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Shoulder Mount for a Wearable Arm Orthosis

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Shoulder Mount for a Wearable Arm Orthosis

A Major Qualifying Project Proposal submitted to the faculty of Worcester Polytechnic Institute in partial fulfillment of the requirements for the Degree of Bachelor of Science

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Abstract

Functionality of the upper limb is vital for performing *Activities of Daily Living (ADLs)*, such as bathing, dressing, and eating. In some cases, motion can be restored with the help of an orthosis. The goal of this project was to design, analyze, manufacture, and test a shoulder mount to be used in conjunction with a wearable powered upper-limb orthosis. The device must enable adequate functionality for completion of *ADLs* and fit multiple users within a range of body types through adjustability.

Tests were performed to confirm functionality of the design by measuring and comparing the joint angles that users were able to achieve in shoulder flexion and shoulder abduction with and without the prototype. The test subjects reported that performing the *ADLs* was relatively easy while wearing the prototype, and results showed that the orthosis enabled the user to achieve a range of motion necessary to complete all *ADLs*. On average, the prototype limits the user's shoulder flexion and abduction envelopes by approximately 43% and 50%, respectively, and is reasonably adjustable to both male and female users in the 25th to 75th percentile range. The final prototype weighed less than 4lbs, was reportedly comfortable to wear, and did not significantly increase the user's body frame. The prototype could serve as a candidate for further design and development by adding powered elements, using alternate materials, and integrating the design with that of an already patented wearable powered upper limb orthosis.

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1. Introduction

The upper limb is a critically important element, as using the arm to reach and grab is essential for functional independence. There are a number of medical conditions, diseases, and injuries that can lead to loss of upper limb functionality. Individuals who lose the ability to effectively use their upper limbs are severely restricted when performing *Activities of Daily Living* such as bathing, dressing, and eating.

Functionality of the upper limb can be restored with the help of an orthosis, which is a form of exoskeleton that is attached to a limb or torso. While a variety of upper-limb orthoses exist, most can be categorized into one of three categories: devices that aid in the rehabilitation process, devices that improve the functional independence of individuals with permanent disabilities, and devices that grant superhuman strength. These can then be broken down further into categories based on whether each device is powered or passive, and whether the orthosis is externally mounted or wearable.

Wearable, powered, upper limb orthoses are typically used to aid individuals in performing *Activities of Daily Living* by assisting users through ranges of motion unachievable independently. By powering the correct joints, an orthosis can be controlled by the user to achieve the desired motions. These devices are typically mounted to the torso or shoulder and then extend distally across the affected limb, attaching at various points. The current methods of mounting orthoses to the shoulder are of concern due to the complex kinematics of the human shoulder. Along the same lines, an orthosis design that fits one user may not necessarily work with other users due to kinematic differences introduced by varying upper limb lengths.

The goal of this Major Qualifying Project is to design, analyze, manufacture, and test a shoulder mount to be used in conjunction with a wearable, powered, upper-limb orthosis. The device must enable adequate mobility and functionality for the user to perform *Activities of Daily Living*. As this device is intended to aid persons with permanent and long-term disabilities by improving their functional independence, it should be discrete, comfortable, and user-friendly. Special emphasis is placed on designs that utilize rapid prototyping to ensure the shoulder mount will be easily modified to fit multiple users within a range of body types.

2. Background

2.1 Shoulder Anatomy & Movement

2.1.1 Anatomical Terms and Definitions

Before exploring the complexity of the shoulder joint, it is necessary to become familiar with the basic terms used for anatomical descriptions. These terms, defining the location and position of features of the body, will be used throughout the paper.

The initial convention, when describing location on the body, is for the body to be in *anatomical position*, or neutral position; standing with arms by the sides, palms facing forward, and feet together. The body is divided into three planes (Figure 1). The horizontal plane is called the *transverse* plane; it differentiates between the upper and lower halves of the body. The *sagittal* or *median* plane is a vertical plane that splits the body into right and left sides. The third plane is the *coronal* or *frontal* plane; it is also vertical and separates the front and back of the body.

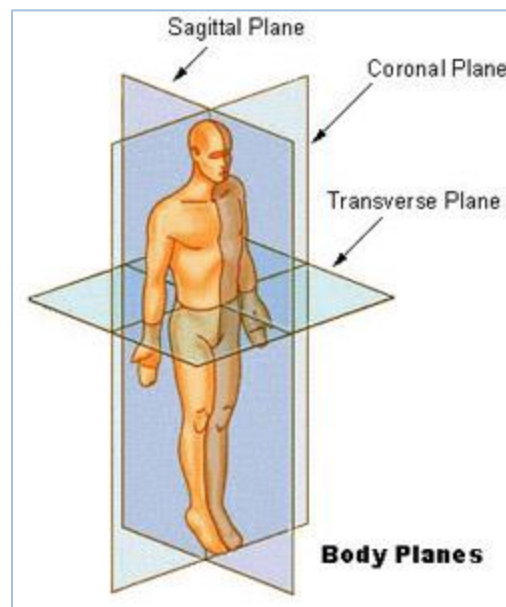


Figure 1— The three major planes of the human body (National Cancer Institute)

The location of body features and parts can be described relative to these planes using additional anatomical terms. Relative to the transverse plane, features above the plane are

referred to as *superior* and features below are considered *inferior*. Parts located toward the middle of the body, near the sagittal plane, are called *medial* while those that are further away are described as *lateral*. Some parts, which are not completely medial or lateral, may be considered intermediate. The front half of the body along the frontal plane is identified as *anterior* as opposed to *posterior*, referring to the back half of the body.

For the extremities, there are several descriptive terms. *Proximal* is used to describe features that are located closer to the limb's area of attachment with the body. Parts that are located furthest from the attachment are considered *distal*. Though the body may not always be in anatomical position, the planes and anatomical terms are still useful in describing locations (Gray, 1918).

A left-handed global coordinate system (Figure 2) is used for reference through this document, with respect to the right shoulder. The X-axis is horizontal and perpendicular to the sagittal plane, the Y-axis is vertical and perpendicular to the transverse plane, and the Z-axis is horizontal and is perpendicular to the frontal plane. The origin of the global coordinate system is located at the centers of the axes of rotation of the shoulder. This means that the humerus rotates around these axes relative to the body. The orientation of the coordinate system is fixed and does not move with movement of the shoulder.

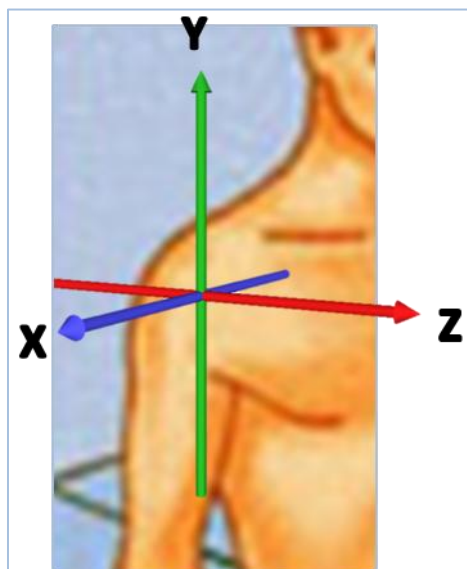


Figure 2— Global coordinate system of the shoulder (National Cancer Institute)

2.1.2 Shoulder Joint & Motion

The shoulder and torso will be the body parts focused on throughout the design and development of the shoulder mount. The torso is the trunk or middle region of the body; it is commonly referred to as the chest. The torso is made up of spinal column, sternum, and the ribs that connect the two (Figure 3). The torso, however, is not the main focus of this project.

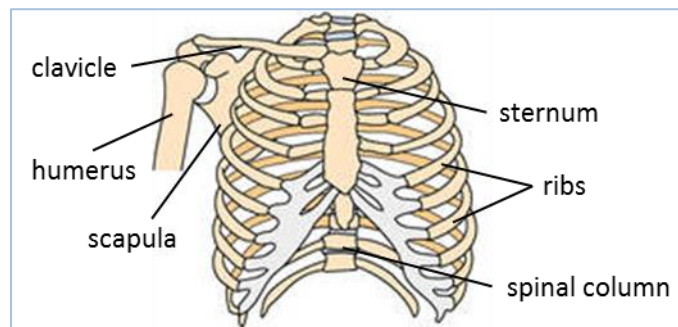


Figure 3—Torso and pectoral girdle (LifeART, 2008)

The pectoral girdle (Figure 4), also known as the shoulder, is made up of only two bones: the scapula and the clavicle. These two bones are connected at the acromioclavicular joint (AC). The scapula is a large, triangular, relatively flat bone that lies parallel to the frontal plane. Between the scapula and the torso is the scapulothoracic plane, which allows for gliding of the scapula during rotation of the arm (Culham & Peat, 1993). The clavicle is a mostly cylindrical bone, which is responsible for connecting the shoulder to the torso by the sternoclavicular joint (SC). The clavicle lies horizontal and parallel with the frontal plane. The clavicle and scapula, combined with the humerus of the upper arm, make up the glenohumeral joint (GH), or the shoulder joint. The humeral head is the part of the humerus that acts in the shoulder joint. The head lies at an angle of 35-40° to the posterior in relation to the axis of the humerus. This angle provides stability to the shoulder joint while still allowing the maximum amount of motion.

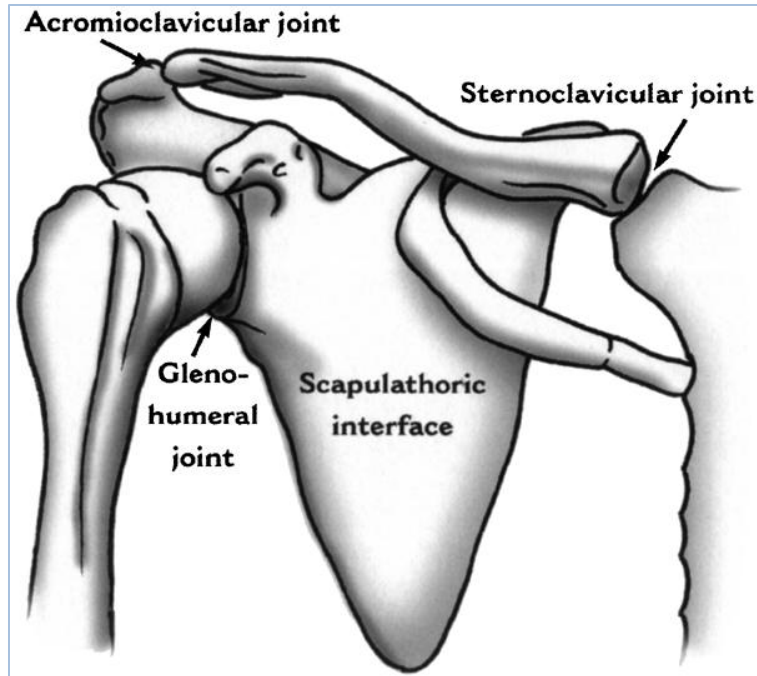


Figure 4—AC, GH, and SC joint locations (Samuelsson, Tropp, & Gerdle, 2004)

The shoulder joint is categorized as a movable joint, which implies that it is also a synovial joint. This means that between the two articulating bones, the humerus and scapula, exists a cavity that contains a synovial membrane and fluid for lubrication of the joint during movement. The shoulder joint is also referred to as a ball and socket joint due to its anatomical geometry (Figure 5).

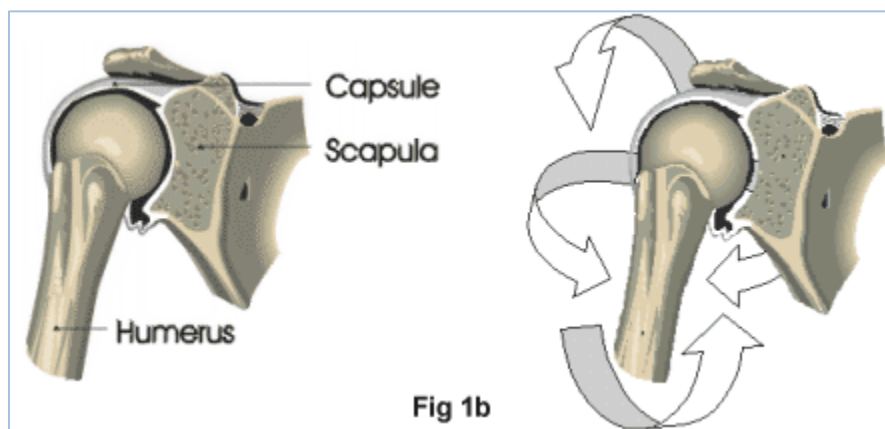


Figure 5—Shoulder ball and socket joint (The Orthopaedic Research Institute, 2012)

The shoulder is modeled as a ball and socket joint because it has three degrees of rotational freedom: pitch, yaw, and roll. These three degrees of freedom can be further explained as three groups of angular movements: flexion and extension (pitch), abduction and adduction (yaw), and internal and external rotation (roll). Flexion and extension describe rotations about the x-axis. Flexion happens when the arm moves forward and up away from the body while extension happens when the arm moves backward and up away from the body. Abduction and adduction describe rotation about the z-axis. Abduction occurs when the arm moves up and away from the midline of the body as opposed to adduction which occurs when the arm moves closer to the midline of the body. Internal and external rotation describes rotation about the y-axis. Internal rotation can be defined as turning the upper arm inward versus turning the upper arm outward for external rotation. These motions are the rotation around each of the three major axes and give mobility to perform *Activities of Daily Living* (Figure 6).

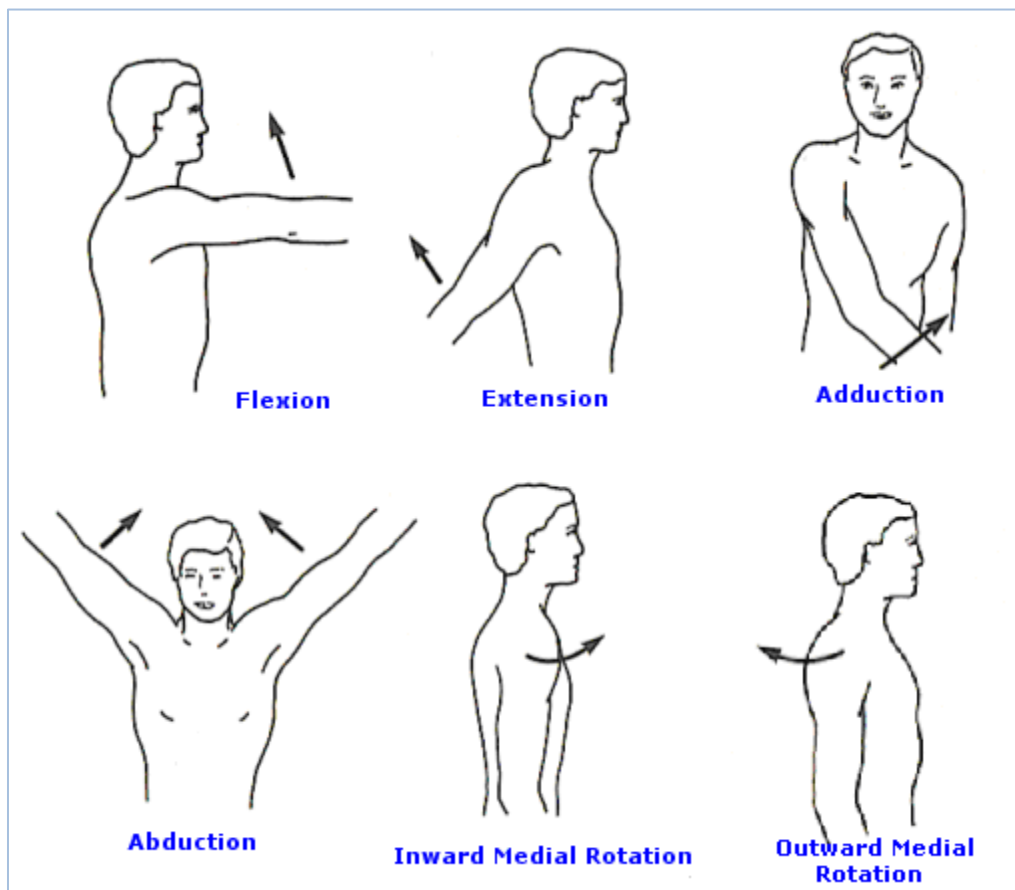


Figure 6—Angular movements of the shoulder (Mackenzie, 2012)

2.1.3 Shoulder Musculature

Though the bones and joints of the shoulder appear to be simple, the set of muscles that accompany them is complex. These muscles not only stabilize the joints and bones, but allow for a large range of motion. According to Gray's Anatomy, muscles are best categorized by origins. Table 1 shows the muscles of the shoulder in three categories: scapula, spinal column, and rib cage. It describes where each muscle's origin and insertion are as well as what actions it performs. Most of the muscles in Table 1 are illustrated in Figure 7.

Table 1— Shoulder and Humerus Muscles Separated by Origin Area (Gray, 1918)

	Muscle	Origin	Insertion	Action
Scapula	Deltoid	Anterior, posterior surfaces of lateral spine of scapula; anterior surface of lateral clavicle	Deltoid tuberosity of humerus	Anterior fibers draw arm forward, rotate medially; posterior fibers draw arm back, rotate laterally; lateral fibers abduct humerus
	Subscapularis	Intermediate anterior surface of scapula	Lesser tubercle of humerus	Stabilize the humeral head in the glenoid cavity
	Supraspinatus	Superior border of anterior edge of scapula	Greater tubercle of humerus	Stabilize the humeral head in the glenoid cavity
	Infraspinatus	Intermediate posterior surface of scapula	Greater tubercle of humerus	Stabilize the humeral head in the glenoid cavity
	Teres Minor	Intermediate inferior border of the scapula	Greater tubercle of humerus	Stabilize the humeral head in the glenoid cavity
	Teres Major	Inferior medial corner of the posterior surface of the scapula	Slightly inferior to the tubercles of the humerus on the posterior surface	Draws humerus back, rotates humerus medially
Spinal Column	Trapezius	Posterior surface of skull through twelfth vertebra	Posterior surface of the lateral third of the clavicle, acromion process	Stabilizes scapula; elevates, rotates forward, retracts scapula
	Latissimus Dorsi	Lower thoracic through lumbar vertebrae	Anterior surface of the superior humerus	Adduction, extension, medial rotation of humerus
	Rhomboids	Fifth cervical through fourth thoracic vertebrae	Medial border and medial spine of scapula	Retracts, depresses, elevates the scapula, depresses the point of the shoulder
	Levator Scapulae	First through fourth cervical vertebrae	Medial angle of the scapula	Retracts, depresses, elevates the scapula, depresses the point of the shoulder
Rib Cage	Pectoralis Minor	Anterior surface of second through fourth rib	Coracoid process of scapula	Protracts, depresses the point of the shoulder
	Serratus Anterior	First through seventh rib	Length of the medial border of the scapula	Rotates scapula forward, protracts

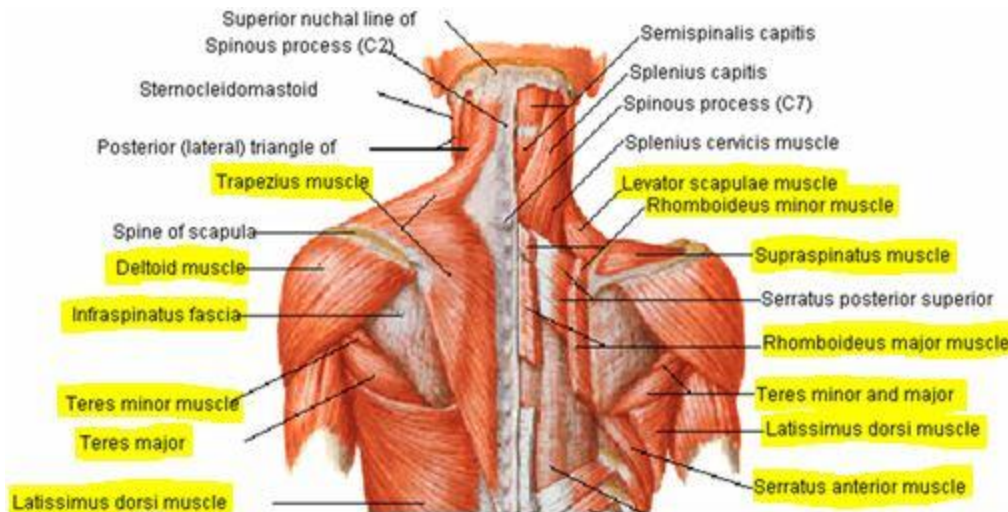


Figure 7—Muscles of the scapula, spinal column, and rib cage highlighted (Hambly, 2011)

The muscles that work together to move the shoulder girdle mostly function as stabilizers. These muscles stabilize the scapula to create a steady base for the muscles that give mobility to the humerus. Additionally, actions that broaden the range of motion even further are the scapular motions that often follow the humeral movements. By moving together in the same directions, the range of motion of the joint is increased.

2.1.4 Activities of Daily Living

The arm has a total of seven degrees of freedom: two in the wrist, two in the elbow, and three in the shoulder. The three degrees of freedom in the shoulder are those mentioned previously. This large range of motion brings about the question of kinetics and kinematics of the arm and shoulder throughout daily life. *Activities of Daily Living* (ADL) are tasks requiring little force for performance “related to personal care and include bathing or showering, dressing, getting in or out of bed or a chair, using the toilet, and eating” (Wiener, Hanley, Clark, & Van Nostrand, 1990). The *Katz Index of Independence in Activities of Daily Living* (Table 2) is a scale used to assess the level of self-sufficiency of an individual depending on how well they are able to perform general tasks. Though this scale is most commonly used to evaluate the elderly, it is possible to use it to assess anyone.

Table 2—Katz Index of Independence in *Activities of Daily Living* (Wallace & Shelkey, 2007)

ACTIVITIES Points (1 or 0)	INDEPENDENCE: (1 POINT)	DEPENDENCE: (0 POINTS)
	NO supervision, direction or personal assistance	WITH supervision, direction, personal assistance or total care
BATHING Points: _____	(1 POINT) Bathes self completely or needs help in bathing only a single part of the body such as the back, genital area or disabled extremity.	(0 POINTS) Needs help with bathing more than one part of the body, getting in or out of the tub or shower. Requires total bathing.
DRESSING Points: _____	(1 POINT) Gets clothes from closets and drawers and puts on clothes and outer garments complete with fasteners. May have help tying shoes.	(0 POINTS) Needs help with dressing self or needs to be completely dressed.
TOILETING Points: _____	(1 POINT) Goes to toilet, gets on and off, arranges clothes, cleans genital area without help.	(0 POINTS) Needs help transferring to toilet, cleaning self or uses bedpan or commode.
TRANSFERRING Points: _____	(1 POINT) Moves in and out of bed or chair unassisted. Mechanical transferring aides are acceptable.	(0 POINTS) Needs help in moving from bed to chair or requires a complete transfer.
CONTINENCE Points: _____	(1 POINT) Exercises complete self-control over urination and defecation	(0 POINTS) Is partially or totally incontinent of bowel or bladder.
FEEDING Points: _____	(1 POINT) Gets food from plate into mouth without help. Preparation of food may be done by another person.	(0 POINTS) Needs partial or total help with feeding or requires parenteral feeding.

In 2003, Murray and Johnson performed a study consisting of ten male unimpaired subjects executing ten *Activities of Daily Living* using their right arms (Murray & Johnson, 2004). These *Activities of Daily Living* can be found in Table 3. This table describes the task to be performed as well as the area of daily life under which each task falls. It also assigns numbers to be used later in the results.

Table 3— Upper Limb Activities (Murray & Johnson, 2004)

Activity	Area of use
1. Reach to opposite axilla	Hygiene
2. Reach to opposite side of neck	Hygiene
3. Reach to side and back of head	Hygiene
4. Eat with hand to mouth	Feeding
5. Eat with a spoon	Feeding
6. Drink from a mug	Feeding
7. Answer telephone	Everyday object
8. Brush left side of head	Hygiene
9. Raise block to shoulder height	Everyday object
10. Raise block to head height	Everyday object

With the results of this study, Murray and Johnson compiled a database of upper limb kinetics and kinematics which included data for the shoulder and elbow. This study used a different set of axis configurations than those previously mentioned. In this study, a right-handed coordinate system is used with the x-axis directed perpendicular to the page, the y-axis pointed forward, and the z-axis pointed upward (Figure 8). The resulting angles of shoulder rotation, abduction, and flexion were recorded and the minimum and maximum ranges of motion can be found in Table 4. The results showed that tasks requiring elevation to shoulder-height or higher necessitated the maximum movement from the individual.

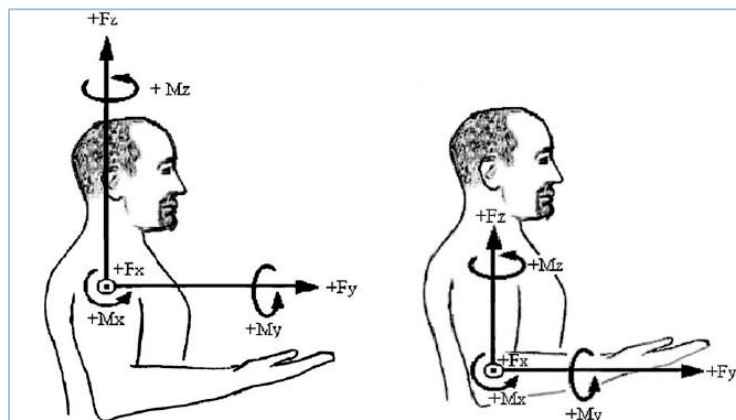


Figure 8— Definition of Shoulder and Elbow Axes (left and right respectively) (Murray & Johnson, 2004)

Table 4—Maximum Ranges of Motion at Elbow and Shoulder for ADLs (Murray & Johnson, 2004)

Angle	Min/Max	Task	Angle (°)	SD
Shoulder flexion	Max	10	111.9	7.4
	Min	10	14.7	7.6
Shoulder abduction	Max	10	39.7	6.9
	Min	2	-20.1	9.2
Shoulder internal rotation	Max	1	85.9	11.7
	Min	10	18.7	7.8
Elbow flexion	Max	3	164.8	8.0
	Min	10	15.6	6.6
Pronation	Max	3	65.3	8.2
	Min	2	-53.7	12.6

It is important to note that this study was completed solely with male test subjects, all of whom were healthy and unimpaired. So for this particular study, the resulting range of motion and direction of motion does not necessarily represent the population of people using prostheses and orthoses. Regardless of what changes may occur prosthetics and orthoses are designed to give the user as much normal functionality as possible. Therefore, by using the *Activities of Daily Living* as a scale for range of motion, the prototype will have a functional and efficient design.

2.2 Types of Orthoses

An upper limb orthosis is a form of exoskeleton that is attached to the upper limb or torso of the user. These devices are developed mainly to assist in rehabilitation therapy and to aid people with disabilities in performing *Activities of Daily Living*. When designing an orthosis, there are a number of topics to consider.

2.2.1 Anthropomorphic vs. Non-Anthropomorphic Architecture

Any orthosis, regardless of what portion of the body it relates to, generally falls into one of two categories: anthropomorphic or non-anthropomorphic. Anthropomorphic devices attempt to exactly match the kinematics of the human body—in this case, the upper limb (Zoss,

Kazerooni, & Chu, 2005). There are many benefits to an anthropomorphic device. Due to the device's links matching the limb lengths of the user, there is little worry that the device will collide with the user or the environment. This type of design also allows for an orthosis that fits tighter to the body, giving it a more discrete and aesthetically-pleasing appearance. However, there are also drawbacks to designing anthropomorphic orthoses, the most significant of which is kinematics. In order for an upper limb anthropomorphic orthosis to exactly match the kinematics of the user's upper limb, the link lengths and joint configurations must be identical to those of the user. If they are not identical, the device will cause large forces on the user due to kinematic differences. This problem increases the difficulty in designing a device that could be adjusted to fit multiple users. The joints in the human body are also very complex, which would increase the complexity of the design, thus reducing its reliability and robustness.

In contrast, the kinematics of non-anthropomorphic orthoses vary from those of the human user while still accomplishing the same basic range of motion (Zoss et al., 2005). Instead of staying close to the body like an exoskeleton, non-anthropomorphic orthoses attach to the user only at endpoints—such as the feet or hands—and contain extra degrees of freedom. The benefit of a non-anthropomorphic design is that the exact dimensions and joint configurations of the user are not critical to the design of the orthosis, which simplifies adaptability to multiple users. Unfortunately there are also significant disadvantages. It is difficult to design a non-anthropomorphic device that will not collide with the user or the environment and will not force the user into naturally unachievable motions. For the purpose of comparison, Figure 9 compares two generic exoskeleton designs, one anthropomorphic and one non-anthropomorphic.

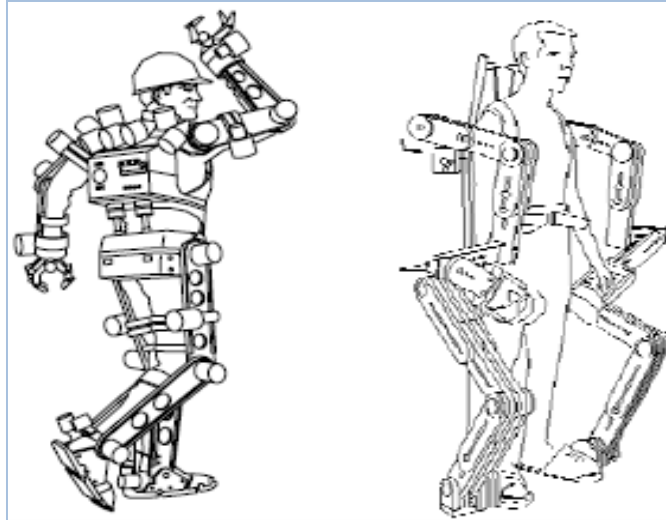


Figure 9—Anthropomorphic (left) versus Non-Anthropomorphic (right) designs (Zoss et al., 2005)

The most practical approach to designing an upper limb orthosis involves a design that is close to being anthropomorphic without exactly replicating the kinematics of the upper limb. This ensures minimal collisions with the user and environment, as well as a simpler and more robust design that is easier to size for multiple users.

2.2.2 Passive Orthoses

The simplest forms of passive upper limb orthoses are shoulder slings and braces. While many upper limb orthoses aid users in achieving certain ranges of motion; slings and braces work by restricting certain movements to allow an injury to heal. While simple slings (Figure 10) hold the upper limbs stationary in a single position, more advanced slings exist (The Brace Shop, 2012). This passive orthosis features several degrees of freedom, each of which can be independently locked in place to restrict the desired movement (Rosenblatt, 1997).

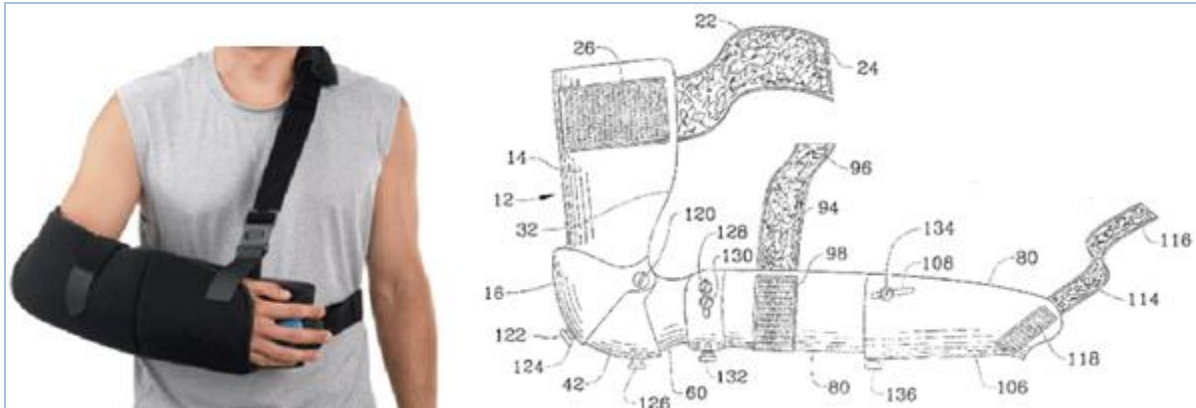


Figure 10—A simple sling (left) and a more complex design (right) (Rosenblatt, 1997)

While these slings are simple devices, it is possible to have a very complicated upper limb orthosis that is still passive. One example is the *Orthosis Device* patented by Tariq Rahman and Whitney Sample (Figure 11) (Rahman & Sample, 2004).

