scores for shoulder movements. However, the difference scores for

horizontal elbow flexion for the left arm and horizontal elbow extension for the right arm do not have a clear trend. This can be explained by the loss of upper extremity strength in individuals with DMD occurring in a proximal to distal gradient. Individuals with DMD typically retain distal AROM longer than proximal AROM. Therefore, support against gravity for the elbows will not provide an increase in AROM that is comparable in magnitude to that of the shoulders because residual strength remains sufficient to generate unsupported voluntary elbow movement in the presence of gravity. This longitudinal study examined the unsupported and water-supported AROM of a subject with DMD for less than a year after ambulation was lost. It is expected that following the same subject for a longer period of time will show trends in AROM difference scores for the elbow that is similar to that seen for the shoulder in this study as strength is lost over a longer period of time.

For all data collection sessions (including those when the subject was ambulatory) the subject exhibited greater ease of movement, smoother movements, and the ability to generate faster movements in water compared to out of the water. This was not necessarily reflected in AROM difference values as, prior to loss of ambulation, the subject did not have consistently larger in-water AROM compared to unsupported AROM. This indicates that when in-water and unsupported AROM values were similar, the movement may still require increased effort from the subject when unsupported compared to when supported against gravity. Future studies could aim to quantify the ability of individuals with DMD to generate sustained voluntary movements in and out of the water and assess fatigue and movement smoothness to further substantiate the potential benefits of support against gravity for these individuals.

Similar to sub-aim 1.1, this longitudinal case study included only one subject. Future studies could also include additional subjects to further substantiate the results and statistically quantify trends in loss of upper extremity strength over time and the degree of residual function. However, the small population of individuals with DMD and the limited number of these individuals willing to participate in a study requiring them to go into a pool provides a barrier to large-scale studies of this nature.

CHAPTER 4

AIM 2: ADMITTANCE CONTROL TO INCREASE UPPER EXTREMITY AROM

4.1 Sub Aim 2.1 Methods

The objective of this sub-aim was to quantify the upper extremity AROM provided by the HapticMASTER admittance control robot and compare that to the upper extremity AROM provided by the Armon Edero, a commercially available passive arm support. The degree of voluntary movement will be determined while the subject's arms are supported by the Armon Edero and again while the subject's arms are supported by the HapticMASTER robot.

Subjects were recruited for this study though the Parent Project Muscular Dystrophy DuchenneConnect registry and the Muscular Dystrophy Association. Subjects were included in the study based on the following criteria: DMD diagnosis, inability to raise their hands to their mouth or difficulty doing so while holding a weighted object but some residual hand function (Brooke scale score of 4 or 5), and no presence of comorbidities affecting the upper extremities. Upper extremity functional status while using each of the arm supports was quantified with the upper extremity reachable workspace evaluation developed and validated by Kurillo et al. and Han et al. [9, 47]. The upper extremity reachable workspace evaluation provides a metric for AROM based on the ability of the subject to perform standardized upper extremity movements. It is closely associated with upper extremity function and the ability to perform activities of daily living and has been shown to be sensitive to clinically meaningful changes in upper extremity function. This method has been shown to be valid, reliable, and sensitive

enough to detect small changes in upper extremity AROM of individuals with neuromuscular disorders including DMD [9, 47]. The reachable workspace evaluation software provides a global metric for upper extremity function, the reachable surface area score. Spherical surface data are fit to the hand trajectory data and the envelope is quantified as a surface area score which is normalized to arm length to allow comparison of results between subjects [9, 47]. The graphical output and reachable surface area score from the reachable workspace evaluation software is shown in Figure 4.1 for a subject with no disability.

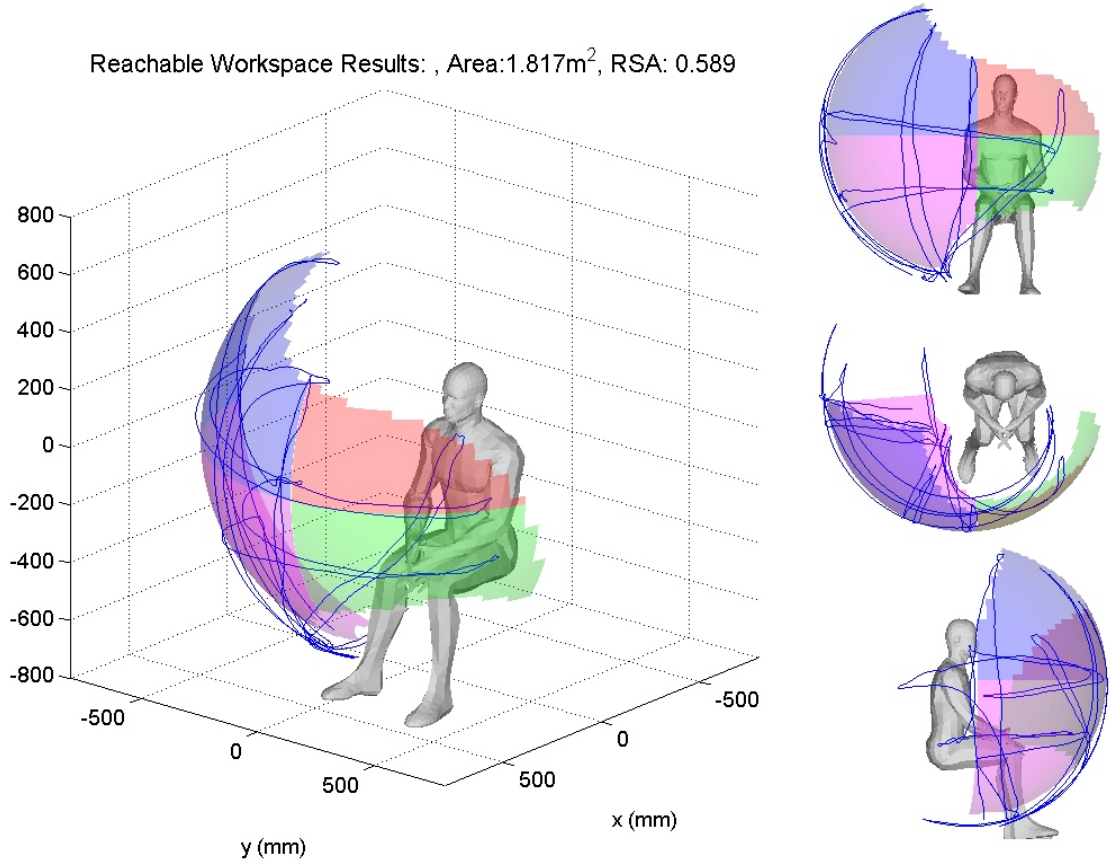

Figure 4.1 The reachable workspace evaluation results of one subject with no disability.

The standardized procedure for the reachable workspace evaluation involves a subject lifting their arm from a resting position to above the head keeping the elbow extended. They then repeated the same movement in vertical planes at 0, 45, 90, and 135 degrees followed by horizontal sweeps at the level of the umbilicus and again at the shoulder. For this aim, all movements were demonstrated to the subject prior to and during the data collection to ensure uniform speed and execution of the movements. Subjects were instructed to use only their arms to generate the movement and to not utilize any compensatory movements. For the purposes of this study, the TrakSTAR motion capture system was used to track the position of the subject's left and right shoulder and the elbow and wrist of the arm being tested, which will be used by the reachable workspace evaluation software to compute the reachable surface area score.

The reachable workspace evaluation was conducted for the subject's right and left arm while unsupported to determine the baseline upper extremity functional status. The reachable workspace evaluation was also conducted passively, with the researcher moving the subject's right and left arms through the reachable workspace evaluation movements to but not exceeding the joint limits in order to determine the maximum passive reachable surface area. Additionally, PROM was collected for each subject. Passive elbow flexion, shoulder forward flexion, shoulder abduction, and shoulder horizontal flexion were measured from the neutral position with a goniometer according to the standardized procedures for PROM set forth by the American Academy of Orthopedic Surgeons [46]. The passive movements measured for this aim were chosen based on movements that influence reachable workspace in the front of the body. The passive reachable workspace and PROM measurements were collected in order to

determine the extent of upper extremity contractures for each subject that may influence upper extremity function.

Three trials of the reachable workspace evaluation were conducted for the right and left arms while supported by the Armon Edero passive arm support, as pictured in Figure 4.2. The support against gravity was adjusted by changing the length of the spring in order to properly balance the subject's arm. Three trials of the reachable workspace evaluation were also conducted for the subject's right and left arm while supported by the HapticMASTER robot, also pictured in Figure 4.2. For each arm, the support against gravity was adjusted by changing the magnitude of an upward constant force in order to properly balance the subject's arm.

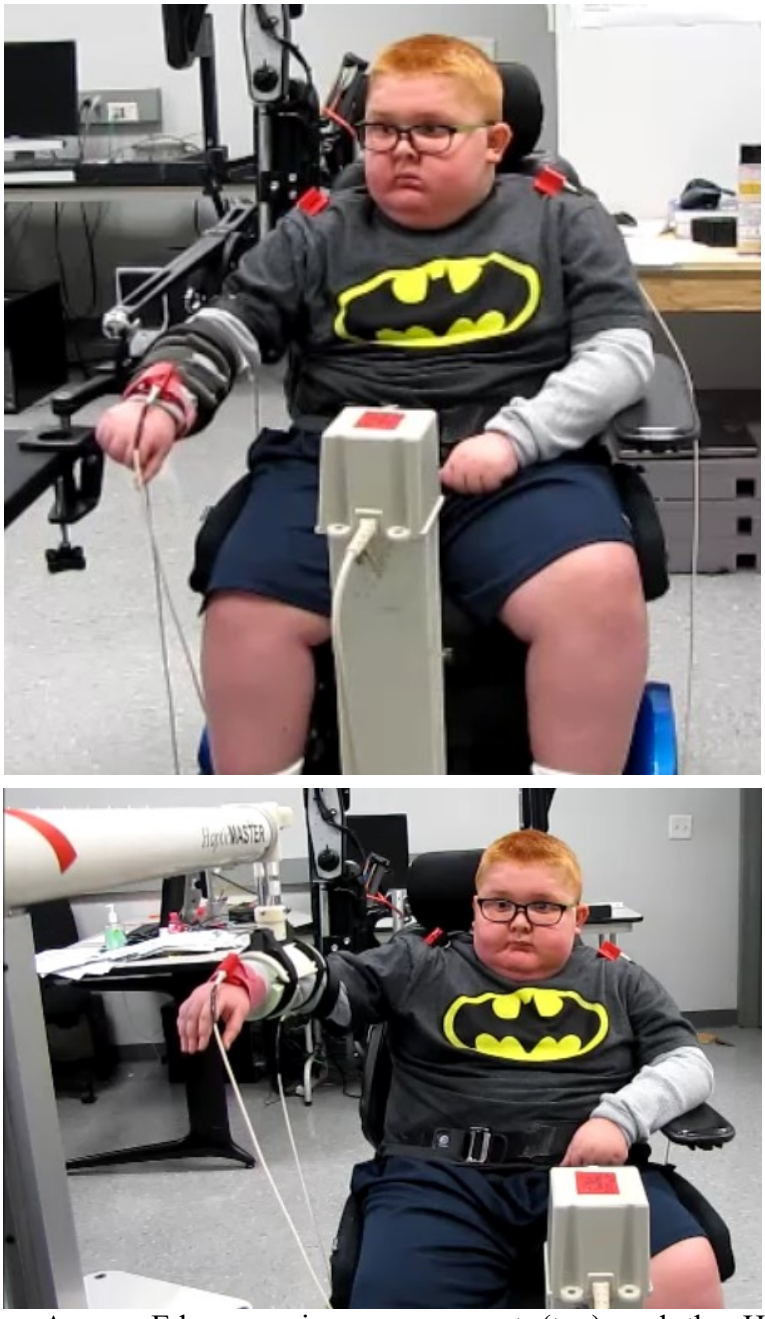

Figure 4.2 The Armon Edero passive arm support (top) and the HapticMASTER admittance control robot (bottom).

Prior to data collection, the workspace of each arm support was aligned to provide a common frame of reference in order to prevent each subject's motion from being restrained by the mechanical limits of either arm support. For both the Armon Edero and the HapticMASTER, the subjects were given control over the amount of support against

gravity provided to their arm by instructing the researcher to increase or decrease support until their arm was “comfortably floating”, felt “weightless”, and provided the greatest ease of movement. The order in which the subject used the arm supports was randomized to avoid order effects including fatigue.

At the end of the data collection session, each subject was given a self-assessment survey (seen in Appendix A) to determine the user’s preferences between the two arm supports and compare user acceptance of the two technologies. The self-assessment survey included five questions comparing the Armon Edero and the HapticMASTER. These questions required subjects to mark their responses on a visual analog scale (VAS), allowing for statistical comparison of answers [48]. The first two questions asked the subject to rate the exertion level required to complete the reachable workspace evaluation movements while supported by the Armon Edero (question 1) and by the HapticMASTER (question 2). For these questions, the subjects were asked to place a mark on a 100mm horizontally positioned VAS with the extremities labeled “least amount of effort” and “most amount of effort”. The VAS was scored by measuring the distance, in millimeters, from the “least amount of effort” end of the line, with a larger score representing greater effort required and a lower score representing less effort required. The next three questions asked the subject to compare the Armon Edero and HapticMASTER supported movements in the horizontal (question 3) and vertical (question 4) directions and for overall movements (question 5). For these questions, the subjects were asked to place a mark on a 100mm horizontally positioned VAS with the extremities labeled “Armon Edero” and “HapticMASTER”. The VAS was scored by measuring the distance, in millimeters, from the “Armon Edero” end of the line, with a

score less than 50 representing easier movement provided by the Armon Edero, a score larger than 50 representing easier movement provided by the HapticMASTER, and a score of 50 representing no difference between the two arm supports.

The position data from the reachable workspace evaluation was filtered with a second order zero-lag, low-pass Butterworth filter with a 6 Hz cutoff frequency. Filtering was performed in MATLAB. The reachable workspace evaluation software was used to compute the reachable surface area scores for each trial. The subject's vertical range of motion was calculated by subtracting the minimum vertical wrist position from the maximum vertical wrist position of each reachable workspace evaluation trial. The mean reachable surface area score and vertical AROM for each subject was determined for Armon Edero supported movements and for HapticMASTER supported movements for the left and right arms by taking the average across three trials.

A Shapiro-Wilk test was used to determine if the population of average reachable surface area difference scores was approximately normal. If the scores were approximately normal, a paired–samples t-test was used to determine whether the HapticMASTER supported movements provide individuals with DMD increased reachable surface area compared to Armon Edero supported movements. If the difference scores violated the assumption of normality, a Wilcoxon signed-ranks test was used. The same statistical tests were used to compare the subject's average vertical AROM for Armon Edero supported movements to HapticMASTER supported movements. The statistical tests were also repeated to compare the reachable surface area scores and the vertical AROM between the dominant and non-dominant arms for Armon Edero and for HapticMASTER supported movements. Similarly, the self-assessment

survey exertion level scores were compared using the same statistical tests. SPSS was used for all statistical analyses.

Preliminary reachable surface area scores collected from 6 subjects suggested an expected effect size of Cohen's d=1.6 for the comparison of reachable surface area scores (large effect size). An a priori power analysis, conducted using G*Power 3.1 software, suggested that a planned sample size of n=6 would be sufficient to obtain a minimum of 80% power (α=0.05, paired-samples t-test) to detect an effect, given this effect size. Accordingly, a total of 10 subjects participated in this sub aim who met the inclusion/exclusion criteria in order to achieve a minimum of 80% power. Additionally, data were collected for one subject with DMD with the ability to fully abduct his arms while unsupported (Brooke scale score of 1). This subject served as a control for this study in order to confirm that neither arm support had a larger workspace than the other, which would bias the data.

Passive reachable surface area, PROM, and unsupported reachable surface area were collected for each subject for the right and left arms to determine baseline upper extremity function. The primary outcome measure of this aim is the reachable surface area scores while supported by the Armon Edero and while supported by the HapticMASTER robot for both arms. The secondary outcome measure is the vertical AROM while supported by the Armon Edero and while supported by the HapticMASTER robot. The outcome measure to evaluate user preferences are the subject-reported survey VAS results.

4.2 Sub Aim 2.1 Expected Results

It is expected that average reachable surface area scores will be greater for HapticMASTER supported movements compared to Armon Edero supported movements. Additionally, the vertical AROM is expected to be larger for HapticMASTER supported movements compared to Armon Edero supported movements. The self-assessment survey exertion level scores are expected to be smaller for HapticMASTER supported movements and all subjects are expected to rate the HapticMASTER as providing greater ease of movement. These results are expected because the HapticMASTER robot operates under admittance control which provides more precise gravity compensation and minimized friction and inertia compared to passive arm supports.

It is expected that the mean reachable surface area scores will be greater for the dominant arm compared to the non-dominant arm for Armon Edero and for HapticMASTER supported movements. Additionally, the vertical AROM is expected to be larger for the dominant arm compared to the non-dominant arm for Armon Edero and for HapticMASTER supported movements. These results are expected because the dominant arm is used most often while performing activities of daily living and, unlike the non-dominant arm, has the potential to be less susceptible to disuse atrophy.

4.3 Sub Aim 2.1 Results

Ten subjects and one control subject with DMD who met the inclusion and exclusion criteria for this aim were enrolled in the study. Table 4.1 shows the age of each subject, handedness, and baseline scores of passive reachable surface area and unsupported

reachable surface area for the left and right arms. Table 4.2 shows the PROM results for each subject for the left and right arms.

Table 4.1 Subjects Enrolled in Aim 2.1

Subject	Age	Hand Dominance	Passive RSA		Unsupported RSA	
			Right	Left	Right	Left
1a	26	Right	0.713	0.321	0.100	0.032
2a	21	Right	0.403	0.184	0.007	0.000
3a	14	Right	0.488	0.296	0.000	0.000
4a	26	Right	0.524	0.227	0.001	0.000
5a	27	Right	0.435	0.709	0.000	0.000
6a	14	Right	0.707	0.615	0.165	0.020
7a	14	Right	0.696	0.549	0.025	0.011
8a	17	Right	0.622	0.446	0.106	0.037
9a	11	Right	0.628	0.598	0.033	0.013
10a	15	Right	0.46	0.482	0.000	0.000
Control	15	Right	0.437	0.470	0.420	0.275

Table 4.2 Passive Range of Motion (PROM) for Subjects in Aim 2.1

Subject	Elbow Flexion (deg)		Shoulder Forward Flexion (deg)		Shoulder Abduction (deg)		Shoulder Horizontal Flexion (deg)	
	Right	Left	Right	Left	Right	Left	Right	Left
1a	113	106	140	145	107	135	94	115
2a	115	114	122	92	116	114	95	93
3a	89	92	126	99	120	98	96	92
4a	91	92	98	94	105	89	96	90
5a	116	108	105	92	120	110	95	105
6a	94	110	123	130	123	114	120	94
7a	110	100	110	150	95	112	116	137
8a	135	102	120	93	94	85	95	111
9a	128	108	149	138	124	130	118	107
10a	142	151	150	153	110	114	110	113
Control	133	134	144	155	143	140	102	100

Figure 4.3 shows the reachable workspace evaluation software graphical output for a single subject while the dominant arm is moved passively by the researcher, unsupported, supported by the Armon Edero passive arm support, and supported by the HapticMASTER robot. For this subject, the reachable surface area when the arm is supported by the HapticMASTER robot is larger than when the arm is supported by the Armon Edero and when the arm is unsupported. Additionally, the unsupported reachable surface area was larger than Armon Edero supported movements. The HapticMASTER allowed for a larger reachable surface are score compared to the Armon Edero. As seen in the figure, the Armon Edero and the HapticMASTER allowed for bilateral reachable surface area above the lap compared to unsupported reachable surface area limited laterally to the right and mostly below the level of the stomach. The figure also shows increased vertical and horizontal distribution of reachable surface area allowed by the HapticMASTER robot compared to the Armon Edero.

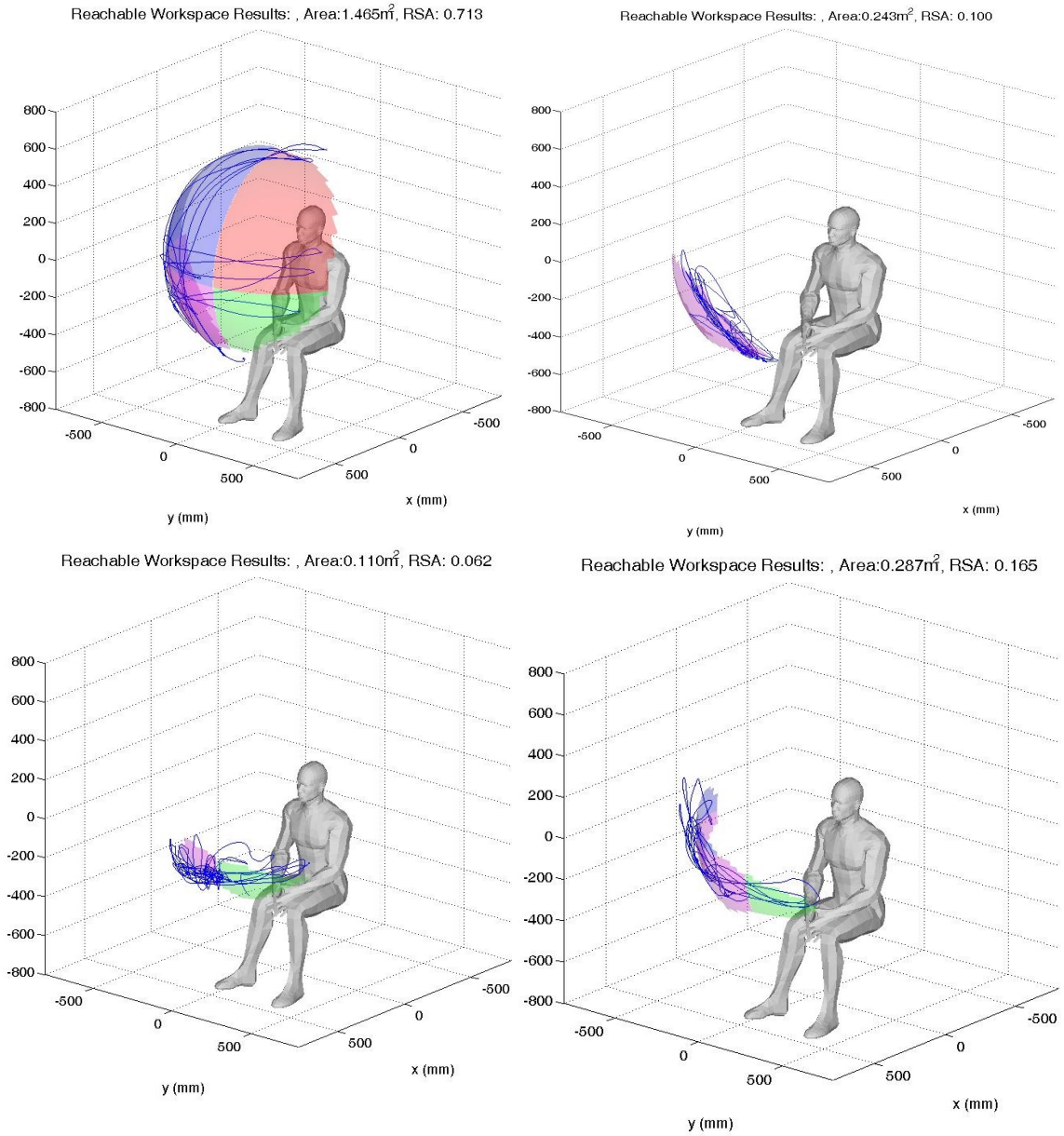

Figure 4.3 The reachable workspace evaluation results from one subject for a single trial while the dominant arm was moved passively by the researcher (top left), unsupported (top right), supported by the Armon Edero passive arm support (bottom left), and supported by the HapticMASTER robot (bottom right).

Figure 4.4 shows the mean reachable surface area scores of Armon Edero and HapticMASTER supported movements for the dominant and non-dominant arms for all 10 subjects. A Shapiro-Wilk test revealed that the reachable surface area difference

scores for the dominant arm have a significant deviation from normality (p=0.004). The HapticMASTER robot significantly increased reachable surface area scores for the dominant arm compared to the Armon Edero passive arm support (Wilcoxon T=5.00, p=0.022, r^2=0.26). An r^2=0.26 denotes a large effect of the HapticMASTER on dominant reachable surface area compared to the Armon Edero. A Shapiro-Wilk test revealed that the reachable surface area difference scores for the non-dominant arm have no significant deviation from normality (p=0.262). The HapticMASTER significantly increase reachable surface area scores for the non-dominant arm compared to the Armon Edero passive arm support (paired-samples t-test, t(9)=4.66, p=0.001, r^2=0.71). An r^2=0.71 denotes a large effect of the HapticMASTER on non-dominant reachable surface area compared to the Armon Edero. A Shapiro-Wilk test revealed that the reachable surface area difference scores for Armon Edero supported movements for the dominant arm compared to the non-dominant arm have a significant deviation from normality (p=0.009). The dominant arm had significantly increased reachable surface area scores compared to the non-dominant arm while supported by the Armon Edero passive arm support (Wilcoxon T=0.00, p=0.005, r^2=0.39). An r^2=0.39 denotes a large effect of hand dominance on reachable surface area for Armon Edero supported movements. A Shapiro-Wilk test revealed that the reachable surface area difference scores for HapticMASTER supported movements for the dominant arm compared to the non-dominant arm have a significant deviation from normality (p=0.002). The dominant arm had significantly increased reachable surface area scores compared to the non-dominant arm for HapticMASTER supported movements (Wilcoxon T=1.00, p=0.002, r^2=0.37). An r^2=0.37 denotes a large effect of hand dominance on reachable surface area for

HapticMASTER supported movements. The control subject had a mean reachable surface area score of 0.232 for Armon Edero supported movements and 0.189 for HapticMASTER supported movements for the dominant arm and 0.167 for Armon Edero supported movements and 0.121 for HapticMASTER supported movements for the non-dominant arm.

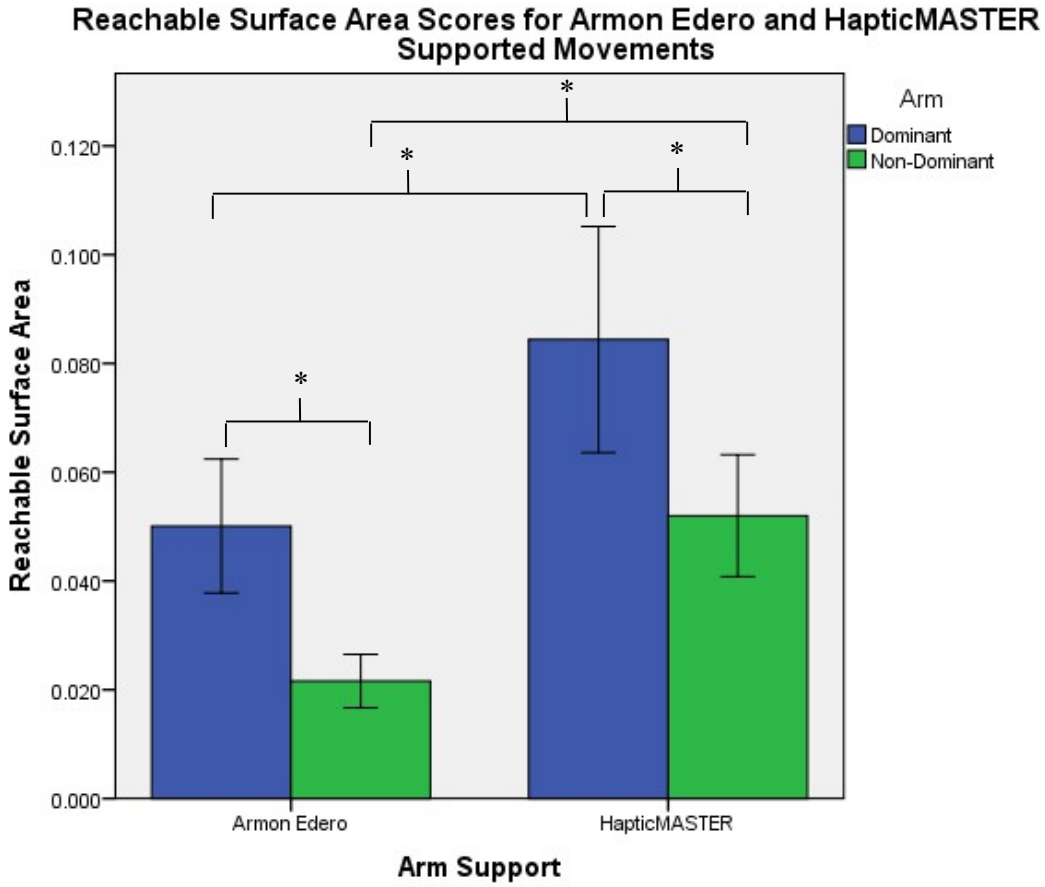

Figure 4.4 Mean reachable surface area scores for Armon Edero and HapticMASTER supported movements for all 10 subjects for the dominant (blue) and non-dominant (green) arms. Error bars show SEM. Asterisks denote statistical significance between groups ($p<0.05$).

Figure 4.5 shows the mean vertical AROM for Armon Edero and HapticMASTER supported movements for the dominant and non-dominant arms for all 10 subjects. A Shapiro-Wilk test revealed that the vertical AROM for the dominant arm

difference scores have no significant deviation from normality (p=0.697). The HapticMASTER significantly increase vertical AROM for the dominant arm compared to the Armon Edero passive arm support (paired-samples t-test, t(9)=2.37, p=0.042, r^2=0.39). An r^2=0.39 denotes a large effect of the HapticMASTER on dominant arm vertical AROM compared to the Armon Edero. A Shapiro-Wilk test revealed that the vertical AROM difference scores for the non-dominant arm have no significant deviation from normality (p=0.887). The HapticMASTER significantly increased vertical AROM for the non-dominant arm compared to the Armon Edero passive arm support (paired-samples t-test, t(9)=8.899, p<0.001, r^2=0.90). An effect size of r^2=0.90 denotes a large effect of the HapticMASTER on non-dominant arm vertical AROM compared to the Armon Edero. A Shapiro-Wilk test revealed that the vertical AROM difference scores for Armon Edero supported movements for the dominant arm compared to the non-dominant arm had no significant deviation from normality (p=0.437). There was no significant change between the dominant arm and the non-dominant arm for Armon Edero supported movements (paired-samples t-test, t(9)=1.50, p=0.169). A Shapiro-Wilk test revealed that the vertical AROM difference scores for HapticMASTER supported movements for the dominant arm compared to the non-dominant arm had a significant deviation from normality (p=0.041). There was no significant difference between the dominant arm and the non-dominant arm for HapticMASTER supported movements (Wilcoxon T=19.00, p=0.386). The control subject also had a vertical AROM of 437mm for Armon Edero supported movements and 423 for HapticMASTER supported movements for the dominant arm and 453mm for Armon Edero supported movements and 381 for HapticMASTER supported movements for the non-dominant arm.

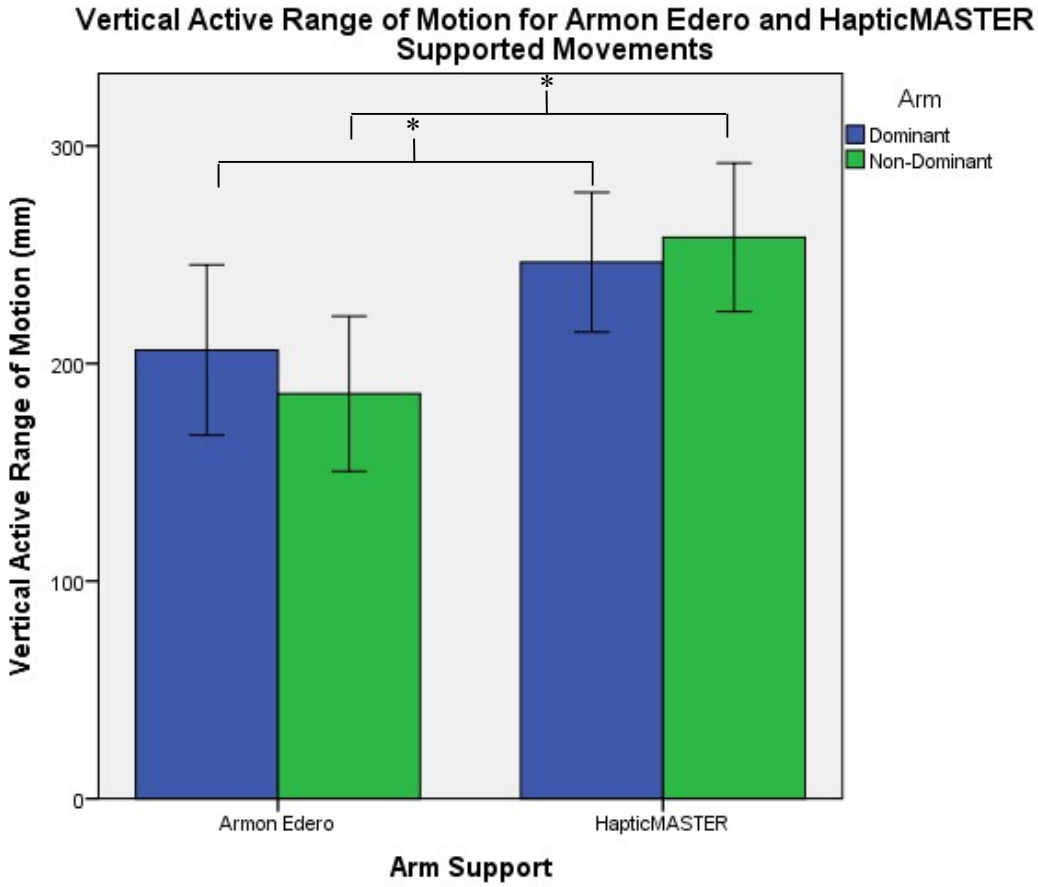

Figure 4.5 Mean vertical AROM for Armon Edero and HapticMASTER supported movements for all 10 subjects for the dominant (blue) and non-dominant (green) arms. Error bars show SEM. Asterisks denote statistical significance between groups ($p<0.05$).

Figure 4.6 shows the mean subject-reported VAS exertion scores values for Armon Edero and HapticMASTER supported movements. A Shapiro-Wilk test revealed that the self-reported exertion level scores have no significant deviation from normality ($p=0.852$). The HapticMASTER significantly decreased subject-reported exertion level scores compared to the Armon Edero passive arm support (paired-samples t-test, $t(9)=-4.45$, $p=0.002$, $r^2=0.69$). An $r^2=0.69$ denotes a large effect of the HapticMASTER on exertion level compared to the Armon Edero. The control subject had a self-reported

exertion level score of 74 for Armon Edero supported movements and 7 for HapticMASTER supported movements.

Figure 4.6 Mean subject-reported exertion level scores for Armon Edero and HapticMASTER movements. Error bars show SEM. Asterisk denotes statistical significance between groups ($p<0.05$).

Figure 4.7 shows the mean subject-reported VAS scores comparing the Armon Edero and HapticMASTER supported horizontal, vertical, and overall movements. The mean VAS response for horizontal movements was 86mm (SD 4mm), with all subjects reporting that the HapticMASTER allowed for the easiest movements in the horizontal direction compared to the Armon Edero. The mean VAS response for vertical

movements was 67mm (SD 10mm), denoting that, on average, subjects reported that the HapticMASTER allowed for the easiest movements in the vertical direction compared to the Armon Edero. The mean VAS response for overall movements was 84mm (SD 5mm), denoting that all subjects reported that the HapticMASTER allowed for the easiest movements overall, with the exception of one outlier who reported a score of 49mm. The control subject reported a VAS score of 93 for horizontal movements, 94 for vertical movements, and 90 for overall movements.

