WORCESTER POLYTECHNIC INSTITUTE

MAJOR QUALIFYING PROJECT

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# Designing a Wearable Shoulder Exoskeleton for Hemiparetic Patients

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# ABSTRACT

Hemiparesis is a condition which affects over 80 percent of stroke victims, and can significantly reduce the overall quality of life in affected individuals. There are currently no assistive devices on the market to address shoulder hemiparesis, and current treatment options for upper-extremity loss of function are expensive and not always effective. To address this need, a cable driven device was created to actively lift the affected arm, increasing the range of motion of the shoulder in two degrees of freedom. Individuals are able to control the activation and position of the device using a variety of sensors, so that they can independently perform activities of daily living (ADLs). From validation testing, the team confirmed that the device was able to accurately and consistently provide 87 degrees of motion in the flexion/extension motion and 76 degrees in the abduction/adduction motion, respectively. The device was also proven to be comfortable and intuitive, and was able to allow users to increase their ADL performance.

# AUTHORSHIP

This report was equally prepared by all team members: Emily DiRuzza, Alyssa Marzella, Tess Meier, and Veronica Rivera. We confirm that "Designing a Wearable Shoulder Exoskeleton for Hemiparetic Patients" and the work presented in it are our own. We confirm that:

- This work was done wholly or mainly while in candidature for an undergraduate degree at Worcester Polytechnic Institute.
- Where we have consulted the published work of others, this is always clearly attributed.
- Where we have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely our own work.
- We have acknowledged all main sources of help.

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# Chapter 1

# Introduction

According to the American Academy of Orthopedic Surgeons, approximately 7.5 million individuals visited a medical professional regarding a shoulder problem in 2006 [1]. One of the most common conditions that affects the shoulder is hemiparesis, the weakening of muscle and partial paralysis on one side of the body. Hemiparesis limits an individual's ability to accomplish Activities of Daily Living (ADL) including feeding oneself, attaining adequate levels of personal hygiene, and transferring oneself from or onto a chair or a bed. Stroke victims are one of the highest populations of injured individuals subjected to hemiparesis, as 80 percent of stroke survivors are left experiencing initial muscle weakness [2].

The rehabilitation process for a hemiparetic individual is long and strenuous as a result of their reduced ability to move their arm without assistance. For individuals with hemiparesis, surgery is currently not a viable option for rehabilitation. Therefore, the gold standard for hemiparetic shoulder injury is physical therapy or occupational therapy. However, this does not always allow an individual to be able to independently move their own arm causing a prevalent need for an assistive device to address this issue. Currently, there are various devices on the market that address loss of function in the elbow and the hand, such as the MyoPro. The MyoPro serves as the current gold standard assistive upper extremity device on the market. It functions by sensing muscle contractions and amplifying these signals from the patient's weakened muscles then uses them to trigger the actuation of the device [3]. The limitations of the MyoPro, however, include that this device does not explicitly address shoulder weakness but rather, elbow and hand weakness. Additionally, this device can cost upward of 60,000 dollars and insurance companies rarely cover the cost of the device.

The goal of this Major Qualifying Project is to design, prototype, and test a shoulder component of a wearable assistive device to mechanically facilitate motion of the shoulder. In order for the individual to use this device on its own, they should have functional ability of their ipsilateral hand, or the hand on the same side of the body as their injured shoulder. This device is intended to be used as an assistive device rather than a rehabilitative device. This means the device will help the individual accomplish everyday tasks that have become difficult due to their injury. This differs from a rehabilitative device that is used in the primary stages of recovery as a treatment to help regain some function. Additionally, the device should mimic the musculature, kinematics, and biomechanics of the shoulder, as well as provide assistance to individuals with hemiparesis in performing primary ADL's. Specifically, this device will focus on assisting individuals with bi-manual tasks, or tasks that require users to use both upper extremities in coordination.

Generally, bi-manual tasks involve one of the upper extremities being used for stability, or gross motor skills, while the other is used for dexterity, or fine motor skills. Gross motor skills refer to bigger movements such as performing flexion and extension, whereas fine motor skills refer to smaller movements that require more coordination

including grasping or holding [4]. Some of the bimanual motions that this device will address include putting objects on a shelf, reaching into a cabinet to obtain a glass, and cutting food during meal preparation.

To accomplish these goals, this device will integrate a variety of mechanical and electrical components including rigid bracing, various user interface methods, and actuators to mimic the natural anatomy of the shoulder. Basic shoulder movements using the device will be tested on an anatomical skeleton model created by the group to ensure that design specifications and functions have been achieved. A human skeleton model will be overlaid with various moldings to ensure the model has the proper flesh-like texture and resilience. The anatomical model will be comparable to the dimensions, weight, and function of the human body. It will be verified that the device has the ability to lift the weight of an average arm as well as the ability to maintain desired arm elevation. The movements tested with this model will demonstrate that the user will be able to accomplish ADL's using the project team's device.

Following this verification, the Fugl Meyer Scale (figure 1) will be utilized to assess how well hemiparetic individuals can accomplish ADLs and bi-manual tasks while using the device. Additionally, financial analysis will be conducted to determine the cost of the device versus the cost of visiting an occupational therapist for physical therapy.

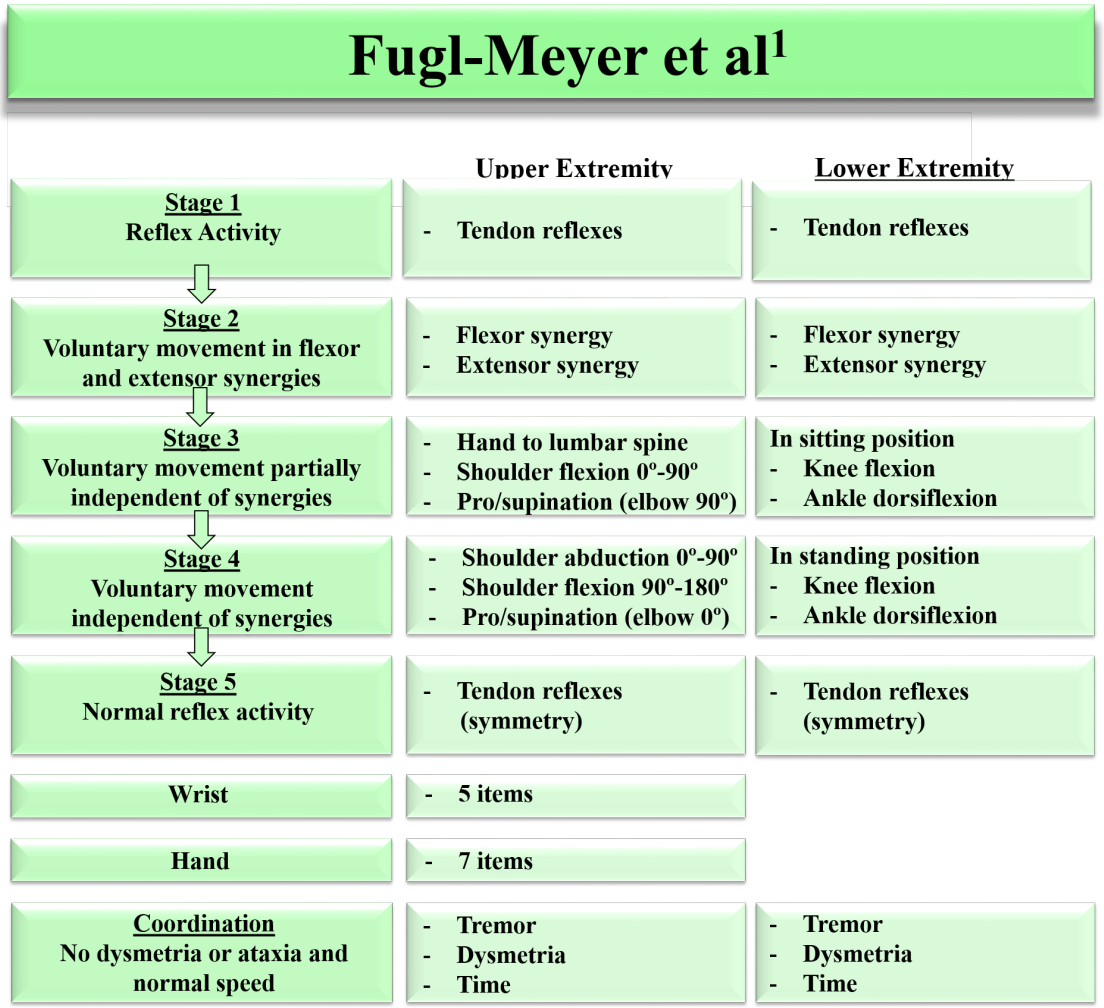



FIGURE 1.1: Hierarchical Properties of the Fugl-Meyer Scale (Modified from [2]

# Chapter 2

# Literature Review

The shoulder has the greatest range of motion of any joint system in the body. As such, it is susceptible to injury and degenerative problems. While there are a multitude of orthoses designed to restore function to the elbow, wrist, and hand, there are very few that restore mobility in the shoulder. A majority of activities of daily living involve lifting or moving the shoulder, including; working at a desk, reaching an eye level shelf, preparing food, or brushing hair. Individuals with the symptoms mentioned above could be candidates for this device. To ensure that the designed device will successfully address diseases that cause shoulder weakness the following chapter examines:

- Anatomical Structure of the Shoulder, Back and Arms
- Populations affected by severe shoulder injury or degeneration
- Current Assistive Devices to Address Hemiparesis
- Methods of Device Control

## 2.1 Anatomy

### 2.1.1 Anatomical Terminology

In order to accurately describe body parts and their position relative to each other, it is important to become familiar with the universal terms used for anatomical descriptions. The initial reference point in describing a body part requires the body to be in anatomical position. This refers to standing with palms facing frontward, arms by the sides and feet together. When in anatomical position, left and right refer to the sides relative to the body, not the viewpoint of the observer. All directional and positional terms refer back to this standard position, regardless of what position the body is actually in [5].

From this position, there are several terms that define how parts of the body are oriented. The appendicular skeleton is composed of the torso and head, and comprises the main part of the body. The axial skeleton is composed of the remaining limbs. Superior refers to positions of muscle and bone which are closer to the top of the body, towards the skull. Inferior refers to positions of the muscle and bone closer to the bottom of the body, towards the feet. Posterior refers to the back of or behind the body. Anterior refers to the front of the body. The Lateral direction points away from the midline of the body, such as the thumb is lateral to the pinky finger when in anatomical position. Medial refers to anything closer to the midline or middle of the body. Proximal refers to parts of a limb closer to the origin point on the body or the point of attachment. Distal refers to parts of a limb farther from the origin point or point of attachment. Origin is the attachment of muscle that remains relatively fixed during muscular contraction. Insertion is the moveable attachment of muscle. Articulation is the junction of two or more bones

[5]. Figure 1 depicts the directional terms relative to the anatomical position of the body [6].

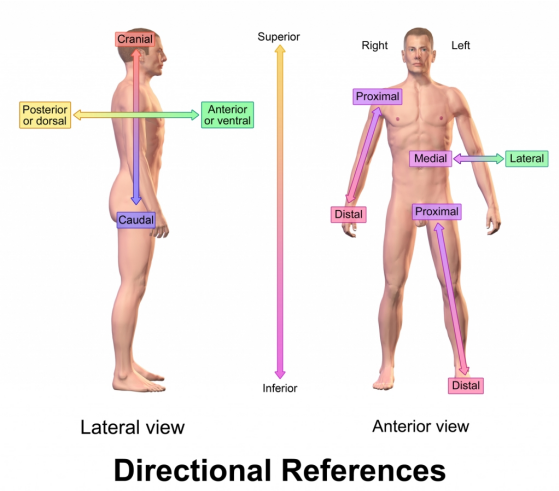



FIGURE 2.1: Directional Terms Relative to Anatomical Position

### 2.1.2 Arm

#### Bones

The arm can be broken into three sections: the upper arm, forearm, and the hand. The humerus is the only bone that makes up the upper arm while the forearm consists of the radius and ulna. The hand has a multitude of bones consisting of eight carpals forming the wrist, five metacarpals forming the palm, and the proximal, intermediate and distal phalanges forming the fingers (the thumb does not have an intermediate phalange). The proximal end of the humerus articulates with the scapula at the shoulder while the distal end articulates at the elbow with both the radius and the ulna. In the forearm, the ulna is located on the medial side of the arm while the radius is located on the lateral side of the arm. Both the radius and the ulna are connected by the interosseous membrane, a thin flat ligament. The ulna composes most of the elbow while the radius primarily composes the wrist [5].

#### Musculature

There are a total of eight muscles that work across the elbow to move the forearm. However, only four of those muscles are primarily in charge of the elbow joint's motion. The biceps brachii and the brachialis are the primary movers that control elbow flexion. Elbow extension is controlled by the triceps brachii while elbow pronation, the inward rotation of the elbow, is controlled by the pronator quadratus. While there are no muscles that are primarily in control of elbow supination or outward rotation, the biceps brachii and the supinator both work together to produce that motion [5].

The muscles that control the motion of the wrist are separated into the anterior and the posterior compartment. In the anterior compartment the flexor carpi radialis, the flexor carpi ulnaris and the flexor digitorum work together as the primary movers for wrist flexion. There are no primary movers responsible for wrist abduction, however, the flexor carpi radialis contributes to such motion and the flexor carpi ulnaris contributes to wrist adduction. In the posterior compartment, the only primary mover is

the extensor digitorum, which allows for wrist extension. There are no primary movers located in the posterior compartment that cause wrist abduction and adduction, however, there are three muscles that do assist with those motions. Both the extensor carpi radialis longus and brevis and the abductor pollicis longus contribute to wrist abduction, while the extensor carpi ulnaris contributes to wrist adduction [5].

#### Joints and Ligaments

The elbow can be categorized as a hinge joint. A hinge joint is a joint that only moves on one axis allowing the joint to flex and extend. The wrist is a condyloid joint which allows it to experience circular motion, flexion and extension [5].

### 2.1.3 Shoulder

#### Bones

There are three bones which compose the main portion of the shoulder: the scapula, the clavicle, and the humerus (figure 2). The scapula is a thin, triangular flat bone which lies on the dorsal surface of the ribcage. Each scapula has three borders: superior, medial, and lateral. The superior border is the shortest, making up the tip of the shoulder. The medial border lies next to the vertebrae, while the lateral border is near the armpit [5]. The most superior point of the scapula is called the acromion process, and is the top of the shoulder girdle. The most anterior portion of the lateral border is the coracoid process, and it is an attachment point of many ligaments and muscles [7]. The clavicle connects the axial skeleton to the appendicular portion of the shoulder girdle (i.e. the arm). The clavicle is S-shaped and composes the front portion of the shoulder girdle. It articulates with one end of the sternum and with the acromion process of the scapula. The humerus, mentioned above in section 2.1.1, articulates with the scapula at the glenoid cavity, connecting the appendicular body to the axial body [5].

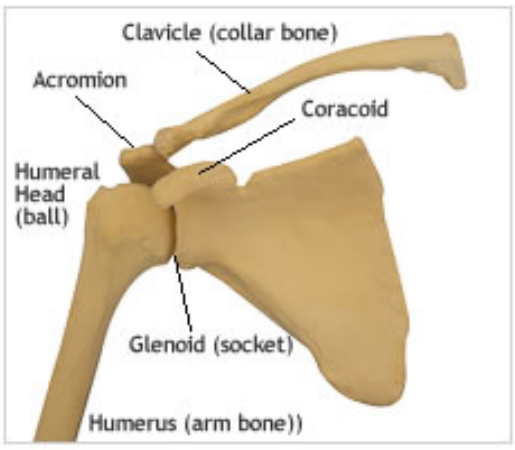



FIGURE 2.2: Bones of the Shoulder Girdle [7]

#### Musculature

As the shoulder is the most mobile system in the body, there are several muscles that interact with each other in the shoulder girdle. Muscles from the arm, back, chest and the shoulder itself all work together to move. The muscles can be broken into the anterior and posterior muscle groups.

The anterior muscle group is composed of the pectoralis minor, pectoralis major,serratus anterior, subclavius, subscapularis, deltoid, and coracobrachialis, as shown in figure 3. The pectoralis minor is a flat, thin muscle that lies directly beneath the pectoralis major. The pectoralis minor originates on the ribs and inserts on the scapula, working to draw the scapula forward and down. The pectoralis major is a large fan-shaped muscle which originates on the clavicle, sternum, and top ribs, and inserts on the sulcus and humerus. The pectoralis major works to adduct and rotate the arm. The serratus anterior is a fan-shaped muscle which originates on the lower ribs and inserts over the entire anterior surface of the scapula. The serratus anterior works to rotate the scapula, protracting to hold the scapula against the chest wall and raise the point of the shoulder. The subclavius connects the top of the ribs to the clavicle, and works to stabilize and depress the pectoral girdle. The subscapularis originates on the scapula and inserts onto the humerus. It is the chief medial rotator of the arm. The deltoid is a thick, rounded muscle which originates on the clavicle and scapula, and inserts itself on the humerus. This muscle is the prime mover of arm abduction, which occurs when all of its fibers contract simultaneously. The Coracobrachialis is a small cylindrical muscle which originates on the coracoid process of the scapula and inserts on the shaft of the humerus, flexing and adducting the arm [5].

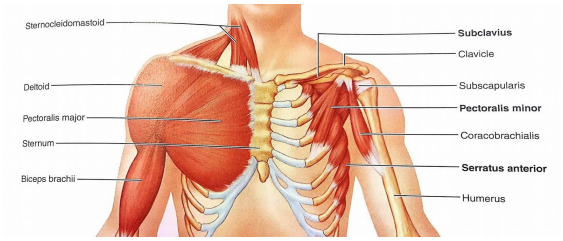



FIGURE 2.3: Anterior Grouping of the Shoulder Girdle Muscles [5]

The posterior group of muscles is composed of the trapezius, levator scapulae, rhomboids, and the latissimus dorsi, as well as the muscles of the rotator cuff, including the supraspinatus, infraspinatus, teres minor, and teres major, observed in figure 4 below. The trapezius is a large, flat triangular muscle which originates on the occipital bone in the skull and inserts on the acromion and spine of the scapula, as well as the clavicle. The trapezius performs several actions within the shoulder, stabilizing, elevating, retracting, and rotating the scapula. The levator scapulae is a thick, strap-like muscle which originates on the upper vertebrae and inserts on the scapula, elevating and adducting it. The rhomboids are diamond shaped muscles which originate on the spinous processes and insert on the scapula, working to stabilize it. The latissimus dorsi are broad, flat triangular muscles which originate on the vertebrae, ribs, iliac crest, and scapula, and insert onto the humerus. These muscles are the prime movers of arm extension, and they rotate the arm at the shoulder. The final four muscles, the supraspinatus, infraspinatus, teres major and teres minor, compose the rotator cuff of the shoulder. The supraspinatus is the most superior of the four, originating on the scapula and inserting onto the humerus. This muscle initiates abduction of the arm. The infraspinatus lies just beneath the supraspinatus and also originates on the scapula and inserts on the humerus. The infraspinatus works to rotate the arm laterally. The teres minor is a small, elongated muscle lying deep to the infraspinatus, originating on the scapula and inserting under the infraspinatus on the humerus. This muscle also works to rotate the arm laterally. The teres minor is the most inferior muscle of the rotator cuff, and small and cylindrical in shape, originating on the coracoid process of the scapula and inserting on the shaft of the humerus. This muscle works to flex and adduct the arm [5].

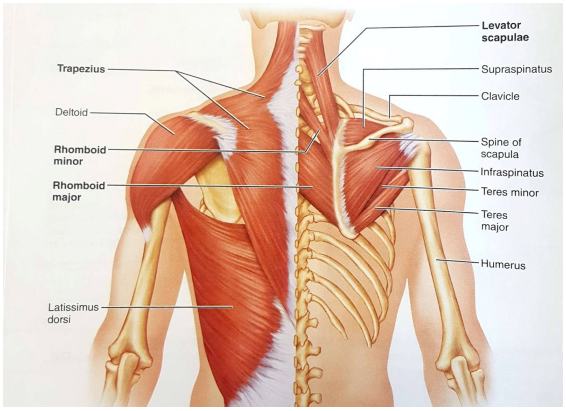



FIGURE 2.4: Posterior Grouping of the Shoulder Girdle Muscles [5]

### Joints and Ligaments

There are four main joints in the shoulder. The glenohumeral joint is most closely modeled by a ball and socket joint, and is what people normally think of when they think of the shoulder. The head of the humerus articulates with the glenoid fossa of the scapula, and the glenoid labrum, a ring of cartilage, provides additional support to the humerus at the joint. The glenohumeral joint is responsible for a majority of movement in the shoulder girdle. The acromioclavicular joint is formed by the lateral end of the clavicle articulating with the acromion process on the scapula. The main function of the acromioclavicular joint is to transmit forces through the upper limb and shoulder to the axial skeleton. It's mobility is limited due to its supporting ligaments, the acromioclavicular ligament and the coracoclavicular ligament, making it sturdy. The sternoclavicular joint occurs at the junction where the sternum articulates with the medial end of the clavicle and the first rib. It is the only joint in the shoulder girdle that actually connects the upper extremity to the axial skeleton. The sternoclavicular joint works in all movements of the upper limbs, particularly throwing and thrusting movements. Finally, the scapulothoracic joint occurs where the scapula articulates with the ribcage. This joint relies entirely on the surrounding musculature for control, including the serratus anterior and the trapezius [8].

## 2.1.4 Biomechanics of the Shoulder

These four joints of the shoulder work together to perform the core motions of the shoulder. While there are many degrees of freedom, the three main degrees of freedom account for the core movements of the shoulder; flexion and extension, abduction and adduction, and internal and external rotation. Flexion and extension refer to the movement of the arm in the x-axis, with flexion bringing the arm up and towards the anterior part of the body and extension bringing the arm down and towards the posterior side of the body. Abduction and adduction refer to rotation of the arm about the z-axis. Abduction contracts the muscles and works to pull the arms up towards the head, while adduction relaxes the muscles and brings the arms down towards the hips. Internal and External rotation refer to the shifting of the shoulder in the y-axis plane, with internal referring to the rotation of the arm medially, while external rotation is the movement of the arm laterally. Figure 5 depicts the different motions of the shoulder girdle [5].

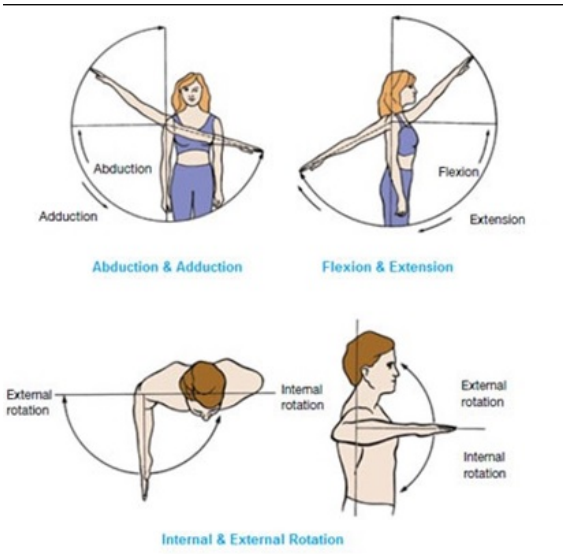



FIGURE 2.5: Core movements of the arm [9]

## 2.2 Hemiparesis

Defined by the National Stroke Association, hemiparesis is the weakening of the muscles on one side of the body. Hemiparesis can affect many different areas of the body including the shoulders, arms, and hands, as well as the legs, feet, and facial muscles. Onset of hemiparesis is generally a result of another condition in the body that results in brain injury and thus damage to the motor neurons. Some of the causes of hemiparesis include vascular conditions including stroke, congenital conditions including cerebral palsy, neoplastic conditions such as brain tumors, and traumatic brain injuries. Of these conditions, stroke victims comprise of the highest population of individuals who endure hemiparesis. Statistically, 80 percent of individuals who experience a stroke develop hemiparesis [10].

General symptoms of hemiparesis often include the loss of the individual's fine motor skills and difficulty for the individual to perform everyday tasks, or Activities of Daily Living (ADLs), such as eating, bathing, dressing, toileting, and walking [11]. The muscle weakness experienced by a hemiparetic individual can result in difficulty performing everyday activities due to a loss of balance, impaired ability to maintain a grasp, and a decreased ability in coordination. Focusing specifically on the shoulder, hemiparetic weakness can make it increasingly difficult for an individual to raise their arm, can cause a faster rate of muscle fatigue, and can decrease the precision with which the individual can move their shoulder and arm [10]. Additional symptoms of hemiparesis can occur as a result of the impairment that caused the hemiparesis. For stroke patients, the side of the body that is affected by hemiparesis reflects the location in the brain where the stroke occurred. Hemiparesis on the right side of the body results from injury in the left side of the brain. The left side of the brain is responsible for controlling speaking and language therefore, individuals with right-sided hemiparesis have the potential to experience difficulty speaking and comprehending others. Hemiparesis on the left side of the body results from brain injury on the right side. Given that the right side of the brain controls an individual's learning, behavior, and nonverbal communication, individuals with left-sided hemiparesis can additionally experience shorter attention span, difficulty with their memory, and excessive speaking [12].

### 2.2.1 Shoulder Hemiparesis

Individuals with hemiparesis often compensate for the loss of muscle function by performing certain tasks using muscles in the body that would generally not be used to complete that task. Looking specifically at individuals with shoulder hemiparesis, it has been found that the weakening of the shoulder muscles has an impact not only in the range of motion of the shoulder, but also in the muscles activated during tasks. A study conducted at Universidad Rey Juan Carlos in Madrid, Spain, found that when individuals with hemiparesis were asked to perform the simple task of drinking water from a cup, their superior trapezius was activated for the entire duration of the task. This was opposed to the control group whose superior trapezius was only activated during the portion of the task to lift the cup to the lips and then returning the cup to the table. Similarly, the anterior, medial, and posterior deltoid fibers were all activated and co-contracted in the hemiparetic patients during while the individual reached for the cup with their hand, grasped the cup, and lifted the cup to their lips. This was opposed to the able-bodied control group in which the activation and contraction of their deltoid fibers was more specific. Their anterior deltoid fibers were activated while the individual moved their hand from its initial position toward the cup and grasped the cup. Their medial fibers were activated while the individual lifted the cup to their lips and returned the cup to the table. Lastly, their posterior fibers were activated only while the individual released the cup and moved their hand back to its original location [13].

### 2.2.2 Populations Affected by Hemiparesis

On average, over 7.5 million individuals visited a medical professional experiencing shoulder pain per year [10]. The reason for these visits varies greatly, as shoulder injuries can occur from both disease and injury. While some of these visits resulted in minimal aftercare, many of these visits require further rehabilitation. In the most severe cases of shoulder injury, hemiparesis, or partial paralysis of a limb, can occur. Patients experiencing hemiparesis often find themselves limited in what they can accomplish in their daily lives. There are numerous diseases and injuries which result in hemiparesis, which encompass the population that this project will be targeting.

#### Stroke

Stroke is the leading cause of long-term disability in the United States, as approximately 795,000 people suffer from a stroke annually. Of the 15 million cases of stroke that occur on a global scale each year, over 5 million cases result in permanent disability. A stroke is characterized by the sudden death of brain cells due to a lack of oxygen [11]. The most common type of stroke is an ischemic stroke, which refers to when a blockage within a blood vessel prevents the delivery of oxygen to the brain. Hemorrhagic stroke, which is more common in children, refers to the rupture of a weakened blood vessel, more commonly known as an aneurysm [12]. The risk of stroke increases with age, and can affect these individuals to various extents, ranging from temporary weakness and headaches to permanent paralysis. In 2009, over 65 percent of individuals who were hospitalized were 65 years of age or older. One of the most prevalent effects of a stroke is paralysis, which usually affects one side of the body, leaving the individual hemiplegic [11].

### Traumatic Brain Injury

While not as prevalent as Stroke, Traumatic Brain Injury (TBI) is also a major contributor of death and disability in the United States. A TBI is caused by a blow or jolt to the head that causes the normal function of the brain to be altered. The severity of a TBI ranges greatly, and can affect cognitive and motor function, sensations and emotions [13]. For a recovering TBI patient it takes a lot of concentration and strength to even attempt to move or relax their paralyzed limb if their accident has left them with high tension in their muscles, as they have to try and overcome both their mental and physical disabilities. Recovery can be frustrating because if the individual is trying to relax and move their fingers but also needs to contract their muscle to lift the arm, all of the muscles in the limb contract once more [14].

### Multiple Sclerosis

Multiple Sclerosis (MS) is a disease in which the immune system attacks the myelin sheath of the central nervous system, deteriorating the function of the nerves and sending weakened or no signals to the brain. Depending on the type of MS a patient has, they may experience only temporary symptoms or they could endure lifelong paralysis [14]. Many people begin to experience symptoms between the ages of 20 and 40, with the initial symptoms being blurred vision and color distortion. Once diagnosed, most patients experience varying levels of muscle weakness as well as difficulties with coordination and balance [15].

### Arthrogryposis Multiplex Congenita

Arthrogryposis Multiplex Congenita is a joint disease in which the joints of the shoulder and pelvis are deformed from birth causing the limbs to be internally rotated. This can cause shortening of the muscles resulting in babies and infants being unable to lift their arms at all [16]. These children still have function in their fingers and hands. In order for them to maintain this level of functionality, it is beneficial for them to keep them moving to prevent atrophy. It is also important for their growth and development that they are able to play with toys and learn how to feed themselves. While this condition is not incredibly common, a wearable shoulder exoskeleton would be critical to their development and independence.

### Muscular Dystrophy

There are approximately 20 different kinds of Muscular Dystrophy, each one with its unique characteristics and complications. Individuals that would benefit the most from this wearable shoulder exoskeleton are those with Limb-Girdle, Facioscapulohumeral, and Emery-Dreifuss Muscular Dystrophy [17]. Each of these lead to the muscle weakness and atrophy of the shoulder muscles to a certain degree. These conditions progress distally so the device actuation could be triggered by a series of hand motions detected with EMG sensors, or using a switch.

### Cerebral Palsy

Cerebral Palsy (CP) is the result of brain damage before, during, or shortly after birth; Cerebral Palsy is the loss or impairment of motor function. CP is a spectrum disorder, meaning individuals can have this condition with varying severity [18]. In mild cases, when the arm and shoulder muscles are affected, a device like this would be useful in

assisting the individual in performing daily life activities. A device as such could also assist the patient's caregiver, or personal nurse, in moving the arms while transferring from bed to chair and vice versa.

### 2.2.3 Assessing Hemiparesis

Once symptoms of hemiparesis are brought to the attention of a doctor, a variety of assessment tools are used to evaluate the abilities of the individual. These assessment scales enable the physician to provide the individual with a proper treatment plan. Currently, doctors generally use one of two assessment scales when evaluating hemiparetic individuals, the Fugl-Meyer Assessment of Physical Performance (FMA) and the Chedoke-McMaster Stroke Assessment (CMSA).

#### Fugl-Meyer Assessment of Physical Performance

The Fugl-Meyer Upper Extremity Scale is used by physicians on stroke patients to analyze the level of impairment the individual has sustained. It was designed specifically to analyze the activity of the individual's reflexes, motor control, and muscle strength of stroke victims. The test is structured so that the individual evaluates their ability to perform 33 different tasks by scoring them from 0 to 2. If the individual cannot perform the task, it is given a score of 0, if the task can partially be performed, it is given a score of 1, and if they individual can perform the task in its entirety, it is given a score of 2. The physician or therapist is able to examine the types of motions that the individual cannot perform or has difficulty performing. With this information, they can construct a treatment plan for the patient that addresses these specific motions in an attempt to restore and retrain the individual's muscles [15].

#### Chedoke-McMaster Stroke Assessment

The Chedoke-McMaster Stroke Assessment test was created by individuals at McMaster University in Ontario, Canada. Similarly to the Fugl-Meyer Assessment, the Chedoke-McMaster Stroke Assessment evaluates the physical impairment of stroke patients. The test is comprised of two sections, the Impairment Inventory component, and the Activity Inventory component. The Impairment Inventory focuses on assessing to what degree of severity a physical impairment exists. To do so, patients are evaluated based on shoulder pain, postural control, and arm, hand, leg, and foot movement. Like the Fugl-Meyer assessment, this test is quantifiable. The presence and severity of a physical impairment in the individual is scored on a scale from 0 to 7, 0 meaning that the individual does not have a physical impairment, 1 meaning that a physical impairment exists however, it is not severe, and 7 meaning that the severity of the physical impairment is high and is imposing on the individual's ability to perform daily tasks [16].

The Activity Inventory component of this test analyzes the individual's ability to complete basic daily tasks. It is scored relative to the individual's ability to complete tasks without assistance. This portion of the test is split into two sections, one evaluating gross motor function and one evaluating the individual's ability to walk on different surfaces. The Gross Motor Function Index portion of the test evaluates tasks including those of Activities of Daily Living including the patient's ability to transfer themselves into and out of bed, feed themselves, and dress themselves. The Walking Index section of the test analyzes the gait of the patient while they walk on smooth surfaces, carpeted surfaces, rough, bumpy surfaces, and while climbing stairs [16]. This exam also enables

a medical professional to analyze the results and create a course of treatment specific to the abilities and disabilities of the patient.

### 2.2.4 Treatment of Hemiparesis

Treatment options for hemiparetic individuals generally include some type of physical or occupational therapy. The main goals of treatment from a medical professional is to stimulate the weakened muscles to try and build back strength and function. Within the physical and occupational therapy sessions, therapists often use a variety of different methods to enhance function of the weakened muscles. These methods of treatment include modified constraint-induced therapy (mCIT), electrical stimulation of the hemiparetic muscles, cortical stimulation, and the use of assistive devices [10].

The main difference between physical and occupational therapy is that physical therapy generally serves to help reduce pain and improve or restore movements whereas occupational therapy serves to assist in improving the patient's ability to perform Activities of Daily Living. For hemiparetic individuals, physical therapy treatments often analyze just the affected portion of the body and treats the muscle weakness in this area from a biomechanical standpoint. A physical therapist would then derive a series of exercises and movements for the hemiparetic individual to perform in order to stimulate the affected muscles [19]. Physical therapists often use modified constraint-induced therapy (mCIT), a method that restricts the patient's ability to use the functioning portion of their body in an attempt to force them to use the hemiparetic muscles in the body. The repetitive use of mCIT can ultimately stimulate and retrain the weakened muscles to improve their function. Additionally, physical therapists use electrical stimulation and cortical stimulation as a method of treatment. Electrical stimulation includes sending electric stimuli into the weakened muscles in order to make them contract and relax. This ultimately strengthens the muscle in the hemiparetic area and improves the motion of the muscle. Cortical stimulation as a treatment method sends an electrical stimuli to the patient's cortex while they practice rehabilitation exercises. This treatment is meant to stimulate the neurons in the brain, retraining them to function a certain way depending on the desired motion [10].

When treating a hemiparetic individual, occupational therapists view the individual as a whole, prescribing treatment methods that will allow the patient to complete basic daily functions. While both occupational and physical therapists are concerned with improving the mobility of the affected area, occupational therapists focus on the mobility of the individual long term. This translates to the occupational therapist's practice of teaching the hemiparetic individual to use other methods to accomplish mobility tasks [20]. For instance, if an individual was hemiparetic on the right side of their body but was also right handed, an occupational therapist, while formulating exercises to increase movement of the right arm and hand, would teach the patient how to accomplish tasks using their left hand.