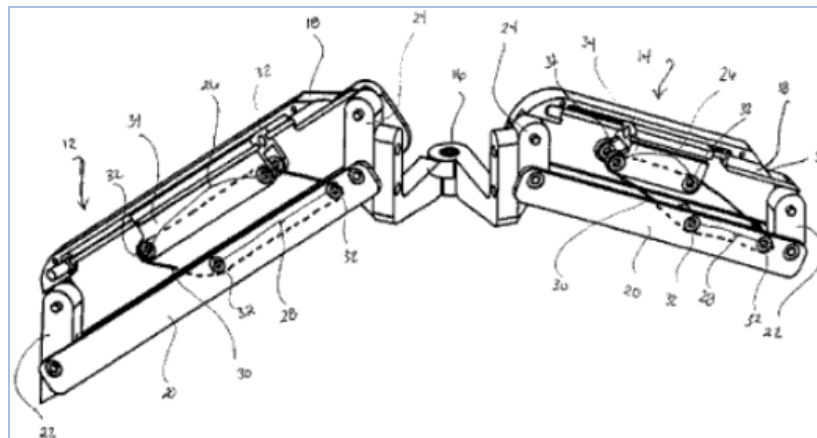


Figure 11—Orthosis Device, US 6,821,259 B2 (Rahman & Sample, 2004)

This passive orthosis, mounted on a wheelchair, features a system of four-bar linkages and springs that allows the orthosis to be in equilibrium at any orientation. In effect, the device balances out the force of gravity, much like that of an architect desk lamp. This frees the user from having to support the weight of his or her arms, which is vital for people who have little strength in their upper limbs.

2.2.3 Powered Orthoses

Many of the orthoses used for therapeutic and rehabilitation purposes are powered devices. Powered orthoses have an advantage over passive orthoses because they can guide users

through motions they normally could not achieve due to disability or injury. One such device (Figure 12) attaches to its user via a vest (Carignan, Liszka, & Roderick, 2005). It is worth noting that this device is a prototype and does not yet include motors to drive each joint.



Figure 12—Prototype of powered upper limb orthosis (Carignan et al., 2005)

Once powered with motors, this orthosis would greatly increase the functional capabilities of its user. A controller would enable the user to control the movement of the links, and thus the motion of his arm. To create this device, a complex linkage assembly was created that closely replicated the kinematics of the shoulder. In theory, this device could be worn by the user to aid in performing *Activities of Daily Living*.

2.2.4 Externally Mounted Orthoses

Most of the orthoses previously discussed have been devices that a user can wear via a vest or strapping system. However, the field of rehabilitation engineering is filled with orthoses that are mounted to external objects, such as wheelchairs, walls, or tables. A table-mounted powered orthosis with seven degrees of freedom is shown in Figure 13.



Figure 13—Table mounted orthosis (Tsagarakis & Caldwell, 2003)

This device must be mounted to a table, therefore its main purpose is training and rehabilitation of the upper limbs (Tsagarakis & Caldwell, 2003). Therapy is provided to the user through this particular device by repeatedly guiding the arm through a range of motions. The repetitive manipulation is one of the greatest benefits of this type of orthosis, as this exercise can traditionally be very labor intensive.

Figure 14 displays another externally mounted upper limb orthosis that serves a different purpose (Nagai et al., 1998). This device could potentially be mounted on the back of a wheelchair and would assist its user in performing *Activities of Daily Living*. Similar to the orthosis in Figure 12, this orthosis would be operated by the user via a control device which would enable movement of the disabled limb to improve functional independence.

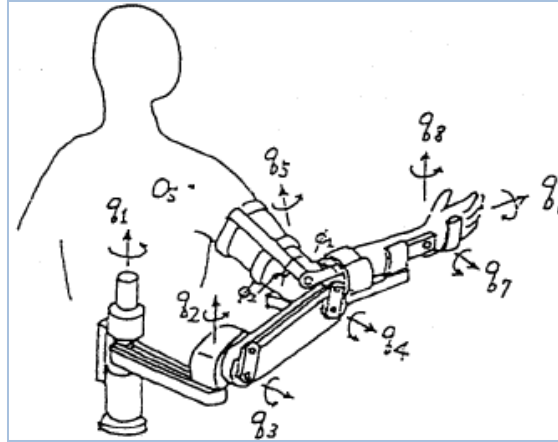


Figure 14—Wheelchair mounted orthosis (Nagai et al., 1998)

Since externally mounted power orthoses are non-anthropomorphic, they must contain extra degrees of freedom to accomplish the desired range of motion at their endpoints. Both of the previously mentioned mounted orthoses connect to the users distally through the forearm.

2.3 Limits of Existing Technology

There are many different types of upper limb orthoses, each with a specific function and target audience. However there are still a number of major problems within the area of wearable, powered upper limb orthoses for the aid of *Activities of Daily Living*. While much has been accomplished in terms of wall and table mounted powered orthoses, these devices are not helpful in a non-therapeutic setting because the user is attached to the machine and must remain stationary. Wheelchair mounted devices are better for increasing functional independence, but the device can only be used by people who also use wheelchairs. These designs also do not grant the user much torso movement because of the fixed placement of the shoulder.

The ideal device to enable people with disabilities to gain more functional independence in performing *Activities of Daily Living* is a wearable, powered, upper limb orthosis. A group of Worcester Polytechnic Institute (WPI) students designed a powered orthosis with two degrees of freedom which is disclosed in US patent 8246559 B2, but it still lacks an adequate shoulder mount (Hoffman, Scarsella, Toddes, & Abramovich, 2012) (Figure 15).

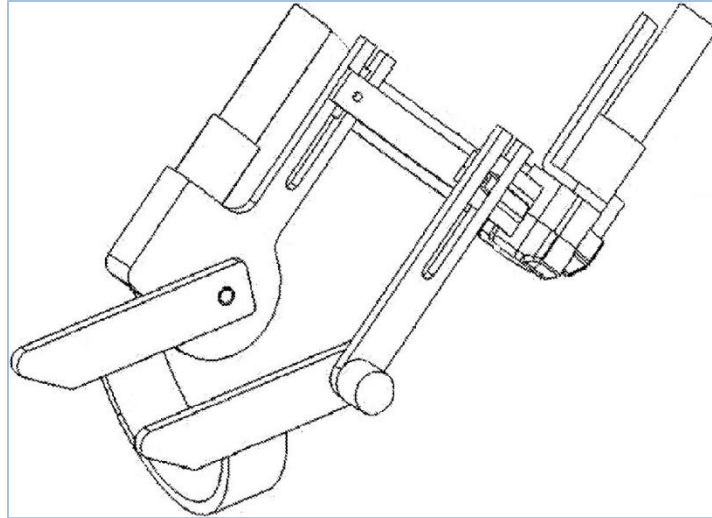


Figure 15— Existing upper limb orthosis (Hoffman et al., 2012)

Previous groups of WPI students have failed to create shoulder mounts that are comfortable, adjustable, and functional. Several of these attempts contained very complicated components that took extensive effort and time to manufacture, especially the 2007 effort (Corliss, Giebenhain, & Gilley, 2007). A major piece of this assembly (Figure 16) had to be redesigned multiple times to enable manufacturability. As a result, parts were not completed on time and the group was not able to perform adequate testing. A design that would utilize rapid prototyping could potentially avoid these setbacks.

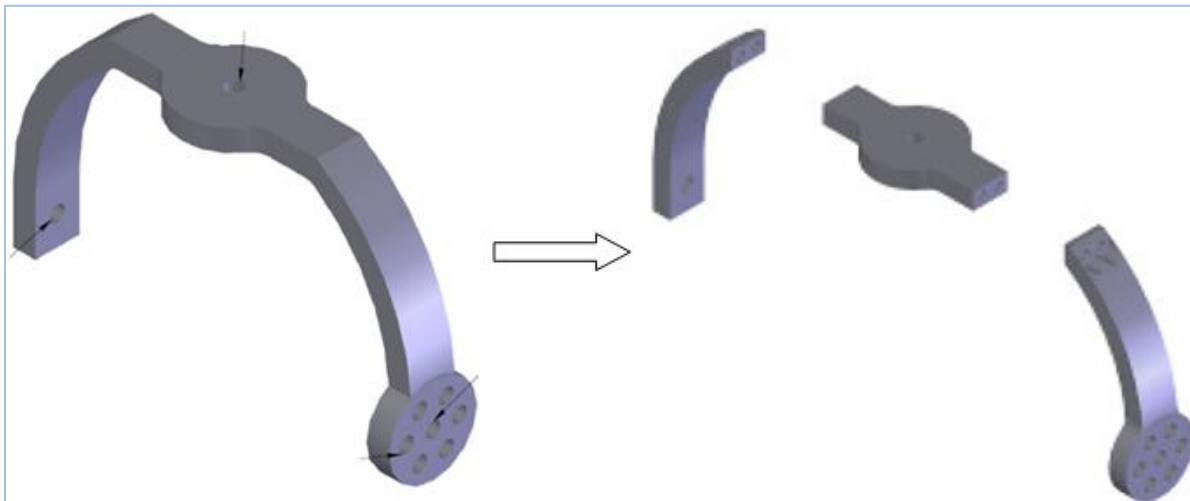


Figure 16—Redesign of part (Corliss et al., 2007)

A well-designed shoulder mount for a wearable, powered, upper limb orthosis is necessary. To avoid the drawbacks of similar devices, a shoulder mount orthosis must be easy to adjust and accommodate multiple users within a range of body sizes. In order to remain robust, this design must be as simple as possible while still accomplishing the range of motions necessary for *Activities of Daily Living*.

2.4 Prospective Users

All potential users of the proposed prototype would be individuals with conditions necessitating the need of a powered or passive arm orthosis. Currently there are numerous medical conditions, diseases, and injuries that cause patients to need an upper extremity orthosis. Some of those conditions include individuals with or suffering from stroke, traumatic brain injury, multiple sclerosis, cerebral palsy, and spinal cord injury (Lansang, 2011).

2.4.1 Stroke

A stroke is an injury that occurs in the brain and is typically caused by the clotting of blood vessels that supply blood to the brain. Strokes can also be caused when a blood vessel bursts inside the brain and leaks a large amount of blood. A stroke can result in significant disability in the victim and routinely causes death. The most common kind of stroke in the United States is an Ischemic stroke, where clots restrict blood flow to the brain. Ischemic strokes currently account for 87% of all strokes that occur. Strokes are the current leading cause of serious long term disabilities, with 795,000 strokes occurring in the United States each year (Centers for Disease Control and Prevention, 2012b).

2.4.2 Traumatic Brain Injury

A Traumatic Brain Injury (TBI) occurs when the brain experiences sudden trauma as a result of violently striking an object, or when an object pierces the skull and enters the brain (National Institute of Neurological Disorders and Stroke, 2013). Currently in the US, 1.7 million people suffer a TBI each year. TBI can be divided into both severe and mild categories with over 75% of all TBIs considered mild and usually the result of concussions. For the needs of this report potential users of the prototype would be persons with severe TBI, which can cause disruption of motor function. Of potential users who suffered a severe TBI there are currently 5.3

million Americans living with a TBI related disability (Centers for Disease Control and Prevention, 2012c).

2.4.3 Multiple Sclerosis

Multiple sclerosis (MS) is an autoimmune disease that primarily focuses on the brain and the spinal cord (Zieve, 2011). This disease works by attacking and destroying the myelin sheath, a protective coating, surrounding neurons in the central nervous system. The disease usually cycles by fluctuating through phases of remissions and exacerbations, but ultimately MS can result in permanent disability (Centers for Disease Control and Prevention, 2011). The precise cause of MS is unknown, but many hypothesize that MS is caused by a combination of genetic susceptibility and triggered by environmental factors. Currently it is estimated that there are 400,000 cases of MS in the US, with the majority of MS cases affecting women (Luzzio, 2013).

2.4.4 Cerebral Palsy

Cerebral Palsy (CP) is a name given to a group of neurological disorders that all involve the brain and central nervous system and appear in the early childhood and infancy stages (Hoch, Kaneshiro, & Zieve, 2009). CP is one of the major causes of childhood disability and is caused by disturbances and damage in the developing fetal and infant brain, specifically in parts that control muscles movements and coordination (Thorogood, 2011). CP does not worsen as a person ages, though the symptoms can change over time. It has been estimated that anywhere from 1.5 to 4 children per every 1,000 births develop CP (Centers for Disease Control and Prevention, 2012a).

2.4.5 Spinal Cord Injury

A spinal cord injury can vary in severity, permanency, and cause but generally results in changes in motor, automatic and sensory function of an individual. Most spinal cord injuries can be categorized into either tetraplegia, injuries that cause loss of muscle strength in the extremities, or paraplegia, injuries in the thoracic, sacral and lumbar segments. These kinds of injuries can occur from direct trauma to the spinal cord, such as compression from bone fragments or disks, or arise from damage to the spinal arteries. Regardless, spinal cord injuries are typically not common and are most often caused by motor vehicle accidents (44.5%), falls (18.1%), violence (16.6%), and sports related injuries (12.7%). It is estimated that the total occurrence of spinal cord injuries in the US is 183,000-230,000 cases, and that 10,000 new cases

are added per year (Chin, 2012). A summary of all the conditions presented in this section is included in Table 5.

Table 5—Conditions of Prospective Users (Centers for Disease Control and Prevention, 2012b; Chin, 2012; Luzzio, 2013)

Condition	Prevalence
Stroke	795,000 per year
Severe Traumatic Brain Injury	425,000 per year
Multiple Sclerosis	400,000 cases estimated
Cerebral Palsy	1.5-4 children per 1,000 births
Spinal Cord Injury	10,000 per year

2.5 Analogous Technology

When designing any mechanical device, it is important to expand one’s area of research to include devices in other technological fields. In this case, the following devices do not relate directly to human orthoses, but they perform similar functions. Therefore, it is worthwhile to analyze their designs to identify concepts that could be used to design a better orthosis shoulder mount.

2.5.1 Space Suits

Space suits are designed to protect astronauts from the harsh environment of outer space, while still allowing them the freedom of movement required to perform their jobs. Many space suits, including the I-Suit designed by ILC Dover (Figure 17) are referred to as “soft suits.” (Ayrey, 2007). Soft suits are constructed mainly of layers of fabric which incorporate bearings at the shoulder, upper arm, upper hip, and upper leg. This combination of fabric and bearings grants the user ease of movement while still retaining the suit’s shape and functionality when pressurized. Like this space suit, an upper-limb orthosis must be carefully designed so it does not overly restrict its user’s range of motion or require excessive effort to operate.



Figure 17—I-Suit series spacesuit (Ayrey, 2007)

2.5.2 Backpacks

A backpack is designed to allow its user to carry heavy loads for long periods of time. It accomplishes this by using straps and buckles to distributing the weight over the shoulders and hips instead of the arms. Due to the nature of their occupation, military personnel make extensive use of heavy-duty backpacks, a typical example of which is shown in Figure 18 (Blackhawk, 2012).



Figure 18—Blackhawk Phoenix Patrol Pack (Blackhawk, 2012)

This particular backpack is constructed of heavy-duty denier nylon and features reinforced shoulder straps, a detachable sternum strap, and a hip strap, all of which are easily adjustable to fit a variety of users and loading sceneries. This strapping system distributes the load over the user's shoulders and hips, while providing stability and comfort. The backpack also features a back ventilation panel to provide further comfort. Creating a rugged yet comfortable strapping system similar to the ones found in military backpacks is a vital component to this design project.

2.5.3 Military Exoskeletons

The Berkeley Lower Extremity Exoskeleton (BLEEX) is an energetically autonomous lower extremity exoskeleton developed at the University of California, Berkeley for the purpose of carrying heavy payloads over long distances with poor terrain. The BLEEX (Figure 19) was sponsored by the Defense Advanced Research Projects Agency (DARPA) and is the first field-operational robotic system of its kind (Zoss et al., 2005).



Figure 19—BLEEX exoskeleton (Zoss et al., 2005)

The BLEEX consists of two powered leg mechanisms, a power supply, and a backpack-frame on which the power supply and load are mounted. The BLEEX shadows its user by sensing forces exerted upon the device and then estimating how to move so that the user feels

very little force. While operating in this manner eliminates the problems associated with measuring interaction forces or muscle activity, it requires an extremely high level of sensitivity.

What is interesting is that BLEEX is connected to its user only at the hips and feet. This configuration allows for a simpler design, as the device will not be required to perfectly mimic the kinematics of a human leg. It is desirable to design a shoulder mounted orthosis in the same way, to ensure that the device is simple, reliable, and able to be easily adjusted for multiple users.

2.6 Rapid Prototyping

Rapid prototyping (RP) is the latest improvement for realizing design concepts into physical reality for initial testing and troubleshooting. The prototyping process previously involved the work of expert modelers and craftsmen, which typically involved significant labor hours and customized machine tooling to realize a single prototype. With the development of the first commercial rapid prototyping machines in 1988, this process became simpler and decreased build time considerably, helping to decrease development periods while also significantly reducing costs of prototyping.

Rapid prototyping, also known as solid free form fabrication or 3D printing among many other names, is a method for taking 3D CAD models from the computer and then quickly constructing physical models. The exact process for which the 3D model is realized varies tremendously, resulting in more than 30 types of RP techniques being commercialized since 1988. The resulting process variation allows for significant differences in the quality of final parts, which can be used for different applications.

There are many advantages rapid prototyping technology that have greatly improved the prototype creation and design process, which have contributed to RP becoming a widely accepted process at many companies and institutions. The primary advantage found with RP is that the time required to create a new prototype is shortened from days down to a matter of hours. RP also allows designers to create increasingly complex designs with little effect on build time and cost, or to even design parts that would normally be difficult or impossible to manufacture with traditional methods. Additionally, the materials used to create RP parts closely match the qualities that the final parts and products can possess, while greatly reducing the overall waste and cost of the design process.

Most rapid prototyping techniques can be classified by either the construction method, or the build material type. The main categories of RP methods are: photocuring, cutting and gluing or joining, melting and solidifying or fusing, and joining or binding. Additionally, the different types of materials that can be used for RP include: solid, liquid, and powdered materials. The solid materials can be divided up further into the forms of pellets, wire, or laminates (Chua, Leong, & Lim, 2010).

This paper will primarily focus on the RP methods that are currently available at Worcester Polytechnic Institute. Currently, Worcester Polytechnic Institute owns and operates a Dimension 1200es Series 3D printer, from Dimension Printing, as well as an Objet 260 Connex. Each RP machine outputs parts at different levels of detail, allowing students and faculty to choose the machine that best fits their rapid prototype needs.

For the Dimension 1200es parts are constructed out of ABS plastic using Stratasys' Fused Deposition Modeling (FDM) method in a 10" by 10" by 12" workspace. It was determined by a previous MQP that, for each layer, parts constructed in WPI's current 3D printer cost \$8 per cubic inch (Pydynkowski, Munchbach, & McGinley, 2010). The Dimension 1200es can create layers with thicknesses that vary between 0.178 and 0.356 mm (.007-.014 in). Dimension series machines are designed to produce parts primarily for concept modeling, creating product mock ups and parts with some functional testing capabilities.

In FDM printing material comes in the form of a plastic filament, which looks very similar to fishing line. The filament is fed into an extrusion head where the ABS plastic is heated into a semi-liquid state, which is then extruded in fine layers to create each part. As the semi-liquid filament is extruded, the lower temperature of the surrounding air quickly solidifies the plastic into a solid layer. To create parts with complex geometries that involve spaces and larger cross-sectional areas located above smaller cross-sectional areas, two materials are used. The ABS filament is the primary material used to create the part, and a secondary support structure material fills in the negative space. Once the full part has been printed the part is put in a solvent that dissolves away the support structure to leave behind the final completed part. Figure 20 shows a schematic of the extruding head (Chua et al., 2010).

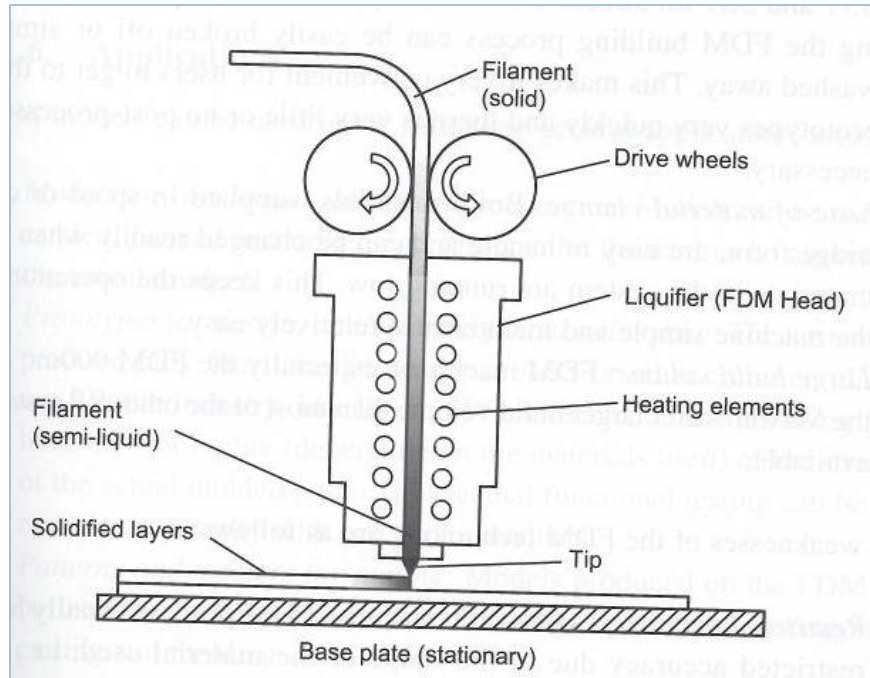


Figure 20—Schematic of the extruder used in FDM (Chua et al., 2010)

There are several advantages to using the FDM method and few disadvantages, which makes this FDM an appealing option among the various commercial RP methods. FDM allows the user to construct prototype parts with materials similar to those used in the final product, allowing the part to have up to 85% of the strength of a final part. Due to the extrusion method used, little raw material is wasted in the creation of each prototype, and the unwanted support material is easily removable. Finally, FDM allows for the RP machine to have a large build volume to allow designers to create larger parts.

The main disadvantage of the FDM method is that parts created with FDM can have greatly reduced dimensional accuracy due to the use of a filament for extruding material. This accuracy reduction appears in parts and features smaller than the width of the extruding filament. On top of this, the FDM method has a relatively slow build process when compared to other commercially available RP methods. In instances where available printing hours are scarce and large product quantities are needed, DFM would not be the best choice. Lastly, due to the rapid heating and cooling of the ABS filament during extrusion, a small amount of unpredictable shrinkage is introduced into printed prototypes. This would be greatly undesirable if parts with tight tolerances were required. If rough fits and tolerances were acceptable, this amount of shrinkage would be negligible (Chua, Leong et al. 2010, Pydynkowski, Munchbach et al. 2010).

For the Objet 260 Connex, parts are constructed out of up to 60 different material options and can include up to 14 separate materials simultaneously in one part. This machine operates through the use of Objet's Polyjet technology in a 10.2" by 10.2" by 7.9" workspace. It was determined by the rapid prototyping MQP that parts printed from this machine cost roughly 4 times that of the Dimension machine, or \$32 per cubic inch (Pydynkowski et al., 2010). The layers on this machine are printed at a thickness of 16 μm (0.00062in).

Objet was founded in 1998 and focuses on creating RP machines for high-resolution printing by using its patented Polyjet inkjet-head technology. In this process the jet head releases both the model material, a resin, and the support material simultaneously. The material is then immediately cured by UV light emitted by the jet head, effectively causing the printing and curing processes to occur simultaneously. This is accomplished through the process of photopolymerization, where the liquid polymers of the printed liquid resin are solidified due to the exposure to electromagnetic radiation, in this case UV light. In this method support material is removed from the part through the use of a water jet (Chua et al., 2010).

With Polyjet inkjet-head printing, the advantages outweigh the disadvantages, making it a very desirable method for printing detailed prototypes. The 16 μm resolution that the Objet operates at is ideal for very high detailed parts that require tight tolerances and a high level of dimensional accuracy. The precise jetting allows for wall thickness of up to 600 μm or less on produced parts. Additionally, Polyjet technology requires minimal post-processing of parts, typically only requiring the washing away of support material upon completion. The user-friendliness of the Objet 260 Connex machine is attributable to the easy replacement of material cartridges, and that the jet nozzles that can be replaced without requiring the whole unit to be replaced. The wide range of materials available in one part and total number of materials available for prototypes is also a primary benefit of the Objet 260 Connex.

The main disadvantages associated with Polyjet technology are primarily involved with the post-processing of parts. Due to the need for a water jet to remove support material from parts, the machine needs to be located close to a regular water supply. The use of a water jet for cleaning can also introduce accidental damage to the parts that are being cleaned, if proper care is not taken with the fine details.

2.7 Kinematics

Kinematics is the study of motion without regard to forces, as opposed to kinetics, which is the study of forces on systems in motion (R. L. Norton, 2012). When designing a mechanism, it is common to first consider the desired kinematic motions and then investigate the kinetic forces associated with these motions. Kinematic configurations can be synthesized graphically, as well as analytically using kinematic equations.

As previously stated, the kinematics of the human shoulder are highly complex, making it difficult to design a device capable of replicating its movements. Adding to this difficulty is the concept of singularity points, which are points within a mechanism's range of motion where the configuration of the device is such that a degree of freedom is lost. For example, the upper-limb powered exoskeleton designed at the University of Washington has three points of singularity in its user's workspace (Figure 21) (Perry, Rosen, & Burns, 2007).

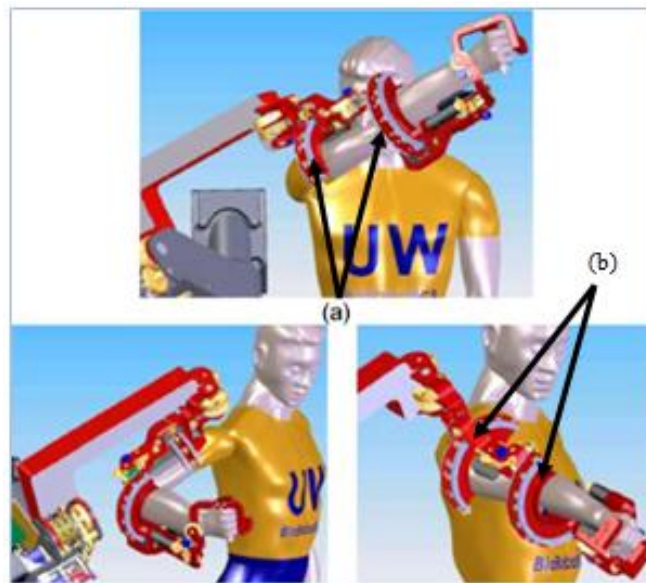


Figure 21—Three singularity points in an exoskeleton (Perry et al., 2007)

In this case, degrees of freedom are lost with the alignment of two rotational axes. In the top image, the joint at the base of the link which connects the device to the mount and the joint that controls the shoulder rotation become aligned (a). Now, the rotation of either of these joints will result in the same motion, in effect eliminating a degree of freedom. The same is true for the configuration shown at the lower left. The lower right image displays a singularity point that

occurs during full elbow extension, when the joints at each end of the humerus link align (b).

This exoskeleton was carefully designed so that the singularity points occur in unreachable or near-unreachable locations so they do not interfere with the operation of the device. Likewise, the shoulder mount will need to be carefully designed to avoid singularity points within the operational range of motion.

3. Goal Statement

The goal of this Major Qualifying Project is to design, analyze, manufacture, and test a shoulder mount to be used in conjunction with a wearable, powered, upper-limb orthosis. The device must enable adequate mobility and functionality for the user to perform *Activities of Daily Living*. As this device is intended to aid persons with permanent and long-term disabilities by improving their functional independence, it should be discrete, comfortable, and user-friendly. Special emphasis is placed on designs that utilize rapid prototyping to ensure the shoulder mount will be easily modified to fit multiple users within a range of body types.

4. Design Specifications

To ensure a complete design, key performance specifications were broken down into distinct, measurable quantities. These specifications were then organized into six categories: performance, safety, user friendliness, reliability, cost, and production. A successful design should fulfill all of these design specifications.

4.1 Performance

- Device must interface with existing powered orthosis with patent number US 8246559 (Hoffman, Scarsella, Toddes, & Abramovich, 2012).
- Convenience to the user
 - Device should ideally weigh less than 5 lbs, but must be no heavier than 8 lbs.
 - Device must not interfere with user's anatomical position at rest.
- Stability
 - Device must remain functional on user's body through full range of motion required to perform *Activities of Daily Living* as described in Table 4 in the Background.
- Range of Motion
 - Device allows sufficient range of motion (flexion and abduction) for completion of *Activities of Daily Living* as described in Table 4 in the Background.
 - Device should allow for full shoulder flexion and abduction as described in Table 4 in the Background.
 - Device must not contain kinematic singularities in its range of motion.
- Loading
 - Device should distribute weight of orthosis over the torso.
 - Device must withstand 10 pounds of force applied axially along the upper arm.

4.2 Safety

- Device must not present a danger to the user.
 - Device must not puncture skin or pinch the user during normal operation.
 - Device must not cause tearing and entanglement of the clothing.

4.3 User Friendliness

Device must accommodate a wide range of potential users.

- Adjustability
 - Device must be easily replicated for both males and females in the 25th-75th percentiles for height (Appendix A).
- Ease of donning and doffing
 - Device can be applied and removed in 2 minutes or less with assistance.
 - Existing arm orthosis must be attached to device after donning.
- Skin Irritation
 - Device components must not cause irritation due to material roughness, allergic reactions, or skin rashes.
 - Device must not cause moisture buildup.
- Aesthetics
 - Device should not increase the dimensions of the user's body frame by more than 127 mm in any direction.

4.4 Reliability

Device must have a competitive lifetime.

- The device must have a lifetime of 5-8 years of normal use.
- The device must be made of durable materials to withstand use in *Activities of Daily Living*.
- Device must be waterproof.
- Device materials must not react to the sweating of the user.

4.5 Maintenance

- Parts to maintain the device must cost less than \$100 per year.
- Maintenance should be accomplishable by a trained technician, such as a prosthetist.
- Parts must be easily accessible and detachable to allow for convenient maintenance.

4.6 Cost

Device must have competitive cost.

- Prototype must cost less than \$450 to create.
- A production model of the device must be potentially manufactured for under \$450.

4.7 Production

- Device must use standard parts and fasteners where possible to aid with maintenance and manufacturability.
- Device should utilize rapid prototyping where appropriate in the design.

5. Preliminary Designs

Several preliminary designs were created, with each theoretically capable of satisfying the design specifications. A decision matrix was utilized to identify which of these preliminary designs most successfully accomplished the design specifications. The shoulder mount was split into two subsystems, the torso mount and the mechanism components.

5.1 Torso Mount Subsystem

The torso mount acts as the interface between the user and the shoulder mount itself. It must be comfortable to wear, as it will be worn for long periods of time. The torso mount system should also keep the shoulder mount firmly secured to the user at all times during operation.

5.1.1 Design 1: Shoulder Pad

A shoulder pad is one potential method of securing the shoulder mount to the torso (Figure 22). Similar to football shoulder pads, this mount would rest on the top of the shoulder. A system of Nylon straps would ensure that the mount remained snug and stationary on the user's shoulder during operation. The mechanism component would either be mounted to the top of the torso mount, or perhaps on the front or the back. The mount would be designed with slots to accept the strapping system and connections to accept the mechanism component.

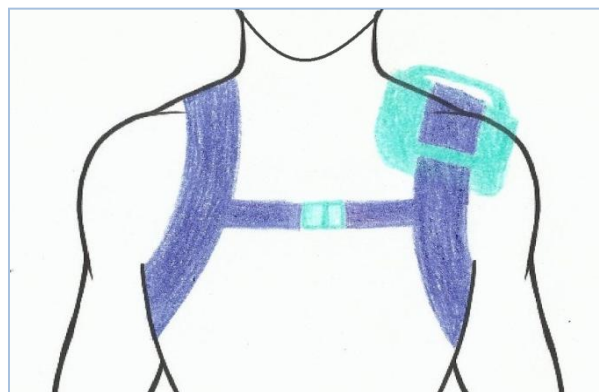


Figure 22—Shoulder pad preliminary design

5.1.2 Design 2: Vest

A vest is a piece of clothing that covers the torso and clasps together at the front of the user (Figure 23). It is generally sleeveless and normally waist-length but the general design could be varied to fit the desired function.



Figure 23—Vest preliminary design

Using a vest would allow the design to fully distribute the applied loads over the entire torso. In addition, this form of attachment would be useful in the discreteness and adjustability of the device. Since the vest would be made from a pattern, several sizes could be created and each size would still be slightly adjustable due to the material and structure. It could be closed using ties or straps to add another form of adjustability. This vest would be custom made to properly fit whichever shoulder mount design was chosen.