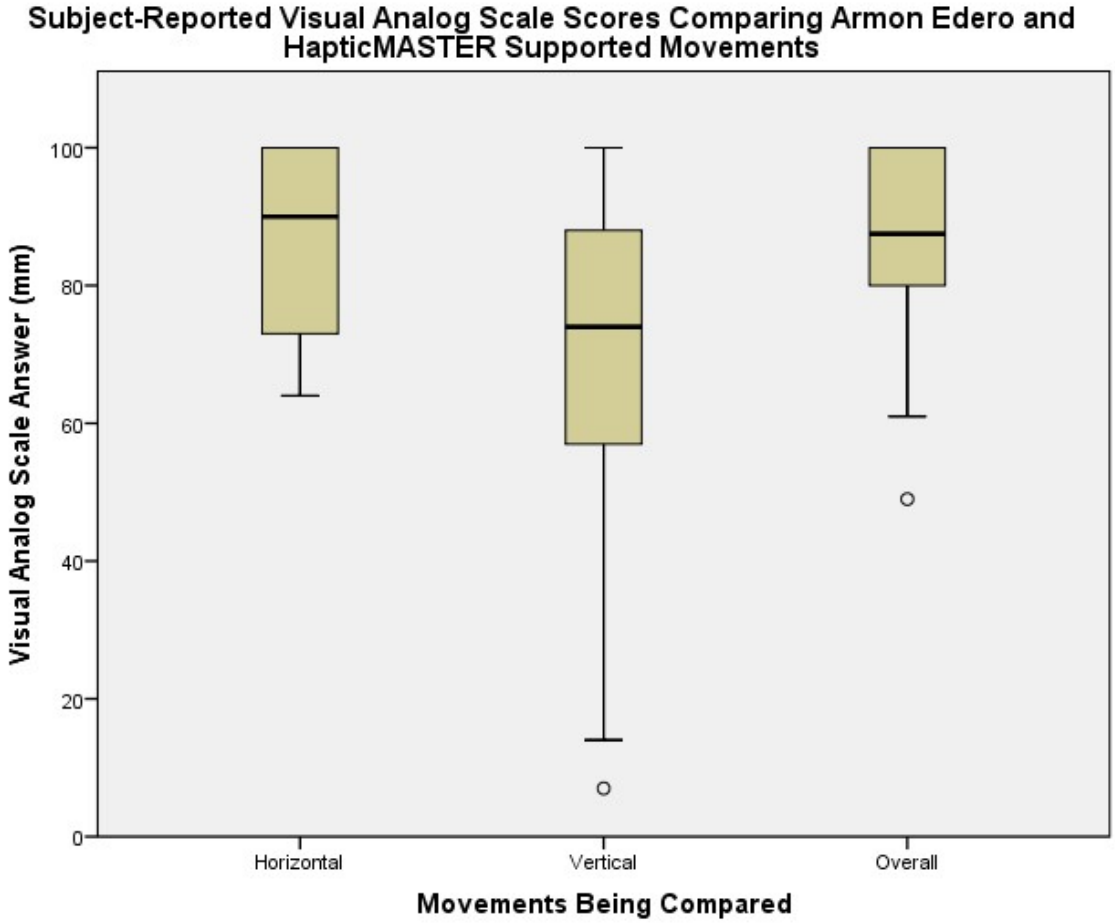

Figure 4.7 Mean subject-reported VAS scores comparing the Armon Edero and HapticMASTER supported horizontal movements, vertical movements, and overall movements. Scores greater than 50 denote a preference for the HapticMASTER robot and scores less than 50 denote a preference for the Armon Edero. Circles denote outliers greater than 1.5 interquartile range from Q1 or Q3.

4.4 Sub Aim 2.1 Discussion

This study explored the effect of admittance control on upper extremity movements in individuals with DMD compared to a commercially available passive arm support. The results support the hypothesis that admittance control increases the AROM of individuals with DMD to a greater degree than a commercially available passive arm support. The reachable surface area scores demonstrate an overall increase in AROM for the dominant and non-dominant arms for HapticMASTER supported movements compared to Armon

Edero supported movements. These results imply that that admittance control allows increased ease of movement compared to passive arm supports, explained by the minimization of friction and inertia and improved gravity compensation provided by admittance control. The vertical AROM results demonstrate an increase in voluntary vertical movements opposed by gravity, explained by the constants upward force provided by the HapticMASTER robot that is used to support the arm against gravity. This gravity compensation method is more precise than the spring of the Armon Edero that brings the arm to a set-point but requires additional force from the user to generate movements above or below this set-point. The subject-reported exertion level results imply that users found the admittance control arm support to require less strength to generate movements compared to the passive arm support, explained by the intuitive control and ease of movement provided by admittance control. Overall, subjects reported a preference for the admittance control robot compared to the passive arm support for assistance with voluntary movement, as reflected in mean subject-reported VAS scores of greater than 50.

The reachable surface area scores show an increase in AROM for the dominant arm compared to the non-dominant arm for both Armon Edero and HapticMASTER supported movements. The dominant arm is used more frequently in daily living tasks and is therefore less susceptible to disuse atrophy. It would follow that the dominant arm has a greater degree of residual strength resulting in larger reachable surface area scores when supported against gravity.

The effect size (r^2) for the statistically significant improvement in reachable surface area scores and vertical AROM for HapticMASTER supported movements is

larger for the non-dominant arm compared to the dominant arm. Given that unsupported reachable surface area scores were smaller for the non-dominant arm, indicating less residual strength than the dominant arm, the effect size results indicate that the benefits of admittance control becomes more substantial compared to a passive arm support as an individual loses muscle strength. This result can be explained by the fact that passive arm supports are useful only for those in the earlier stages of functional loss as residual strength is sufficient to provide a functional increase in AROM.

The HapticMASTER provided subjects with three translational DOFs in the x, y, and z directions and one passive rotational DOF in the yaw direction, with roll and pitch movements restricted. The Armon Edero restricted roll movements only, allowing passive x, y, z, pitch and yaw. Even more, approximate maximum workspace of the Armon Edero ($0.087m^2$) is larger than the maximum workspace of the HapticMASTER ($0.067m^2$). For these reasons, it is expected that any bias in results would occur toward the Armon Edero and not the HapticMASTER. This is further supported by the results from the control subject who exhibited larger reachable surface area scores and vertical AROM while using the Armon Edero compared to the HapticMASTER. It is expected that an admittance control robot equal in maximum workspace and DOFs to a passive arm support will result in a larger increase in reachable surface area and vertical AROM than reported in this study. Additionally, the control subject reported smaller exertion level scores and larger VAS scores for the HapticMASTER compared to the Armon Edero despite having greater AROM with the passive arm support. These results indicate that an individual who has sufficient muscle strength to benefit from a passive arm

support may still find an admittance control arm support easier to use and preferable to a passive arm support.

The HapticMASTER robot was set to an inertia value of 6kg in order to keep the system stable and allow for safe user-robot interaction. Therefore, the user was opposed only by the inertia of a 6kg frictionless point mass. The Armon Edero weighs approximately 1.8kg and the human arm has a mass of about 5% of the total body mass. Therefore, the inertia opposing the movements of an 80kg person using the Armon Edero would be approximately 6kg, about equal to that of the HapticMATSER robot. Because the inertia of the Armon Edero and the HapticMASTER robot is approximately the same, it is expected that the improvements in reachable surface area scores, vertical AROM, exertion level scores, and VAS scores are due primarily to the improved gravity compensation provided by the HapticMASTER robot compared to the Armon Edero. It is expected that an admittance control arm support with the virtual mass inertia value set lower than 6kg will result in a larger increase in reachable surface area and vertical AROM and a larger decrease in exertion level than reported in this study. This introduces the potential of admittance control to be beneficial to individuals with DMD in the later stages of functional loss.

4.5 Sub Aim 2.2 Methods

The objective of this sub aim was to track the changes in upper extremity AROM provided by the HapticMASTER in a longitudinal study over the course of about one year and compare that to the changes in upper extremity AROM provided by the Armon Edero over the same period of time. Subjects were recruited for this study though the

Parent Project Muscular Dystrophy DuchenneConnect registry and the Muscular Dystrophy Association. Subjects were included in the study using the same inclusion/exclusion criteria as sub aim 2.1.

The data collection protocol in sub-aim 2.1 was repeated for each subject at 3 sessions over the course of about 1 year to determine if the increase in AROM provided by the HapticMASTER would be sustained over that period of time. Average reachable surface area and average vertical AROM was calculated across 3 trials for each session for the right and left arms for Armon Edero and HapticMASTER supported movements. Unsupported and passive reachable workspace and subject-reported exertion level scores were also collected at each session using the same protocol as sub aim 2.1 to track changes in baseline upper extremity function, contractures, and user preferences.

In order to track changes in upper extremity strength, each subject's force output capabilities was quantified by conducting maximum voluntary isometric contraction (MVIC) for eight shoulder- and elbow-resisted movements. MCIV, among the most common measurement techniques that has been used extensively with individuals with neuromuscular conditions, is a safe and simple method used to quantify muscle strength [49]. MVIC was conducted while each subject's shoulder is abducted in neutral flexion, abduction, and rotation with the elbow flexed at 90 degrees and the forearm position in neutral pronation/supination, a protocol adapted from Burgar, et al. [50]. The subject's arm was strapped into a stationary cuff attached to an ATI Industrial Automation force sensor. The peak normal force was recorded for eight movements: elbow flexion, elbow extension, external rotation, internal rotation, shoulder abduction, shoulder adduction,

shoulder flexion, and shoulder extension. Peak force values were collected and averaged across three trials for the right and left arms.

The reachable workspace evaluation trajectory data was filtered and analyzed using the same protocol from sub aim 2.1. An examination of studentized residuals for values greater than +/-3 was used to determine if there were any outliers for reachable surface area scores, vertical AROM, and subject-reported exertion level scores. A Shapiro-Wilk test was used to assess the normality of the studentized residuals. Mauchly's test of sphericity was used to test the assumption of sphericity. A two-way repeated measures ANOVA was used to compare the reachable surface area scores, the vertical AROM, and the self-reported exertion level scores for the Armon Edero and HapticMASTER movements at each of the three sessions for the dominant and non-dominant arms.

A Shapiro-Wilk test was used to assess if the population for time, reachable surface area scores, vertical AROM, and subject-reported exertion level scores are normally distributed. If the population for these variables is approximately normal and the assumption of homoscedasticity is met then a Pearson's r was used to assess the relationship between time and reachable surface area scores, vertical AROM, and subject reported exertion level scores. If either of the assumptions are violated, a Spearman's rank-order correlation was run to assess the relationship. The same statistical tests were used to assess the relationship between the Armon Edero and HapticMASTER supported reachable surface area scores and vertical AROM and shoulder abduction, adduction, flexion, and extension MVIC.

Passive reachable surface area, MVIC, and unsupported reachable surface area were outcome measures used to track the upper extremity functional status of the subjects at each session. The primary outcome measure of this sub aim is the reachable surface area scores while supported by the Armon Edero and while supported by the HapticMASTER robot at each of the three sessions. The secondary outcome measure is the vertical AROM while supported by the Armon Edero and while supported by the HapticMASTER robot at each of the three sessions. The outcome measure to evaluate user preferences is the subject-reported exertion level scores.

4.6 Sub Aim 2.2 Expected Results

Due to the progressive nature of DMD, it is expected that unsupported reachable surface area, passive reachable surface area, and MVIC will decrease with each session. It is expected that the reachable surface area scores will decrease over time for both the HapticMASTER and Armon Edero supported movements. However, because of the benefits of admittance control, it is expected that the reachable surface area scores for the HapticMASTER supported movements will remain larger and decrease at a slower rate compared to the Armon Edero supported movements at each session. Similarly, vertical range of motion is expected to remain larger and decrease at a slower rate for HapticMASTER supported movements compared to Armon Edero supported movements. The self-reported exertion level scores are expected to remain smaller for the HapticMASTER while also increasing at a slower rate compared to the Armon Edero.

It is expected that time is positively correlated with Armon Edero and HapticMASTER supported reachable surface area scores and vertical AROM and

negatively correlated with subject-reported exertion level scores. It is expected that shoulder abduction, adduction, flexion, and extension MVIC are positively correlated with Armon Edero and HapticMASTER supported reachable surface area scores and vertical AROM.

4.7 Sub Aim 2.2 Results

Five subjects and one control subject with DMD who met the inclusion and exclusion criteria for this aim were enrolled in the study. Table 4.3 shows the age of each subject, handedness, baseline scores of passive reachable surface area and unsupported reachable surface area for the left and right arms at the first session, and the month each session was conducted for each subject. Session 1 was conducted at month 0, session 2 was conducted between months 3 and 6, and session 3 was conducted between months 9-12.

Table 4.3 Subjects Enrolled in Aim 2.2

Subject	Age	Hand Dominance	Passive RSA		Unsupported RSA		Session (months)		
			Right	Left	Right	Left	1	2	3
1b	26	Right	0.713	0.321	0.100	0.032	0	4	11
2b	21	Right	0.403	0.184	0.007	0.000	0	4	12
3b	26	Right	0.524	0.227	0.001	0.000	0	3	9
4b	27	Right	0.435	0.709	0.000	0.000	0	4	11
5b	11	Right	0.628	0.598	0.033	0.013	0	6	11
Control	15	Right	0.437	0.470	0.420	0.275	0	5	10

Figure 4.8 shows the passive reachable surface area scores for the dominant arm for all 6 subjects at each of the 3 sessions. Subjects 1, 2, 3, and 5 had a smaller passive reachable surface area score for the dominant arm at their third session compared to their first session, indicating an increase in the development of contractures over the course of

the study. Subject 4 and the control subject had larger passive reachable surface area scores for the dominant arm at their third session compared to their first indicating a decrease in contractures over the course of the study.

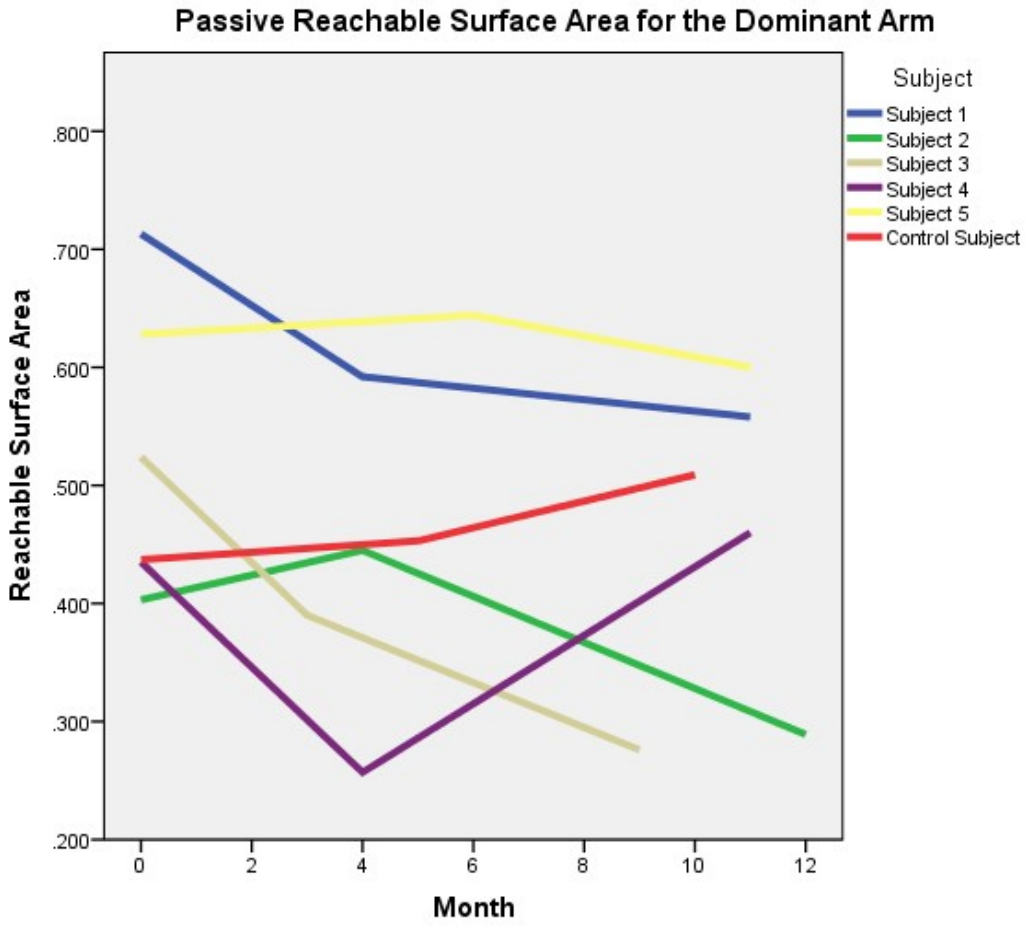

Figure 4.8 Passive reachable surface area scores for the dominant arm for 5 subjects and 1 control subject with DMD over 3 sessions.

Figure 4.9 shows the passive reachable surface area scores for the non-dominant arm at the same 3 sessions. Subjects 3, 4, 5, and 6 had smaller passive reachable surface area scores for the non-dominant arm at their third session compared to their first session, indicating an increase in contractures over the course of the study. Subjects 1 and 2 had larger passive reachable surface area scores for the non-dominant arm at their third

session compared to their first session, indicating a decrease in contractures over the course of the study.

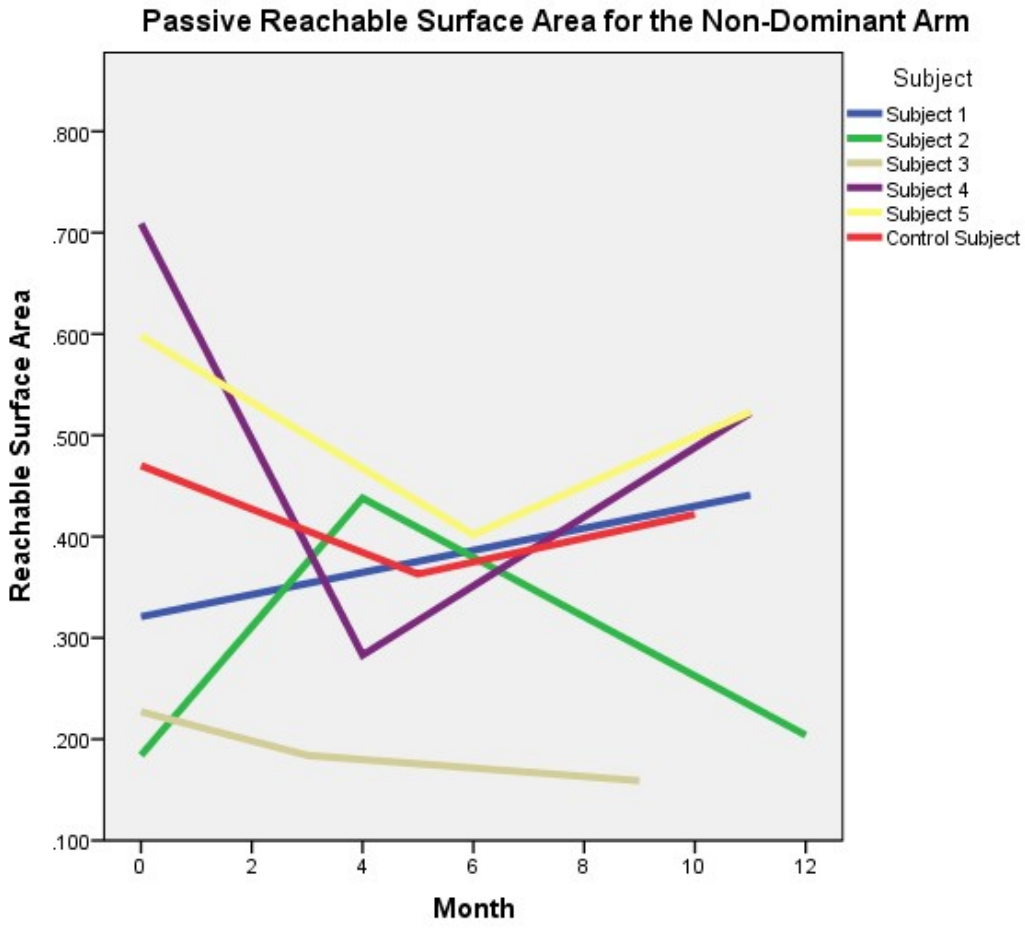

Figure 4.9 Passive reachable surface area scores for the non-dominant arm for 6 subjects with DMD over 3 sessions.

Figure 4.10 shows the unsupported reachable surface area scores for the dominant arm for all 5 subjects. Subjects 1, 2, and 5 had a smaller unsupported reachable surface area score for the dominant arm at their third session compared to their first session, indicating a decrease in upper extremity function over the course of the study. Subject 4 had an unsupported reachable surface area score for the dominant arm of 0.000 at each session and therefore had no change between sessions. Subjects 3 had larger unsupported

reachable surface area scores for the dominant arm at the third session compared to the first session, indicating no decrease in upper extremity function over the course of the study. The control subject has unsupported reachable surface area scores for the dominant arm of 0.420 at session 1, 0.419 at session 2, and 0.462 at session 3. The control subject had larger unsupported reachable surface area scores at the third session compared to the first session.

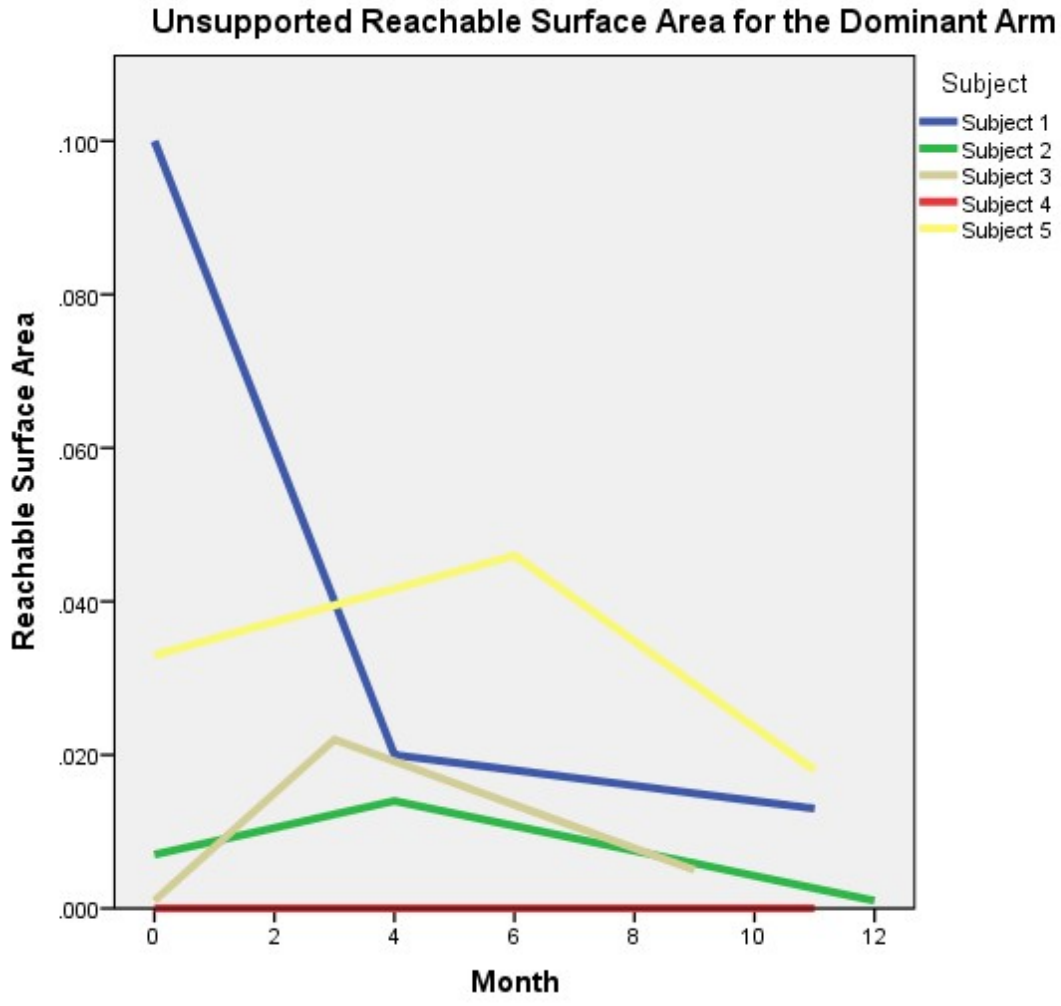

Figure 4.10 Unsupported reachable surface area scores for the dominant arm for 5 subjects with DMD over 3 sessions.

Figure 4.11 shows the unsupported reachable surface area scores for the non-dominant arm for all 5 subjects at the same 3 sessions. Subjects 1 and 5 had smaller unsupported reachable surface area scores for the non-dominant arm at the third session compared to the first session, indicating a decrease in upper extremity function over the course of the study. Subjects 2, 3, and 4 had larger unsupported reachable surface area scores for the non-dominant arm at the third session compared to the first session, indicating no decrease in upper extremity function over the course of the study. The control subject had unsupported reachable surface area scores for the non-dominant arm of 0.275 at session 1 and 0.242 at session 2. There was no data available for the unsupported reachable surface area for the non-dominant arm for the control subject at the third session. The control subject had a smaller unsupported reachable surface area score at the second session compared to the first session.

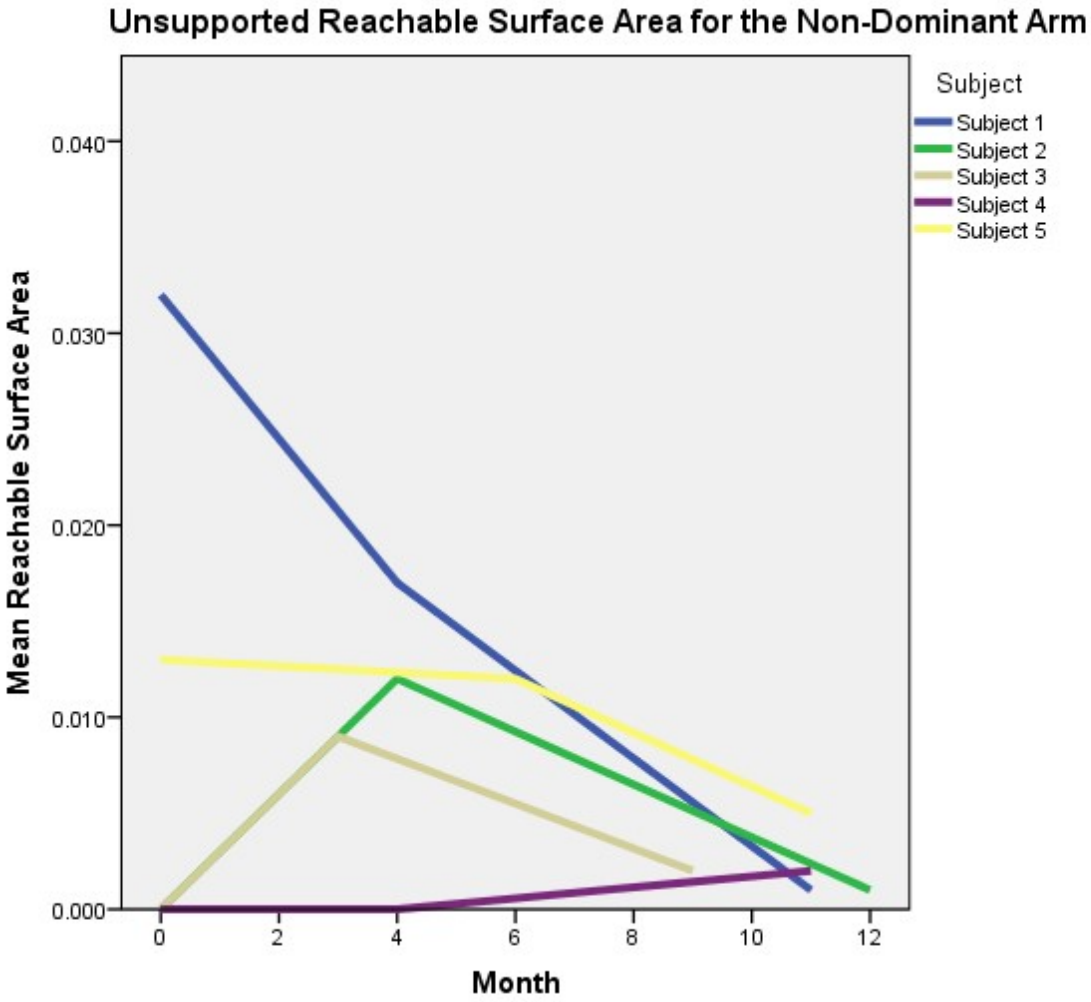

Figure 4.11 Unsupported reachable surface area scores for the non-dominant arm for 5 subjects with DMD over 3 sessions.

Figure 4.12 shows the reachable surface area scores for the dominant arm for Armon Edero and for HapticMASTER supported movements for all 5 subjects and 1 control subject over 3 sessions. Subjects 1, 2, and 4 had larger reachable surface area scores for HapticMASTER supported movements compared to Armon Edero supported movements for the dominant arm at all sessions. Subjects 3 and 5 had larger reachable surface area scores for HapticMASTER supported movements compared to Armon Edero supported movements for the dominant arm at all sessions except session 2 (subject 3) and session 1

(subject 5). The control subject had larger reachable surface area scores for Armon Edero supported movements for the dominant arm at session 1 and 2 and had larger reachable surface area scores for HapticMASTER supported movements at session 3.

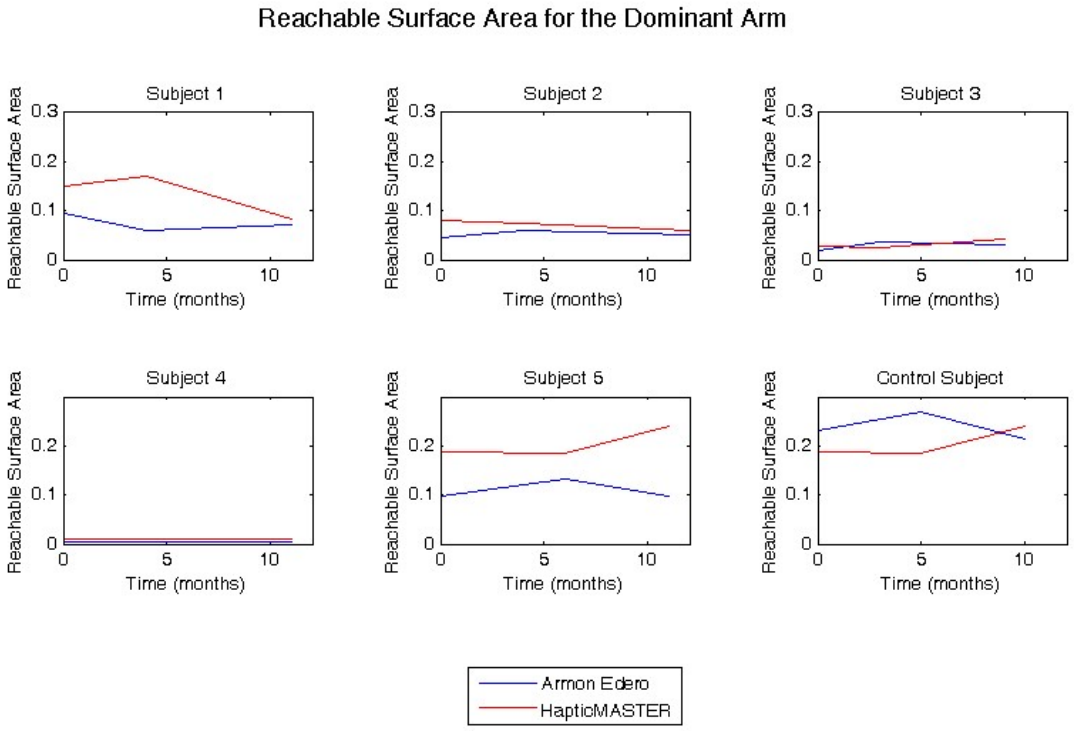

Figure 4.12 Reachable surface area scores for the dominant arm for Armon Edero (blue) and HapticMASTER (red) supported movements for 5 subjects and 1 control subject with DMD over 3 sessions.

Figure 4.13 shows the reachable surface area scores for the non-dominant arm for Armon Edero and for HapticMASTER supported movements for all 5 subjects and 1 control subject over 3 sessions. Subjects 2, 4, and 5 had larger reachable surface area scores for HapticMASTER supported movements compared to Armon Edero supported movements for the non-dominant arm at all session. Subjects 1 and 3 had larger reachable surface area scores for HapticMASTER supported movements compared to Armon Edero supported movements for the non-dominant arm at all sessions except for

session 3. The control subject had larger reachable surface area scores for Armon Edero supported movements for the non-dominant arm at sessions 1 and 3 and had larger reachable surface area scores for HapticMASTER supported movements at session 2.

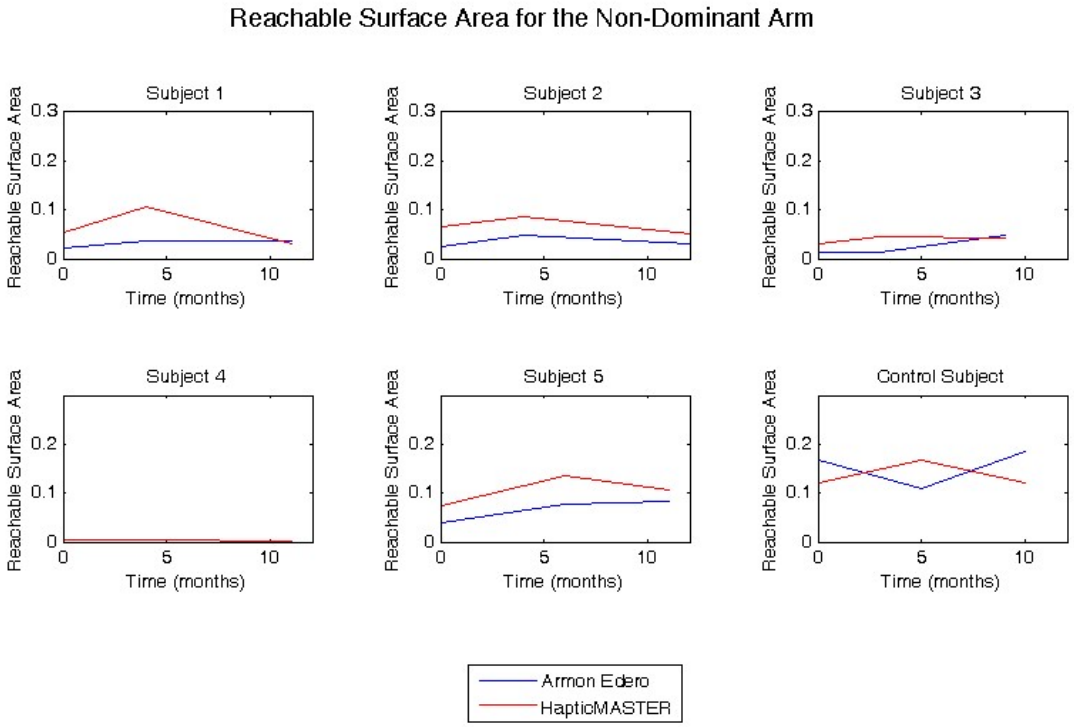

Figure 4.13 Reachable surface area scores for the non-dominant arm for Armon Edero (blue) and HapticMASTER (red) supported movements for 5 subjects and 1 control subject with DMD over 3 sessions.