Both occupational and physical therapists also treat patients using various assistive devices. These devices can range from a brace or orthosis to keep the hemiparetic area of the body contained so that motion can be controlled, to a cane or crutches to assist the individual with movement. Additionally, these assistive devices can be exoskeletons that the individual wears daily which serve to assist the patient in moving the hemiparetic body segments so that they can perform their Activities of Daily Living [10].

## 2.3 Exoskeletons

There is currently a plethora of shoulder orthosis available for the average person, however, there are practically no shoulder/upper extremity exoskeletons available. An orthosis is a passive device meant for being rigid and adding support while an exoskeleton augments a part of the wearer's body. Fabric shoulder slings are a popular treatment for shoulder problems such as dislocation of the shoulder, and need for immobilization. There is currently a need in the market for an shoulder exoskeleton that can function beyond immobilization, to allow users to use their arms and shoulder as their current medical condition prevents it. While engineers all over the world have designed shoulder exoskeletons, the vast majority have not made it to the public.

### 2.3.1 Device Classification

Shoulder exoskeletons can be divided into two categories, rehabilitative and assistive. Rehabilitation exoskeletons are designed to be used as part of a treatment for a condition. For example, in a physical therapy office patients could use an exoskeleton as a part of their therapy. These machines are typically large, bulky and not meant for everyday use, but only for an hour or so. Rehabilitation exoskeletons help patients work on the mechanics of movements and controlling their limbs without requiring them to lift their own weight.

Assistive exoskeletons are meant to be worn everyday to assist the individual with their activities of daily living. These devices are intended to restore lost function, allowing the individual to resume the same, or an improved lifestyle they were accustomed to living prior to their medical condition. Because of the frequency of their use, these devices tend to be more compact and less heavy so that the individual is comfortable.

### 2.3.2 Current Devices

#### Rehabilitation Device: Exoskeleton

A unique aspect of this design is that the device is able to function in a variety of different ways, as a rehabilitative device, an assistive device for power amplification, a teleportation system, and as a haptic device. However, for the purpose of this project only the assistive device functionality of this device will be discussed. [21] Figure 6 below depicts a current exoskeleton on the market.

The device is anthropomorphically designed with the joints and links in the device corresponding to the human body as well as moving in seven degrees of freedom. It allows an individual using the device to be able to have full range of motion of the glenohumeral, elbow, and wrist joints. The exoskeleton's axes of rotation coincide with the corresponding anatomical axis. The shoulder specifically is able to move in three degrees of freedom (flexion-extension, abduction-adduction, and internal-external rotation) and is modeled as a sphere to simplify the system. As most activities do not require more than 90 degrees of arm elevation, this simplification is acceptable. [21]

The human machine interface of this device works at the neuromuscular level allowing the device to move more naturally by accounting for the electrochemical-mechanical delay. This phenomenon refers to the delay from when the signal is sent to the muscle to when the muscle actually contracts. Surface EMG signals that are processed by the microcontroller work to actuate the device in a similar fashion to the way the body naturally initiates muscle movement. This device also uses visual feedback to control the device allowing for the device to function more closely to natural movement. [21]

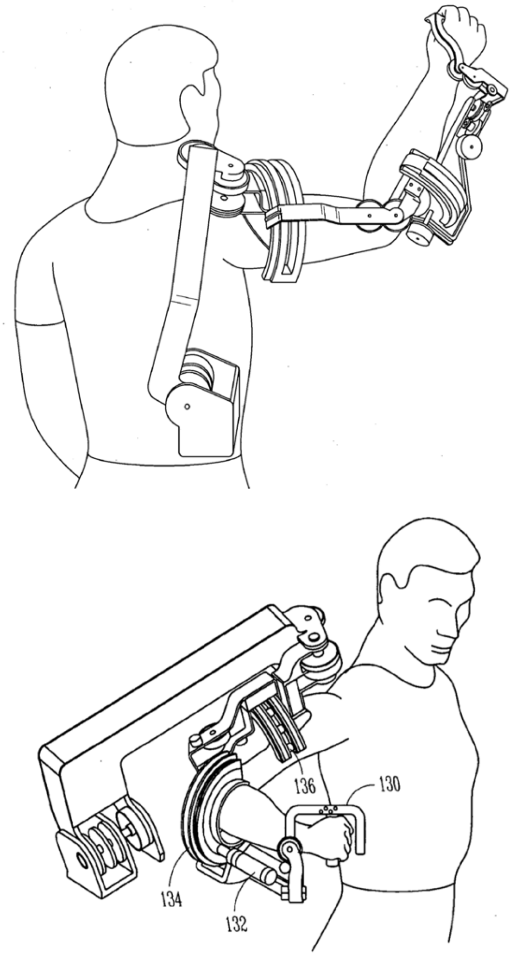



FIGURE 2.6: Front and Side view images of device [21]

A cable drive transmission is used in this device allowing for loads to be transmitted a large distance and mimic the tendons in the body. The cables controlling joint movement are strategically placed through joint axes as well as being maintained at a constant length.

There are a variety of different safety considerations for this device such as a shut off switch, physical joint limits, redundant sensing (potentiometer and optical encoder), force limits as well as the way an individual would put the device on. This device allows for users to be able to easily slip into and out of the device as this could be a difficult task depending on the severity of the individual's limited motion. [21]

This device does have various limitations for use as an assistive device. To ensure for a sufficient power to weight ratio the system is not portable meaning that the device would need to be attached to a powered wheelchair which would make the device unsuitable for day to day life for those who are able to walk. [21]

**Portable Arm Exoskeleton**

The device is a powered exoskeleton for shoulder rehabilitation. It uses either direct drive or a mechanical transmission to move the joints present. To allow for more natural shoulder rotation one of the joint axes is slightly skewed along the frontal plane so that no more than two of the three planes are intersecting at a time. This design has

four different substructures which consist of scapula elevation, shoulder rotation, elbow pitch and wrist roll. [22] Figure 7 below depicts depicts a portable arm exoskeleton.

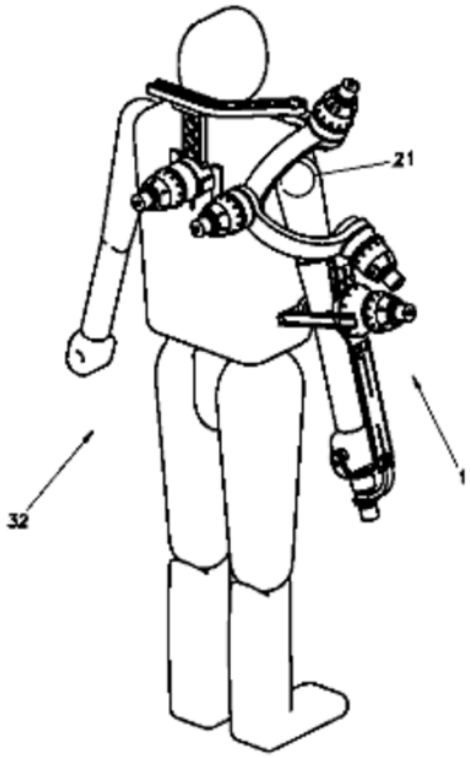



FIGURE 2.7: Portable Arm Exoskeleton [22]

This exoskeleton was designed to have the lowest number of degrees of freedom that would still allow for full exercise therapy of the shoulder. While the arm has a total of seven degrees of freedom this device has a five degrees of freedom along with having a scapula joint included to allow for more rotation. For the design it was determined that three joints would be needed to allow for glenohumeral shoulder rotation. The shoulder was modeled as a three connected pins rather than a ball and socket joint in this design to allow for independent three axis rotation about the shoulder [23].

The main limitation to this device is that it is meant to be used as a therapeutic device rather than something an individual would wear in their everyday life.

#### Parallel Actuation and a Passive Slip Interface Exoskeleton

This device uses a 3 degree of freedom (DoF) spherical parallel manipulator and a 2 DoF passive slip interference. This device incorporates the use of a parallel manipulator which is a series of rotational or linear actuators in a parallel configuration as opposed to in a line. This improves the end effector performance as far as precision and torque generation. It also incorporates slip interference to prevent any mechanical issues that many arise from joint misalignment. Three rotary actuators and curved linkages are used to control three rotational degrees of freedom. Each actuator used had 3DoF two of which are rotational and one is translational [24] Figure 8 depicts a parallel actuation and passive slip interference device.

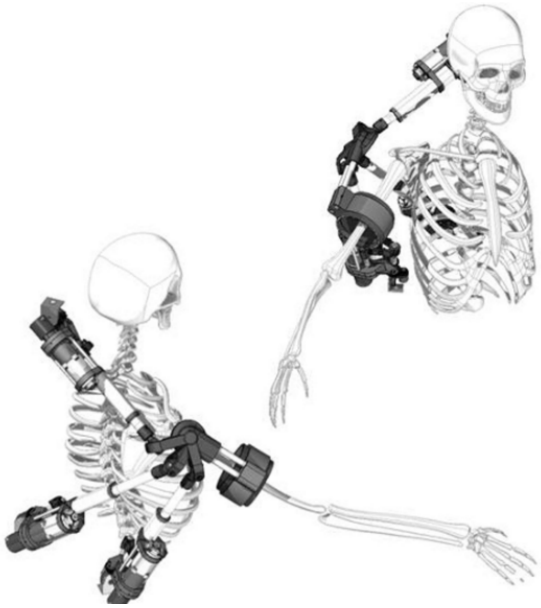


FIGURE 2.8: Theoretical image of the parallel actuation and passive slip interference device [24]

The main limitation to this device idea is that it would have to be mounted on a wheelchair for an individual to use rather than having the ability to be worn.

**Assistive Devices**

The myomo powered orthosis is a device currently on the market as an assistive and rehabilitative device for individuals suffering from hemiparesis. A variety of different validation tests have shown that this device is is able to significantly improve a patient's ability to perform many different ADLs. The device has an upper and lower section that are connected by a pivot that is meant to be aligned with a joint in the human body connecting two segments [25]. Figure 9 depicts the Myopro.


FIGURE 2.9: Myopro powered orthosis [26]

The device is controlled by the EMG signals generated by the user's muscles. The amount of force generated as well as the speed to which the device moves the limb are determined by the magnitude of signal that is detected by the arm [27]. Along with this there is also a communication system that allows a clinician fitting and individual to the device to set custom limits for the amount of force required to cause motion. This enables clinicians to help their patient's muscles grow stronger over time while using

the device as well as allowing the amount of signal needed for actuation to be catered to the needs of different users [25].

Multiple modes are used in this device meaning that users with both high and low muscle tone are able to use the device as it can actively stretch and relax the muscle [27]. The device also accounts for individuals who only have asymmetrical control of their joints, meaning that they are only able to either flex or extend their joint not do both at once, using a control algorithm that mimics that way joint would naturally move in a healthy individual. A clinician is able to set a threshold for how much force the individual needs to generate to trigger either flexion or extension [25]

A variety of safety controls are in place to ensure that the user is safe such as an automatic shut off if a sensor in no longer in contact with the body, limiting the range of motion to only those possibly in the body, limiting current to the actuators, and using motors that only function in biological range [25]

Some of the limitations of this device are that there are many guidelines that restrict what population is able to use this device. For example, if an individual is unable to rotate their shoulder at least 30 degrees they are not eligible to use the device. An individual is also no longer able to use the device if their shoulder has begun to undergo subluxation since the device could weight down the arm making the shoulder dislocated sooner [27].

#### Difficulties

A crucial requirement that allows for anthropomorphism is the alignment of the center of rotation between the body and the exoskeleton. The shoulder is a very complex and flexible joint due to the floating center of rotation in the joint. One difficulty with mechanical exoskeletons is that a tradition 3 degree of freedom joint is designed with a fixed center of rotation that does not accurately mimic the shoulder [28]

## 2.4 Methods of Device Control

To address the symptoms outlined, the team will be exploring a multitude of motors, actuators, and spring systems to be used to counterbalance gravity allowing the individual to move their arms more easily.

### 2.4.1 Sensing Possibilities

In order to allow for more independence of the individual wearing the device, sensors must considered to initiate the actuation. After outlining the symptoms the team intend to concentrate on, it could be assumed that the individual is only displaying these symptoms unilaterally, leaving the rest of their body mostly functional.

#### Electromyography (EMG)

Electromyography is the study of muscle function by measuring and evaluating the electrical signals generated by the muscles [29]. The propagation of electrical signals from nerves to the motor unit cause the depolarization and repolarization of the semipermeable cell membrane of the cells. When the action potential is reached the signal is generated as a voltage. When the muscle contracts the voltage increases and when the muscle is relaxed the voltage is essentially zero. This voltage recorded is actually a potential difference between the two electrode poles. In a bipolar electrode, the distance will affect this potential difference. The ideal distance is typically 1-2 cm [29].

The placement of skin surface EMG electrodes is imperative for recording a useful signal. These surface electrodes should be placed in a central position on the muscle belly. This will yield the strongest signal with a smaller signal to noise ratio [29]. This placement system is extended to every muscle in the body. It is crucial for the sensor to be placed in the same location for every use because that will yield more consistent results.

A common use for EMG sensing is in exoskeleton and assistive device actuation. The electrodes are placed on the user and when the user contracts the muscle, the signal is sent to the device telling it to perform some action, such as turn on a motor. Raw EMG signals must be processed before they are used for this purpose to ensure that the muscle signal was intentional. The data should be rectified which means that absolute value of the negative data points are added to the positive values at the corresponding time [29]. This will result in a signal that is easier to distinguish between muscle contraction and muscle relaxation.

Low Pass filtering and mean-average-value (MAV) filtering essentially both eliminate high frequency noise. A low pass filter has a faster response time which makes it ideal for a graphical user interface however, a MAV filter functions better in real time signal processing on the microcontroller as a result of it being a simpler calculation. The slightly slower response time of the MAV filter processing is a small trade-off for the functionality of the fast real time processing.

### Microcontrollers

Devices use microcontrollers to store and manipulate data as it is being collected. A microcontroller is a small computer that has memory, computational power, and input and output options, all of which should be considered when choosing a microcontroller [30]. Three popular options for hobbyist projects and assistive devices are the Arduino, the Raspberry Pi, and the mbed LPC1768. Images of these various microcontrollers are depicted in figures 10 through 12 below.

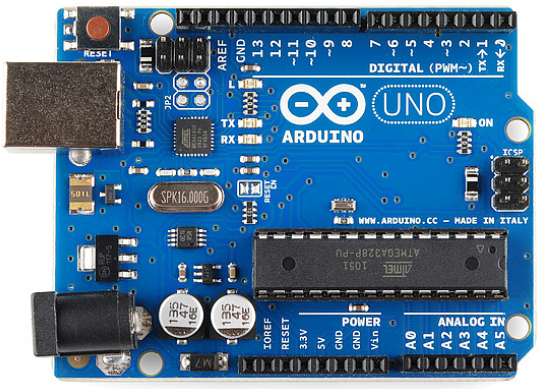



FIGURE 2.10: An Arduino Microcontroller [31]

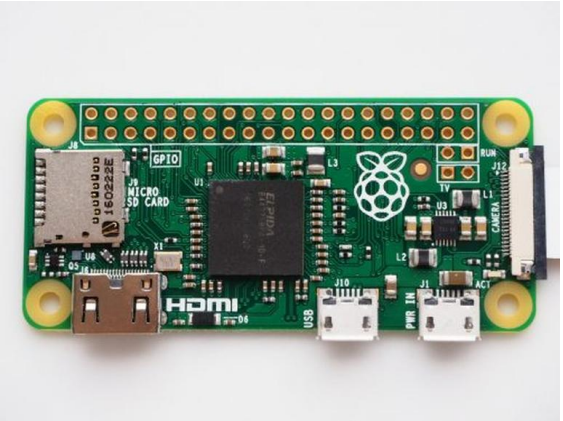



FIGURE 2.11: A Raspberry Pi Microcontroller [32]

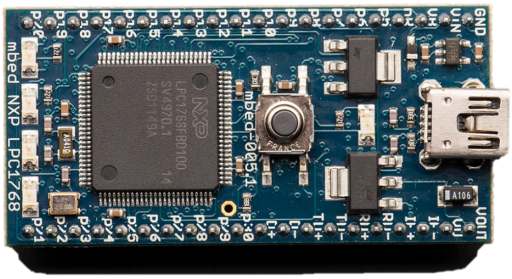



FIGURE 2.12: An mbed LPC1768 Microcontroller [33]

### Actuation

Motors can be classified as brushless or brushed with varying degrees of backdrivability. There are pros and cons for both kinds of motors for this application of an assistive exoskeleton. Brushed DC motors are usually less expensive than brushless motors, and also require a less expensive motor driver because only a power and ground connection are required to run the motor. A brushless motor requires power, ground, a positive reference voltage and a negative reference voltage in order to turn the motor. Because there are two references, the motor can be turned in either direction. Brushless motors are typically more efficient than brushed motors.

A backdrivable motor is not usually lightweight or compact in size, but it provides a more stable force control because of the linear relationship between the current output and the torque. The other option for motors is the non-backdrivable variety which is stiffer to improve precision and supporting heavy loads [34]. While this stiffness is necessary for motor response, a series elastic actuator can be added to a non backdrivable motor to absorb some of the load before it's applied to the motor. This actuator acts as a "low pass filter for shock loads" [34]. Non-backdrivable motors are also usually more compact and lightweight making them more suitable for use in a wearable device. The force sensing is slightly more complicated with this kind of motor but the benefits outweigh the drawbacks.

Linear actuators are non- backdrivable motors that apply force and move in a linear fashion giving them their name. Characterized mainly by their stroke length and the

force required of them, linear actuators come in vary of sizes. The way they accomplish this linear motion is usually through the rotation of a lead screw which extends a shaft as it follows the grooves of the screw [35].

### Position Sensing

Many assistive devices use position sensing as a way to know where the device is in space, so that it can be moved a known amount to another position in space. In assistive devices for the elbow and wrist, this position sensing can be accomplished using encoders. When these devices are only moving in one degree of freedom then they can measure the angle of the device and know where the rest of the limb segment is. Because the shoulder has 3 degrees of freedom, position sensing cannot be accomplished by a sensor as simple as encoders [35].

An alternate method to control the device is through the use of IMUs or Inertial Measurement Units. These sensors contain an accelerometer, a magnetometer, and a gyroscope and output the X, Y, and Z position of the device. After calibration, this sensing method would be able to theoretically control the device by setting a start and end position for the arm to follow.

# Chapter 3

# Methods

## 3.1 Initial Client Statement

Our initial client statement was to develop a way to address shoulder immobility in patients with hemiparesis in order for them to be able to move their shoulder to complete activities of daily living. The broad scope of this client statement allowed for the team to be able to determine what method would be the most beneficial and cost effective way to address this issue.

## 3.2 Technical Design Requirements

### 3.2.1 Objectives

The primary objective of this project is to develop a shoulder device that will brace the shoulder and allow patients with hemiparesis to perform core activities of daily living. To accomplish this objective, the team divided the project into four secondary objectives, which will each have it's own tasks and means of accomplishment. The four objectives are to make the device able to be facilitate shoulder motion, increase ADL performance, is a customized solution, and is safe for the wearer. These four objectives are further broken down in figure 1 below.

| **Project Objectives** | |
|---|---|
| **Facilitate Shoulder Motion** | The device should be able to move the arm in two directions: flexion and extension, and abduction and adduction. |
| **Increase ADL Performance** | The device should assist the user so that they can more easily complete their activities of daily living, thus increasing their quality of life and increasing user independence. |
| **Provide a Customized Solution** | The produced device should be customized to one individual but have ability to be tailored to another wearer. |
| **Ensure the Safety of Users** | The safety of the user should be kept at utmost importance when designing the device, ensuring that there are mechanical safety stops and an emergency stop mechanism. |

FIGURE 3.1: Functional Block of Secondary Project Objectives

To accomplish these objectives, the device must adhere to certain design functions. These functions will satisfy a component of each of the objectives, and when all of the requirements are met, the device should operate as intended. The team split the design requirements into mechanical requirements and sensing requirements. Mechanical requirements refer to those components which directly affect how the machine moves, such as controlling the applied forces of the machine. The sensing requirements refer to how various sensors will work to deliver information to the machine so that it can operate normally, such as maintaining the limb's position in space. A full list of these requirements can be seen below in figure 2.

| Design Functions | Value or Attribute |
|---|---|
| **Mechanical** | |
| **Can control the forces applied on the shoulder** | Able to tailor applied forces for the wearer based on their specifications |
| **Non-restrictive motion** | Joint cannot be simplified as a sphere due to fitted sphere being ±2 cm away from the data |
| **Prevents arm subluxation** | Shoulder weakness naturally leads to shoulder dislocation. A brace can hold the anatomy in place to prevent this |
| **Weight of device is evenly distributed on wearer's body** | Use a durable back brace and spread out mechanical and electrical components across it |
| **Is able to adjust to fit various body types** | Has an adjustable arm brace component and back brace component to fit an individual's physiology |
| **Can lift the arm from a resting, anatomical position** | Device should be able to elevate and lower the arm at the shoulder and account for gravitational force acting upon the upper limb. |
| **Mimics natural motions of the shoulder** | All motors/cables should align with natural musculature. |
| **Sensing** | |
| **Maintain desired location of arm in space** | Device uses sensing to detect the arm's location in space and then signals the motors to apply the proper forces on the arm. |
| **Uses reliable muscle sensing** | Place EMG sensors on functioning muscles in the individual's body |
| **Has the ability to process the signals and output the correct readings** | Use microcontroller to obtain and process data from multiple sensors. |

FIGURE 3.2: Design Functions

For each design requirement, the team developed a series of potential means of accomplishing each task. From this table, the project team will evaluate which means is best. If it is determined that more than one means of accomplishing a design function is best, they will develop the device so the means work in coordination with each other to provide the best possible solution to address each function. The full table of Functions and means for the device can be seen below in figure 3.

| Design Function | Possible Means of Accomplishing Function | | | |
|---|---|---|---|---|
| **Controlled force application** | Motors | Springs | Series Elastic Actuator | Cables |
| **Adjustable arm brace component** | Compression Sleeve | Velcro | Custom Fitting to User | Elastic Material |
| **Adjustable back brace component** | Rigid Brace | Cloth Brace | Backpack with Straps | "Lifting Belt" Type System |
| **Position Sensing** | IMU | String Potentiometer | Flex Sensor | |
| **Muscle Activity Sensing** | EMG Sensors | Force Sensors | | |
| **Sensor processing** | Rasberry Pi | Arduino | mbed LPC1768 | |
| **Prevent subluxation** | Rigid Arm Brace | Crosses Body Strap | | |
| **Mimic Musculature** | Cables | Placement of Components | Series of Elastic Bands | Muscle Insertion Points |

FIGURE 3.3: Design Functions and Means

### 3.2.2 Constraints

The design of the upper extremity exoskeleton was constrained by specific requirements that need to be addressed in order to allow the device to function properly. In regards to anatomical constraints, the device must be built within the appropriate range of dimensions of the shoulder. The average shoulder is between 10 and 16 inches in girth [36]. The dimensions of patients with hemiparesis must also be considered, as their muscle mass and bones density decrease without muscle stimulation [2]. It is also important for the device to operate within the appropriate range of motion, and that the applied forces moving the shoulder do not exceed those required to move the arm naturally. Additionally, this device will be worn directly on the individual's body as opposed to being attached to a wheelchair or being a stationary device. This constraint then generates a constraint regarding the weight of the device. The device should not be too heavy in order to enable the individual to wear the device for longer durations of time without experiencing pain or soreness. It is important to take into consideration that the individuals using this device already have degenerated and weak muscles so they are most likely unable to carry or hold as much weight as a healthier individual. The design constraints of this device can be seen in figure 4.

| Constraints | |
|---|---|
| **Does not exceed natural range of motion** | The device should not allow the individual to move their arm in a way that the natural anatomy normally prevents. |
| **Does not exceed natural forces** | A force larger than those that the arm muscles typically endure should not be able to be applied by this device. |
| **Worn directly on the body** | The device is directly connected to the users' body via a brace. |
| **Weight of the device** | Weight of the device as a whole should not be too heavy so the individual can wear the device for durations of time. |

FIGURE 3.4: Design Constraints for the Device

Additionally, the project as a whole was constrained by cost, time, and available or accessible resources. A final device has to be completed within an eight month time period, and the team intends to spend no more than 2,000 dollars when assembling the exoskeleton. The monetary constraints restrict the materials that the project team is able to purchase for the manufacturing of this device as well as means of experimentation and testing.

### 3.2.3 Design Specifications

The team also created design specifications that needed to be adhered to while designing the device. Three design specifications were developed which provide a guideline for the forces needed to be exerted by the device, the range of motion the device should allow for, and the weight of the device. Figure 5 below provides a broken down image of the specifications.

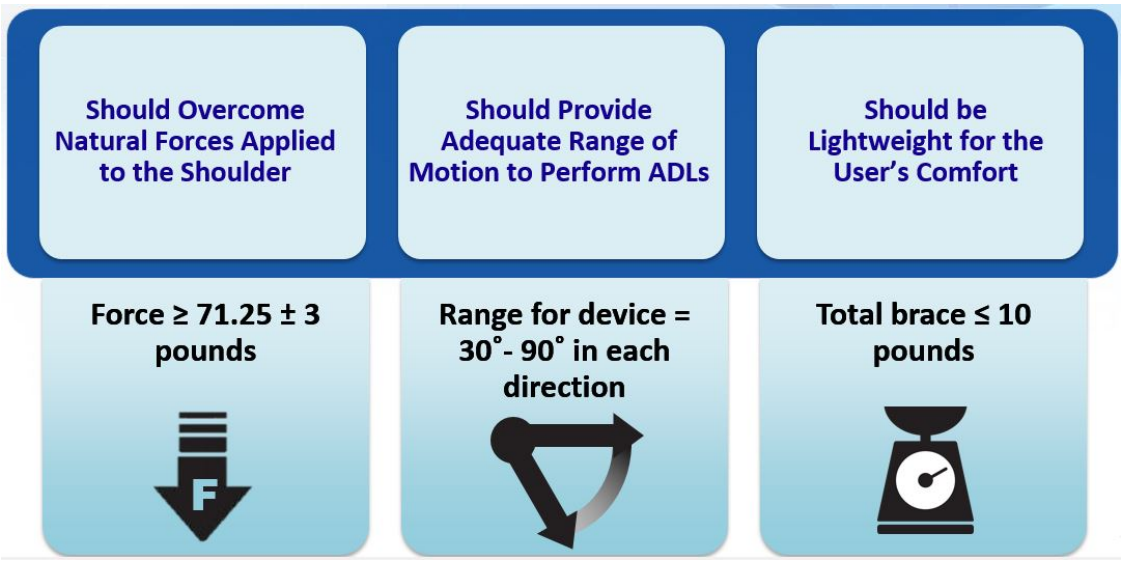



FIGURE 3.5: Design Specifications Developed for the Device

**Specification 1: Overcoming Natural Forces**

Ensuring that the amount of force that the device applies to the body does not exceed that of the natural human body is essential in maintaining the individual's safety. If this force were to exceed the forces of the natural human body, a problem could arise in which the individual's arm could dislocated or further injured. However, it is equally as important to ensure that the device is able to exert enough force to overcome the natural forces applied by the body onto the shoulder. It is reported by Medical Physics Publishing that the amount of force exerted by the human body to elevate the arm is approximately 7.5 times the weight of the component being moved [37]. To develop this specification, the average weight of an arm of a male in the 50th percentile which is reported by NASA to be about 9.5 lbs, was used [38]. This calculation resulted in the specification that the device should be able to exert at minimum 71.25 lbs in order to move the shoulder. Components that will be used to actuate the device and provide force to move the arm must be programed accordingly so as to overcome natural forces.

**Specification 2: Adequate Range of Motion**

To accomplish the objective of increasing ADL performance, the team needed to ensure that the device provided an appropriate range of motion so that the user could adequately perform these tasks. The team set the specification to lift the arm in both directions between 30 and 90 degrees. The upper limit was decided upon based on the fact that most ADLs do not require an individual to lift their arm higher than 90 degrees for completion. The lower limit was decided upon based on the fact that some lower arm exoskeletons on the market, such as the MyoPro, require an individual to be able to lift their arm at the shoulder at least 30 degrees in order for that individual to even qualify to purchase the device [3].

**Specification 3: Lightweight**

The team wanted to ensure that the device was lightweight in order to provide comfort to the user while they wear the device. Current upper extremity exoskeletons are incredibly lightweight, with the myopro arm weighing approximately 2.5 pounds [3].

Unfortunately, this device cannot be this lightweight, as it needs to overcome significantly larger forces than that of the elbow and wrist, which are the only forces that current upper extremity devices need to address. However, the team realized that if the device weighed too much, long periods of use could alter the individuals' biomechanics. To overcome the natural forces of the arm, the device needs to use two motors which alone weigh in total 6 pounds.To ensure that the device would be able to provide the desired outcomes, while also remaining lightweight enough to not alter individuals' biomechanics after long periods of use, the team agreed that the device as a whole could not exceed 10 pounds.

## 3.3 Standards for Design Requirements

Since the goal of this project is to develop a device which will attach to a patient and work to move extremities of the body, it is imperative that all standards related to patient safety and rights, assistive technology, and rehabilitation are met.

The first set of standards that the team must consider were developed by the International Organization of Standardization (ISO). ISO 17966:2016 discusses the requirements and testing methods for assistive products for personal hygiene that support users [36]. This standard specifies all safety and performance requirements that will apply during normal, day-to-day use of the device, and how to prepare for any foreseeable misuse or failure of the product. This standard also specifies how to measure the forces necessary and identify all force limits to safely operate controls of the device. This will be extremely useful when developing the device. While this project is not targeted specifically at addressing personal hygiene, this standard will provide us with a base of important things to consider and help us to develop good testing methods to evaluate the effectiveness of the device. The second ISO standard the team must consider is ISO 16201:2006, which addresses environmental control systems for daily living for persons with disability. This standard lists the functional and technical requirements and testing methods for devices which are intended to compensate for a disability [39]. This standard is very relevant to this project, and as such this project must satisfy all requirements of this standard.

In addition to ISO regulations, it is important to follow all FDA regulations, as the final model produced during this project will classify as a Class II FDA device. This means that the device provides a moderate risk to patients, and that it directly interacts with the body [40]. The FDA has an approved lower limb powered exoskeleton which actuates in a similar fashion to how the team hopes the device will work. If the project team read through this FDA classification and approval, it should help ensure that the device is following all regulations for FDA class II medical devices.

From an Ethical standpoint, it is also important to consider the regulations administered by the ADA, or Americans with Disabilities Act. This Act was established in 1990 in order to, "provide a clear and comprehensive national mandate for the elimination of discrimination against individuals with disabilities" [41]. In a paper discussing the ethical issues of exoskeletons, the author mentioned that developing technology which will replace functionality in a missing or dysfunctional limb will create confusion in the general public as well as service industries about who classifies as a disabled person [42]. Taking this into consideration, the team needs to make sure that ADA regulations are being met and that patients using this device will still receive the necessary benefits.

Once the team begins testing of the final prototype, it will be important to ensure that the device allows patients to perform the core activities of daily living. To evaluate the effectiveness of the device, the project group will use the Fugl Meyer Scale [43], which

is a performance based impairment index (See Figure 1.1). This scale is often used to assess how well a stroke patient's joints are functioning and how their rehabilitation improves their muscle function over time. By using this scale to evaluate the device, the team will be able to determine how well it will allow patients to complete their ADLs, as described by the test.

## 3.4 Revised Client Statement

After conducting preliminary research as well as meeting with the advisors for this project, a revised client statement was drafted. This project aims to develop a shoulder component of a wearable assistive device to mechanically facilitate motion of the shoulder. The device should be able to move the shoulder in the motions of adduction and abduction, flexion and extension, and medial adduction and abduction. This device is intended to assist patients with hemiparesis to perform primary activities of daily living (ADL). The ability to complete their ADL's will improve the user's quality of life.

## 3.5 Management Approach

### 3.5.1 Year Schedule

The major goals and project objectives can be seen throughout the Gantt charts in this section (Figures 6 through 9). A Term was focused on essentially setting up the project with gathering background information and conducting preliminary testing. Prototyping and testing of individual components happened in B Term so that the device could be assembled and tested on able bodied subjects in C Term. In D Term the team planned on conducting patient population testing before wrapping up the project with the final paper and presentation.