5.1.3 Design 3: Strapped Harness

Another system that can be used to harness the various mechanism devices to the user is a strapping system. In a strapping system, a series or network of straps, that may be interwoven or attached together, anchors points of the device to specific points on the body. An example of one strapping system involving a belt and a shoulder strap is shown in the Figure 24. A strapping system helps to distribute the weight somewhat evenly across a user's torso. This fact allows for minimal contact between the user and the straps allowing increased flexibility, comfort, and versatility. The versatility arises because the number of straps in any design could be varied, as

well as the areas of the body and the device that the straps can connect to. These locations can be chosen to best suit each design concept and then optimized for user comfort and aesthetics.

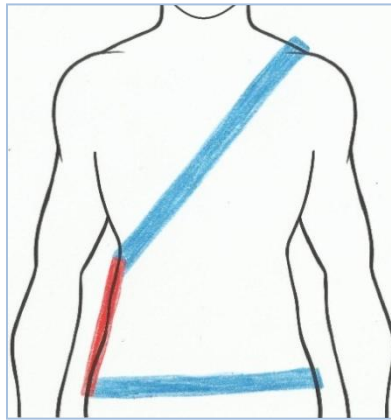


Figure 24—Strapped Harness example preliminary design

5.2 Mechanism Subsystem

The mechanism subsystem is the component of the shoulder mount that provides the necessary range of motion for the upper limb, and connects to the existing powered arm orthosis.

5.2.1 Design 1: Cable Vest Mechanism

Multiple ideas were created to solve the problem of designing a wearable, adjustable, functional shoulder mount. One of these ideas uses cables as the mechanisms for allowing mobility and functionality of the shoulder. This concept avoids mimicking the linkages created by the shoulder joint itself, as the shoulder is a very complex joint to copy. Instead, the cables will be flexible enough to move with the shoulder but sturdy enough to assist in load distribution of the connected arm orthosis.

The cables, shown in blue, would be threaded through a vest-like piece of clothing, shown in green (Figure 25). The vest would be produced in multiple sizes to accommodate various users. The cables will be connected from the arm orthosis to the rigid plates, shown in dull yellow on the shoulder blades, in the vest located on the back of the user. These plates, along with the vest, will help to distribute the forces and loads from the powered arm orthosis. In addition, these plates could be produced in different sizes to match the different sized vests.

The vest would consist of one piece with an opening in the front. The pattern could be closed using different methods: a zipper, several snaps, or even straps that tie or buckle. The

straps would allow an extra option for a closer fit, as the user could adjust the length of the straps or tie them to ensure a comfortable and secure fit.

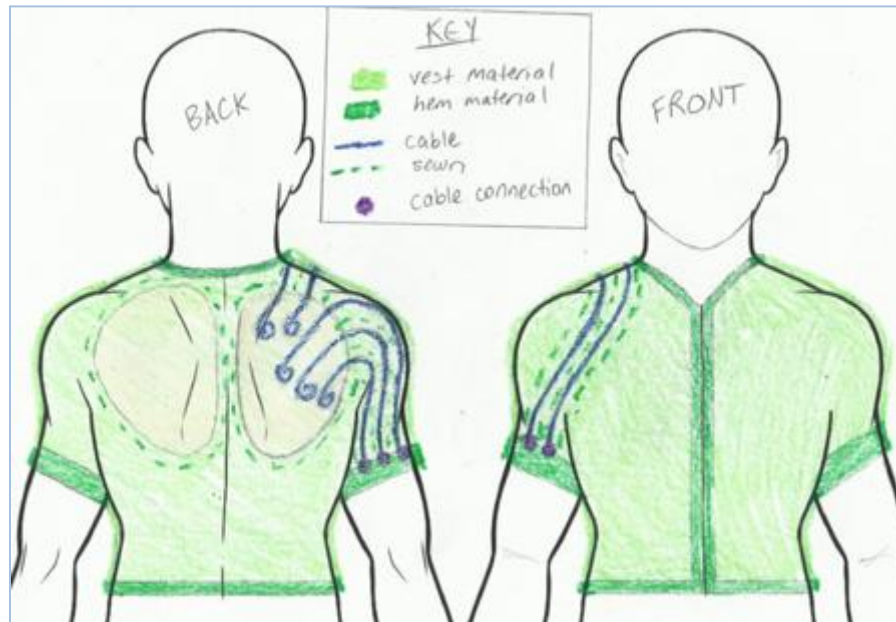


Figure 25—Cable vest preliminary design

This design would require short sleeves near the attachment of the orthosis so that the cables would be hidden and have a path to follow. A waist-length vest would be unnecessary as the components of the device would only be located near the shoulder and chest areas. This means the vest could stop below the ribcage area and use less material which might even add to comfort and mobility.

The functionality in this design is provided by the mobility of the vest, as well as the strength of the cables. The cables allow for the shoulder to move in any direction within the natural range of motion. The cables would be wound up on a reel and located on the top portion of the back plates. They would be spring loaded such that they will move with the motion of the user's shoulder. Theoretically, they could also be wound up and let out by a small motor. The three cables connecting to the back of the arm would allow for abduction and adduction, while the two cables running to the front of the arm would allow for flexion and extension.

The last portion of the design is the connection between the shoulder mount and the orthosis. A number of attachments can be used from strapping to screws. It would be necessary that the cables attach to the arm orthosis and the arm for optimal movement and functionality.

5.2.2 Design 2: Side Plate Mechanism

Another concept created for the mechanism device concentrated on locating the mechanism subsystem under and behind the shoulder, in contrast to navigating around the outer side of the shoulder. By taking this route, the mechanism could potentially be smaller because of the shorter distances that need to be covered.

In this design, the majority of the weight being distributed by the shoulder mount is transferred to the torso through a plate that is located on the user's side. By having a wide plate located on the user's torso below the shoulder mechanism, a significant amount of force will be transferred from a vertical direction into a horizontal direction, due to the effects of moments. The plate is labeled with the letter A (Figure 27).

The plate could be held flush to the user's side through the use of a belt and shoulder strap setup, which will attach to certain anchor points. Alternatively a full vest could be used as the support system, which the plate would be woven into. Examples of the various strapping methods are a vest, on the left, and strapping, on the right (Figure 26). The side plate is depicted in red.

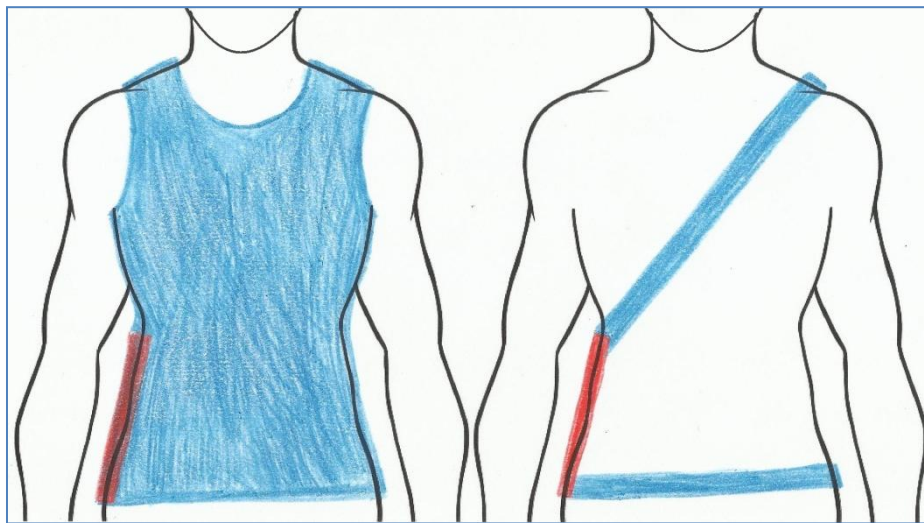


Figure 26—Side plate preliminary design with vest mount (left) or strap mount (right)

The mechanism subsystem itself is made up of four pieces that attach to the side plate (Figure 27). The vertical rod B is connected directly to the plate; the rod extends up from the side plate and locates the horizontal bar C at shoulder height. The rod connects to the horizontal bar C

with a pin joint. This joint allows for rotation around the vertical axis, giving the mechanism one degree of freedom.

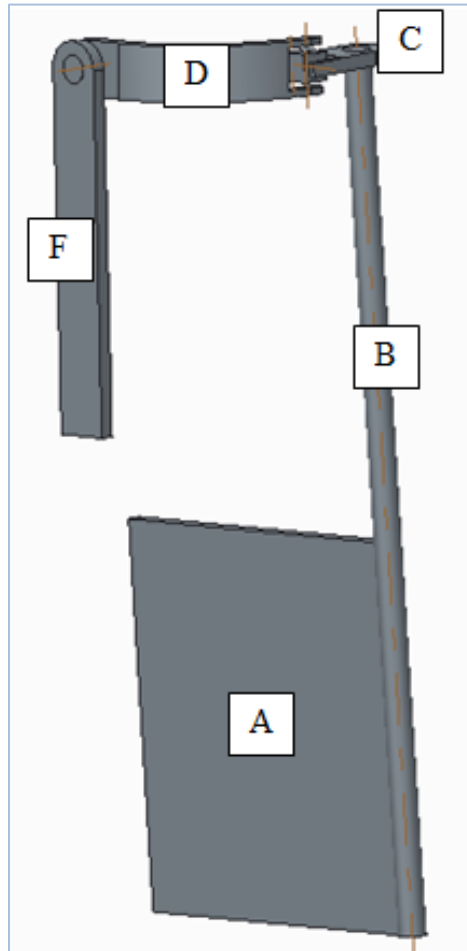


Figure 27—Side plate preliminary design

Horizontal bar C extends from rod B and terminates at a universal joint that connects with curved piece D. This universal joint is made up of pins extending from horizontal bar C and curved piece D into square E (Figure 28). The combination of pins in this joint adds two additional axes of rotation. One of these axes provides a primary degree of freedom to the device while the other adds additional rotation to aid in user comfort.

Orthosis connector arm F is connected to curved piece D through a pin joint. Arm piece F extends down the user's forearm and meets the powered arm orthosis. This pin adds the third and final degree of freedom needed to replicate the kinematics of the shoulder joint. Additionally, connector arm F is attached at its terminus to the powered arm orthosis by a connecting

subsystem. This subsystem could utilize various standard fasteners such as screws and bolts to other methods such as Velcro and ratchet straps.

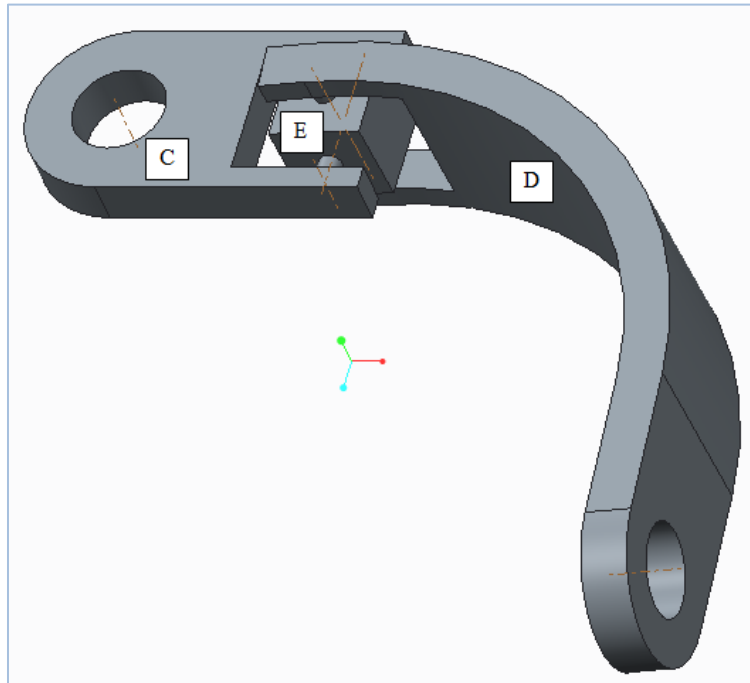


Figure 28—Side plate universal joint

5.2.3 Design 3: Rear Scapula Mechanism I

This rear scapula design is composed of four pieces (Figure 29 & Figure 30). Plate A is connected to the shoulder via the torso mount subsystem. Part A and Part B form a pin joint which allows for rotation about the y-axis, and the connection between Part B and Part C allows for rotation about the z-axis. A pin joint between Part C and Part D allows for rotation about the x-axis, and the existing orthosis is attached to Part D via standard fasteners.

This design has three degrees of freedom, which grant the user the ability for flexion/extension, abduction/adduction, as well as rotation around the axis perpendicular to the transverse plane. While currently presented as simple bars, the geometry of Part B, Part C, and Part D can be modified to ensure the joints are located in the correct positions to allow for smooth movement. Each of these links will be adjustable lengthwise to add to the adjustability for multiple users, as well as to simplify the process of aligning the centers of rotation of the mechanism with those of the shoulder.

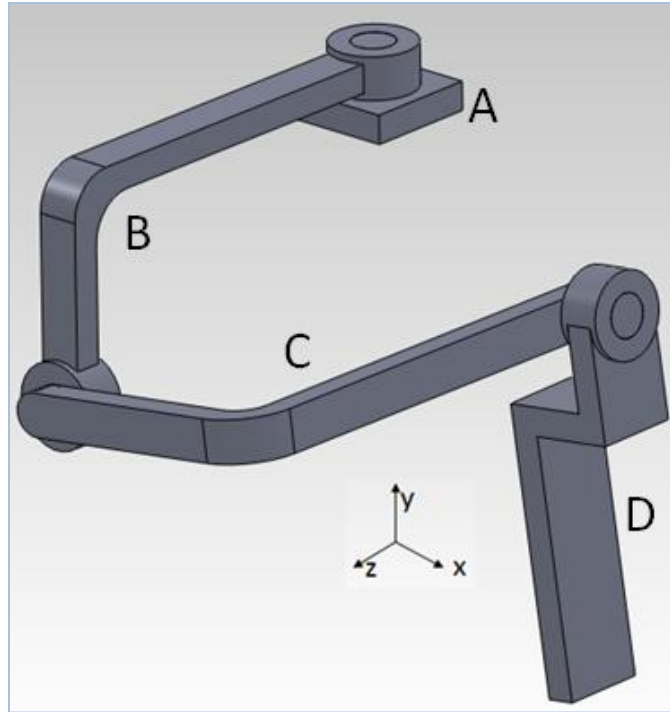


Figure 29—Rear scapula I preliminary design

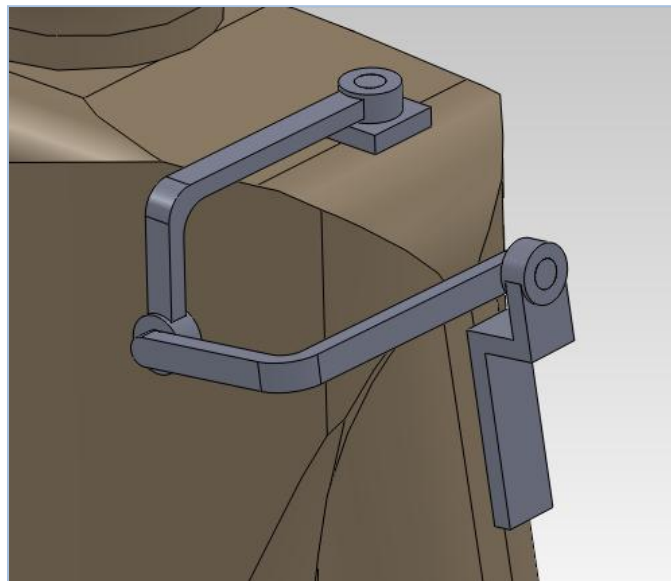


Figure 30—Rear scapula I preliminary design on user

5.2.4 Design 3: Rear Scapula Mechanism II

This second rear scapula design is similar to the first except that it is anchored to the user's back and reaches over the top of the shoulder, as opposed to being mounted on the shoulder and reaching down behind the back (Figure 31 & Figure 32). This design is also

composed of four pieces. Plate A is connected to the back via the torso mount subsystem. Part A and Part B form a pin joint which allows for rotation about the z-axis, and the connection between Part B and Part C allows for rotation about the y-axis. A pin joint between Part C and Part D allows for rotation about the x-axis, and the existing orthosis is attached to Part D via standard fasteners. As with the previous rear scapula design, each link will be adjustable lengthwise, and the geometries will be carefully refined to ensure smooth movement and strength.

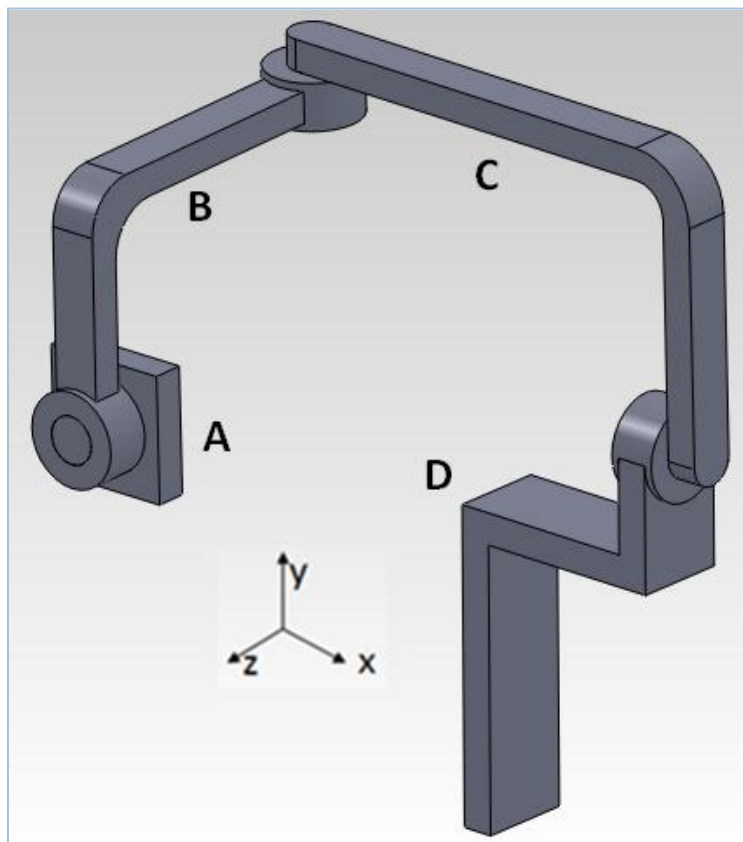


Figure 31—Rear scapula II preliminary design

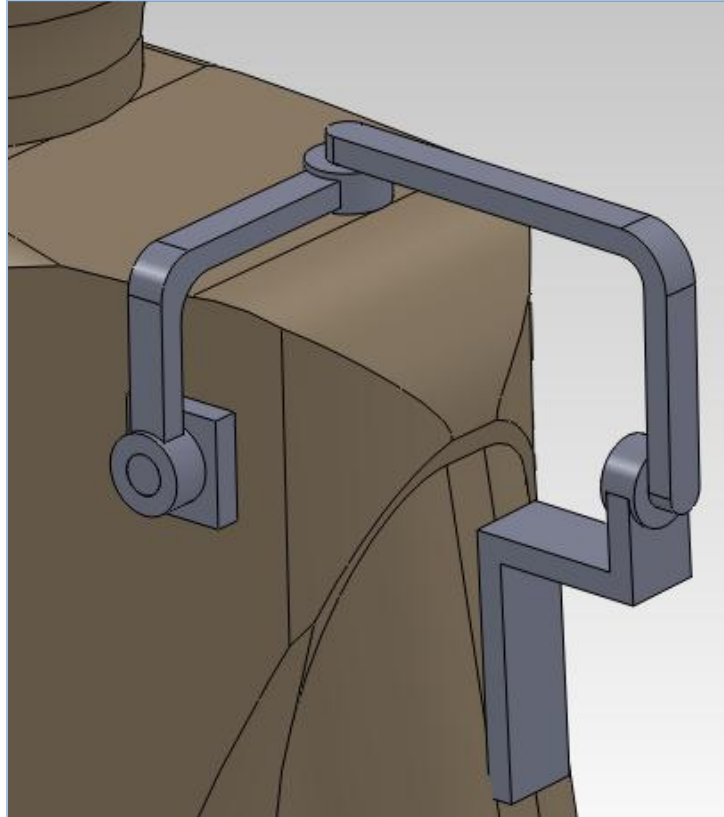


Figure 32—Rear scapula II preliminary design on user

6. Decision Matrix

Choosing the “best” preliminary design was an important step in the design process. A logical, systematic method was needed to determine which concept to develop further. A decision matrix—or design matrix—is best suited for this purpose. Important design specifications are listed in this matrix and each is assigned a weighting value in relation to importance. First, six subsections were created and each subsection was attributed with multiple specifications. Then each specification in a specific subsection was assigned a number to denote its importance in the design. These numbers added up to a sub-total of 1 for each subsection. Next, each subsection was assigned a weighting value to denote its importance and again, these numbers added to a total of 1. This method is similar to how a professor might weigh certain assignments within a class to have more or less of an effect on the final score.

Once completing the decision matrix, each design concept was scored according to how well it met each specification. The scores were assigned after reevaluating each preliminary design as a team. There was communication about how well each design would rate in the category of each specification until a number was mutually agreed upon. These scores were then multiplied by their respective weighting values and added together. Whichever preliminary designs scored the highest were determined to be the “best” designs and were considered for further development. Several of the top designs were considered because the assigning of scores is subjective and often easily influenced by biases and intuitive judgments (Volland, 2004). An example of the decision matrix that was used for this project is displayed below (Table 6).

Comparing the results of the two decision matrices (Table 7 & Table 8), the combination of the Vest and Rear Scapula II was chosen as the final design. The Strapped Harness and the Side Plate concepts also scored well and were considered alongside the current final design. However, after some deliberation it was decided that the Vest and Rear Scapula II concepts would be simpler to design and manufacture, ensuring a more reliable final design.

Table 6—Example Decision Matrix

Categories	Weight	Design 1		Design 2	
		Score	Wtd. Sc.	Score	Wtd. Sc.
Performance	0.3				
Interface with existing orthoses	0.1				
Convenience to the user	0.225				
Stability	0.175				
Range of motion	0.2				
Load distribution	0.15				
Load capacity	0.15				
Sub-Total:	1				
Safety	0.2				
No sharp edges	0.5				
Minimize pinch points	0.5				
Sub-Total:	1				
User Friendliness	0.15				
Adjustability	0.25				
Don/Doff Ease	0.25				
Ease of Maintenance	0.2				
Non-irritating to skin	0.15				
Aesthetics	0.15				
Sub-Total:	1				
Reliability	0.15				
Shock Resistant	0.3				
Waterproof	0.15				
Cleanable Parts	0.15				
Sweat resistance	0.15				
Safety factor	0.25				
Sub-Total:	1				
Cost	0.05				
Materials	0.4				
Manufacture	0.4				
Maintenance costs	0.2				
Sub-Total:	1				
Production	0.15				
Ease of Manufacture	0.5				
Ease of Assembly	0.5				
Sub-Total:	1				
TOTAL	1				

Table 7—Torso Mount Decision Matrix

Categories	Weight	Shoulder Pad		Vest		Strapped Harness	
		Score	Wtd. Sc.	Score	Wtd. Sc.	Score	Wtd. Sc.
Performance	0.3		0.19575		0.267		0.2295
Interface with existing orthoses	0.1	1	0.1	1	0.1	1	0.1
Convenience to the user	0.225	0.5	0.1125	0.9	0.2025	0.7	0.1575
Stability	0.175	0.6	0.105	0.9	0.1575	0.7	0.1225
Range of motion	0.2	0.7	0.14	0.8	0.16	0.8	0.16
Load distribution	0.15	0.5	0.075	0.9	0.135	0.7	0.105
Load capacity	0.15	0.8	0.12	0.9	0.135	0.8	0.12
Sub-Total:	1		0.6525		0.89		0.765
Safety	0.2		0.13		0.2		0.18
No sharp edges	0.5	0.7	0.35	1	0.5	1	0.5
Minimize pinch points	0.5	0.6	0.3	1	0.5	0.8	0.4
Sub-Total:	1		0.65		1		0.9
User Friendliness	0.15		0.10875		0.1095		0.117
Adjustability	0.25	0.6	0.15	0.4	0.1	0.9	0.225
Don/Doff Ease	0.25	0.8	0.2	0.9	0.225	0.6	0.15
Ease of Maintenance	0.2	0.9	0.18	0.9	0.18	0.9	0.18
Non-irritating to skin	0.15	0.7	0.105	0.8	0.12	0.7	0.105
Aesthetics	0.15	0.6	0.09	0.7	0.105	0.8	0.12
Sub-Total:	1		0.725		0.73		0.78
Reliability	0.15		0.12525		0.13275		0.1275
Shock Resistant	0.3	1	0.3	1	0.3	1	0.3
Waterproof	0.15	0.8	0.12	0.9	0.135	0.9	0.135
Cleanable Parts	0.15	0.8	0.12	0.6	0.09	0.8	0.12
Sweat resistance	0.15	0.8	0.12	0.9	0.135	0.8	0.12
Safety factor	0.25	0.7	0.175	0.9	0.225	0.7	0.175
Sub-Total:	1		0.835		0.885		0.85
Cost	0.05		0.033		0.033		0.043
Materials	0.4	0.6	0.24	0.7	0.28	0.9	0.36
Manufacture	0.4	0.7	0.28	0.6	0.24	0.8	0.32
Maintenance costs	0.2	0.7	0.14	0.7	0.14	0.9	0.18
Sub-Total:	1		0.66		0.66		0.86
Production	0.15		0.1125		0.09		0.12
Ease of Manufacture	0.5	0.7	0.35	0.6	0.3	0.8	0.4
Ease of Assembly	0.5	0.8	0.4	0.6	0.3	0.8	0.4
Sub-Total:	1		0.75		0.6		0.8
TOTAL	1		0.70525		0.83225		0.817

Table 8—Mechanism Decision Matrix

Categories	Weight	Cable Vest		Side Plate		Rear Scapula 1		Rear Scapula 2	
		Score	Wtd. Sc.	Score	Wtd. Sc.	Score	Wtd. Sc.	Score	Wtd. Sc.
Performance	0.3		0.222		0.23325		0.207		0.23475
Interface with existing orthoses	0.1	0.5	0.05	0.8	0.08	0.8	0.08	0.8	0.08
Convenience to the user	0.225	0.8	0.18	0.7	0.1575	0.7	0.1575	0.8	0.18
Stability	0.175	0.8	0.14	0.8	0.14	0.7	0.1225	0.7	0.1225
Range of motion	0.2	0.5	0.1	0.8	0.16	0.6	0.12	0.8	0.16
Load distribution	0.15	0.9	0.135	0.8	0.12	0.7	0.105	0.8	0.12
Load capacity	0.15	0.9	0.135	0.8	0.12	0.7	0.105	0.8	0.12
Sub-Total:	1		0.74		0.7775		0.69		0.7825
Safety	0.2		0.15		0.15		0.13		0.15
No sharp edges	0.5	0.9	0.45	0.7	0.35	0.7	0.35	0.7	0.35
Minimize pinch points	0.5	0.6	0.3	0.8	0.4	0.6	0.3	0.8	0.4
Sub-Total:	1		0.75		0.75		0.65		0.75
User Friendliness	0.15		0.09975		0.111		0.114		0.12075
Adjustability	0.25	0.9	0.225	0.6	0.15	0.8	0.2	0.8	0.2
Don/Doff Ease	0.25	0.6	0.15	0.7	0.175	0.7	0.175	0.7	0.175
Ease of Maintenance	0.2	0.4	0.08	0.8	0.16	0.8	0.16	0.8	0.16
Non-irritating to skin	0.15	0.5	0.075	1	0.15	1	0.15	1	0.15
Aesthetics	0.15	0.9	0.135	0.7	0.105	0.5	0.075	0.8	0.12
Sub-Total:	1		0.665		0.74		0.76		0.805
Reliability	0.15		0.10275		0.11325		0.11325		0.11325
Shock Resistant	0.3	0.9	0.27	0.7	0.21	0.7	0.21	0.7	0.21
Waterproof	0.15	0.6	0.09	0.8	0.12	0.8	0.12	0.8	0.12
Cleanable Parts	0.15	0.4	0.06	0.7	0.105	0.7	0.105	0.7	0.105
Sweat resistance	0.15	0.6	0.09	0.8	0.12	0.8	0.12	0.8	0.12
Safety factor	0.25	0.7	0.175	0.8	0.2	0.8	0.2	0.8	0.2
Sub-Total:	1		0.685		0.755		0.755		0.755
Cost	0.05		0.036		0.032		0.032		0.032
Materials	0.4	0.9	0.36	0.6	0.24	0.6	0.24	0.6	0.24
Manufacture	0.4	0.5	0.2	0.7	0.28	0.7	0.28	0.7	0.28
Maintenance costs	0.2	0.8	0.16	0.6	0.12	0.6	0.12	0.6	0.12
Sub-Total:	1		0.72		0.64		0.64		0.64
Production	0.15		0.075		0.09		0.0975		0.0975
Ease of Manufacture	0.5	0.5	0.25	0.6	0.3	0.6	0.3	0.6	0.3
Ease of Assembly	0.5	0.5	0.25	0.6	0.3	0.7	0.35	0.7	0.35
Sub-Total:	1		0.5		0.6		0.65		0.65
TOTAL	1		0.6855		0.7295		0.69375		0.74825

7. Analysis of Design

After a final design was chosen, it was subjected to several analyses to test various features. The goal of these analyses was to examine certain aspects of the design and then make revisions, where necessary, based upon the results. The following section will outline the various analyses completed and any design revisions that resulted.

7.1 Movement Envelope Analysis

The first iteration of the design was developed in an attempt to give maximum kinematic motion to the device. This was done in an attempt to mimic the full range of motion of the shoulder joint. The design created with this goal in mind resulted in the device extending far beyond the user's shoulder. This occurred because the device's parts were designed to avoid all possible interference with each other throughout the entire range of motion (Figure 33).

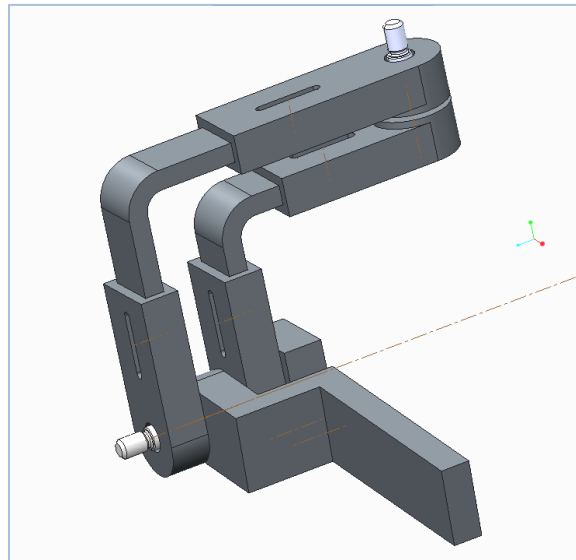


Figure 33—Device in maximum rotated position

While this additional range of motion was beneficial, the resulting bulkiness of the design was aesthetically displeasing and inconvenient to the user. Due to the fact that the final device must be worn by individuals and ultimately accepted into the user's daily life, any features that would negatively affect user perception should be avoided. In this instance the ability to mimic

full shoulder movement was of decreased importance and far exceeded the original design specifications. The design specifications only required the device to provide the range of motion necessary to complete the designated *Activities of Daily Living*. The angles of motion needed to complete *Activities of Daily Living* are included in Table 4 of the background. The angles pertinent to this analysis are those of the shoulder’s abduction and adduction, which to simplify analysis—and to be consistent with the ADL data—adduction was measured and labeled as negative abduction. The maximum abduction angle was 39.7 degrees and the minimum was -20.1 degrees. An explanation of the coordinate system used to define these angles is included in Figure 34, where the thick red line represents the users arm at 0 degrees.