Figure 4.14 shows the vertical AROM for the dominant arm for Armon Edero and for HapticMASTER supported movmeents for all 5 subjects and 1 control subject over 3 sessions. Subjects 1 and 4 had larger vertical AROM for HapticMASTER supported movements compared to Armon Edero supported movements for the dominant arm at all 3 sessions. Subjects 2 and 3 had larger vertical AROM for HapicMASTER supported movements compared to Armon Edero supported movements for the dominant arm at all sessions except for session 2 (subject 2) and session 2 and 3 (subject 3). Subject 5 and

the control subject had larger vertical AROM for Armon Edero supported movements compared to HapticMASTER supported movements for the dominant arm at all 3 sessions.

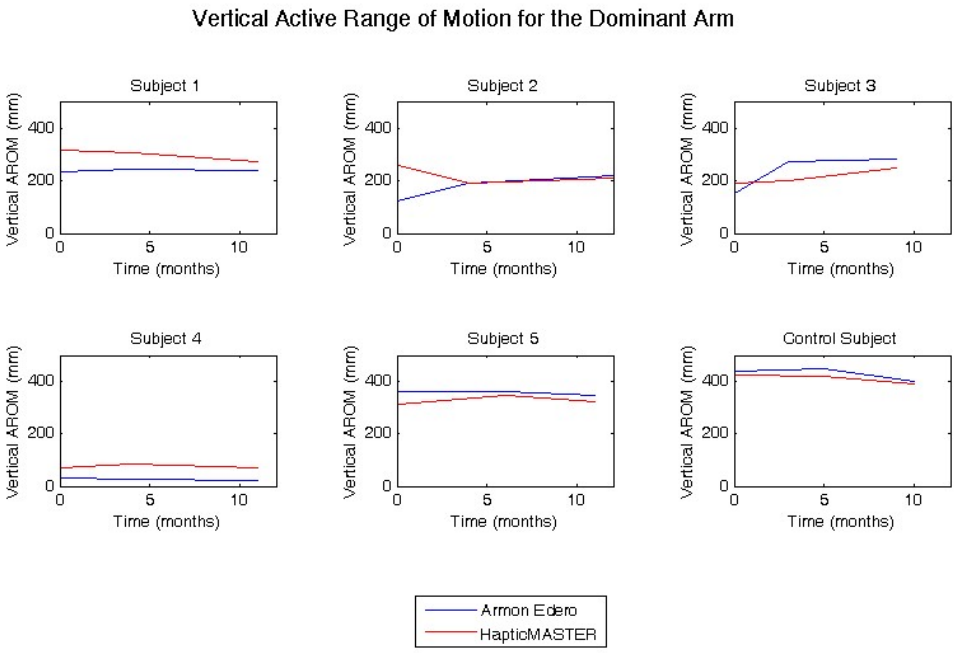

Figure 4.14 Vertical AROM for the dominant arm for Armon Edero (blue) and HapticMASTER (red) supported movements for 5 subjects and 1 control subject with DMD over 3 sessions.

Figure 4.15 shows the vertical AROM for the non-dominant arm for Armon Edero and for HapticMASTER supported movements for all 5 subjects and 1 control subject over 3 sessions. Subjects 1, 2, 4, and 5 had larger vertical AROM for HapticMASTER supported movements compared to Armon Edero supported movements for the non-dominant arm at all 3 sessions. Subject 3 had larger HapticMASTER supported movements compared to Armon Edero supported movements for the non-dominant arm at all sessions except for session 3. The control subject had larger vertical

AROM for Armon Edero supported movements for the non-dominant arm at sessions 1 and 3 and larger HapticMASTER supported movements at session 2.

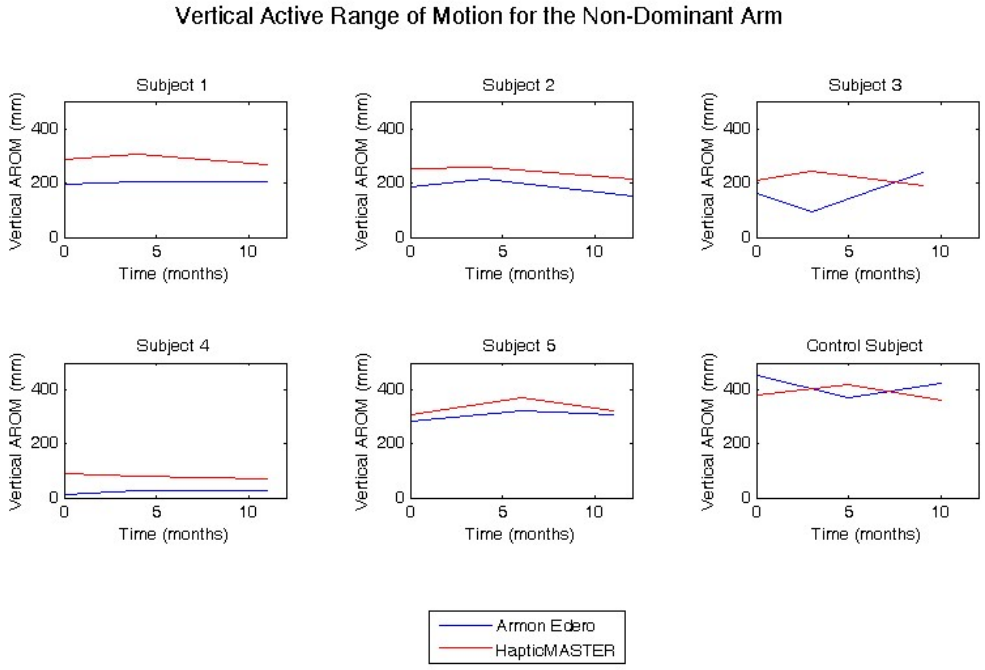

Figure 4.15 Vertical AROM for the non-dominant arm for Armon Edero (blue) and HapticMASTER (red) supported movements for 5 subjects and 1 control subject with DMD over 3 sessions.

Figure 4.16 shows the mean reachable surface area for Armon Edero and HapticMASTER supported movements for the dominant arm for all 5 subjects and 1 control subject across 3 sessions. The mean reachable surface area scores were 0.052 (SD 0.043) for Armon Edero supported movements and 0.070 (SD 0.054) for HapticMASTER supported movements for session 1, 0.058 (SD 0.047) for Armon Edero supported movements and 0.091 (SD 0.079) for HapticMASTER supported movements for session 2, and 0.051 (SD 0.036) for Armon Edero supported movements and 0.063 (SD 0.041) for HapticMASTER supported movements for session 3. The control subject had reachable surface area scores for Armon Edero supported movements of 0.232 at

session 1, 0.268 at session 2, and 0.214 at session 3. The control subject had reachable surface area scores for HapticMASTER supported movements of 0.189 at session 1, 0.184 at session 2, and 0.241 at session 3. There were no outliers, as assessed by examination of studentized residuals for values greater than +/-3. Reachable surface area scores for the dominant arm were normally distributed ($p>0.05$), as assessed by Shapiro-Wilk's test of normality on the studentized residuals. Mauchly's test of sphericity indicated that the assumption of sphericity was met for the two-way interaction ($\chi^2(2)=0.683$, $p=0.711$). Mauchly's test of sphericity also indicated that the assumption of sphericity was met for session number ($\chi^2(2)=0.258$, $p=0.879$). There was no statistically significant two-way interaction between arm support type and session number ($F(2,8)=0.812$, $p=0.478$). The main effect of arm support type showed no statistically significant difference in reachable surface area scores ($F(1,4)=4.411$, $p=0.104$). The main effect of session number showed no statistically significant difference in reachable surface area ($F(2,8)=1.353$, $p=0.312$).

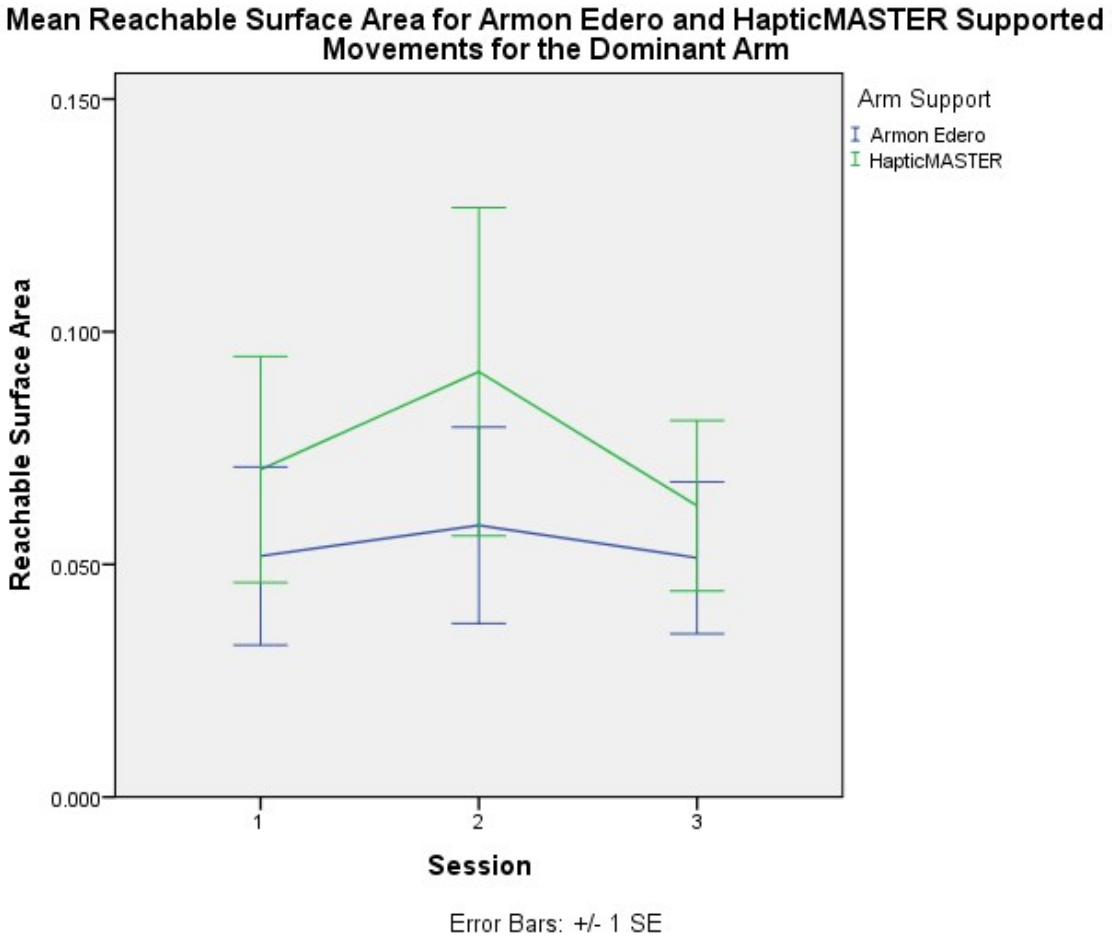

Figure 4.16 Mean reachable surface area for Armon Edero (blue) and HapticMASTER (green) supported movements for the dominant arm (n=5) at 3 sessions. Error bars show SEM.

Figure 4.17 shows the mean reachable surface area for Armon Edero and HapticMASTER supported movements for the non-dominant arm for all 5 subjects across 3 sessions. The mean reachable surface area scores were 0.020 (SD 0.014) for Armon Edero supported movements and 0.045 (SD 0.028) for HapticMASTER supported movements for session 1, 0.035 (SD 0.031) for Armon Edero supported movements and 0.075 (SD 0.052) for HapticMASTER supported movements for session 2, and 0.039 (SD 0.030) for Armon Edero supported movements and 0.046 (SD 0.038) for

HapticMASTER supported movements for session 3. The control subject had reachable surface area scores for Armon Edero supported movements of 0.167 at session 1, 0.108 at session 2, and 0.186 at session 3. The control subject had reachable surface area scores for HapticMASTER supported movements of 0.121 at session 1, 0.168 at session 2, 0.121 at session 3. There were no outliers, as assessed by examination of studentized residuals for values greater than +/- 3. Reachable surface area scores for the non-dominant arm were normally distributed ($p>0.05$), as assessed by Shapiro-Wilk's test of normality on the studentized residuals. Mauchly's test of sphericity had been violated for the two-way interaction, ($\chi^2(2)=6.176$, $p=0.046$). Mauchly's test of sphericity indicated that the assumption of sphericity was met for session number ($\chi^2(2)=0.040$, $p=0.980$). There was no statistically significant two-way interaction between arm support type and session number ($F(1.068,4.273)=7.110$ $p=0.640$). The main effect of arm support type showed no statistically significant difference in reachable surface area scores ($F(1,4)=12.992$, $p=0.023$). The main effect of session number showed no statistically significant difference in reachable surface area ($F(2,8)=3.005$, $p=0.106$).

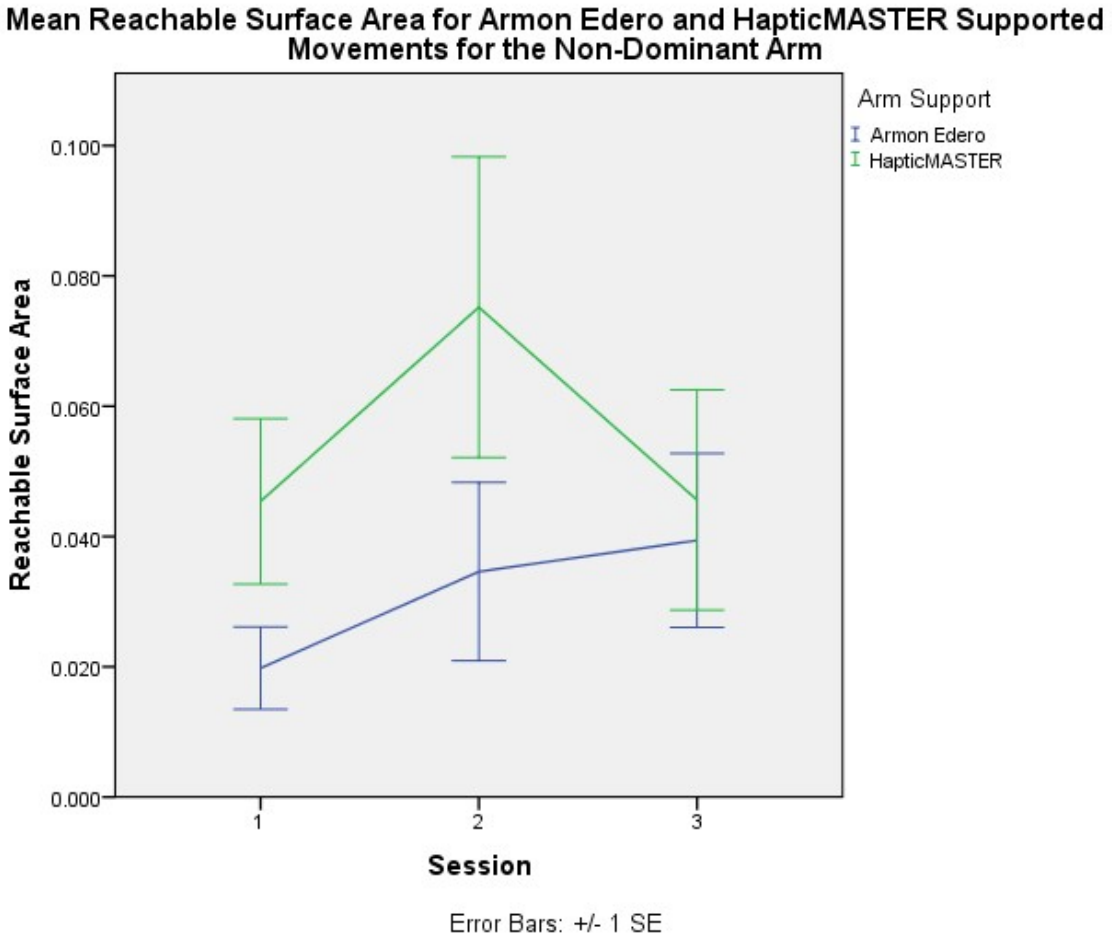

Figure 4.17 Mean reachable surface area for Armon Edero (blue) and HapticMASTER (green) supported movements for the non-dominant arm (n=5) 3 sessions. Error bars show SEM.

Figure 4.18 shows the mean vertical AROM for Armon Edero and HapticMASTER supported movements for the dominant arm for all 5 subjects across 3 sessions. The mean vertical AROM was 180mm (SD 124mm) for Armon Edero supported movements and 231mm (SD 103mm) for HapticMASTER supported movements for session 1, 220mm (SD 125mm) for Armon Edero supported movements and 227mm (SD 104mm) for HapticMASTER supported movements for session 2, and 223mm (SD 121mm) for Armon Edero and 225mm (SD 96mm) for HapticMASTER

supported movements for session 3. The control subject had vertical AROM for Armon Edero supported movements of 437mm at session 1, 448mm at session 2, and 402mm at session 3. The control subject had vertical AROM for HapticMASTER supported movements of 423mm at session 1, 422mm at session 2, 392mm at session 3. There were no outliers, as assessed by examination of studentized residuals for values greater tha +/- 3. Vertical AROM for the dominant arm were normally distributed ($p>0.05$), as assessed by Shapiro-Wilk's test of normality on the studentized residuals. Mauchly's test of sphericity indicated that the assumption of sphericity was met for the two-way interaction, ($\chi^2(2)=3.867$, $p=0.145$). Mauchly's test of sphericity indicated that the assumption of sphericity was met for session number ($\chi^2(2)=3.342$, $p=0.188$). There was no statistically significant two-way interaction between arm support type and session number ($F(2,8)=1.774$, $p=0.230$). The main effect of arm support type showed no statistically significant difference in vertical AROM, ($F(1,4)=1.234$, $p=0.329$). The main effect of session number showed no statistically significant difference in vertical AROM ($F(2,8)=0.925$, $p=0.435$).

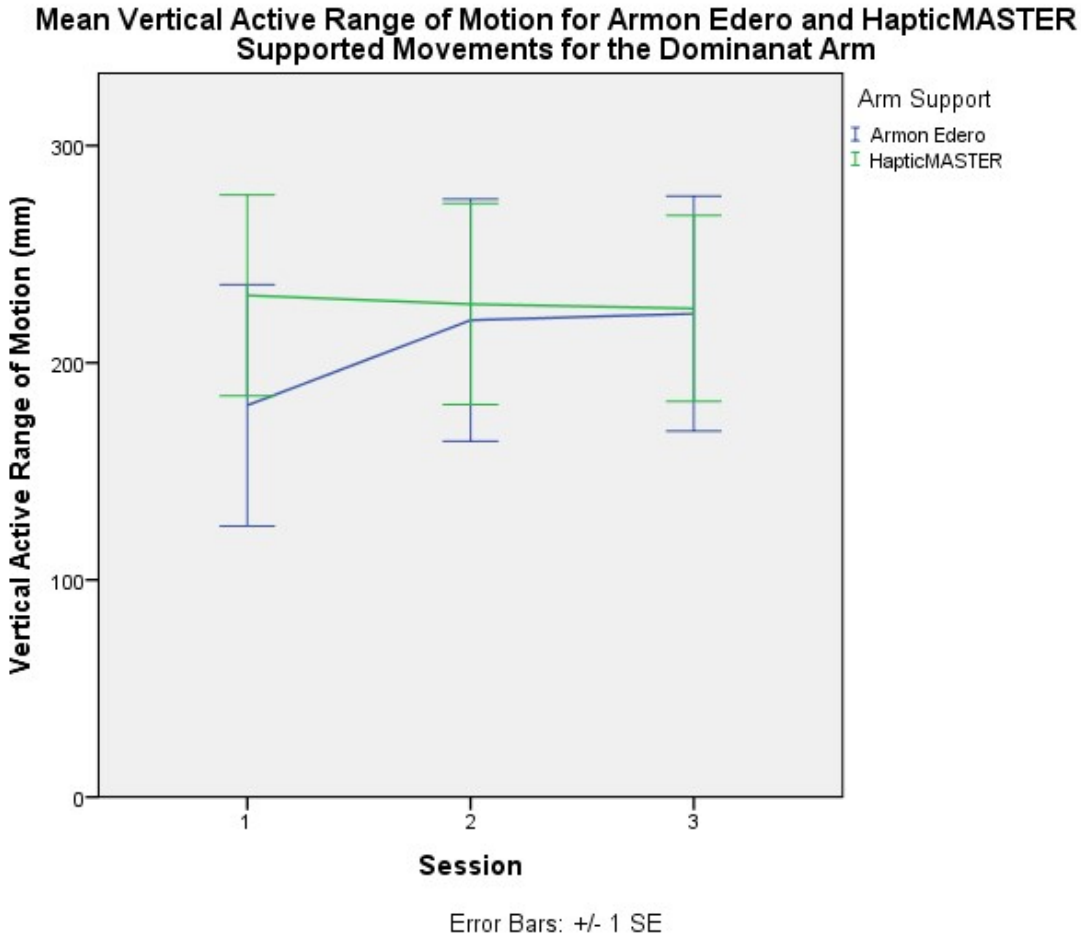

Figure 4.18 Mean vertical AROM for Armon Edero (blue) and HapticMASTER (green) supported movements for the dominant arm (n=5) at 3 sessions. Error bars show SEM.

Figure 4.19 shows the mean vertical AROM for Armon Edero and HapticMASTER supported movements for the non-dominant arm for all 5 subjects across 3 sessions. The mean vertical AROM was 169mm (SD 99mm) for Armon Edero supported movements and 230mm (SD 86mm) for HapticMASTER supported movements for session 1, 173mm (SD 116mm) for Armon Edero supported movements and 252mm (SD 109mm) for HapticMASTER supported movements for session 2, and 188mm (106mm) for Armon Edero supported movements and 213mm (SD 95mm) for HapticMASTER supported movements for session 3. The control subject had vertical

AROM for Armon Edero supported movements of 453mm at session 1, 369mm at session 2, and 424mm at session 3. The control subject had vertical AROM for HapticMASTER supported movements of 381mm, 418mm, 362mm for sessions 1, 2, and 3. There were no outliers, as assessed by examination of studentized residuals for values greater tha +/- 3. Vertical AROM for the non-dominant arm were normally distributed ($p>0.05$), as assessed by Shapiro-Wilk's test of normality on the studentized residuals. Mauchly's test of sphericity had been violated for the two-way interaction, ($\chi^2(2)=6.461$, $p=0.040$). Mauchly's test of sphericity indicated that the assumption of sphericity was met for session number ($\chi^2(2)=1.117$, $p=0.572$). There was no statistically significant two-way interaction between arm support type and session number ($F(1.062,4.246)=1.995$, $p=0.229$). The main effect of arm support type showed a statistically significant difference in vertical AROM, ($F(1,4)=36.233$, $p=0.004$). The mean difference between vertical AROM is 55mm (95% CI, -81mm, -29mm). The main effect of session number showed no statistically significant difference in vertical AROM ($F(2,8)=0.0.546$, $p=0.600$).

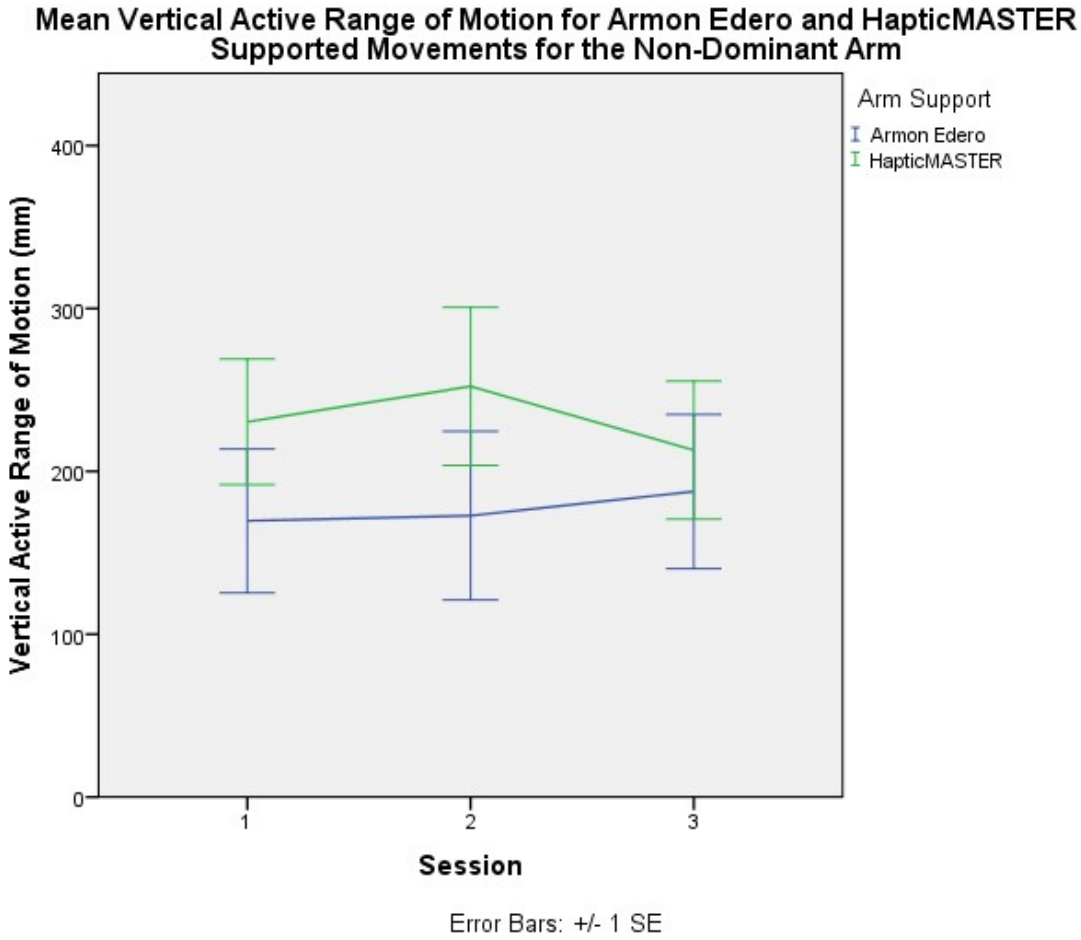

Figure 4.19 Mean vertical AROM for Armon Edero (blue) and HapticMASTER (green) supported movements for the non-dominant arm (n=5) at 3 sessions. Error bars show SEM.

Figure 4.20 shows the mean subject-reported exertion level scores for the Armon Edero and HapticMASTER supported movements for all 3 sessions. The mean subject-reported exertion level score was 60mm (SD 21mm) for Armon Edero supported movements and 28mm (SD 22mm) for HapticMASTER supported movements for session 1, 85mm (SD 15mm) for Armon Edero supported movements and 31mm (SD 22mm) for HapticMASTER supported movements for session 2, and 73mm (SD 13mm) for Armon Edero and 12mm (SD 10mm) for HapticMASTER supported movmenets for

session 3. The control subject reported exertion level scores for the Armon Edero of 74mm at session 1, 60mm at session 2, and 83mm at session 3. The control subject reported exertion level scores for HapticMASTER supported movements of 7mm at session 1, 31mm at session 2, and 9mm at session 3. There were no outliers, as assessed by examination of studentized residuals for values greater tha +/- 3. Subject-reported exertion level scores were normally distributed ($p>0.05$), as assessed by Shapiro-Wilk's test of normality on the studentized residuals. Mauchly's test of sphericity indicated the assumption of sphericity was met for the two-way interaction, ($\chi^2(2)=0.717$, $p=0.407$). Mauchly's test of sphericity indicated that the assumption of sphericity was met for session number ($\chi^2(2)=1.796$, $p=0.699$). There was a statistically significant two-way interaction between arm support type and session number, ($F(2,8)=15.014$, $p=0.002$). The mean difference in exertion level scores was 32mm (95% CI, 15mm to 49mm) for Armon Edero supported movements compared to HapticMASTER supported movements at session 1. This was a statistically significant difference ($F(1,4)=25.924$, $p=0.007$). The mean difference in exertion level scores was 54mm (95% CI, 38mm to 70mm) for Armon Edero supported movements compared to HapticMASTER supported movements at session 2. This was a statistically significant difference ($F(1,4)=89.726$, $p=0.001$). The mean difference in exertion level scores was 61mm (95% CI, 42mm to 80mm) for Armon Edero supported movements compared to HapticMASTER supported movements at session 3. This was a statistically significant difference ($F(1,4)=81.176$, $p=0.001$). There was no statistically significant effect of session number on exertion level for Armon Edero supported movements ($F(2,8)=4.215$, $p=0.056$). There was no statistically

significant effect of session number on exertion level for HapticMASTER supported movements ($F(2,8)=3.150$, $p=0.098$).

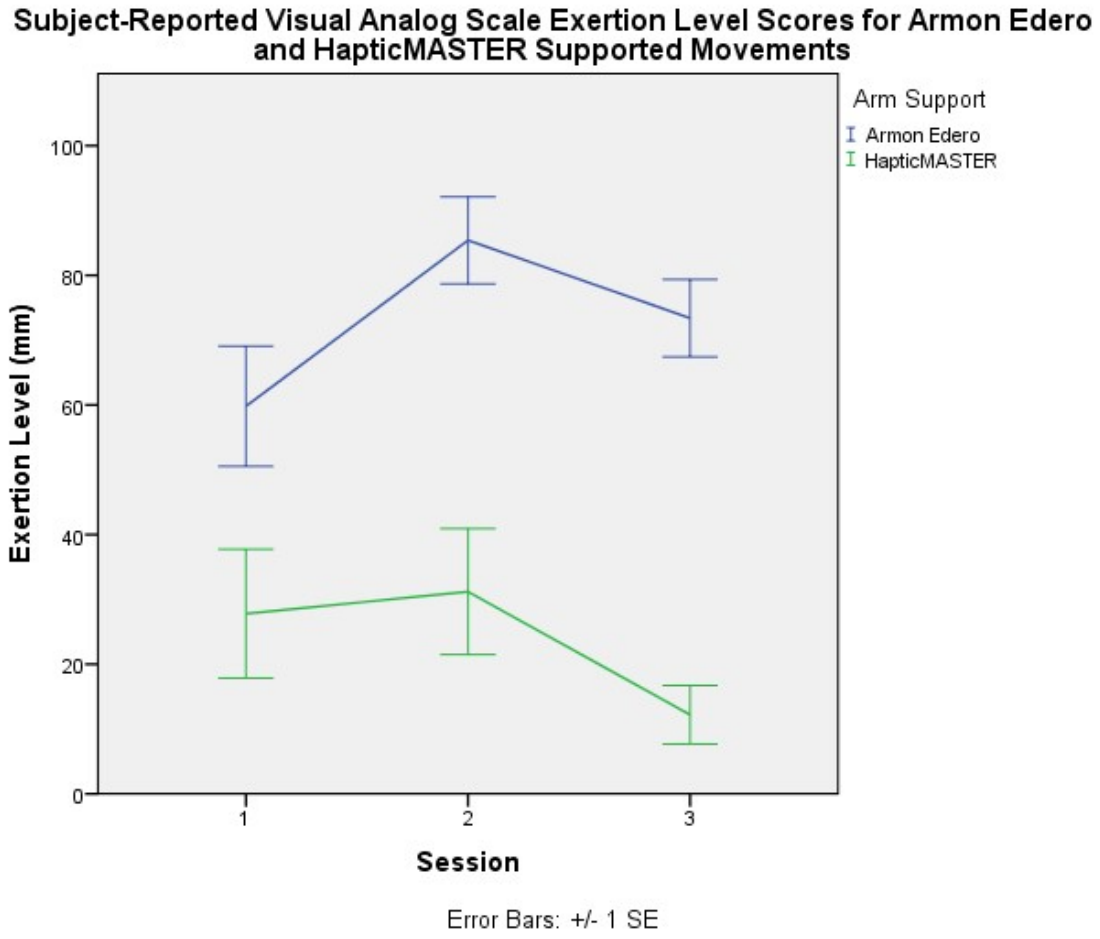

Figure 4.20 Mean subject-reported exertion level scores for Armon Edero (blue) and HapticMASTER (green) supported movements (n=5) at 3 sessions. Error bars show SEM.

Figure 4.21 shows the reachable surface area scores for Armon Edero supported movements for the dominant arm for all 5 subjects plotted versus time. Figure 4.22 shows the same results for HapticMASTER supported movements. A Shapiro-Wilk test revealed that the population for time has a significant deviation from normality ($p=0.016$). There was no statistically significant relationship between time and reachable

surface area scores for Armon Edero supported movements for the dominant arm (Spearman's Correlation, r_s=0.079, p=0.780). There was no statistically significant relationship between time and reachable surface area scores for HapticMASTER supported movements for the dominant arm (Spearman's Correlation, r_s=0.042, p=0.881).

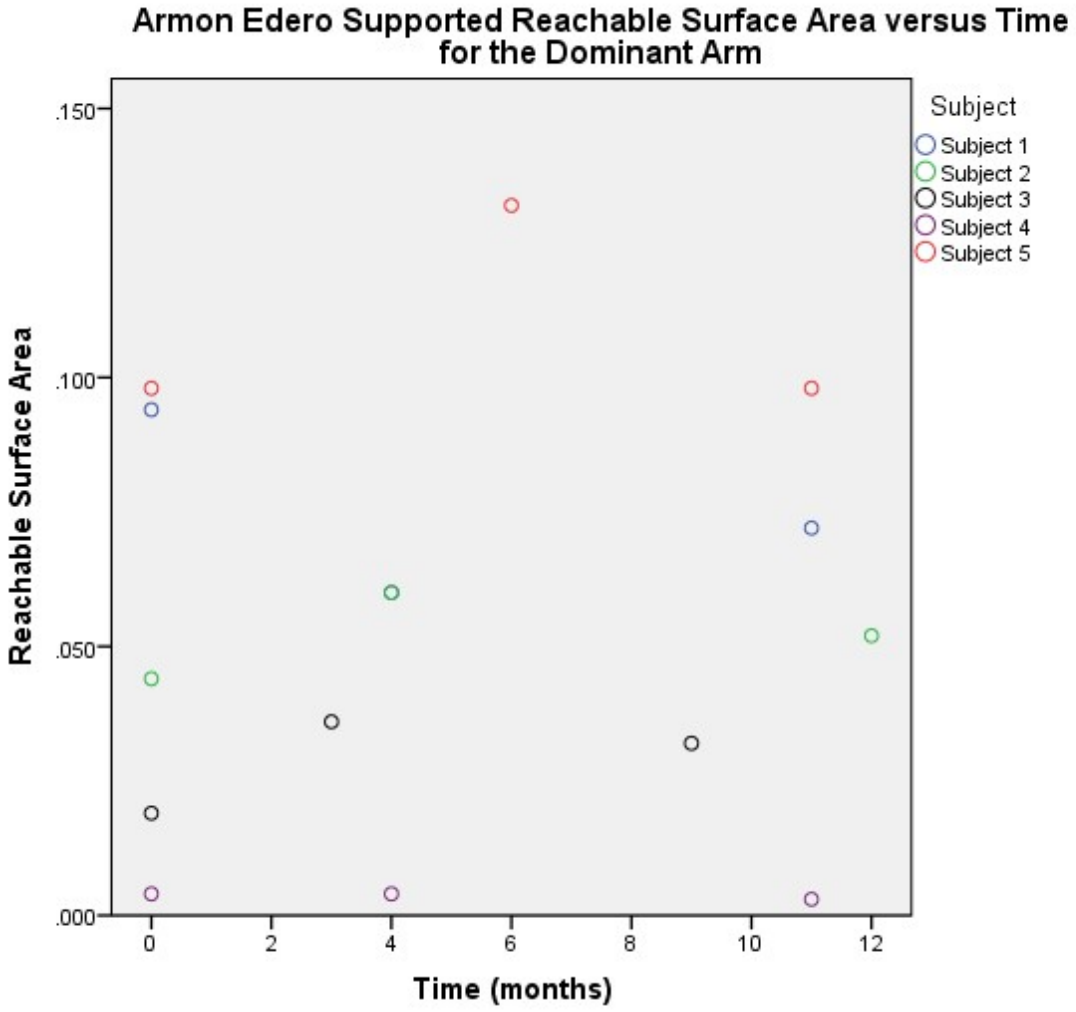

Figure 4.21 Reachable surface area scores for Armon Edero supported movements for the dominant arm for all 5 subjects versus time.