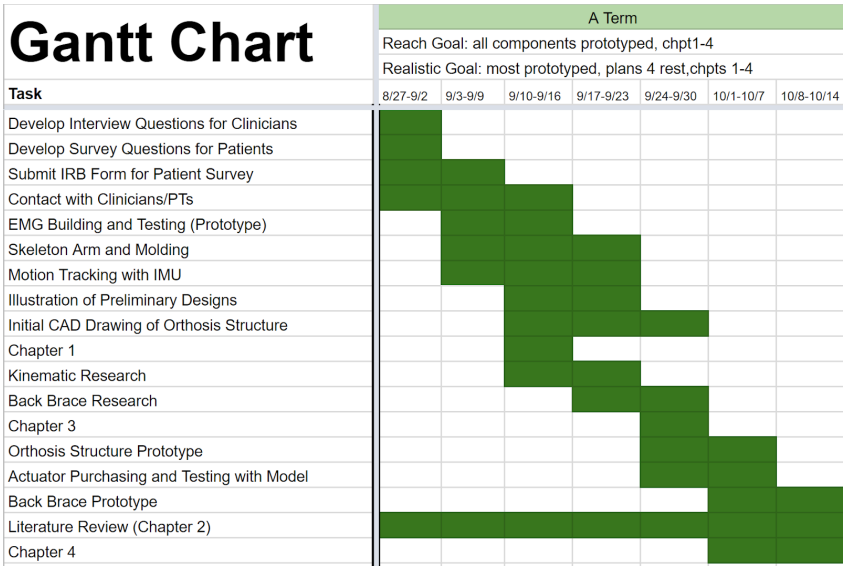



FIGURE 3.6: Gantt Chart for A-Term

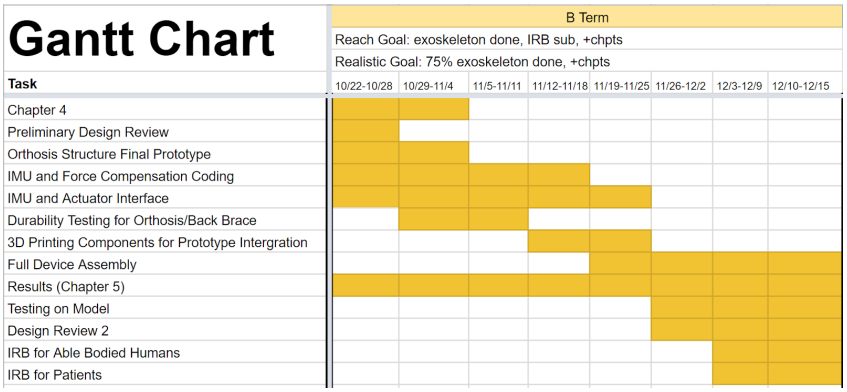



FIGURE 3.7: Gantt Chart for B-Term

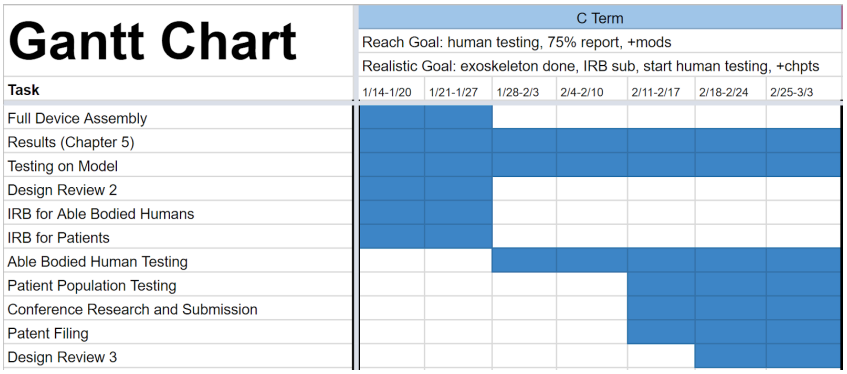



FIGURE 3.8: Gantt Chart for C-Term

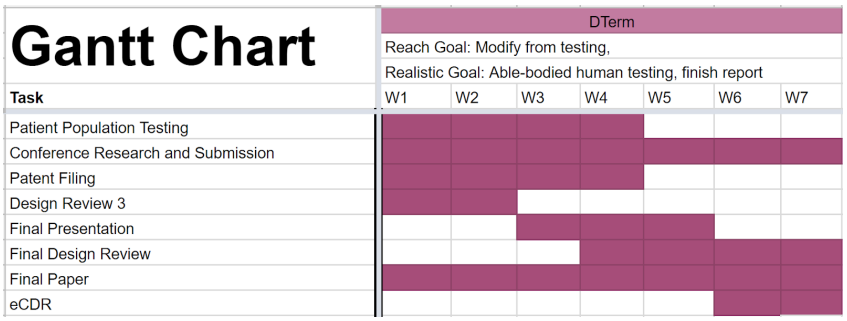



FIGURE 3.9: Gantt Chart for D-Term

### 3.5.2 Project Section Managers

In order to ensure that all aspects of the design are being progressed throughout the duration of the project, each team member was in charge of managing a key aspect of the device's development. The manager for each section was responsible for keeping all tasks on time for their part of the project. Device development can be broken down into these four sections:

- Instrumentation and Actuation
- Mechanics of the Device
- Back Brace
- Analysis and Coding

While each manager is expected to take the lead on their section, they are by no means expected to accomplish the pertinent tasks by themselves, as every team member should assist in the completion of every aspect of device development. The project manager will simply be in charge of organizing the aspects of that goal and making sure that all other team members are contributing to the efficient completion of those tasks.

### 3.5.3 Financial Considerations

To properly organize and effectively budget the resources for this project, the total funds contributed were considered. A total of one thousand dollars (250 dollars per team member) was contributed by the Biomedical Engineering Department at WPI. After considering the expenses needed to complete this project, the team decided to match this dollar amount increasing the total budget to two thousand dollars.

As seen in figure 10 below, the total budget was divided into three main categories: Testing Equipment, Hardware, and Brace Materials. The largest amount of money was allocated to being spent on hardware for the device. This includes all of the sensors and mechanical components that were used on the device. The second largest portion of the budget went to brace materials, such as fabric, metal supports, and 3D printed parts. The last category, testing equipment, included the purchase of the skeleton for the body model as well as other modeling supplies.

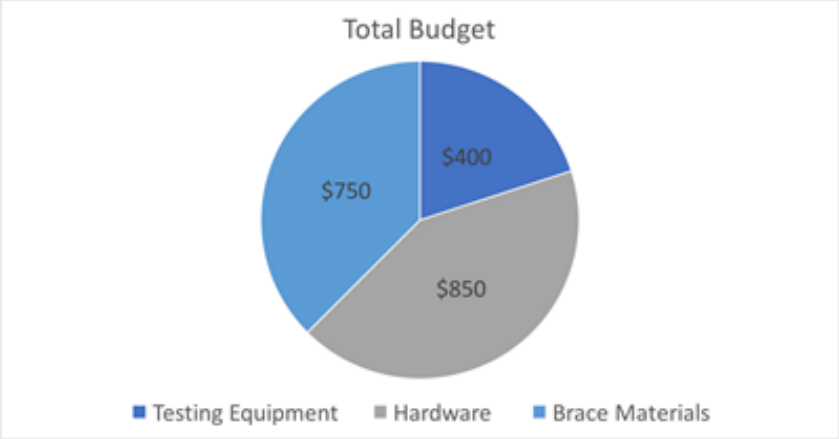



FIGURE 3.10: Breakdown of Financial Constraints

The above figure depicts the upper limits of what the team intends to spend on each aspect of the project. The project group was prepared to spend these amounts. While these estimations are justified, the team acknowledged that funds may need to be allocated differently upon progress and completion of the project.

# Chapter 4

# Design Process

## 4.1 Preliminary Testing

In order to being developing concept designs for the device, the team first conducted preliminary testing to characterize the shoulder so that a guideline could be established. Preliminary testing included EMG testing and using motion capture testing to establish whether the shoulder joint could be modeled as a sphere and to determine the joint center of the glenohumeral joint.

The team also conducted interviews with physical therapists and clinicians to understand what kind of patients would most benefit from this device as well as some key factors to be remembered while designing the device. A full script of these interviews can be seen in Appendix A.

### 4.1.1 Exploration of EMG for User Input Device Control

Biological signals, such as Electromyography, are commonly used as a means for users to control their wearable device as a result of the fact that it mimics the body's process of using muscles to move a limb, even if the muscle is not strong enough to actually accomplish movement of the limb [26]. Devices which implement an EMG user input can also be seen as rehabilitative due to the repetitive training and usage that naturally happens when the device is being used daily by an individual.

A series of tests were conducted to define the placement of the EMG electrodes and the procedure for signal processing, as well as verify the fabricated EMG electrodes for reliability and accuracy.

#### EMG Electrode Testing - Part 1: Preliminary Electrode Placement

The main goal of this test was to collect EMG signals from a wide variety of muscles in the body for the purpose of evaluating the viability of their use as the final electrode placement. The requirements for viable electrode placement for the control of a unilateral upper extremity exoskeleton are as follows:

- The EMG signal must show a clear increase in voltage when the muscle is contracted compared to the resting potential; this makes signal processing and setting a threshold more stable
- The test subject and future device user should be able to easily isolate the muscle for contraction for ease of use
- The muscle group should be reliably contracted with the intention of activating the device in order to minimize the risk of the device being unintentionally activated

- The muscle group must align with the muscle function and ability of a hemiparetic individual with upper extremity weakness.

These requirements must be kept in mind throughout the data acquisition and processing to conclude viability.

A Vernier EKG Sensor was used for data acquisition of the EMG signals for each muscle through 3 surface electrode leads (+, -, GND) placed on a variety of muscles on one subject to obtain and evaluate the usability of each muscle for the device's user interface.

A grounding electrode was placed on the lower arm or at a location away from the other electrodes, and two electrodes on either end of each of the following muscles: the biceps brachii, the medial and anterior deltoid, the triceps brachii, the rectus femoris, the brachioradialis, the gastrocnemius, and the trapezius. The electrodes were placed parallel to the muscle fibers to record the myoelectric signals which are created by the "physiological variations in the state of muscle fiber membranes" [29] [44]. When the muscle contracts the voltage will increase. The subject was instructed to flex each muscle with a small amount of force, then a medium amount of force and then the most force she could.

The sampling frequency used was 200Hz because this was the default setting on the LabView software used to run the sensor. This could've caused some misrepresentations in the processed data. It was later realized that the minimum sampling rate for an accurate EMG is 1000Hz [29].

After doing more research on how far apart the leads should be placed, it was realised this was incorrect for the purpose of measuring EMG signals; they should be placed approximately 1 cm apart to muscle signal propagation delays. For this test, the effect of the incorrect placement is negligible as the team was interested more in the general characteristics of the muscle behavior.

For each muscle that was tested, the EMG signal was recorded and judgments on the aforementioned requirements were made. The anterior and medial deltoid provided a viable signal which can be seen below in the figure below. When the amplitude of the signal is high, the muscle is contracting which you can see from approximately 18 seconds to 22 seconds in figure 1 below.

Many current prosthetics for the upper limb use EMG signals from the bicep and tricep to actuate the device. If a person has strong bicep and tricep muscles despite their amputation, as well as good muscle control, then a practitioner might decide to give them a prosthesis that can be controlled using both muscles. For those who only exhibit strength in the bicep, than the flex in the muscle will tell the arm to bend and then next signal will tell the arm to straighten. A similar example of this is using the EMG signals from two muscles to actuate two degrees of freedom, the elbow and the wrist simultaneously. This results in a more natural movement [45]. Our data shows that the bicep, tricep, and deltoid are the best choices because they are easy to isolate, and they provide strong signals that could be differentiated based on how hard the subject was flexing the muscle. The only drawback is that a person who has a stroke may not be able to activate those muscles on their affected side. The electrodes could be placed on their unaffected side but that might interfere with how they use their sound side.

Although the signals from the gastrocnemius were strong and easy to isolate, it would not be practical to use it to collect EMG signals for the device because if the person can produce a strong enough signal then they will most likely be able to walk. If they are constantly walking around then the muscle will be firing almost every second. It would be very hard to discern when the person is walking from when the person

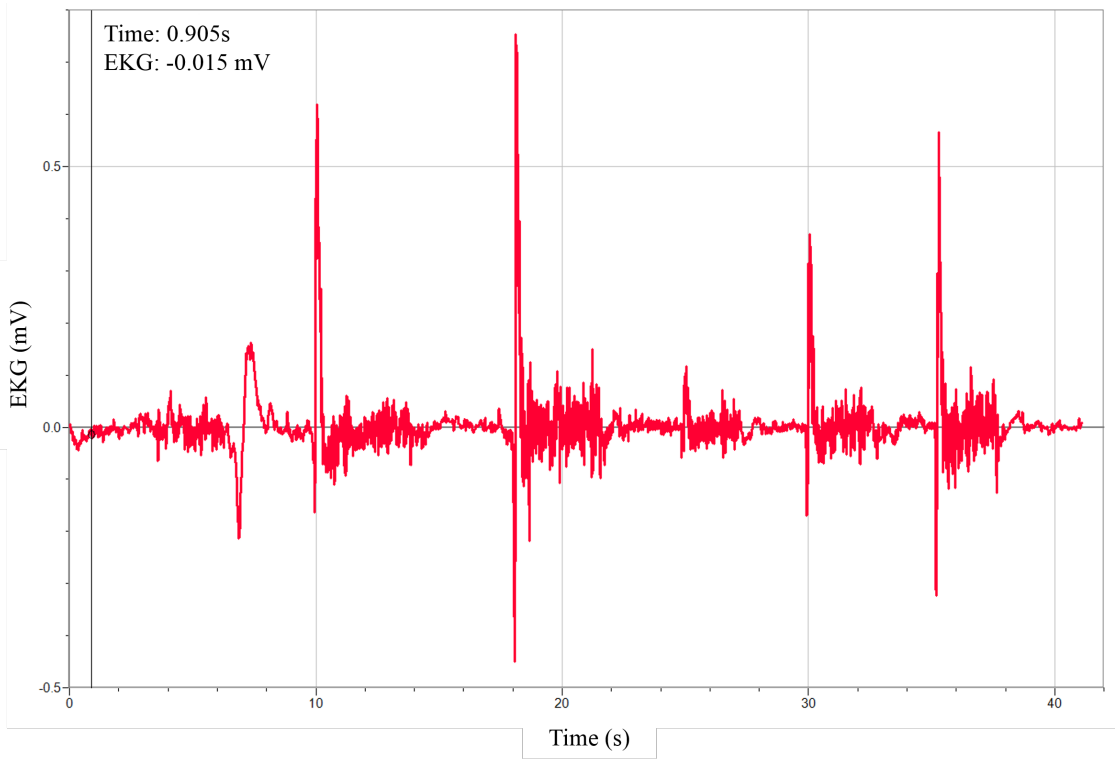



FIGURE 4.1: Deltoid EMG Raw Data

is intentionally flexing their calf to lift their arm. While people can be trained for this practice, it is not intuitive.

**EMG Electrode Testing - Part 2: Signal Processing Methods**

Perhaps more important than the placement of the electrodes for recording the EMG signal is the decision of how to process the EMG signal so that the user interface can be reliable. A variety of filters were designed to evaluate the raw signal. Some of these filters would be better for post processing and some would be ideal for real-time filtering of the EMG signal. A common way to process EMG data is to rectify the signal and then apply a low pass filter. When designing the low pass filter it is important to understand the passband and stopband parameters of the filter as well as the sampling frequency.

Another way to process EMG is called MAV (mean-average-value) which averages up the values in a window around the current time. There a a few variations of this kind of processing which were explained in a Matlab toolbox created to process EMG signals [46]

Some of the filters produced signals that were very smooth and stable but had a significant phase shift, while others were hardly shifted but were very rough and unstable. A balance between the two provides the best signal to be used in the device controls. The best signals from all of the filters tested were plotted together to be compared which can be seen in figure 2 below.

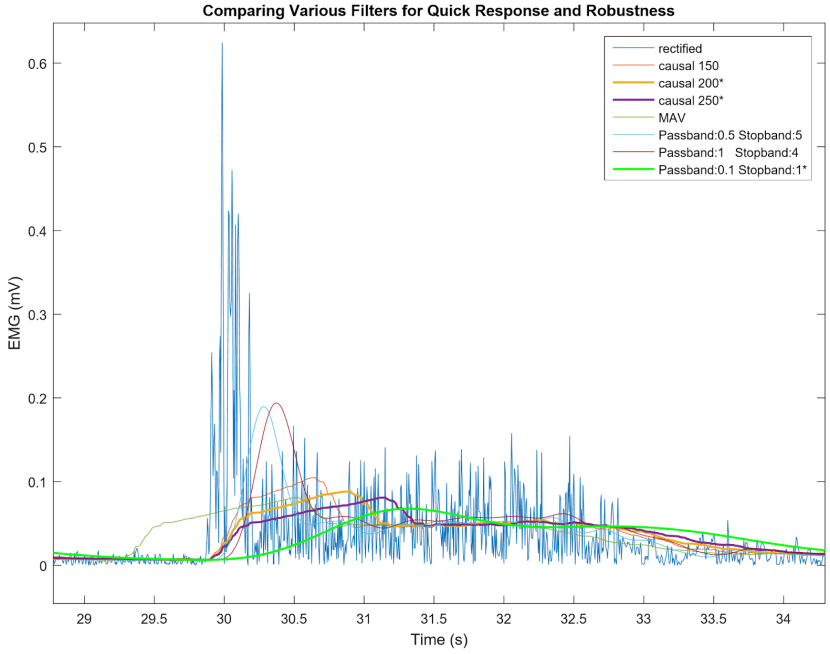



FIGURE 4.2: Comparing the Best Filters (one contraction)

From this plot it was decided that the best filter for this raw data was the MAV causal 200, which is shown by itself in figure 3, because it reacted quickly to the user input and is fairly robust in the way that most of the noise has been eliminated.

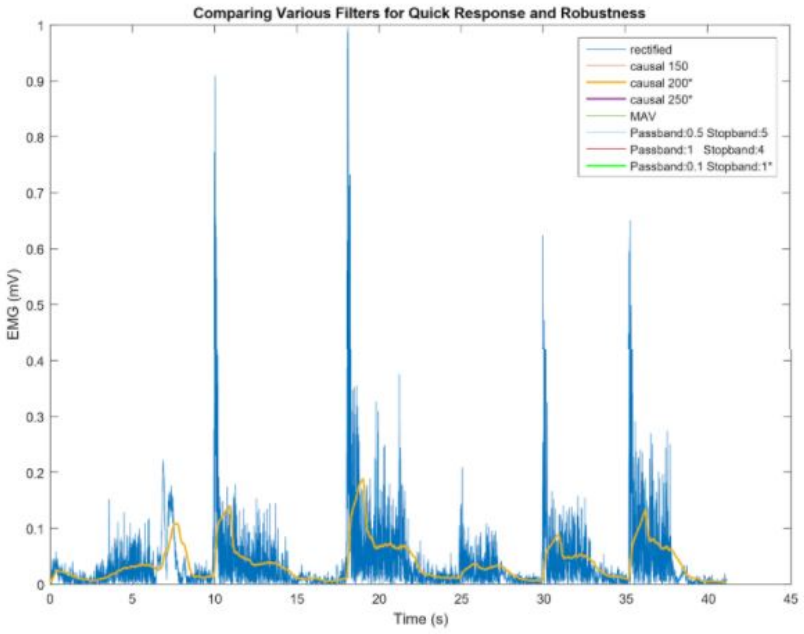



FIGURE 4.3: Causal 200 Filter Compared to the Rectified Data

Low Pass filtering and MAV filtering essentially both eliminate high frequency noise. These two kinds of filters are shown in Figure 4 below. The Low Pass filter has a faster response time which makes it ideal for a user interface but an MAV filter will work better in real time signal processing on the microcontroller because of it being a simpler calculation. The slightly slower response time of the MAV filter processing is a small

trade-off for the functionality of the fast real time processing.

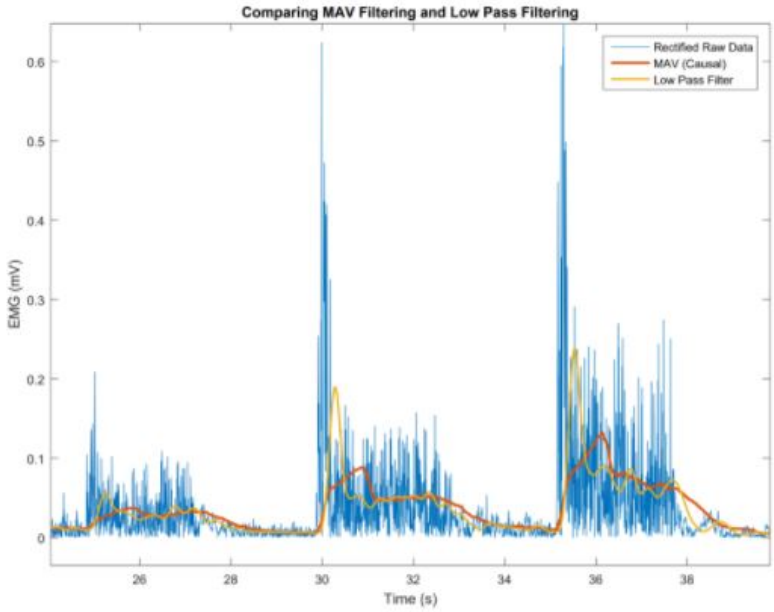



FIGURE 4.4: MAV Filter and Low Pass Filter

The MatLab code used to generate these plots can be used again to filter future EMG data, in order to find the best filter. This experiment will need to be performed again in the future with a sampling rate above the standard 1000Hz [29].

**EMG Electrode Testing - Part 3: Fabrication and Finalized Placement**

A graduate student in the AIM lab streamlined the process of fabricating EMG electrodes that are modeled after the Bagnoli$^{TM}$ Surface EMG Sensor by Delsys. Parts were ordered and 3 electrodes were fabricated by the team according to the established procedure. The fabrication process began by soldering surface mount components to a circuit board designed by graduate student. The electrode casing was 3D printed out of VeroWhite. After the circuit board was soldered to a cable, the casing was secured around the circuit board, including 2 parallel bars of silver wire which conduct the signal from the skin.

The completed EMG electrode can be seen in figure 5 below:

FIGURE 4.5: Electrodes Fabricated by the Team

Throughout the fabrication process, the electrode was tested using an oscilloscope and multimeter to ensure that there were no short or open circuits. The completed electrodes were determined to be well made and working properly.

After considering the results from the preliminary electrode placement test and revisiting the muscles working in the shoulder, the electrode was connected to the benchtop oscilloscope and tested on the anterior deltoid and the medial deltoid. When the subject contracted each of the previously stated muscles, the EMG signal clearly increased. The anterior deltoid will be used to activate the flexion motion and the medial deltoid will be used to activate the abduction motion. Because these muscles are used for those respective motions in natural human movement it makes sense to try to use them for the device trying to mimic that natural movement. Individual with hemiparesis and weakness of their upper extremity should have some remaining control of their shoulder muscles. Even if their muscles are weak, the EMG electrodes should still be able to pick up the signals, allowing a proper threshold to be set. The threshold would be 70 percent of the average of the signal amplitudes.

### 4.1.2 Motion Capture for Shoulder Characterization

A series of motion capture studies were performed to inform the team about the biomechanics and the complexity of the shoulder joint and to provide a simplified model of the shoulder joint. The motion capture software (Motive, Natural Point, Inc., Corvallis Oregon) utilizes 8 infrared cameras to record reflective marker positions in 3D space.

#### Motion Capture - Part 1: Modeling the Glenohumeral Joint

Two rigid bodies were attached to the subject, one on her back and one on the outside of her upper arm, as seen in Figure 6.


FIGURE 4.6: Motion Capture Rigid Body Positions on the Subject

The subject was asked to do a series of calibration motions such as lifting her arm straight out in front of her. The range of motion was from 0 degrees (arm at her side) to approximately 180 degrees(arm above her head). Each of the rigid bodies has three reflective markers on it to define the position and orientation of the rigid body. These motions were recorded and the markers were labeled. The rigid body (labeled RB1, RB2, and RB3) on the subject's arm were used to calculate the center of motion of the

shoulder using Gamage's method of least squares fitting which is good for spherical joints [47]. The rigid body on the subject's back was used as the reference frame.

From there, a sphere was fitted to the average distance between the center of rotation and each data point for RB1, RB2, and RB3 respectively and the error was graphed to visualize the accuracy of the assumption that the shoulder can be simplified to a spherical joint. The following histograms and spheres were created from the motion capture data. In figure 7A, 8A, and 9A, the position of each Rigid Body (RB1, RB2, and RB3) for all of the calibration motions in red, green and blue respectively can be seen. A sphere was fit to the data with the radius of the sphere obtained by averaging the distance of each data point from the center of rotation, calculated previously. The histograms depicted in figures 7B, 8B, and 9B respectively show the error of the spherical fitting. This error is shown as a distance. For all three markers, most of the data points fell within 1cm of the sphere, but there was also a portion of the data points that were up to 2cm and 3cm away from the sphere. For this range of motion (0 degrees - 180 degrees) the shoulder joint cannot be completely simplified to a sphere.

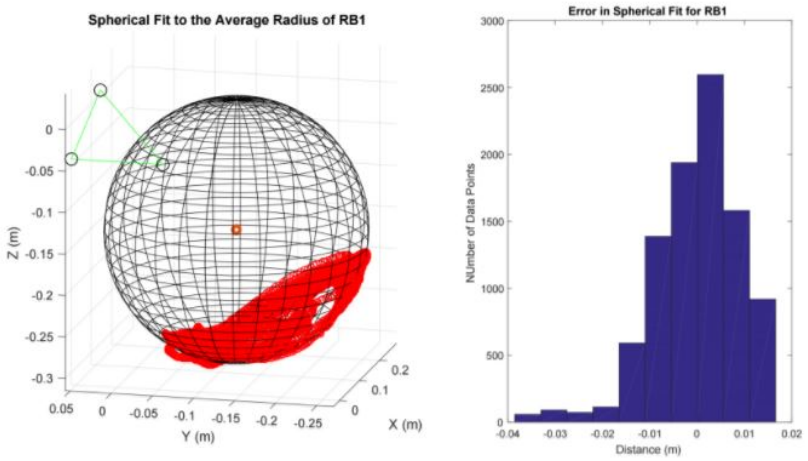



FIGURE 4.7: A: RB1 Position, B: Fitting Error

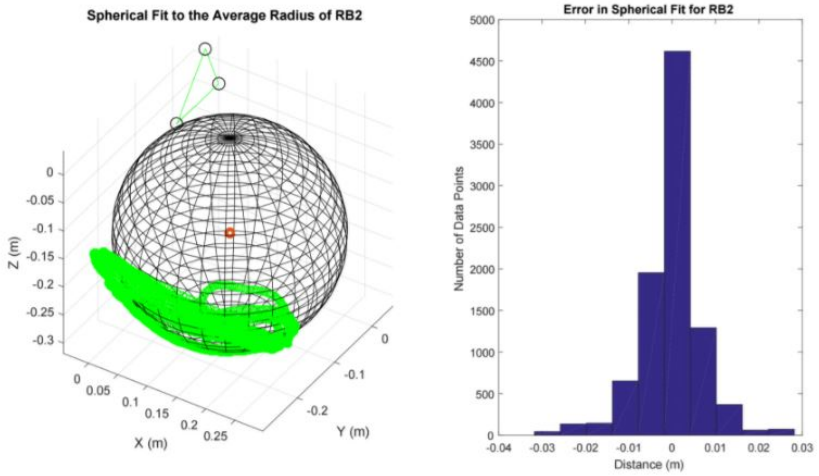



FIGURE 4.8: A: RB2 Position, B: Fitting Error

More research was conducted and previous literature claimed that the shoulder could indeed be modeled as a sphere if the range of motion was 0 degrees - 90 degrees [47]. This was verified by taking new motion capture data and processing it as

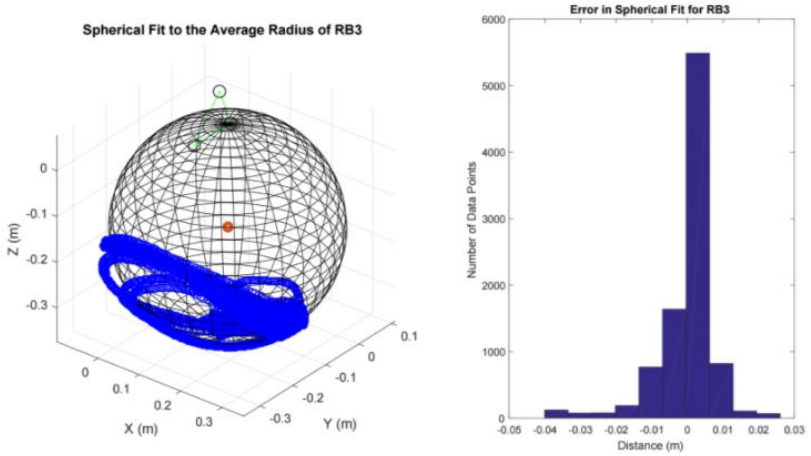



FIGURE 4.9: A: RB3 Position, B: Fitting Error

mentioned previously.

**Motion Capture - Part 2: Evaluating the Glenohumeral Joint Center**

Reflective markers were attached in sets of 3 to the surface of the skin on the rounded part of the shoulder in the configuration seen below. (labeled marker picture) There was also a rigid body with 3 markers attached to the distal end of the humerus similar to how it was in the first study. Instead of having another rigid body on the back, it was decided to put 3 markers on the subjects chest on her collarbone and sternum. The subject was asked to move her arm in flexion/extension motions to 90 degrees and adduction/abduction motions to 90 degrees. The marker data was uploaded to MATLAB and a script was written to get the distance from the center of each marker set of 3 to the joint center. These distances were instrumental in calculating the torque of the arm at the shoulder as well as building the physical shoulder model and brace model in CAD. (Graph of distances).

**Motion Capture - Part 3: Stroke Length Determination**

Another study was conducted to measure the stroke length required to lift the shoulder. Markers were placed on the subject to reference the ends of the humerus, the top of the shoulder, on the rounded most part of the shoulder, and on the back. The subject was instructed to do an abduction/adduction motion. After the first take was captured with the markers on the skin surface, a 1 inch offset was added on top of the skin at each location in the stroke line and the motion was captured. This process was repeated with 2 inch offsets. The distance between the markers can be calculated using MATLAB which will inform how much cable needs to be spooled up in order to lift the arm.

## 4.2 Development of Arm Model

In order to test the various prototypes of the orthosis without involving human subjects, the team decided to develop a model of a human arm. To do this, project members investigated several methods of life casting. After conducting research, the team came up with a 4 step process to replicate a human arm. Prior to this process, the team purchased a life-size skeleton to develop the arm mold on, so that they could perform testing on an

accurate, life-sized model of a human shoulder. Once the skeleton was purchased, the team selected the right arm to be used for design and analysis.

First, the team decided which member's arm should be replicated. They determined this based off of which arm would most likely be the most accurate to national standards for the weight of an arm. Once this was decided, the team member selected protected their clothing and assumed a proper position. The team had this member sit on the floor with their right arm abducted slightly so that they could cast the entirety of the arm. Then, the team members' arm was covered in the first layer of casting material, called Body Double Silk from Smooth-On! located in Macungie, Pennsylvania. This product was purchased from Reynolds Advanced Materials located in Brighton, Massachusetts. This material is a self-releasing silicone rubber molding material. The Body Double Silk allowed for the team to create an accurate and detailed cast of the selected team member's arm.

After it dried, the team covered the Body Double Silk Rubber in plaster, while still on the selected team member's arm. This allowed for a hard cast of the arm to be made, so that when the team left the artificial arm to dry, there would be a stiff surface to retain the shape of the arm. Once the plaster dried completely, the project members removed the plaster layer from the arm and laid it out on the floor. The team then, very carefully, removed the project member's arm from the Silicone Rubber molding. Once the team member's arm was completely removed, the Silicone molding was placed in the Plaster casting.

Next, the team prepared a mixture of Ecoflex, which is a different type of silicone rubber casting that would more reflect the texture of skin. The Ecoflex is also sold by Smooth On! located in Macungie, Pennsylvania however, the team purchased it from Reynolds Advanced Materials located in Brighton, Massachusetts. Once prepared, the Ecoflex was poured into the Body Double Silk mold, and the mold was turned at a constant rate so that the Ecoflex covered the interior of the molding in a smooth, even layer. Once this layer was cured, the team prepared the final layer of Silicone molding, created using DragonSkin made by Smooth On! located in Macungie, Pennsylvania. The team purchased this product from Reynolds Advanced Materials located in Brighton, Massachusetts. Once the DragonSkin was prepared, the team poured it into the mold. Before the Dragon Skin Cured, the team inserted the arm of the skeleton model into the mold as well, so that they could make sure the mold was proportioned correctly to the skeleton, and to allow for ease of attachment of the model to the skeleton.

Once the final product was allowed to cure overnight, the team removed the plaster cast, and then carefully peeled away the external Body Double Silk rubber from the Arm Mold. After examination, the team was satisfied with the end result, and used the developed arm mold to conduct initial testing of all prototypes on this model. The final Arm Model can be seen below in Figure 10.

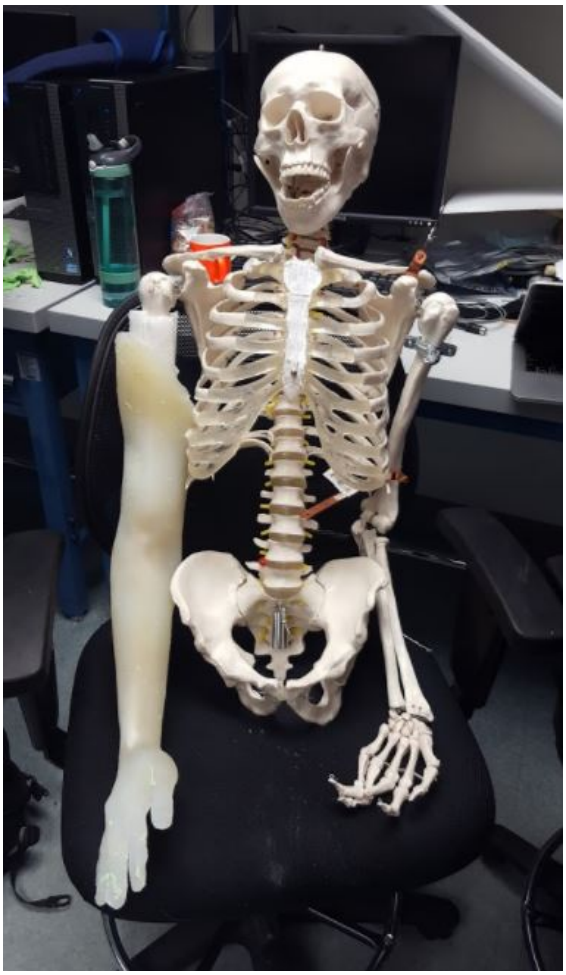


FIGURE 4.10: Final Developed Arm Model on Skeleton

## 4.3 Concept Designs

Two motions were determined to be the focus of the device based off of the movements necessary to complete different activities of daily living. With those movements in mind, three conceptual designs were created to allows individuals to perform shoulder adduction and abduction in the frontal plane and flexion and extension in the sagittal plane.

### 4.3.1 Telescoping Pole

The first conceptual design utilizes three telescoping poles to control arm movement in each of the specified body planes. The poles that are responsible for adduction and abduction in the frontal plane as well as flexion and extension in the sagittal plane would be placed on the lower back and the pole responsible for the movement of the arm in the transverse plane would be located on the upper back. The idea behind this concept was the push the weight of the arm up rather than pull up on the arm. figure 11 depicts this concept.

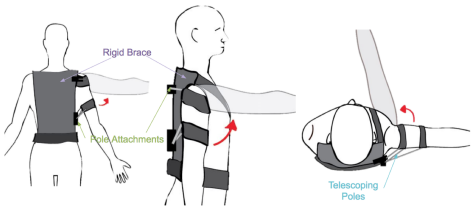



FIGURE 4.11: Concept design one with telescoping poles to push the arm to the desired elevation/location

### 4.3.2 Hybrid Cable Brace

The second conceptual design uses a combination of soft and rigid bracing. On the arm and torso there is a soft brace while there are three rigid rings as well as some rigid bars on top of the sleeve. Along with this there are cables running through the rigid braces that will attach to motors located on the back of the brace. This concept is depicted in figure 12.

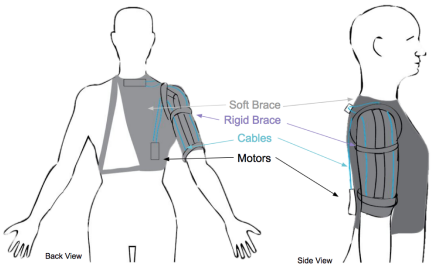



FIGURE 4.12: Concept design two of a hybrid cable brace. This design uses both a soft sleeve as well as rigid rings to attach to the body and cables attached to motors in order lift the arm.

### 4.3.3 Rigid Cable System

The final conceptual design consists of three rigid rings on the arm with cables and springs connecting the rings to each other. This concept can be seen below in figure 13. The cables will attach to motors located on the back that will lie on a soft sleeve across the back covered with a hard shell.

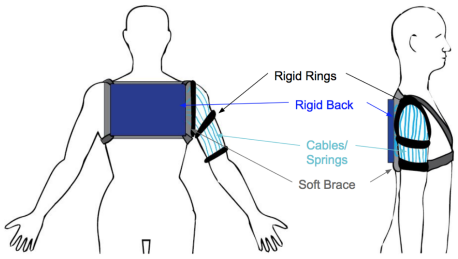



FIGURE 4.13: Concept design three of a rigid cable system. This design has rigid rings around the arm that are connected to one another with cables and springs.