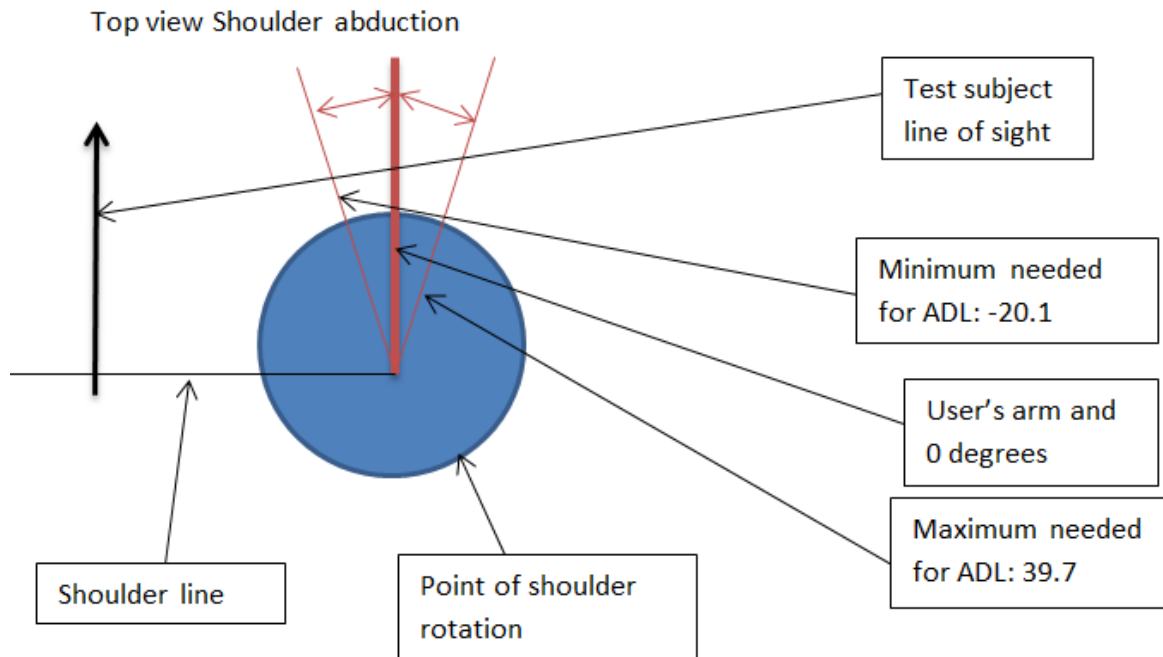


Figure 34—Explanation of angle measurements for right shoulder

The original design iteration that avoided all part interference resulted in a maximum abduction angle of 90 degrees, as seen in Figure 33. From this direct analysis it was quickly determined that the initial bulky design iteration could be altered to allow some interference to occur, while still meeting the range of motion design specification. After the creation of a revised design that shortened the “L” piece and eliminated the “s” shaped piece, a maximum abduction angle of 54 degrees was achieved (Figure 35). This angle exceeded the required maximum abduction angle needed to perform *Activities of Daily Living* by 14.3 degrees.

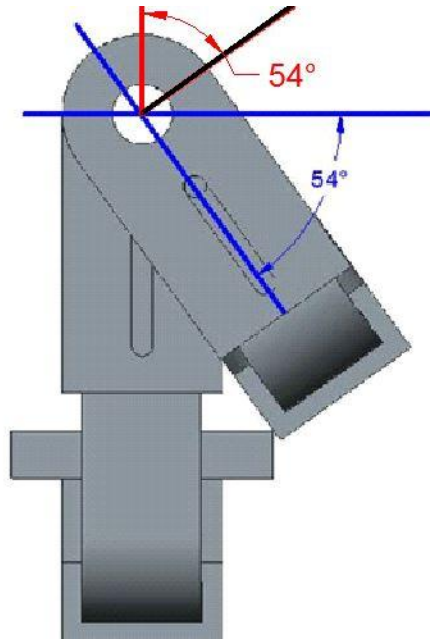


Figure 35—Top view representation of new maximum abduction angle

In Figure 35, the black line represents the orientation of the user’s extended arm as it would appear while wearing the device in the maximum abduction position. The red line here corresponds with the thick red line in Figure 34, which depicts the 0 degree marker. The angle depicted in Figure 35 shows the rotation of the device and the user’s arm 54 degrees from the 0 degree orientation.

7.2 Kinematic Analysis

One way to ensure that the device would work correctly in conjunction with the shoulder was to conduct a kinematic analysis. This was done by analyzing the links and joints within the design concept and then using the Kutzbach formula to determine mobility (R. L. Norton, 2012). The full Kutzbach formula for a three dimensional linkage is seen below:

$$M = 6(L - 1) - 5J_1 - 4J_2 - 3J_3 - 2J_4 - J_5$$

In this equation the M denotes the degrees of freedom of the mechanism. The L variable represents the number of links in the mechanism. Variables J1 through J5 all denote the quantities of different types of joints in the mechanism. J1 represents full joints, which remove five degrees of freedom, and J2 represents half joints, which remove four degrees of freedom.

The remaining numbered J variables represent for joints that remove one less degree of freedom than the previous variable.

When the shoulder mounted mechanism was examined it was found to have four links including the ground link. The mechanism utilizes three pin joints, which remove five degrees of freedom each. When these values are substituted into the equation it is found that the mechanism has 3 degrees of freedom, which is shown in the equation below. Such a result is promising because the shoulder joint naturally has three inherent degrees of freedom.

$$M := 6(4 - 1) - 5(3) - 4(0) - 3(0) - 2(0) - 0 = 3$$

It was noted during initial design analysis that the team might chose to lock one of the pin joints in place to improve functionality. This action effectively eliminates one whole link and one pin joint from the equation. With this new input it is found that the modification results in a mechanism with two degrees of freedom rather than three. The acceptability of this modification was determined through ADL testing with several male and female test subjects. The equation is supplied below:

$$M := 6(3 - 1) - 5(2) - 4(0) - 3(0) - 2(0) - 0 = 2$$

7.3 Free Body Diagram

Due to the design's interface with the user's body, and the sharing of loads between the device and user, one primary position was identified for analysis. The position chosen was the *anatomical position* with the user's arms pointing straight down at the ground, as if holding a brief case (Figure 36). This position was chosen because it is here that the maximum load would be felt by the device during normal operation. During many other activities it was determined that loads on the shoulder mount would decrease as the users own arm and skeleton would support increasing portions of the total load in these other positions.

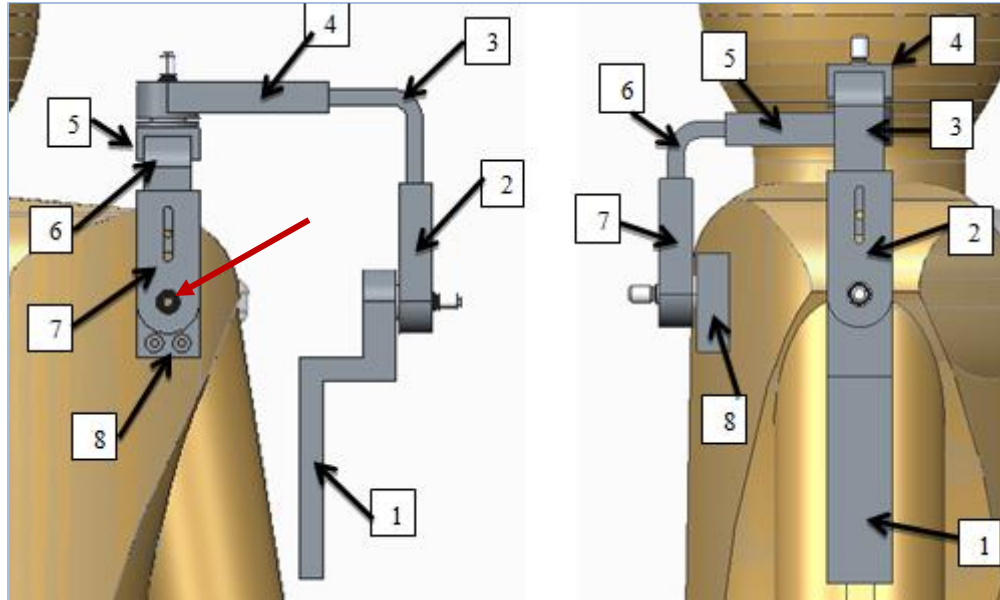


Figure 36—Device in the neutral position with parts numbered.

All calculations made during this analysis assumed that the user's arm was not supporting any portion of the load. In actual usage situations this would not be the case as the user's skeleton would naturally support a portion of the device's weight. This assumption greatly simplified the free body diagrams and calculations, and also added an inherent safety factor. Any forces or moments calculated during the analysis would therefore be higher than those actually experienced.

The analysis was first conducted on each part individually and then, where appropriate, on groups of parts to better understand the forces on the whole assembly. All fasteners were approximated as rigid joints or pin joints, where suitable, to aid in simplifying the models and assumptions made. If a connection showed severe and significant forces, the connection was remodeled with all fasteners included to examine the interaction closer. Reaction forces and moments were identified, calculated, and then carried through to each subsequent part. This allowed the increasing forces and moments to be observed as the analysis moved closer to the final part connecting the mechanism to the torso mount subsystem.

7.3.1 Results

The free body diagram analysis revealed two possible flaws in the initial design. The first was the discovery of unnecessary moments due to suboptimal part geometries. The second was the lack of an opposing moment at the anchoring pin joint indicated with an arrow (Figure 36).

Complete free body diagrams and unabridged calculations can be found in Appendices B and D, respectively.

The first part analyzed in the chain, where the load was directly applied, was Part 1 or the connection piece. This piece is where the mechanism would connect directly to the powered orthosis (Figure 37). The first design iteration of the assembly resulted in this part having a vague “s” shape. This geometry was found to be suboptimal because it added a significant moment to the assembly compared to the other parts. A moment of 1.5 Nm (M_1) was created. By revising the part’s design to remove the creation of this moment, or significantly reduce it, unnecessary stress and forces were removed from the first pin joint.

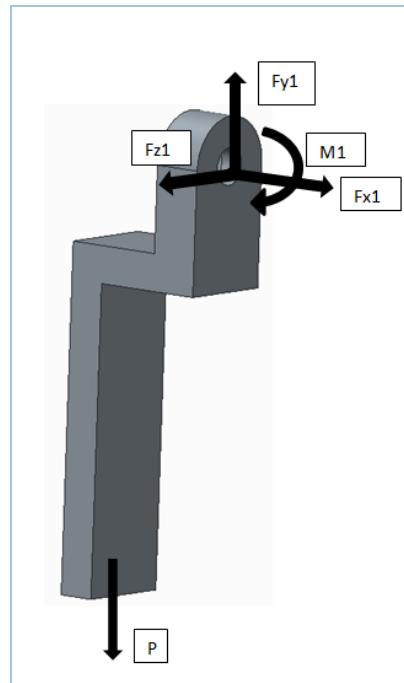


Figure 37—Part 1: Component that connects to powered orthosis

The removal of the M_1 moment was accomplished by modifying the original part into a single straight piece (Figure 38). By straightening the connection part the moment arm was reduced from 41 mm to a negligible length. While the magnitude of the moment removed through this redesign was small, it was still larger than that of a properly optimized design, where this moment can be made effectively nonexistent.

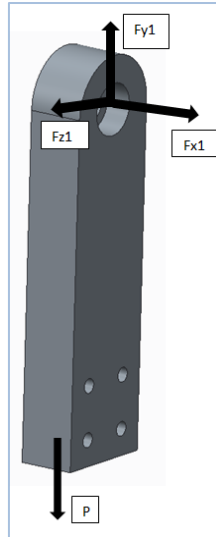


Figure 38—Revised Part 1

The second issue arose when the moments were carried through to every part during the analysis. On Part 7 the pin joint did not provide a reaction moment to counter the $M6b$ moment, highlighted in red (Figure 39). Without this reaction moment, or other reaction forces, the analysis indicated that this part was not in static equilibrium. In the context of the whole mechanism assembly, this apparently unbalanced moment would cause rotation of the entire device around the indicated pin joint (Figure 39). While this pin joint was initially added to increase user mobility and provide a third degree of freedom, this finding indicated the need for the joint to remain rigid reducing the device's degrees of freedom to two.

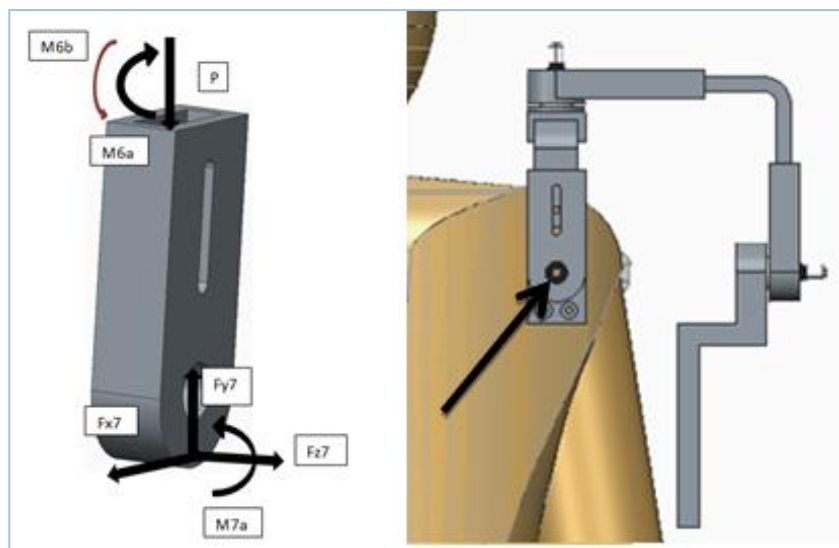


Figure 39— Free body diagram for Part 7 and its pin joint

A simplified representation of the whole assembly was modeled, including the placement of the user's arm, to help determine static equilibrium. When the mechanism was modeled in this fashion the reaction force to counter the moment was found. The mechanism is held in equilibrium due to a horizontal reaction force between the users arm, represented in the figure by the black shape, and the device represented in blue (Figure 40). Full free body diagrams and equilibrium calculations of the finalized design can be found in Appendices B through E.

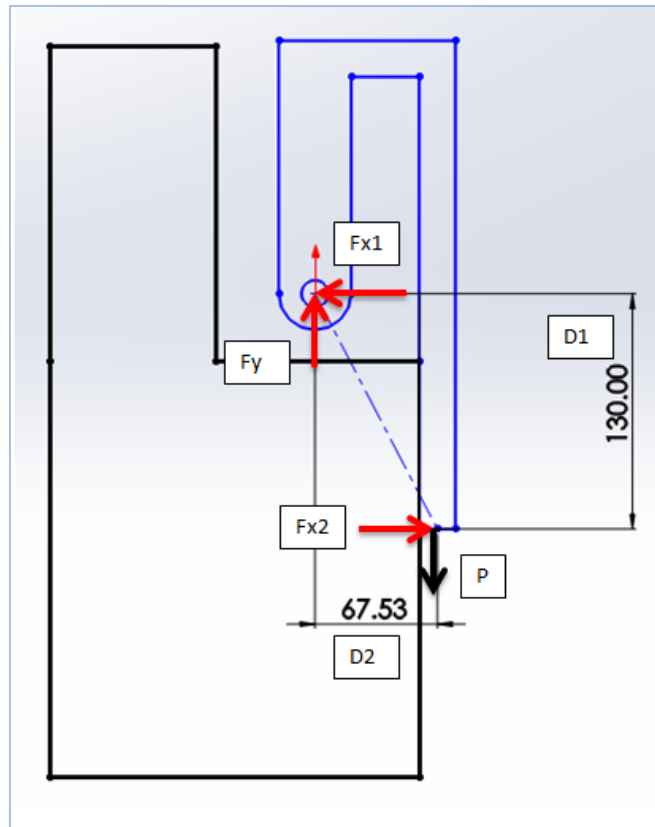


Figure 40—Simplified whole Assembly free body diagram

7.4 Finite Element Analysis

Stress analysis was conducted on each major mechanism part using the FEA software package included in Creo Parametric. This analysis was used to examine possible failure points on the various parts due to the expected loads and stresses. Certain part geometries were then modified based upon the results obtained from the FEA. All changes were made to reduce stress concentrations, which would lower the possibility of failure.

Each part of the mechanism was assessed individually using data from the static equilibrium analysis for inputs. The resulting information was displayed upon the parts in a “heat map,” where the warmer colors indicated higher levels of von Mises stresses than the cooler colors. The von Mises stress is equivalent to the combination of multi-axial tension and shear stresses, and is commonly compared to the yield stress of a material to determine if it will fail. These stress concentrations are clearly visible in the FEA (Figure 41).

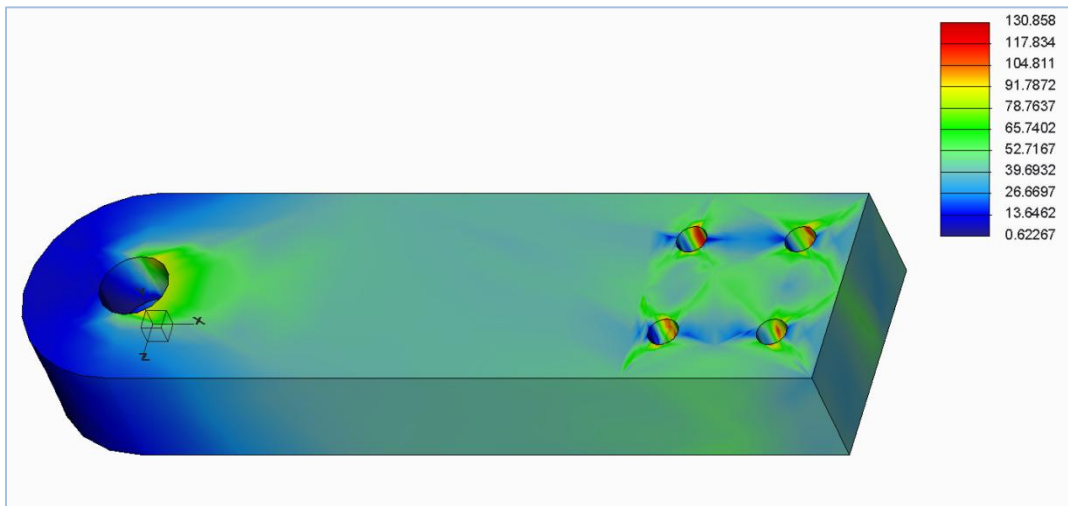


Figure 41—FEA of Part 1 with heat map (kPa)

Material properties for ABS plastic, the chosen material for the groups design, were included in the program. These properties indicated that ABS plastic had a tensile strength of 30,000 kPa. This means that the ABS plastic can withstand stress magnitudes up to 30,000 kPa before necking and eventual fracture. All parts analyzed, except for Part 6, were found to have stress magnitudes less than 5,000 kPa in uniaxial tension, which gives a safety factor of at least 6. The stress level for Part 6 was found to be much greater, with a stress value over 11,000 kPa. When relevant moments were applied to the analysis the troublesome stress value increased to 20,740 kPa (Figure 42).

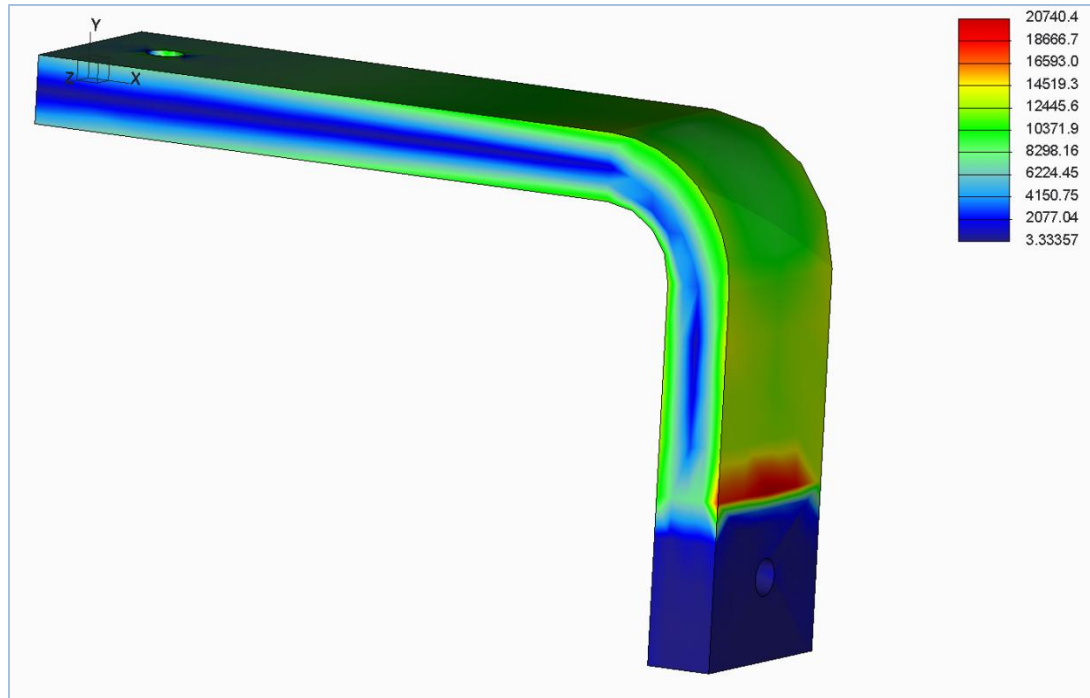


Figure 42—FEA of Part 6 with high Von Mises stresses (kPa)

These findings indicate a safety factor of about 1.4 for the part in question, which is less than the desired safety factor of 2 desired for the team’s design. However, it was concluded that a significant portion of the high stress levels observed resulted from the inadequacy of the FEA model used. The model failed to perfectly simulate the reality of the forces and interactions taking place on this specific part. The simulation was flawed in that it could not accurately mimic the actual clamping that holds part 6 in static equilibrium. Part 6 is inserted within Part 7 and held in place with a fastener, which goes through the hole visible in Figure 42. In the simulation this interaction was modeled by designating two surface regions on the front and back faces of Part 6 and defining these surfaces as rigid. This may have resulted in an artificial inflation of the stress values as is indicated by the greatest stress values occurring directly along the boundary of the rigidly defined surface. Additionally, the powered arm orthosis supported by the shoulder mount orthosis will also be partially supported by the user’s skeleton, reducing the actual total load compared to that of the FEA. Lower stresses will therefore occur under normal use than the worst case scenario utilized in the FEA stress analysis. The full FEA analysis for each part can be found in Appendix F.

7.5 Fastener Analysis

The four types of fasteners analyzed were the M5 and M6 Socket Head Cap Screw, M10 Shoulder Screw, and M5 Button Head Screw. Using these four standard fasteners aided the ease of manufacturability, assembly, disassembly, and adjustment. All the standard fasteners used were supplied by McMaster-Carr and MSC.

A full analysis was conducted to ensure that the chosen dimensions and materials would not cause failure of the fasteners. This analysis was not performed to check the use of these fasteners with any particular design; instead, it was to determine the stresses and failures of the fasteners individually. Consideration was given to two possible failure methods: axial tensile failure and shear failure of the fastener threads (R. L. Norton, 2011). The dimensions and measures of various values for each screw type were researched and recorded (Table 9).

Table 9—Fastener Information

	M5 Socket Head Cap Screw	M6 Socket Head Cap Screw	M10 Shoulder Screw	M5 Button Head Screw
Diameter (in)	0.1969	0.2362	0.3937	0.1969
Threads per Inch (1/in)	31.75	25.4	16.93	31.75
Tensile Area (in²)	0.022	0.031	0.089	0.022
Shear Area (in²)	0.014	0.02	0.052	0.014

The following section includes a discussion of the two types of failure analyses based on the fasteners' dimensions. Full and unabridged calculations for these tests can be found in Appendix G.

7.5.1 Tensile failure

Tensile failure of a fastener occurs when the axial forces experienced by the fastener exceed the allowable limit. This would cause fracture in the fastener, resulting in failure and a broken prototype. The results from the analysis indicate that the fasteners will not fail in tension, since the forces required for such failure significantly exceed expected forces during normal usage (Table 10).

Table 10—Force Required to Fail Through Tension

	M5 Socket Head Cap Screw	M6 Socket Head Cap Screw	M10 Shoulder Screw	M5 Button Head Screw
Actual Failure Force	2,192 lbs	3,105 lbs	14,160 lbs	3,255 lbs
Design Force to Allow Safety Factor of 3	731 lbs	1,035 lbs	4,718 lbs	1,085 lbs

After finding the actual force required to fail each fastener axially, a safety factor of three was applied. This ensured that the force used for any design considerations allowed significant room for error and extreme situations. Even with the allowable force value reduced by a factor of three, the calculated strengths still exceed the forces expected during normal use.

7.5.2 Thread shear failure

A more likely scenario for fastener failure would be from the shearing of threads. This stems from the fact that the thread cross sectional area is much smaller than the overall fastener cross sectional area. When the analysis was conducted the failure force was first calculated for a single thread (Table 11).

Once failure force was determined for a single thread, it was extrapolated to the whole fastener. First, the length of engagement of the fastener was determined. This was then used to determine the number of threads actively loaded. Next, the failure force for a single thread was multiplied by the number of threads active to determine the total force needed to fail all threads (Table 11).

Table 11—Shear Force Required to Fail Threads

	M5 Socket Head Cap Screw	M6 Socket Head Cap Screw	M10 Shoulder Screw	M5 Button Head Screw
Length of Engagement	0.157 in	0.186 in	0.318 in	.157 in
Number of Threads Engaged	4.97	4.72	5.38	4.92
Shear Force to Fail 1 Thread	1,300 lbs	1,928 lbs	4,953 lbs	1,300 lbs
Total Shear Force to Fail All Threads	6462 lbs	9,099 lbs	26,670 lbs	6462 lbs
Design Force to Allow Safety Factor of 3	2154 lbs	3,033 lbs	8,889 lbs	2154 lbs

As was the case with the tensile calculations, a safety factor of three was added to determine the failure forces for design considerations. Once again, the failure forces far exceed the expected loading of the device during normal usage. The user would be injured from these applied loads much sooner than the fasteners would fail in shear from thread pullout. These results determine that all four standard fasteners would work with whichever final design was chosen.

8. Final Design

Modifications were made to each subsystem to reflect various issues that arose during analysis of the conceptual design. Each of the final subsystems is described in detail below and the full assembly with both subsystems and a humanoid model is pictured (Figure 43). Complete mechanical drawings of each part are included in Appendix H.



Figure 43—Mechanism and torso mount subsystems together in final design, conceptual (left) and prototype (right)

8.1 Mechanism Subsystem

The final mechanism design (Figure 44) is mounted to the torso subsystem via Part 8 using four countersunk M6 screws. Part 8 and Part 7 are connected with a 12mm shoulder screw that allows Part 7 to act as a pin joint, with a bronze sleeve bearing press-fit into Part 7 to ensure smooth rotation. This shoulder screw can also be replaced with a standard M12 screw to lock the

pin joint at a certain angle and eliminate one degree of freedom if necessary. The hole in Part 8 is countersunk so that it is flush with the attachment plate from the torso subassembly.

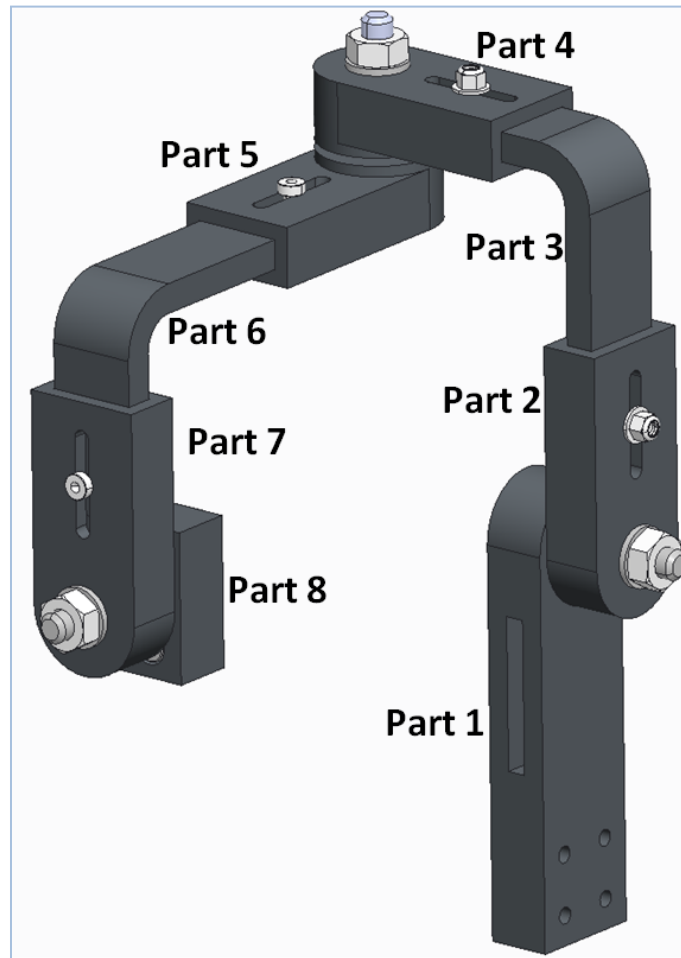


Figure 44—Final mechanism design

A slot in Part 7 accepts the end of Part 6, creating a slider joint which enables the user to adjust the height of the rest of the mechanism with relation to Part 8. An M5 screw is used to lock the two pieces together at the desired distance. This configuration allows for 15mm of adjustment in either direction, giving a total adjustment range of 30mm. The upper portion of Part 6 connects to Part 5 in a similar fashion, utilizing the same method of adjustment.

Part 5 and Part 4 are similar in nature to Part 8; however they each feature raised protrusions concentric with the end radii of the parts to allow for clearance of the 15mm adjustment screws. A 13mm washer is located between the two parts to reduce friction when Part 4 is rotating. A 12mm shoulder bolt connects Part 5 and Part 4 the same way as previously

described, with a countersunk hole in Part 5 and bronze sleeve bearings in both parts. While the rotation of Part 4 will eventually cause the mechanism to collide with itself, this situation would only occur well outside of the range of motion necessary to complete *Activities of Daily Living*.

Part 4, Part 3, and Part 2 all connect similar to previously described methods, with the adjustment sliders operating the same way. Part 1 features a countersunk hole to accept the head of a third shoulder bolt, allowing connection to Part 2 and rotation of Part 1. Part 1 would then connect to the existing powered arm orthosis via standard fasteners. However, the final prototype of the shoulder mount design was not intended to actually interface with the existing powered arm orthosis. This fact caused some necessary modifications to the prototype to ensure proper functionality. When the device is properly attached to existing powered arm orthosis the shoulder mount would follow the greater motion of the upper limb via the connection established by the arm orthosis. Lacking the interface with the existing arm orthosis a proper connection with the user's upper arm needed to be established. This was achieved by adding a slot with a Velcro strap to Part 1 of the prototype. The Velcro strap is used to connect the motion of part one with that of the user's humerus. This strapping configuration was necessary for the proper functionality of the final prototype to be achieved.

One of the important benefits of this design is that its simplicity makes modifying the design to fit a range of users simple. For example, this device is designed to adjust to fit users in the 25th to 75th percentiles. If one were to alter this device to fit users outside of this adjustable range, the only parts required to change would be Part 6, Part 3, and Part 1 (Figure 44). This means that only a select few parts would need to be remanufactured, instead of the entire design. An exploded view of the entire device assembly is depicted (Figure 45).