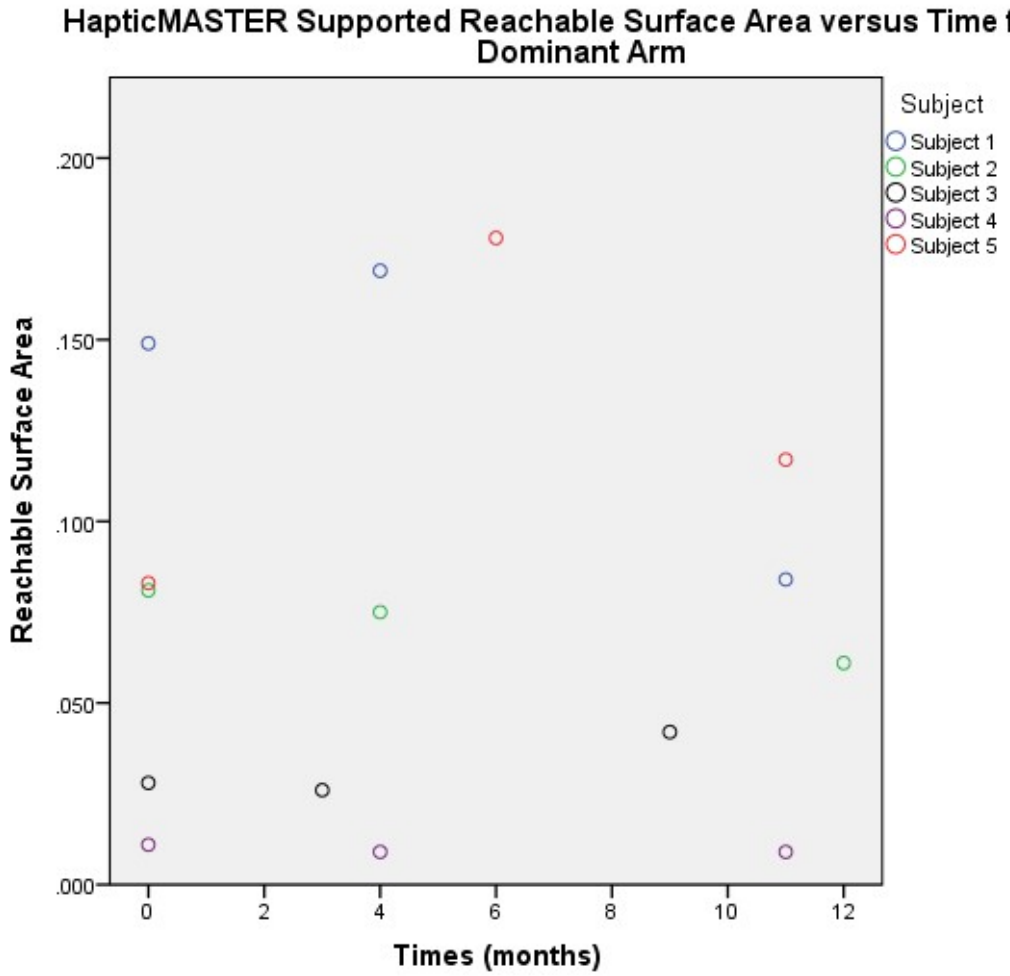

Figure 4.22 Reachable surface area scores for HapticMASTER supported movements for the dominant arm for all 5 subjects versus time.

Figure 4.23 shows the reachable surface area scores for Armon Edero supported movements for the non-dominant arm for all 5 subjects plotted versus time. Figure 4.24 shows the same results for HapticMASTER supported movements. There was no statistically significant relationship between time and reachable surface area scores for Armon Edero supported movements for the non-dominant arm (Spearman's Correlation, r_s=0.340, p=0.214). There was no statistically significant relationship between time and

reachable surface area scores for HapticMASTER supported movements for the non-dominant arm (Spearman's Correlation, r_s=-0.018, p=0.948).

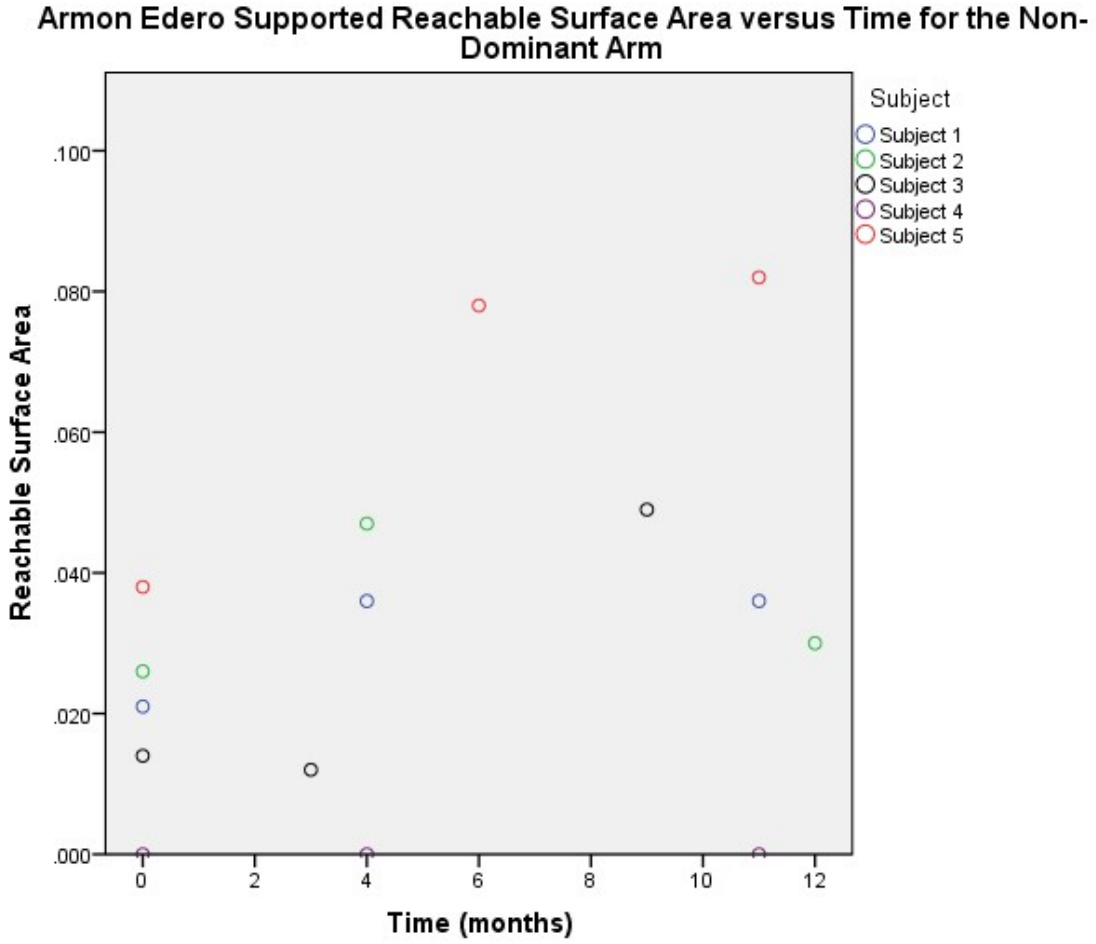

Figure 4.23 Reachable surface area scores for Armon Edero supported movements for the non-dominant arm for all 5 subjects versus time.

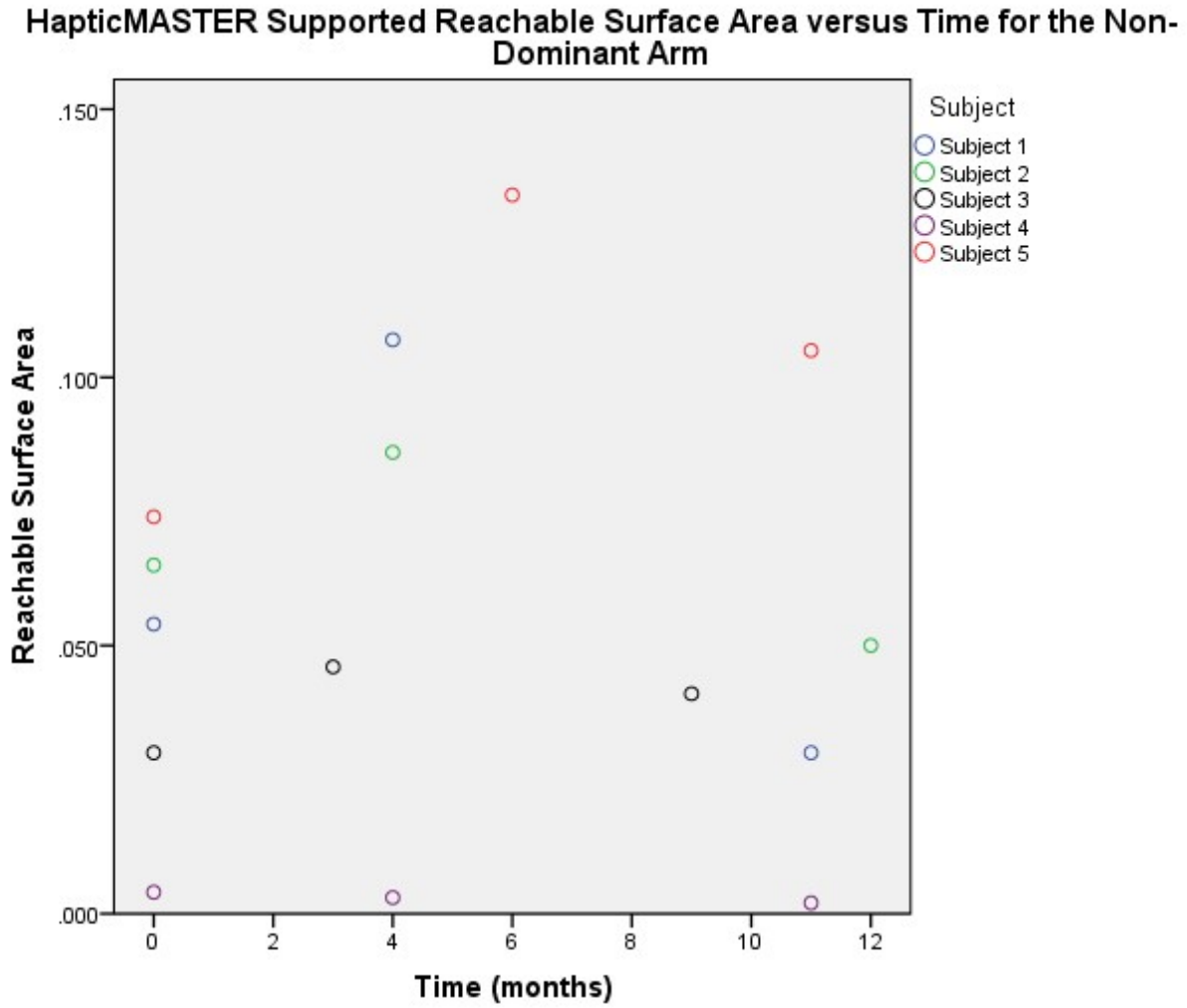

Figure 4.24 Reachable surface area scores for HapticMASTER supported movements for the non-dominant arm for all 5 subjects versus time.

Figure 4.25 shows the vertical AROM for Armon Edero supported movements for the dominant arm for all 5 subjects plotted versus time. Figure 4.26 shows the same results for HapticMASTER supported movements. There was no statistically significant relationship between time and vertical AROM for Armon Edero supported movements for the dominant arm (Spearman's Correlation, r_s=0.139, p=0.621). There was no statistically significant relationship between time and vertical AROM for

HapticMASTER supported movements for the dominant arm (Spearman's Correlation, r_s=0.077, p=0.785).

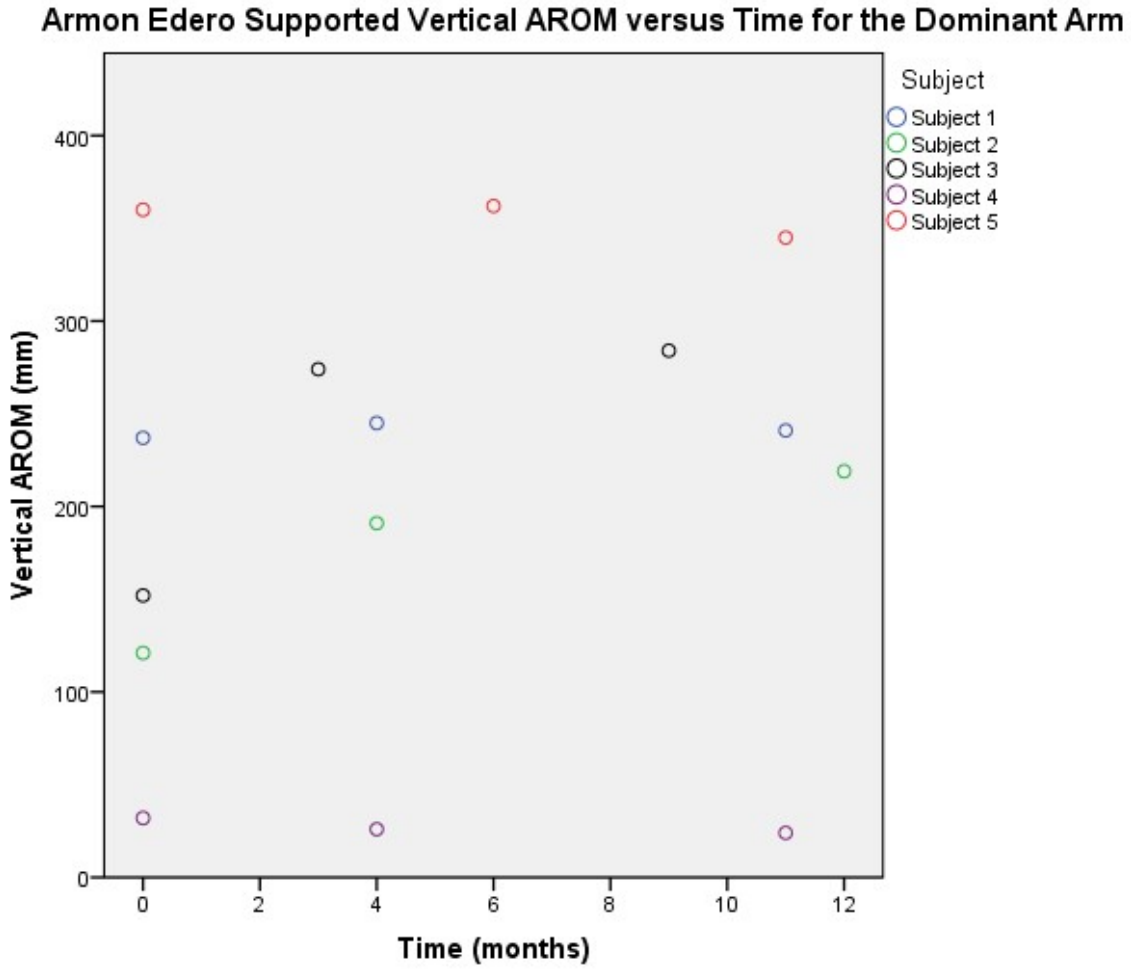

Figure 4.25 Vertical AROM for Armon Edero supported movements for the dominant arm for all 5 subjects versus time.

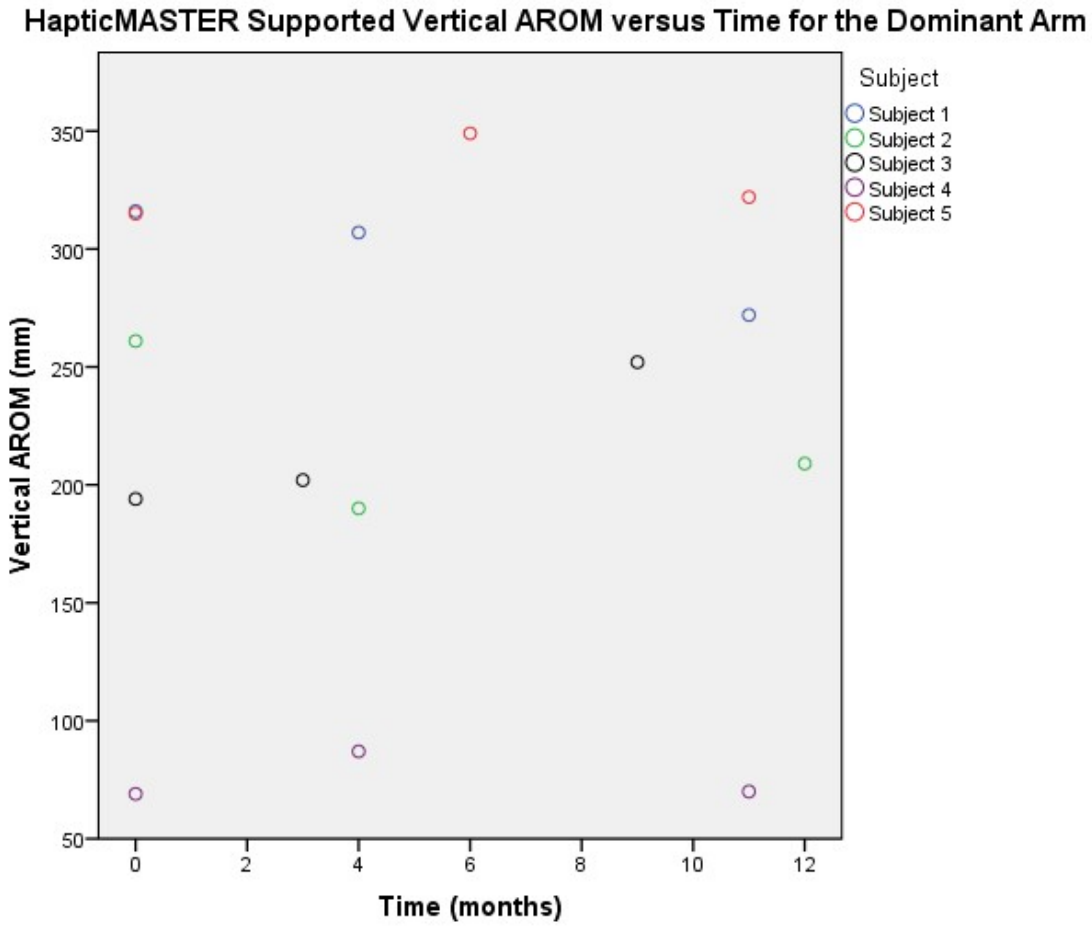

Figure 4.26 Vertical AROM for HapticMASTER supported movements for the dominant arm for all 5 subjects versus time.

Figure 4.27 shows the vertical AROM for Armon Edero supported movements for the non-dominant arm for all 5 subjects plotted versus time. Figure 4.28 shows the same results for HapticMASTER supported movements. There was no statistically significant relationship between time and vertical AROM for Armon Edero supported movements for the non-dominant arm (Spearman's Correlation, r_s=0.194, p=0.488). There was no statistically significant relationship between time and vertical AROM for HapticMASTER supported movements for the non-dominant arm (Spearman's Correlation, r_s=-0.009, p=0.974).

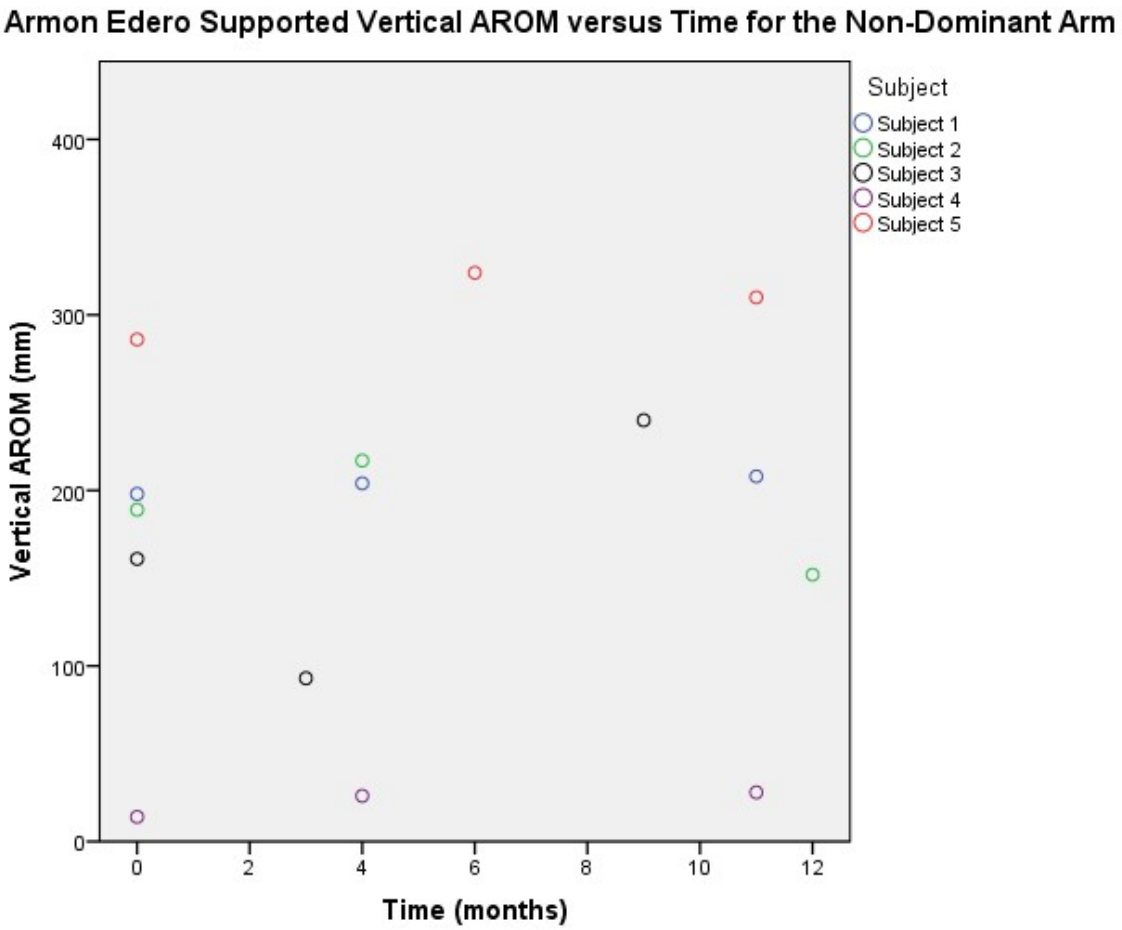

Figure 4.27 Vertical AROM for Armon Edero supported movements for the non-dominant arm for all 5 subjects versus time.

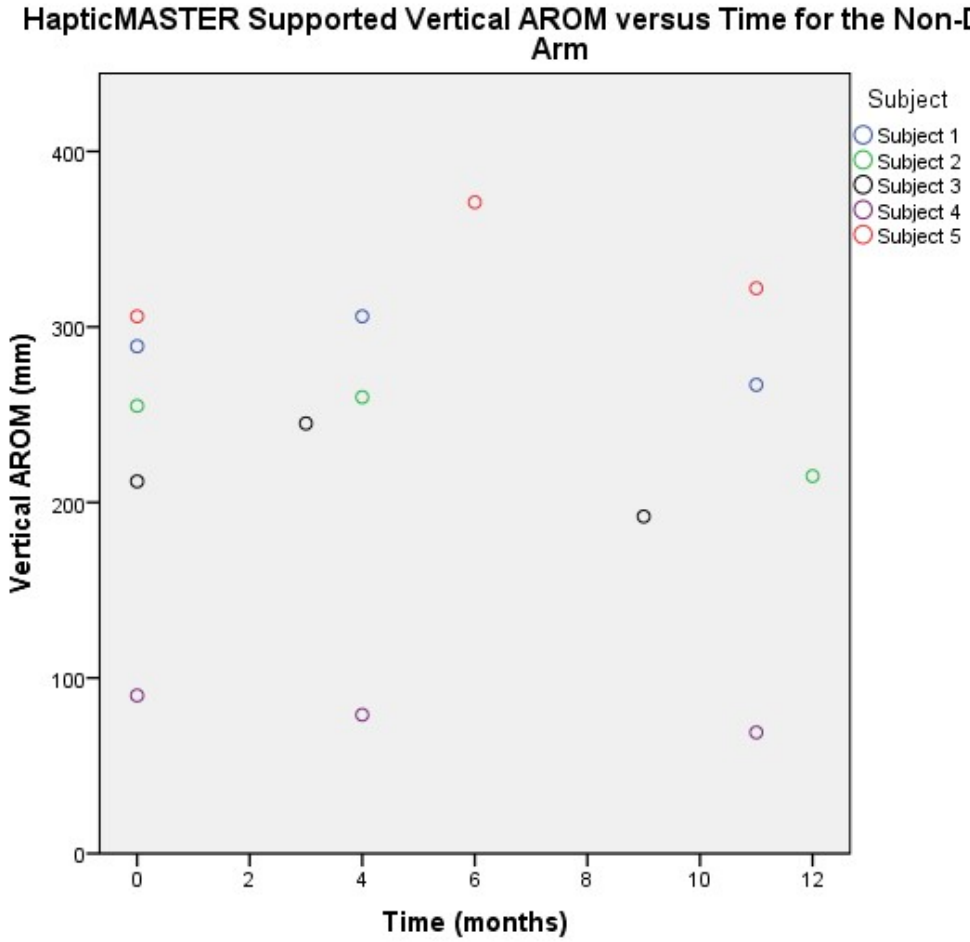

Figure 4.28 Vertical AROM for HapticMASTER supported movements for the non-dominant arm for all 5 subjects versus time.

Figure 4.29 shows the subject-reported visual analog scale exertion level scores for Armon Edero supported movements for all 5 subjects plotted versus time. Figure 4.30 shows the same results for HapticMASTER supported movements. There was no statistically significant relationship between time and subject-reported exertion level scores for Armon Edero supported movements (Spearman's Correlation, r_s=0.193, p=0.491). There was no statistically significant relationship between time and subject-reported exertion level scores for HapticMASTER supported movements (Spearman's Correlation, r_s=-0.413, p=0.126).

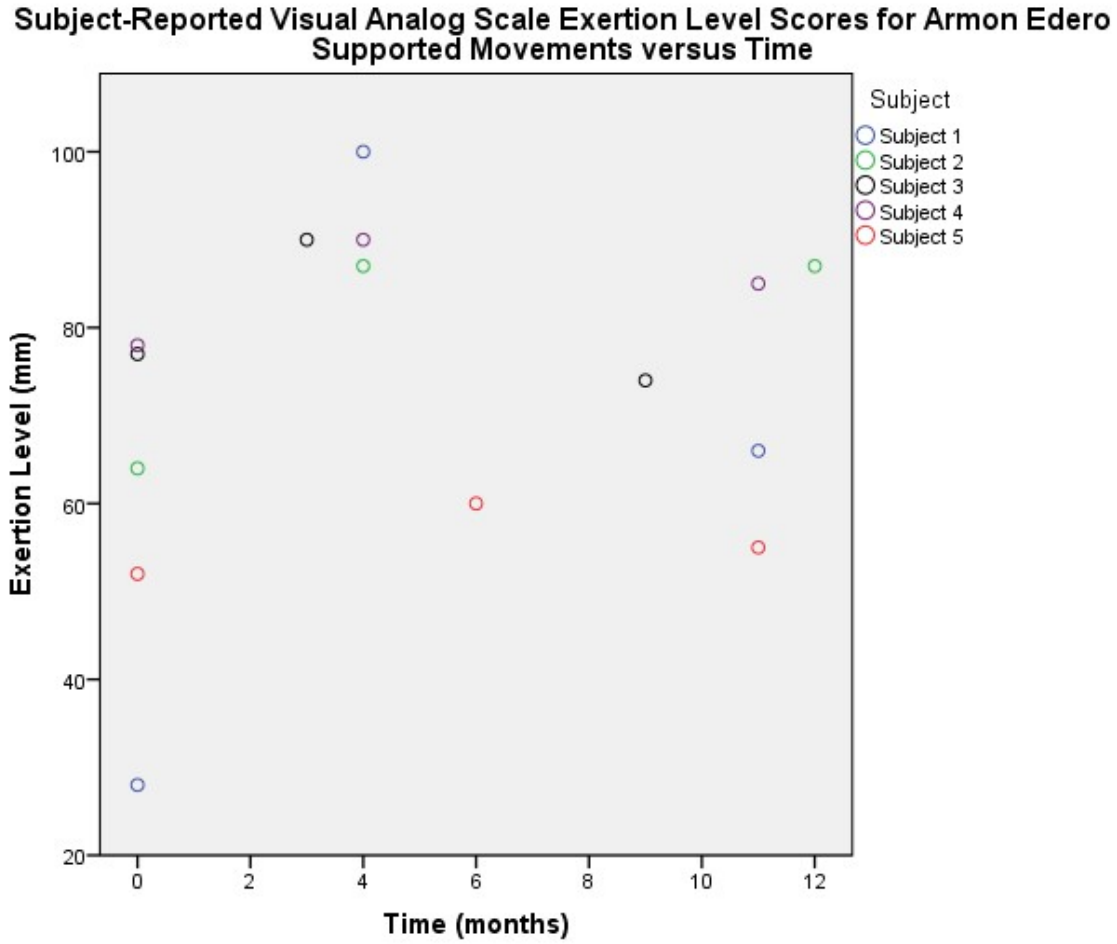

Figure 4.29 Subject-reported visual analog scale exertion level scores for Armon Edero supported movements for all 5 subjects versus time.

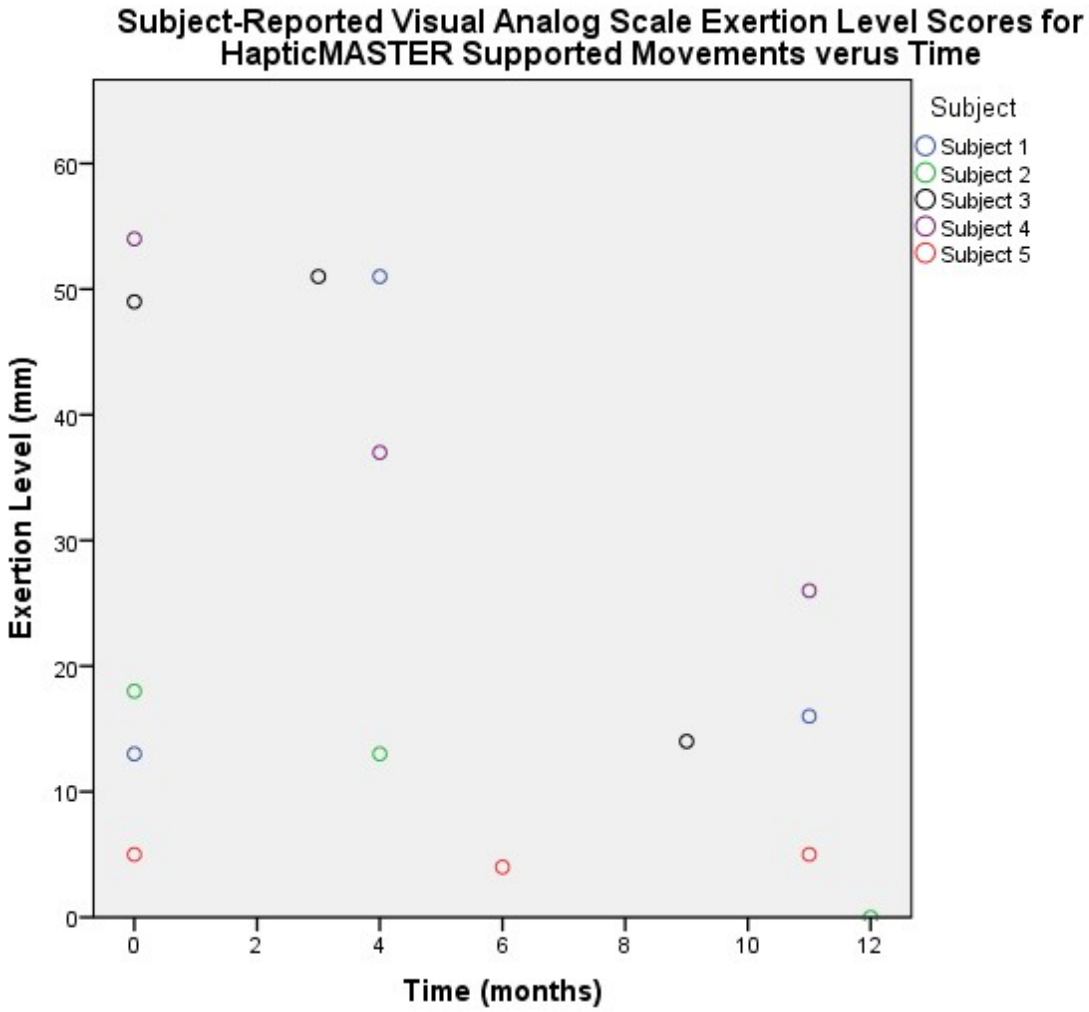

Figure 4.30 Subject-reported visual analog scale exertion level scores for HapticMASTER supported movements for all 5 subjects versus time.

Figure 4.31 shows the MVIC results for the dominant elbow for each of the 5 subjects and the control subject across 3 sessions. Figure 4.32 shows the MVIC results for the non-dominant elbow for each of the 5 subjects and the control subject across 3 sessions. Elbow MVIC results are for the following movements: elbow flexion, elbow extension, elbow external rotation, and elbow internal rotation.