Using a pairwise comparison and pugh analysis, the team decided to move forward into the prototyping phase with a combination of concepts 2 and 3. The materials used for this analysis can be seen in Appendix C.

## 4.4 Proof of Concept

### 4.4.1 Model to Evaluate the Placement of Cables

To evaluate the placement of the pulling cables on the arm brace component of the device, the team decided to develop a proof of concept prototype. The preliminary prototype consisted of four aluminum rings with attached 3-D printed fins through which the cables were strung. Once this initial prototype was produced, the experiment was conducted on the prototype to determine whether the placement of the cables would allow for movement of the arm in the correct orientation.

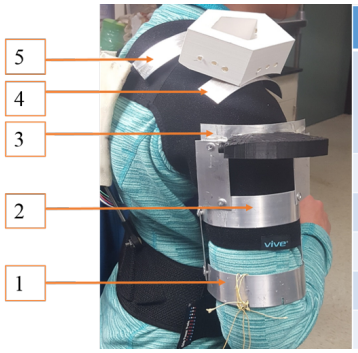
In beginning this test, the team discussed dimensions for CAD models of the various components of the prototype needed to be created. The rings were originally thought to each be a 360 degree ring, fully encompassing the wearer's arm. However, after consideration, the group decided against this dimension, as they felt that this would restrict the user's range of motion. Additionally, the group felt that the wearer may experience discomfort while in a resting position as the arm would not rest against the body. Rather, the group elected for a 270 degree cuff, to remove the uncomfortable and unnecessary portion of the rings. The fins each had an offset of 2 inches to obtain a proper lever arm for the pulling of the cables but at a height that would not inhibit motion for the wearer. Figure 14 below depicts the proof of concept prototype developed by the team.

FIGURE 4.14: Proof of Concept Prototype

Once dimensioning was complete, the team began creating CAD drawings for the components of the prototype. Five different rings were first created to be worn on various locations on the arm. The rings were dimensioned with a circumference relative to the location of the arm at which they would be worn. Following the rings, the fin offsets were then created in CAD. The fins were created to be epoxied to the top of the rings and, therefore, the dimensions of the fins varied relative to the diameter of the rings on which they would be adhered.

The team then began printing the rings however, upon commencement of the printing, the team realized that a different method of fabrication was needed. Due to the

duration of time it would take to print all of the prototype components, as well as the fact that the material was not durable enough for the rings, the group elected to transition from 3D printed rings to aluminum made rings. Aluminum sheet rods of the same width were cut to the appropriate diameter of each segment of the arm that the team wanted the brace to rest on. The various dimensions of these aluminum strips can be seen in figure 15. These strips were then manipulated into rings by hammering them into a rounded component.




| Ring Dimensions Table | | | |
|---|---|---|---|
| | Description (how much of a circle is it) | Diameter (Inches) | Circumference (Inches) |
| Ring 1 | 0.75 | 4.5 | 10.6029 |
| Ring 2 | 0.75 | 4.75 | 11.1919 |
| Ring 3 | 0.5 | 5.9 | 9.2677 |
| Ring 4 | 0.25 | 7.34 | 5.7648 |
| Ring 5 | 0.5 | 8.2 | 12.8805 |

FIGURE 4.15: Ring Dimensions and Locations

Once the aluminum sheets were fabricated and the 3D printing of the fins was complete, hot glue and epoxy were used in conjunction to adhere the fins to the aluminum rings. Figure 16 depicts an isometric view of one of the assemblies.

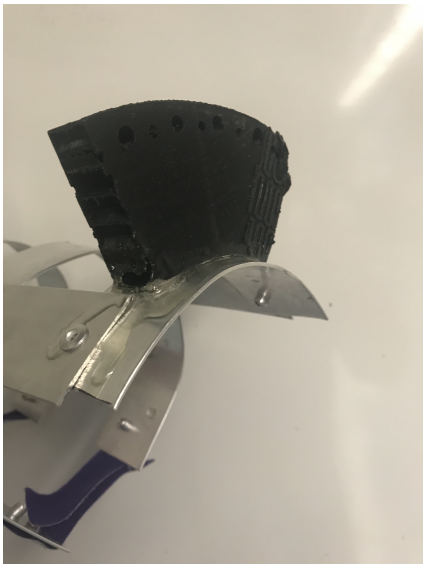


FIGURE 4.16: 3D printed fin epoxied to the fabricated aluminum sheet. This assembly would be the cuff worn on the deltoid and triceps brachii on the arm.

The ring/fin assemblies were then placed on the proper locations of the arm of the team's skeleton model. Kevlar cables were then run through the holes on the fins, starting at the most distal fin near the elbow and running up through the remaining 3 fins. To ensure for an easier threading process, the ends of the Kevlar cables were lined with hot glue to mimic the structure of shoelaces. To secure the Kevlar cables in place, knots were tied at the opposite end of the cable that would be pulled. With these cables, the team

tried to accomplish two different arm motions, forward elevation or flexion, and sideways elevation or abduction. To begin the pull test, three cables were threaded through three holes closest to the middle of the fins.

With the cables threaded through each component of the brace, the team began the pull test. One team member stood behind the skeleton model and pulled on the cables in a medial direction across the back. The cables were pulled from the affected shoulder to toward the skeleton's opposite shoulder, to a location where the team believed one of the motors would be placed (Figure 17). In this orientation, the arm was able to accomplish the abduction movement. The team then pulled the cables from the superior of the back to the inferior; in a motion down the back, towards the location where the team believed the second motor would be placed (Figure 17). This motion was thought to allow for arm flexion however, the shoulder was unable to accomplish this motion.

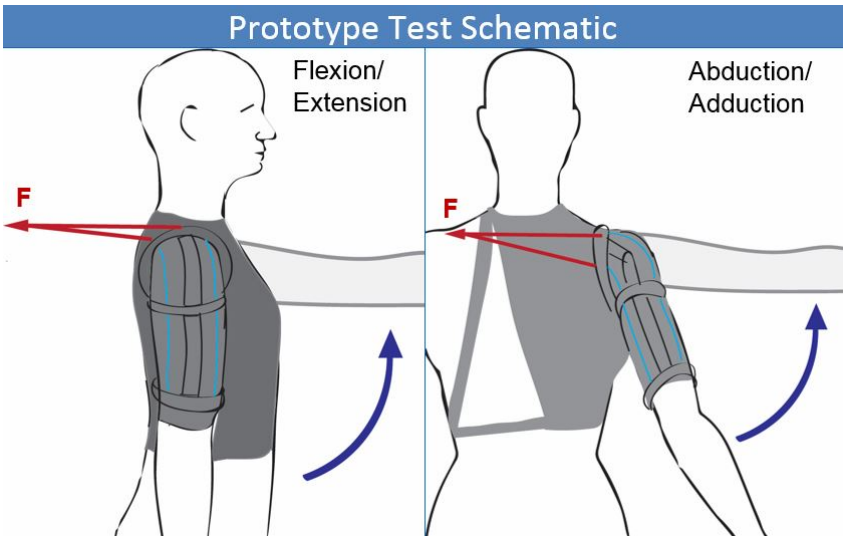



FIGURE 4.17: Schematic of the Pull Tests Conducted

The team then decided to thread the cables through the back brace in a different orientation, this time using six cables, three to control the adduction motion and three to control the flexion motion. The pull test was conducted again with the new cable orientation and the arm was able to complete both motions.

### 4.4.2 Arm Force Calculations

One of the most important calculations in order to design the shoulder exoskeleton was to determine the force needed to lift the arm. The goal of these calculations was to determine what force would be needed to lift the arm at either a 1 inch or 2 inch offset from the joint center.

From the motion capture tests, it was determined that the shoulder could be modeled as a sphere as long as the arm did not go above 90 degrees in abduction or extension. With this information, it was determined the forces needed to pull the arm could be found using a static system. The shoulder joint was assumed to work as a pulley with the mass of the arm concentrated at the end and the radius of the pulley being the distance between the joint center and the skin and the offset height. As the shoulder acted as a sphere, the team could use this calculation for both extension and abduction.

From these calculations, it was determined that with an offset of 2 inches from the joint center it would take 70N of force to lift the arm in abduction and extension. Detailed calculations can been seen in Appendix B.

### 4.4.3 Selecting a Motor

The team's priority for choosing a motor was that it could supply the amount of torque needed to lift the arm. Calculations were done using MATLAB to find a range of torque values for a 50th percentile female's arm and a 90th percentile male's arm. The motor for this device had to be able to provide enough torque for a 90th percentile male's arm to be lifted. This required torque was 70 N, as stated above.

Linear actuators and rotary motors were considered in the process of choosing a motor. It was decided that a rotary motor would be the better option because they are less weight, less mass and they are not restricted in their stroke length. After establishing the torque and optimal physical characteristics of the motor, the team chose to look for a maxon motor, as they are the most widely known for producing high quality motors. After completing more calculations regarding the nominal torque and a theoretical gearhead, a motor and gearhead configuration were chosen. Ideally the gearhead would be less than 20:1 in order to maintain some backdrivability of the motor. While having a motor that is backdrivable is not necessary to the function of the orthosis, it allows users to feel less restricted in their voluntary moments, which led the team believe this would be the better option.

Due to their expensive cost and long lead time, however, the team was unable to obtain the desired, backdrivable motor. The team was given two maxon brushless motors that the AIM Lab at WPI allowed them to use for this prototype. These motors can provide up to 63.6 mNm nominal torque, with a gearing ratio of 111:1, translates to approximately 158.7 lbs of force (seen in the brief calculation), which is excess for what was needed. The driver used to control each motor is a AZBE12A8 which can run on up to 12A of current and 80VDC. This driver also has four mode options: current, duty cycle, encoder velocity, and tachometer velocity. The calculations below show how much force the motor is able to supply.

*(Nominal torque * gearhead)/ spindle diameter = force generated*
*(63.6 mNm * 111)/ .01m = 706N = 158.7 lbs*

### 4.4.4 Material Selection for Bracing and Back Brace

In order to determine what materials the arm brace back orthosis should be made out of, the team conducted an analysis of possible materials. These components needed to be strong, sturdy, and have a large lifespan. Based on initial research, the five materials the team decided to investigate were: Aluminum Sheet Metal, Polyurethane, Polyethylene, Fiberglass, and Carbon Fiber. Using CES EduPack, a materials property database, the team developed a table of important properties for the six properties listed above. This table can be observed below in figure 18.

| *Properties* | ABS plastic | Aluminum | Polyurethane | Polyethylene | Fiberglass | Carbon Fiber |
|---|---|---|---|---|---|---|
| *Yield Strength (MPa)* | 18.5 - 51 | 30 - 500 | 40 - 53.3 | 17.9 - 29 | 1930 -2050 | 3750 - 4000 |
| *Melting Point (Celsius)* | 61.9-76.9 | 475-677 | 75 - 136 | 125 - 132 | 344 - 347 | 3.69x10^3 - 3.83x10^3 |
| *Density (10^3 kg/m3)* | 1.01-1.21 | 2.5-2.9 | 1.12 - 1.24 | 0.939 - 0.960 | 2.55 - 2.6 | 1.8-1.84 |
| *Price ($/kg)* | 2.4-2.84 | 2.21-2.53 | 4.46 - 4.89 | 1.61 - 1.65 | 1.63 - 3.26 | 25.10 - 33.60 |
| *Moldable* | Customizable, | Yes | Thermoset | Thermoplastic | Yes | Yes |

FIGURE 4.18: Properties of Possible Bracing Materials

The team conducted a pairwise and Pugh analysis to evaluate which material would be best. For the pairwise comparison, yield strength, thermal properties, price, weight/density, and the moldability of each material were compared. This can be observed below in figure 19. From this comparison, it was found that the most important considerations were the thermal properties, the moldability, and the weight of the material, followed closely by the yield strength. The price was the least important property, as the team felt that a more expensive product that would last longer would be worth it.

| | Yield Strength | Thermal Properties | Moldability | Price | Weight/ Density | Total |
|---|---|---|---|---|---|---|
| *Yield Strength* | X | 1 | 0 | 0.5 | 0 | **1.5** |
| *Thermal Properties* | 0 | X | 1 | 1 | 0.5 | **2.5** |
| *Moldability* | 1 | 0 | X | 0.5 | 1 | **2.5** |
| *Price* | 0.5 | 0 | 0.5 | X | 0 | **1** |
| *Weight/Density* | 1 | 0.5 | 0 | 1 | X | **2.5** |

FIGURE 4.19: Pairwise Comparison Table of Bracing Materials

Using the weights determined in the pairwise comparison above, the team conducted a Pugh Analysis. This can be observed below in figure 20. Using ABS plastic as a baseline, as that was the material the team's initial 3D-printed testing parts were made of, the Pugh Analysis evaluated whether each material performed better, worse or equal to ABS plastic under each material property. From this analysis, it was found that Fiberglass would be the best property to make the bracing and back orthosis out of.

| | Weight | Baseline (ABS) | Aluminum | Polyurethane | Polyethylene | Fiberglass | Carbon Fiber |
|---|---|---|---|---|---|---|---|
| Yield Strength | 1.5 | 0 | 1 | 0 | 0 | 1 | 1 |
| Thermal Properties | 2.5 | 0 | 1 | 1 | 1 | 1 | 1 |
| Moldability | 2.5 | 0 | 0 | 0 | 1 | 1 | 1 |
| Price | 1 | 0 | 1 | -1 | 1 | 0 | -1 |
| Weight/Density | 2.5 | 0 | 1 | 0 | -1 | 1 | 1 |
| Total | | 0 | 7.5 | 1.5 | 3.5 | 9 | 8 |

FIGURE 4.20: Pugh Analysis of Bracing Materials

### 4.4.5 Orthosis Development: Back Brace

Originally, the team was going to construct the entire back brace out of fiberglass. To do so, an image of the subject's back was taken using a kinect 3D so it could be analyzed using the skanect software for proper angles, elevations, and overall shape of the back. This image can be seen in figure 21. However, upon converting this image to a CAD file, it was concluded that due to the complex geometry of the image and the absence of a flat plane, this method would have been too complicated to pursue correctly. As a result, the team considered alternate methods to fabricate the back brace.

Upon inquiry, the team was advised to use an alternate material for the initial construction of the brace then fiberglass over the material. The team decided to use PCL pellets to solidify the necessary shape of the back brace and then fiberglass over this material. These pellets were selected for their ability to be molded and ease of use. To mold these pellets, water was heated to above 65 degrees Fahrenheit. Once the desired temperature was reached, the pellets were placed in the water so they could melt and form a putty-like material.

While the plastic pellets were melting, the test subject was instructed to lie down on their stomach so the brace could be molded to their back. Parchment paper was wrapped around the individual's back to avoid the material from sticking to clothes.

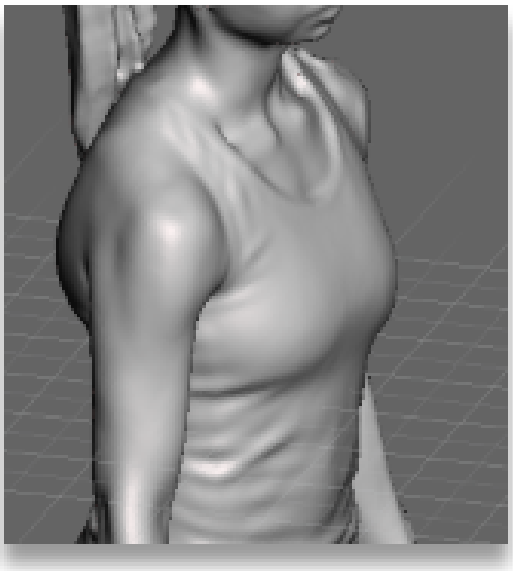


FIGURE 4.21: Kinect Image of Project Partner

Parchment paper was also placed on the workspace to prevent the material from sticking to the table being worked on. On this paper, a rectangle was drawn in the dimensions that the brace would ultimately have. Once the pellets had melted, the putty was removed from the water and placed on the parchment paper on the table. A rolling pin was used to flatten the putty into a level sheet. The sheet was then placed in the subject's back and left to cool so that it would conform to the shape of the subject's back.

After cooling, the brace was placed in cold water to ensure that it was properly set throughout. The brace was then cut into the proper dimensions using a band-saw. The brace was also sanded down to remove any excess material and smooth the edges.

Once this was completed, the team applied fiberglass over the material. To do this, two sheets of fiberglass cloth were cut to the size of the brace, with a 1 inch border on each side. The first layer of fiberglass was laid on the PCL brace, and predetermined parts of resin and epoxy were combined in a container. Once the combination was clear and there were no apparent streaks in the mixture, the team poured the contents of the container over the brace. The team then evenly distributed the mixture around the brace, smoothing out bumps and making sure the fiberglass was sticking to the PCL plastic. Once the first layer of fiberglass was set, the team layed down the second sheet of fiberglass, rotated 90 degrees from the direction of the first layer, so that the fibers were going in different ways with each layer to increase stiffness. The process was then repeated with the second layer. The brace was then left to dry overnight so that the resin could set properly.

For finishing of the brace, the team sanded the fiberglass casing to remove any extraneous threads and to ensure there were no sharp points or corners that could injure the user. An image of the finished brace can be seen below in figure 22. Once the team deemed the exterior of the brace finished, they added orthopedic foam on the interior of the brace to provide comfort to the user.

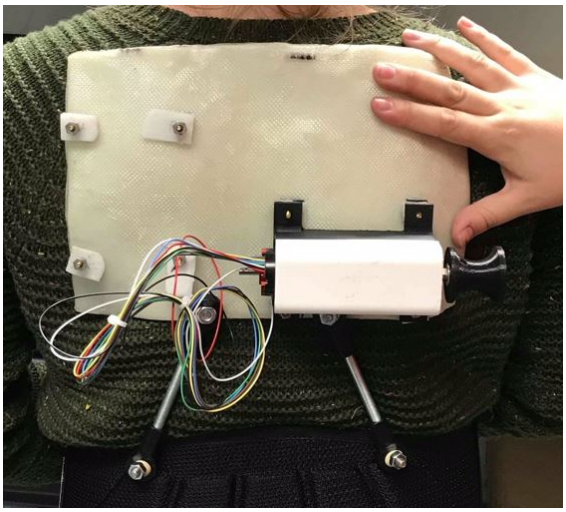


FIGURE 4.22: Completed Back Brace

## 4.5 Prototype Iterations

### 4.5.1 First Prototype Iteration

The initial prototype of the device can be seen in Figure x and was designed as four semi-rings, two located on the upper arm, one on the shoulder joint, and the last brace located on the shoulder next to the neck. The two rings located on the upper arm were three-quarters of the way around the arm and the top brace portion was a half circle. The brace located on the shoulder joint was in the shape of a hyperbolic paraboloid, resembling that of a Pringle $^{TM}$ chip. An image of the first prototype can be seen below in figure 23.

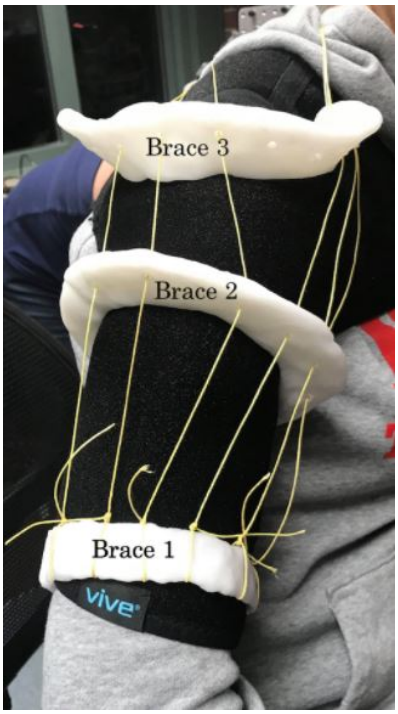



FIGURE 4.23: Initial Prototype of Design (Note: Brace 4 and Struts not Pictured)

In order to pull the arm up 90 degrees in both extension and abduction, cables were attached to Brace 1 while Brace 2 and Brace 3 had holes in them allowing the cables the run through them. The hyperbolic paraboloid shape of Brace 3 was used to provide better leverage for lifting the arm. Brace 3 was 2in tall as this was the offset that was determined to be the most appropriate from our force calculations. Brace 2 had a 1in offset to allow for the cables to have a gradual incline. In this design each brace portion was one solid piece apart from the medical grade foam attached where the brace meet the arm. To hold the braces together struts would be attached to Brace 1 and 2 holding them together with underlying fabric holding Brace 2, 3, and 4.

Once a prototype of the design was developed it was found that while the "Pringle" shape helped with abduction, it prevented the arm from fully extending as the side of the Brace limited the arm's movement.

### 4.5.2 Second Prototype Iteration

Using the knowledge gained from the shortcomings of the initial prototype, another design was generated. The key differences between the two designs are: multiple components for each brace section, an additional offset and brace, and new strut attachments.

In the initial prototype each brace was thought to be made out of one piece, however it was determined that this would be difficult to manufacture and for the user to be able to tighten or loosen. To solve this issue the team decided to split each brace into three components: foam, aluminum ring, and offset. This allowed the ring and the offset to be made of different materials, aluminum sheets for the rings and 3D printed Nylon with Fiberglass reinforcements for the offsets. Both of these components would then be attached to each other with screws and the foam would be attached to the ring with adhesive. The offsets were also originally thought to be 1 complete piece however, after consideration and evaluation of the machinery available, the team decided to cut the offsets on Brace 1 and 2 in half and 3D print them as two separate components, again allowing the user to be able to tighten and loosen the brace with more ease.

To solve the problem that the shape of Brace 3 posed, it was decided that the offsets for extension and abduction should be two separate components. A pentagon shaped offset was designed to be placed on the shoulder along with an additional brace for more support. The purpose of the pentagonal shape was to provide an offset for extension of the arm and to act a cable guiding mechanism for both sets of cables (those in charge of extension and those in charge of extension).

As a result of the offset for arm extension being moved, it was determined that Braces 1-3 could be attached together with one long strut attaching all three. The other two braces would be attached to each other through the extension offset and then Brace 5 would be attached to the back brace. This method of attachment would help ensure a user did not potentially injure themselves by putting on the brace incorrectly. The final model of the secondary prototype can be seen below in figure 24.

While the new design allowed the arm to have the desired range of motion in both flexion and extension, the cabling method described in Section 4.4.1 was found to be inefficient when attaching the cables to the motors as there was no way to ensure there was the same amount of tension in each cable. The cable housing also proved to be an issue for 2 reasons as the original tubing that was selected to house the cable was meant to resist compressive force rather than allow the cable to move freely within it and caused the back plate and the arm braces to move towards each other. Secondly, having the cable housing throughout the device didn't allow the distance between pentagon offset and the Brace offsets to change which is necessary for the device to be able to move.

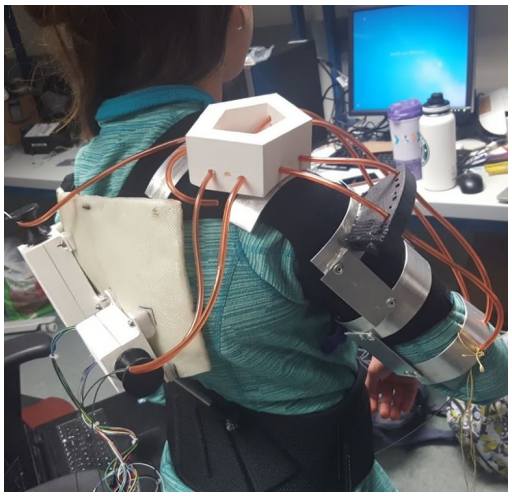


FIGURE 4.24: Second Prototype

### 4.5.3 Third Prototype Iteration

The cable and cable housing issues presented in the second design where addressed in four ways: selecting a new cable housing, minimizing the amount of cable housing, adding pneumatic connectors, and creating a pulley system. Due to these changes the pentagon offset was also redesigned to only have two holes per motion in the offset, with the holes facing the back plate made larger to fit the pneumatic connectors. The third prototype can be seen below in figure 25.

FIGURE 4.25: Third Prototype

The new cable housing selected was designed for cable to easily be able to move within it. Along with this the amount of housing used was dramatically decreased and four four pneumatic connectors were added, two in the pentagon offset and two on the back plate leading to the motors. The cable housing was placed between the connectors on the pentagon and those on the back plate rather than being incorporated throughout the device. These connectors created a fixed distance between the back plate and the arm braces, allow the cable to move freely in the system, and allow for a changing distance between the offsets on the arm and the pentagon offset.

The pulley system was created to ensure that all of the cables in the device were at a constant tension. Two small rings were made out of aluminum in the lathe, one for the adduction motion and one for extension. For adduction, one cable was then attached through the holes on Brace 1 and Brace 3 put through the ring and then back down the holes on Brace 3 and Brace 1. There was then another cable attached to the ring that was threaded though the hole on the pentagon and then through the pneumatic connector in the pentagon and on the back to end up threaded through the motor spool. For this motion it was found that using this new system Brace 2 was no longer needed and that for both motions one of the cable holes on each Brace was not needed as well.This prototype was ultimately chosen to be our final design.

# Chapter 5

# Final Design Verification

## 5.1 Mechanical Features

The final device consists of four 3D printed offset components, 5 aluminum semi-circular rings, a back plate, a weight belt, and a variety of velcro straps and rod connectors. Figure 1 below depicts the final design.

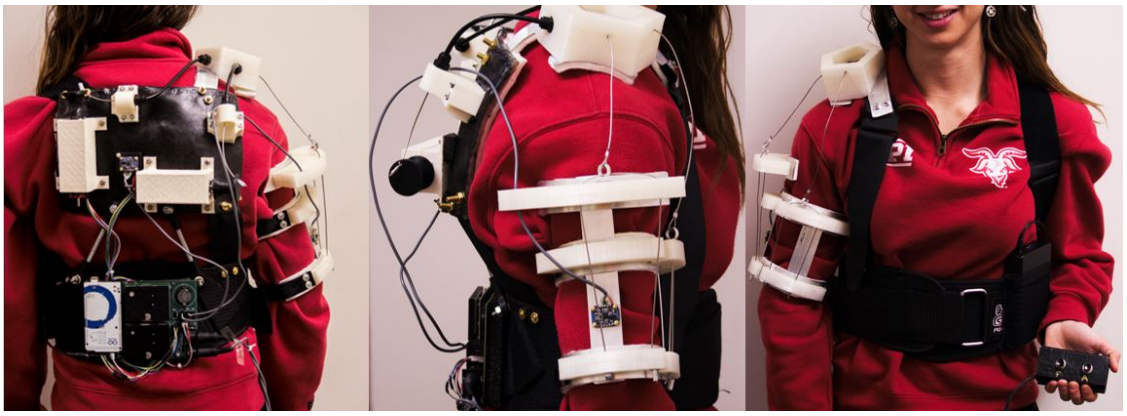


FIGURE 5.1: Final Device Design

### 5.1.1 Bracing

There are a total of 4 different bracing components in the design. Each 3D printed component is attached to an aluminum ring using screws and plastic inserts with the exception that the pentagon offset is attached to two aluminum rings (Ring 4 and Ring 5). Brace 1 and Brace 2 have two separate offsets attached to each ring, Brace 3 has one two inch offset for the adduction motion, and the pentagon features a two inch offset needed for the flexion motion. Brace 1 and Brace 2 contain a velcro strap on the open side of the ring facing the body. This allows the user to be able to tighten and loosen the device as needed.

The cable routing is unique for each intended motion. For the flexion and extension motion, the cables are routed through the two holes farthest away from the body on Brace 1 and Brace 2 with the pulley located above Brace 2. In the adduction and abduction motion the cables are routed through the two holes closest to the flexion offsets on Brace 1 and Brace 3 with the pulley located about Brace 3. For each motion the single cable is routed through the appropriate hole on the pentagon offset. Once the cable reaches the pneumatic connector in the pentagon offset, it goes through the cable housing until it leaves the housing through the pneumatic connector on the back brace. From here the cable goes through the spool located on the motor and is crimped at the end to keep the cable in place.

### 5.1.2 Back Plate

The back plate of the device was custom molded to the user's back. The back plate was fabricated using a mold-able thermoplastic PCL that was then covered in fiberglass and resin for reinforcement and spray painted black. All the the components on the back plate, the two motors and two pneumatic connector mounts, were attached to the back plate with PCL spacers and a variety of screws and bolts. The arm brace components were attached to the back plate through bolts going through Ring 5.

With the back plate containing the majority of the device's weight, it was attached to the weight belt using two threaded rods. The placement of the rods were determined based of force calculations on the back that can be seen in Appendix D to ensure the forces from the overall weight of the device and the motors were being accurately counteracted. There is also a fixed velcro strap attached to the back plate and the weight belt to ensure the distance between the two is fixed.

There are two adjustable straps that also connect the back plate to the weight belt and allow the user to tighten or loosen to device to ensure a proper fit. One strap is attached to the left side, or the unaffected side, of the user with the loop on the back plate and the strap on the weight belt resembling a backpack strap. The second strap is attached to Ring 5 and the right side of the weight belt resembling suspenders.

### 5.1.3 Motors

The team chose to use the brushless maxon motors found in the lab, described in Chapter 4.4, which are able to provide 158.7 lbs of force. The first specification was thus accomplished as the force to be overcome was approximately 70 degrees. The motors were powered from the Arduino through the motor driver, using power and ground, as well as a positive reference and negative reference. This positive and negative reference was supplied to each motor using a Pulse Width Modulation (PWM) signal with a duty cycle of 75 percent and 0 percent respectively. This direction the motor is rotating is dictated by which reference (positive or negative) is at a higher duty cycle; this allows the motor to change the direction of rotation.

When powered, the motors maintain some level of backdrivability, which is beneficial because it will prevent the arm from being locked into place. The backdrivability also allows the arm to be subjected to gravity which could be a method of returning the arm back to a relaxed position as far as controls are considered. Because the motors can spin in either direction, another control method is to program the motors to spin the opposite way and lower the arm.

The AZBE12A8 motor driver was used in current control mode which means the device will apply a constant torque by varying the current to the motor. This control mode allows the device to lift the arm with a constant force.

## 5.2 Electrical and Sensing Features

### 5.2.1 Circuit Board

A custom circuit board was created using a software called Altium. The board was designed to have connections for the Arduino Mega, Motor Drivers, Motors which are powered using a 12V rechargeable battery. There is also a connection for two 6 pin DIN connectors, which are for the user interface connections- the EMG electrodes and a button; powered by a 3V coin battery. Additional connections were added for future expansion of the system. These include three IMU connections including an I2C expander

and two encoders connections. For each of these components a schematic was made, and all of the pins were labeled according to each respective components datasheet. For each components schematic, a PCB footprint was either created or found in the component vault which is built into the Altium software. These footprints were designated to each component schematic. After all of the components has individual schematics and footprint, a schematic of the top layer of the circuit board was designed. Within this schematic all of the connections were made from components to component using nets or wires. This schematic can be seen in Appendix H.

Most of the components on the circuit board connect with the Arduino as an input or an output. The motor drivers are connected to power, ground, and two PWM inputs. These PWM inputs dictate which direction the motor turns. The EMG or button connects to an analog input to the arduino so the values can be read and the motor driver can respond accordingly. The IMU connections use I2C for communication with the Arduino. After ensuring that all connections were made on the schematic, a 4 inch by 6 inch PCB board was generated. All of the individual footprints were placed and arranged on the board in a logical and compact way, taking into account components that need to be in close proximity. When the components were placed in a satisfactory configuration, copper traces were drawn to connect components. Vias and pours were also used to connect components on the board. The final circuit board was a 4 layer board, including the top layer, a ground layer, a 5 V layer, and a bottom layer. When the PCB was completely assembled in Altium, the gerber files (figure 2) were sent to Advanced Circuits to be created and shipped to the team. All other components such as connectors, resistors, and capacitors were gathered from the lab or ordered from Digi-Key.

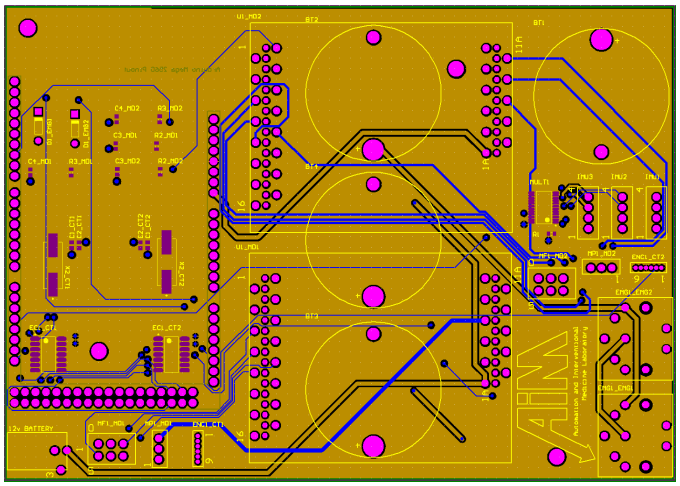


FIGURE 5.2: Gerber file of custom designed circuit board

The board arrived and was assembled. This assembly process included soldering all of the connectors as well as the surface mount components to the board. Due to some footprint sizing inaccuracies, as well as errors in the schematic, there were a few issues with the board. All errors were promptly found and mitigated, allowing the team to test the device with a fully functioning custom circuit board. The completed circuit board can be seen in Figure 3 below.

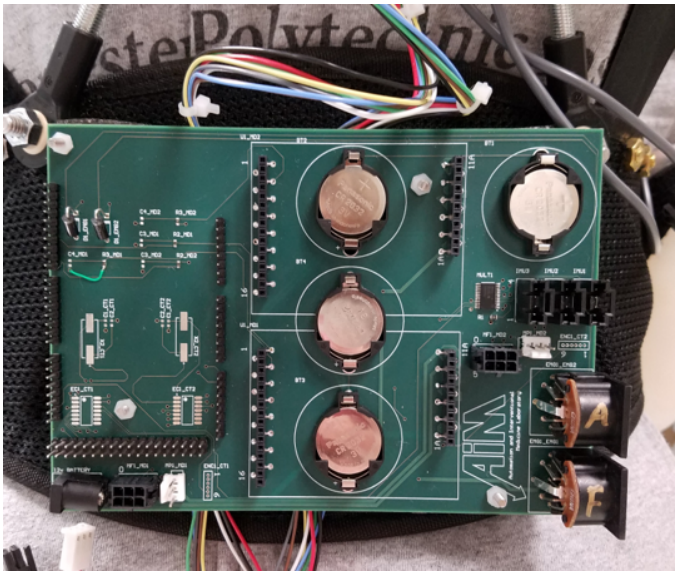


FIGURE 5.3: Final custom designed circuit board

### 5.2.2 Inertial Measurement Units (IMUs)

As previously mentioned in Chapter 2, one method of position sensing for this device are inertial measurement units. IMUs were included in the circuit board because of their ability to monitor the position and orientation of the arm in reference to the back. One IMU would be mounted on the center of the back plate (stationary) and the other would be mounted on a strut on the arm brace (moving).