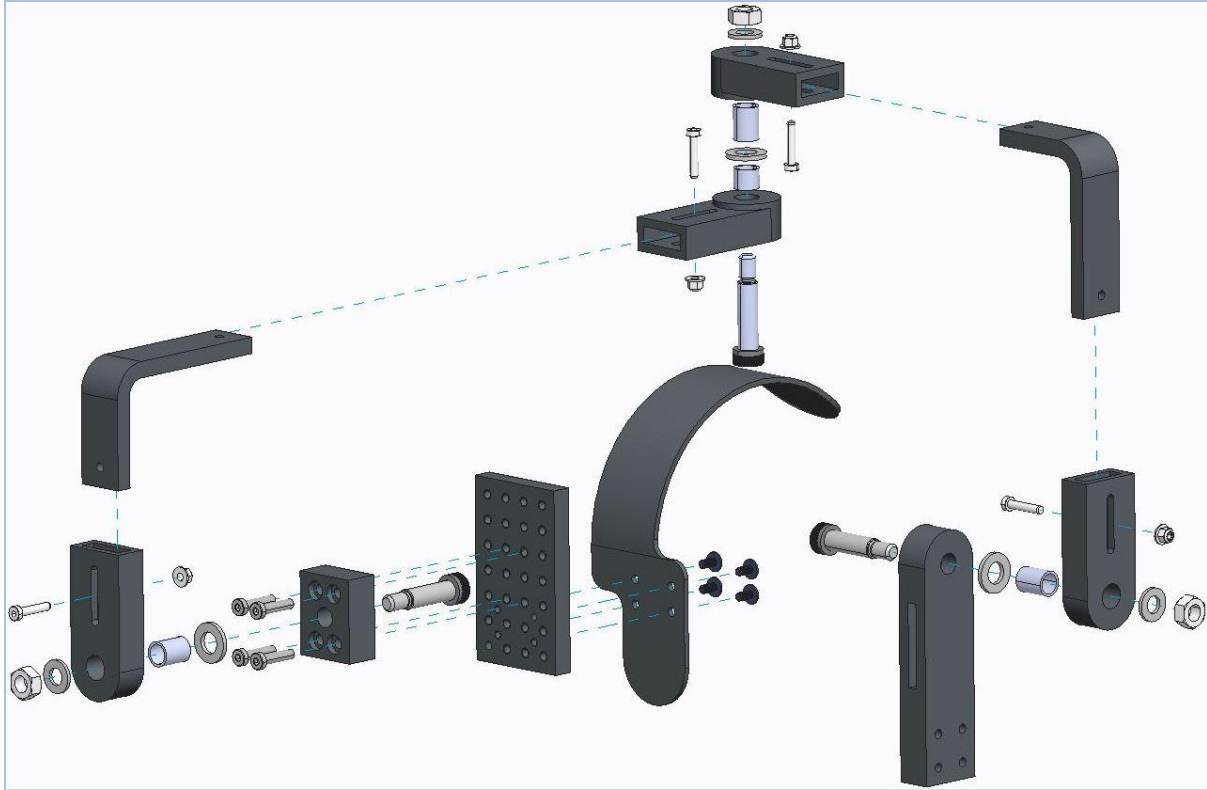


Figure 45—Exploded view of entire device

8.2 Torso Mount Subsystem

The final torso mount subsystem (Figure 46) is attached to the mechanism subsystem via Part 9 with the use of four M6 screws. Part 9 is designed with 28 identically spaced M6 holes so that Part 8 of the mechanism subsystem may be adjusted accordingly to closely match the axes of rotation of the shoulder.

Part 10 is designed to distribute the weight of the whole design using the support of the user's shoulder. Part 10 is embedded within a custom designed vest. Part 9, which is situated outside the vest, is connected to Part 10 using four M5 flange button head screws inserted through the material of the vest. A removable flap of material and padding will cover the heads of the four M5 flange button head screws.

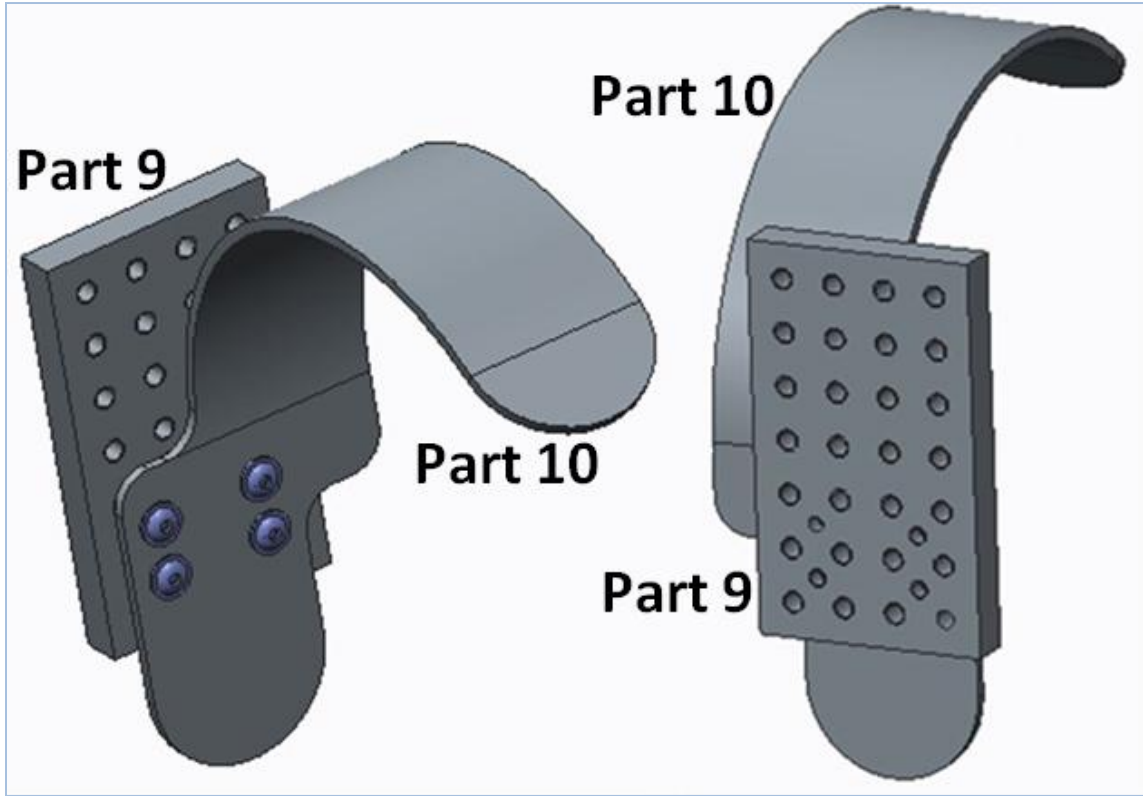


Figure 46—Final torso mount subsystem

9. Prototype Manufacturing

Each component of the prototype was either manufactured by the group in the Higgins machine shop with the assistance of a lab monitor, or produced using WPI's rapid prototyping machine. The vest was manufactured by the group with the assistance of a purchased vest pattern. All standard components and raw materials were purchased by the group, who then assembled the prototype upon completion of manufacturing.

9.1 Budget

All of the costs incurred by the project team during the entire prototype design and manufacturing processes are included in Table 12. The table also includes information about the part number, supplier, quantity, and all associated costs.

Table 12—Budget

Subsystem	Supplier	Part #	Description	Qty	Unit Price	Discount	Sub Total	Shipping	
Vest	Wal-Mart	-	Poly-Fil Tru-Foam	1	\$7.95	-	\$7.95	\$0.00	
	Wal-Mart	-	Thermolam Plus Fabric	2	\$4.22	-	\$8.44		
	Wal-Mart	-	Red Velcro	1	\$0.84	-	\$0.84		
	Wal-Mart	-	Red Duck Fabric	1	\$19.05	-	\$19.05		
	Wal-Mart	-	Vest Pattern	1	\$3.16	-	\$3.16		
	Jo-Ann Fabrics	-	Krazy Glue Craft Gel	1	\$4.24	-	\$4.24		
	Jo-Ann Fabrics	-	2" Black Webbing	3	\$2.99	-	\$8.97		
	Jo-Ann Fabrics	-	1" Black Webbing	2	\$1.79	-	\$3.58		
	Jo-Ann Fabrics	-	1" Parachute Buckle	1	\$3.99	-	\$3.99		
	Jo-Ann Fabrics	-	2" Parachute Buckle	1	\$6.49	-	\$6.49		
Mechanism	Ultimate Plastics	-	ABS plastic 1.5"x5.5"x18"	1	\$56.38	-	\$56.38	\$5.40	
	Ultimate Plastics	-	ABS plastic 0.125"x6"x48"	1	\$7.00	-	\$7.00		
	McMaster-Carr	8975K415	Aluminum Stock (6061) 0.5"x3"x12"	1	\$16.02	-	\$16.02		
	McMaster-Carr	6658k11	12mm Bronze Sleeve Bearing	1	\$0.96	-	\$0.96		
	McMaster-Carr	6658k13	20mm Bronze Sleeve Bearing	3	\$1.10	-	\$3.30		
	McMaster-Carr	92461a200	M5 Nylon-Insert Hex Flange Locknut	1	\$6.34	-	\$6.34		
	McMaster-Carr	92981a406	M10 40mm Shoulder Screw	1	\$4.21	-	\$4.21		
	McMaster-Carr	92981a415	M10 35mm Shoulder Screw	2	\$4.16	-	\$8.32		
	MSC	00496745	M5 Socket Head Cap Screw	1	\$26.66	19%	\$21.57		\$0.00
	MSC	67493080	M10 Flat Washer	1	\$5.04		\$4.08		
	MSC	68060565	M5 Button Head Cap Screw	1	\$11.75		\$9.51		
	MSC	67493122	M12 Flat Washer	1	\$9.51		\$7.69		
	MSC	67477166	M10 Hex Nut	1	\$7.76		\$6.28		
MSC	00496802	M6 Socket Head Cap Screw	1	\$26.66	\$21.57				
MSC	00496802	M6 Socket Head Cap Screw	1	\$26.66	\$21.57				
Testing	-	-	Shipping for Tripod	1	\$0.00	-	\$0.00	\$11.13	
Total							\$256.47		

9.2 Mechanism Subsystem

9.2.1 Rapid Prototyping

Manufacturability is an important consideration when designing any mechanical system. Rapid prototyping methods were utilized for several of the parts in the mechanism subassembly, due to their complicated geometry. The four “pin joint” components (Parts 2, 4, 5, and 7 from

Figure 44) were made with rapid prototyping due to the difficulty of manufacturing the deep slots necessary to accept the slider components (Figure 47). Since the device is not expected to encounter the application of high loads, rapid prototyping these parts should still provide adequate strength.



Figure 47—Parts created using rapid prototyping

9.2.2 Machining

The remaining components (Parts 1, 3, 6, and 8 from Figure 44) were manufactured using ABS plastic (Figure 48). A single block of ABS plastic that was approximately 40mm thick was purchased since the ABS parts share relatively similar dimensions. The process of machining began by cutting the large block into several roughly-dimensioned blocks, one for each part. Since the parts were not being cut very precisely at this point, a band saw was utilized.

The next step was to import the CAD files into the Computer Aided Manufacturing (CAM) program ESPRIT, which was used to create a program that could be read by a CNC machine. After the ESPRIT file and correct tooling was loaded into the CNC machine, and the corresponding part was properly secured, the milling was performed automatically. Along with this CNC machine, a manual milling machine was also utilized to perform less-complicated operations, such as planing faces and drilling simple clearance holes. A slot was also added to Part 1 to allow for a Velcro band to attach the part to the upper arm of the user.

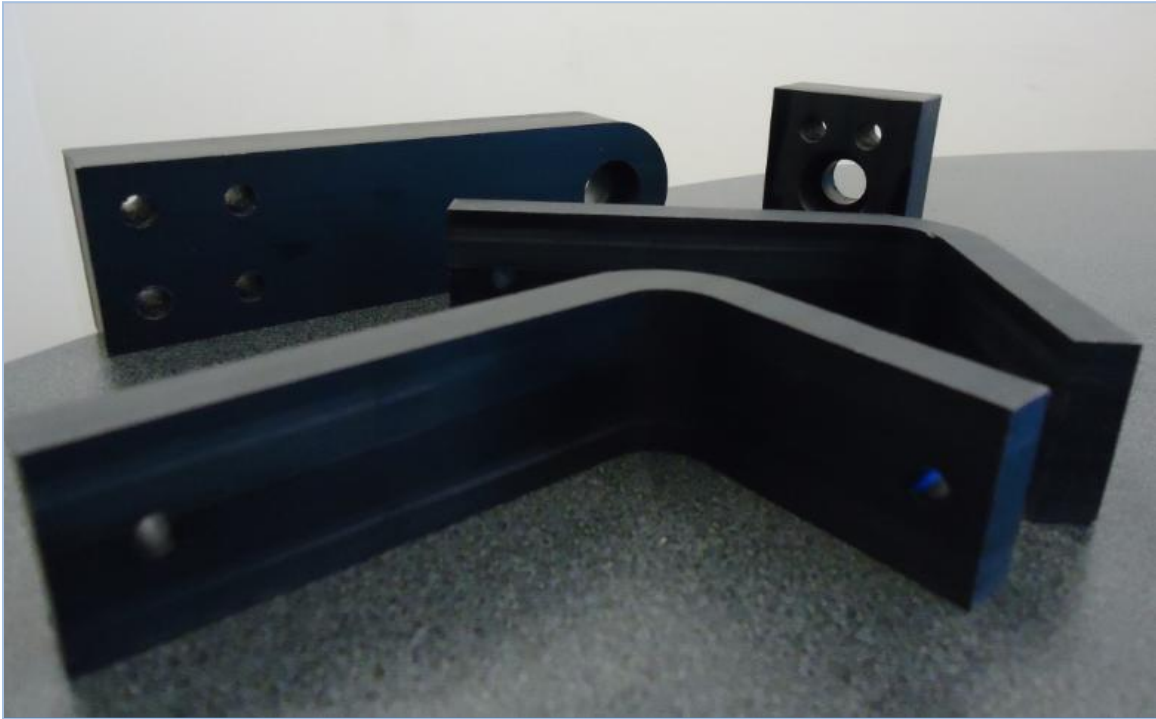


Figure 48—Machined parts for the mechanism subassembly

Tolerances were added to the dimensions of all parts prior to manufacturing. Proper tolerances ensured that each component fit correctly, with the adjustable sliders being fairly snug and the pin joints rotating freely.

9.3 Torso Mount Subsystem

9.3.1 Machining

Similar to the machined parts from the previous section, Part 9 in the torso mount subsystem was manufactured using a combination of the band saw, manual milling machine, and CNC machine. While the previous components were created out of ABS plastic, this attachment plate part was made out of rectangular aluminum stock (Figure 49). This part needed twenty-eight M6 tapped holes in it, as well as four M5 threaded holes. The proper taps were acquired and the CNC machine was used to tap these holes.

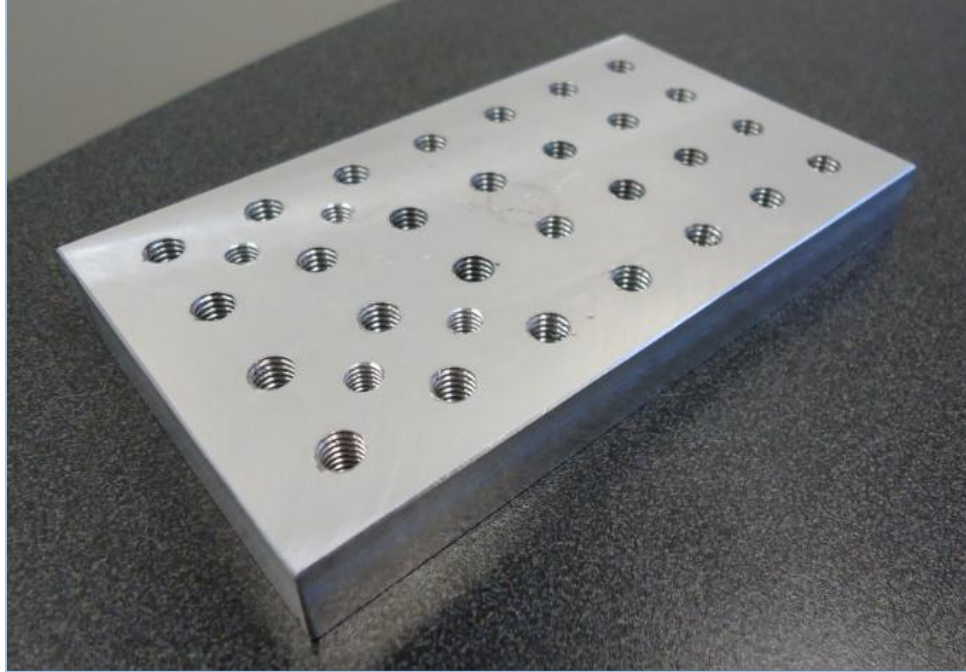


Figure 49—Part made from aluminum stock

9.3.2 Thermoplastic Shoulder Piece

Since the shoulder piece that is inserted into the vest (Part 10 in Figure 46) is thin and curved, a long flat sheet of thermoplastic was used as the material. Since the sheet was so thin, it could not be manufactured conventionally with any of the available machines. Instead, the lab monitor used the CNC machine to mill the outline of the flattened part into a piece of wood. The plastic was then laid over this wood and a router tool was used to follow this outline and cut the plastic to the same profile. After simple clearance holes were drilled, the entire part had to be bent into the correct U-shape with the help of a high-powered heat gun. The part was heated uniformly until it was reasonably malleable, at which point it was wrapped around a plastic tube of the correct diameter and held there, where it cooled until arriving at the final shape (Figure 50).

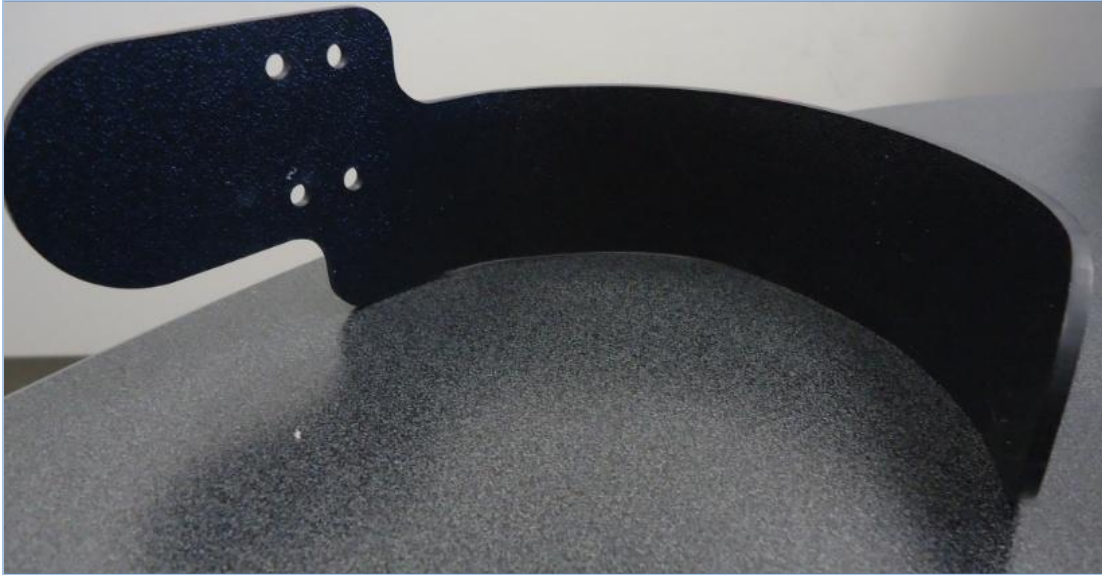


Figure 50—Shoulder piece in its final shape after bending

9.3.3 Vest

The basis for the design of the vest was pattern A6036 Size Extra-Large by New Look Patterns. Size Extra-Large was chosen to accommodate any extra material needed for extra seam allowances, foam, and other material that would be included. The vest was made from thermolam plus and duck fabric. The pattern was pinned to the fabric and the back and both front sides were cut out of the duck fabric twice and the thermolam once. Slight alterations were made when cutting out the pieces (Figure 51 & Figure 52).



Figure 51—Back of vest cut out of duck fabric



Figure 52—Front sides of vest cut out of duck fabric

Once all nine pieces were cut out, the corresponding pieces were pinned together with the outside faces against each other and the thermolam on the outside (Figure 53).

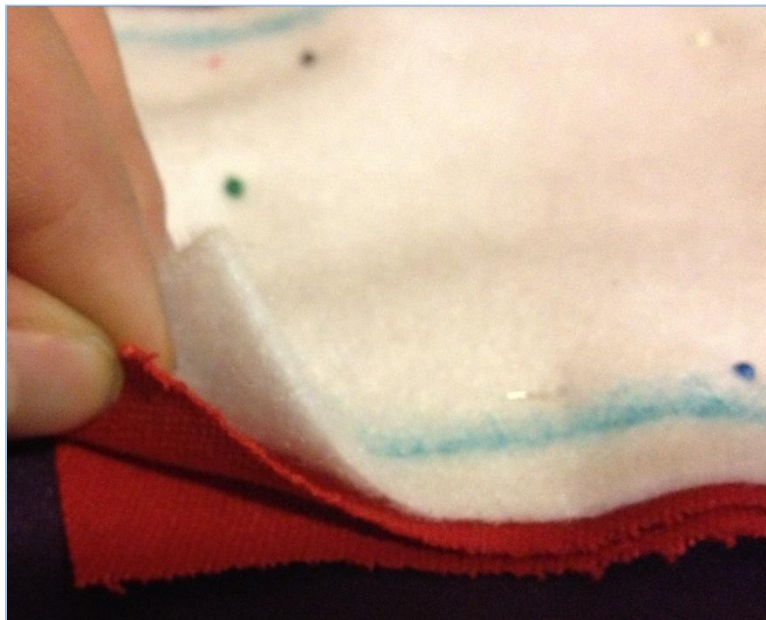


Figure 53—Pieces pinned together in the correct combination

Once the pieces were properly pinned together, a blue line was drawn around the outside to act as a guideline to follow while sewing (Figure 53). Each set of three pieces were sewn together using a sewing machine. These pieces were unpinned and flipped so that they were right side out. Once flipped, the pieces were ironed to flatten the seams and make the pieces easier to

work with (Figure 54). The seams were all reinforced by sewing around the edges again (Figure 55).



Figure 54—Back of vest sewn, flipped right side out, and ironed



Figure 55—Back of vest with reinforced seam

Reinforced seams were sewn on each of the three pieces of the vest. The side pieces were pinned to the back piece and sewn together (Figure 56) and the left shoulder was also sewn to the back of the vest (Figure 57).



Figure 56—Side sewn to back of vest



Figure 57—Side and shoulder sewn to back of vest

Belt loops were made by folding duck fabric into threes and sewing the edges for reinforcement (Figure 58). Then the seven belt loops were sewn onto the vest in the appropriate locations. Two inch strapping was threaded through the belt loops with buckles on the end. Following this, one inch wide straps were sown to the top part of the vest with buckles attached.



Figure 58—Belt loop attached to vest

Once Part 10 was manufactured and ready to be embedded in the vest, poly-fil tru-foam was cut to size and glued to it. This part was then put inside the shoulder and the front and backs of the vest were hand-stitched around it. This finalized the vest portion of the torso mount subsystem construction (Figure 59).



Figure 59—Completed vest

10. Prototype Testing Procedures

To test whether the prototype met its functional requirements as outlined in the design specifications, several tests were performed. Based on the results of these tests, the final prototype was modified to better optimize its performance. The prototype needed to accomplish the design specifications to be deemed successful. Therefore, each of the tests was based around a category defined within the design specifications. These categories included general information, range of motion, *Activities of Daily Living* (ADL), strength characteristics, and user friendliness. The range of motion, ADL testing, and user friendliness involved the use of nonbiased test subjects unfamiliar with the prototype's development.

10.1 General Testing

This testing category included physical measurements of the prototype. The tests were completed on both the torso mount and mechanism subsystems separately, as well as the fully constructed prototype. The prototype's weight and major dimensions were recorded, as well as identification of possible part interferences and an examination of fastener performance.

To obtain the prototype's weight, a group member was weighed on a scale without the prototype then once again while holding the prototype and the weight difference was calculated. This procedure was completed with the group member holding the torso mount and mechanism subsystems separately and also as a completed prototype. For the prototype's general dimensions three types of measurements were taken, all dimensions focused on the mechanism subsystem. First measurements in the length (Z), width (X), and height (Y) directions were taken, for both the maximum and minimum adjustment settings of the prototype. Secondly, the prototype was donned by a group member, properly adjusted, and then measurements were taken for the distances that the mechanism extended beyond the user's shoulder surface along each major axis (Figure 60).

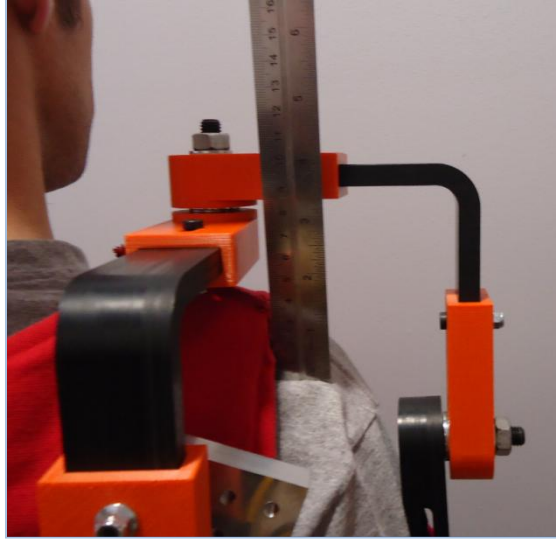


Figure 60—Measuring extension beyond the shoulder

To examine the fasteners, the main joints were operated continuously for 100 repetitions and any loosening of fasteners or lack thereof was recorded. For interference testing, the prototype was adjusted to its maximum and minimum settings, operated through its full range of motion, and any part interferences or obstructions were recorded.

10.3 Strength Characteristics

A variety of strength tests were performed to determine how the prototype reacted under loading. The prototype is intended to accomplish *Activities of Daily Living*, and therefore is unlikely to encounter high loads, which would result in failure due to part fracture. While fracture was unlikely through the application of expected loads, significant deflection of the mechanism parts was expected. It was important to measure and quantify resulting deflections and ensure continued functional performance.

The strength testing of the prototype was accomplished in several steps. First, the entire prototype assembly was statically loaded with a five pound weight and then a ten pound weight, attached with string to Part 1. The orthosis prototype was then loaded both individually, through attachment to a wooden board, and while worn by a user (Figure 61). All loadings were completed with the prototype in the neutral position.



Figure 61—Strength testing while on user (left) and mounted to board (right)

10.2 Range of Motion & ADL testing

Range of motion and ADL testing were completed to determine if the final prototype had an adequate motion envelope and overall functionality to satisfy the design specifications. At the minimum, the device was required to allow a user to successfully complete the designated ADL tasks. Both types of testing required the cooperation of third party subjects for an unbiased test of the prototype shoulder mount. All testing procedures received prior approval from the WPI Institutional Review Board.

It was determined early on that each test subject would serve as their own control. This was accomplished by having each test subject complete each test both with and without wearing the prototype. Therefore, it became important for the order of tasks to be meticulously planned and structured to prevent premature exposure to the prototype. By initially limiting the test subject's exposure to the prototype, the group intended to capture any adaptive learning exhibited by the test subjects upon first exposure. Adaptive learning is defined as any noticeable differences observed in a test subject's execution of each ADL task once the prototype was worn.

To develop the structured order of the user testing, both the range of motion and ADL testing were fully completed by one group member to find possible problems with the testing

procedure and ensure all that necessary data was collected. As a result of the preliminary testing a detailed document of testing procedures was created (Appendix I). Additionally, the preliminary testing was used to verify the accuracy of certain data collection methods.

Upon arrival, test subjects were given a consent form which stated the various testing procedures and data collection methods utilized, such as video recording and photography (Appendix J). The first data collected from the test subjects consisted of demographic and biographical data such as gender, height, handedness, and various limb dimensions. Next, the subjects underwent the range of motion testing procedures without the prototype. This was then followed by the completion of the ADL testing procedures, also without the prototype. Upon completion, the test subjects donned the prototype and had it properly adjusted by the group members to maximize comfort and functionality. The test subjects then completed the ADL testing for a second time, which was followed by a repetition of the range of motion testing while also wearing the prototype. After completion of this final task, the test subjects had completed all direct testing. After filling out a user friendliness questionnaire test subjects were free to leave.

The range of motion testing was intended to determine the user's original motion envelope, and then the reduced envelope that resulted when the prototype was used. To complete the range of motion testing, the test subject was requested to perform several specific arm movements with the final positions photographed (Figure 62).

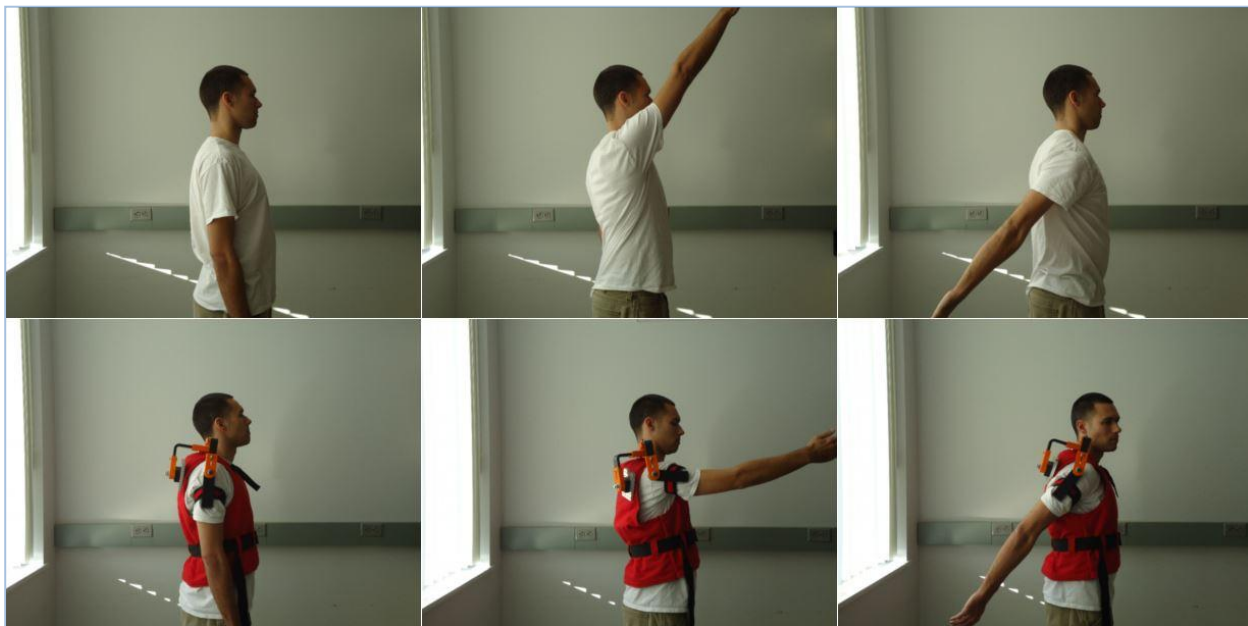


Figure 62—Maximum and minimum flexion, with and without prototype

Before testing started, test subjects were asked to stand in the neutral position, with their hands by their sides. To simplify data collection and procedures—and to be consistent with the ADL data—extension was labeled as negative flexion, and adduction was labeled as negative abduction. The test subjects then raised their right arm forward, elbow locked, to the maximum flexion position. Next, the test subjects moved their arm to the minimum flexion position. The third movement involved the subjects raising their arm to shoulder height and then moving the arm left to the maximum abduction position. This was followed by a right arm movement to the minimum abduction position (Figure 63).



Figure 63—Maximum and minimum abduction, with and without prototype

The ADL testing was started following completion of the range of motion testing. The activities completed for the ADL testing involved both sitting and standing tasks from the following categories: hygiene, everyday object use, and feeding. The test subject began the ADL testing with the standing activities. First, the test subject was asked to reach the opposite armpit, the opposite side of the neck, and the back of the head with the right arm. Next the subject was given a 5 lb weight to hold and was directed to raise the weight to both shoulder height and head height while the arm remained straight. The subject then moved on to the sitting activities. The test subject was asked to simulate eating and drinking with an apple, a spoon, and a coffee mug.

The ADL testing concluded when the test subject simulated the answering of a telephone. Examples of some of the ADL tests are displayed in Figure 64.



Figure 64—ADL examples shown from two angles

10.4 User Friendliness

Testing related to user friendliness was performed in conjunction with range of motion and ADL testing. All user friendliness testing involved the ratings of the prototype on a prepared questionnaire using a five point Likert Scale (Appendix K). The scale went as follows: 1=Extremely unfriendly , 2=Somewhat, 3=Neutral, 4=Not Very, 5=Not at All. Six test subjects were used to gather the test data. The test subjects were requested to fill out each section of the user friendliness questionnaire directly following the relevant action within the greater range of motion and ADL testing procedures. This questionnaire was separated into four sections: comfort while donning the device, comfort while wearing the device in a neutral position, comfort while completing range of motion and ADL activities, and comfort while doffing the device. Space was provided for users to insert additional comments that arose after the conclusion of prototype testing.

11. Results

The raw data that resulted from the various prototype tests is included in the following sections. The data is a combination of quantitative measures and dimensions, qualitative descriptions, and comments provided by the test subjects, as well as observations noted by the team members.

11.1 General Testing

To find the final results for the prototype's weight, each measure was taken three times and then averaged to increase accuracy. A test subject weighing 185 lbs was used to hold each prototype section as they were weighed. Following this procedure it was found that the mechanism subsystem and the torso mount subsystem weighed 1.4 lbs and 2.0 lbs respectively. This resulted in an overall mechanism weight of 3.4 lbs. Complete weight and dimensional data can be found in Appendix L.

To gauge the overall size and bulkiness of the final design, the dimensions along each of the major axis were measured. At the maximum adjustment setting the prototype was found to have length (z), width (x), and height (y) measurements of 203 mm x 200 mm x 282 mm, respectively. At the minimum adjustment settings the measurements were found to be 173 mm x 170 mm x 252 mm, respectively. A better test for the bulkiness was how far the prototype extended beyond the user's shoulder in each major axis direction. These measurements were 89 mm (z), 95 mm (x), and 108 mm (y) (Figure 65).