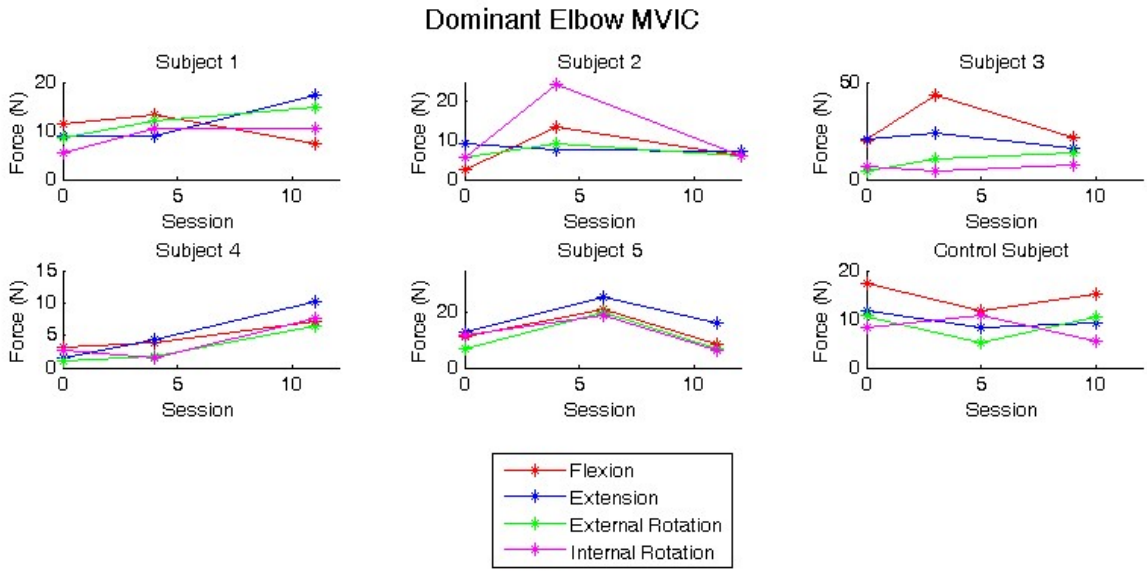

Figure 4.31 Dominant elbow MVIC results for each of the 5 subjects and 1 control subject with DMD across 3 sessions.

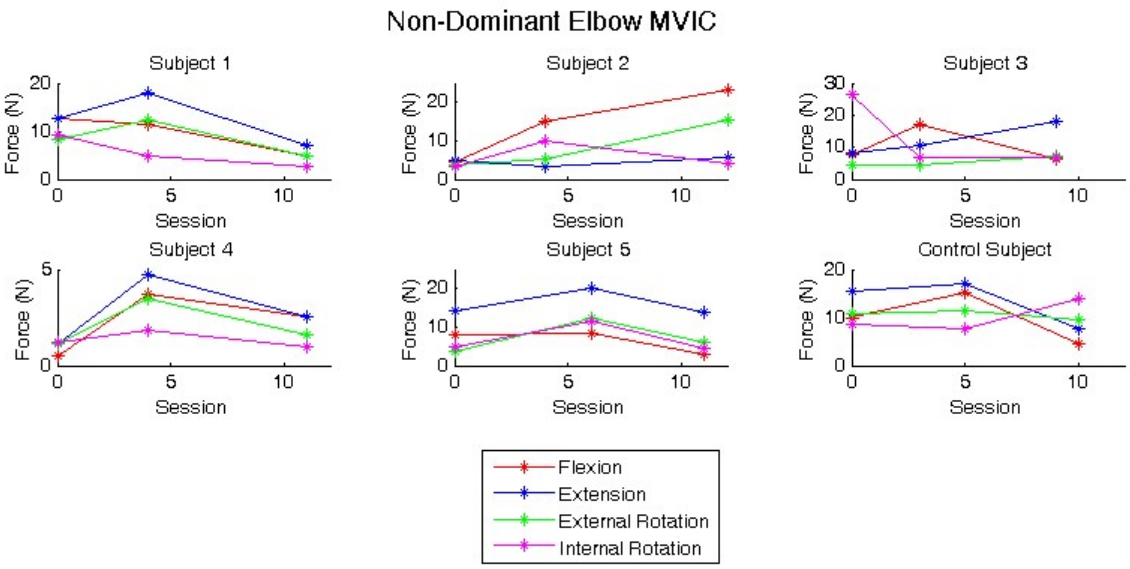

Figure 4.32 Non-dominant elbow MVIC results for each of the 5 subjects and 1 control subject with DMD across 3 sessions.

Figure 4.33 shows the MVIC results for the dominant shoulder for each of the 5 subjects and the control subject across 3 sessions. Figure 4.34 shows the MVIC results for the non-dominant shoulder for each of the 5 subjects and the control subject across 3 sessions. Shoulder MVIC results are for the following movements: shoulder abduction, shoulder adduction, shoulder flexion, and shoulder extension.

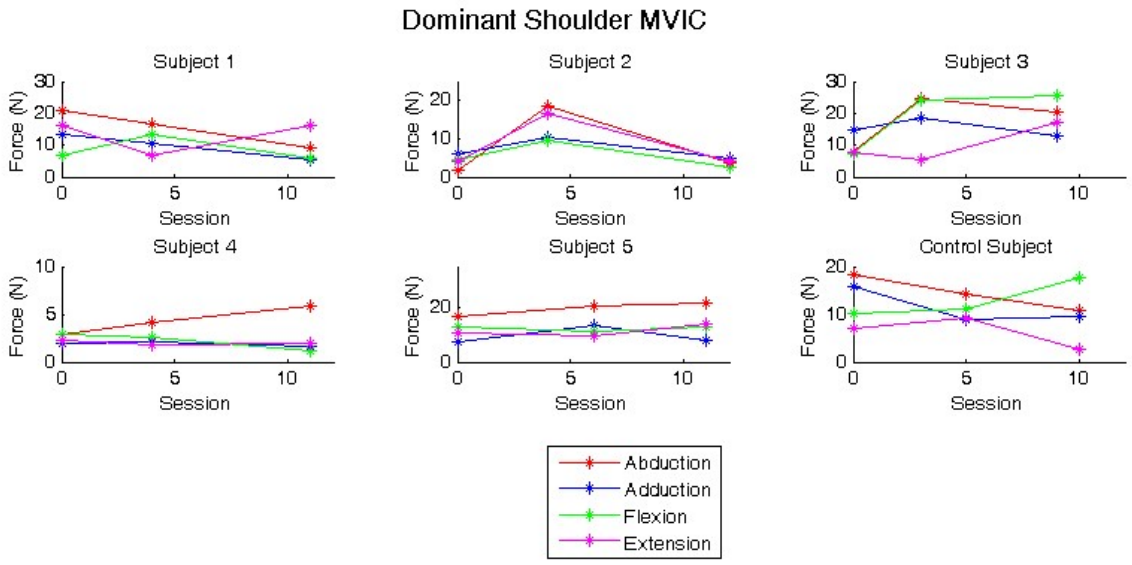

Figure 4.33 Dominant shoulder MVIC results for each of the 5 subjects and 1 control subject with DMD across 3 sessions.

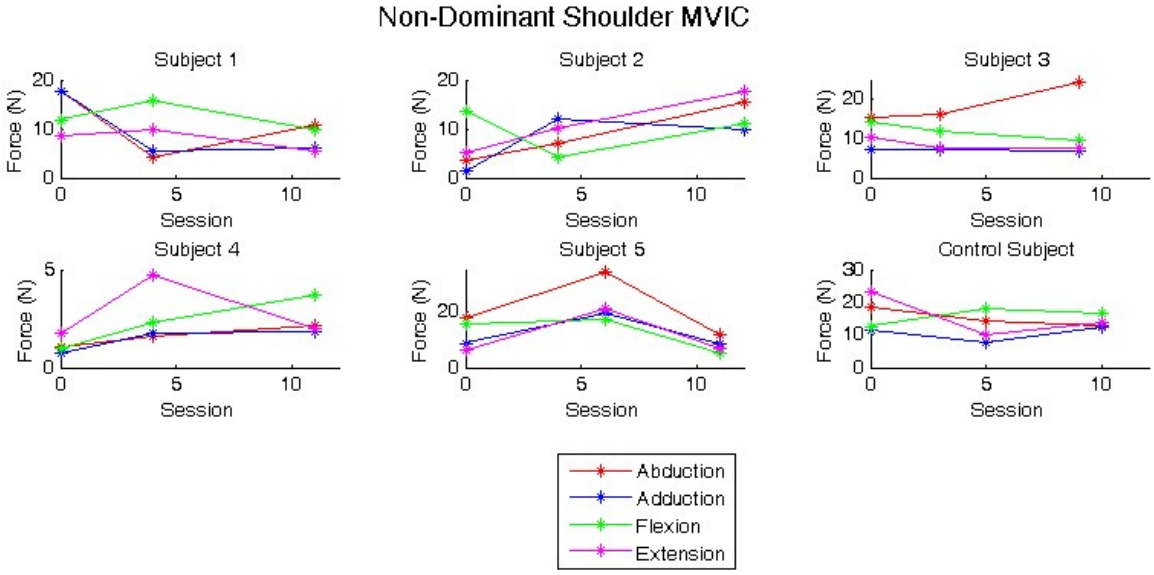

Figure 4.34 Non-dominant shoulder MVIC results for each of the 5 subjects and 1 control subject with DMD across 3 sessions.

Figure 4.35 shows the reachable surface area and vertical AROM results for Armon Edero and HapticMASTER supported movements plotted versus shoulder abduction MVIC for the dominant arm. A Shapiro-Wilk test revealed that the population

for for dominant abduction MVIC has a significant deviation from normality (p=0.043). There was no significant relationship between dominant shoulder abduction MVIC and Armon Edero and supported reachable surface area scores for the dominant arm (Spearman's Correlation, r_s=0.503, p=0.056). There was no significant relationship between dominant shoulder abduction MVIC and HapticMASTER supported reachable surface area scores for the dominant arm (Spearman's Correlation, r_s=0.416, p=0.123). There was a significant positive correlation between dominant shoulder abduction MVIC and Armon Edero supported vertical AROM for the dominant arm (Spearman's Correlation, r_s=0.711, p=0.003). There was also a significant positive correlation between dominant shoulder abduction MVIC and HapticMASTER supported vertical AROM for the dominant arm (Spearman's Correlation, r_s=0.518, p=0.048).

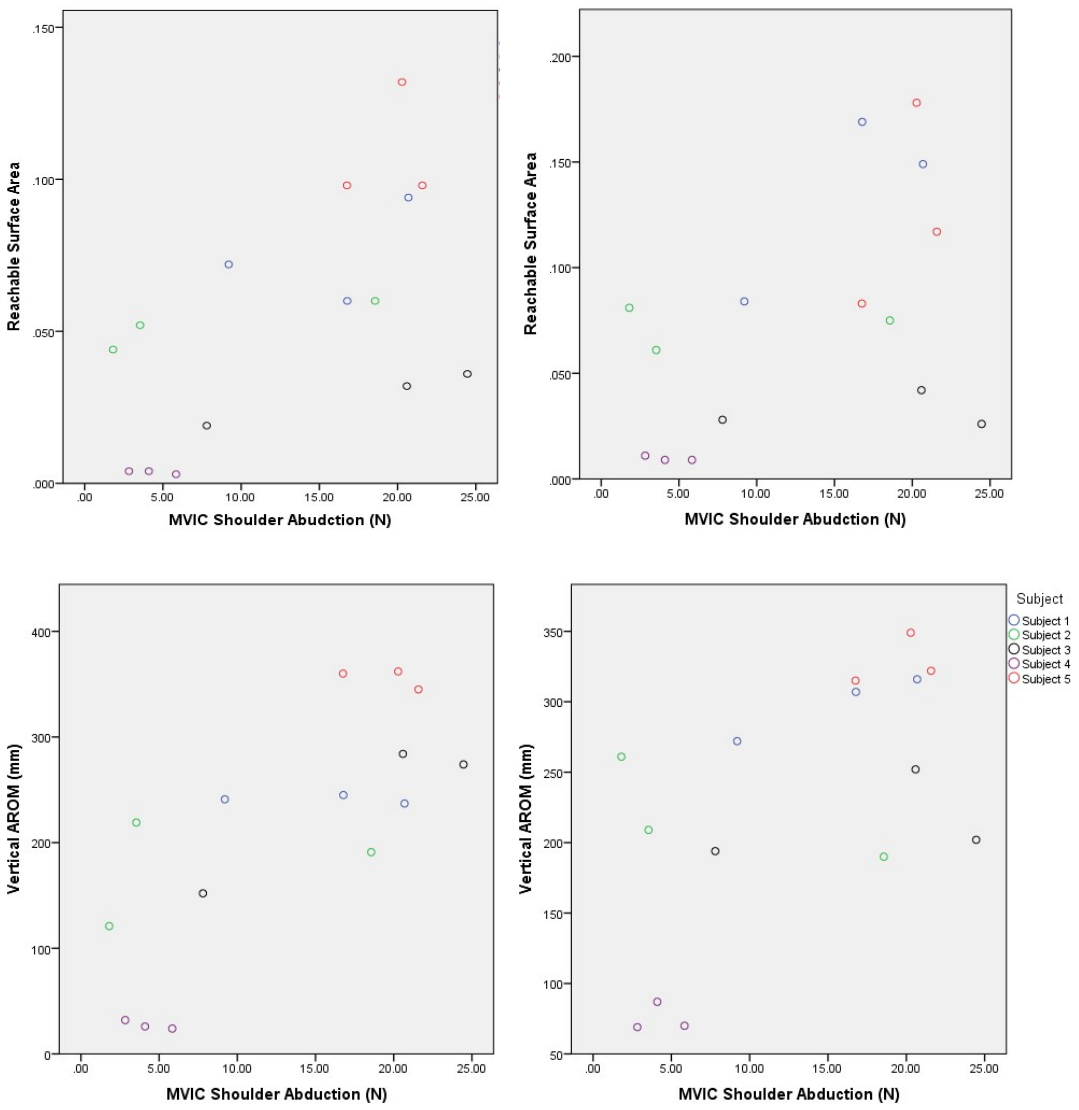

Figure 4.35 Reachable surface area for Armon Edero (upper left) and HapticMASTER supported movements (upper right) and vertical AROM for Armon Edero (lower left) and HapticMASTER (lower right) supported movements plotted versus shoulder abduction MVIC for the dominant arm.

Figure 4.36 shows the reachable surface area and vertical AROM results for Armon Edero and HapticMASTER supported movements plotted versus shoulder adduction MVIC for the dominant arm. A Shapiro-Wilk test revealed that the population for dominant shoulder adduction MVIC is approximately normal (p=0.578). A Shapiro-Wilk test also revealed that the population for reachable surface area and vertical AROM

for Armon Edero and HapticMASTER supported movements for the dominant arm were approximately normal (p=0.467, p=0.130, p=0.175, p=0.094). There was no significant relationship between shoulder adduction MVIC and Armon Edero supported reachable surface area for the dominant arm (Pearson's r, r=0.356, p=0.193). There was no significant relationship between shoulder adduction MVIC and HapticMASTER supported reachable surface area for the dominant arm (Person's r, r=0.346, p=0.206). There was a significant positive correlation between shoulder adduction MVIC and Armon Edero vertical AROM for the dominant arm (Perons' r, r=0.595, p=0.019). There was also a significant positive correlation between shoulder adduction MVIC and HapticMASTER supported vertical AROM for the dominant arm (Person's r, r=0.519, p=0.047).

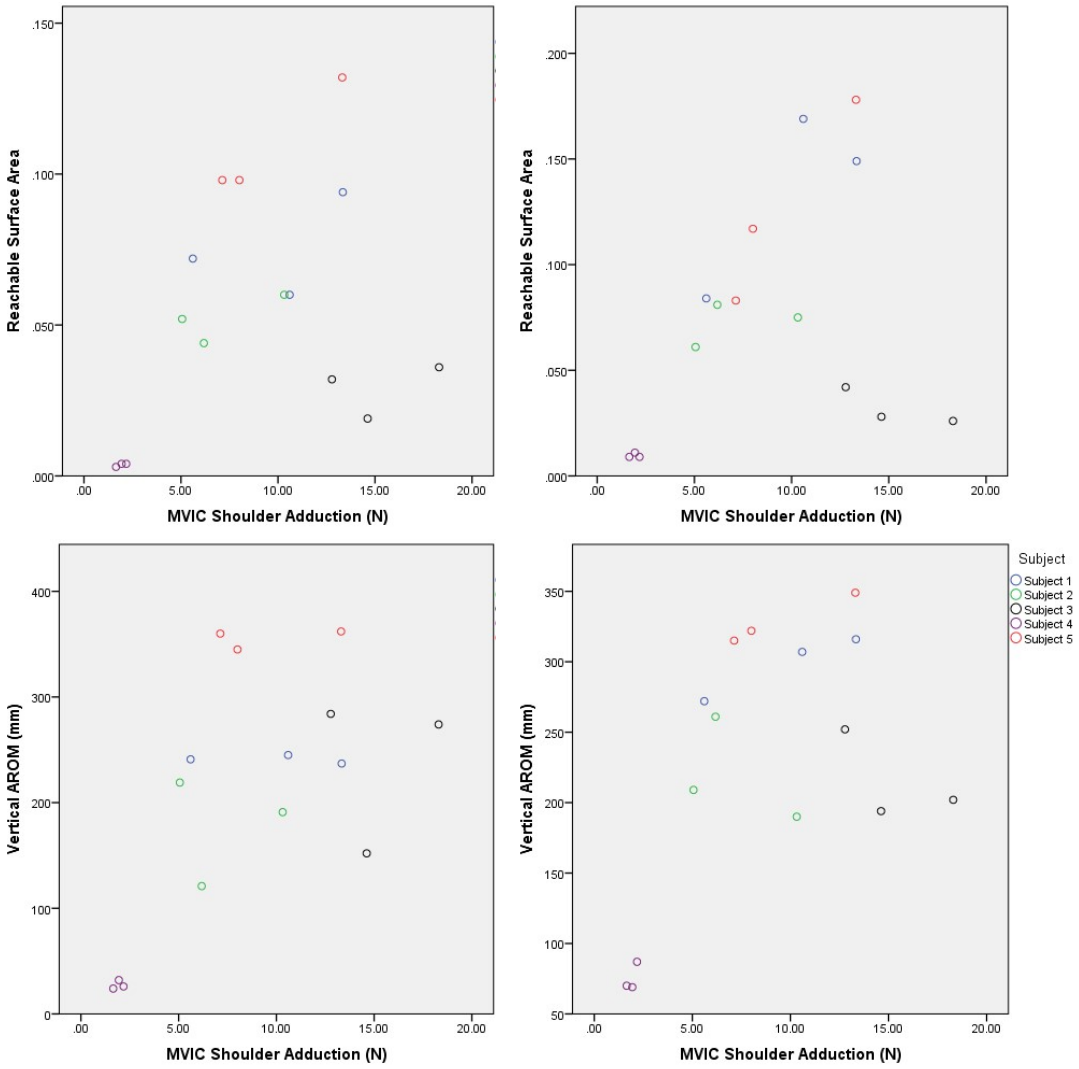

Figure 4.36 Reachable surface area for Armon Edero (upper left) and HapticMASTER supported movements (upper right) and vertical AROM for Armon Edero (lower left) and HapticMASTER (lower right) supported movements plotted versus shoulder adduction MVIC for the dominant arm.

Figure 4.37 shows the reachable surface area and vertical AROM results for Armon Edero and HapticMASTER supported movements plotted versus shoulder flexion MVIC for the dominant arm. A Shapiro-Wilk test revealed that the population for MVIC for dominant flexion has a significant deviation from normality ($p=0.043$). There was no significant relationship between dominant shoulder flexion and Armon Edero and

supported reachable surface area scores (Spearman's Correlation, r_s=0.430, p=0.110). There was no significant relationship between dominant shoulder flexion MVIC and HapticMASTER supported reachable surface area scores (Spearman's Correlation, r_s=0.422, p=0.117). There was a significant positive correlation between dominant shoulder flexion MVIC and Armon Edero supported vertical AROM (Spearman's Correlation, r_s=0.789, p<0.000). There was no significant correlation between dominant shoulder flexion MVIC and HapticMASTER supported vertical AROM (Spearman's Correlation, r_s=0.493, p=0.062).

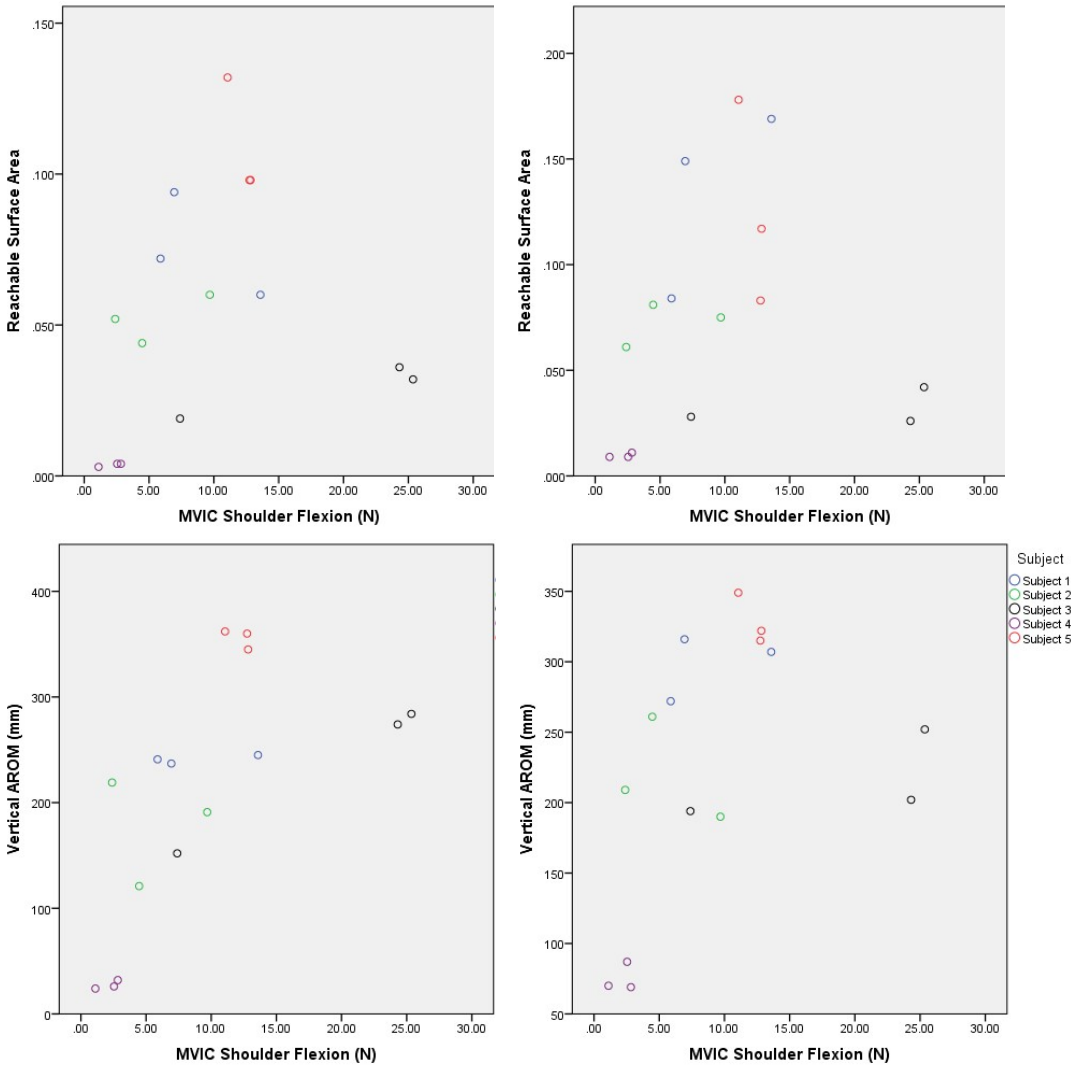

Figure 4.37 Reachable surface area for Armon Edero (upper left) and HapticMASTER supported movements (upper right) and vertical AROM for Armon Edero (lower left) and HapticMASTER (lower right) supported movements plotted versus shoulder flexion MVIC for the dominant arm.

Figure 4.38 shows the reachable surface area and vertical AROM results for Armon Edero and HapticMASTER supported movements plotted versus shoulder extension MVIC for the dominant arm. A Shapiro-Wilk test revealed that the population for dominant shoulder extension MVIC is approximately normal (p=0.069). There was a significant positive correlation between shoulder extension MVIC and Armon Edero supported reachable surface area for the dominant arm (Persons' r, r=0.583, p=0.023).

There was no significant relationship between shoulder extension MVIC and HapticMASTER supported reachable surface area for the dominant arm (Person's r, r=0.453, p=0.090). There was a significant positive correlation between shoulder extension MVIC and Armon Edero supported vertical AROM for the dominant arm (Person's r, r=0.637, p=0.011). There was also a significant positive correlation between shoulder extension MVIC and HapticMASTER supported vertical AROM for the dominant arm (Person's r, r=0.620, p=0.014).

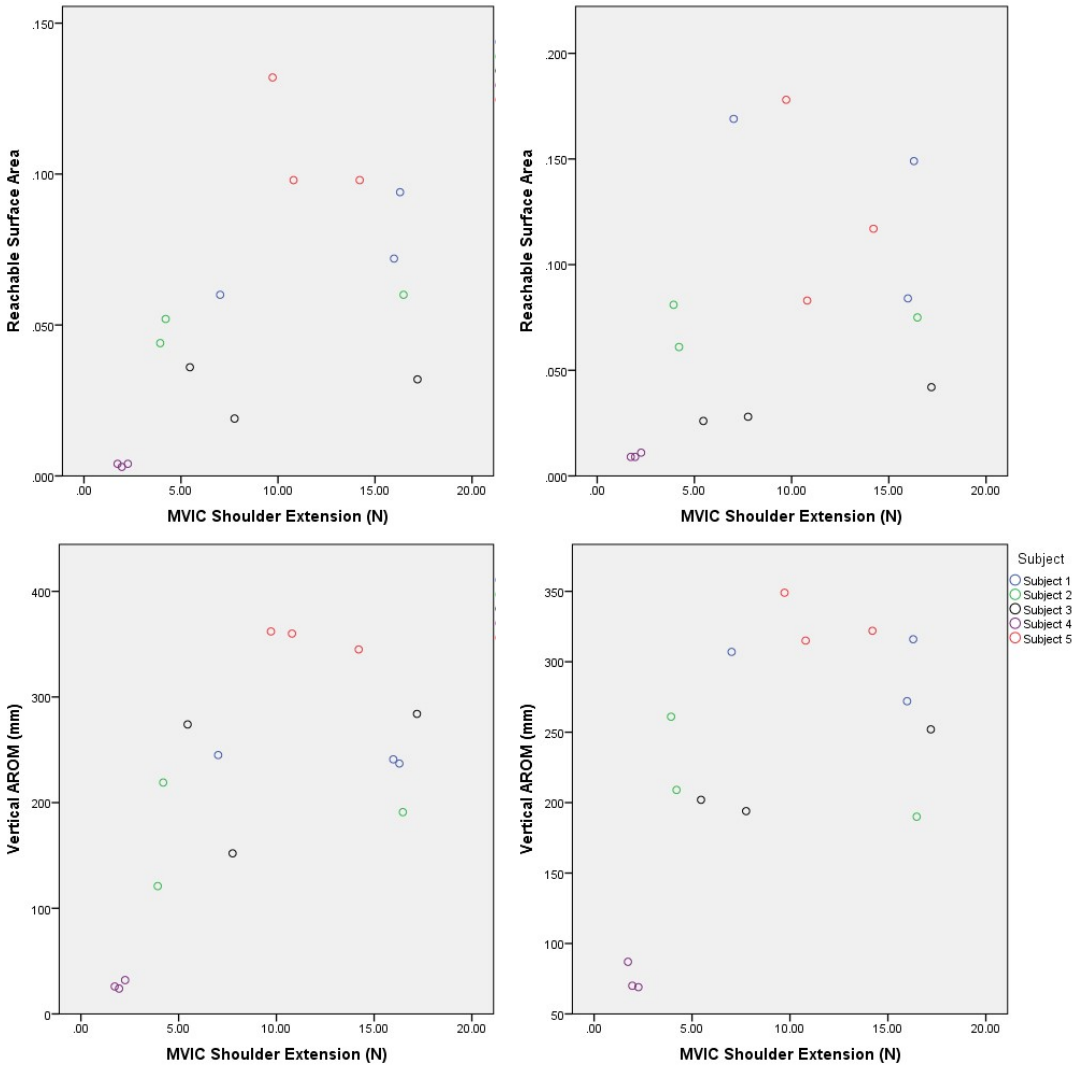

Figure 4.38 Reachable surface area for Armon Edero (upper left) and HapticMASTER supported movements (upper right) and vertical AROM for Armon Edero (lower left) and HapticMASTER (lower right) supported movements plotted versus shoulder extension MVIC for the dominant arm.

Figure 4.39 shows the reachable surface area and vertical AROM results for Armon Edero and HapticMASTER supported movements plotted versus shoulder abduction MVIC for the non-dominant arm. A Shapiro-Wilk test revealed that the population for non-dominant shoulder abduction MVIC is approximately normal ($p=0.211$). A Shapiro-Wilk test also revealed that the population for reachable surface area and vertical AROM for Armon Edero and HapticMASTER supported movements

for the non-dominant arm were approximately normal (p=0.205, p=0.562, p=0.280, p=0.160). There was a significant positive correlation between shoulder abduction MVIC and Armon Edero supported reachable surface area for the non-dominant arm (Person's r, r=0.586, p=0.022). There was no significant relationship between shoulder abduction MVIC and HapticMASTER supported reachable surface area for the non-dominant arm (Persons's r, r=0.478, p=0.072). There was a significant positive correlation between shoulder abduction MVIC and Armon Edero supported vertical AROM for the non-dominant arm (Person's r, r=0.651, p=0.009). There was also a significant positive correlation between shoulder abduction MVIC and HapticMASTER supported vertical AROM for the non-dominant arm (Person's r, r=0.585, p=0.022).

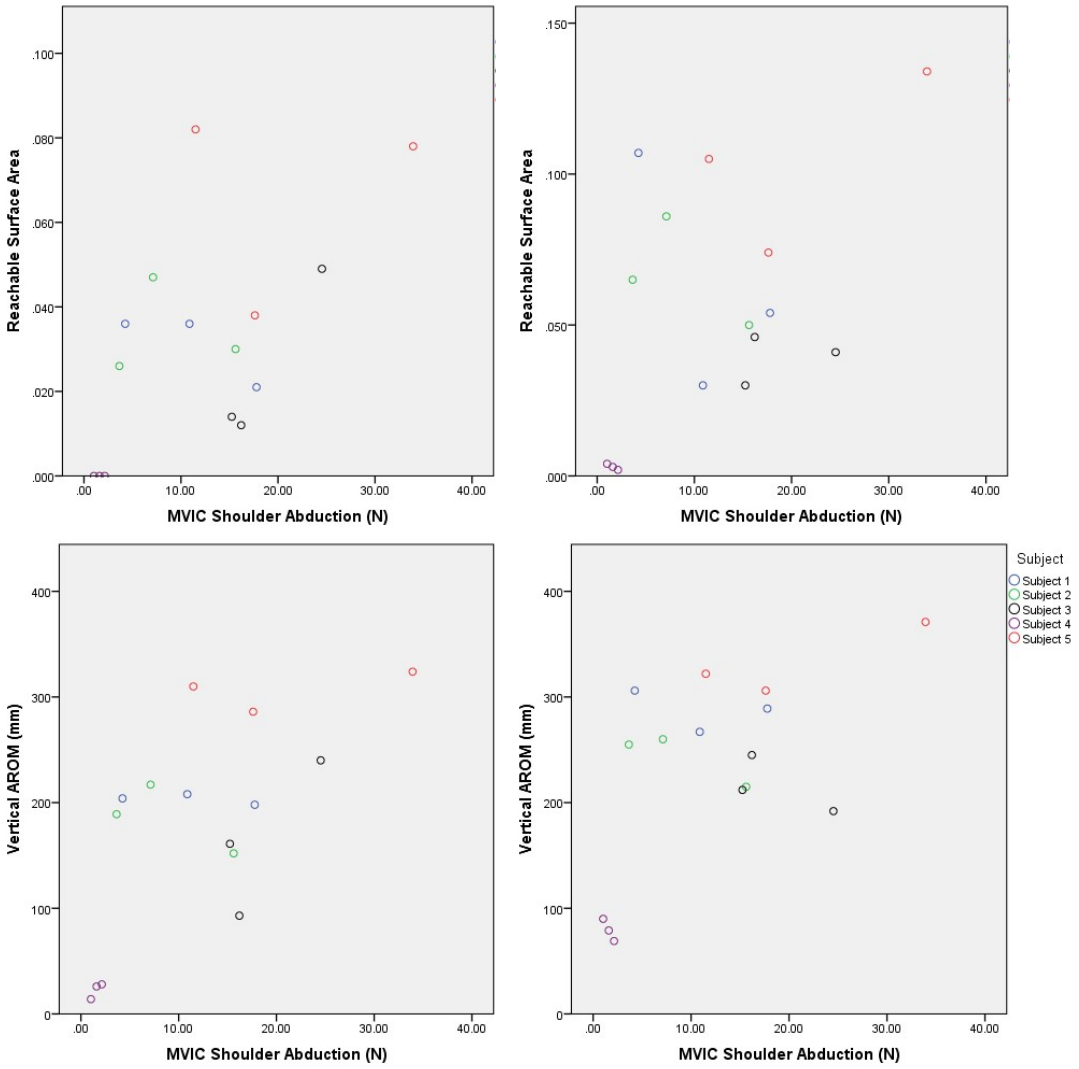

Figure 4.39 Reachable surface area for Armon Edero (upper left) and HapticMASTER supported movements (upper right) and vertical AROM for Armon Edero (lower left) and HapticMASTER (lower right) supported movements plotted versus shoulder abduction MVIC for the non-dominant arm.

Figure 4.40 shows the reachable surface area and vertical AROM results for Armon Edero and HapticMASTER supported movements plotted versus shoulder adduction MVIC for the non-dominant arm. A Shapiro-Wilk test revealed that the population for non-dominant shoulder adduction MVIC is approximately normal ($p=0.130$). There was a significant positive correlation between shoulder adduction MVIC and Armon Edero supported reachable surface area for the non-dominant arm

(Persons' r, r=0.582, p=0.023). There was a significant positive correlation between shoulder adduction MVIC and HapticMASTER supported reachable surface area for the non-dominant arm (Person's r, r=0.629, p=0.012). There was a significant positive correlation between shoulder adduction MVIC and Armon Edero supported vertical AROM for the non-dominant arm (Person's r, r=0.642, p=0.010). There was also a significant positive correlation between shoulder adduction MVIC and HapticMASTER supported vertical AROM for the non-dominant arm (Person's r, r=.699, p=0.004).