### 5.2.3 Electromyography (EMGs)

To reiterate what was said in our testing in Chapter 4, Electromyography is the recording of the electrical signals from muscle contraction. EMG electrodes are commonly used in prosthetics and orthotics to sense a user's muscle activation and trigger the device actuation. A graduate student in the AIM Lab designed EMG electrodes which were then fabricated by the team. In order to use EMG electrodes with this device, there needs to be a soft brace that comes into direct contact with the skin, allowing the EMG sensors to measure the electrical signals on the skin. After locating the medial and anterior deltoid muscles, and the corresponding location on a soft brace, the EMG electrodes were sewn into the brace to remain in a fixed position. This soft brace will be worn under the users clothes while the device will be worn over the user's clothes. These Electrodes are connected to the board using a 6 pin DIN connector, being supplied by +6V and -6V using the on-board coin batteries. Even though the circuit board was designed to accommodate the EMG electrodes and the arduino can be easily programmed to measure the output, it was decided that using a button for controlling the device would be more reliable for this iteration of the device.

## 5.3 System Controls

The controls schematic of the device can be seen below in figure 4. To control the device the user provides an input signal to the Arduino, which could be a button press or an EMG signal from flexing their muscle. From this input the Arduino signals the motor driver which in turn signals the motors to spin. To control how long the motors are spinning the Arduino monitors the set incremental parameter so that when the increment is achieved a signal is sent to the motor driver causing the motor to stop.

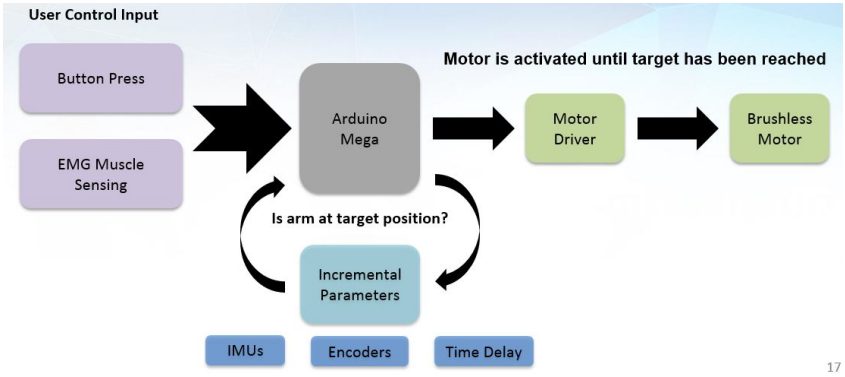



FIGURE 5.4: Control Schematic for Device Actuation

There are three possible ways to control and monitor the incremental parameters of the device, IMUs, encoders, and time delays. The IMUs measure the position and orientation of the arm in real time and can be programmed to have a "home" and "end" position which would then signal the Arduino when the device has reached the desired position. Encoders can also be used to measure how many turns of the motor it takes to reach the desired position of the arm. The final option would be a time delay which would run the motor for a set amount of time. For the final design a button was used as the user input with a time delay as the incremental parameter detected by the Arduino.

## 5.4 Safety Features

A priority while designing this device was to ensure the safety of the user. There are two main safety features on the device, mechanical stops and an emergency off switch. The nature of our design created two mechanical stops in the forms of the crimps on the cable at the aluminum ring. These crimps stop the arm from moving more than 90 degrees as they create a physical stop once they reach the pentagon offset on the shoulder.

Along with this there is also a battery located on the left side of the weight belt to be easily accessible to the user with their normally functioning side. While this is used to turn on the device, it can also be used to turn the device at any point if the user feels uncomfortable. Turning the battery off will leave the arm at its current location and slowly allow the motors to unwind and lower the arm. Various emergency control stops were evaluated along with what the stop should do either stop in place or return back to an initial position. As the device will never be able to physically move the arm outside of normal ranges of motions, the team determined that having the emergency stop keep the arm at its current location was sufficient.

# Chapter 6

# Final Design Validation

## 6.1 Experimental Methods

### 6.1.1 Range of Motion

To evaluate the range of motion that the device could provide a user, the team first conducted testing on the relationship between arm elevation and time delay increments. In each direction, the motor in question was signaled to run on time delays, which increased in increments of 500ms between 500ms and 4000ms. Once the motor ceased running, a goniometer was used to measure the degree at which the arm was elevated, with the stationary arm placed along the bony landmarks on the trunk, and the moving arm in line with the humerus (figure 1). The degree the arm was raised was recorded. This experiment was performed three times for each direction, and an average trend line was calculated.

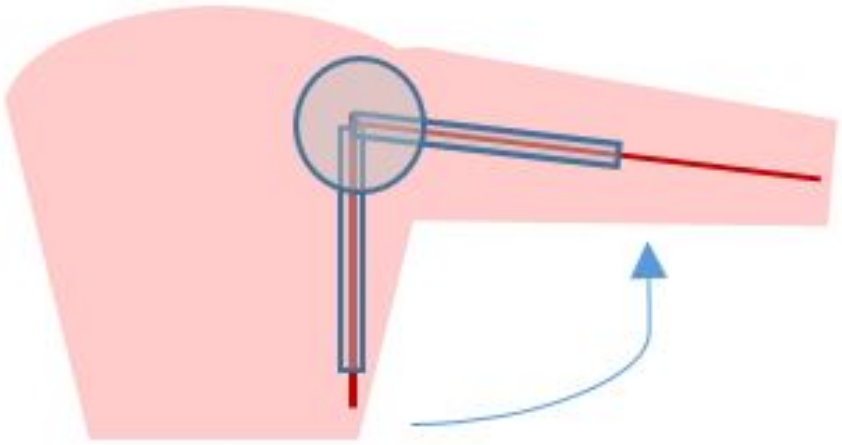


FIGURE 6.1: Goniometer Used to Measure Angle of Elevation

This experiment found that there was a linear relationship between the elevation of the arm and the time delay, in both directions, as indicated by the graphs below (figure 2). The full trial information can be seen in Appendix E. This indicated to the team that this could, in theory, provide an accurate method of providing incremental actuation of the device to users. This led the project members to choose three time delays for each direction of motion to test, so as to evaluate the accuracy and consistency of this method of device actuation.

Ten trials of testing were conducted for each time increment chosen. After the three time increments for each time had been tested in full, the team calculated the average arm elevation degree for each increment, as well as the standard deviations for each

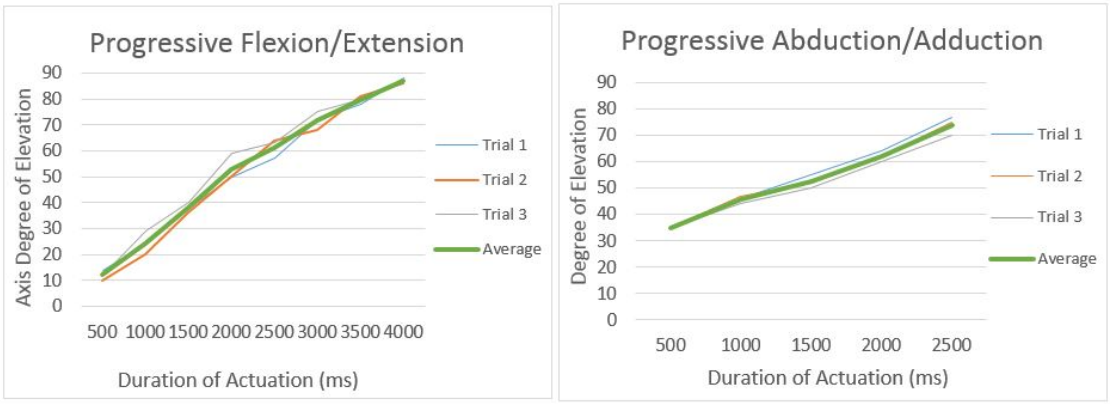



FIGURE 6.2: Linear Relationship Between Time Delay and Angle for A: flexion/extension, and B: abduction/adduction

trial (figure 3). In the flexion/extension motion, the increments achieved were approximately 36, 67, and 87 degrees, respectively. In the abduction/adduction motion, the increments achieved were approximately 33, 50, and 76 degrees, respectively. These results also indicated an average standard deviation of within two degrees for all six increments of elevation. This indicated to the team that the device was both accurate and consistent when using time delays as a method of actuation, and provided the desired range of motion in both directions.

| Incremental Evaluation for Abduction/Adduction | | | |
|---|---|---|---|
| Trial | 500ms | 1500ms | 2500ms |
| 1 | 31 | 50 | 72 |
| 2 | 32 | 50 | 74 |
| 3 | 35 | 49 | 79 |
| 4 | 30 | 47 | 78 |
| 5 | 35 | 50 | 78 |
| 6 | 34 | 50 | 76 |
| 7 | 33 | 52 | 75 |
| 8 | 36 | 53 | 74 |
| 9 | 34 | 53 | 77 |
| 10 | 33 | 48 | 78 |
| **Average** | **33.3** | **50.2** | **76.1** |
| **SD** | **1.791647** | **1.886796** | **2.1656408** |

| Incremental Evaluation for Flexion/Extension | | | |
|---|---|---|---|
| Trial | 500 ms | 1500 ms | 2500 ms |
| 1 | 37 | 70 | 89 |
| 2 | 35 | 66 | 90 |
| 3 | 35 | 66 | 85 |
| 4 | 37 | 65 | 87 |
| 5 | 39 | 68 | 84 |
| 6 | 34 | 66 | 87 |
| 7 | 34 | 70 | 86 |
| 8 | 37 | 67 | 89 |
| 9 | 38 | 70 | 88 |
| 10 | 37 | 64 | 90 |
| **Average** | **36.3** | **67.2** | **87.5** |
| **SD** | **1.6155** | **2.0881** | **1.9621** |

FIGURE 6.3: A: Time delays for flexion/extension motion, B: Time delays for abduction/adduction motion

### 6.1.2 ADL Performance

To evaluate whether the final device could provide an increased ability to perform activities of daily living, the team evaluated the device performance in five separate activities. These activities included: brushing teeth, opening a cupboard, cutting food, eating out of a bowl, and pouring a substance into a lifted cup. For each activity, the subject was asked to rank the device in four categories: comfort, ability to perform, ease of use, and overall intuition. Comfort referred to how physically comfortable the device was while in motion. Ability to perform asked the user to evaluate how well they believed they could accomplish the ADL in question while using the device. Ease of use was in reference to how easy it was to operate the device to perform the ADL in question.

Finally, Overall intuitiveness asked the subject how natural the device was to use and learn throughout the entirety of the experiment. Each category was ranked between 1 and 5, with 1 referring to an ineffective actuation method, and 5 indicating that the device was operating comparative to normal function of the ADL. Each task was performed five times, with the subject ranking all four categories in each trial. The results of this experiment can be seen in figure 4. A table with the original data can be seen in Appendix F.

The first three categories yielded an average ranking of 3.5, indicating that overall the device was relatively comfortable, that the subject felt it was able to perform the task at hand adequately, and that overall the device was easy to use to perform these necessary tasks of daily living. In regards to overall intuitiveness, the subject found that the device averaged a ranking of a 4 out of 5, indicating that it was easy to learn how to operate the device. From these results, the team can confidently say that the device increased overall ADL performance for users.

| ADLs | Comfort During Use | | Ease of Use | | Ability to Perform ADL | |
|---|---|---|---|---|---|---|
| | Average | STDEV | Average | STDEV | Average | STDEV |
| Brushing Teeth | 3.8 | 0.447 | 3.8 | 0.518 | 3.8 | 0.447 |
| Feeding Yourself | 3.6 | 0.548 | 3.6 | 0.59 | 4.2 | 0.447 |
| Pouring a cup | 4 | 0 | 3.6 | 0.501 | 3.6 | 0.548 |
| Cutting Food | 4.4 | 0.548 | 4.2 | 0.358 | 4.8 | 0.447 |
| Opening/Reaching into a cupboard | 3.6 | 0.548 | 3.4 | 0.607 | 4.2 | 0.837 |
| Overall Intuitiveness | 4 | 0.707 | | | | |

FIGURE 6.4: Test results for the ADL test for A: flexion/extension, and B: abduction/adduction

## 6.2 Reproducibility Guidelines

To create the device, the team purchased the necessary components that would yield a complete device. A complete list of materials can be seen below in figure 5.

| Bracing Materials | Hardware |
|---|---|
| 3-D Printed Pentagon | Arduino mega |
| 3-d Printed Fins | buttons |
| Velcro straps, rivets for harness | Circuit Board Supplies |
| Orthopedic Foam patting | more circuit board supplies |
| Weight Belt | Power Supply (x2) |
| Plastic PCL Pellets | Encoder Counter (x2) |
| Bowden Cables | Motor Driver |
| Threaded Rod | Encoders |
| Bowden Cable Tubing | Maxon Brushless Motors (x2) |
| screws and pneumatics | |
| pneumatic connectors | |
| Crimps | |
| Fiberglass Cloth | |
| Resin Composite | |
| Hex Nuts and Bolts | |

FIGURE 6.5: List of Materials for Final Device

### 6.2.1 Structural Components

To develop the rigid bracing along the arms, aluminum bars were dimensioned relative to the individual's arms, and were rolled into the three cuffs which were incorporated in the final design. The fins which were attached along the arm bands were developed in SolidWorks$^{TM}$. These 3-Dimensional fins were printed with holes for threaded inserts which were drilled perpendicular to the cable housing holes, so that the fins could be attached tangent to the aluminum rings. A parameterized table was developed which is set to predetermined ratios, so altering the dimensions of one of the arm rings will correctly dimension the other rings, as well as the fins and pentagon. This table, as well as the CAD files can be found in Appendix G.

A Bowden cable was threaded proximally through one set of holes, through a small aluminum ring, and then and distally through the other set of holes on each set of fins, and was crimped firmly in place on the exterior of the bottom fin. At each aluminum ring, another Bowden cable was crimped, and this cable was run through the pneumatic connectors to the motors, effectively creating a pulley system for each direction of motion. This configuration can be seen in the figure 6.

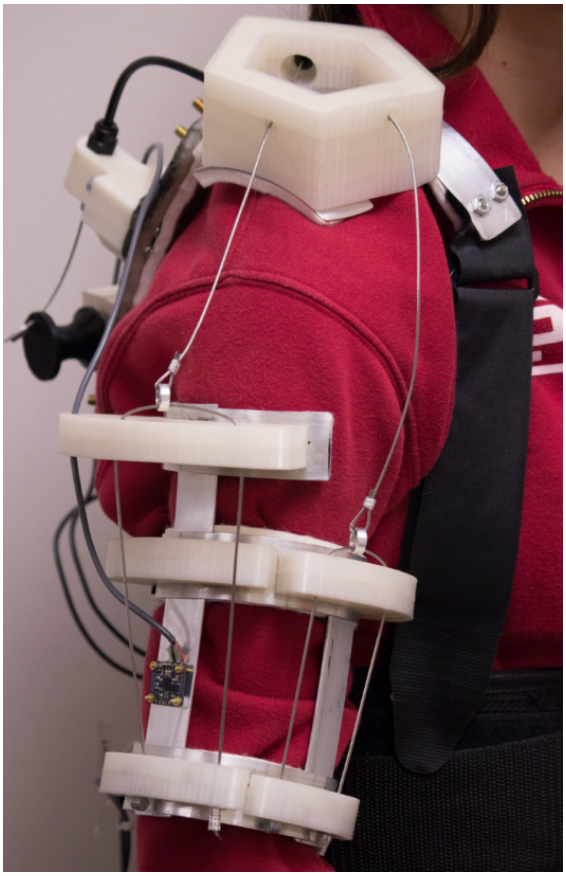


FIGURE 6.6: Pulley Cable System

To develop the back plate, the team heated PCL mold-able pellets to over 65 degrees Celsius. The material properties of these pellets allow them to melt and merge together to form one large portion of plastic. While the plastic was heated to the required temperature, a group member was prompted to lay prone on the floor, face down. Plastic wrap was placed on the subjects' back to avoid the plastic sticking to their clothes, and to provide a smooth surface on the finished brace. Once the plastic was heated to the required temperature, it was placed on the subjects back and covered in parchment paper. The plastic was then rolled out using a rolling pin to ensure an even and complete covering of the back. After the brace was allowed to partially cool and harden, the brace was removed from the subject's back and immersed in chilled water so that it could harden completely. After the fabrication was complete, the edges of the brace were sanded down to become uniform.

Once the plastic component of the brace was molded, the team added two layers of fiberglass coating to the exterior portion of the back plate. This was done to provide stiffness to the orthosis and to allow it to accommodate for the forces that would be acting upon it. To add the fiberglass, fiberglass cloth was laid vertically across the plate, with a 1 inch overhang on each side of the plate. A two-part resin composite was poured over the cloth and evenly spread over the entirety of the back brace, ensuring that every portion of the cloth was covered, including the overhang, so the cloth stuck to the plastic and did not fray. This method was repeated, with the cloth placed horizontally, to ensure that all directions of force were addressed by the fiberglass. The back plate was then set out to dry overnight, so that the resin could dry completely. Once the final back orthosis was complete, any remaining threads of fiberglass were sanded off to ensure the safety and comfort of the user.

To evenly distribute the weight of the device as well as the forces acting upon the brace by each motor, as well as to provide an adjustable means of donning and doffing the device, over-the-shoulder Velcro straps were bolted to each side of the back plate, and attached on each side of the hip at the weight belt. This allowed for a back-pack like strap mechanism, which allowed for the user to adjust the positioning of the orthosis on their back, and distributed the weight of the device evenly to the weight belt.

To further distribute the forces along the weight belt, two threaded rods with swivel rod ends were attached along the bottom of the orthosis in the center of the plate. It was calculated that these rods should be placed at at 135 degree angle so that the forces of the motors would not rotate the back orthosis too much, and so that the weight would be distributed to the weight belt.

To incorporate a holster for the rechargeable battery, the team cut out a square of durable black synthetic fabric which was larger than the surface area of the battery that would be extending out from the weigh belt. The sides of the fabric were rolled and stitched using a sewing machine to prevent fraying. Then, the team placed the battery on the weight belt and pinned the fabric to the weight belt accordingly, so that the holster would fit the battery snugly. The team then used a sharpened upholstery needle to hand sew the fabric square to the weight belt.

### 6.2.2 Electrical Components

The circuit board of the Device was developed using Altium software. The board was custom made to accommodate for all of the necessary and potentially future electrical components that this device could implement. The circuit top layer board schematic can be seen in Appendix H.

The device is controlled using a code that was developed in Arduino $^{TM}$. The code signals the time delays to activate the motor for the desired amount of time. The full Arduino code can be found in Appendix I.

A User Guide was developed for this device to allow for an individual to confidently reproduce and operate the device with ease. This in depth manual can be found in Appendix J.

## 6.3 Project Considerations and Impact

In developing this orthosis, various factors were taken into consideration when making decisions regarding the design process, manufacturing, and testing. These considerations include ones related to economic impacts, environmental impacts, societal influence, political ramifications, ethics, health and safety concerns, manufacturability, and sustainability.

### 6.3.1 Economic Impact

There is currently not another assistive shoulder exoskeleton on the market that allows the wearer to move around and partake in daily activities therefore, the team cannot necessarily compare the cost of our device to others. However, compared to other upper extremity exoskeletons on the market, such as the MyoPro, the team's suspects that our device will be significantly cheaper. This is mainly a result of the complexity of other devices as compared to ours as well as the materials used to manufacture the devices. Current devices on the market can cost upwards of 60000 dollars and are well out of the user's financial capabilities. Our device has the capability to produce the desired outcome of moving the individual's shoulder, similar to the other devices, however, it is much cheaper. To manufacture our device, the cost would be about 2579 dollars for the raw materials with an additional labor cost. A budget for the device can be observed in Appendix K.

### 6.3.2 Environmental Impact

Potential environmental impacts that this device may have are associated with battery waste since a battery is used to power the device as a whole. In order to counter this impact, rechargeable batteries were used so as to decrease the need to dispose of the battery. In the event that the battery would need to be disposed of, it is recommended that they be properly recycled.

The team anticipates that the durability of the device will allow for a long lifespan of the materials and thus, materials will not need to be replaced during the duration of use. Once the user no longer needs the device, it is recommended that the components of the device that can be recycled, are done so properly. The aluminum that was used to create the cuffs of the device and the PCL pellets used to create the back brace can be recycled and reused. The entire motion control system of the device could be reused however, it would need to be on a different molded back plate or a different system entirely. Therefore, the only components of the device that cannot necessarily be recycled and reused are the back plate. It is therefore recommended that they be disposed of properly.

The device was designed to be slimmer than and not as bulky as some exoskeletons currently on the market, thus using less materials.

### 6.3.3 Societal Influence

Every year, approximately 800,000 Americans suffer from strokes with about 80 percent of these individuals experiencing initial muscle weakness [2], [48]. Additionally, given that shoulder hemiparesis is defined as the muscle weakness on one side of their body, as the baby boomer generation continues to age, the population of individuals experiencing hemiparesis due to age is continually increasing. From these two populations alone, the number of individuals that serve as potential users of our device is high not to mention other potential users including those who experience other degenerative muscle conditions. Therefore, providing individuals with a device that allows them to regain shoulder and arm mobility is essential.

This device was designed to be worn in day to day life, allowing for the wearer to perform ADLs necessary to live. Many ADLs and other actions necessary to perform in the workforce are easier completed with two functioning arms. Individuals who lack this capability can become discouraged or even depressed with their decreased abilities and quality of life. A study conducted in 2006 by Lara Caeiro et al regarding depression in stroke patients concluded that of the 178 stroke victims, depression was prevalent in 46 percent with hemiparesis being an associated factor [49]. This device will allow for hemiparetic individuals to have functionality in both arms, complete ADLs, and regain some of their independence. In allowing for these actions to be completed, this device poses a positive societal impact in that these individuals can perform more efficiently and productively in day to day life as well as in the workforce. This will increase their quality of life and, hopefully, decrease depression in these populations.

### 6.3.4 Political Ramifications

Political ramifications of the developed device could potentially arise if the device were to be manufactured and sold by the team. In order for the device to be sold, testing would need to occur in which case FDA regulations pertaining to class 2 medical devices would play a vital role. Once approved by the FDA for manufacturing, the location in which manufacturing would occur would most likely be outside the United States given the production cost would be lower. Potential political concerns could arise as a result of this.

Another political concern pertains to various religious groups and communities who do not believe in the use of electricity on certain days if at all. For example, members of the Orthodox Jewish community do not use electricity in any form on the Sabbath day, and members of the Amish community of Neo-Luddism do believe in the use of electricity or modern technology. Given that this device is battery powered and would need to be charged, members of this community either have restrictions on when they can use this device, or not be able to at all. Political concerns may also arise due to the fact that individuals in third world countries, who have a lack of access to electricity, will not be able to use this device.

### 6.3.5 Ethics

Potential ethical concerns surrounding this device pertain generally to two categories: human testing and the definition of a successful device. Thus far, the device has only been tested on a skeleton model and on a member of the project team. From these tests, the team concluded that the device functions properly however, ethical concerns can arise as a result of this. Given that the members of the team want to see the device be successful, results could potentially be viewed as biased. A positive outcome of these tests however, is that testing was non-invasive and did not cause harm to the test

subject. The team recognizes that in order for this device to be manufactured and sold, additional testing would need to be conducted on both able bodied individuals and on the target population. Keeping in mind that the test subject was not harmed during testing, the group believes that the device will not cause pain to any future test subjects or users thus making it safe and ethical.

Additional ethical concerns could potentially arise from the expectations the user has for the device and whether those expectations are met. The team's goal for developing this device was to provide individuals with a device that allows for adduction between 30 and 90 degrees, and flexion between 30 and 90 degrees. The device may allow for some users to obtain full mobility of their hemiparetic limb however, for others, it may not be as helpful.

### 6.3.6 Health and Safety Concerns

This device is intended to be used by individuals with shoulder hemiparesis who experience difficulty moving their shoulder and arm on their own. The team's purpose in developing this orthotic device is to improve the quality of life of this target population. However, with any orthotic device, various health and safety concerns arise. Given that a portion of this device will come into direct contact with the wearer's skin, there is the possibility that the user could have an allergic reaction to the materials used to develop the device. This is unlikely however, given that the only portion of the device in contact with the skin is the shoulder brace component that is sold in general stores and intended to be worn on the skin. To further prevent this from occurring, foam padding was used to line the rings. Additionally, the possibility of chafing arises if the strap of the shoulder brace is worn under the armpit. This too is unlikely, given that the shoulder brace strap is meant to be situated over the chest. The backplate of the device was developed by using fiberglass over plastic. A potential health concern as a result of this is that fiberglass is considered an irritant. It can cause irritation to the skin, eyes, and throat with sufficient exposure. The team does not anticipate this being of concern however, given that the back plate does not come in contact with the wearer's skin. Additionally, the backplate was well sealed so fiberglass shards are not anticipated to break from the backplate.

One major health and safety concern involves the ways in which the device will influence the user's arm to move. It is possible that, depending on the wearer, the device could move the arm in a motion that the wearer is not used too, is not comfortable with, or is not physically capable of. However, the team suspects that this is unlikely for multiple reasons. As a result of tests run by the team, the device only has the capability to raise the arm 91 degrees in flexion and 76 degrees in abduction, both of which are in the range of normal human body capabilities. Additionally, the emergency stops provide the user with the ability to cease motion at any time.

Many positive health impacts result from this device. The wearer will have the ability to move their shoulder, thus being able to utilize their arm in their everyday life. This will allow for increased ability and ease in completing activities of daily living such as feeding oneself, bathing and dressing, and toileting. Having this capability will improve the user's quality of life and allow for more independence in completing these tasks. Additionally, this device will allow for engagement of the shoulder joint and muscles thus preventing shoulder subluxation and further muscle weakening from lack of use.

### 6.3.7 Manufacturability

The final orthosis that was produced at the conclusion of this project was molded to the shape and size of one subject thus making it customized. However, to reconstruct the design to fit the needs of other clients, the SolidWorks model of the cuffs and fins (Appendix G) can be tailored as appropriate. By tailoring the SolidWorks model, the circumferences of the rings could be changed to reflect the size of the user's arm. If this device were to be manufactured large scale and sold, it would be available to clients in 5 different sizes: extra small, small, medium, large, and extra-large. These sizes would be relative to the dimensions of the individuals back and shoulders, as well as the circumference of their affected arm.

### 6.3.8 Sustainability

The final device built at the culmination of this project can be classified as sustainable due to the materials that were used to develop the device. The materials used, including ABS plastic and aluminum, are durable enough to withstand the various loads that will be applied to them. The team believes that the mechanical components of the orthosis should only have to be replaced once every five years if being used regularly. The front straps on the device will likely have to be replaced after one year of use due to wear and tear. The Velcro front straps of the device are relatively inexpensive and can be found at a local general store. When replaced, the straps should be properly disposed of. Additionally, the wires on the circuit board may need to be replaced prior to the rest of the device however, with proper soldering, they should last for approximately one year.

Although the straps and the wires will likely need to be replaced more frequently than the rest of the device, it is anticipated that the device as a whole will last the user about five years. The overall power consumption of the device is high however, rechargeable batteries are used so that the device as a whole is more sustainable and batteries are not constantly being purchased and disposed of.

# Chapter 7

# Discussion

This chapter will detail how the team accomplished each of the four objectives and three specifications established in Chapter 3.

## 7.1 Objective 1: Facilitate Shoulder Motion

The prototype that was developed upon completion of this project has the ability to elevate the arm in the two specified directions: flexion and extension, and abduction and adduction. The design utilized two brushless motors. One motor specifically controlled the flexion motion and the other motor controlled the abduction motion. Each motor, and thus each direction of motion, had its own cabling system responsible for elevation. The separate cabling system allowed for more precise and controlled motion in the two directions.

## 7.2 Objective 2: Increase ADL Performance

The validation testing that was performed proved that the device aids the user in lifting their arm to the necessary position to perform a variety ADLs. As can be read in Chapter 6.1, ADL testing consisted of having the wearer complete five ADLs including brushing ones teeth, feeding oneself, pouring a cup, cutting food, and opening and reaching into a cabinet. They were then asked rate on a scale of one to five how they felt the device allowed them to accomplish the activity. Additionally, the individual was asked to rate how comfortable the device was during use, the ease of use, and the overall intuitiveness of the device while being used to accomplish the specific ADL. The goal in performing this test was to achieve ratings of 3 or higher and to observe that the test subject was able to accomplish the ADL specified. If both of these were accomplished, it would validate that the device allowed for an increased ADL performance. Overall, the average rating given to the device in each category was at least a 3.4 out of 5 and the overall intuitiveness of the device was rated as a 4. These ratings can be further observed more clearly in the figure 6.4 in Chapter 6.

The ratings that were given to the device allowed for the team to conclude that the device did allow for an increased performance in ADLs.

Another observation the team made was that the subject was able to adapt their use of the device throughout the five trials of each ADL. This shows that users can adaptively learn how to control this device to between suit their comfort and preferences.

## 7.3 Objective 3: Provide a Customized Solution

The entire device was custom designed to one team member. The back plate of the device was molded to the group partner's back using PCL plastic and fiberglass so that

it fit to the geometry of the individual's back. This was important so that the device was secure while being operated. Additionally, the arm cuffs of the mechanical brace were dimensioned relative to the circumference of the team member's arm so that they have a snug fit in their proper locations. The device is also designed with back pack straps and a weight belt strap that can be adjusted to the tightness that the wearer requires.

If the device were to be manufactured and sold, it could be customized to the specific client using the customization guidelines provided in the user manual in Appendix G.

## 7.4 Objective 4: Ensure the Safety of Users

The team was able to accomplish this objective by way of safety features that were incorporated into the design of the device. These safety features include mechanical safety stops, an emergency power button, and the potential to use a current inhibitor. More about these features can be read in Chapter 5.4 safety features.

The crimps used at the ends of each cable serve as motion limiters, not allowing the device to raise any higher once the safety stop comes into contact with the brace. These crimps restrict the range of motion of the arm to a maximum of 90 degrees. Additionally, the crimps serve as an indicator to the user. As the crimp approaches the upper fin on the brace, the user knows that the maximum range of motion is being approached and they do not need to press the activation buttons much more.

An emergency stop button was also incorporated into the design of the device by way of the power button on the battery. The battery is located on the weight belt of the device and is within easy reach of the user. The user has the ability to turn the device off at any point and this will automatically stop the device from elevating and will lock the device into place.

Lastly, the device has the potential to incorporate a current inhibitor which would act as a safety stop. When the mechanical stops of the device are hit, the current to the motor increases. If this inhibitor were to be implemented, our motor driver has the capability to allow for a signal to be sent to the Arduino when a specified current threshold was reached. This in turn would signal the Arduino to shut off power to the motors.

As stated, the current inhibitor is not currently implemented in the device therefore, it can not be used to conclude that the team accomplished this objective. However, the mechanical safety stops and the emergency stop button allowed for this objective to be accomplished.

However, one safety factor that arose during testing of the device had to do with the exposed motors. The test subject for the project had long hair and the possibility of the the subject's hair being caught in the motors came about. To ensure that this does not occur, the team recommends that the entire back plate be enclosed to hide the motors and further keep the wearer safe.

## 7.5 Specification 1: Overcome Natural Forces

In the final selection of motors, the team chose to use two maxon brushless motors. These motors have the ability to provide up to 63.6 mNm nominal torque and have a gearing ratio of 111:1. This translates to approximately 158.7 lbs of force, which sufficiently exceeds the 71 lbs of force necessary for the motors to be able to exert.

## 7.6 Specification 2: Adequate Range of Motion

To actuate the device, the team used a time delay. To choose which delay times would be used to actuate the device, the team completed validation testing that can be read about in Chapter 6.1 of the paper.

For the flexion motion, a 1300 millisecond time delay was used. This delay allows the device to raise by approximately 29 degrees. The next time the flexion button is pressed, the device lifts the arm an additional 29 degrees allowing it to reach 58 degrees. Three presses of the flexion button elevates the arm to 87 degrees.

In the abduction motion, a 500 millisecond time delay was used to actuate the device in this direction. This delay allows for the arm to be elevated by 25 degrees. The first time the abduction button is pressed, the arm is elevated to 25 degrees. The next time it is pressed, the arm elevates to 50 degrees. On the third time the button is pressed, the device elevates the arm to 75 degrees.

Overall, the team found that the device was able to lift the arm to 87.5 degrees in flexion and 76 degrees in abduction. This ability allowed for the team to conclude that they successfully achieved the specification of elevating the arm between 30 and 90 degrees in both directions.

## 7.7 Specification 3: Lightweight

Upon completion of the final prototype, the team weighed the device. One team member stepped on a scale and weighed themselves both with and without the device. The difference was taken to be the total weight of the device. From this, it was found that the device weighs 9.5 lbs which is 0.5 lbs under the specification.

The weight of the device is distributed through the back plate and to the weight belt. This allows for the weight of the device to be distributed through the user's pelvis. This was done since the pelvis is one of the largest weight bearing areas of the body. By distributing the forces this way, virtually none of the weight of the device is applied to the user's affected arm.

# Chapter 8

# Conclusions and Recommendations

## 8.1 Conclusions

The purpose of this project was to develop a shoulder component of a wearable assistive device that mechanically facilitates shoulder motion in two degrees of freedom: flexion and extension, and abduction and adduction. The device was intended to assist patients with shoulder hemiparesis to perform primary activities of daily living. A series of experiments were conducted in order to inform the design including measuring EMG signals from various muscles, a motion capture test to determine the shape of the glenohumeral joint, and an additional motion capture test to determine the joint center of the shoulder relative to the skin surface. Project specifications were then developed followed by the project team brainstorming possible preliminary design concepts for this device. A pairwise comparison and Pugh analysis were used to determine the design concept that would be pursued. Four prototype iterations were developed and tested using a pull test to ensure proper facilitation of shoulder and arm motion. A final design was achieved, possessing various mechanical, electrical, and sensing design features. The mechanical features of the final prototype were designed using aluminum, PCL plastic, fiberglass, and 3D printed components made of nylon fibers reinforced with fiberglass. The electrical and sensing components of the final design include a custom circuit board and buttons for actuation.

Additional testing was conducted to ensure that the fabricated device accomplished the objectives defined by the team. The objectives include mechanically facilitating shoulder motion in the specified directions between 30 and 90 degrees, increasing ADL performance, ensuring the safety of the user, and providing a custom solution. Mechanical facilitation was proven through a series of trials, measuring the angle of elevation using a goniometer. ADL performance was evaluated on a 1 to 5 scale, using the device to perform three basic ADLs; brushing one's teeth, eating from a bowl, and obtaining something from a cabinet. Safety was ensured by way of mechanical stops, current limiting motor inhibition, and providing a user controlled emergency stop. A custom solution was provided during the manufacturing process by designing the device to be custom fit to one team member. The team budget of 2000 dollars was also considered and the final fabricated orthosis costs 1225 dollars. The final budget can be seen below Appendix H. This cost is significantly cheaper than current exoskeletons on the market. Due to time constraints and IRB approval, the device was not tested on the target population.

The development of a wearable shoulder assistive device is a novel attempt at providing a solution to shoulder hemiparesis. Currently, an assistive shoulder exoskeleton does not exist on the market. The device that was developed can be used by individuals with weakened shoulder muscles in their everyday lives to complete activities of daily living, provide independence, and improve their quality of life.

## 8.2 Recommendations

The team was successful in accomplishing all project goals and objectives that were defined however, improvements to the device can be made. Some recommendations the team has for future work on the device are listed in the remainder of this chapter.