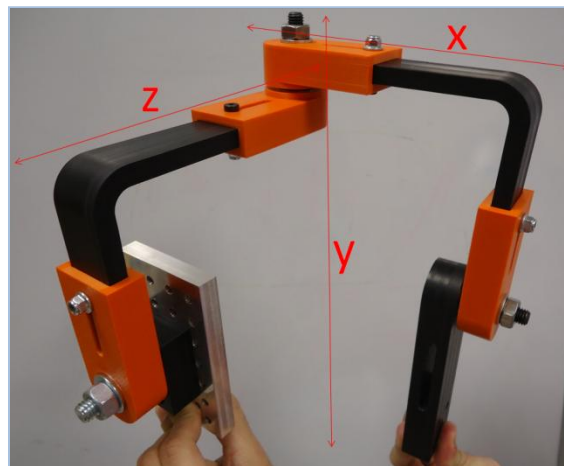


Figure 65—Measurement axes for mechanism subsystem

For the fastener analysis each major pin joint was oscillated through 100 cycles. After this simulated high-usage activity, the pin joint fasteners were examined for loosening. After all cycles were completed for each fastener the team noticed no adverse loosening of any of the fasteners. The current fasteners chosen provide sufficient force for a sound assembly.

Two incidences of interference were found through the interference testing. All incidences of interference occurred when the prototype was adjusted to its minimum setting, and no incidences of interference occurred at the maximum adjustments. Part interference occurred between Part 8 and the adjustment screw attached to Part 7. This interference occurred between the minimum adjustment setting—0 mm—and continued until a positive adjustment of 9 mm. An additional interference occurred between Part 5 and the shoulder “u-piece” (Part 10), when Part 6 and Part 7 were adjusted to the minimum setting. The locations of interferences that occurred at the minimum adjustment setting are displayed in red (Figure 66).

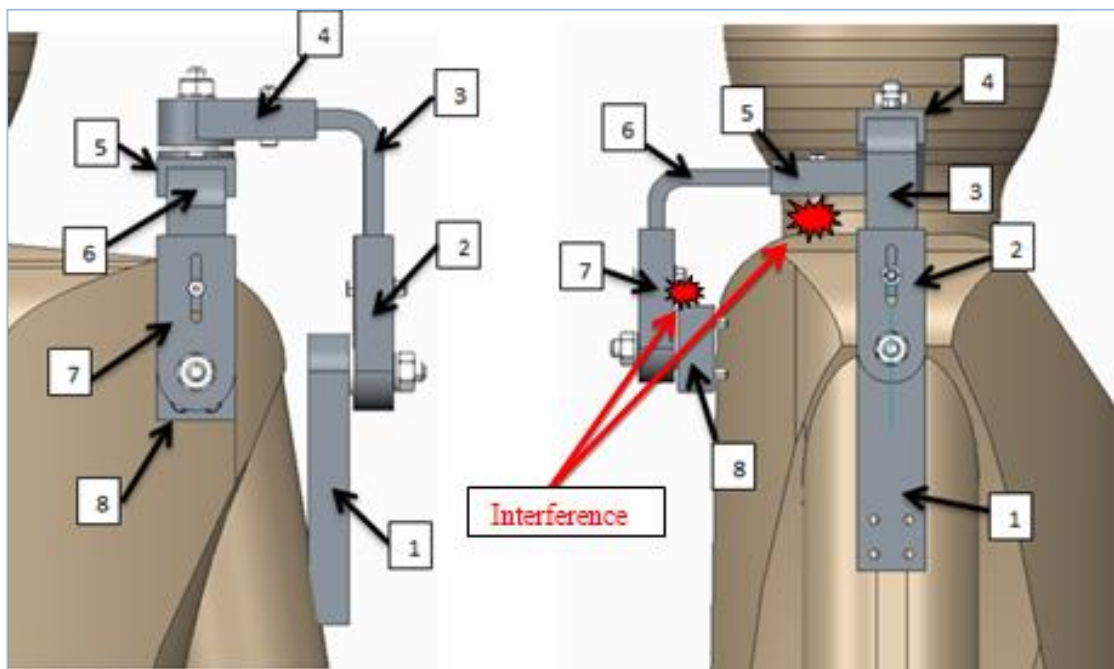


Figure 66—Part interference during operation

During general testing, the group found that the device did not function well with all three degrees of freedom enabled. The whole device would rotate and fall during use, and then would not return to its initial position when the user returned their arm to the neutral position.

The group therefore locked one degree of freedom by replacing the shoulder bolt in Part 7 and Part 8 with a normal bolt, as explained in previous sections. The rest of the testing and analysis was performed with two degrees of freedom enabled.

11.2 Strength Characteristics

To determine the strength of the prototype under loading, a variety of strength tests were performed. The prototype was loaded with a 5 lb and then a 10 lb weight while clamped to a board and the deflection of Part 6 along the x-axis was recorded at both minimum and maximum settings. The deflection when loaded with a 5 lb (22.24 N) weight was 3 mm and 5 mm for the minimum and maximum settings, respectively (Table 13). For the prototype loaded with a 10 lb (44.48 N) weight on minimum settings, there was a deflection of 8 mm. From this result, along with the fact that adjusting the settings from minimum to maximum increased the deflection by a factor of two, it was decided that 10 lbs at the maximum setting would be unsafe. Furthermore, the situation would be unrealistic because the arm itself would support a majority of the weight.

Table 13—Prototype Strength Testing Results

	Weight (lb)	Adjustment Setting	Resulting Deflection
Device Mounted to Board	5 (22.24 N)	Min	3 mm
	5 (22.24 N)	Fully Extended	5 mm
	10 (44.48 N)	Min	8 mm
	10 (44.48 N)	Fully Extended	Not Tested
Device Worn on User	5 (22.24 N)	User	Passed
	10 (44.48 N)	User	Undeterminable

In addition to this test, the prototype was fitted to a user and the weights were attached again at the user's settings. With the 5 lb weight, the prototype was able to withstand the loading, though there was some discomfort to the user. The user expressed a pressure point on the shoulder when the weight was added. The 10 lb test did not produce useable results when the weight was added, as the vest simply slid off of the user's shoulder. This is most likely due to the

vest's structure not being the most suitable for this prototype, meaning that it is not fitted well enough to the user.

11.3 Range of Motion & ADL testing

Data was collected for the range of motion and ADL testing for each test subject while both wearing and not wearing the prototype. This allowed for each test subject to act as a control to reveal any differences caused by the use of the prototype. Data for the range of motion was collected in the form of pictures and then quantified while the ADL testing was collected in the form of video recording and then analyzed. Potentially relevant information and measurements for each subject were recorded (Table 14).

Table 14—Test Subject General Data

ID	Gender	Handedness	Age	Relevant Body Dimensions					Height Percentile
				Height	Bi-Deltoid	Humerus	Forearm	Hand	
Test Subject 1	Female	Right	20	5' 2"	15.5"	13.5	10"	6.5"	25%
Test Subject 2	Male	Right	21	5' 7"	17.5"	14"	12"	7"	25%
Test Subject 3	Female	Right	21	5' 6"	16.5"	14"	11"	7.5"	75%
Test Subject 4	Male	Right	22	5' 9"	19.5"	14"	12"	8.5"	50%
Test Subject 5	Female	Right	21	5' 4"	16.6"	14"	11"	6.5"	50%
Test Subject 6	Male	Right	21	5' 11"	19"	14"	11"	7"	75%

11.3.1 Range of Motion

To properly measure angles of flexion and abduction, photographs were taken perpendicular to the sagittal (side view) and transverse (top view) planes and then imported into the program AutoCAD. From here, these angles were able to be quickly and easily measured (Figure 67).

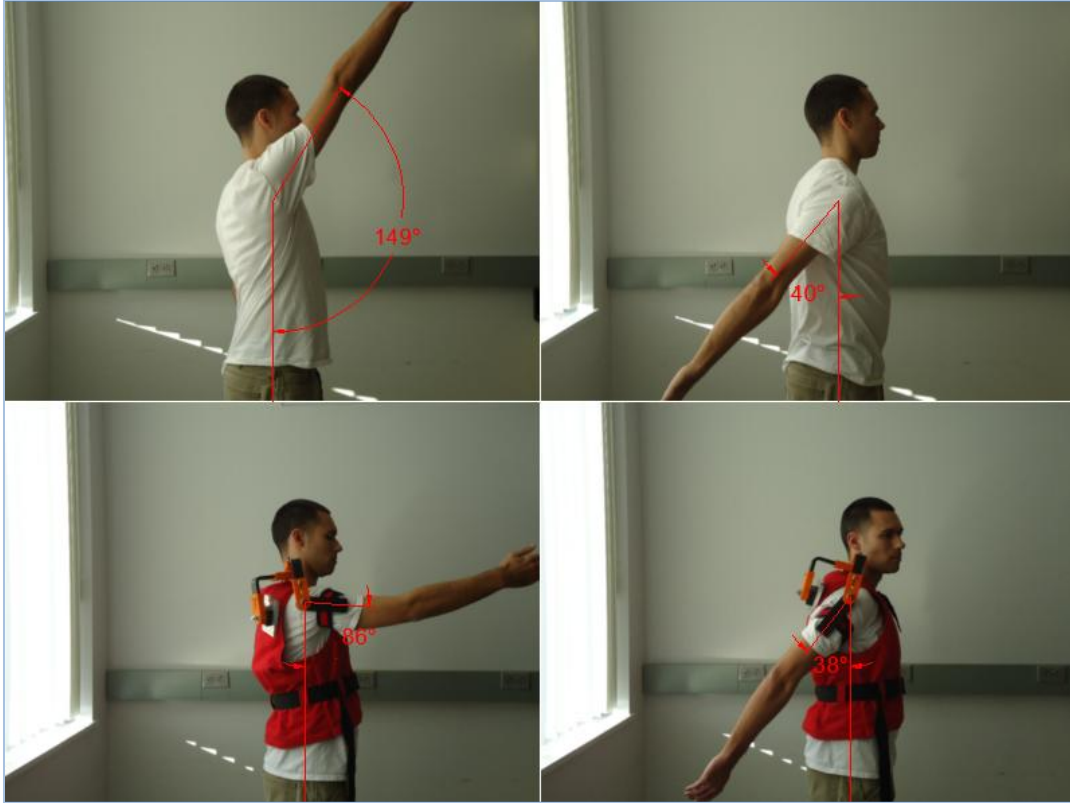


Figure 67—Measuring flexion (left) and extension (right) angles, with and without prototype

When measuring flexion, a line was first drawn straight down from the approximate center of rotation of the shoulder joint, and then a second line was drawn from the same center point along the upper arm. This second line was drawn parallel to the humerus when the subject was unrestricted and parallel to Part 1 of the prototype when it was worn. This was to ensure that the measurement did not take compliance of the vest or slipping of the armband into account. The resulting angle measurement between the two lines was recorded in an Excel sheet, a portion of which is displayed (Table 15). While further analysis can be found in the next section, this table includes the angles required to complete the ADLs. The complete set of recorded data can be found in Appendix K.

Table 15—Range of Motion Angle Measurements for First Test Subject

Test Subject #1	Shoulder Flexion			Shoulder Abduction		
	Unrestricted	W/ Device	Required for ADLs (Murry & Johnson, 2004)	Unrestricted	W/ Device	Required for ADLs (Murry & Johnson, 2004)
Maximum	137°	95°	111.9°	98°	32°	39.7°
Minimum	-51°	-24°	14.7°	-39°	-40°	-20.1°
Maximum w/ Vest Compliance	-	119°	-	-	-	-
Total Range of Motion	188°	119°	97.2°	137°	72°	59.8°

Once again, to simplify analysis—and to be consistent with the ADL data—extension was measured and labeled as negative flexion, and adduction was measured and labeled as negative abduction.

11.3.2 ADL testing

The purpose of the ADL testing was to confirm that each test subject was able to accomplish all designated *Activities of Daily Living* both without and with the prototype shoulder mount being worn. A secondary purpose for this testing was to observe and record any adaptive learning that occurred for each test subject. Adaptive learning is defined as any noticeable differences observed in a test subject’s execution of each ADL task once the prototype was worn. All ADL testing data was recorded on video from two views, which were perpendicular to the sagittal (side view) and coronal (front view) planes.

Each test subject was successfully able to complete all *Activities of Daily Living*, both unrestricted and while wearing the prototype (Table 16). It was found that the majority of adaptive learning that occurred for each test subject was during the task which required the user to touch the back of the head. This difference was noticed in 75% of all test subjects (Table 17). Full and unabridged data tables for each test subject including observational comments are located in Appendix N.

Table 16—ADL Testing Checklist

		Were Activities of Daily Living Accomplished?					Check = Yes		X = No	
		Touch Armpit	Touch Neck	Touch Back of Head	Lift Weight to Shoulder	Lift Weight to Head	Eat Apple	Use Spoon	Drink Mug	Answer Phone
Female 25%	Natural	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Orthosis	✓	✓	✓	✓	✓	✓	✓	✓	✓
Female 50%	Natural	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Orthosis	✓	✓	✓	✓	✓	✓	✓	✓	✓
Female 75%	Natural	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Orthosis	✓	✓	✓	✓	✓	✓	✓	✓	✓
Male 25%	Natural	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Orthosis	✓	✓	✓	✓	✓	✓	✓	✓	✓
Male 50%	Natural	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Orthosis	✓	✓	✓	✓	✓	✓	✓	✓	✓
Male 75%	Natural	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Orthosis	✓	✓	✓	✓	✓	✓	✓	✓	✓

Table 17—Adaptive Learning Checklist

Task	Did Adaptive Learning Take Place?			Check = Yes			X = No		
	Female 25%	Female 50%	Female 75%	Male 25%	Male 50%	Male 75%	Female 25%	Female 50%	Female 75%
Touch Armpit	✗	✗	✗	✗	✗	✗	✗	✗	✗
Touch Neck	✗	✗	✗	✗	✗	✗	✗	✗	✗
Touch Back of Head	✓	✓	✗	✓	✓	✗	✗	✗	✗
Lift Weight to Shoulder	✗	✗	✗	✗	✗	✗	✗	✗	✗
Lift Weight to Head	✗	✗	✗	✗	✗	✗	✗	✗	✗
Eat Apple	✗	✗	✗	✗	✗	✗	✗	✗	✗
Use Spoon	✗	✗	Maybe	✗	✗	✗	✗	✗	✗
Drink Mug	Maybe	✗	✗	✗	✗	✗	✗	✗	✗
Answer Phone	✗	✗	✗	✗	✓	✗	✗	✗	✗

11.4 User Friendliness

The purpose for the five point Likert scale questionnaire was to gauge the comfort and user friendliness of the shoulder mount prototype. The scale went as follows: 1=Extremely unfriendly, 2=Somewhat, 3=Neutral, 4=Not Very, 5=Not at All. Each test subject completed the questionnaire and the results were recorded into an Excel spreadsheet (Table 18). The average rating was calculated to obtain a general quantitative data for each question. The lowest scored question, with an average rating of 3.00, was about noticeability of the device while standing in neutral position. After completing the table of average values, a bar graph was created to act as a visual aid of the results (Figure 68).

Table 18—Comfort and User-Friendliness Questionnaire Results;
Scale: 1=Extremely, 2=Somewhat, 3=Neutral, 4=Not Very, 5=Not at All.

1 being "Extremely" and 5 being "Not at All"	Average Rating	Subject Responses					
		1	2	3	4	5	6
Donning							
How difficult is it to don the device?	3.33	4	3	2	2	5	4
How difficult is it to fasten the straps?	4.33	5	4	5	2	5	5
Neutral Position							
How noticeable is the device?	3.00	2	4	4	2	2	4
Activities of Daily Living Testing							
<i>Hygiene</i>							
How difficult is it to reach left armpit?	5.00	5	5	5	5	5	5
How difficult is it to reach left side of neck?	5.00	5	5	5	5	5	5
How difficult is it to reach left side of head?	4.67	5	5	5	4	5	4
How difficult is it to reach back of head?	4.67	5	5	5	5	5	3
<i>Feeding</i>							
How difficult is it to eat with hand to mouth?	5.00	5	5	5	5	5	5
How difficult is it to eat with spoon?	5.00	5	5	5	5	5	5
How difficult is it to drink from mug?	5.00	5	5	5	5	5	5
<i>Everyday Object</i>							
How difficult is it to answer a telephone?	4.67	5	4	5	5	5	4
How difficult is it to raise weight to shoulder height?	4.83	5	5	5	5	4	5
How difficult is it to raise weight to head height?	4.83	5	5	5	5	4	5
Doffing							
How difficult is it to unfasten the straps?	4.83	4	5	5	5	5	5
How difficult is it to doff the device?	4.67	4	5	5	4	5	5

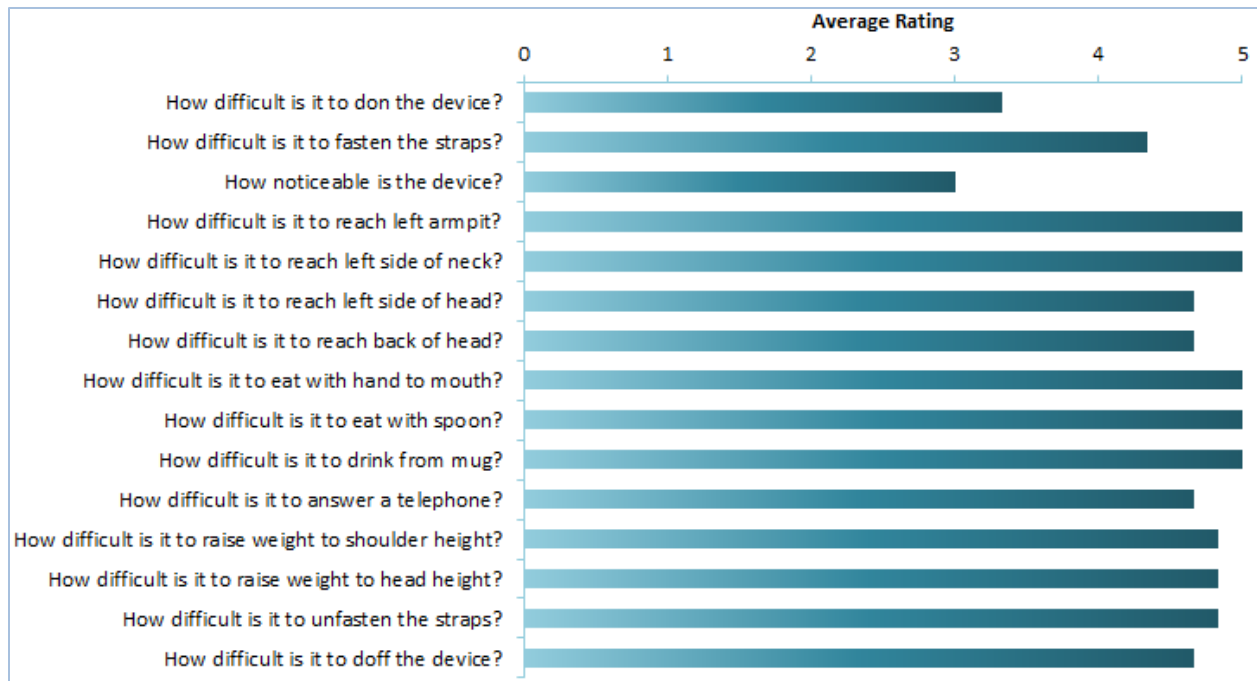


Figure 68—Results from the comfort and user-friendliness questionnaire; Scale: 1=Extremely unfriendly, 2=Somewhat, 3=Neutral, 4=Not Very, 5=Not at All.

11.5 Cost of Single Prototype

The previously described budget outlined the total costs associated with the entire development of the final prototype. However, this does not accurately reflect how much it would actually cost to manufacture one complete shoulder mount device, and thus estimate and suggest a possible price. To create this new budget the cost of the total material for each component was multiplied by the percentage of the material actually used within the prototype. This calculation resulted in a lower cost that ignored all extra raw materials.

Additionally, estimations for various manufacturing costs were made to reflect the actual manufacturing methods needed to create the proposed prototype. This was necessary because the initial budget did not include manufacturing costs, since manufacturing in the WPI labs and faculties is free for WPI students. Estimations for manufacturing were based on quotes from the WPI machine shop faculty for a proposed production scale of 100 parts. For the vest subsystem, the manufacturing cost estimation was based on examining the retail price of similar vests and adjusting the cost accordingly.

Based on the described estimations, the current cost for a single prototype is \$197.49. However, it is estimated that this price can easily be reduced by \$47.49 down to \$150.00, due to alternate fastener selection and scaling up the quantities of fasteners per order. Cost savings could also be found in scaling up raw material purchasing as well and by utilizing alternate materials for rapid prototype parts, as these were the single most expensive parts in the prototype. The full proposed cost of one prototype is detailed in Table 19.

Table 19—Cost of Single Prototype

Subsystem	Supplier	Description	Total Cost	Unit Type	Total Units	Units Used	Sub Total
Vest	Wal-Mart	Poly-Fil Tru-Foam	\$7.95	Inches ³	510	37.5	\$0.58
	Wal-Mart	Thermolam Plus Fabric	\$8.44	Yards	2	1.8	\$7.60
	Wal-Mart	Red Velcro	\$0.84	Units	1	1	\$0.84
	Wal-Mart	Red Duck Fabric	\$19.05	Yards	3	2	\$12.70
	Wal-Mart	Vest Pattern	\$3.16	Items	1	1	\$3.16
	Jo-Ann Fabrics	Krazy Glue Craft Gel	\$4.24	Ounces	14	14	\$4.24
	Jo-Ann Fabrics	2" Black Webbing	\$8.97	Inches	108	76.5	\$6.35
	Jo-Ann Fabrics	1" Black Webbing	\$3.58	Yards	72	29.5	\$1.47
	Jo-Ann Fabrics	1" Parachute Buckle	\$3.99	Items	1	1	\$3.99
	Jo-Ann Fabrics	2" Parachute Buckle	\$6.49	Items	1	1	\$6.49
Mechanism	Ultimate Plastics	ABS plastic 1.5"x5.5"x18"	\$56.38	Inches ³	53.6	15.1	\$15.87
	Ultimate Plastics	ABS plastic 0.125"x6"x48"	\$7.00	Inches ³	36	3.1	\$0.60
	WPI	PR ABS: 4 Parts, 18.61 in ³	\$40.76	Items	4	4	\$40.76
	McMaster-Carr	Aluminum Stock (6061) 0.5"x3"x12"	\$16.92	Inches ³	18	4.8	\$4.51
	McMaster-Carr	12mm Bronze Sleeve Bearing	\$1.86	Items	1	1	\$1.86
	McMaster-Carr	20mm Bronze Sleeve Bearing	\$4.20	Items	3	3	\$4.20
	McMaster-Carr	M5 Nylon-Insert Hex Flange Locknut	\$7.24	Items	100	4	\$0.29
	McMaster-Carr	M10 40mm Shoulder Screw	\$5.11	Items	1	1	\$5.11
	McMaster-Carr	M10 35mm Shoulder Screw	\$9.22	Items	2	2	\$9.22
	MSC	M5 Socket Head Cap Screw	\$21.57	Items	100	4	\$0.86
	MSC	M10 Flat Washer	\$4.08	Items	100	3	\$0.12
	MSC	M5 Button Head Cap Screw	\$9.51	Items	100	4	\$0.38
	MSC	M12 Flat Washer	\$7.69	Items	100	3	\$0.23
	MSC	M10 Hex Nut	\$6.28	Items	100	3	\$0.19
	MSC	M6 Socket Head Cap Screw	\$21.57	Items	100	4	\$0.86
Labor	WPI	Machining Costs	\$45.00	-	-	-	\$45.00
	Nikole	Vest Creation	\$20.00	-	-	-	\$20.00
Total							\$197.49

12. Discussion

12.1 Range of Motion Testing

Once the angle measurements were recorded, a detailed analysis of the data was performed to get a better understanding of the functionality of the prototype. The angles of rotation with and without the prototype were compared to each other and to the angles required to accomplish the ADLs. This analysis was performed separately for flexion (Table 20) and abduction (Table 21). Each table has six rows of data—one for each test subject—which display the angles that were recorded during the range of motion testing. These angles were compared with the required maximum and minimum angles taken from the ADL data, which are separated into their own columns. The right side of the table displays the percentage by which the prototype restricts the user’s movement. For example, if a subject’s maximum flexion was measured as 100° while unrestricted and 25° while wearing the device, their maximum flexion would be reduced by 75%. The angles are displayed in green, yellow, or red, depending on whether or not that angle requirement was met. Since it was difficult to get extremely accurate angle measurements during analysis of the testing photographs, the group concluded that recorded angles that were within 3° of the required angles were within an acceptable margin of measurement error and could be considered acceptable.

Table 20—Flexion Angle Analysis Results with Color Key, Comparing Required Angles with Recorded Angles

		Required Maximum Angle: 111.9°		Required Minimum Angle: 14.7°		Green = Pass	Yellow = Within Error	Red = Failed
		Unrestricted	W/ Device	Unrestricted	W/ Device	Total Motion Envelope Reduction	Maximum Flexion Reduction	Minimum Flexion Reduction
Recorded Angles	Subject1	137°	95°	-51°	-24°	37%	31%	53%
	Subject2	138°	91°	-55°	-12°	47%	34%	78%
	Subject3	157°	93°	-40°	-20°	43%	41%	50%
	Subject4	158°	90°	-62°	-30°	45%	43%	52%
	Subject5	158°	91°	-44°	-12°	49%	42%	72%
	Subject6	169°	96°	-64°	-45°	39%	43%	30%

The results shown that using this shoulder mount reduced the user's total flexion motion envelope by an average of 43%, while reducing maximum and minimum flexion by an average of 39% and 56%, respectively. The minimum flexion required for ADLs was listed as 14.7°, which was easily exceeded by an average of 68° unrestricted and 39° with the prototype. In all cases, the subjects were able to rotate far beyond the minimum requirement and actually achieved negative flexion, also called extension.

As expected, the data showed that all subjects were able to achieve the acceptable angles of flexion when unrestricted. However, all six test subjects failed to achieve the required maximum flexion while wearing the prototype. While these results are obviously not desirable, there are several reasons to explain why they are initially misleading. The first has to do with how the prototype was physically attached to the user's upper arm. As explained in previous sections, Part 1 includes a milled slot to hold an armband that attaches to the user's upper arm, which partially simulates the connection to the existing orthosis in the absence of the physical device. The problem with this armband was that it attached to the user's upper arm far too proximal to the shoulder, just below the armpit. This means that Part 1 has difficulty remaining parallel to the upper arm during rotation (Figure 69).

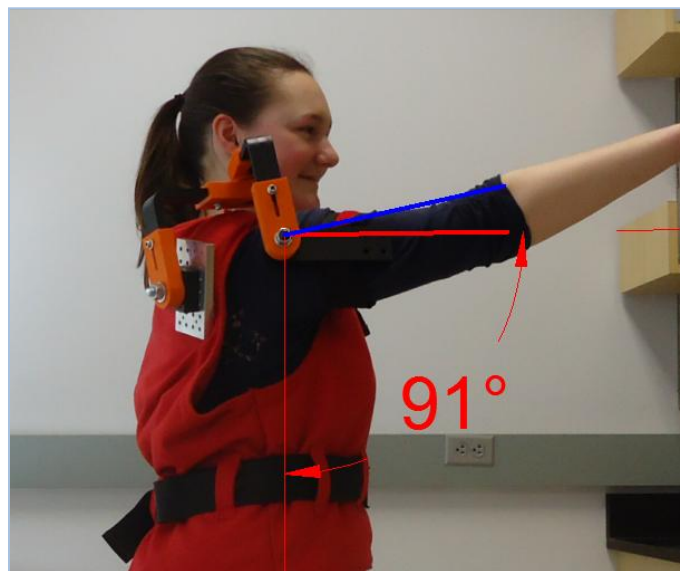


Figure 69—Difference between lines drawn parallel to Part 1 (red line) and the user's upper arm (blue line)

The flexion angles were measured parallel to Part 1 of the prototype, not parallel to the upper arm itself, regardless of whether or not Part 1 could theoretically achieve the same angle of

rotation. In reality Part 1 would also be attached to the existing orthosis, which will more securely hold the device in its proper orientation aligned with the upper arm. In that situation, the angle measured should be higher and nearly match the angle of flexion in the upper arm.

Another reason that the prototype’s apparent failure to achieve the required maximum flexion is misleading is because these results were calculated using measurements that only took into account the rotation of Part 1, and did not consider compliance of the vest. Test subjects were also instructed to raise their arm as high as they possibly could, letting the vest shift and move to allow for extended rotation. When these absolute maximum flexion angles were compared to the maximum flexion required by the ADLs, all test subjects were able to exceed it by an average of 20°.

During testing and analysis, the group also determined that the maximum flexion required for the ADL may be unnecessarily high. For example, while the ADL data states that this angle must be 111.9°, test subjects were able to raise a block to head height with only 86° rotation and touch the back of their heads at approximately 90° rotation, due to the help of the lower arm when accomplishing these tasks. It is apparent from this analysis that the published range of motion required to complete the ADLs may be flawed. As explained in a previous section, each test subject was able to successfully complete all the ADLs, even though the test data shows they were not always able to achieve the “required” angles of rotation.

An identical analysis was performed using the abduction data, which yielded similar results (Table 21). For the purpose of this analysis, adduction was measured and labeled as negative abduction.

Table 21—Abduction Angle Analysis Results with Color Key, Comparing Required Angles with Recorded Angles

		Required Maximum Angle: 39.7°		Required Minimum Angle: -20.1°		Green = Pass	Yellow = Within Error	Red = Failed
		Unrestricted	W/ Device	Unrestricted	W/ Device	Total Motion Envelope Reduction	Maximum Abduction Reduction	Minimum Abduction Reduction
Recorded Angles	Subject1	98°	32°	-39°	-40°	47%	67%	-
	Subject2	74°	30°	-33°	-17°	56%	49%	48%
	Subject3	104°	46°	-25°	-28°	43%	56%	-
	Subject4	98°	42°	-36°	-20°	54%	57%	44%
	Subject5	93°	38°	-44°	-41°	42%	59%	7%
	Subject6	110°	33°	-54°	-39°	56%	70%	28%

These results show that using this shoulder mount reduced the user's total abduction/adduction motion envelope by an average of 50%, while reducing abduction and adduction by an average of 61% and 32%, respectively. Two test subjects were actually able to achieve slightly greater adduction angles while wearing the prototype than they were able to unrestricted, but this was attributed to measurement and testing error.

While all six test subjects were able to achieve the required angle of adduction while wearing the prototype (within an acceptable margin of measurement error), about half of them were unable to achieve the required angle of adduction. These three subjects fell short of the required angle by an average of 8°. As stated earlier, even though half the subjects technically failed to achieve the "required" angles for abduction, all the subjects were able to successfully complete the ADLs. Therefore, there is a strong possibility that the existing ADL data, as published by Murray and Johnson (2004) is flawed and should be reevaluated.

12.2 ADL Testing

All ADL testing data was initially recorded in the form of raw video footage that needed proper analysis to be useful for drawing conclusions. Two types of analysis were performed on the video footage: one analysis to verify completion of each ADL task, and the other analysis to detect any possible adaptive learning. Once again, adaptive learning is defined as any noticeable differences observed in a test subject's execution of each ADL task once the prototype was worn.

A review of the collected footage was needed to confirm completion of the ADL tasks. A group member watched the recorded footage for each test subject, first without and then with the prototype worn, and recorded if the test subject succeeded or failed to complete the requested task. For this analysis, only footage from the coronal plane (front view) was reviewed, as it was clear from that single angle whether a task was completed without the need for a second viewpoint.

The method for observing and confirming adaptive learning was a much more complicated and involved process. First, two video feeds of the same test subject and viewpoint were opened simultaneously, one of the test subject with and the other without the prototype worn. Next, one of the feeds was played until a critical moment in an ADL task was reached, and then the video was paused. Using the task of "touching the back of the head" as an example, the

video feed would be paused at the moment where the back of the head is touched. The second video feed is then played and stopped at the same moment as the first video feed. The pausing of both video feeds provides easily comparable pictures of a critical point within each task that can then be directly compared for differences in arm angles and any other differences (Figure 70).



Figure 70— Comparison of the critical moment in the “touch back of head” task, demonstrating adaptive learning

Once all differences have been recorded, the video is advanced to the critical point of the following ADL task. The method is then repeated for each subsequent task until the end of the recorded footage is reached. Once the footage from the first viewpoint is finished, the procedure described above is repeated but with the alternate camera viewpoint opened in each video feed. The alternate viewpoint allows for further observations and notes to be recorded about any observed adaptive learning.