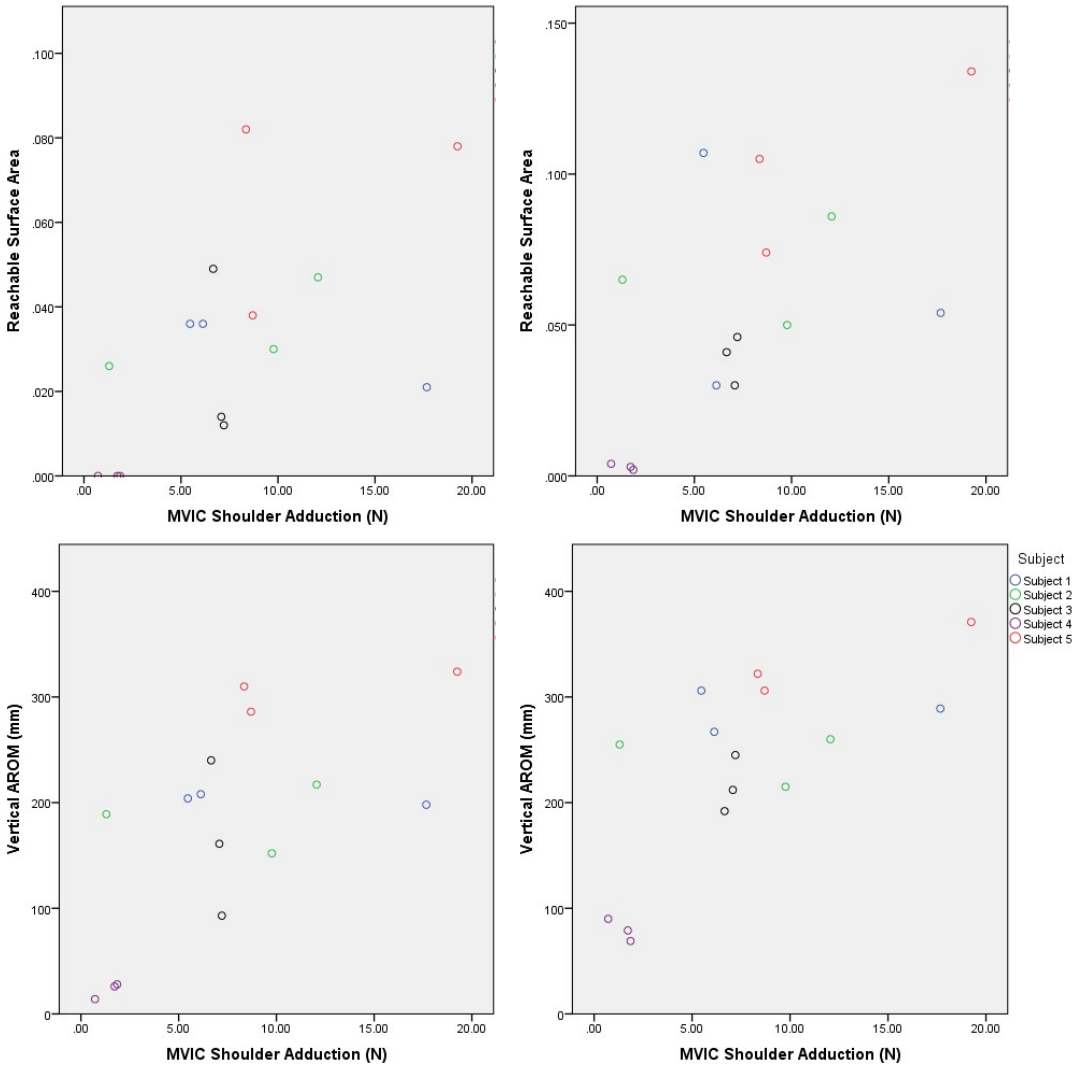

Figure 4.40 Reachable surface area for Armon Edero (upper left) and HapticMASTER supported movements (upper right) and vertical AROM for Armon Edero (lower left) and HapticMASTER (lower right) supported movements plotted versus shoulder adduction MVIC for the non-dominant arm.

Figure 4.41 shows the reachable surface area and vertical AROM results for Armon Edero and HapticMASTER supported movements plotted versus shoulder flexion MVIC for the non-dominant arm. A Shapiro-Wilk test revealed that the population for non-dominant shoulder flexion MVIC is approximately normal (p=0.290). There was no significant relationship between shoulder flexion MVIC and Armon Edero supported

reachable surface area for the non-dominant arm (Person's r, r=0.334, p=0.223). There was a significant positive correlation between shoulder flexion MVIC and HapticMASTER supported reachable surface area for the non-dominant arm (Person's r, r=0.562, p=0.029). There was a significant positive correlation between shoulder flexion MVIC and Armon Edero supported vertical AROM for the non-dominant arm (Person's r, r=0.587, p=0.021). There was also a significant positive correlation between shoulder flexion MVIC and HapticMASTER supported vertical AROM for the non-dominant arm (Person's r, r=0.717, p=0.003).

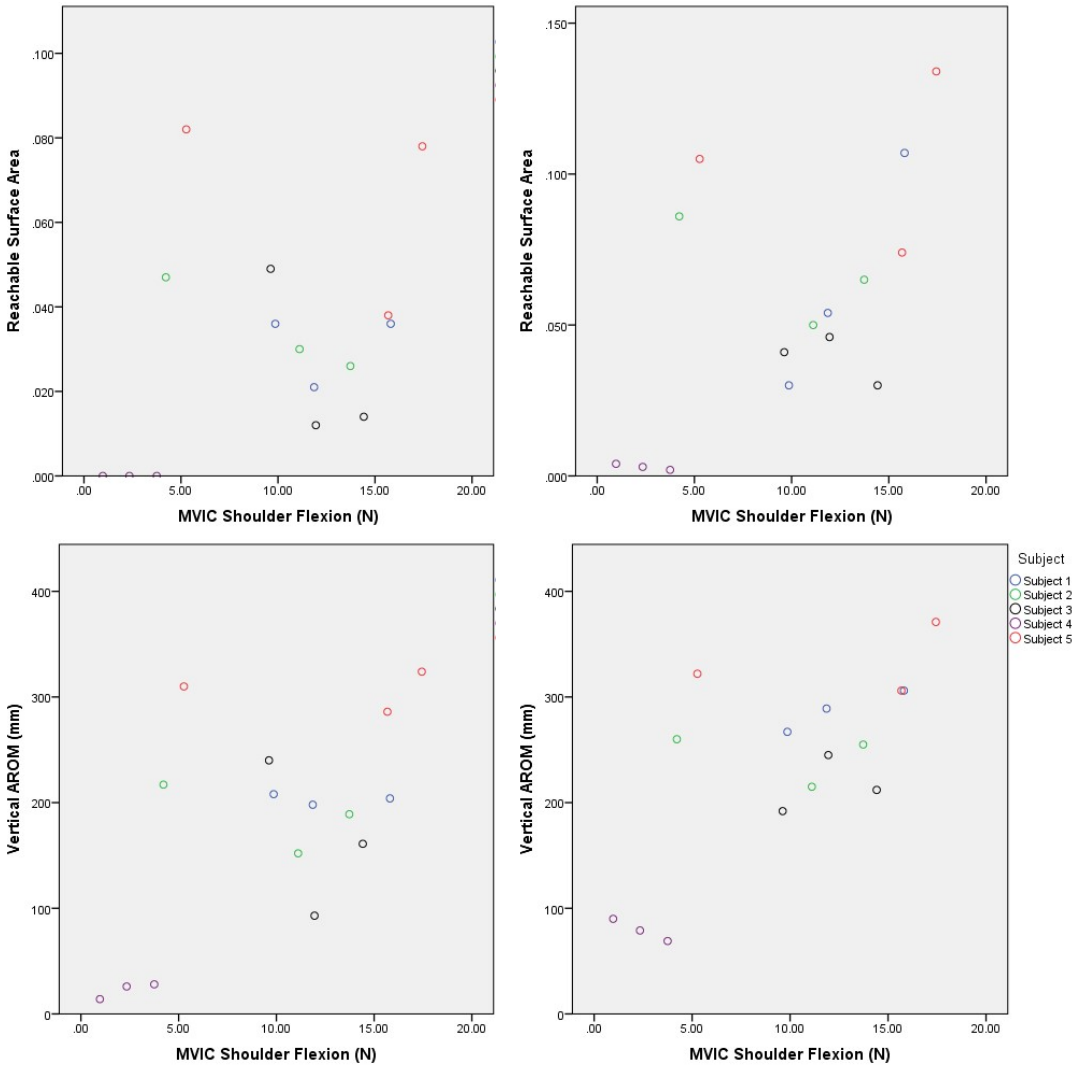

Figure 4.41 Reachable surface area for Armon Edero (upper left) and HapticMASTER supported movements (upper right) and vertical AROM for Armon Edero (lower left) and HapticMASTER (lower right) supported movements plotted versus shoulder flexion MVIC for the non-dominant arm.

Figure 4.42 shows the reachable surface area and vertical AROM results for Armon Edero and HapticMASTER supported movements plotted versus shoulder extension MVIC for the non-dominant arm. A Shapiro-Wilk test revealed that the population for MVIC for non-dominant shoulder extension has a significant deviation from normality ($p=0.050$). There was no significant relationship between non-dominant shoulder extension MVIC and Armon Edero and supported reachable surface area scores

(Spearman's Correlation, r_s=0.513, p=0.051). There was a significant positive correlation between non-dominant shoulder extension MVIC and HapticMASTER supported reachable surface area scores (Spearman's Correlation, r_s=0.586, p=0.022). There was no significant relationship between non-dominant shoulder extension MVIC and Armon Edero supported vertical AROM (Spearman's Correlation, r_s=0.456, p=0.088). There was no significant correlation between non-dominant shoulder extension MVIC and HapticMASTER supported vertical AROM (Spearman's Correlation, r_s=0.493, p=0.062).

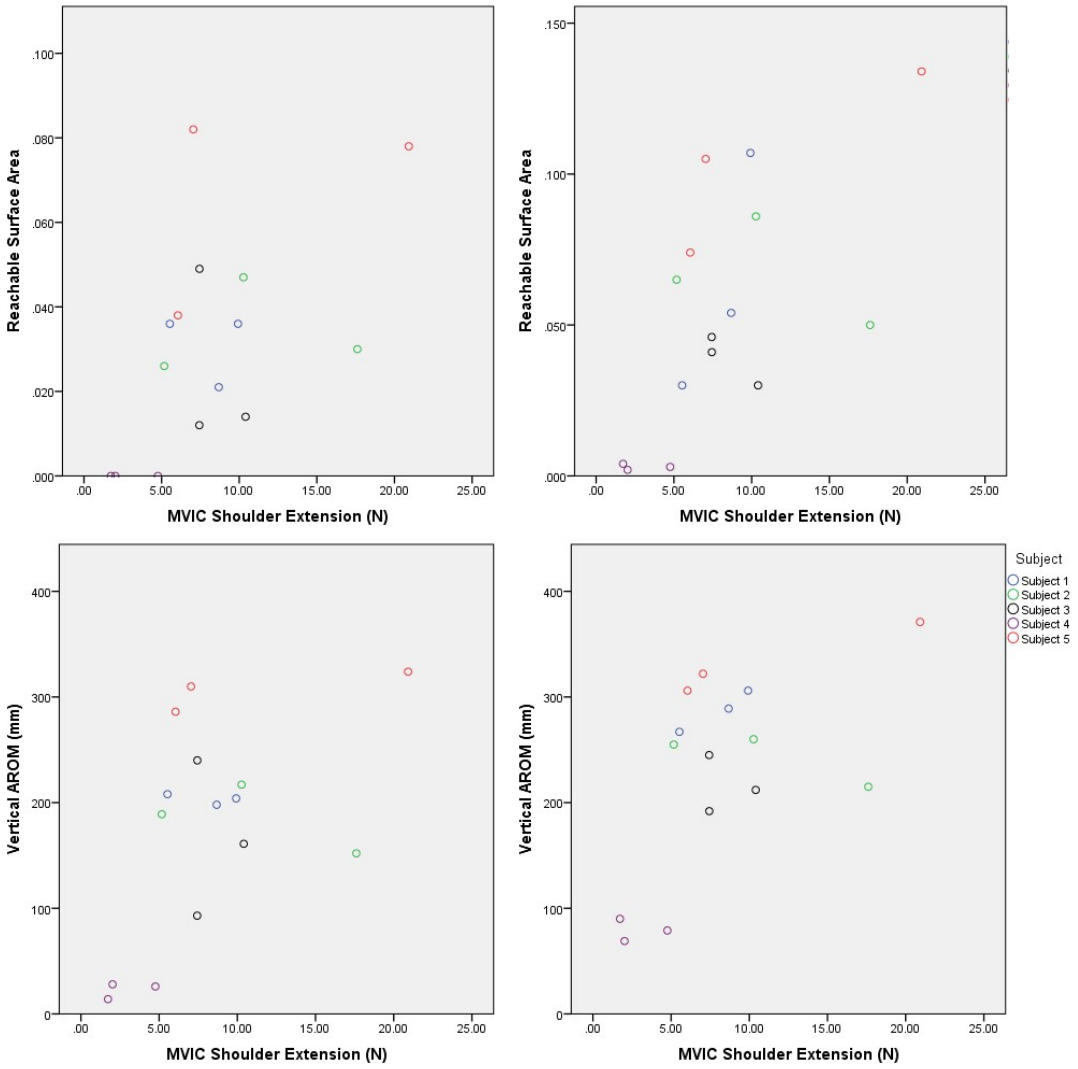

Figure 4.42 Reachable surface area for Armon Edero (upper left) and HapticMASTER supported movements (upper right) and vertical AROM for Armon Edero (lower left) and HapticMASTER (lower right) supported movements plotted versus shoulder extension MVIC for the non-dominant arm.

4.8 Sub Aim 2.2 Discussion

The results of this sub-aim track the changes in upper extremity AROM of 5 subjects with DMD when the arms are supported by the HapticMASTER and by the Armon Edero passive arm support over the course of 3 sessions. These three sessions occurred over 9 months to 1 year, depending on the subject. The results show that the mean reachable

surface area scores for HapticMASTER supported movements were greater at every session than the mean reachable surface area scores for Armon Edero supported movements for the dominant and the non-dominant arms. The results also show that the mean vertical AROM was greater for HapticMASTER supported movements at every session compared to Armon Edero supported movements for the dominant and the non-dominant arms. These results support the hypothesis that admittance control provides individuals with DMD increased AROM compared to a commercially available passive arm support due to the benefits of admittance control. However, these differences were not statistically significant. Additionally, the reachable surface area scores and vertical AROM did not decrease over time as expected. These results can be explained by the limited number of subjects included in this study and the variability in progressive loss of muscle strength in DMD. The progressive upper extremity functional loss associated with DMD is highly variable from individual to individual and can depend on secondary factors such as disuse atrophy and contractures. For this reason, a large sample size may be necessary to see statistically significant differences in HapticMASTER and Armon Edero supported AROM over multiple sessions. However, due to the small population of individuals with DMD and limited number of those individuals willing to participate in a longitudinal study requiring multiple visits prevented a study of this nature. In addition, due to the variability in progressive loss of upper extremity function, it is possible that results would demonstrate decreasing AROM over time for Armon Edero and HapticMASTER supported movements if the study were conducted over multiple years instead of over a single year. Based on the results of this study, 9-12 months is not a sufficient amount of time to see statistically significant changes in AROM over time.

This is further substantiated by the passive and unsupported reachable surface area data, as these results did not demonstrate a trend of decreased upper extremity function or increased development of contractures for all subjects over the course of 3 sessions.

The mean subject-reported exertion level scores were smaller for the HapticMASTER compared to the Armon Edero for every session, indicated greater ease of movement provided by the HapticMASTER robot. The mean Armon Edero exertion level scores increased with session number indicating an increase in effort required to generate movements with the Armon Edero over time. Conversely, the mean HapticMASTER exertion level scores decreased with session number indicating a perceived decrease in effort required to generate movements with the HapticMASTER over time. These results support the hypothesis that the difference between the ease of movement provided by the HapticMASTER compared to the Armon Edero will increase over time as an individual loses muscle strength. However, these differences and trends were not statistically significant. It is expected that a study with a larger sample size conducted over a longer period of time may reveal statistically significant results; however, the small sample size and limited number of individuals willing to participate in a long-term study prevented a study of this nature.

There were no statistically significant correlations between time and reachable surface area scores, vertical AROM, or subject-reported exertion level scores. These results can be explained by the relatively short duration of the longitudinal study (9-12 months) given the variability associated with loss of upper extremity function in individuals with DMD. It is expected that a study run for multiple years may reveal correlations between HapticMASTER and Armon Edero reachable surface area scores,

vertical AROM, and exertion level scores. An additional limitation of this study regarding study duration and individuals sessions was the difference in timing of sessions from subject to subjects. It was originally intended that data collection sessions would occur at the same intervals for each subject; however, scheduling conflicts of the subjects and their families and the distance some subjects had to travel to the laboratory caused differences in timing for data collection sessions. Future studies could avoid this limitation, and potentially provide motivation for additional subjects to enroll in a study, by having the researchers travel to the subjects' homes instead of conducting the data collection in the laboratory.

Dominant shoulder abduction MVIC and dominant shoulder adduction were both positively correlated with Armon Edero and HapticMASTER supported vertical AROM. Dominant shoulder flexion was positively correlated with Armon Edero supported vertical AROM. Dominant shoulder extension MVIC was positively correlated with Armon Edero supported reachable surface area scores and HapticMASTER supported vertical AROM. Non-dominant shoulder abduction MVIC was positively correlated with Armon Edero supported reachable surface area scores and Armon Edero and HapticMASTER supported vertical AROM. Non-dominant shoulder adduction MVIC was positively correlated with Armon Edero and HapticMASTER supported reachable surface area scores and vertical AROM. Non-dominant shoulder flexion MVIC was positively correlated with HapticMASTER supported reachable surface area scores and Armon Edero and HapticMASTER vertical AROM. And, non-dominant shoulder extension was positively correlated with HapticMASTER supported reachable surface area scores. For the remaining MVIC values, there was no statistically significant

correlation with reachable surface area scores or vertical AROM. It was expected that all AROM outcome measures would be positively correlated with shoulder MVIC scores given the dependence of upper extremity AROM on upper extremity strength. The fact that this trend was not seen for all outcome measures can be explained by the limitations observed during data collection of MVIC. Subjects were instructed to make the force sensor resisted movements with their arm and avoid compensatory movements including movement of the torso and swinging of the arm. Additionally, when making the reachable workspace movements with the Armon Edero and the HapticMASTER, subjects were instructed to only move their arm and restrict compensatory movements. However, despite being instructed to avoid compensatory movements, many of the subjects found it difficult or impossible to avoid such movements. This is likely to due the fact that these individuals regularly use compensatory movements for activities of daily living due to limited upper extremity muscle strength and have difficultly deviating from this convention. Even more, it was observed that subjects were motivated by the tasks and outcome measures in this study and tended to resort to the use of compensatory movements to achieve a maximum AROM and/or larger MVIC. The use of compensatory movements leads to variability in results as they prevent measurements from being truly representative of upper extremity function.

An additional limitation of this study was the daily changes in upper extremity function. A number of subjects stated that their upper extremity strength and energy level changes significantly from day to day. Given that this study was conducted over the course of 9-12 months, functional changes due to the progression of DMD may not be

detectible in the presence of daily changes in function. It is expected that more frequent data collection sessions over the course of multiple years would reduce this limitation.

Finally, the results from this sub-aim showed no significant decrease in AROM for HapticMASTER or Armon Edero supported movements with session number or with time. These results indicate that a period of 9-12 months is not a sufficient amount of time to observe a decrease in the AROM provided by either arm support. These results are promising given the progressive nature of DMD. They indicate that progressive loss of muscle strength over the course of about 1 year will not render either device significantly less useful in terms of the increase in function they provide compared to unsupported movements. This is a positive outcome as it indicates that an arm support or exoskeleton for individuals with DMD has the potential to be a viable commercial product given that progressive loss over 1 year does not render either device less useful. Future studies will evaluate the length of time in which either device would no longer provide a statistically similar increase in function.

CHAPTER 5

AIM 3: ADMITTANCE CONTROL TO INCREASE INDEPENDENCE

5.1 Sub Aim 3.1 Methods

The objective of this sub aim was to establish user-defined priority tasks based on tasks they have difficulty performing or cannot perform independently due to upper extremity functional deficits and would consider most important to be able to perform while using an upper extremity assistive device. Subjects were asked to report these priority tasks based on their individual daily living needs and current upper extremity functional limitations. In addition, subjects were asked to weight each priority task based on importance, using the values and corresponding importance listed in Table 5.7.

Table 5.1 Weighting Scale for Importance

Weight	Importance
0	Not at all important
1	A little important
2	Moderately important
3	Very important

Source: [51]

Subjects were be recruited for this study though the Parent Project Muscular Dystrophy DuchenneConnect registry and the Muscular Dystrophy Association. Subjects will be included in the study based on the following criteria: DMD diagnosis, inability to raise their hands to their mouth or difficulty doing so while holding a weighted object but some residual hand function (Brooke scale score of 4 or 5), and no presence of comorbidities affecting the upper extremities.

5.2 Sub Aim 3.1 Expected Results

It is expected that the subjects will report priority tasks that reflect an objective of independently performing activities of daily living such as feeding themselves, drinking and using a computer and tasks reflecting individual interests and hobbies.

5.3 Sub Aim 3.1 Results

Seven subjects with DMD who met the inclusion and exclusion criteria for this sub aim were enrolled in the study. Table 5.2 shows the age of each subject, handedness, and baseline scores of passive reachable surface area and unsupported reachable surface area for the left and right arms.

Table 5.2 Subjects Enrolled in Aim 3.1 and 3.2

Subject	Age	Hand Dominance	Passive RSA		Unsupported RSA	
			Right	Left	Right	Left
1c	26	Right	0.713	0.321	0.100	0.032
2c	21	Right	0.403	0.184	0.007	0.000
3c	15	Right	0.437	0.470	0.420	0.275
4c	14	Right	0.488	0.296	0.000	0.000
5c	26	Right	0.524	0.227	0.001	0.000
6c	27	Right	0.435	0.709	0.000	0.000
7c	11	Right	0.628	0.598	0.033	0.013

Figure 5.1 shows a histogram of all of the upper extremity priority tasks named by the 7 subjects. In total, 45 upper extremity priority tasks were named by the 7 subjects. Eating independently was a priority task named by every subject. Drinking, itching/scratching the head, face, and nose, and petting a cat or dog were tall tasks named by 5 subjects. Using a phone and using a computer were tasks named by 4 subjects.

Three subjects named brushing teeth, opening doors, adjusting glasses, picking up objects, and using a video game controller.

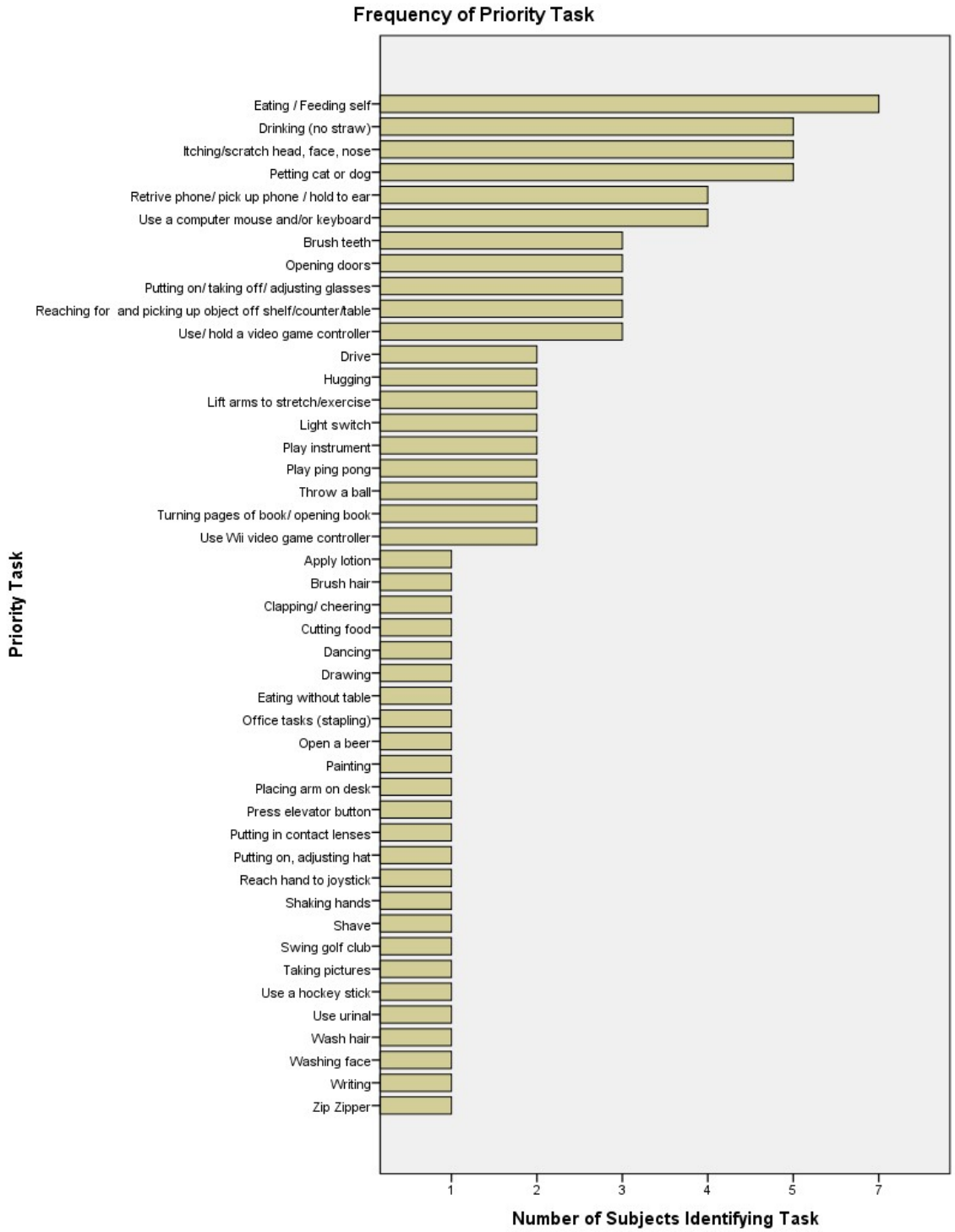

Figure 5.1 The frequency of each upper extremity priority task named by 7 subjects.

Figure 5.2 shows the mean weight of each priority tasks according to Table 5.1. Twenty-one of the priority tasks had a mean weight of 3, meaning that the task is very important. Forty-one of the tasks had a mean weight of 2 or above, meaning that 91% of the tasks named were rated to have at least moderate importance. Brushing teeth, playing ping pong, playing an instrument, and adjusting a hat were the only tasks with a mean importance score of less than 2; however, all of these tasks had a score of at least 1, meaning they were at least "a little" important to the subjects that named the task.

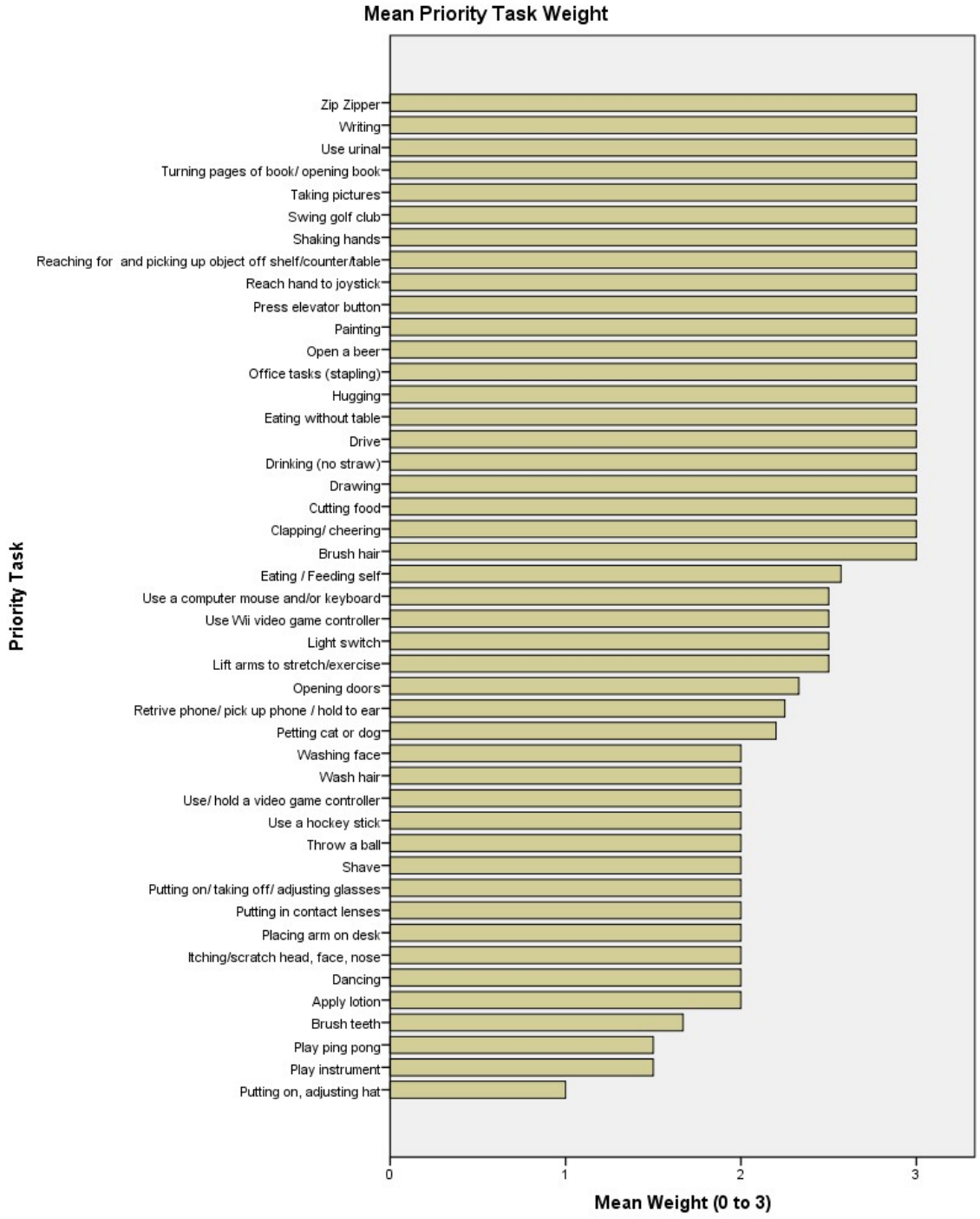

Figure 5.2 The mean weight of each upper extremity priority task.

5.4 Sub Aim 3.1 Discussion

This sub-aim allowed for the identification of user-defined priority tasks based on tasks these individuals have difficulty performing or cannot perform independently due to upper extremity functional deficits and would consider most important to be able to perform while using an upper extremity assistive device. The results of this aim support the hypothesis that individuals with DMD who have limited upper extremity function have priority tasks based on activities of daily living and individual interests and hobbies.

Eating independently and drinking were among the most commonly named priority tasks. This can be explained by the frequency of meals and the assumed intrusiveness and burden associated with needing to be fed by a family member, friend, or personal care attendant. Itching/scratching was also a commonly named task, with those naming it specifically identifying the head and nose as areas that are difficult to reach. This is explained by the fact that scratching the head and face is made difficult or impossible when individuals with DMD lose anti-gravity strength. And, itching/scratching is a task that can be considered intrusive and even uncomfortable if needed to be performed by a caretaker. There were also a number of tasks identified that reflect individual interests and hobbies such as playing sports or petting animals. Two subjects even named a task they had never performed but would be interested in trying if they had the ability: playing a musical instrument. This indicates that priority tasks can be born out of interest as much as they can be born out of necessity. All of the priority tasks had an average weight of 2 or more (indicating an importance level of moderately or very important) with the exception of putting on a hat, playing an instrument, playing ping pong, and brushing teeth. This indicates that personal care tasks are not necessarily

considered more important than hobbies and work-related tasks. It follows that an upper extremity assistive device should allow for increased independence in activities of daily living relating to hygiene and personal care as well as personal interests and hobbies.

5.5 Sub Aim 3.2 Methods

The objective of this sub-aim is to determine whether the use of an admittance control motorized arm support will allow for improvements in independence while performing priority tasks by having users evaluate their experiences doing so. The priority tasks identified in sub aim 3.1 that could be reproduced in the laboratory were set up for the subjects to attempt unsupported. The users qualitatively evaluated their limitations. The subject's dominant arm was then be supported by the HapticMASTER, with the gravity compensation adjusted to the needs of each subject and the subject re-attempted their priority tasks while supported.

Goal attainment scaling (GAS) was used to allow subjects to quantify the achievement of priority tasks while supported by the HapticMASTER compared to while unsupported. GAS provides a quantitative method of rating the extent to which subjects can perform their priority tasks, allowing for statistical analysis. GAS allows for the scoring of individualized, weighted tasks and has been shown to be a good measure of outcome that is sensitive to clinical changes in goal achievement [51]. Execution of each priority tasks was individually rated on a 5-point scale, based on the GAS scoring algorithm in Figure 5.3, modified from [51]. Positive scores denote the ability to perform the task better while supported by the HapticMASTER robot compared to while unsupported, negative scores denote worse performing while supported by the

HapticMASTER compared to while unsupported, and a score of 0 denotes no change in performance while supported by the HapticMASTER compared to while unsupported. Baseline scores were determined according to the subject's ability to perform each priority task while the arms were unsupported. The overall GAS score for each subject was computed using Equation 5.1, where W_i is the weight assigned to the i-the goal and X_i is the numerical value achieved of the i-th goal based on the GAS algorithm. Overall GAS scores of greater than 50 mean that overall, taking into account the importance of each priority task, the subject could perform their priority tasks better while supported by the HapticMASTER compared to while unsupported. Overall GAS scores of less than 50 mean that overall, taking into account the importance of each priority task, the subject performed their priority tasks worse while supported by the HapticMASTER compared to while unsupported.

$$Overall\ GAS = 50 + \frac{10\sum(W_i X_i)}{\sqrt{\left(0.7\sum W_i^2 + 0.3\left(\sum W_i^2\right)\right)}} \tag{5.1}$$

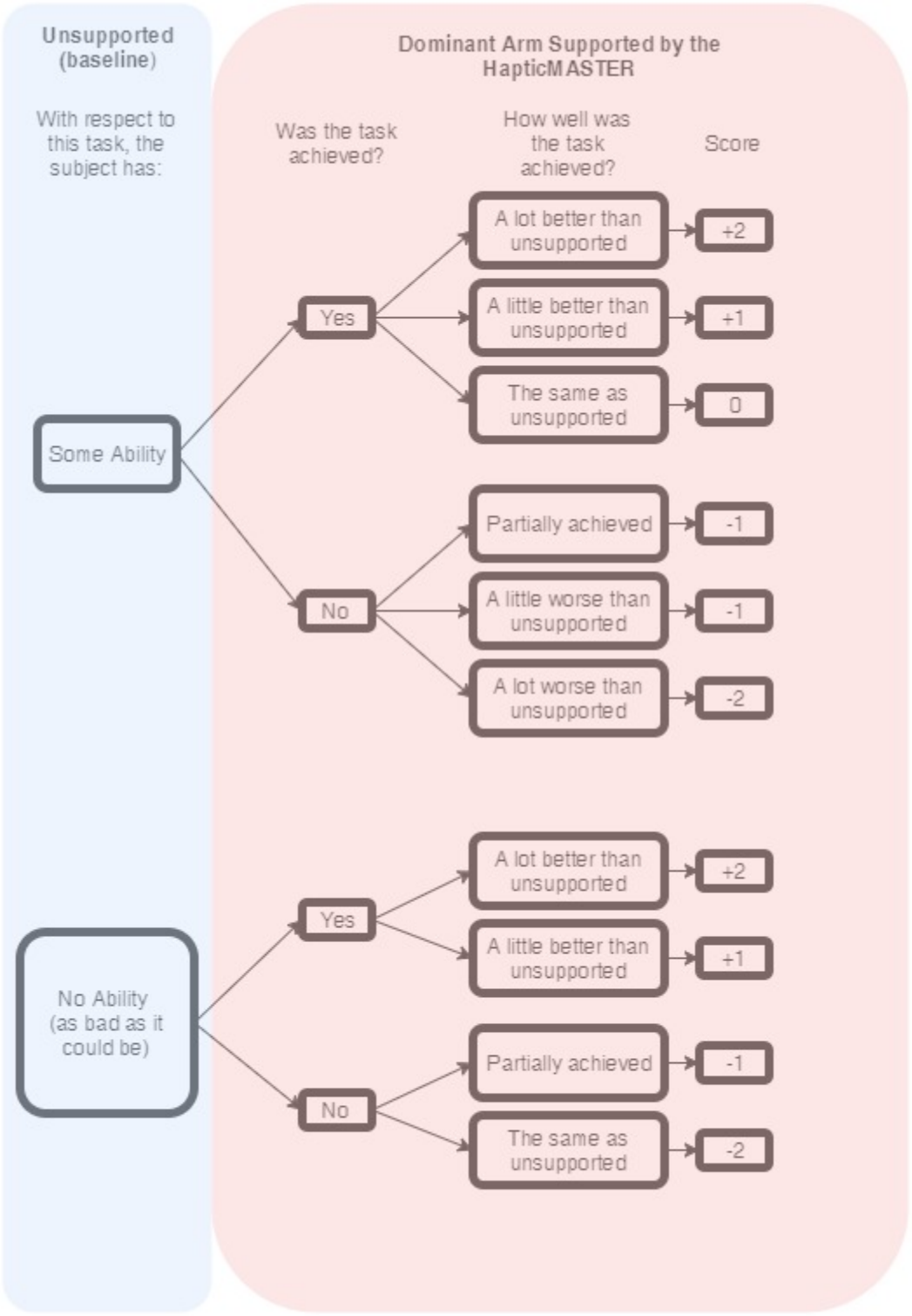

Figure 5.3 Algorithm for determining GAS score.