### 8.2.1 Incorporate Position Sensing Using IMUs and Encoders

Inertial measurement units (IMUs) were explored as an incremental parameter for the device to acquire the position of the arm in space. The IMU signal could be used to determine the remaining distance that the device needed to move the arm in order to obtain the desired height and position. A downfall of IMUs is that they drift which affects the outputted signal which was an issue the team was not able to overcome. To enhance the signal and obtain a more accurate reading, the team recommends that further testing be done using IMUs and that encoders be used in conjunction with them. The encoders will estimate the required revolutions of the motor which will pull the cables. It is recommended that they be used together since one of the downfalls of encoders is that they can slip. However, when used together, both of these flaws will be compensated for by the other sensor and will allow for the most accurate movement of the device.

### 8.2.2 Minimize Design Volume

It is recommended that future work aim to reduce the size of the device and make is less bulky. The team designed the device to be sleek and use as little material as possible however, the mechanical components of the design, specifically the bracing mechanism, can be modified to decrease the volume. The team recommends that the middle fin/cuff assembly on the arm brace be removed completely since it ended up not being used or needed in the final wiring of the device. Additionally, the remaining fins can be shortened since the outermost holes drilled into the fin were not used. The removal of these excess materials will significantly decrease the volume of the device as well as make the device more comfortable for the user.

### 8.2.3 Increase Stroke Length for Abduction/Adduction Motion

The original specification for the stroke lengths in both directions set by the team was between the range of 30 degrees and 90 degrees. In the flexion/extension motion, the device was able to move the arm to 91 degrees however, in the abduction/adduction motion, the device was able to achieve 76 degrees. Although 76 degrees achieves the specification defined by the team, it is recommended that future work try to increase this stroke length to the full 90 degree potential. This will allow for a greater range of motion for the user which in turn will make accomplishing certain ADLs, such as reaching up into a cabinet or combing one's hair, easier for the individual. To pursue this recommendation, the team suggests that individuals continuing work on this project try to modify the bracing mechanism and the mechanical stops so that the cables can be pulled more thus increasing the stroke length.

### 8.2.4 Additional Alternative Control Modes

To allow for the device to be more available to users with a winder range of abilities, the team recommends that future work attempt to incorporate more control modes for actuation. The use of buttons as a method of actuation was pursued by the team. This

was done since the team believed that the push buttons would be the easiest method for user input since the user could push the button with their unaffected hand. However, additional methods of actuation that the team recommends be explored include EMGs for myoelectric signaling. Incorporating additional methods of actuation will provide more options for user input and allow for the user to use the method that is most beneficial to them. Using EMG signaling, individuals with slight muscle function in their affected limb would be able to contract their muscles in order to move the device.

### 8.2.5 Additional Testing

In order to obtain a more accurate representation of the success of the device, additional testing would need to be conducted. The conclusions from this project were a result of tests conducted on one individual. This means that, although these conclusions are an accurate representation of the tests conducted, they are not necessarily an accurate representation of the capabilities of the device as a whole. It is recommended that testing of the device be done on more people, both able bodied individuals and the target population, in order to obtain more data for statistical analysis and comparison. Additionally, testing the device on more individuals would allow for analysis regarding whether the device functions similarly for all users thus allowing for more accurate conclusions about the functionality of the device to be made.

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# Appendix A

# Clinician Interviews

## A.1 Confidentiality and Project Description Statements for All Interviews

### A.1.1 Project Introduction:

Good afternoon. We are a group of biomedical engineering students at Worcester Polytechnic Institute working to complete or senior year project. Our project entails designing and prototyping a wearable upper extremity exoskeleton for individuals with unilateral muscle weakness or loss of muscle function in their shoulder. While we intend for our machine to specifically address shoulder weakness, we recognize that some patients may need additional assistance in their upper extremity, so our design will be able to be used in addition to other assistive devices, or be built upon in the future if needed. We would like to conduct this interview with you today in order to ensure that there is a need for a device, and to understand the limitations that this type of disorder imposes on the patients who have it. Additionally, we would like to gather information on what you believe would be the most beneficial and helpful application of this device, features that you believe would be vital in a device as such, and to ensure that our target population encompasses a range of individuals that would benefit from our device. If at any time during the duration of this interview you feel uncomfortable answering a question or continuing with the interview, you are entitled to opt out and request that your answers be deleted from record.

### A.1.2 Confidentiality Statement:

In order to maintain confidentiality, the group will not be publishing any direct quotes from this interview in our project report or poster without consent from you, the interview subject.

## A.2 A Local Physical Therapy Clinic

Date of the Interview: 9/12/2017 Location: The Physical Therapy Clinic Group members present: Veronica, Emily, Tess, Alyssa Start Time: 12:15 PM End Time:

Questions: What are the biggest challenges that patients with upper-extremity unilateral muscle weakness face?

- PT1: stroke patients, subluxations can have it all in their arm and it's painful Wash the face, shave, bra hooking
- PT2: wants to put her hair back, wash the hair fasten bra and can't Subluxation of the shoulder with stroke patients

- PT3: Be able to put her hair back
- PT5: early on rotator cuff, can't use his arm, hand function but no upper arm his complaint is he can't lift his arm to the counter so he'd love to have that for some people In dealing with these patients, what are the biggest struggles that you as a clinician experience?
- PT1: getting them to activate the correct muscles so they aren't compensating Sequencing - over uses one to make up for the other - shoulder is not weight bearing joint, need to make sure there is not bone on bone
- PT2: Activating the correct muscles not to compensate
- PT5:overuse one to make up for another, lead to more problems down the road

How often do you encounter someone with upper extremity unilateral muscle weakness?

- PT1: 6 patients with dysfunctional shoulders - 2nd most common, Pelvis and ribs stronger than lower back for bracing
- PT5: each day is different, but today i had 6 patients, 4 of which had no function, shoulder is second to lower back

In these individuals that you have encountered, what types of physical ailments have resulted in them having upper extremity unilateral muscle weakness?

- PT1: Rotator Cuff, sometimes stroke Stroke, brain injury, rotator cuff, musculoskeletal Sports injury not a good candidate
- PT2: MS
- PT3: MS
- PT5:Stroke/ TBI/ Rotator Cuff

Do they still have enough muscle in their arms to use the forearm and hand once the shoulder is raised for them by a device?

- PT1: Mostly hand and forearm are function - in this setting though
- PT5: hand and arm are usually functional

Do patients with these symptoms still have enough muscle mass in other areas to be able to control an EMG based device?

- PT1: For MS yes, stroke will vary
- PT2: Yeah Stroke could vary, musculoskeletal yes

What are the key features that you would be looking for for your patients in an assistive device of this nature?

- PT1: Lightweight, inexpensive, bioness (expensive but great)
- PT2: Easy to put on/take off
- PT3: Easy to put on and take off, lightweight, cheap cost, bioness (muscle stimulator)

Do you think patients would see the benefit of such a device and use a device of this nature in their everyday life? Do you think it would work well with PT?

- PT1: Depends on how well the device works
- PT5: Depends on how well it works and how well you guys do. It sounds like you're designing for last hope people, so i think it's good because it means we couldn't do it more. Probably be more dangerous than helpful for rotator cuff

In your experience, have insurance companies been willing to pay for all or at least part of an assistive device such as this?

- PT1: Bioness, only had 1 person that got coverage, most insurance won't pay for it, Fairlong device
- PT5: Almost would need to have a clinic purchase it for marketing purposes in order for people to have access to it and get insurance

What tasks are most important for patients to accomplish with this type of device

- PT1: Personal grooming - ADLs are very basic functions
- PT2: stuff out of cabinets
- PT3: Reaching up to cabinets
- PT5: personal grooming, feeding

Any additional comments/questions/suggestions?

- Claw mechanism
- Biggest thing for stroke/ms, if the shoulder isn't working then the hand/arm isn't as well so just think about that Where to brace device?
- Pelvis/ ribs are more stable, try there
- PT1: Would not want to use this for rotator cuff, would be dangerous and could do more harm than good
- PT2: Fairlawn - something to use for stroke patients, they are the only ones who have it

How useful will a shoulder be if they can't move the rest of their arm?

- PT8: Look up claw prosthetic

## A.3 A Physical Therapist

Date of the Interview: 9/12/2017 Location: WPI Library, over the phone Group members present: Veronica and Emily Start Time: 4:01 PM End Time: 4:27 PM

Interview Questions

What are the biggest challenges that patients with upper-extremity unilateral muscle weakness face?

- Depends on who you ask (I'm a PT), I'll hook you up with an OT, you'll get a really nice balance

- Depends on the person, you can talk to someone who's 20 and a young athlete who wants to do house repairs or you could talk to someone in their 50's and wants to fasten their bra. Biggest challenge will be identifying what's super important to the most amount of people.
- What is your goal?
  - ADLs
  - Even those will require a lot of range of motion Pure flexion and rotation are basically useless
  - EX: comb your hair. You can get your arm out in front of you, but then if you can't rotate your arm you can't get your arm to the back of your head.
  - Really need triplanar motion
  - Brush your teeth, your hair, put a jacket on, bathing/dressing, open a door

In dealing with these patients with unilateral muscle weakness, what are the biggest struggles that you as a clinician experience?

- Not a ton of experience with this type of weakness

How often do you encounter someone with upper extremity unilateral muscle weakness?

- Everything is hard, every movement
- If the shoulder is/isn't working, how are the hand and elbow working? If your elbow/hand don't work, lifting shoulder is pointless.

In your experience, do you believe that they still have enough muscle in their arms to use the forearm and hand once the shoulder is raised for them by a device?

- Someone with hemiparesis, shoulder can pull the ball out of the socket, slow creep of the ligaments that slowly stretch into almost dislocation
- Would be helpful to have the exoskeleton also work as a brace to hold the ball in the socket would be helpful When dealing with neurology, it's really complicated
- Going to have to look really far away from the affected shoulder
- Most likely limb to be in tact is either the other arm or the opposite side leg, but it's 50/50, in both cases you would be excluding someone. Arm might reach more people and be easier

Do patients with these symptoms still have enough muscle mass in other areas to be able to control an EMG based device?

- Depends on the person, depends on how good of a job you will do
- Some people would rather just adapt to a different way of functioning than learning to operate a device
- Will largely depend on how easy it is to use and how well it functions
- Younger people tend to be less concerned with looks of it, might use it more

- Is what you can provide with this device attractive to the population who will actually use it? It depends on your audience, probably should be a younger crowd, but make sure that the benefit is worth it

What are the key features that you would be looking for to best benefit your patients in an assistive device of this nature?

- Needs to be easy to use, look good, function well Do you think patients would see the benefit of such a device and use a device of this nature in their everyday life?
  - 100 percent depends on what it can do and how much it can help

In your experience, have insurance companies been willing to pay for all or at least part of an assistive device such as this?

- Not worked in a setting that this would apply
- General opinion-> INSURANCE IS EVIL
- If it will save them money in the long term, it will be much easier to get insurance
- Alternative to this device is occupational therapy and other adaptive devices, OT isn't cheap so if you can save them the cost by using it that would be good
- Problem is they might still have to go to OT so they aren't likely to pay for it

What tasks are most important for patients to accomplish with this type of device? Do you have any additional comments/questions/suggestions?

- Can definitely call me and keep me updated, and feel free to ask me more questions as the design progresses
- Can get OT friend to answer questions.

What can you do with your arm if the elbow and hand aren't working?

- There isn't a lot, so might want to think about that in your design. Gross motor function might be a better thing to focus on.
- Navigating in and out of bed, actually really tricky without a functioning upper extremity, should also be a target ADL Getting out of a chair
- Maybe could use shoulder depression for this?

# Appendix B

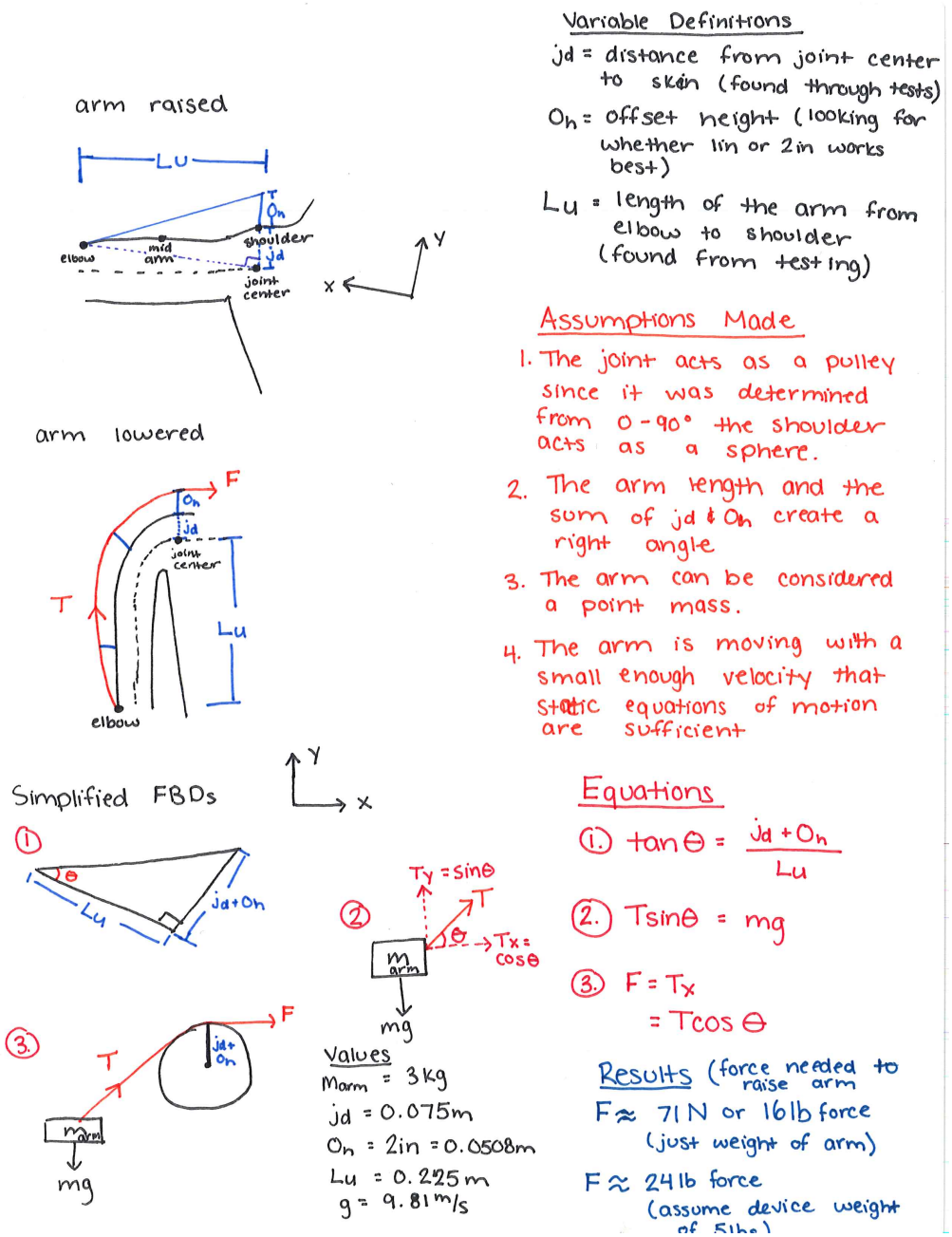
# Pairwise and Pugh Analysis for Concept Designs

| | Aesthetically Pleasing | Weight | Independently able to don and doff | Self Containing Elements | Manufacturing Cost | Comfortable | Intuitiveness of Use | Adjustable | Power Needed | Total |
|---|---|---|---|---|---|---|---|---|---|---|
| Aesthetically Pleasing | X | 0 | 0 | 0 | 1 | 0.5 | 0 | 0 | 0 | 1.5 |
| Weight | 1 | X | 0.5 | 1 | 1 | 0.5 | 1 | 0.5 | 1 | 6.5 |
| Independently able to don and doff | 1 | 0.5 | X | 1 | 1 | 1 | 0.5 | 0.5 | 0 | 5.5 |
| Self Containing Elements | 1 | 0 | 0 | X | 1 | 0 | 0 | 0 | 0.5 | 2.5 |
| Manufacturing Cost | 0 | 0 | 0 | 0 | X | 0 | 0 | 0 | 0 | 0 |
| Comfortable | 0.5 | 0.5 | 0 | 1 | 1 | X | 0.5 | 1 | 0.5 | 5 |
| Intuitiveness of use | 1 | 0 | 0.5 | 1 | 1 | 0.5 | X | 1 | 0 | 5 |
| Adjustable | 1 | 0.5 | 0.5 | 1 | 1 | 0 | 0 | X | 0 | 4 |
| Power Needed | 1 | 0 | 1 | 0.5 | 1 | 0.5 | 1 | 1 | X | 6 |

| | Weight | Baseline (Telescoping) | Hybrid Brace | Rigid Brace with Springs |
|---|---|---|---|---|
| Aesthetically Pleasing | 1.5 | 0 | 1 | 1 |
| Weight | 6.5 | 0 | 1 | 1 |
| Independently able to don and doff | 5.5 | 0 | 1 | 1 |
| Self Containing Elements | 2.5 | 0 | 1 | 0 |
| Manufacturing Cost | 0 | NA | NA | NA |
| Comfortable | 5 | 0 | 1 | 0 |
| Intuitiveness of use | 5 | 0 | 1 | 1 |
| Adjustable | 4 | 0 | 0 | 0 |
| Power Needed | 6 | 0 | 1 | 1 |
| Total | | 0 | 32 | 24.5 |

## Appendix C

# Arm Force Free Body Diagrams and Calculations




Variable Definitions

jd = distance from joint center to skin (found through tests)

$O_n$ = offset height (looking for whether 1in or 2in works best)

Lu = length of the arm from elbow to shoulder (found from testing)

Assumptions Made

1. The joint acts as a pulley since it was determined from 0-90° the shoulder acts as a sphere.
2. The arm length and the sum of jd & $O_n$ create a right angle
3. The arm can be considered a point mass.
4. The arm is moving with a small enough velocity that static equations of motion are sufficient

Equations

① $\tan\theta = \frac{jd + O_n}{Lu}$

② $T\sin\theta = mg$

③ $F = T_x$
$= T\cos\theta$

Values

$m_{arm}$ = 3kg

jd = 0.075m

$O_n$ = 2in = 0.0508m

Lu = 0.225m

g = 9.81 m/s

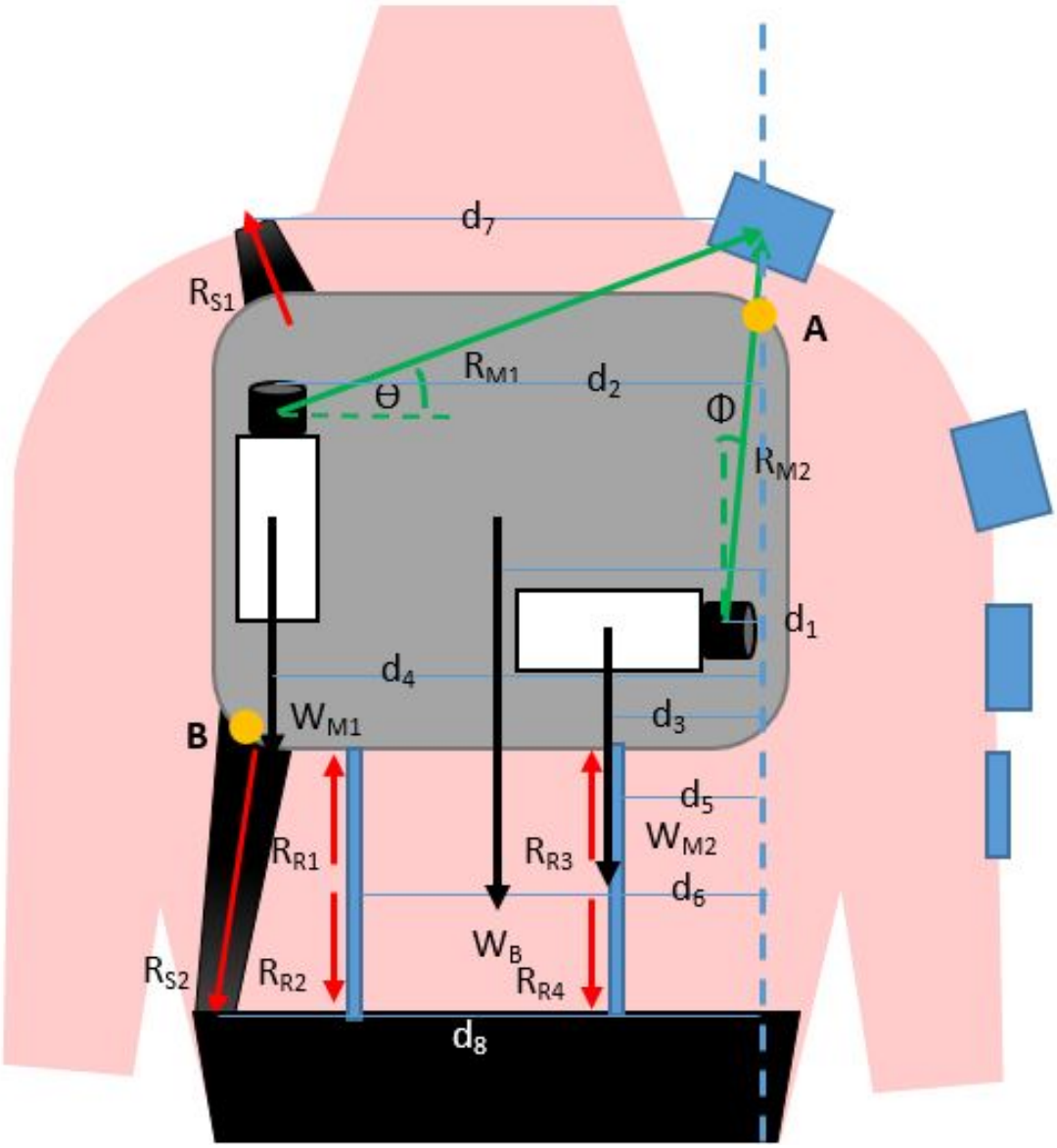
Results (force needed to raise arm

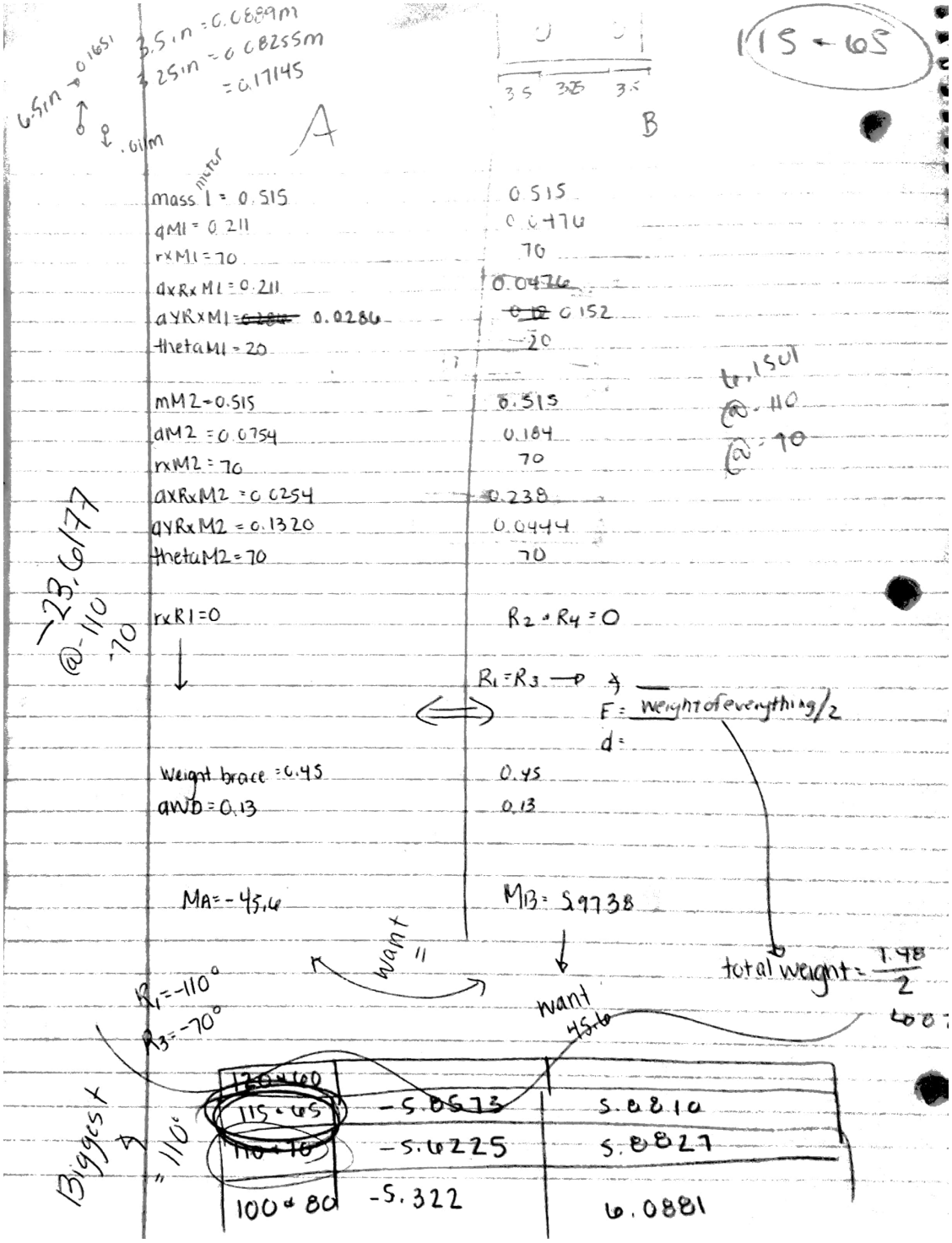
F ≈ 71N or 16lb force (just weight of arm)

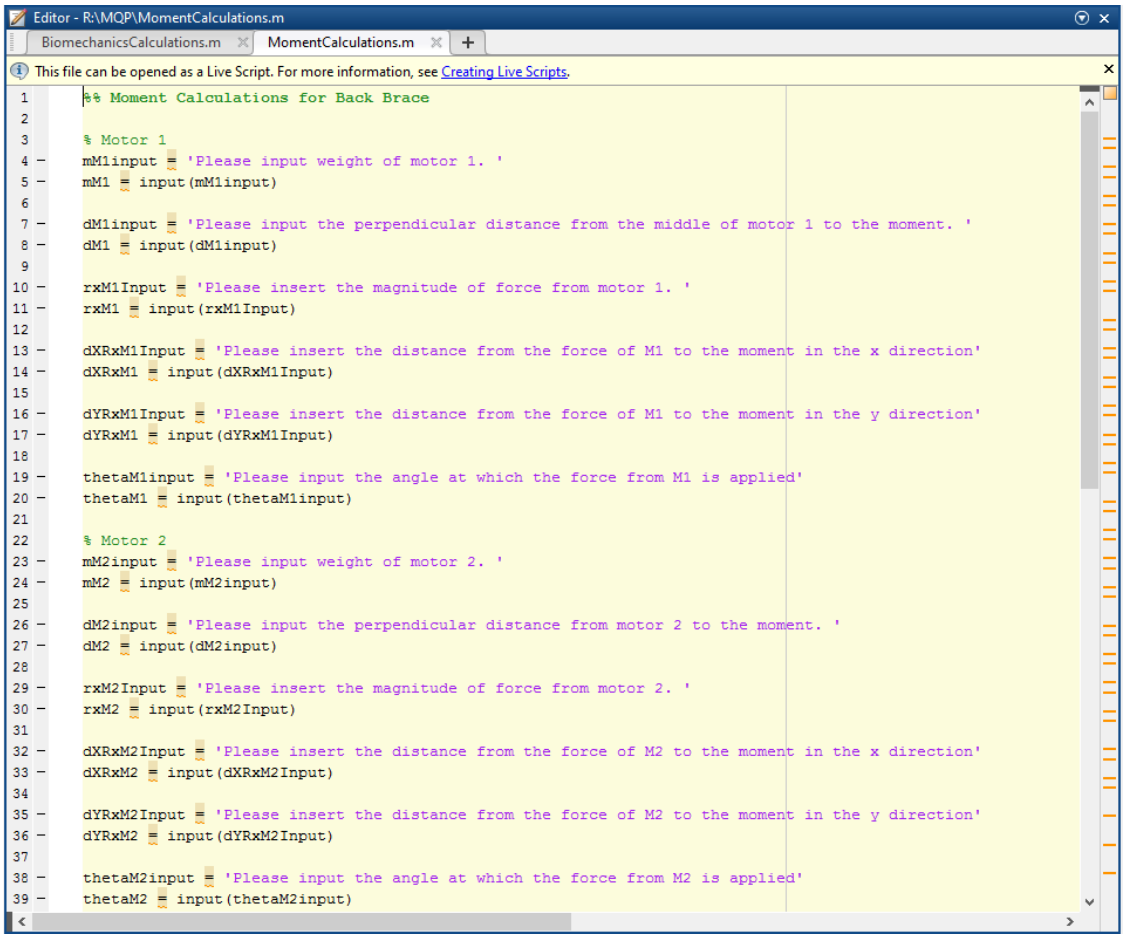
F ≈ 24lb force (assume device weight of 5lbs)

## Appendix D

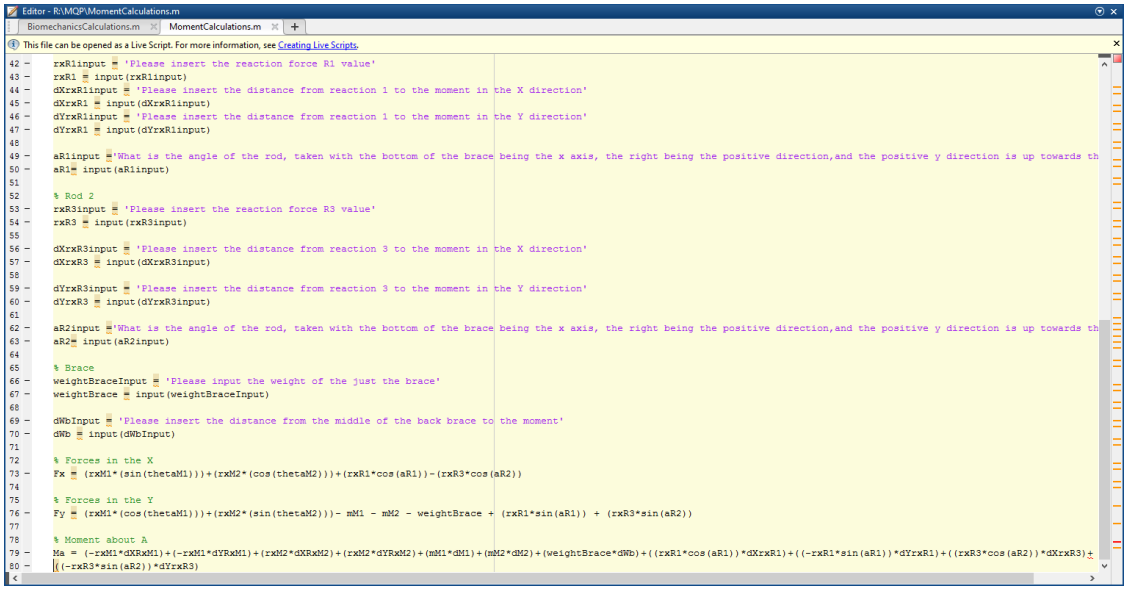
# Back Plate Weight Distributions calculations



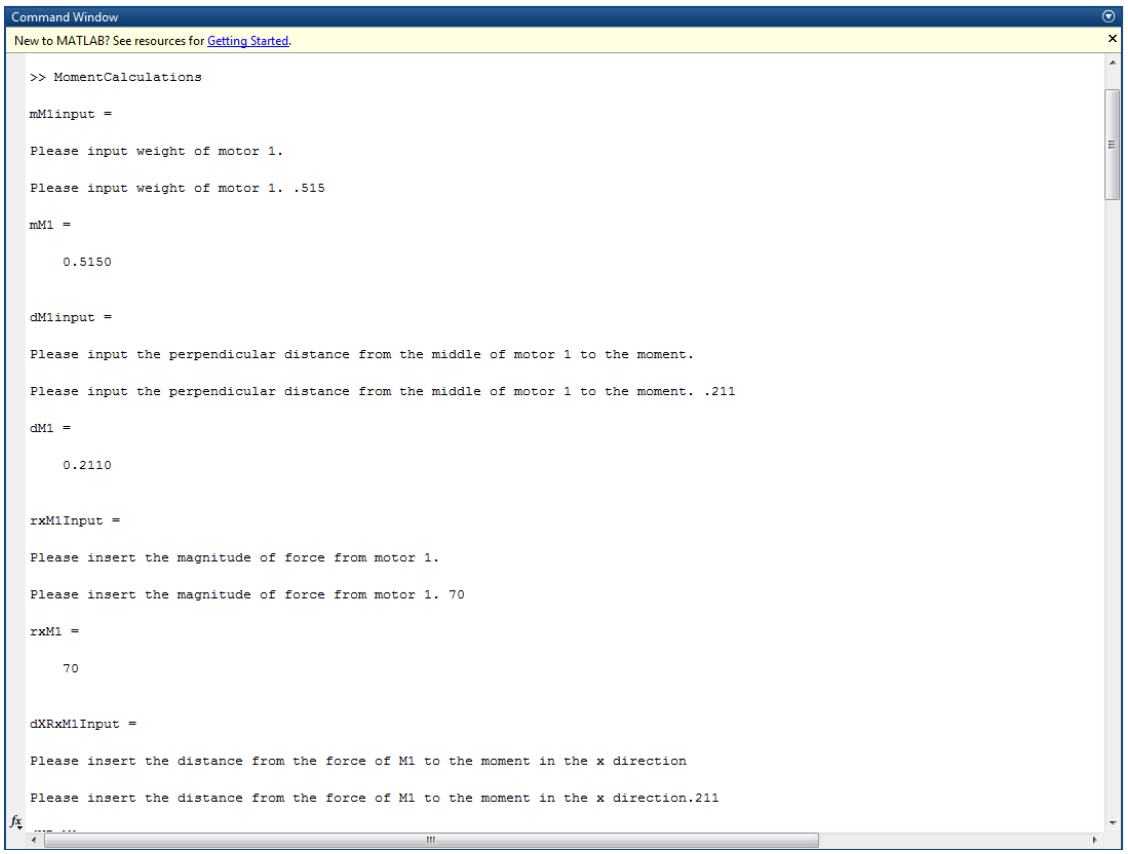

A
B
mass 1 = 0.515
qM1 = 0.211
rxM1 = 70
qxRxM1 = 0.211
qyRxM1 = 0.0286
thetaM1 = 20
mM2 = 0.515
qM2 = 0.0754
rxM2 = 70
qxRxM2 = 0.0254
qyRxM2 = 0.1320
thetaM2 = 70
rxR1 = 0
Weight brace = 0.45
qWB = 0.13
MA = -45.6
MB = 5.9738
R1 = -110°
R3 = -70°
want 0
want 45.6
total weight = 1.48/2
Biggest
115 + 65
-5.0573
5.0810
-5.0225
5.0827
100 + 80
-5.322
6.0881