Adaptive learning was observed for every test subject except for the 75th percentile of both genders during the “touch the back of the head” ADL task. Interestingly, each test subject exhibited similar differences in behavior for this test when the prototype was worn. This indicates a general discomfort in the user’s range of motion when attempting to reach the back of

the head. However, by adapting to this discomfort, the user was still able to complete the ADL task successfully.

In each instance where adaptive learning was observed, the adaption involved a lower angle of flexion for the user's right arm, along with an angling of the head downwards. The angling of the head downwards decreased the distance the hand was required to cover to complete the task, thus decreasing the flexion required to complete the motion.

As previously stated, one possible reason for the modified behavior observed was the user's attempt to decrease discomfort felt. Reaching to the extreme flexion angles necessary to reach the back of the head may induce slightly more discomfort compared the other ADL tasks executed by the user. Each test subject exhibited the logical solution to the situation by modifying the reaching behavior for easier execution. A good description to classify this behavior is that the test subjects subconsciously sought out the, "path of least resistance," to complete the requested action.

12.3 User Friendliness

From the comfort and user-friendliness questionnaire, it is clear that the most difficult tasks were to don and fasten the straps of the device; however, even these tasks were not ranked as extremely difficult (Table 18). The scale went as follows: 1=Extremely difficult, 2=Somewhat, 3=Neutral, 4=Not Very, 5=Not at All. The tasks of performing the ADLs and doffing the device were all averagely ranked at 4.67 or higher, meaning that they were not very difficult to complete. This shows that the device does not restrict users to a degree in which they become uncomfortable completing ADLs.

Specifically, the tasks which required less movement of the shoulder scored higher on the questionnaire. For example, reaching the left armpit or left side of the neck received scores of 5.00, meaning it was not at all difficult, while reaching the left side and back of head received average scores of 4.67. The first two tasks appear to use much less motion of the shoulder, therefore leading to easier completion. The same occurrence can be seen in the sitting ADLs where eating and drinking received scores of 5.00 and answering a telephone received scores of 4.67.

Although completing the ADLs proved to be relatively easy, the subjects indicated that the prototype was slightly noticeable while being worn. This is not an unexpected result, as no

device is going to be seamless and unnoticeable. Additionally, one of the test subjects described the prototype as “being no less comfortable or noticeable than wearing a jacket.” These opinions and ratings of the device were formed after less than a 30 minute encounter with the prototype and may very well change if worn for longer periods of time. This is important because the comfort and user-friendliness of the device are what will determine if this is a successful solution to the problem at hand. These aspects of the device may seem insignificant, but in reality they are just as important as functionality of the device. If the user is not comfortable wearing the prototype, they will be unwilling to purchase and use it. The results of the questionnaire indicate that this design and prototype, if proven functional, would be successful based on the user’s comfort.

12.4 Design Specifications

At the outset of this project the group had the original goal, “to design, analyze, manufacture, and test a shoulder mount to be used in conjunction with a wearable, powered, upper-limb orthosis.” To determine the success or failure of this goal, design specifications were formulated that covered seven general categories. These categories provide the framework to determine how effectively the group’s final design for the orthosis shoulder mount met expectations.

12.4.1 Performance

The first, and arguably most important, category of specifications is the key performance specifications. All of these specifications are related to primary functionality of the orthosis shoulder mount prototype. Any failure of performance design specifications would result in a significantly hindered prototype that would not be acceptable for users.

The first and most specific design specification for the entire project was that the device must interface with existing powered orthosis with Patent Number US 8246559. The group interpreted the initial goal of the project to specifically develop a shoulder mount for potential attachment to Patent 8246559 and not to develop the specific attachment. This conclusion was assumed due to the fact that a proper interface solution would most likely require design modifications to both the group’s final shoulder mount prototype as well as to the Patent 8246559 prototype, which is clearly outside the scope of this project. Therefore, it can be stated

that the final prototype design passed the compatibility specification without actual physical coupling, attachment or interfacing between prototypes.

The first subcategory within the key performance specifications were those that had to do with user convenience. The device was required to weigh less than 5 lbs and actually weighed 3.4 lbs, which is well within the specifications. Additionally, the final prototype device was required to not interfere with the user's *anatomical position*, standing with arms by the sides, palms facing frontward, and feet together. Test subjects on average gave the prototype a rating of 3 on a 5 point Likert Scale. This rating corresponds to the stated descriptor of "neutral" when describing the noticeability. Additionally, it was observed that all test subjects were successfully able to rest and continually return to the anatomical position without interference from the prototype, verifying the specification.

The next subcategory deals with specifications related to the prototype's stability. The final prototype was required to remain functional on a user's body through full range of motion required to perform *Activities of Daily Living*. As shown by the ADL testing and the range of motion testing, the device remained functional and properly attached during all testing.

The range of motion subcategory was an important design specification, as this would primarily determine whether or not the device allowed user's to achieve sufficient mobility to for *Activities of Daily Living*. As explained earlier, the device alone successfully accomplishes the minimum flexion and abduction, and with vest compliance it is also able to accomplish maximum flexion. However, only 50% of users were able to reach the maximum abduction angle while wearing the vest. While this is less than desirable, the fact remains that all users were able to achieve a sufficient range of motion while wearing the device that enabled them to complete all the ADLs. From this fact the group concluded that the device met this design specification. Lastly, as the device was rotated through the full range of motion during testing it was confirmed that the users did not find any kinematic singularities.

The last subcategory dealt with all specifications related to the loading of the prototype. The device was required to distribute the weight of the prototype evenly over the user's torso. This specification was met through the use of the vest subsystem with in the final design. The device also had to withstand 10 lbs of force applied axially along the upper arm. This specification was confirmed during the strength testing of the prototype where the prototype deflected 8 mm without fracture when loaded with 10lbs.

12.4.2 Safety

Just as important as key performance were the safety design specifications. If a prototype was shown to injure or harm potential users, it would clearly be a failed design. The two main safety considerations outlined were that the device could not puncture or pinch the skin, as well as not cause tearing or entanglement of user's clothing. Through the extensive ADL and range of motion testing it was shown that the final prototype did not pose such safety hazards. No pinching, puncturing, or tearing was observed or reported by the test subjects during any and all tests.

12.4.3 User Friendliness

The third significant category of design specifications is user friendliness. If the device is both functional and safe, yet is not user friendly, it will not be accepted by users and will not be used. The user friendliness category was divided into four subcategories, all of which the final prototype passed.

The adjustability subcategory was confirmed when the device was successfully adjusted to all the test subjects used in the ADL and range of motion testing. The prototype was tested on a height percentile range of 25th to 75th for both men and women. Additionally, during testing the ease of donning and doffing were confirmed. Each test subject was able to don and doff the device in significantly less time than 2 minutes, with the greatest amount of time needed for the initial adjustment of the prototype, which did not factor into the time.

Two other minor subcategories addressed within user friendliness were skin irritation and aesthetics. The final prototype was required to not cause skin irritation, allergic reactions, rashes, or moisture build up. From the user testing it was observed that no significant amount of skin irritation or moisture buildup occurred, nor did any test subject comment on any such discomfort. For the aesthetic subcategory, the prototype needed to not increase the dimensions of the users body frame by more than 5". During the general testing it was found that the prototype extended beyond the shoulder in the z-direction by 3.5" (length), in the x-direction by 3.75" (width), and in the y-direction by 4.25" (height). This confirmed that the device did not extend 5" or greater beyond the user's shoulder in any axis direction.

12.4.4 Reliability

The final prototype design did not fail any reliability design specifications, but one was deemed inconclusive. The water-proof and sweat-proof specifications were passed due to the material selection, and did not require actual testing to confirm. The specifications required the design to be both waterproof and to not react to the sweat of the user. By utilizing various forms of ABS plastic and aluminum, among other generally inert materials, the design would be water- and sweat-proof. Additionally through the ADL testing, it was confirmed that the prototype device passed the specification requiring the materials to be durable to withstand *Activities of Daily Living* by not fracturing or failing throughout the course of testing.

The specification that was deemed inconclusive was that the device must have a lifetime of 5-8 years of normal use. No specific test could be feasibly conducted to verify this specification, which is clearly outside of the time limitations and scope of the project. To fully confirm and verify this specification, long term testing, such as fatigue testing, is necessary. Currently, due to the significant durability of the materials used to construct the prototype, it is estimated that the prototype will have a lifetime of at least 5 years. Thus the final design is considered to meet the reliability specifications.

12.4.5 Maintenance

It was determined that the device could be assembled and maintained by a trained technician, and that parts are easily accessible and detachable. Both of these specifications were confirmed through the adjustments made by the team members for the user testing. All adjustments went smoothly, utilized standard tools found in an everyday tool box, and did not require special knowledge exclusive to orthoses to complete.

One specification that remained inconclusive was that replacement parts to maintain the device must cost less than \$100 per year. No specific test was conducted to verify this specification, which would have gone outside the time limitations and scope of the project. To fully confirm and verify this specification, long term testing related to consistent use of the final prototype would be needed. Currently, due to the significant use of standardized parts and simple geometries of the milled parts, it is estimated that part replacement costs would not be exceptionally high. Thus the final design is likely to pass the maintenance specifications category successfully.

12.4.6 Cost

All cost specifications were successfully met by the final prototype. The two cost specifications required that the final design have both a material cost and manufacture cost less than \$450. After completion of the prototype, the estimated material costs and manufacture costs were \$132.49 and \$65, respectively, easily meeting all specifications.

12.4.7 Production

The final prototype design successfully met all production design specifications. There were two subcategories within the production category, which both were related to certain material and part utilizations. The first subcategory was that the device must utilize standardized fasteners where appropriate to aid in maintenance and manufacturability. The final prototype successfully met this specification by using all standardized parts for all fasteners. The second subcategory required the design to utilize rapid prototyping where appropriate. Four parts within the final design were created with the rapid prototype machine, satisfying the specification.

13. Conclusions

The goal of this project was to design, analyze, manufacture, and test a shoulder mount to be used in conjunction with a wearable, powered, upper-limb orthosis. In addition to the general problem, there were certain specifications which were vital to finding a viable solution: enable adequate mobility and functionality for *Activities of Daily Living (ADLs)*; be discrete, comfortable, and user-friendly, and ensure easy modification to fit multiple male or female users within the 25th to 75th percentiles for height. In order to solve this problem, research was conducted, preliminary designs were conceptualized, analysis was completed, a final design was manufactured, and lastly, the device was tested.

Conclusions were drawn from three sources: the data collected during testing, the analyzed data from the results, and the opinions formed in the discussions. The main conclusion is that the final design of the device is a viable solution to the presented problem. It allows the user to perform the necessary *ADLs* comfortably and without much difficulty. The device can withstand the forces which it would encounter through daily use and is successful in adjusting to both male and female users of the 25th to 75th height percentiles. Furthermore, the device is relatively discrete in terms of increasing body frame size and test subjects reported it is only slightly noticeable when wearing the device.

A second conclusion was discovered while analyzing the data for the range of motion testing. While finding the angles needed to accomplish each task and comparing them to those in a published study (Murray & Johnson, 2004), it was found that some of the test subjects were able to complete select *ADLs* in smaller angles than the minimum required angles in the study. Due to this finding, it seems that these angles need to be reevaluated to account for adaptive learning in certain circumstances which may decrease the minimum angle needed to accomplish various *ADLs*.

14. Recommendations

Once the design had been conceptualized, manufactured, and tested, the final step was to make recommendations for improvement. One usually expects to encounter issues with first generation prototypes, and it is important to learn from these issues when moving forward. The following section outlines several recommendations for future work related to this prototype shoulder mount device.

14.1 Torso Mount Subsystem

14.1.1 Vest

During prototype testing, the group noticed that the vest did not fit any test subject very well. This was due to the fact that the vest was purposely oversized during production to account for the extra padding that was stitched between the layers of cloth. Extra material was also used because the group decided that it would be better to create a vest that was slightly too big, rather than too small. To ensure a better-fitting vest, it is recommended that less material is used to make the vest. Enlisting the help of a skilled seamstress with experience in creating custom clothes would also result in a vest that would be more comfortable to wear, and provide a more stable platform for the mechanism subsystem.

14.1.2 Vest Components

In this prototype, the component that is embedded in the vest and hooks over the shoulder (Part 10) was a simple flat piece of plastic that was bent into an approximate U-shape (Figure 72). This part rested on an angle when it was worn by the user, due to the fact that Part 10 was flat and the shoulder sloped down slightly. This angle difference caused the rest of the device to rotate along with it, instead of remaining parallel to the axis of rotation. While the pin joint between Part 7 and Part 8 allowed for correction of this rotation, it is recommended to redesign Part 10 to be concentric with the user's shoulder (Figure 71).

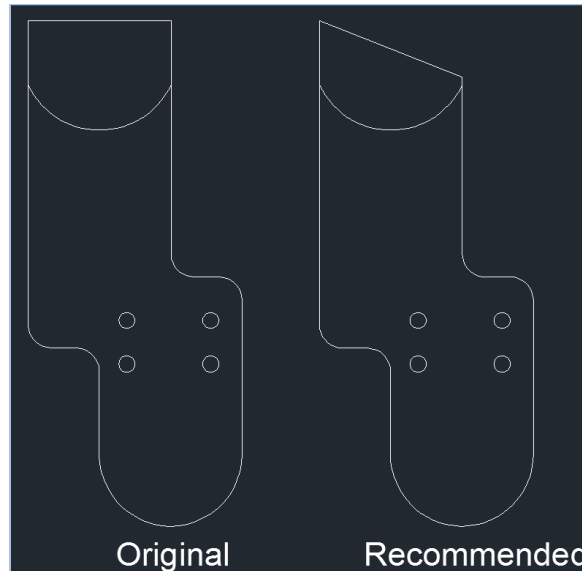


Figure 71—Original part with flat top (left) versus recommended part with slanted top (right)

Twenty-eight holes were tapped in Part 9 to allow for a range of attachment options for the mechanism subsystem. However, the group never encountered a situation which required the use of any of the extra holes. In the future it is recommended that Part 9 only include the holes that are required to attach Part 8 or possibly consider a design that completely eliminate Part 9 altogether. Each of these extra adjustment holes needed to be tapped, which was extremely time-consuming and therefore added significantly to the estimated manufacturing costs.

14.2 Mechanism Subsystem

14.2.1 Materials & Geometries

The prototype was not expected to encounter high loads, as it was primarily tested to confirm its range of motion. Therefore, the majority of parts were either made from ABS plastic or printed with a rapid prototype machine. In the future it is recommended that these parts be made out of a light metal such as aluminum. The increased strength of this material would allow the parts to be thinner and smaller, decreasing the device's overall size. The components that were rapid prototyped would need to be redesigned to be easily-machinable by more traditional manufacturing methods. The edges on all parts should be rounded off so as not to harm the user.

In general, the part geometries can all be improved to be more efficiently designed. Further FEA analysis is recommended for each part, and modifications should be made to remove excess material where it is not needed.

As explained in previous sections, the prototype encountered interference when rotated at a certain angle, but only when Part 6 was adjusted to its most retracted setting. This interference could be eliminated by rounding off the corners of Part 8 (Figure 72).

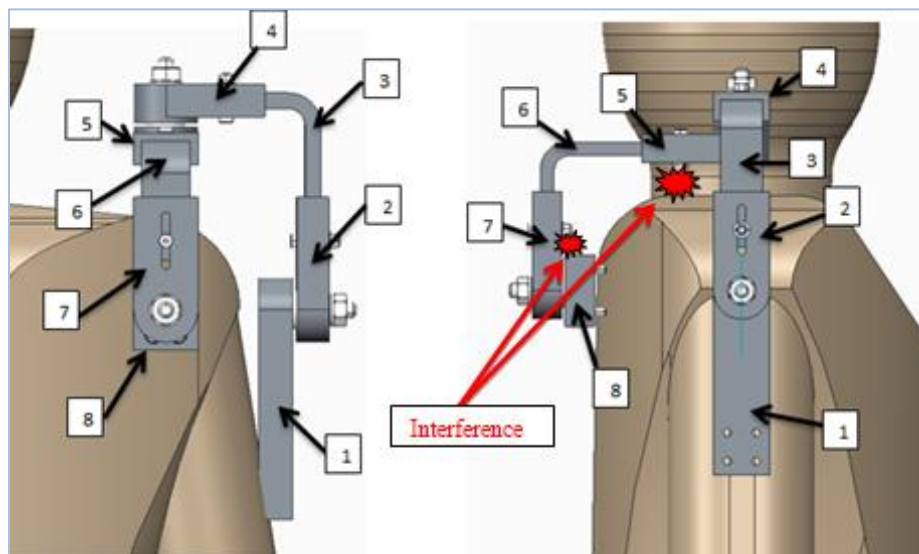


Figure 72—Part interference during operation

14.2.2 Adjustment Methods

The group recommends altering the methods by which the mechanism device is adjusted. The current method consists of a simple bolt and nut, which is loosened and tightened to adjust the device. While this method was successful, a second-generation prototype could benefit from a more advanced method of adjustment. Pull pins could be utilized to make adjustment more user-friendly and able to be accomplished without the use of tools.

14.2.3 Integration with Existing Orthosis

While this project focused on creating a shoulder mount for an already-existing arm orthosis, the prototype as it exists now cannot be connected to the orthosis. The two devices will connect with each other at Part 1, which needs further modification to allow for successful integration. It is also possible that the both the shoulder mount and the existing orthosis will need to be modified to allow for successful integration.

14.3 Alternative Design

This prototype was designed with three degrees of freedom in an effort to recreate the motion of the human shoulder. However it was quickly discovered that the prototype was able to accomplish its intended range of motion with only two degrees of freedom. The group replaced the shoulder bolt between Part 7 and Part 8 with a normal bolt, locking this degree of freedom (Figure 72). It is recommended in future designs to eliminate this entire pin joint, which would greatly simplify the design (Figure 73).

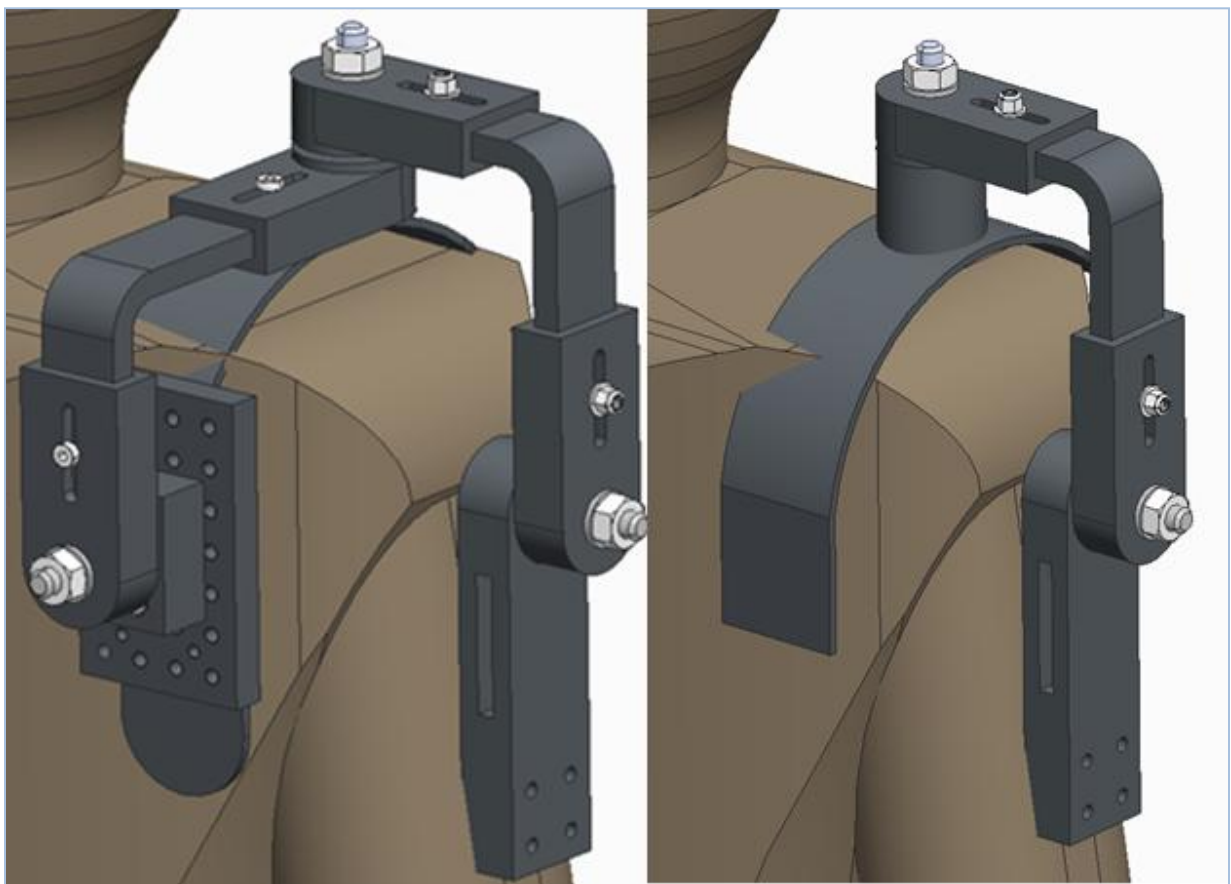


Figure 73—Three DOF device (left) versus conceptual shoulder pad two DOF device (right)

This alternative design concept would be lighter, less complicated, and requires less parts. If the shoulder mount device created for this MQP will be improved upon in the future, it is strongly suggested that this alternative design be further explored.

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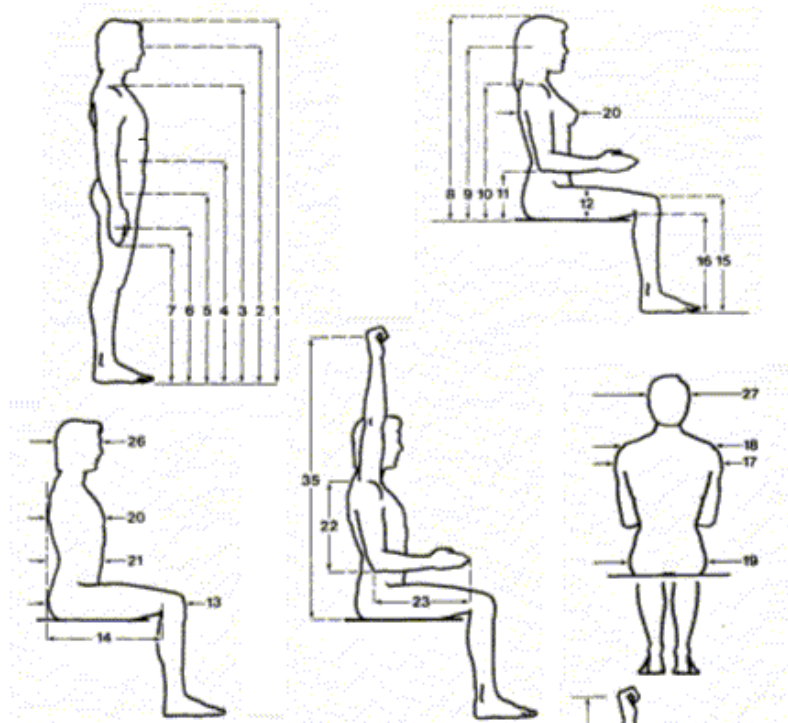
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Appendix A: Anthropometric Data

Data found within this section was used to determine the male and female dimensions for many key parameters. The source for data was the U.S. Department of Health and Human Services Centers for Disease Control and Prevention National Center of Health Statistics (Fryar, Gu, & Ogden, 2012). The figures quoted in the reference were subsequently based on National Health and Nutrition Examination Surveys conducted by the CDC from 2007-2010. Data was provided for the 5th, 25th, 50th, 75th and 95th percentiles as well as the standard error. The quoted data pertains to US citizens of all racial and ethnic groups aged 20 years and over.

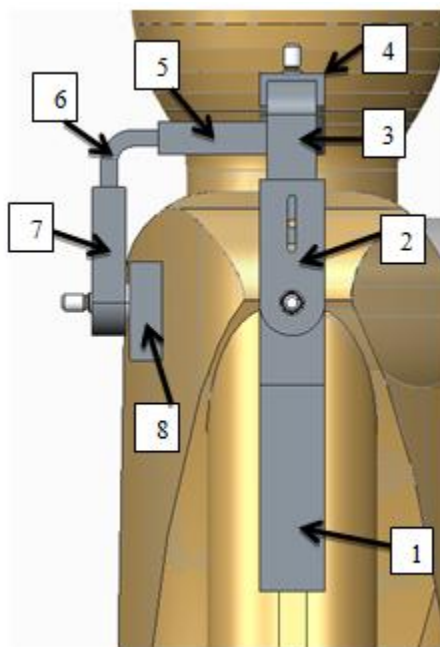
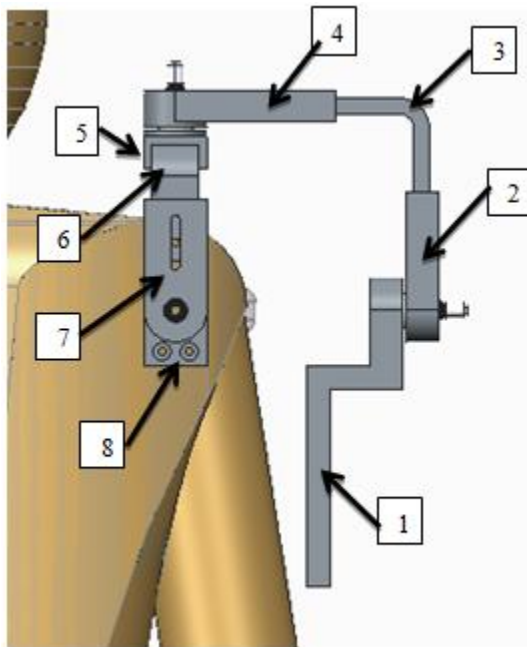
Anthropometric Data								
Measurement Name	Gender	Picture Label	5th Percentile	25th Percentile	50th Percentile	75th Percentile	95th Percentile	SE
Standing Height (cm)	M	1	163.2	170.9	176.1	180.9	188.2	0.20
Standing Height (in)	M	1	64.3	67.3	69.3	71.2	74.1	0.08
Standing Height (cm)	F	1	150.7	157.3	162.1	166.8	170.9	0.14
Standing Height (in)	F	1	59.3	61.9	63.8	65.7	68.4	0.05
Weight (kg)	M	-	61.5	75.0	86.1	98.9	124.1	0.45
Weight (lbs)	M	-	135.5	165.2	189.8	218	273.6	0.99
Weight (kg)	F	-	50.2	56.6	71.3	85.5	113.8	0.35
Weight (lbs)	F	-	110.7	134.6	157.2	188.6	250.9	0.78
Upper Arm length (cm)	M	22	35.2	37.5	39.0	40.6	42.9	0.07
Upper Arm length	F	22	32.2	34.3	35.8	37.1	39.4	0.06



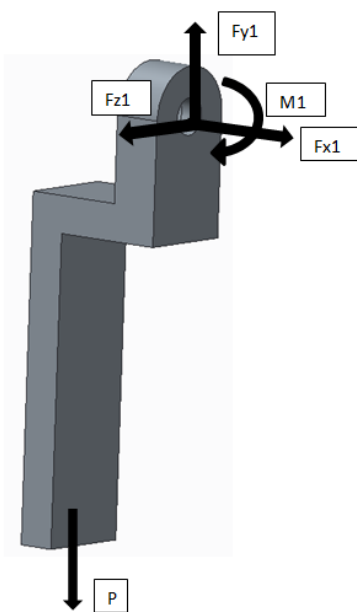
Anthropometric Diagrams (Karwowski, 2006)

Appendix B: Preliminary Free Body Diagrams

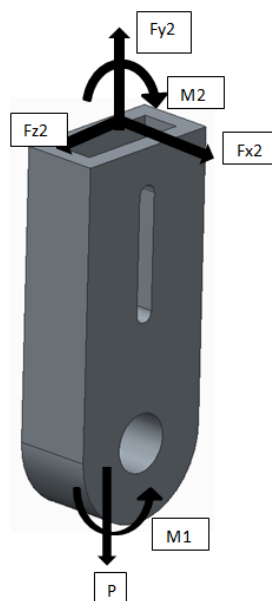
Assembly



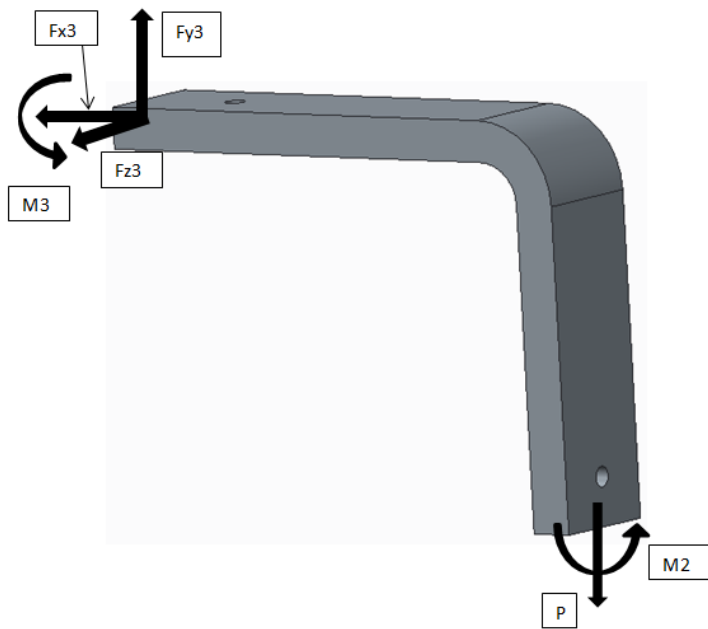
Part 1



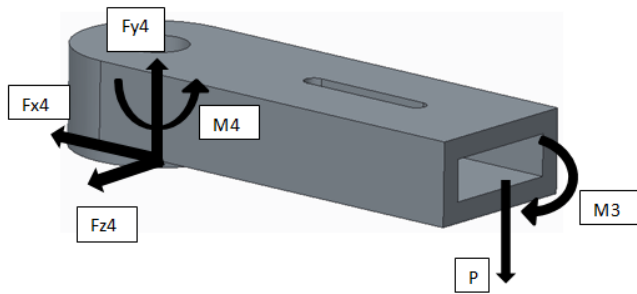
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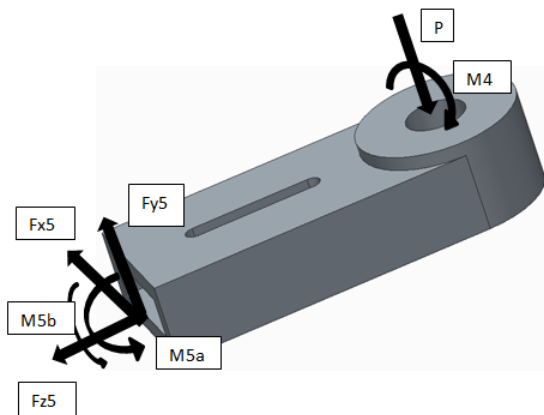
Part 3



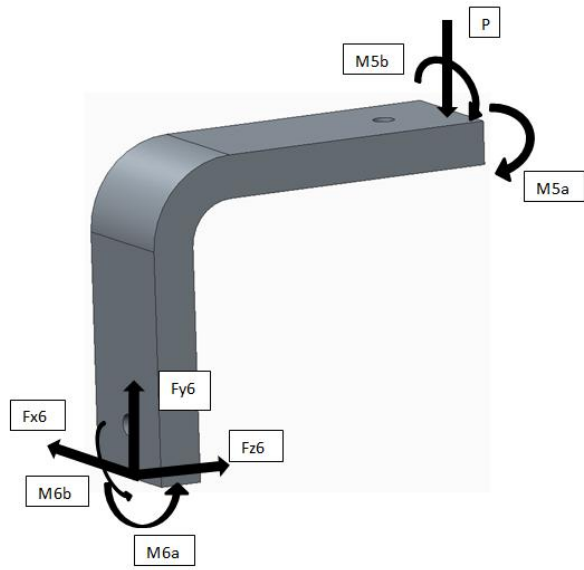
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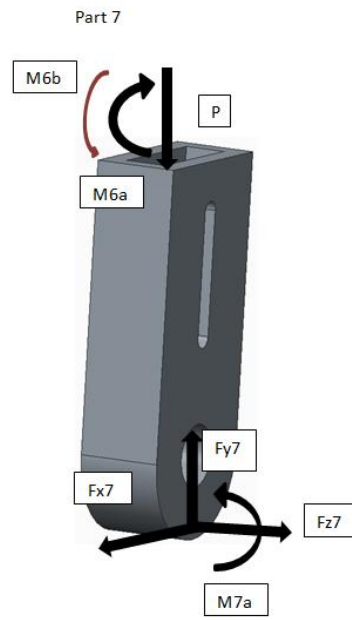
Part 5