Source: Adapted from [51]

Subjects were also asked to fill out a self-assessment survey (see Appendix A) similar to the VAS scale in aim 2 to rate their exertion level while performing each priority tasks unsupported and while supported by the HapticMASTER robot. The subject-reported exertion level scores were averaged for each subject. A Shapiro-Wilk test was used to determine if the population of mean subject-reported exertion level scores was approximately normal. If the scores were approximately normal, a paired–samples t-test was used to determine whether the HapticMASTER required less effort to perform priority tasks compared to while unsupported. If the difference scores violated the assumption of normality, a Wilcoxon signed-ranks test was used. SPSS was used for all statistical analyses.

5.6 Sub Aim 3.2 Expected Results

Due to the benefits of admittance control, it is expected that subjects will be able to successfully perform their priority tasks while the dominant arm is supported by the HapticMASTER robot and that successful achievement will be reflected in GAS scores of +1 or +2 and overall GAS scores of greater than 50. Subjects are expected to experience greater ease of execution of priority tasks and decreased effort required while supported by the HapticMASTER compared to unsupported movements. For tasks that require bimanual manipulation, some difficulty in performance is expected as only one arm will be supported by the HapticMASTER robot.

5.7 Sub Aim 3.2 Results

Seven subjects with DMD who met the inclusion and exclusion criteria for this aim were enrolled in the study. Table 5.3 shows the age of each subject, handedness, and baseline scores of passive reachable surface area and unsupported reachable surface area for the left and right arms.

Table 5.3 Subjects Enrolled in Aim 3.2

Subject	Age	Hand Dominance	Passive RSA		Unsupported RSA	
			Right	Left	Right	Left
1c	26	Right	0.713	0.321	0.100	0.032
2c	21	Right	0.403	0.184	0.007	0.000
3c	15	Right	0.437	0.470	0.420	0.275
4c	14	Right	0.488	0.296	0.000	0.000
5c	26	Right	0.524	0.227	0.001	0.000
6c	27	Right	0.435	0.709	0.000	0.000
7c	11	Right	0.628	0.598	0.033	0.013

Figure 5.4 shows a boxplot of the GAS scores for all 7 subjects. The mean GAS score was 63 (SD 6). The minimum GAS score was 55 and the maximum GAS score was 73. All GAS scores were greater than 50.

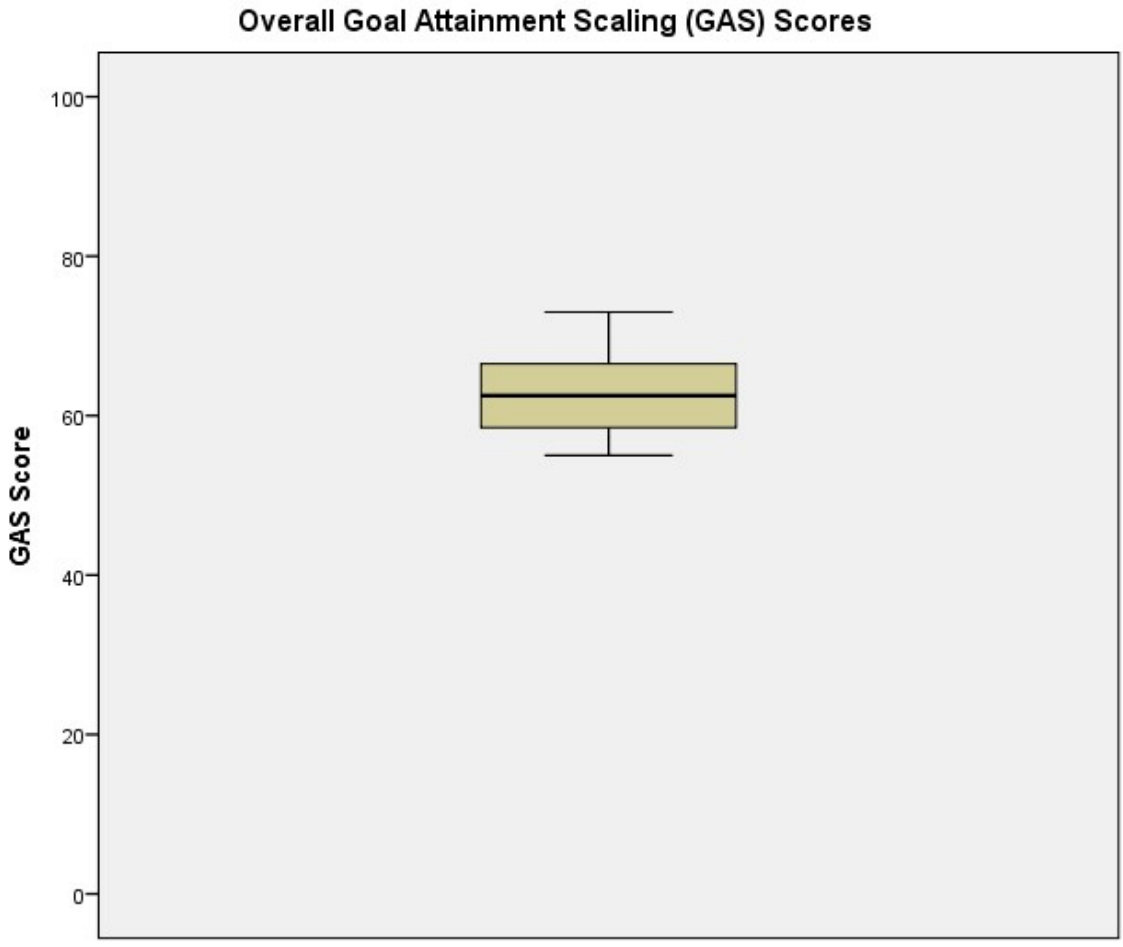

Figure 5.4 Boxplot of GAS Scores for 7 subjects.

Figure 5.5 shows the mean VAS subject-reported exertion level scores while performing their priority tasks unsupported and while supported by the HapticMASTER. A Shapiro-Wilk test revealed that the self-reported exertion level scores have no significant deviation from normality ($p=0.734$). The HapticMASTER resulted in a statistically significant decrease in self-reported exertion levels while performing priority tasks compared to performing the same tasks while unsupported (paired-samples t-test, $t(7)=4.51$, $p=0.003$, $r^2=0.74$). An $r^2=0.74$ denotes a large effect size of the

HapticMASTER on the self-reported exertion level scores while performing priority tasks compared to performing the same tasks while unsupported.

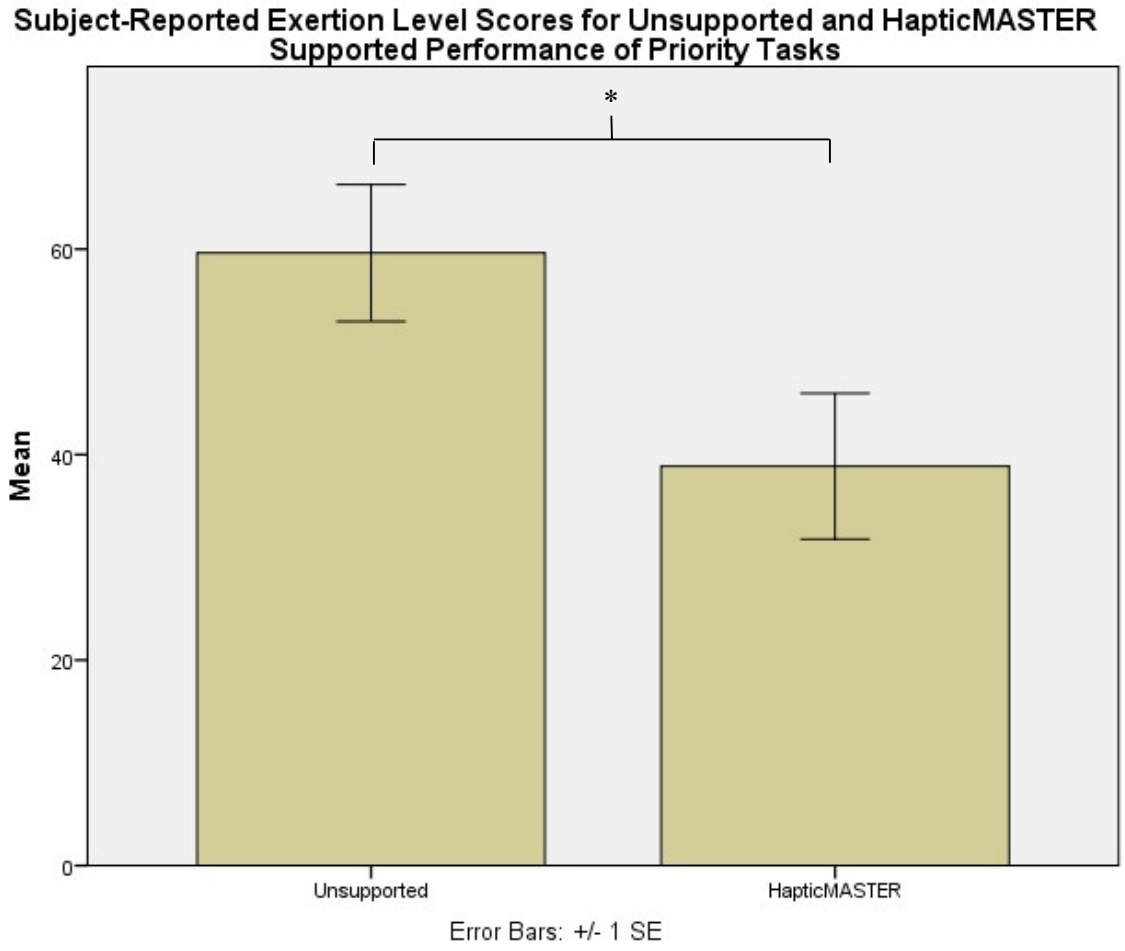

Figure 5.5 Mean subject-reported exertion level scores for unsupported and HapticMASTER supported performance of priority tasks. Error bars show SEM. Asterisk denotes statistical significance between groups ($p<0.05$).

5.8 Sub Aim 3.2 Discussion

This sub-aim investigated the feasibility of using an admittance control motorized arm support to provide individuals with DMD increased independence performing priority tasks. The results of the study support the hypothesis that an admittance control arm

support allowed individuals with DMD to successfully perform their priority tasks compared to when they were unsupported, as indicated by overall GAS scores of greater than 50. Furthermore, subjects reported decreased exertion level scores required to perform the priority tasks while supported by the admittance control robot compared to unsupported movements. These results are explained by the benefits of admittance control, especially the support against gravity that is provided in order to offload the arm and the intuitive control and ease of movement provided by minimization of inertia and friction.

Subjects who had more significantly limited upper extremity strength exhibited smaller GAS scores and greater exertion level scores. The HapticMASTER virtual mass inertia value was set to 6kg. Inertia values lower than 6kg resulted in an unstable system in which the robot vibrated or oscillated and would have been unsafe for user-robot interaction. This means that the subjects were opposed by the inertia of a 6kg point mass when they were performing their priority tasks. Therefore, the robot requires a degree of muscle strength to generate movements despite the minimization of inertia and friction and support against gravity. As a result, those with more limited muscle strength will have increased difficulty performing a task even if it is easier than when unsupported. It is expected that an admittance control arm support with capabilities of further minimizing the inertia value will result in greater overall GAS scores and smaller exertion level scores.

The HapticMASTER robot has 3 translational, motorized DOFs operating under admittance control. It also has a rotation DOF operating passively (yaw). However, two rotational DOFs (roll and pitch) are fixed. Therefore, the subjects could not rotate their

arm in 2 DOFs while performing their priority tasks. This posed a difficulty for the performance of some tasks that required rotation, such as drinking from a cup without a straw, a task that requires roll of the forearm. It is hypothesized that an admittance control arm support that has 6 DOFs (3 motorized translational DOFs and 3 motorized or passive DOFs) will allow for increased independence in activates of daily living for tasks that require or benefit from the ability to generate rotational movements.

Individuals with DMD who have significantly limited upper extremity strength typically have contractures that limit passive range of motion due to lack of active stretching of the joints. It was observed in this study that individuals who had significant contractures had difficulty performing priority tasks that requires range of motion beyond that of their PROM abilities. It is hypothesized that early integration of an admittance control arm support could reduce the development of contractures by promoting regular use and active stretching of the arms.

In addition to the limitations imposed by contractures, the ability to perform priority tasks while supported by the HapticMASTER robot was further hindered by the inability for some subjects to overcome the set-point of their arm. For example, while supported by the robot, some of the subjects with more significant muscle weakness were unable to keep their arm close to the mouth while attempting to eat independently. These subjects were unable to overcome the natural tendency for their arm to come to a neutral posture and had to utilize compensatory movements, such as swinging the arm and movement of the torso and head, in order to get food to their mouth. It is proposed that a future study could involve the mapping of the distribution of forces resulting from the arm's natural set-point. Doing so would allow for the integration of a counteracting

force-field into the admittance control loop that will minimize the force required by the user to make movements that deviate from the neutral arm posture.

A limitation of this study was the fact that a single HapticMASTER robot was used; therefore, only the dominant arm could be supported. As a result, bimanual tasks were more difficult or not possible to perform, especially for those with more limited muscle strength. If two robots were available and both arms could be supported, this study would be hypothesized to further substantiate the benefits of admittance control by showing greater GAS scores and smaller exertion level scores, especially for tasks that require or could benefit from the use of both arms.

CHAPTER 6

AIM 4: DESIGN OF AN ADMITTANCE CONTROL ARM SUPPORT

6.1 Sub Aim 4.1 Methods

6.1.1 Mechanical Design

The phase 1 prototype, pictured in Figure 6.1, uses the Armon Edero 5 DOF passive arm support as the base. This passive device has low-friction joints and an adjustable spring to provide support against gravity. Robotis MX Series Dynamixel Smart Servo motors were mounted to control the angular position of each of the 6 joints. A 6 DOF ATI Industrial Automation force/torque sensor was mounted under the forearm cuff to sense the user's applied force in the x, y, and z directions and applied torque in the pitch and yaw directions. The custom motor mounts, gears, force sensor mounts, and forearm cuff were designed using Pro/ENGINEER and Creo Parametric 3.0 CAD Software by PTC and fabricated using a Flashforge Creator Pro 3D Printer.

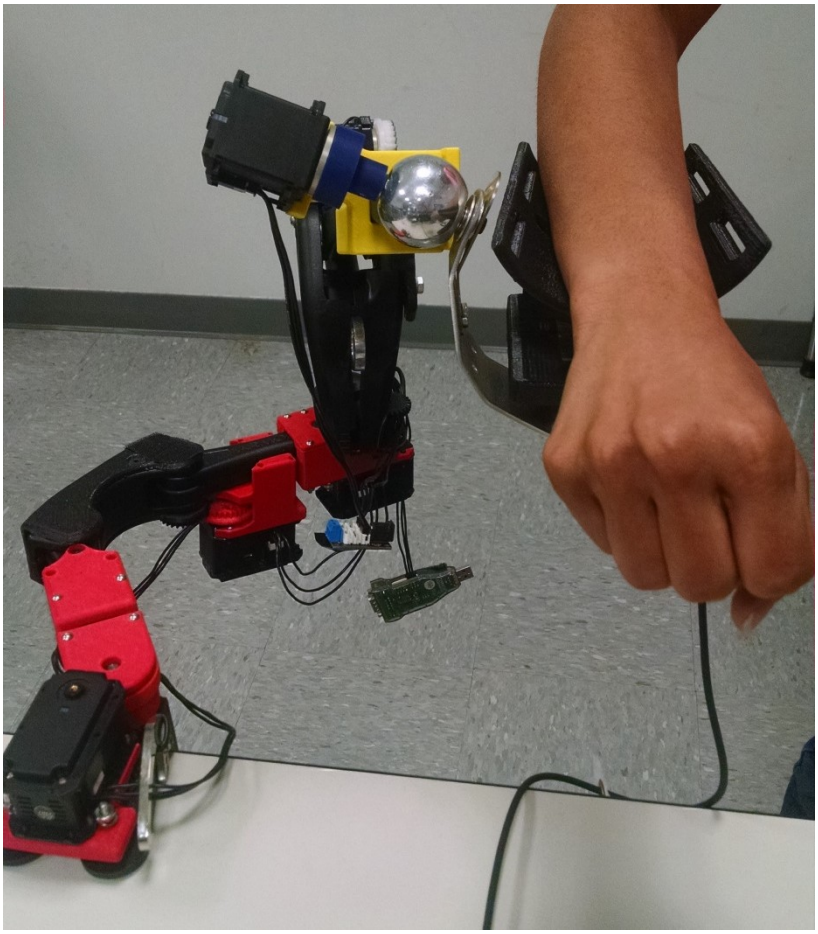

Figure 6.1 The 5 DOF Armon Edero retrofit with motors and force/torque sensor to operate under admittance control in all DOFs.

6.1.2 Control Algorithm

Figure 6.2 shows the control loop implemented in MATLAB to control the position and orientation of the motorized Armon Edero based on the user's applied force and torque. The user's applied force and torque is sensed by the 6 DOF force/torque sensor. The x, y, and z forces are divided by a virtual mass of 0.05kg. The resulting acceleration is integrated twice using CVode, an ordinary differential equation solver developed at Eindhoven University [52], to calculate the position to which the virtual mass would move under the user's applied force and specified damping. The x and z torques are

divided by the moment of inertia of a 0.05kg point mass. The resulting angular acceleration is integrated twice using CVode [52] to calculate the angle to which the virtual mass would rotate under the user's applied torque and specified damping.

The damping coefficients were determined empirically in order to keep the system stable while minimizing the force opposing the user's movement. The damping coefficients were set to 10N*sec/m in the x and y directions, 12N*sec/m in the z direction, and 25Nm*sec/rad in the yaw and pitch directions. These values are multiplied by the calculated velocity and subtracted from the user's applied force and torque for each iteration of the admittance control loop.

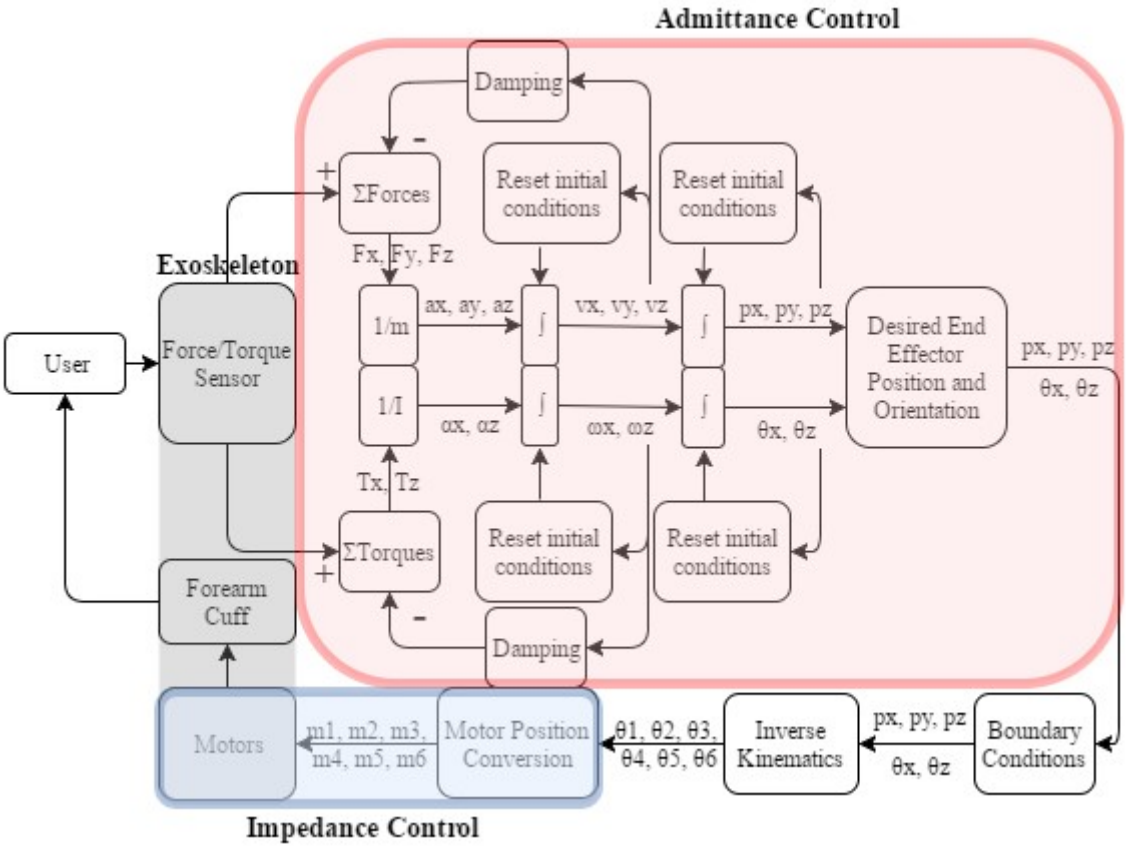

Figure 6.2 The control loop utilizing admittance control (red) to control the position and orientation of the exoskeleton (gray).

The desired position and orientation of the exoskeleton end effector, or forearm cuff, calculated by the admittance control loop is checked for whether it satisfies boundary conditions at each iteration of the control loop, and if not, the position and orientation is reset accordingly. Custom inverse kinematics calculates the six joint angles required to achieve the desired end effector position and orientation. Equations 6.1-6.4 show the inverse kinematics equations used to calculate the joint angles (θ_1, θ_2, θ_3, and θ_5) required to achieve the desired end-effector position (x, y, and z) based on the link lengths of the Armon Edero (l1, l2, l3, and l5). The angles of joints 4 and 6 (θ_4 and θ_6), controlling the orientation of the end-effector, were determined directly from the control algorithm based on the user's applied torque. The resulting joint angles are converted to motor positions and used to control the angle of each Dynamixel motor to translate and orient the forearm cuff (and the user's arm) to the desired position and orientation for each iteration of the control loop based on the applied force and torque. As a result, the user is intuitively controlling the motion of the forearm cuff in while only being opposed by the inertia of the 0.5kg virtual mass and the specified damping required to keep the system stable.

$$\theta_1 = a\tan 2(y - l_3 \sin\phi, x - l_3 \cos\phi) - a\tan 2(l_2 \sin\theta_2, l_1 + l_2 \cos\theta_2) \tag{6.1}$$

$$\theta_2 = 2\tan^{-1}\left(\frac{(l_1+l_2)^2 - (x_3^2 + y_3^2)}{(x_3^2 + y_3^2) - (l_1 - l_2)^2}\right) \tag{6.2}$$

$$\theta_3 = \phi - \theta_1 - \theta_2 \tag{6.3}$$

$$\theta_5 = \sin^{-1}\left(\frac{z}{l_5}\right) \tag{6.4}$$

Assistance against gravity is achieved by calibrating the force/torque sensor while the user's arm is at rest in the forearm cuff. Doing so provides the user with an upward force equal and opposite to the force of gravity that is acting on the user's arm during the calibration of the sensor.

6.1.3 Prototype Improvements

A number of advancements were made to the initial prototype, including control algorithm optimization and hardware improvements in order to enhance the user-robot interaction. The phase 2 prototype is pictured in Figure 6.3.

Figure 6.3 The phase 2 prototype of the multi-DOF Armon Edero retrofit with motors and force sensor to operate under admittance control in 3 DOFs.

The mechanical design of the prototype was improved by eliminating the gears at joints 1, 2, and 3 that control the x and y position of the end effector. By attaching the motor horns so that they directly drive the joint instead of using gears eliminates the

backlash, or play, that can propagate motor error to end effector position error. The ATI force/torque sensor used in the phase 1 prototype was replaced with an Optoforce 200N 3DOF force sensor to improve the input force signal. This sensor was chosen because it has a capacity and resolution more appropriate for human interaction and does not have the hysteresis, oscillations, and other signal imperfections that the ATI force sensor does.

Improvements to the control software was made in order to decrease the loop time. The control software for the phase 1 prototype was run using 32bit MATLAB. The phase 2 prototype used 64bit MATLAB to allow for larger memory. The return delay time of the Dynamixel motors was set to 2microseconds to minimize the time per data value that it takes from the transmission of the instruction packet until the return of the status packet. The motor baud rate was increased to 2Mbps to maximize the baud rate to communicate with the controller. The phase 1 prototype required an instruction packet to be sent to each motor individually in order to command a desired motor position and to read a current motor position. The result was a total of 12 instruction packets to read and write to each motor for each iteration of the control loop. In order to reduce the read and write times "syncwrite" and "syncread" were used as it allowed for a single instruction packet to be sent in order to command a desired position to all 6 motors and a single instruction packet to be sent in order to read the current position from all 6 motors. As a result, each iteration of the control loop required 2 instruction packets instead of 12. Because the Armon Edero has a redundant horizontal link (i.e. has 3 links to achieve the desired x and y position) the inverse kinematics involves solving for an infinite number of solutions. The phase 1 prototype dealt with the redundancy by limiting the number of solutions in the range of 90˚ to 270˚ in increments of 0.1˚. The result was 1800 possible

joint angle solutions to achieve the desired x, y position. This inverse kinematics code was optimized for the phase 2 prototype by limiting the range of possible solutions to +/- 5˚ from the previous joint angles in increments of 0.02˚. The result was only 500 possible solutions, 1300 fewer calculations than the phase 1 prototype. Even more, because of the decreased range, the increments of possible solutions was decreased from 0.1˚ to 0.02˚ to allow for increased resolution. Lastly, the mass and damping values were tuned to improve the smoothness and ease of movement. The mass was set to 0.25kg and the damping value to 5 N*sec/m.

6.1.4 Evaluation of Design

In order to evaluate the design of the phase 1 prototype, a user with no disability was instructed to generate movements with the device in each DOF. The accuracy of the control algorithm was evaluated by examining the user's applied force and torque and comparing the resulting desired position and orientation as calculated by the admittance control loop to the actual position and orientation achieved by the exoskeleton. The percent error between the desired end effector position and orientation in each DOF as calculated by the control loop and the actual end effector position was calculated using Equation 6.5. The time delay of each iteration of the control loop was determined by using MATLAB's "tic" and "toc" functions.

In order to evaluate the design of the phase 2 prototype, a user with no disability was instructed to generate movements with the device using all 3 DOFs for 10 trials, each lasting 30 seconds. The average percent error was calculated for each trial in each DOF and the time delay of each iteration of the control loop and each section of the software was averaged across each trial.

$$\%error = abs\left(\frac{actual - desired}{desired}\right)*100 \tag{6.5}$$

6.2 Sub Aim 4.1 Results

Figure 6.4 shows the user's applied forces for movements in the x, y, and z directions for using the phase 1 prototype. The corresponding x, y, and z desired positions as calculated by the admittance control loop are shown in this Figure with the actual exoskeleton end-effecotr position following the desired position closely. Figure 6.5 shows the user's applied torques for movements in the yaw and pitch directions using the phase 1 prototype. The corresponding yaw and pitch orientations as calculated by the admittance control loop are shown in the figure with the actual exoskeleton end-effector orientation similarly following the desired orientation closely. Table 6.1 shows the percent error between the desired and actual position for each of the DOFs for the phase 1 prototype. The mean control loop time was 0.0327seconds.

Table 6.1 Phase 1 Prototype Percent Error Results

DOF	Percent Error
x	1.36%
y	1.48%
z	8.06%
yaw	1.46%
pitch	1.80%

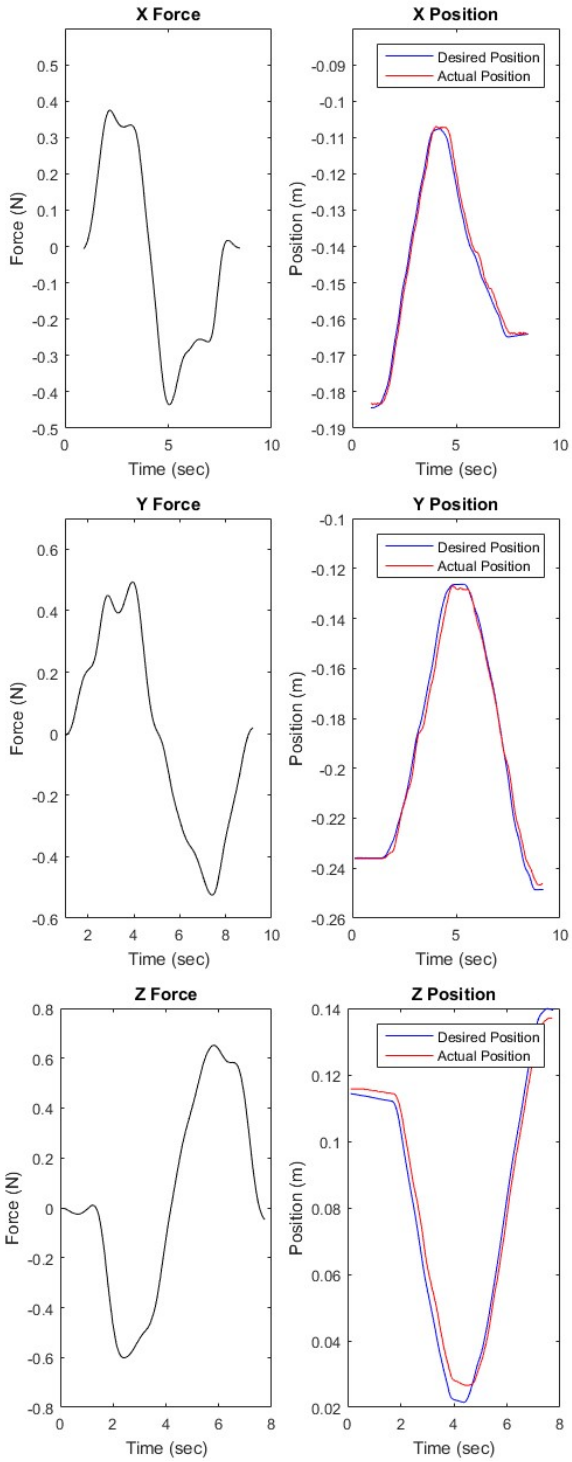

Figure 6.4 The user's applied force (black) in the x (top), y (middle), and z directions (bottom) and the corresponding desired x, y, and z positions computed by the admittance control algorithm (blue) and actual end effector position (red) for the phase 1 prototype.

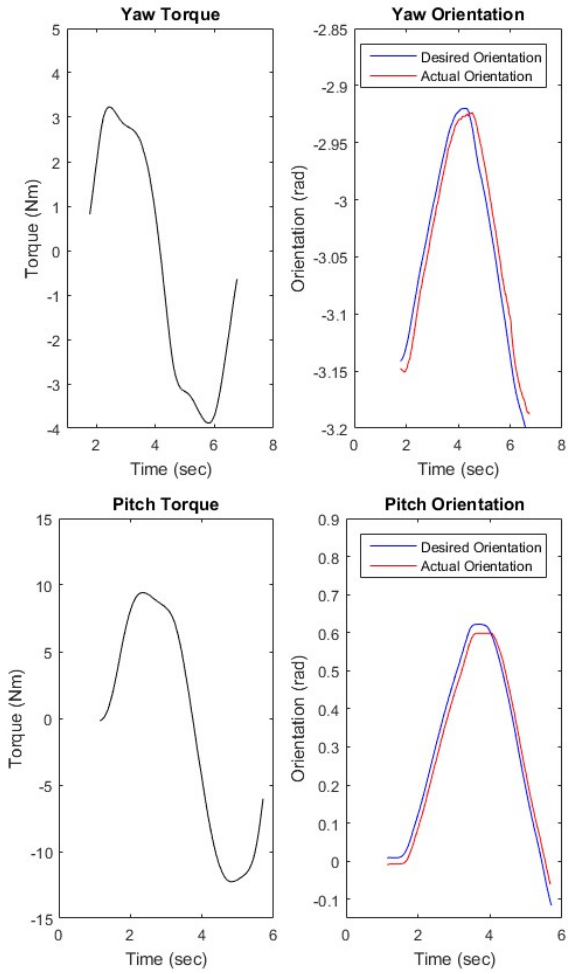

Figure 6.5 The user's applied torque (black) in the yaw (top) and pitch (bottom) directions and the corresponding desired yaw and pitch orientations computed by the admittance control algorithm (blue) and actual end effector orientation (red) for the phase 1 prototype.

Figure 6.6 shows the user's applied forces for movements in the x, y, and z directions for using the phase 2 prototype for a single trial. The corresponding x, y, and z desired positions as calculated by the admittance control loop are shown in this figure with the actual exoskeleton end-effector position following the desired position closely. Figure 6.7 shows the control loop time for a single trial. Table 6.2 shows the average percent error between the desired and actual position for each of the DOFs for the phase 2

prototype for each of the 10 trials. Table 6.3 shows the average control loop time and the average time for each section of the software for all 10 trials.

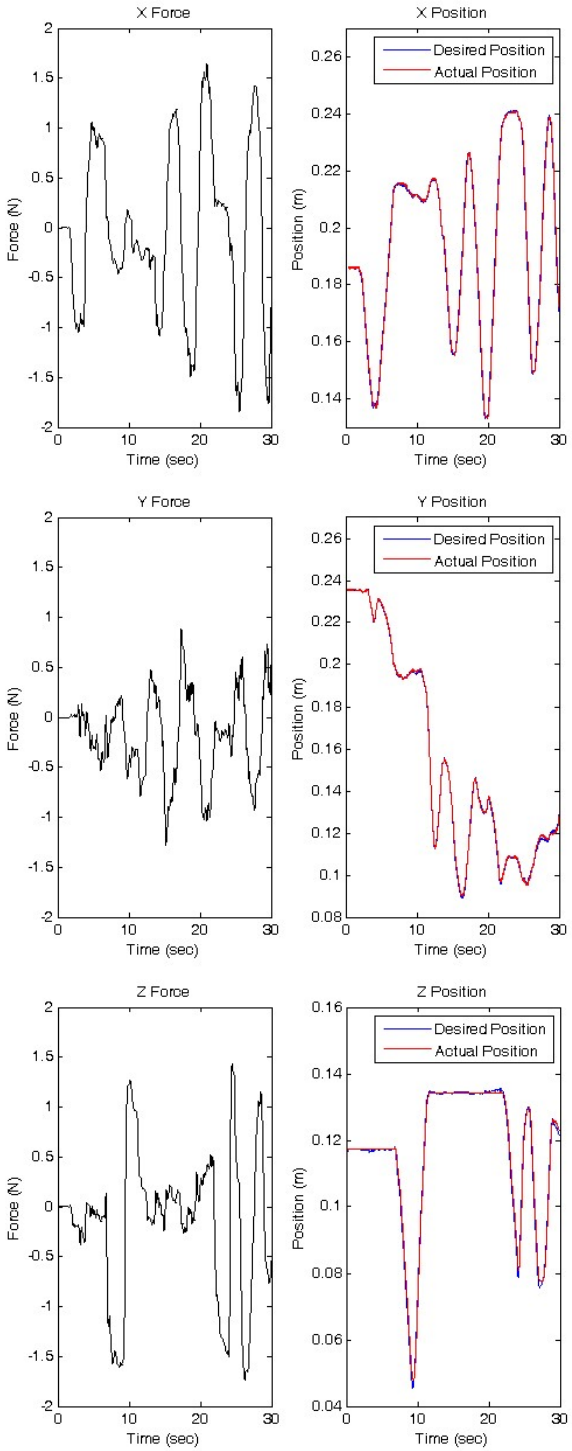

Figure 6.6 The user's applied force (black) in the x (top), y (middle), and z directions (bottom) and the corresponding desired x, y, and z positions computed by the admittance control algorithm (blue) and actual end effector position (red) for the phase 2 prototype.