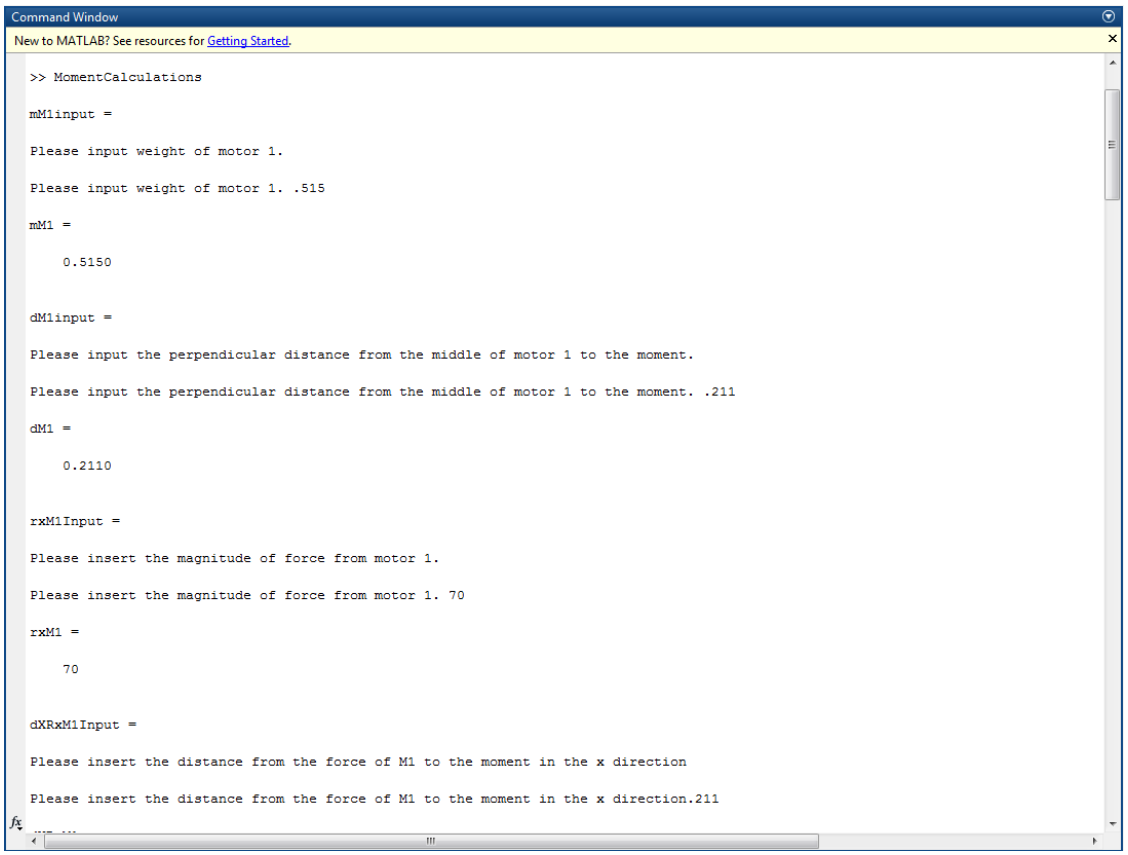


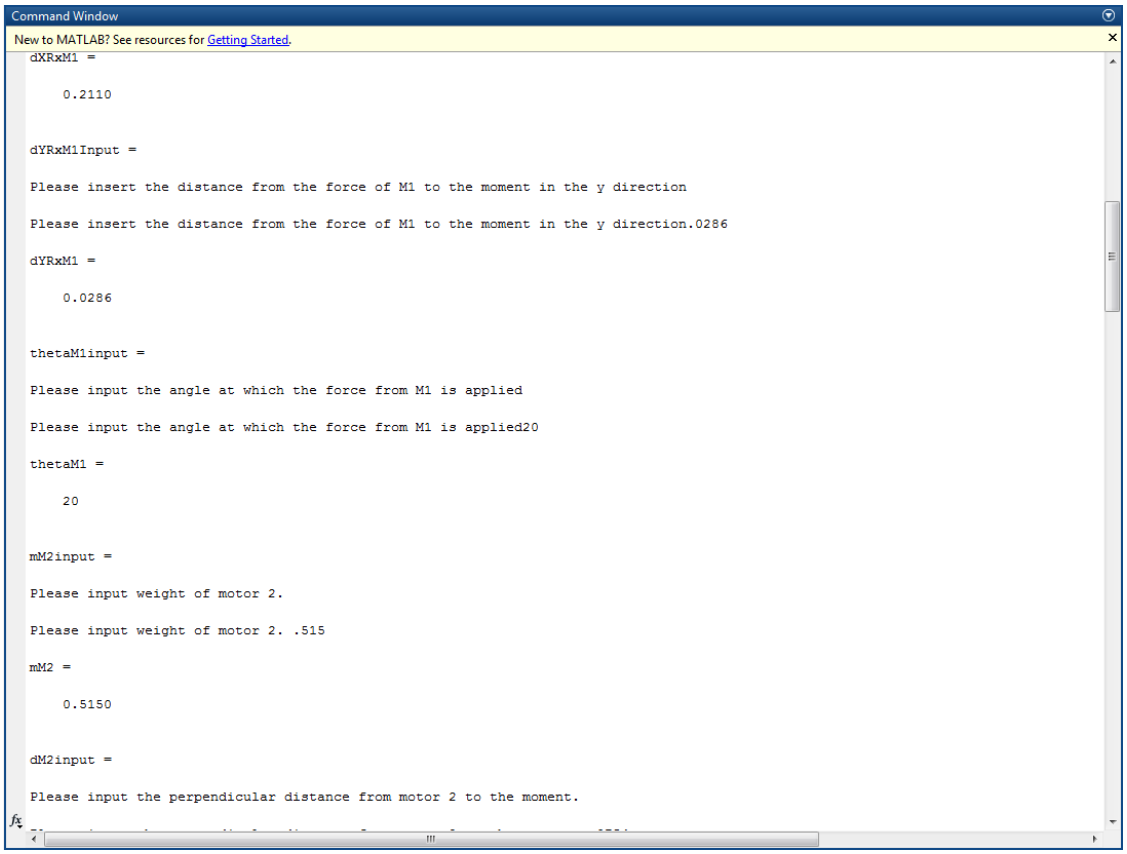
```
Editor - R:\MQP\MomentCalculations.m
BiomechanicsCalculations.m | MomentCalculations.m
This file can be opened as a Live Script. For more information, see Creating Live Scripts.

%% Moment Calculations for Back Brace

% Motor 1
mM1input = 'Please input weight of motor 1. '
mM1 = input(mM1input)

dM1input = 'Please input the perpendicular distance from the middle of motor 1 to the moment. '
dM1 = input(dM1input)

rxM1Input = 'Please insert the magnitude of force from motor 1. '
rxM1 = input(rxM1Input)

dXRxM1Input = 'Please insert the distance from the force of M1 to the moment in the x direction'
dXRxM1 = input(dXRxM1Input)

dYRxM1Input = 'Please insert the distance from the force of M1 to the moment in the y direction'
dYRxM1 = input(dYRxM1Input)

thetaM1input = 'Please input the angle at which the force from M1 is applied'
thetaM1 = input(thetaM1input)

% Motor 2
mM2input = 'Please input weight of motor 2. '
mM2 = input(mM2input)

dM2input = 'Please input the perpendicular distance from motor 2 to the moment. '
dM2 = input(dM2input)

rxM2Input = 'Please insert the magnitude of force from motor 2. '
rxM2 = input(rxM2Input)

dXRxM2Input = 'Please insert the distance from the force of M2 to the moment in the x direction'
dXRxM2 = input(dXRxM2Input)

dYRxM2Input = 'Please insert the distance from the force of M2 to the moment in the y direction'
dYRxM2 = input(dYRxM2Input)

thetaM2input = 'Please input the angle at which the force from M2 is applied'
thetaM2 = input(thetaM2input)
```

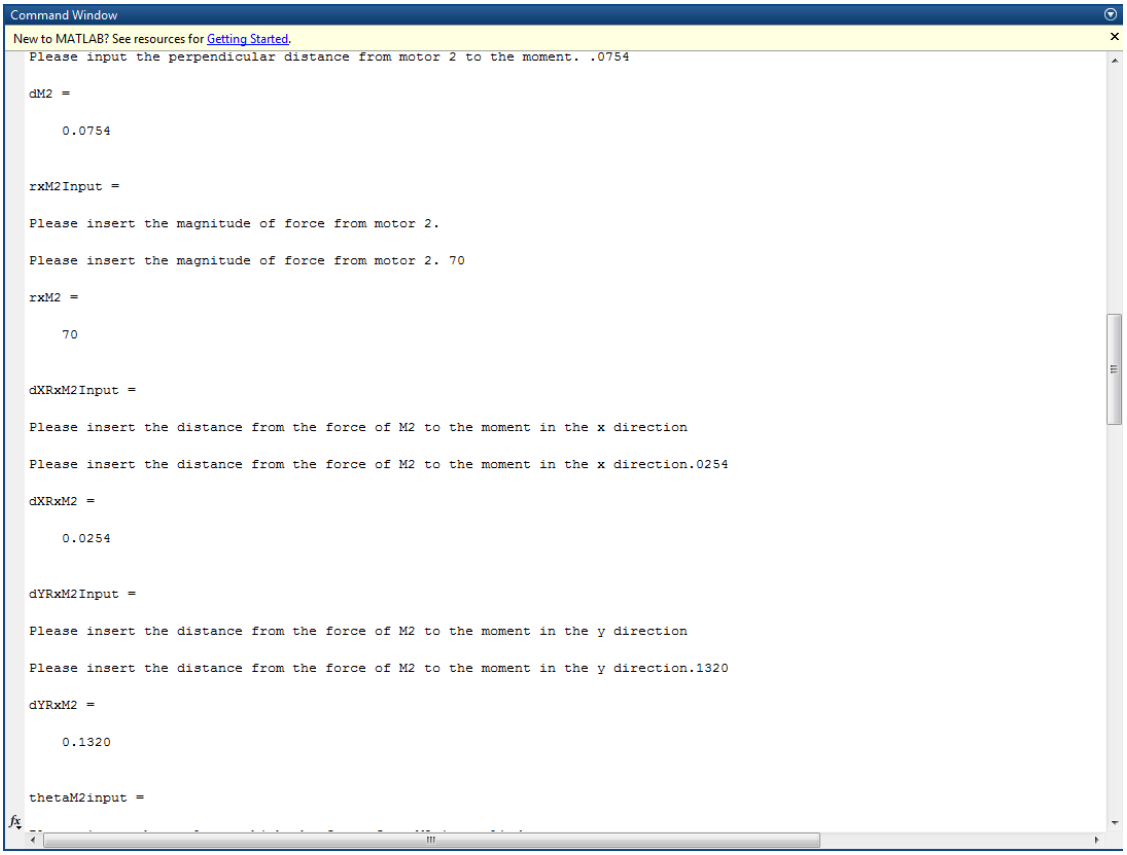


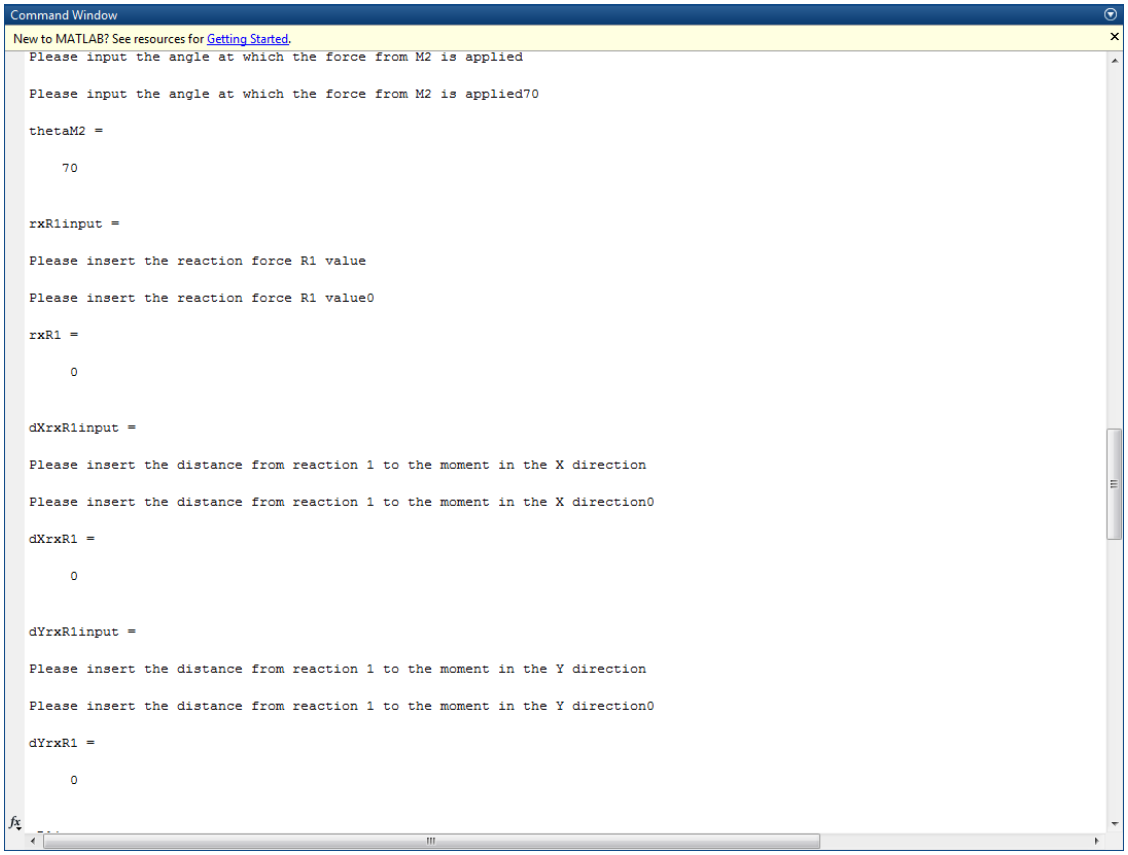
```
Editor - R:\MQP\MomentCalculations.m
BiomechanicsCalculations.m | MomentCalculations.m
This file can be opened as a Live Script. For more information, see Creating Live Scripts.

rxR1input = 'Please insert the reaction force R1 value'
rxR1 = input(rxR1input)
dXrxR1input = 'Please insert the distance from reaction 1 to the moment in the X direction'
dXrxR1 = input(dXrxR1input)
dYrxR1input = 'Please insert the distance from reaction 1 to the moment in the Y direction'
dYrxR1 = input(dYrxR1input)

aR1input ='What is the angle of the rod, taken with the bottom of the brace being the x axis, the right being the positive direction,and the positive y direction is up towards th
aR1= input(aR1input)

% Rod 2
rxR3input = 'Please insert the reaction force R3 value'
rxR3 = input(rxR3input)

dXrxR3input = 'Please insert the distance from reaction 3 to the moment in the X direction'
dXrxR3 = input(dXrxR3input)

dYrxR3input = 'Please insert the distance from reaction 3 to the moment in the Y direction'
dYrxR3 = input(dYrxR3input)

aR2input ='What is the angle of the rod, taken with the bottom of the brace being the x axis, the right being the positive direction,and the positive y direction is up towards th
aR2= input(aR2input)

% Brace
weightBraceInput = 'Please input the weight of the just the brace'
weightBrace = input(weightBraceInput)

dWbInput = 'Please insert the distance from the middle of the back brace to the moment'
dWb = input(dWbInput)

% Forces in the X
Fx = (rxM1*(sin(thetaM1)))+(rxM2*(cos(thetaM2)))+(rxR1*cos(aR1))-(rxR3*cos(aR2))

% Forces in the Y
Fy = (rxM1*(cos(thetaM1)))+(rxM2*(sin(thetaM2)))- mM1 - mM2 - weightBrace + (rxR1*sin(aR1)) + (rxR3*sin(aR2))

% Moment about A
Ma = (-rxM1*dXRxM1)+(-rxM1*dYRxM1)+(rxM2*dXRxM2)+(rxM2*dYRxM2)+(mM1*dM1)+(mM2*dM2)+(weightBrace*dWb)+((rxR1*cos(aR1))*dXrxR1)+((-rxR1*sin(aR1))*dYrxR1)+((rxR3*cos(aR2))*dXrxR3)+
((-rxR3*sin(aR2))*dYrxR3)
```

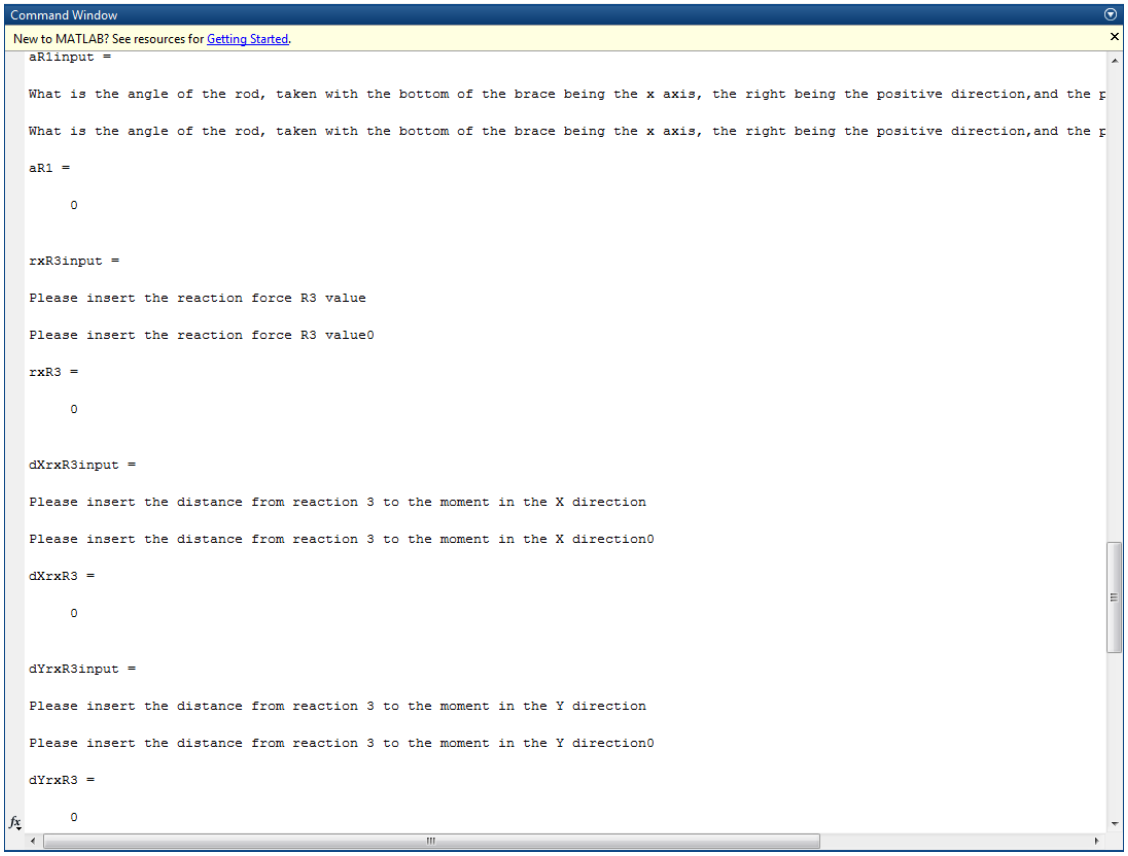

Command Window
New to MATLAB? See resources for Getting Started.
>> MomentCalculations
mM1input =
Please input weight of motor 1.
Please input weight of motor 1. .515
mM1 =
0.5150
dM1input =
Please input the perpendicular distance from the middle of motor 1 to the moment.
Please input the perpendicular distance from the middle of motor 1 to the moment. .211
dM1 =
0.2110
rxM1Input =
Please insert the magnitude of force from motor 1.
Please insert the magnitude of force from motor 1. 70
rxM1 =
70
dXRxM1Input =
Please insert the distance from the force of M1 to the moment in the x direction
Please insert the distance from the force of M1 to the moment in the x direction.211

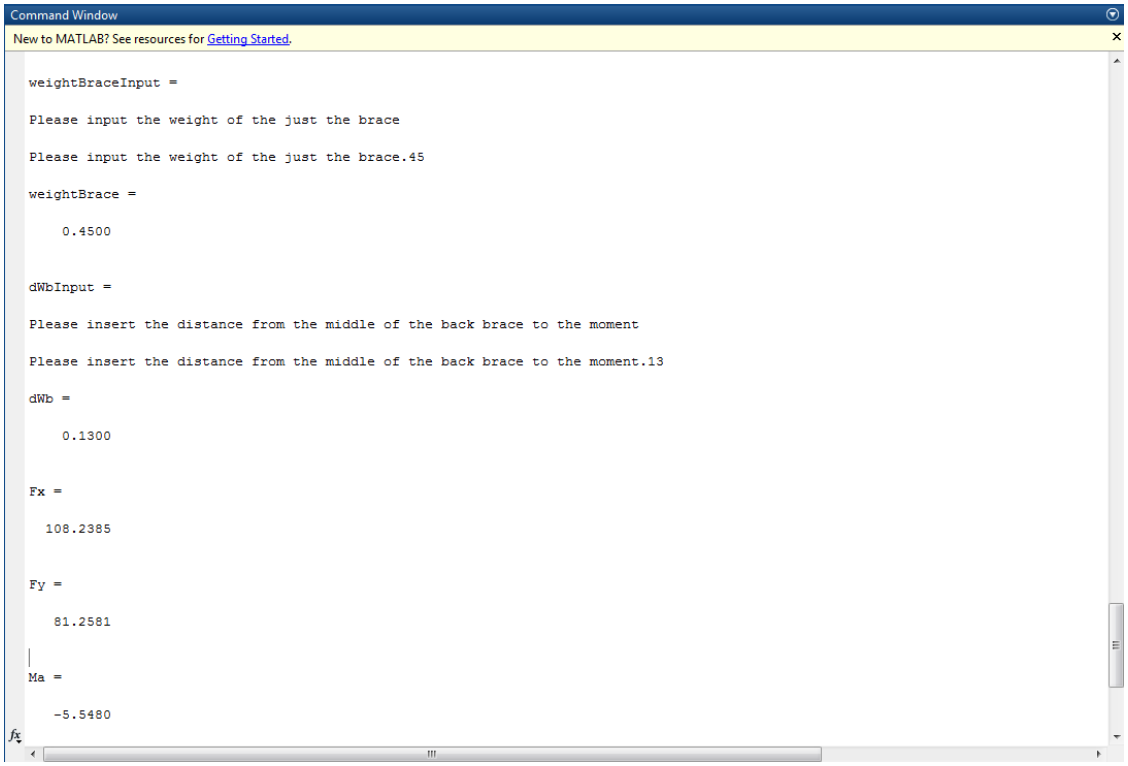

Command Window
New to MATLAB? See resources for Getting Started.
>> MomentCalculations
mM1input =
Please input weight of motor 1.
Please input weight of motor 1. .515
mM1 =
0.5150
dM1input =
Please input the perpendicular distance from the middle of motor 1 to the moment.
Please input the perpendicular distance from the middle of motor 1 to the moment. .211
dM1 =
0.2110
rxM1Input =
Please insert the magnitude of force from motor 1.
Please insert the magnitude of force from motor 1. 70
rxM1 =
70
dXRxM1Input =
Please insert the distance from the force of M1 to the moment in the x direction
Please insert the distance from the force of M1 to the moment in the x direction.211

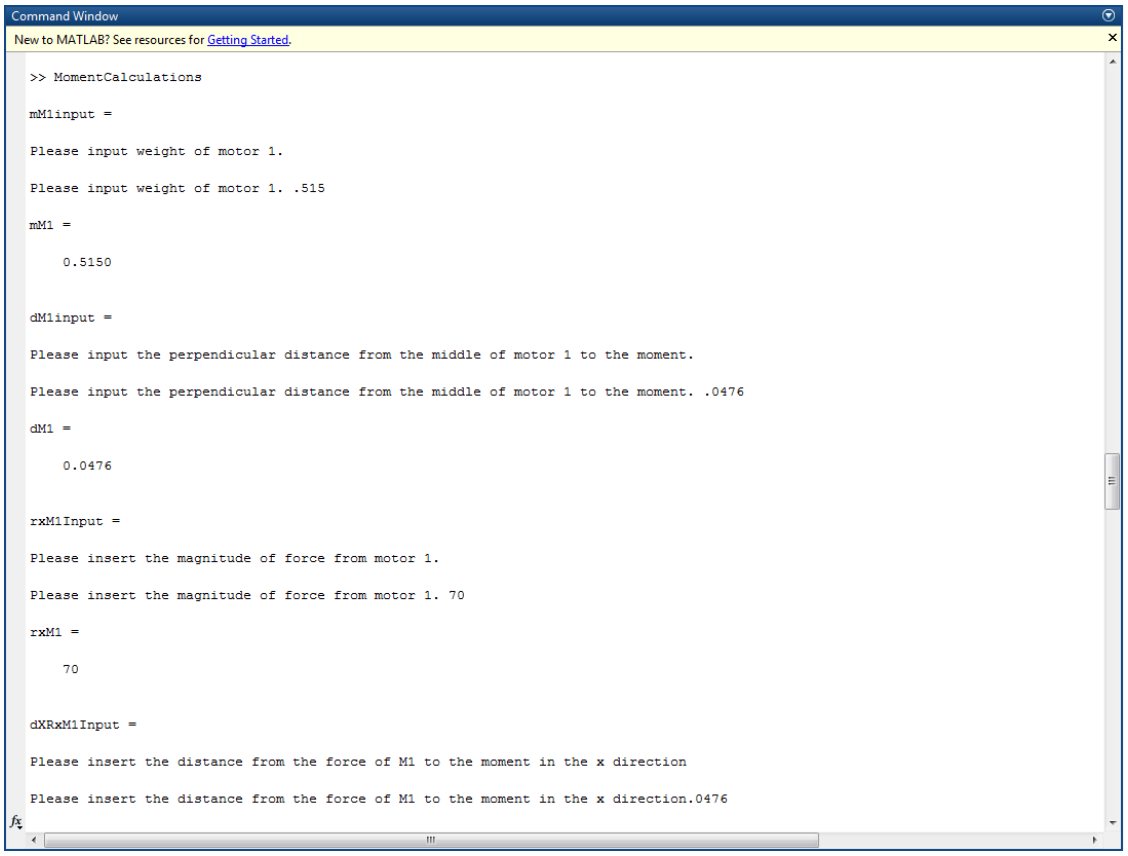

Command Window
New to MATLAB? See resources for Getting Started.
dXRxM1 =
0.2110
dYRxM1Input =
Please insert the distance from the force of M1 to the moment in the y direction
Please insert the distance from the force of M1 to the moment in the y direction.0286
dYRxM1 =
0.0286
thetaM1input =
Please input the angle at which the force from M1 is applied
Please input the angle at which the force from M1 is applied20
thetaM1 =
20
mM2input =
Please input weight of motor 2.
Please input weight of motor 2. .515
mM2 =
0.5150
dM2input =
Please input the perpendicular distance from motor 2 to the moment.

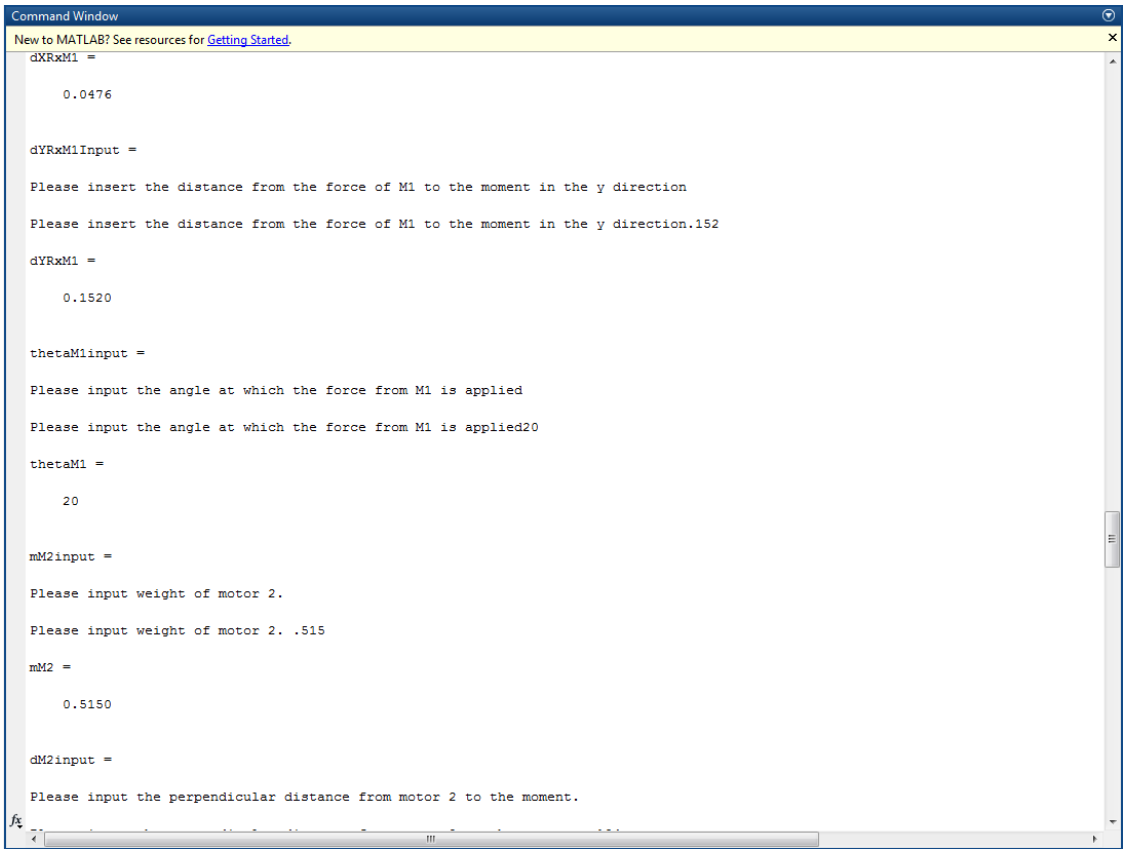

Command Window
New to MATLAB? See resources for Getting Started.
Please input the perpendicular distance from motor 2 to the moment. .0754
dM2 =
0.0754
rxM2Input =
Please insert the magnitude of force from motor 2.
Please insert the magnitude of force from motor 2. 70
rxM2 =
70
dXRxM2Input =
Please insert the distance from the force of M2 to the moment in the x direction
Please insert the distance from the force of M2 to the moment in the x direction.0254
dXRxM2 =
0.0254
dYRxM2Input =
Please insert the distance from the force of M2 to the moment in the y direction
Please insert the distance from the force of M2 to the moment in the y direction.1320
dYRxM2 =
0.1320
thetaM2input =

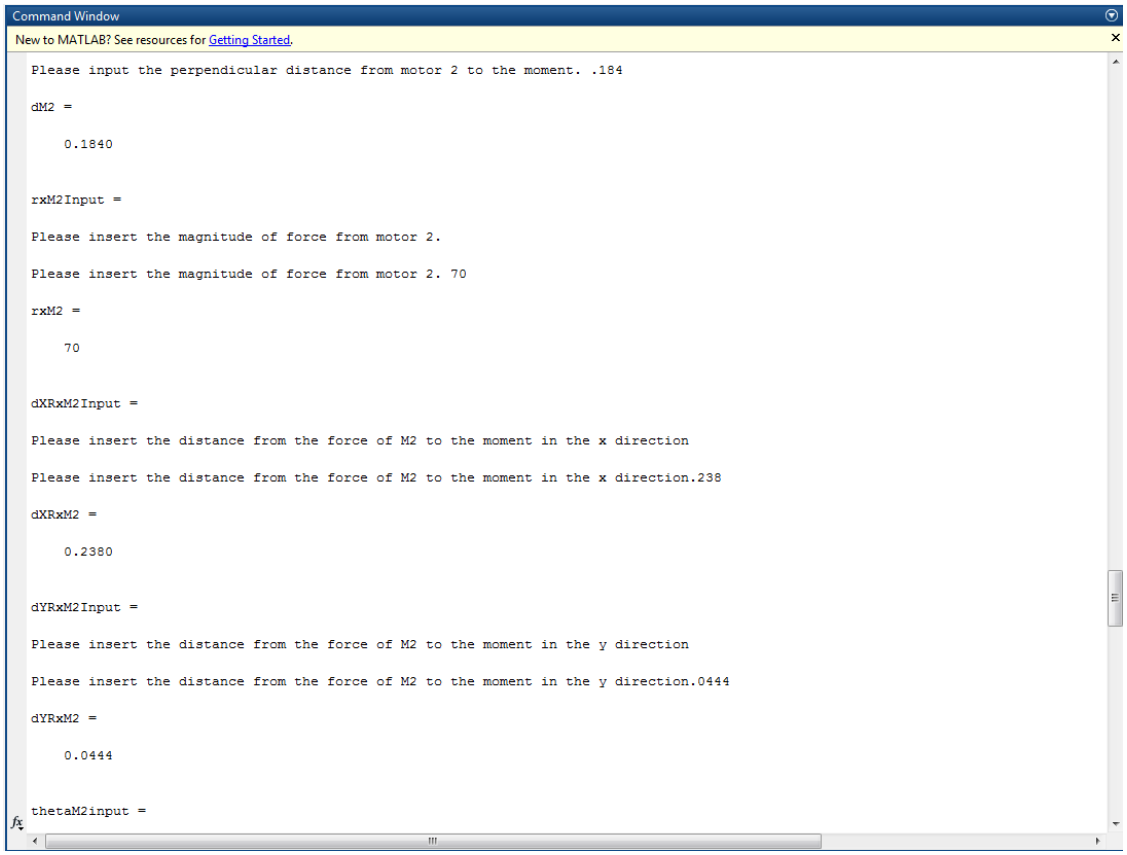

Command Window
New to MATLAB? See resources for Getting Started.
Please input the angle at which the force from M2 is applied
Please input the angle at which the force from M2 is applied70
thetaM2 =
70
rxR1input =
Please insert the reaction force R1 value
Please insert the reaction force R1 value0
rxR1 =
0
dXrxR1input =
Please insert the distance from reaction 1 to the moment in the X direction
Please insert the distance from reaction 1 to the moment in the X direction0
dXrxR1 =
0
dYrxR1input =
Please insert the distance from reaction 1 to the moment in the Y direction
Please insert the distance from reaction 1 to the moment in the Y direction0
dYrxR1 =
0