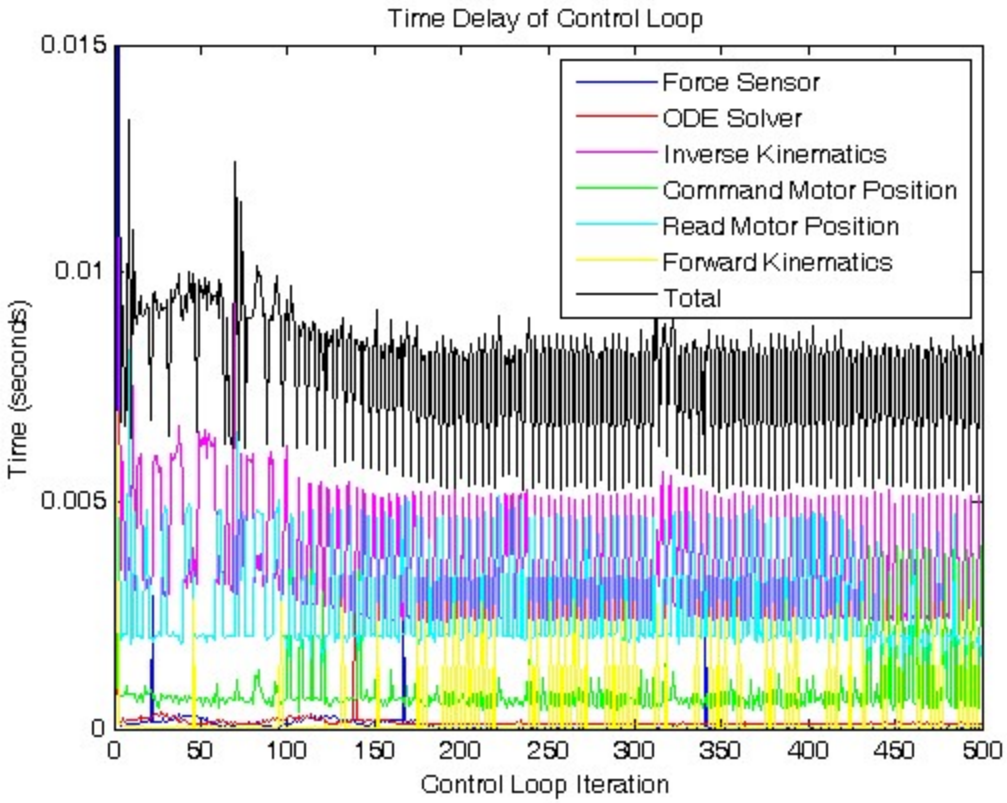

Figure 6.7 The time delay of the control loop for 1 trial showing the time to read the force sensor (blue), the time to solve the ordinary differential equation (red), the time to perform inverse kinematics calculations (magenta), the time to command the motors (green), the time to read the current motor positions (cyan), the time to perform forward kinematics calculations (yellow), and the total runtime of the control loop (black).

Table 6.2 Phase 2 Prototype Percent Error Results

Trial	x	y	z
1	0.65%	0.53%	0.96%
2	0.82%	0.66%	0.96%
3	0.75%	1.00%	1.60%
4	0.61%	0.96%	1.37%
5	0.68%	1.20%	1.78%
6	0.77%	0.85%	1.71%
7	1.17%	0.90%	2.49%
8	0.86%	0.70%	1.40%
9	0.84%	1.09%	1.53%
10	0.68%	0.68%	1.07%
Average	0.78%	0.85%	1.49%
Standard Deviation	0.16%	0.21%	0.46%

Table 6.3 Phase 2 Prototype Time Delay

Trial	Force Sensor	ODE Solver	Inverse Kinematics	Command Motors	Read Motors	Forward Kinematics	Total
1	0.07ms	0.13ms	3.32ms	0.85ms	2.72ms	0.31ms	7.66ms
2	0.06ms	0.12ms	3.32ms	1.01ms	2.63ms	0.23ms	7.64ms
3	0.06ms	0.13ms	3.44ms	0.78ms	2.68ms	0.23ms	7.66ms
4	0.06ms	0.11ms	3.31ms	0.97ms	2.72ms	0.29ms	7.70ms
5	0.05ms	0.11ms	3.27ms	1.05ms	2.73ms	0.16ms	7.78ms
6	0.06ms	0.12ms	3.36ms	1.10ms	2.65ms	0.20ms	7.78ms
7	0.06ms	0.12ms	3.25ms	0.77ms	2.69ms	0.23ms	7.41ms
8	0.05ms	0.11ms	3.27ms	0.95ms	2.74ms	0.25ms	7.64ms
9	0.06ms	0.11ms	3.13ms	1.01ms	2.63ms	0.21ms	7.43ms
10	0.08ms	0.13ms	2.95ms	1.16ms	2.57ms	0.13ms	7.40ms
Average	0.06ms	0.12ms	3.26ms	0.97ms	2.68ms	0.22ms	7.61ms
Standard Deviation	0.01ms	0.01ms	0.14ms	0.13ms	0.06ms	0.05ms	0.15ms

6.3 Sub Aim 4.1 Discussion

The prototype presented in this sub-aim demonstrates a novel approach to upper extremity exoskeleton design. The 5 DOF prototype using the Armon Edero as the base demonstrated successful implementation of admittance control as the control paradigm for fully motorizing all DOFs of a commercially available passive arm support. The force and position plots demonstrate the successful implementation of an intuitive control paradigm in which the motion of the exoskeleton is based on the magnitude and direction of the user's applied force and torque.

Minimization of the control loop time delay is of great importance when implementing admittance control. Because the motion of the robot is based on the user's applied force, any time delay that is significant enough to be perceived by the user will result in an oscillating, unstable system. In order to ensure stable and comfortable interaction between the user and the exoskeleton, the control loop should have a maximum delay of 10ms [53]. Even more, a time delay beyond 10ms can result in the virtual mass feeling heavier to the user [54]. The HapticMASTER robot, which has an estimated control loop delay of 10ms, further substantiates this required minimum time delay [54]. The phase 2 prototype had an average time delay of 7.61ms; however, the force sensor was set to a maximum frequency of 100Hz. Though the force sensor has capabilities to operate at up to 1000Hz, the MATLAB code used to operate the exoskeleton required the frequency to be set at 100Hz. Therefore, the force sensor data would be quantized at a control loop speed of 7.61ms causing the actual time delay to be bottlenecked by the force sensor frequency at 10ms. This 10ms time delay met the target time delay to ensure optimal interaction between the user and the exoskeleton.

Further, this time delay was a greater than a 3x improvement compared to the phase 1 prototype. Improvements in the time delay were due to a decrease in DOFs from 5DOF to 3DOF, the use of 64bit MATLAB, decrease in return delay time of the motors, increase in motor baud rate, use of "syncread" and "syncwrite" functions, and optimization of the inverse kinematics code. For the phase 2 prototype, the inverse kinematics code accounted for the largest portion of the time delay. This runtime of each iteration of the control loop can be further decreased to improve the responsiveness of the system by replacing the current MATLAB code with C or C++. Implementing a force software that allows the force sensor to read at a frequency greater than 100Hz will also improve the runtime. Improvements beyond 10ms will increase the responsiveness of the system.

Errors between the desired and actual positions and orientations of the exoskeleton end effector (forearm cuff) were less than 0.25% for the x and y directions and less than 0.5% for the z direction for the phase 2 prototype. The error between the desired and actual position for the phase 2 prototype was almost 1/10 of the error for the phase 1 prototype for the x and y directions, and almost 1/20 of the error for the z direction. The improvements in error for the phase 2 prototype can be explained by the decrease in time delay and use of a force sensor with improved resolution. The error between the desired and actual position in the z direction is about twice that of the x and y directions. This is explained by the gear ratio for the joint controlling the z position of the end effector. The gear ration is about 2, meaning that error between the desired motor position and actual motor position will be doubled for any given iteration of the control loop.

6.4 Sub Aim 4.2 Methods

6.4.1 Mechanical Design

The vertical assist prototype, pictured in Figure 6.8, uses the X-Ar 5 DOF commercially available passive arm support as the base. This device has low-friction joints and an adjustable spring housed in a four-bar linkage to provide support against gravity. In order to demonstrate the modular nature of this design approach, a Dynamixel motor was mounted to control the position of the four-bar linkage, therefore controlling the elevation (or z position) of the forearm cuff based on the user's applied force in the z direction while the x and y positions and pitch and yaw orientations were left to operate passively. A 3 DOF Optoforce force sensor was mounted under the forearm cuff to sense the user's applied for in the z direction. The custom motor mount, gears, and force sensor mount were designed using Pro/ENGINEER and fabricated using a Flashforge Creator Pro 3D Printer.

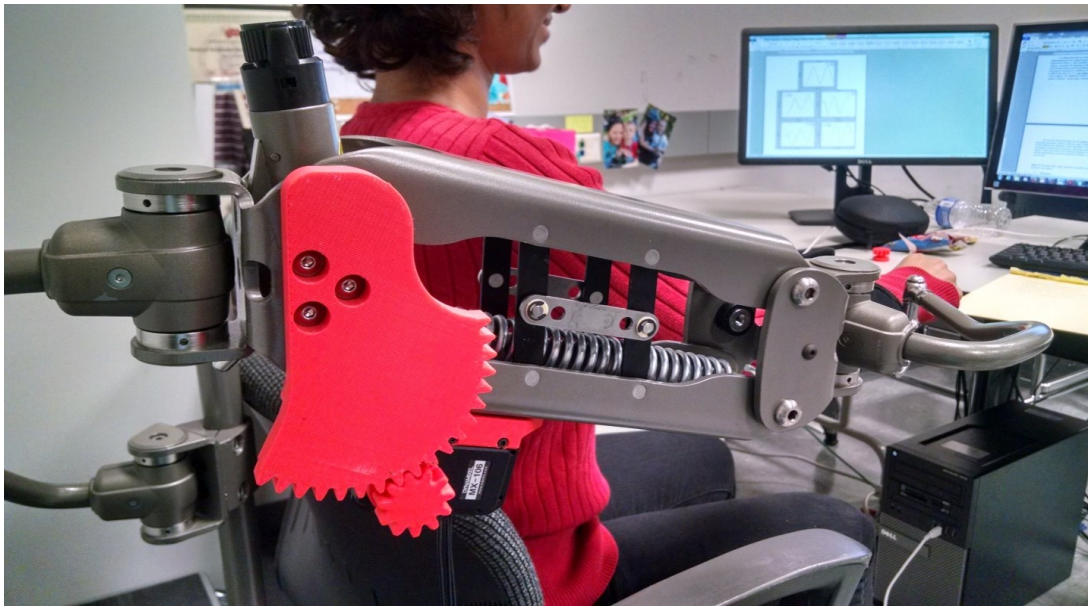

Figure 6.8 The vertical assist module mounted on the X-Ar to operate vertically under admittance control while remaining passive in the other DOFs.

6.4.2 Control Algorithm

The control loop shown in Figure 2 was used to calculate and control the z position of the forearm cuff based on the user's applied force in the z direction. Equation 6.4 was used to calculate the joint angle required to achieve the desired elevation for each iteration of the control loop. The virtual mass was set to 0.5kg and damping coefficient was set to 25N*sec/m.

6.4.3 Evaluation of Design

The time delay of each iteration of the control loop and the percent error between desired and actual end effector position was determined for this prototype. A user with no disability was instructed to generate movements with the device in the positive and negative vertical direction for 10 trials, each lasting 30 seconds. The average percent error was calculated for each trial and the time delay of each iteration of the control loop was averaged across each trial.

6.5 Sub Aim 4.2 Results

Figure 6.9 shows the user's applied forces for movements in the z direction for using the vertical assist prototype for a single trial. The corresponding z desired position as calculated by the admittance control loop is shown in this figure with the actual exoskeleton end-effecotr position following the desired position closely. Table 6.4 shows the average percent error between the desired and actual position for the vertical assist prototype for each of the 10 trials and the average time for each iteration of the control loop.

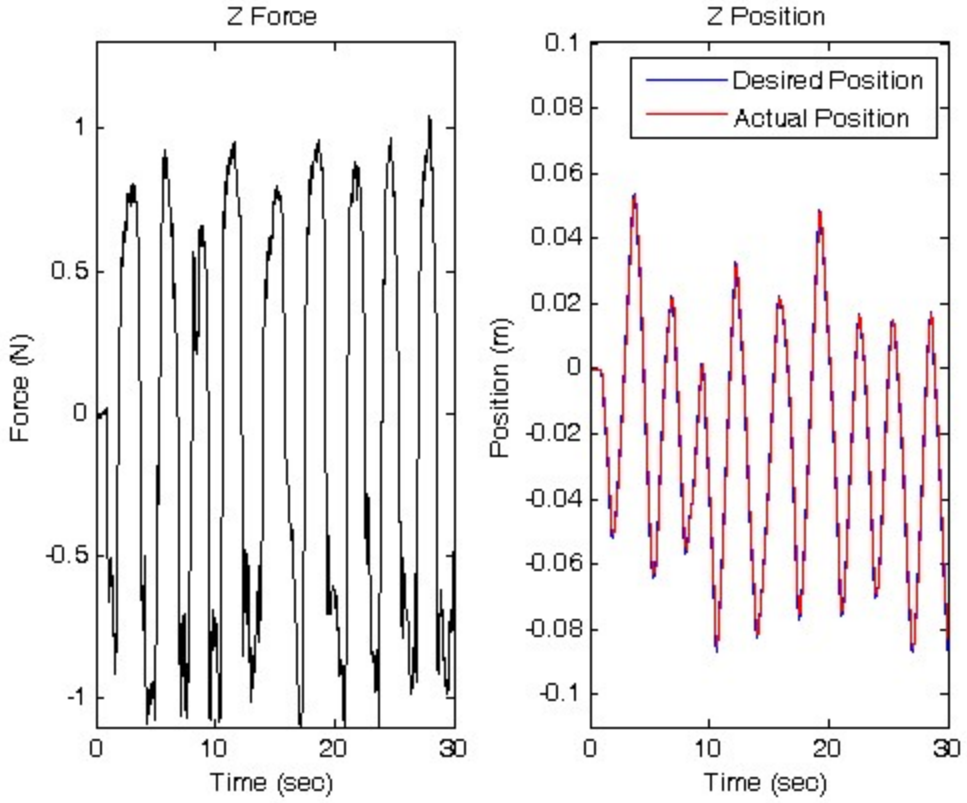

Figure 6.9 The user's applied force (left) and the desired z position (right, blue) and actual z position (right, red) of the exoskeleton end effector for one trial.

Table 6.4 Vertical Assist Prototype Results

Trial	Percent Error	Control Loop Time Delay (ms)
1	0.00027%	1.10
2	0.00012%	1.10
3	0.00029%	1.10
4	0.00014%	1.10
5	0.00021%	1.10
6	0.00008%	1.10
7	0.00064%	1.10
8	0.00025%	1.10
9	0.00015%	1.10
10	0.00015%	1.10
Average	0.00023%	1.10
Standard Deviation	0.00016%	0

6.6 Sub Aim 4.2 Discussion

This sub-aim demonstrated the feasibility of using 3D printing technology to modularly retrofit a force sensor and motor to a commercially available passive arm support. The prototype demonstrates this modular approach through the successful implementation of one motorized DOF while keeping the other DOFs passive. This novel approach has the potential to allow for customization of an exoskeleton to individuals based on their capabilities. Individuals with varying degrees of upper extremity function can benefit from the same device by the addition of motorized DOFs in the form of "assist modules", so that the device can be purely passive, purely motorized, or have some subset of the DOFs motorized. The result is a more compact design in which the device is never bulkier, more technically complicated, or more expensive than required. Even more, this modular approach has the potential to be well suited for individuals with DMD who have changes in functional status over time.

The time delay of the control loop for this prototype was 1.10ms. However, the force sensor was set to operate at 100Hz. Similar to the Armon Edero prototype, this means that the force sensor data will be quantized at control loop speeds greater than 10ms. The result is a control loop delay limited to 10ms, which is at the target time delay to ensure comfortable and stable interaction with the user. The use of a force sensor that operates at a faster frequency will allow for further reduction in the error between the desired and actual end effector position.

CHAPTER 7

CONCLUSION AND FUTURE DIRECTIONS

7.1 Conclusion

This dissertation presented a novel approach to increase upper extremity AROM for individuals with DMD with the intention of increasing independence in activities of daily living by using admittance control. The results of these aims support they hypothesis that a motorized arm support utilizing the admittance control paradigm will provide individuals with DMD an intuitive and effective means of increasing upper extremity AROM and an increase in independence in activities of daily living. Further, the development work presented in this dissertation demonstrated the successful fabrication of an admittance control motorized arm support in multiple DOFs and by using a modular approach. The novel approach presented herein has the potential to help individuals with DMD maintain self-sufficiency and improve quality of life.

7.2 Future Directions

Disuse atrophy and the development of contractures are known secondary contributors to loss of upper extremity function for individuals with DMD. Sub-maximal use of residual muscle strength and stretching of the joints and muscles are prescribed to minimize disuse atrophy and contractures. If implemented for daily use to assist with activities of daily living, an admittance control exoskeleton will promote the use of residual muscle strength and active stretching of the joints and muscles. Therefore, it is hypothesized that regular use of an admittance control arm support will delay the loss of upper extremity

function for individuals with DMD by reducing these secondary factors. Future work will evaluate the delay in upper extremity function over time associated with regular use of an admittance control arm support.

Future work will also investigate the implementation of additional motorized DOFs. A fully motorized 7DOF admittance control device (3 translational DOFs, 3 rotational DOFs, and a gripper) will be fabricated and evaluated with individuals with DMD. Using a modular approach, the researchers can evaluate the importance of each motorized DOF and identify stages at which each DOF needs to be motorized as upper extremity function decreases over time.

An ongoing translational study conducted by the researchers in collaboration with Talem Technologies, funded by Parent Project Muscular Dystrophy (PPMD), will involve the fabrication and evaluation of a passive arm support with admittance control implemented in the vertical direction. Thirty individuals with DMD will receive a passive arm support developed by Talem Technologies. Changes in AROM and independence in activities of daily living while using the arm support will be quantified compared to unsupported movements. After six months of regular use of the device, a "vertical assist kit" will be installed on each user's passive arm support to motorize the vertical DOF using admittance control. Changes in AROM and independence in activities of daily living while using the motorized device will be evaluated and compared to the purely passive arm support and to unsupported movements. User feedback will be collected on a regular basis to ensure that the device design meets user needs and provides an increase in upper extremity function that outweighs any burden associated with the use of an assistive device of this nature. At the conclusion of the

study, design improvements will be implemented based on the result of the study and on user input with the intention of becoming a commercially available device for individuals with DMD and other conditions resulting in limited upper extremity muscle strength.

APPENDIX A

SURVEYS

Self-Assessment Survey for Aim 2

While making the reachable workspace movements with *the Armon Edero passive arm support*, please rate the exertion level required for you to complete the movements (mark your answer on the line):

Least amount of effort Most amount of effort

While making the reachable workspace movements with *the HapticMASTER robot*, please rate the exertion level required for you to complete the movements (mark your answer on the line):

Least amount of effort Most amount of effort

Compare your movements with the Armon Edero passive arm support and with the HapticMASTER robot. Which condition allowed for the easiest movements in the horizontal direction (mark your answer on the line)?

Armon Edero HapticMASTER

Compare your movements with the Armon Edero passive arm support and with the HapticMASTER robot. Which condition allowed for the easiest movements in the vertical direction (mark your answer on the line)?

Armon Edero HapticMASTER

Do you have any additional comments regarding your experience with the Armon Edero and the HapticMASTER robot?

Self-Assessment Survey for Aim 3.2

While performing your priority task *unsupported*, please rate the exertion level required for you to complete the task (mark your answer on the line):

Least amount of effort Most amount of effort

While performing your priority task while supported by *the HapticMASTER robot*, please rate the exertion level required for you to complete the task (mark your answer on the line):

Least amount of effort Most amount of effort

REFERENCES

[1] K. R. Q. Lim, R. Maruyama, T. Yokota, "Eteplirsen in the Treatment of Duchenne Muscular Dystrophy," Drug Design, Development and Therapy, vol. 11, pp. 533-545, 2017.

[2] I. Y. Jung, J. H. Chae, S. K. Park, J. H. Kim, J. Y. Kim, S. J. Kim, M. S. Bang, "The Correlation Analysis of Functional Factors and Age with Duchenne Muscular Dystrophy," Annals of Physical and Rehabilitation Medicine, vol. 36. pp. 22-32, 2012.

[3] B. Bartels, R. F. Pangelila, M. P. Bergen, N. A. M. Cobben, H. J. Stam, M. E. Roebroeck, "Upper Limb Function in Adults with Duchenne Muscular Dystrophy," Journal of Rehabilitation Medicine, vol. 43. pp. 770-775, 2011.

[4] C. D. Markert, F. Ambrosio, J. A. Call, R. W. Grange, "Exercise and Duchenne Muscular Dystrophy: Toward Evidence-Based Exercise Prescription," Muscle & Nerve, vol. 43. pp. 464-478, 2001.

[5] M. Kohler, C. F. Clarenbach, L. Boni, T. Brack, E. W. Russi, K. E. Bloch, "Quality of Life, Physical Disability, and Respiratory Impairment in Duchenne Muscular Dystrophy," American Journal of Respiratory and Critical Care Medicine, vol. 172, pp. 1032-1036, 2005.

[6] E. Gomez-Merino, J. R. Bach, "Duchenne Muscular Dystrophy: Prolongation of Life by Noninvasive Ventilation and Mechanically Assisted Coughing," American Journal of Physical Medicine & Rehabilitation vol. 81, no. 6, pp. 411-415, 2002.

[7] E. S. Mazzone, G. Vasco, C. Palermo, F. Bianco, C. Galluccio, V. Ricotti, A. D. Castronovo, M. S. DiMAuro, M. Pane, A. Mayhew, E. Mercuri, "A Critical Review of Functional Assessment Tools for Upper Limbs in Duchenne muscular dystrophy," Developmental Medicine & Child Neurology, vol. 54, pp. 879-885, 2012.

[8] B. F. Steffensen, S. Lyager, B. Werge, J. Rahbek, E. Mattsson, "Physical Capacity in Non-Ambulatory People with Duchenne Muscular Dystrophy or Spinal Muscular Atrophy: A Longitudinal Study," Developmental Medicine & Child Neurology, vol. 44, pp. 623-632, 2002.

[9] J. J. Han, G. Kurillo, R. T. Abresch, A. Nicorici, R. Bajcsy, "Validity, Reliability, and Sensitivity of a 3D Vision Sensor-based Upper Extremity Reachable Workspace Evaluation in Neuromuscular Diseases," PLOS Currents Muscular Dystrophy, 2013.

[10] "Genworth 2014 Cost of Care Survey," Genworth Financial, Inc., 2014.

[11] G.W. Romer, H. J. Stuyt, A. Peters, “Cost-Savings and Economic Benefits due to the Assistive Robotic Manipulator,” in Proceedings of the 2005 IEEE, Chicago, IL, 2005, pp. 201-204.

[12] E. H. Cup, A. J. Pieterse, J. M. ten Broek-Pastoor, M. Munneke, B. G. van Engelen, H. T. Hendricks, G. J. van der Wilt, R. A. Oostendorp, “Exercise Therapy and Other Types of Physical Therapy for Patients With Neuromuscular Diseases: A Systematic Review,” Archives of Phyiscal Medicine and Rehabilitation, vol. 88, pp. 1452-1464, 2007.

[13] C. D. Markert, L. E. Case, G. T. Carter, P. A. Furlong, R. W. Grange, “Exercise and Duchenne Muscular Dystrophy: Where We Have Been and Where We Need to Go,” Muscle & Nerve, pp. 746-751, 2012.

[14] K. Bushby, R. Finkel, D. J. Birnkrant, L. E. Case, P. R. Clemens, L. Cripe, A. Kual, K. Kinnett, C. McDonald, S. Pandya, J. Poysky, F. Shapiro, J. Tomezsko, C. Constantin, “Diagnosis and Management of Duchenne Muscular Dystrophy, Part 2: Implementation of Multidisciplinary Care,” The Lancet Neurology, 2009.

[15] M. Jansen, I. JM de Groot, N. vanAlfen, A. C. H. Geurts, “Physical Training in Boys with Duchenne Muscular Dystrophy: The Protocol of the No Use is Disuse Study,” BMC Pediatrics, vol. 10. no. 55, 2010.

[16] M. Eagle, “Report on the Muscular Dystrophy Campaign Workshop: Exercise in Neuromuscular Diseases,” Neuromuscular Disorders, vol. 12, pp. 975-983, 2002.

[17] R. Ramanatha, S. P. Eberhardt, T. Rahman, W. Sample, R. Seliktar, M. Alexander, “Analysis of Arm Trajectories of Everyday Tasks for the Development of an Upper-Limb Orthosis,” IEEE Transactions on Rehabilitation Engineering, vol. 8, no. 1, pp. 60-70, 2000.

[18] C. A. Stanger, C. Anglin, W. S. Harwin, D. P. Romilly, “Devices for Assisting Manipulation: A Summary of User Task Priorities,” IEEE Transactions on Rehabilitation Engineering, vol. 2, no. 4, pp. 256-265, 1994.

[19] R. Rahman, W. Sample, R. Seliktar, M. Alexander, M. Scavina, “A Body-Powered Functional Upper Limb Orthosis,” Journal of Rehabilitation Research and Development, vol. 37. no. 6, 2000.

[20] Talem Technologies LLC, X Ar. [Online]. Available: http://www.talemtech.com/x-ar/ (accessed on March 20, 2017).

[21] Armon Products, Edero. [Online]. Available: http://products2.armonportal.com/products/edero/ (accessed on March 20, 2017).

[22] R. Daniel, T. Rahman, W. Sample, S. Agrawal, "Dynamic Simulation and Experimental Validation of an Upper Extremity Powered Orthosis," in Proceedings of IEEE/ASME International Conference on Advanced Intelligent Mechatronics, Montreal, Canada, 2010, pp. 1-6.

[23] F. Casolo, S. Cinquemani, M. Cocetta, "A Passive Support To Motion Capability Of Subjects Affected By Neuromuscular Diseases," in World Congress on Engineering, London, UK, 2008.

[24] J. L. Herder, "Development of a Statically Balanced Arm Support: ARMON," in Proceedings of IEEE 9th International Conference on Rehabilitation Robotics, Chicago, IL, 2005, pp. 281-286.

[25] J. L. Herder, N. Vrijlandt, T. Antonides, M. Cloosterman, P. L. Mastenbrock, "Principle and Design of a Mobile Arm Support for People with Muscular Weakness," Journal of Rehabilitation Research & Development, vol. 43, no. 5, pp. 591-604, 2006.

[26] S. Landsberger, P. Leung, V. Vargas, J. Shaperman, J. Baumgarten, Y. L. Yasuda, E. Sumi, D. McNeal, R. Waters, "Mobile Arm Supports: History, Application, and Work in Progress," Topics in Spinal Cord Injury Rehabilitation, vol. 11, no. 2, pp. 74-94, 2005.

[27] R. Rahman, W. Sample, R. Seliktar, M. T. Scavina, A. L. Clark, K. Moran, M. A. Alexander, "Design and Testing of a Functional Arm Orthosis in Patients with Neuromuscular Diseases," IEEE Transactions on Neural Systems and Rehabilitation Engineering, vol. 15, no. 2, pp. 244-251, 2007.

[28] N. Tobias, R. Robert, "ARMin – Design of a Novel Arm Rehabilitation Robot," in Proceedings of IEEE 9th International Conference on Rehabilitation Robotics, Chicago, IL, 2005, pp. 57-71.

[29] D. P. Romilly, C. Anglin, R. G. Gosine, C. Hershler, S. U. Raschke, "A Functional Task Analysis and Motion Simulation for the Development of a Powered Upper-Limb Orthosis," IEEE Transactions on Rehabilitation Engineering, vol. 2, no. 3, pp. 119-129, 1994.

[30] H. Martin, S. Chevallier, E. Monacelli, "Fast Calibration of Hand Movement-Based Interface for Arm Exoskeleton Control," in Proceedings of European Symposium on Artificial Neural Networks, Computational Intelligence and Machine Learning, Bruges, Belgium, 2012, pp. 25-27.

[31] S. K. Agrawal, V. N. Dubey, J. J. Gangloff, E. Brackbill, V. Sangwan, "Optimization and Design of a Cable Driven Upper Arm Exoskeleton," in Proceedings of ASME 2009 International Design Engineering Technical Conference & Computers and Information in Engineering Conference IDETC/CIE, San Diego, CA, 2009, pp. 1-8.

[32] Y. Wakita, N. Yamanobe, K. Nagata, N. Ando, M. Clerc, "Development of User Interface with Single Switch Scanning for Robot Arm to Help Disabled People Using RT-Middleware," in Proceedings of 10th International Conference on Control, Automation, Robotics and Vision, Hanoi, Vietnam, 2008, pp. 1515-1520.

[33] Assistive Innovations, iARM: Intelligent Arm Robot Manipulator. [Online]. Available: http://assistive-innovations.com/robotic-arms/iarm-feeder (accessed on March 20, 2017).

[34] M. Shramowiat, J. R. Bach, C. Bocobo, "Functional Enhancement of Patients with Duchenne Muscular Dystrophy with the Use of Robot-Manipulator Trainer Arms," Journal of NeuroEngineering and Rehabilitation, vol. 3, pp. 129-132, 1989.

[35] J. R. Bach, A. P. Zeelenberg, C. Winter, "Wheelchair-Mounted Robot Manipulators," American Journal of Physical Medicine & Rehabilitation, vol. 69, no. 2, pp. 55-59, 1990.

[36] N. Pellegrini, B. Guillon, H. Prigent, M. Pellegrini, D. Orlikovski, J. C. Raphael, F. Lofaso, "Optimization of Power Wheelchair Control for Patients with Severe Duchenne Muscular Dystrophy," Neuromuscular Disorders, vol. 14, pp. 297-300, 2004.

[37] B. E. Becker, "Aquatic Therapy: Scientific Foundations and Clinical Rehabilitation Application," American Academy of Physical Medicine and Rehabilitation, vol. 1, pp. 859-872, 2009.

[38] M. Fragala-Pinkham, S. M. Haley, M. E. O'Neil, "Group Aquatic Aerobic Exercise for Children with Disabilities," Developmental Medicine & Child Neurology, vol. 50, pp. 822-827, 2008.

[39] K. R. Wagner, N. Lechtzin, D. P. Judge, "Current Treatment of Adult Duchenne Muscular Dystrophy," BBA – Molecular Basis of Disease, 2011.

[40] M. Getz, Y. Hutzler, A. Vermeer, "Effects of Aquatic Interventions in Children with Neuromotor Impairments: A Systematic Review of the Literature," Clinical Rehabilitation, vol. 20, pp. 927-936, 2006.

[41] M. Corrigan, R. Foulds, "Admittance Control of the Intelligent Assistive Robotic Manipulator for Individuals with Duchenne Muscular Dystrophy: A Proof-of-Concept Design," Journal of Rehabilitation Robotics, vol. 3, pp. 1-5, 2015.

[42] R. Q. Van der Linde, P. Lammertse, E. Frederiksen, B. Ruiter, "The HapticMaster, A New High-Performance Haptic Interface," unpublished. [Online]. Available: http://www.eurohaptics.vision.ee.ethz.ch/2002/notused/thefile.pdf (accessed on March 20, 2017).

[43] T. M. Sukal, M. D. Ellis, J. P. A. Dewald, “Dynamic Characterization of Upper Limb Discoordination Following Hemiparetic Stroke,” in Proceedings of the 2005 IEEE 9th International Conference on Rehabilitation Robotics, Chicago IL, 2005, pp 519-521.

[44] H. Bastiaens et al., “Facilitating Robot-Assisted Training in MS Patients with Arm Paresis: A Procedure to Individually Determine Gravity Compensation,” in Proceedings of 2011 IEEE International Conference on Rehabilitation Robotics (ICORR), 2011.

[45] J. Lobo-Prat, “Implementation of EMG-and Force-based Control Interfaces in Active Elbow Supports for Men with Duchenne Muscular Dystrophy: a Feasibility Study,” in Proceedings of IEEE Transactions on Neural Systems and Rehabilitation Engineering, 2016, pp. 1179-1190.

[46] American Academy of Orthopaedic Surgeons, “Joint Motion: Method of Measuring and Recording,” Edinburgh: Churchill Livingstone, 1965.

[47] G. Kurillo, J.J. Han, A. Nicorici, L.B. Johnson, R.T. Abresch, E.K. Henricson, C.M. McDonald, R. Bajcsy, “Upper Extremity Reachable Workspace Evaluation in DMD Using Kinect,” Neuromuscular Disorders, vol. 23, 2013.

[48] P. E. Bijur, W. Silver, E. J. Gallagher, “Reliability of the Visual Analog Scale for Measurement of Acute Pain,” Academic Emergency Medicine, vol. 8, no. 12, pp. 1153-1157, 2001.

[49] D. Meldrum, E. Cahalane, R. Conroy, D. Fitzgerald, O. Hardiman, “Maximum Voluntary Isometric Contraction: Reference Values and Clinical Application,” Amyotrophic Lateral Sclerosis, vol. 8, pp. 47-55, 2007.

[50] C. G. Burgar, P. S. Lum, P. C. Shor, H.F. Machiel Van der Loos, “Development of Robots for Rehabilitation Therapy: The Palo Alto VA/Stanford experience,” Journal of Rehabilitation Research & Development, vol. 37, no. 6, 2000.

[51] L. Turner-Stokes, “Goal Attainment Scaling (GAS) in Rehabilitation: A Practical Guide,” Clinical Rehabilitation, vol. 23, pp. 362-370, 2009.

[52] N. Van Riel, "Speeding Up Simulations of ODE Models in Matlab using CVode and MEX files,” unpublished, Eindhoven University of Technology, 2012.

[53] G. C. Burdea, Force and Touch Feedback for Virtual Reality. New York, NY: Wiley; 1996.

[54] I. A Kuling, J. B. J. Smeets, P. Lammertse, B. Onneweer, W. Mugge, “Delays in Admittance-Controlled Haptic Devices Make Simulated Masses Fell Heavier,” PLOS ONE, vol .10, no. 9, 2015.