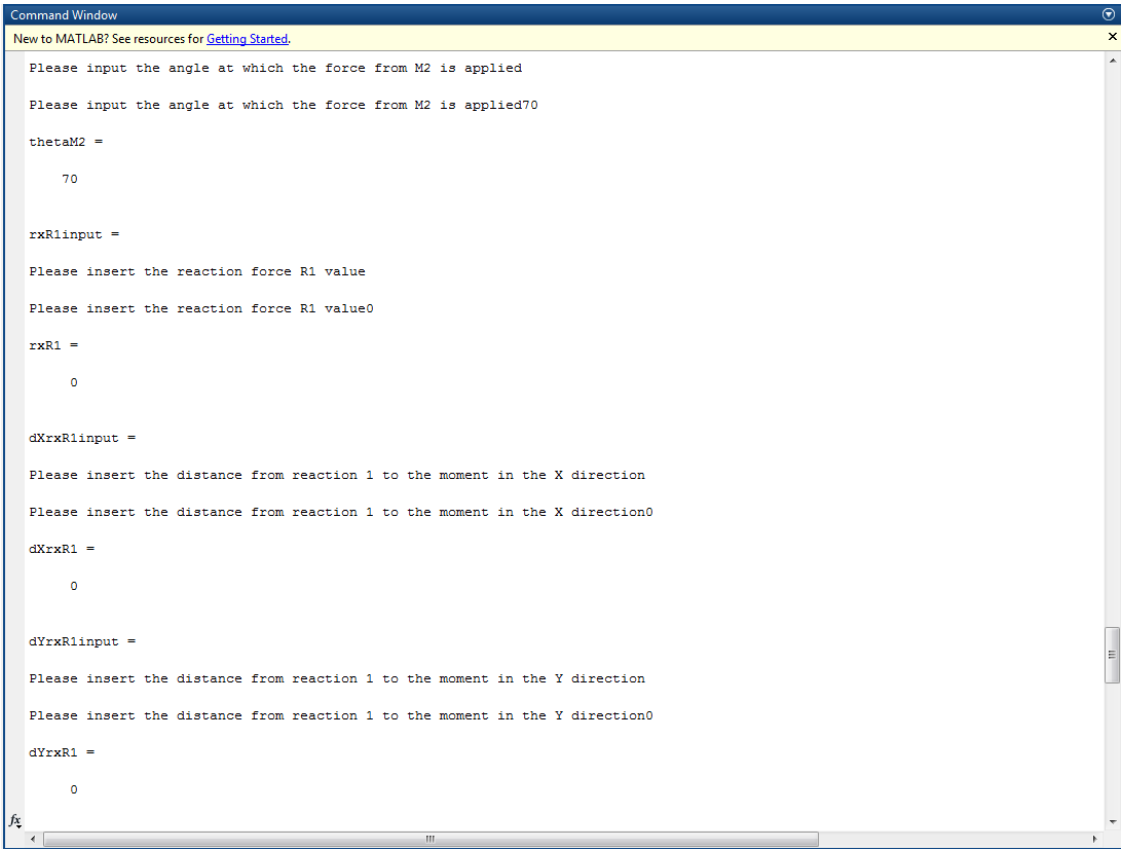

Command Window
New to MATLAB? See resources for Getting Started.
aR1input =
What is the angle of the rod, taken with the bottom of the brace being the x axis, the right being the positive direction,and the p
What is the angle of the rod, taken with the bottom of the brace being the x axis, the right being the positive direction,and the p
aR1 =
0
rxR3input =
Please insert the reaction force R3 value
Please insert the reaction force R3 value0
rxR3 =
0
dXrxR3input =
Please insert the distance from reaction 3 to the moment in the X direction
Please insert the distance from reaction 3 to the moment in the X direction0
dXrxR3 =
0
dYrxR3input =
Please insert the distance from reaction 3 to the moment in the Y direction
Please insert the distance from reaction 3 to the moment in the Y direction0
dYrxR3 =
0

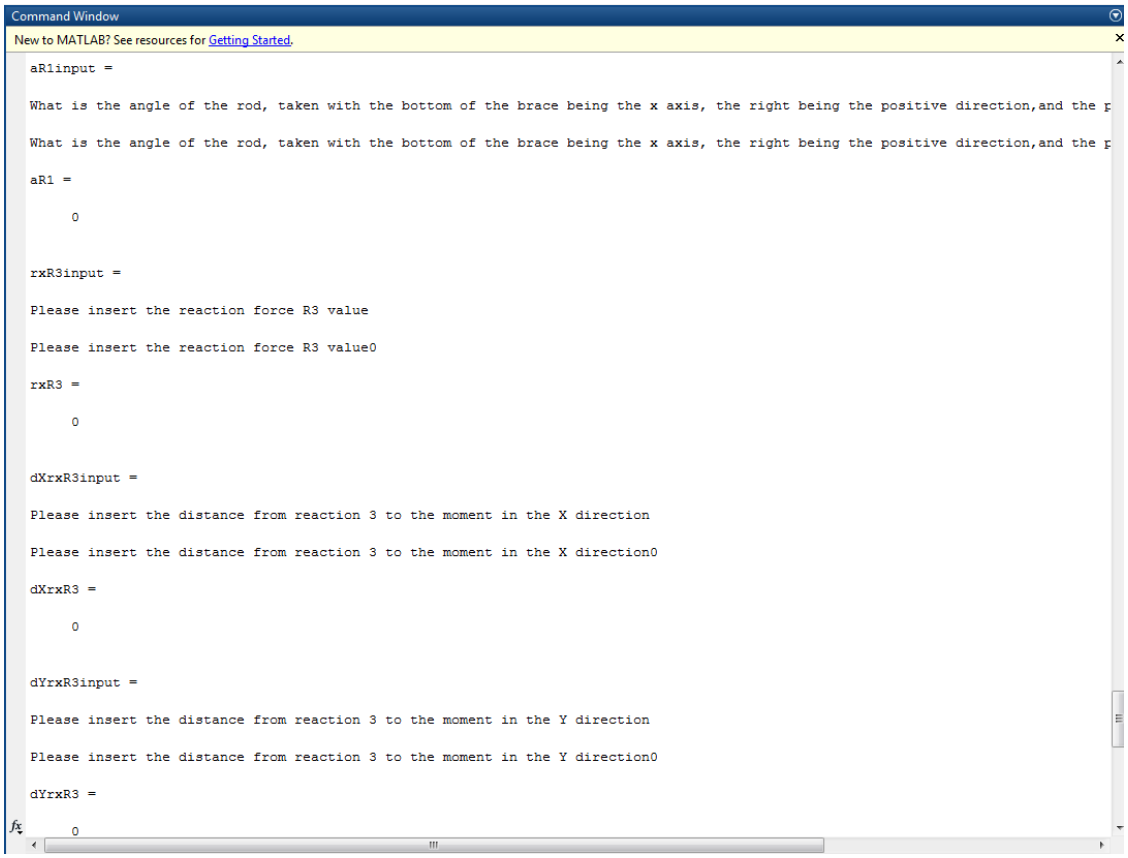

Command Window
New to MATLAB? See resources for Getting Started.
weightBraceInput =
Please input the weight of the just the brace
Please input the weight of the just the brace.45
weightBrace =
0.4500
dWbInput =
Please insert the distance from the middle of the back brace to the moment
Please insert the distance from the middle of the back brace to the moment.13
dWb =
0.1300
Fx =
108.2385
Fy =
81.2581
Ma =
-5.5480

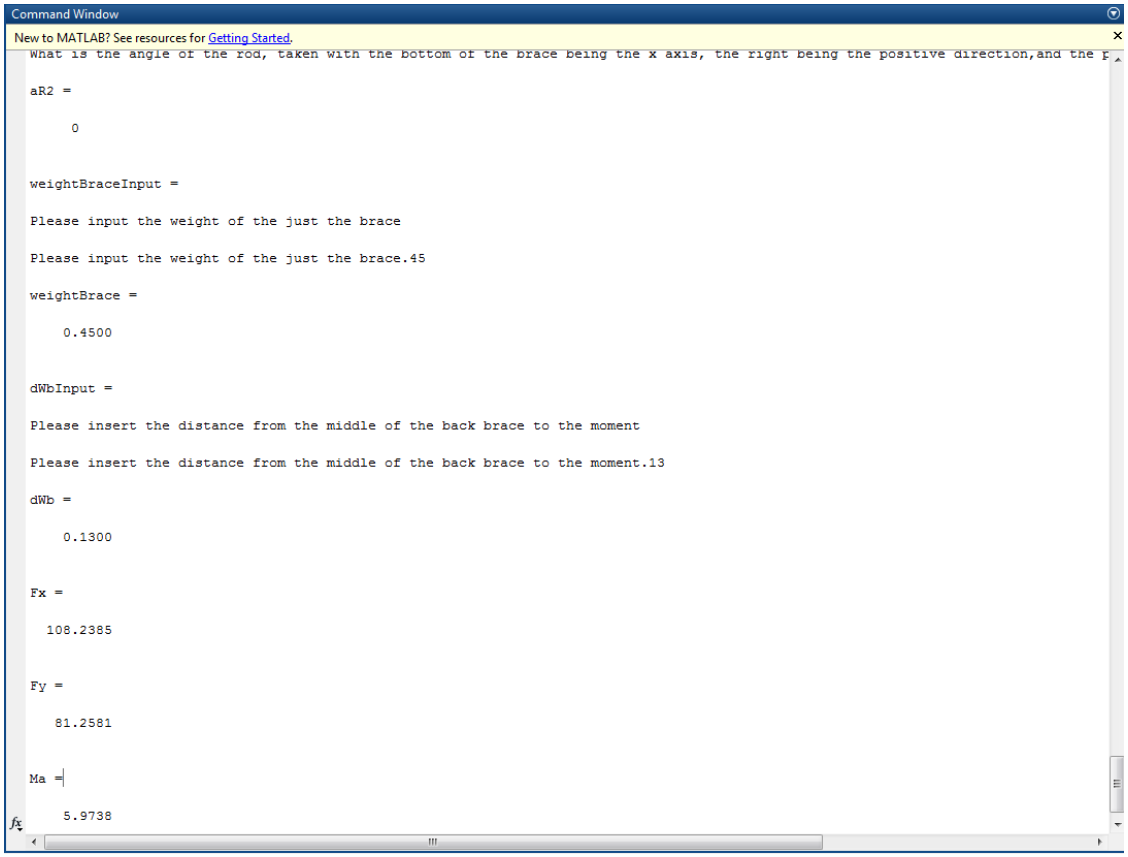

Command Window
New to MATLAB? See resources for Getting Started.
>> MomentCalculations
mM1input =
Please input weight of motor 1.
Please input weight of motor 1. .515
mM1 =
0.5150
dM1input =
Please input the perpendicular distance from the middle of motor 1 to the moment.
Please input the perpendicular distance from the middle of motor 1 to the moment. .0476
dM1 =
0.0476
rxM1Input =
Please insert the magnitude of force from motor 1.
Please insert the magnitude of force from motor 1. 70
rxM1 =
70
dXRxM1Input =
Please insert the distance from the force of M1 to the moment in the x direction
Please insert the distance from the force of M1 to the moment in the x direction.0476


Command Window
New to MATLAB? See resources for Getting Started.
dXRxM1 =
0.0476
dYRxM1Input =
Please insert the distance from the force of M1 to the moment in the y direction
Please insert the distance from the force of M1 to the moment in the y direction.152
dYRxM1 =
0.1520
thetaM1input =
Please input the angle at which the force from M1 is applied
Please input the angle at which the force from M1 is applied20
thetaM1 =
20
mM2input =
Please input weight of motor 2.
Please input weight of motor 2. .515
mM2 =
0.5150
dM2input =
Please input the perpendicular distance from motor 2 to the moment.


Command Window
New to MATLAB? See resources for Getting Started.
Please input the perpendicular distance from motor 2 to the moment. .184
dM2 =
0.1840
rxM2Input =
Please insert the magnitude of force from motor 2.
Please insert the magnitude of force from motor 2. 70
rxM2 =
70
dXRxM2Input =
Please insert the distance from the force of M2 to the moment in the x direction
Please insert the distance from the force of M2 to the moment in the x direction.238
dXRxM2 =
0.2380
dYRxM2Input =
Please insert the distance from the force of M2 to the moment in the y direction
Please insert the distance from the force of M2 to the moment in the y direction.0444
dYRxM2 =
0.0444
thetaM2input =


Command Window
New to MATLAB? See resources for Getting Started.
Please input the angle at which the force from M2 is applied
Please input the angle at which the force from M2 is applied70
thetaM2 =
70
rxR1input =
Please insert the reaction force R1 value
Please insert the reaction force R1 value0
rxR1 =
0
dXrxR1input =
Please insert the distance from reaction 1 to the moment in the X direction
Please insert the distance from reaction 1 to the moment in the X direction0
dXrxR1 =
0
dYrxR1input =
Please insert the distance from reaction 1 to the moment in the Y direction
Please insert the distance from reaction 1 to the moment in the Y direction0
dYrxR1 =
0


Command Window
New to MATLAB? See resources for Getting Started.
aR1input =
What is the angle of the rod, taken with the bottom of the brace being the x axis, the right being the positive direction,and the p
What is the angle of the rod, taken with the bottom of the brace being the x axis, the right being the positive direction,and the p
aR1 =
0
rxR3input =
Please insert the reaction force R3 value
Please insert the reaction force R3 value0
rxR3 =
0
dXrxR3input =
Please insert the distance from reaction 3 to the moment in the X direction
Please insert the distance from reaction 3 to the moment in the X direction0
dXrxR3 =
0
dYrxR3input =
Please insert the distance from reaction 3 to the moment in the Y direction
Please insert the distance from reaction 3 to the moment in the Y direction0
dYrxR3 =
0


Command Window
New to MATLAB? See resources for Getting Started.
What is the angle of the rod, taken with the bottom of the brace being the x axis, the right being the positive direction,and the p
aR2 =
0
weightBraceInput =
Please input the weight of the just the brace
Please input the weight of the just the brace.45
weightBrace =
0.4500
dWbInput =
Please insert the distance from the middle of the back brace to the moment
Please insert the distance from the middle of the back brace to the moment.13
dWb =
0.1300
Fx =
108.2385
Fy =
81.2581
Ma =
5.9738

## Appendix E

# Range of Motion, Linear Time Delay Relationship

| Abduction/Adduction Time Delays vs. Arm Elevation | | | | |
|---|---|---|---|---|
| | Trial 1 | Trial 2 | Trial 3 | Average |
| 500 | 14 | 10 | 12 | 12 |
| 1000 | 24 | 20 | 29 | 24.33333 |
| 1500 | 38 | 36 | 40 | 38 |
| 2000 | 50 | 50 | 59 | 53 |
| 2500 | 57 | 64 | 63 | 61.33333 |
| 3000 | 72 | 68 | 75 | 71.66667 |
| 3500 | 78 | 81 | 80 | 79.66667 |
| 4000 | 88 | 86 | 87 | 87 |

| Flexion/Extension Time Delays vs. Arm Elevation | | | | |
|---|---|---|---|---|
| | Trial 1 | Trial 2 | Trial 3 | Average |
| 500 | 35 | 35 | 35 | 35 |
| 1000 | 46 | 47 | 44 | 45.66667 |
| 1500 | 55 | 52 | 50 | 52.33333 |
| 2000 | 64 | 62 | 60 | 62 |
| 2500 | 77 | 75 | 70 | 74 |

# Appendix F

# ADL Performance Trials

| ADLs | Comfort During Use | | Ease of Use | | Ability to Perform ADL | |
|---|---|---|---|---|---|---|
| | Average | STDEV | Average | STDEV | Average | STDEV |
| Brushing Teeth | 3.8 | 0.447 | 3.8 | 0.518 | 3.8 | 0.447 |
| Feeding Yourself | 3.6 | 0.548 | 3.6 | 0.59 | 4.2 | 0.447 |
| Pouring a cup | 4 | 0 | 3.6 | 0.501 | 3.6 | 0.548 |
| Cutting Food | 4.4 | 0.548 | 4.2 | 0.358 | 4.8 | 0.447 |
| Opening/Reaching into a cupboard | 3.6 | 0.548 | 3.4 | 0.607 | 4.2 | 0.837 |
| Overall Intuitiveness | **4** | **0.707** | | | | |

# Appendix G

# CAD Design Tables

| Brace Dimensions Table (all in inches) | | | | | |
|---|---|---|---|---|---|
| **Part Name** | **diameter** | **radius** | **width** | **thickness** | **Hole Locations** |
| Foam_1 | 4.5 | | 1.25 | 0.25 | |
| Foam_2 | 4.75 | | 1.25 | 0.25 | |
| Foam_3 | 5.9 | | 1.25 | 0.25 | |
| Foam_4 | 6.84 | 3.42 | 1.25 | 0.25 | |
| Foam_5 | 8.2 | | 1.25 | 0.25 | |
| Ring_1 | 5 | | 1.25 | 0.0625 | |
| Ring_2 | 5.25 | | 1.25 | 0.0625 | |
| Ring_3 | 6.4 | | 1.25 | 0.0625 | |
| Ring_4 | 7.34 | 3.67 | 1.25 | 0.0625 | |
| Ring_5 | 8.7 | | 1.25 | 0.0625 | |
| Offset_1 | 5.125 | 2.5625 | 0.75 | 0.5 | 2.75 |
| Offset_2 | 5.375 | 2.6875 | 0.75 | 1 | 3.375 |
| Offset_3 | 6.525 | 3.2625 | 0.75 | 2 | 4.95 |
| Offset_4 (right) | 7.465 | 3.7325 | | | 3.42 |
| Offset_4 (left) | 8.825 | 4.4125 | | | 4.1 |

| **Notes** |
|---|
| Offset_1 thickness dependant on cable diameter |
| Foam material is beige cotton |
| Ring 1 material is polished aluminum |
| Offset material is carbon fiber design fabric |
| Foam dimentions come from measured arm dimentions |
| Ring diameter dimension are the corresponding foam dimension with the the foam thickness added |
| Offset diameter dimensions are the corresponding ring dimension with the the ring thickness added |
| Hole Loctions in reference to diameter of offset |

# Appendix H

# Circuit Board

This appendix shows the circuit board design from schematic to assembly completion.

Step 1. All components of the circuit board were connected through a top layer schematic (figure 1).

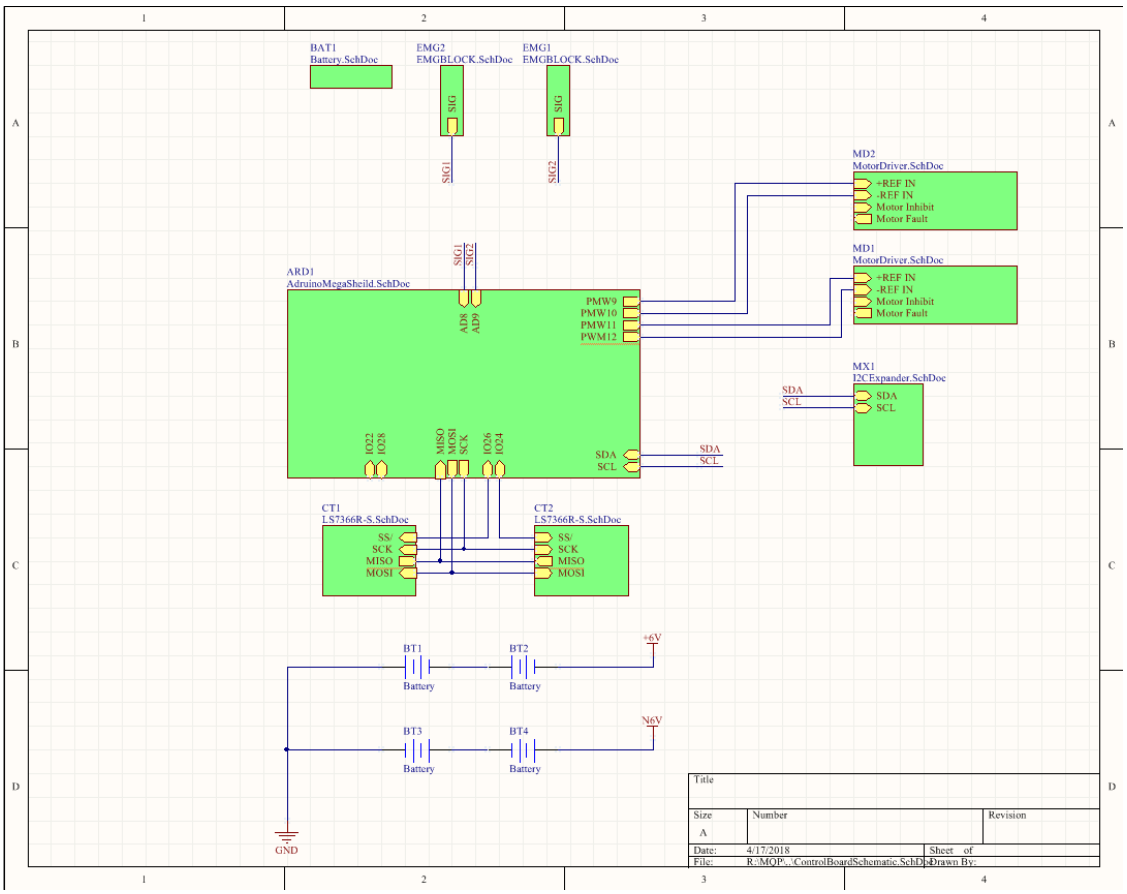



FIGURE H.1: Top-Layer Schematic for Circuit Board

Step 2. The components were placed on the PCB board in a logical and organized manner. The Gerber file shown below was submitted to Advanced Circuits website for manufacturing (figure 2).

Step 3. A four layer PCB board arrived in the mail a week and a half later (figure 3).

Step 4. Connectors were obtained and soldered onto the board (figure 4).

Step 5. The electronics and sensors were connected to the board. Small mistakes in the board were found and corrected (figure 5).

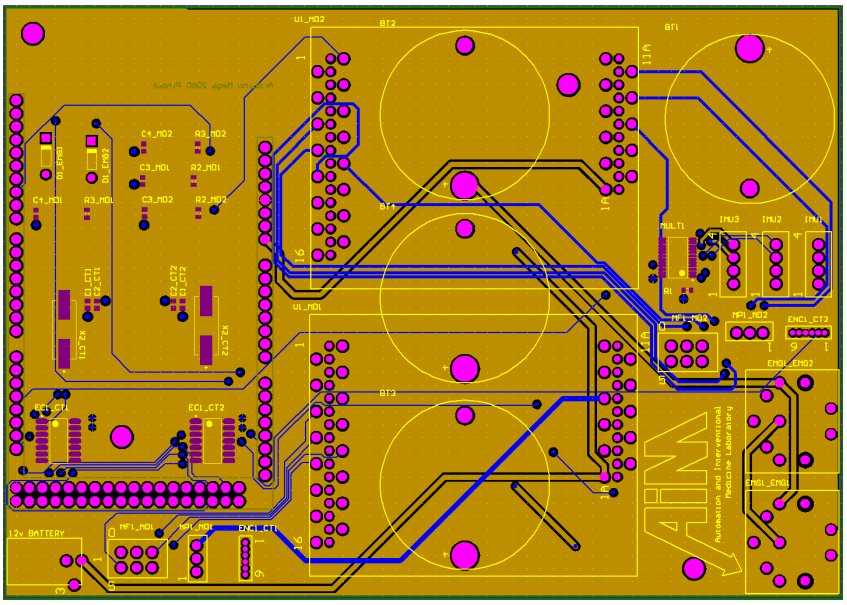


FIGURE H.2: Gerber File of PCB Board

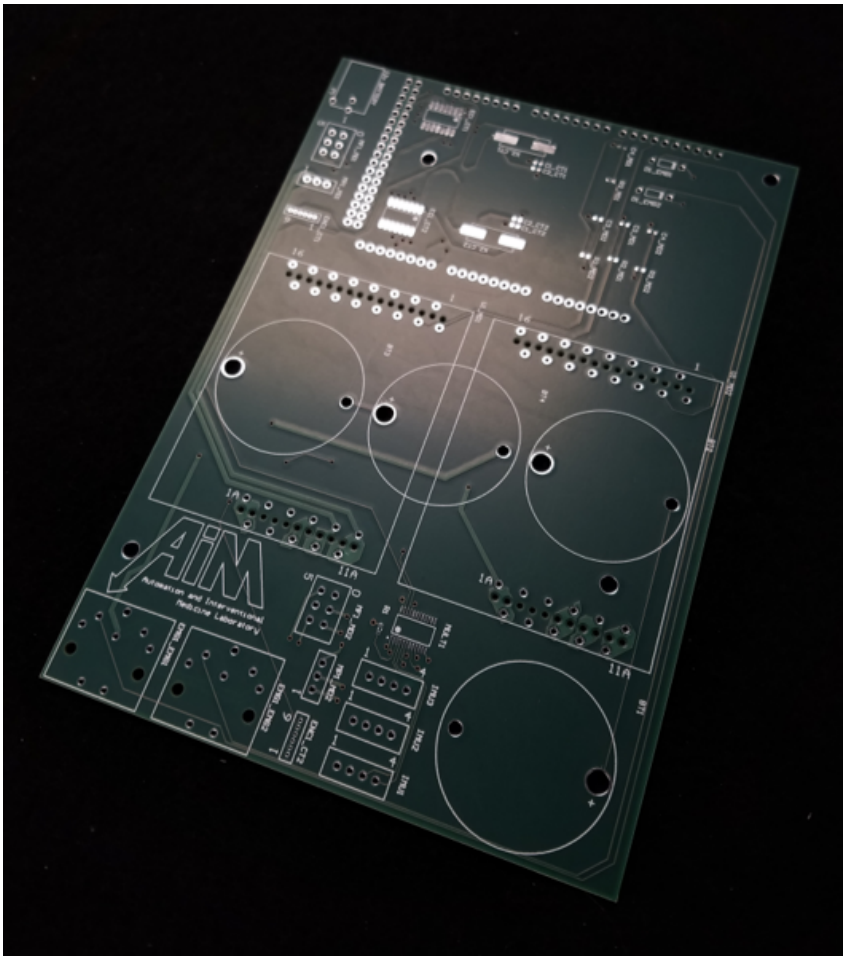


FIGURE H.3: Manufactured PCB Board

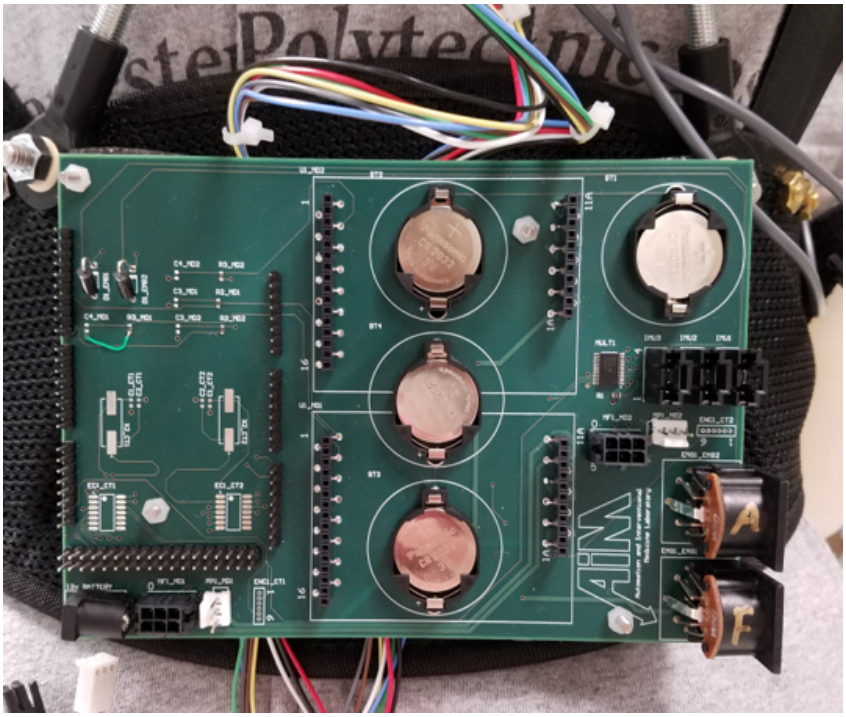


FIGURE H.4: Assembled Circuit Board

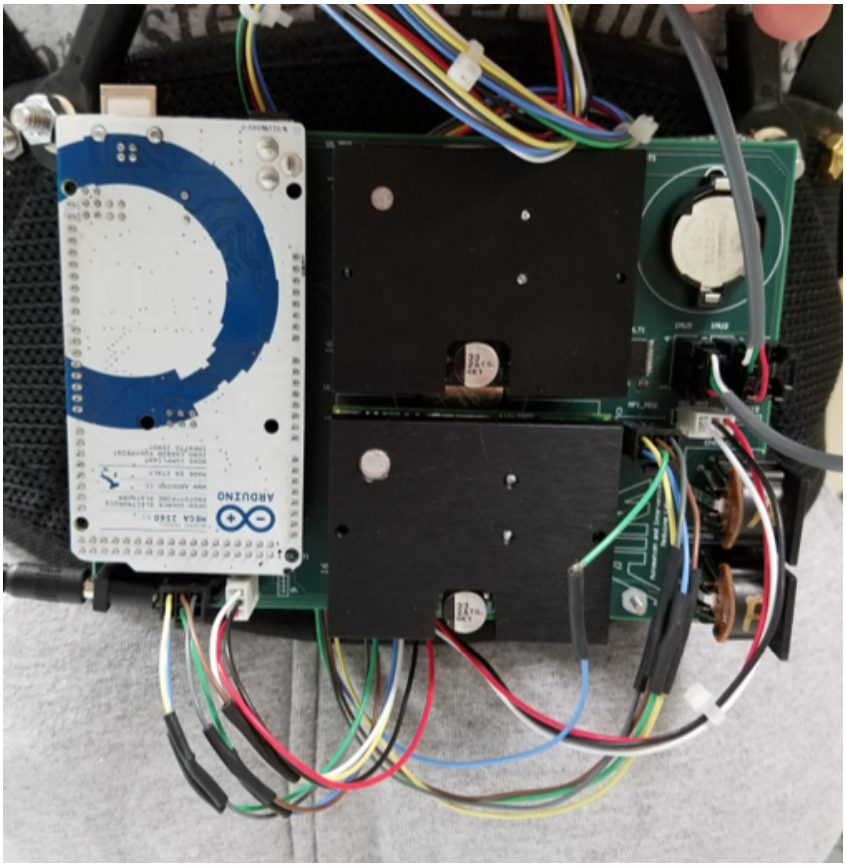


FIGURE H.5: Assembled Circuit Board with Components

# Appendix I

# Arduino Code

https://github.com/vrivera465/WSE-Controls
**Debugging Code**

- Button_Test
  - Code to test if the button is working
  - Uses the Serial Monitor to print our different statements if the button is pushed
- Dual_IMU_Control
  - This code works to control both IMUs at the same time
  - It loads the previously stored calibration data onto the IMU or starts saving calibration data if none is found
  - Displays the calibration status in real time of each IMU
  - Displays the position of each sensor in quaternion data
  - Creates a rotation matrix from both IMU sensors
  - Inverts the rotation matrix for the IMU on the back, this allows us to multiply the inverse by the rotation matrix on the arm to create a new matrix that corresponds to the arm being in reference to the back
  - From each matrix displays the roll, pitch, and yaw angles
- Motor_Test
  - Test to make sure the motors are running when attached to the circuit board
  - Runs each motor back and forth for a set amount of time and constantly loops
- TCA9548A_Scanner
  - Tests which ports on the multiplexer the IMUs are connected too
  - Prints out what ports IMUs were detected to be located on

**Controls Code**

- Exoskeleton_Controls
  - Controls the motors from pressing the button using delays
  - When a button is pressed it spins the motor for the set delay time amount
- Final_Controls
  - Controls the motors with a button push and stops based off the IMU position

- It loads the previously stored calibration data onto the IMU or starts saving calibration data if none is found
- Displays the calibration status in real time of each IMU
- Displays the position of each sensor in quaternion data
- Creates a rotation matrix from both IMU sensors
- Inverts the rotation matrix for the IMU on the back, this allows us to multiply the inverse by the rotation matrix on the arm to create a new matrix that corresponds to the arm being in reference to the back
- From each matrix displays the roll, pitch, and yaw angles
- When the button is pressed the code reads the current position of the IMU and then stops when the IMU is about 15 degrees about the starting point

# Appendix J

# User Guide

**Upon receiving device for testing or use, inspect the device and storage container to ensure you have the following items:**

- Physical Bracing
  - Arm bracing
  - Back plate
  - Weight belt
  - Spools
  - Cabling
- EC max 30, 30 diameter, brushless, 60 Watt motors (2)
- AZBE12A8 Motor driver (2)
- Arduino Mega
- 12V Rechargeable Battery
- 3V Coin Batteries (4)
- 6 pin DIN connector button box
- EMG electrodes (optional)
- IMU sensors (optional)

**Before donning the device, connect all components to circuit board. To view a complete schematic and the PCB board lay out, see Appendix H**

1. The Arduino Mega to the Arduino footprint on the left of the board
2. 3V coin batteries in circular holders BT1, BT2, BT3, BT4
3. Motor drivers to U1_MD1, U1_MD2
4. Abduction motor feedback to MF1_MD1
5. Abduction motor power to MP1_MD1
6. Flexion motor feedback to MF1_MD2
7. Flexion motor power to MP1_MD2

**Donning the device:**

** Assistance is suggested

1. Place the back plate and shoulder component on back and shoulder
2. Adjust and secure the weight belt around your midsection, it should be sitting on your pelvic bones
3. Locate the Velcro strap on your left side, it originates towards the back of the weight belt
   (a) Should be pulled around to the front and up through a plastic loop located over your left shoulder
   (b) Tighten and secure the Velcro on itself
   (c) This strap should mimic a backpack strap
4. Locate the Velcro strap on you right side, it originates in the front of the weight belt
   (a) Put Velcro through the plastic loop attached to the shoulder component
   (b) Tighten and secure Velcro on itself
5. The arm bracing should fit onto the arm in a tight fashion
   (a) The arm bracing should sit comfortably, approximately 2-3 inches above the elbow
   (b) The arm brace can be tightened using Velcro on the inside of the rings
6. The 12V Rechargeable Battery should be connected to "12V Battery" on circuit board
7. Button or EMG should be connected to EMG1_EMG1, EMG1_EMG2, noting the fact that the cord labeled "Flexion" should be plugged into the connector with an "F" on it, and the cord labeled "Abduction" should be plugged into the connector with an "A" on it.

**Using the Device**

1. The device should be entirely secure on the user.
2. Turn battery on using the switch directly on the battery
3. Using the button box, press "F" for an incremental movement in the flexion direction
4. Using the button box, press "A" for an incremental movement in the abduction direction

**Safety**

For more information on the safety features of our device please see Chapter 7.4 in the body of the text.

**Doffing the Device**

Refer to the previous section "Donning the Device" and do the steps in the reverse order

**Modifying the Device**

- If you would like to change the increment in which each direction moves download our control code from Github using Appendix I
  - In the file labeled "Exoskeleton Controls" read the comments and find the time delay set for the flexion movement and the abduction movement
- If you would like to use EMG sensing instead of the buttons, you can alter the file "Exoskeleton Control" mentioned previously to include a threshold of an analog value instead of a button press. This threshold must be found through experimentation.
- If you would like to as position sensing confirm that there are IMU's mounted on the back plate and the arm strut
  - Connect the IMU's to IMU2 and IMU3 on the circuit board
  - Visit our Github files using Appendix I and locate Dual_IMU_Control and Final_Control
  - This code is our suggestion of how to begin reading accurate position and orientation of the arm in relation to the back, the equations and code should be revisited and redone in order to ensure that the IMU are reporting the accurate positions

**Other options for expansion**

- The circuit board was designed to include encoders
  - To find more information about what components need to be obtained and soldered on the board, go to the AIM drive and search " Wearable Shoulder Exoskeleton". There will be a folder that says "Circuit Board". This will contain Altium files.