Part 6

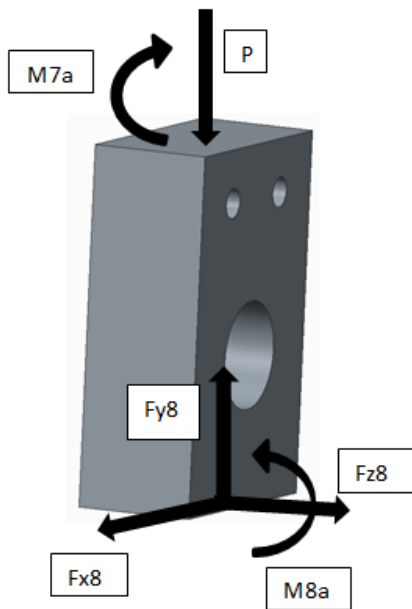


Part 7



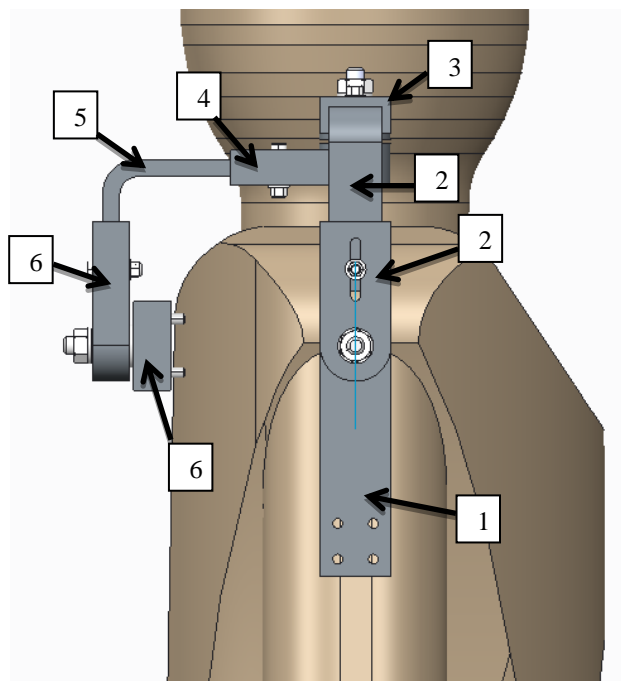
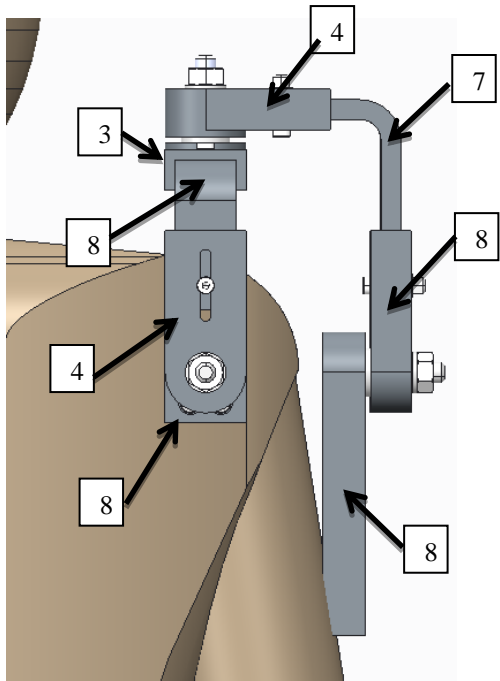
No reaction moment for M6b

Part 8



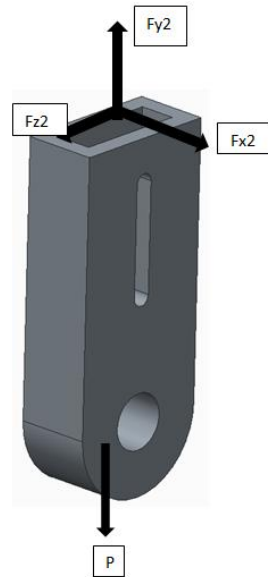
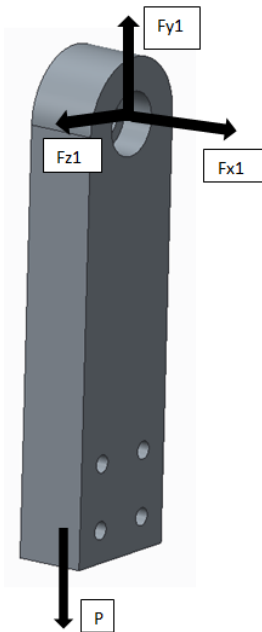
Appendix C: Final Free Body Diagrams

Assembly

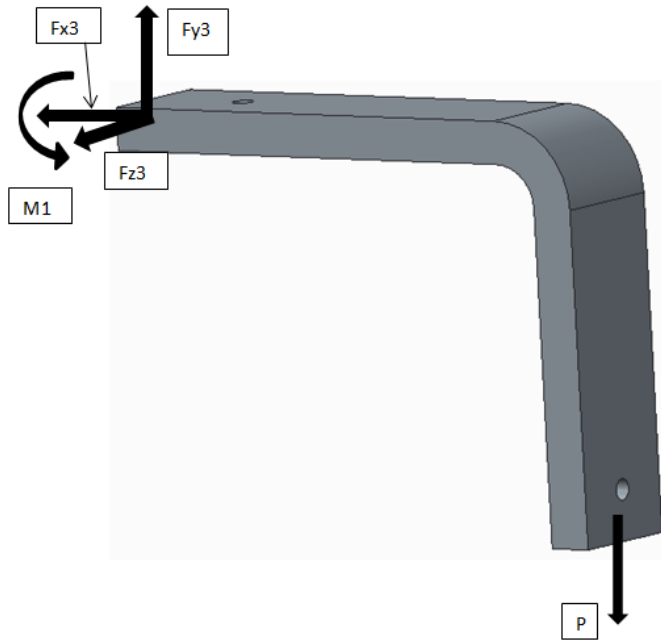


Part 1

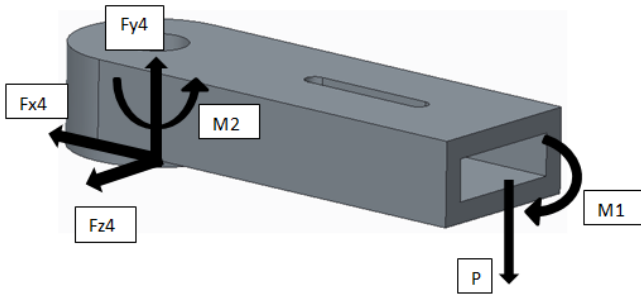
Part 2



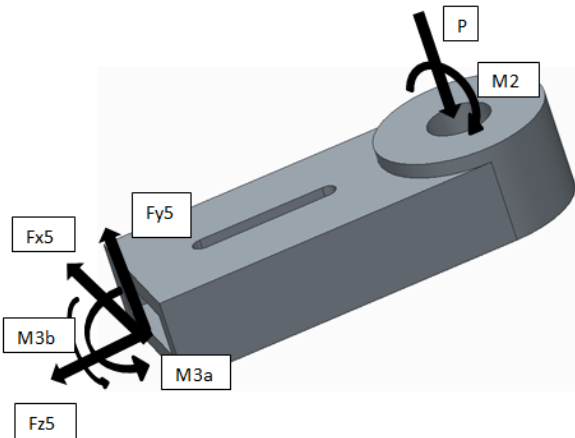
Part 3



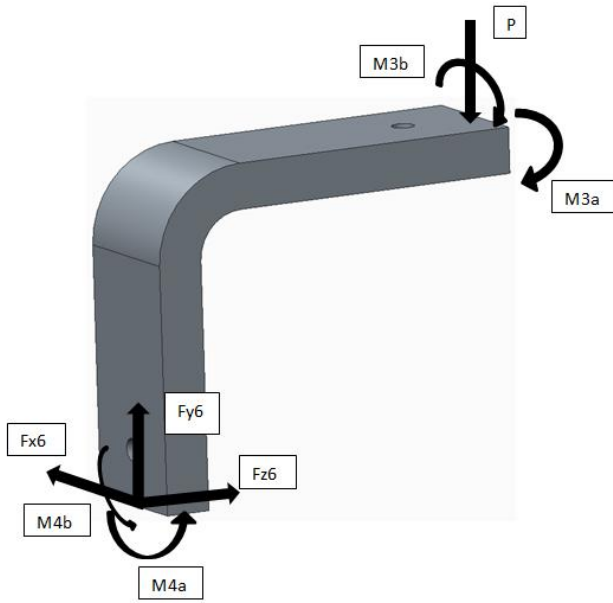
Part 4



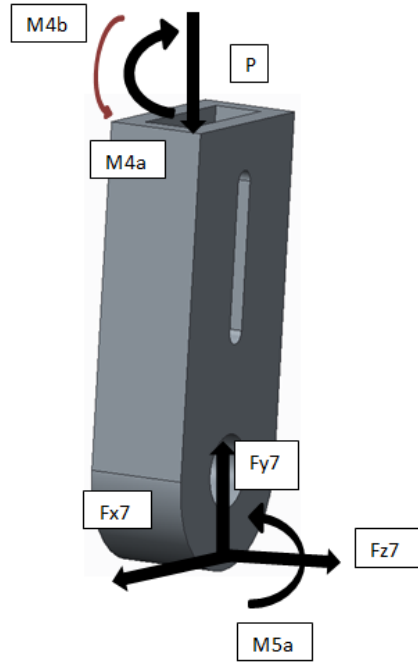
Part 5



Part 6

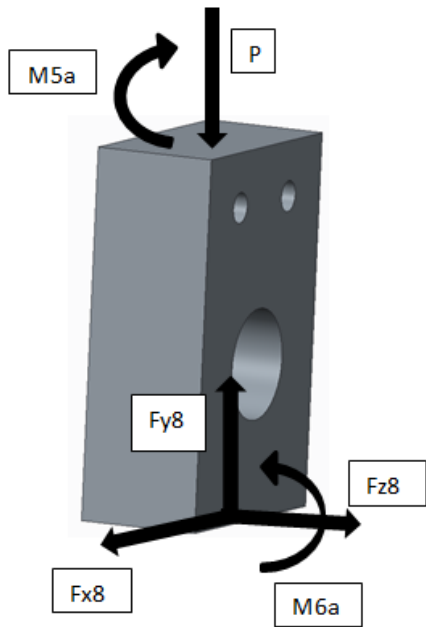


Part 7



No reaction moment for M4b

Part 8



Appendix D: Preliminary Static Equilibrium Calculations

Given:

Force Applied $P := 35.59\text{N}$ (8lbf)

Solution:

For Part 1

$$d_1 := 41\text{mm}$$

Summing the forces in the Y direction

$$\Sigma F_y = 0 = -P + F_{y1}$$

$$F_{y1} := P = 35.59\text{N}$$

Summing the forces in the X direction

$$\Sigma F_x = 0 = F_{x1}$$

$$F_{x1} := 0\text{N} = 0\cdot\text{N}$$

Summing the forces in the Z direction

$$\Sigma F_z = 0 = F_{z1}$$

$$F_{z1} := 0\text{N} = 0\cdot\text{N}$$

Summing the moments

$$\Sigma M = 0 = -P \cdot d_1 + M_1$$

$$M_1 := P \cdot d_1 = 1.459\text{N}\cdot\text{m}$$

For Part 2

Summing the forces in the Y direction

$$\Sigma F_y = 0 = -P + F_{y2}$$

$$F_{y2} := P = 35.59\text{N}$$

Summing the forces in the X direction

$$\Sigma F_x = 0 = F_{x2}$$

$$F_{x2} := 0\text{N} = 0\cdot\text{N}$$

Summing the forces in the Z direction

$$\Sigma F_z = 0 = F_{z2}$$

$$F_{z2} := 0\text{N} = 0\cdot\text{N}$$

Summing the moments

$$\Sigma M = 0 = -P \cdot d_1 + M_2$$

$$M_2 := P \cdot d_1 = 1.459\text{N}\cdot\text{m}$$

For Part 3

$$d_3 := 55\text{mm}$$

Summing the forces in the Y direction

$$\Sigma F_y = 0 = -P + F_{y3}$$

$$F_{y3} := P = 35.59\text{N}$$

Summing the forces in the X direction

$$\Sigma F_x = 0 = F_{x3}$$

$$F_{x3} := 0\text{N} = 0\cdot\text{N}$$

Summing the forces in the Z direction

$$\Sigma F_z = 0 = F_{z3}$$

$$F_{z3} := 0\text{N} = 0\cdot\text{N}$$

Summing the moments

$$\Sigma M = 0 = -P\cdot d_1 + P\cdot d_3 - M_3$$

$$M_3 := -P\cdot d_1 + P\cdot d_3 = 0.498\text{N}\cdot\text{m}$$

For Part 4

$$d_4 := 101.25\text{mm}$$

Summing the forces in the Y direction

$$\Sigma F_y = 0 = -P + F_{y4}$$

$$F_{y4} := P = 35.59\text{N}$$

Summing the forces in the X direction

$$\Sigma F_x = 0 = F_{x4}$$

$$F_{x4} := 0\text{N} = 0\cdot\text{N}$$

Summing the forces in the Z direction

$$\Sigma F_z = 0 = F_{z4}$$

$$F_{z4} := 0\text{N} = 0\cdot\text{N}$$

Summing the moments

$$\Sigma M = 0 = (-P\cdot d_1 + P\cdot d_3) + P\cdot d_4 - M_4$$

$$M_4 := (-P\cdot d_1 + P\cdot d_3) + P\cdot d_4 = 4.102\text{N}\cdot\text{m}$$

For Part 5

$$d_5 := 81.25\text{mm}$$

Summing the forces in the Y direction

$$\Sigma F_y = 0 = -P + F_{y5}$$

$$F_{y5} := P = 35.59\text{N}$$

Summing the forces in the X direction

$$\Sigma F_x = 0 = F_{x5}$$

$$F_{x5} := 0\text{N} = 0 \cdot \text{N}$$

Summing the forces in the Z direction

$$\Sigma F_z = 0 = F_{z5}$$

$$F_{z5} := 0\text{N} = 0 \cdot \text{N}$$

Summing the moments

$$\Sigma M_a = 0 = P \cdot d_5 - M_{5a}$$

$$M_{5a} := P \cdot d_5 = 2.892\text{N} \cdot \text{m}$$

$$\Sigma M_b = 0 = (-P \cdot d_1 + P \cdot d_3 + P \cdot d_4) - M_{5b}$$

$$M_{5b} := (-P \cdot d_1 + P \cdot d_3 + P \cdot d_4) = 4.102\text{N} \cdot \text{m}$$

For Part 6

$$d_6 := 30\text{mm}$$

Summing the forces in the Y direction

$$\Sigma F_y = 0 = -P + F_{y6}$$

$$F_{y6} := P = 35.59\text{N}$$

Summing the forces in the X direction

$$\Sigma F_x = 0 = F_{x6}$$

$$F_{x6} := 0\text{N} = 0 \cdot \text{N}$$

Summing the forces in the Z direction

$$\Sigma F_z = 0 = F_{z6}$$

$$F_{z6} := 0\text{N} = 0 \cdot \text{N}$$

Summing the moments

$$\Sigma M_a = 0 = P \cdot d_5 + P \cdot d_6 - M_{6a}$$

$$M_{6a} := P \cdot d_5 + P \cdot d_6 = 3.959\text{N} \cdot \text{m}$$

$$\Sigma M_b = 0 = (-P \cdot d_1 + P \cdot d_3 + P \cdot d_4) - M_{6b}$$

$$M_{6b} := (-P \cdot d_1 + P \cdot d_3 + P \cdot d_4) = 4.102\text{N} \cdot \text{m}$$

For Part 7

Summing the forces in the Y direction

$$\Sigma F_y = 0 = -P + F_{y7}$$

$$F_{y7} := P = 35.59\text{N}$$

Summing the forces in the X direction

$$\Sigma F_x = 0 = F_{x7}$$

$$F_{x7} := 0\text{N} = 0\cdot\text{N}$$

Summing the forces in the Z direction

$$\Sigma F_z = 0 = F_{z7}$$

$$F_{z7} := 0\text{N} = 0\cdot\text{N}$$

Summing the moments

$$\Sigma M_a = 0 = P\cdot d_5 + P\cdot d_6 - M_{7a}$$

$$M_{7a} := P\cdot d_5 + P\cdot d_6 = 3.959\text{N}\cdot\text{m}$$

$$\Sigma M_b = 0 = (-P\cdot d_1 + P\cdot d_3 + P\cdot d_4)$$

For Part 8

Summing the forces in the Y direction

$$\Sigma F_y = 0 = -P + F_{y8}$$

$$F_{y8} := P = 35.59\text{N}$$

Summing the forces in the X direction

$$\Sigma F_x = 0 = F_{x8}$$

$$F_{x8} := 0\text{N} = 0\cdot\text{N}$$

Summing the forces in the Z direction

$$\Sigma F_z = 0 = F_{z8}$$

$$F_{z8} := 0\text{N} = 0\cdot\text{N}$$

Summing the moments

$$\Sigma M_a = 0 = P\cdot d_5 + P\cdot d_6 - M_{8a}$$

$$M_{8a} := P\cdot d_5 + P\cdot d_6 = 3.959\text{N}\cdot\text{m}$$

Appendix E: Final Static Equilibrium Calculations

Equilibrium calculations

Given:

Force Applied $P := 35.59\text{N}$ (8lbf)

Solution:

For Part 1

$$d_1 := 4 \text{ m}$$

Summing the forces in the Y direction

$$\sum F_y = 0 = -P + F_{y1}$$

$$F_{y1} := P = 35.59\text{N}$$

Summing the forces in the X direction

$$\sum F_x = 0 = F_{x1}$$

$$F_{x1} := 0\text{N} = 0\text{N}$$

Summing the forces in the Z direction

$$\sum F_z = 0 = F_{z1}$$

$$F_{z1} := 0\text{N} = 0\text{N}$$

For Part 2

Summing the forces in the Y direction

$$\sum F_y = 0 = -P + F_{y2}$$

$$F_{y2} := P = 35.59\text{N}$$

Summing the forces in the X direction

$$\sum F_x = 0 = F_{x2}$$

$$F_{x2} := 0\text{N} = 0\text{N}$$

Summing the forces in the Z direction

$$\sum F_z = 0 = F_{z2}$$

$$F_{z2} := 0\text{N} = 0\text{N}$$

For Part 3

$$d_3 := 5.5 \text{ m}$$

Summing the forces in the Y direction

$$\sum F_y = 0 = -P + F_{y3}$$

$$F_{y3} := P = 35.59\text{N}$$

Summing the forces in the X direction

$$\sum F_x = 0 = F_{x3}$$

$$F_{x3} := 0\text{N} = 0\text{N}$$

Summing the forces in the Z direction

$$\sum F_z = 0 = F_{z3}$$

$$F_{z3} := 0\text{N} = 0\text{N}$$

Summing the moments

$$\sum M = 0 = P \cdot d_3 - M_1$$

$$M_1 := P \cdot d_3 = 1.957\text{m}\cdot\text{N}$$

For Part 4

$$d_4 := 101.26\text{mm}$$

Summing the forces in the Y direction

$$\sum F_y = 0 = -P + F_{y4}$$

$$F_{y4} := P = 35.59\text{N}$$

Summing the forces in the X direction

$$\sum F_x = 0 = F_{x4}$$

$$F_{x4} := 0\text{N} = 0\text{N}$$

Summing the forces in the Z direction

$$\sum F_z = 0 = F_{z4}$$

$$F_{z4} := 0\text{N} = 0\text{N}$$

Summing the moments

$$\sum M = 0 = (P \cdot d_3) + P \cdot d_4 - M_2$$

$$M_2 := (P \cdot d_3) + P \cdot d_4 = 5.561\text{m}\cdot\text{N}$$

For Part 5

$$d_5 := 81.26\text{mm}$$

Summing the forces in the Y direction

$$\sum F_y = 0 = -P + F_{y5}$$

$$F_{y5} := P = 35.59\text{N}$$

Summing the forces in the X direction

$$\sum F_x = 0 = F_{x5}$$

$$F_{x5} := 0\text{N} = 0\text{N}$$

Summing the forces in the Z direction

$$\sum F_z = 0 = F_{z5}$$

$$F_{z5} := 0\text{N} = 0\text{N}$$

Summing the moments

$$\sum M_a = 0 = P \cdot d_5 - M_{3a}$$

$$M_{3a} := P \cdot d_5 = 2.892 \text{ m}\cdot\text{N}$$

$$\sum M_b = 0 = (P \cdot d_3 + P \cdot d_4) - M_{3b}$$

$$M_{3b} := (P \cdot d_3 + P \cdot d_4) = 5.56 \text{ m}\cdot\text{N}$$

For Part 6

$$d_6 := 30 \text{ mm}$$

Summing the forces in the Y direction

$$\sum F_y = 0 = -P + F_{y6}$$

$$F_{y6} := P = 35.59 \text{ N}$$

Summing the forces in the X direction

$$\sum F_x = 0 = F_{x6}$$

$$F_{x6} := 0 \text{ N} = 0 \text{ N}$$

Summing the forces in the Z direction

$$\sum F_z = 0 = F_{z6}$$

$$F_{z6} := 0 \text{ N} = 0 \text{ N}$$

Summing the moments

$$\sum M_a = 0 = P \cdot d_5 + P \cdot d_6 - M_{4a}$$

$$M_{4a} := P \cdot d_5 + P \cdot d_6 = 3.959 \text{ m}\cdot\text{N}$$

$$\sum M_b = 0 = (P \cdot d_3 + P \cdot d_4) - M_{4b}$$

$$M_{4b} := (P \cdot d_3 + P \cdot d_4) = 5.56 \text{ m}\cdot\text{N}$$

For Part 7

Summing the forces in the Y direction

$$\sum F_y = 0 = -P + F_{y7}$$

$$F_{y7} := P = 35.59 \text{ N}$$

Summing the forces in the X direction

$$\sum F_x = 0 = F_{x7}$$

$$F_{x7} := 0 \text{ N} = 0 \text{ N}$$

Summing the forces in the Z direction

$$\sum F_z = 0 = F_{z7}$$

$$F_{z7} := 0 \text{ N} = 0 \text{ N}$$

Summing the moments

$$\sum M_a = 0 = P \cdot d_5 + P \cdot d_6 - M_{5a}$$

$$M_{5a} := P \cdot d_5 + P \cdot d_6 = 3.959 \text{ m} \cdot \text{N}$$

$$\underline{\underline{\Sigma M_b = 0 = (P \cdot d_3 + P \cdot d_4)}}$$

For Part 8

Summing the forces in the Y direction

$$\underline{\underline{\Sigma F_y = 0 = -P + F_{y8}}}$$

$$F_{y8} := P = 35.59 \text{ N}$$

Summing the forces in the X direction

$$\underline{\underline{\Sigma F_x = 0 = F_{x8}}}$$

$$F_{x8} := 0 \text{ N} = 0 \cdot \text{N}$$

Summing the forces in the Z direction

$$\underline{\underline{\Sigma F_z = 0 = F_{z8}}}$$

$$F_{z8} := 0 \text{ N} = 0 \cdot \text{N}$$

Summing the moments

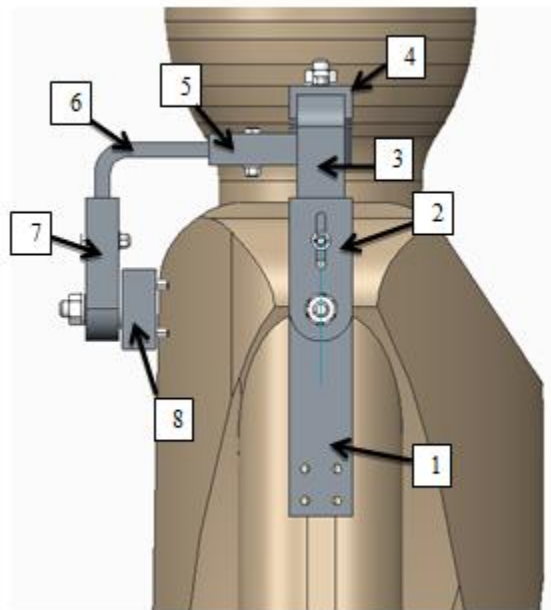
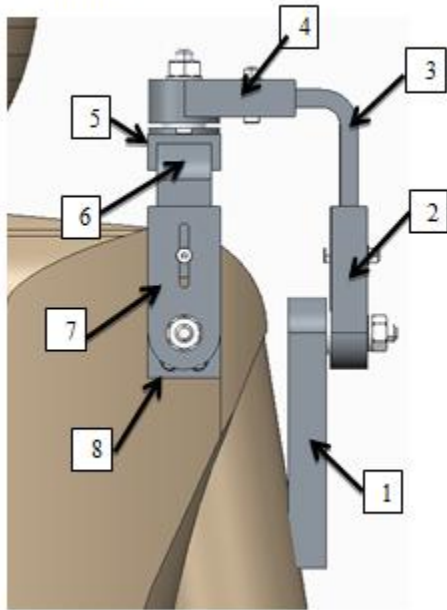
$$\underline{\underline{\Sigma M_a = 0 = P \cdot d_5 + P \cdot d_6 - M_{6a}}}$$

$$M_{6a} := P \cdot d_5 + P \cdot d_6 = 3.959 \text{ m} \cdot \text{N}$$

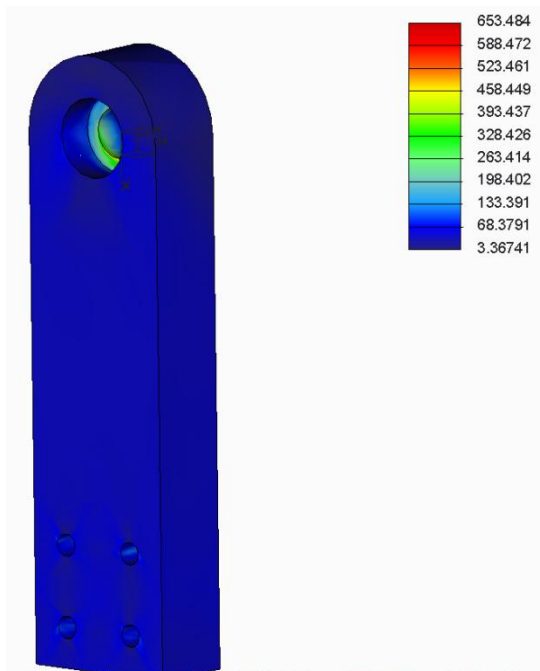
Appendix F: Finite Element Analysis

All units for the FEA analysis are in kPa.

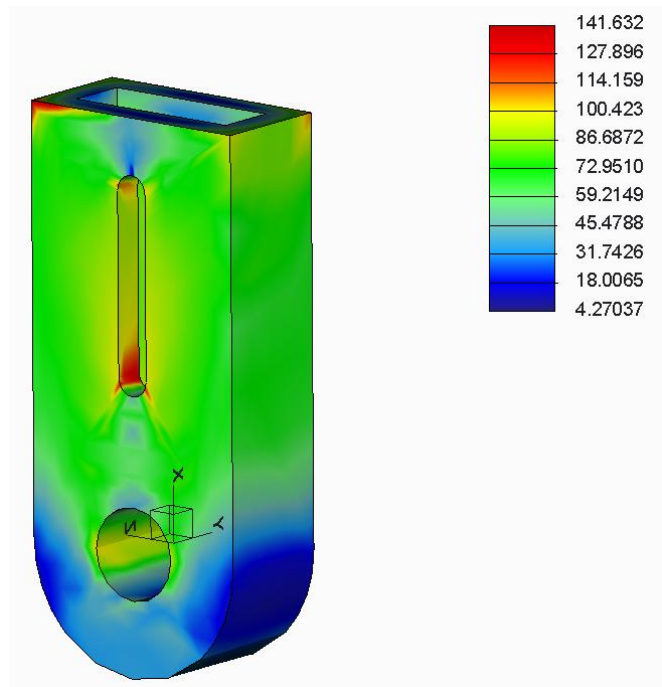
Assembly



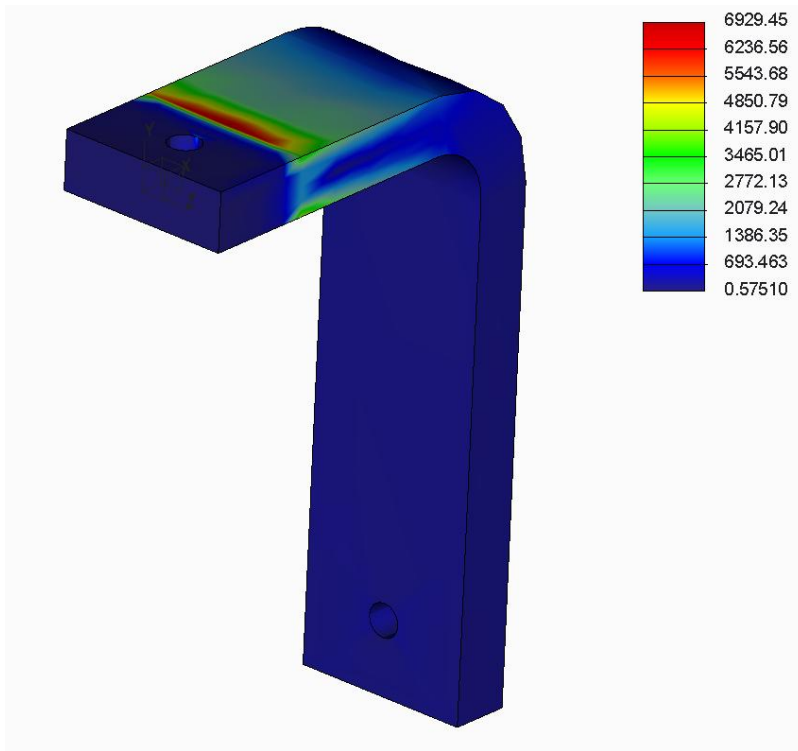
Part 1



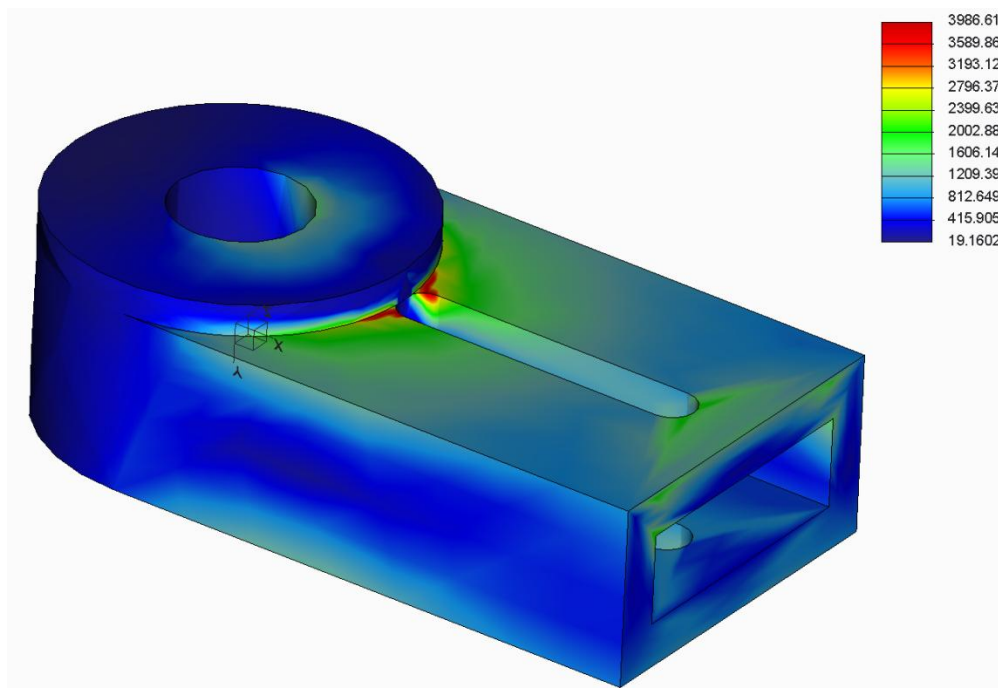
Part 2



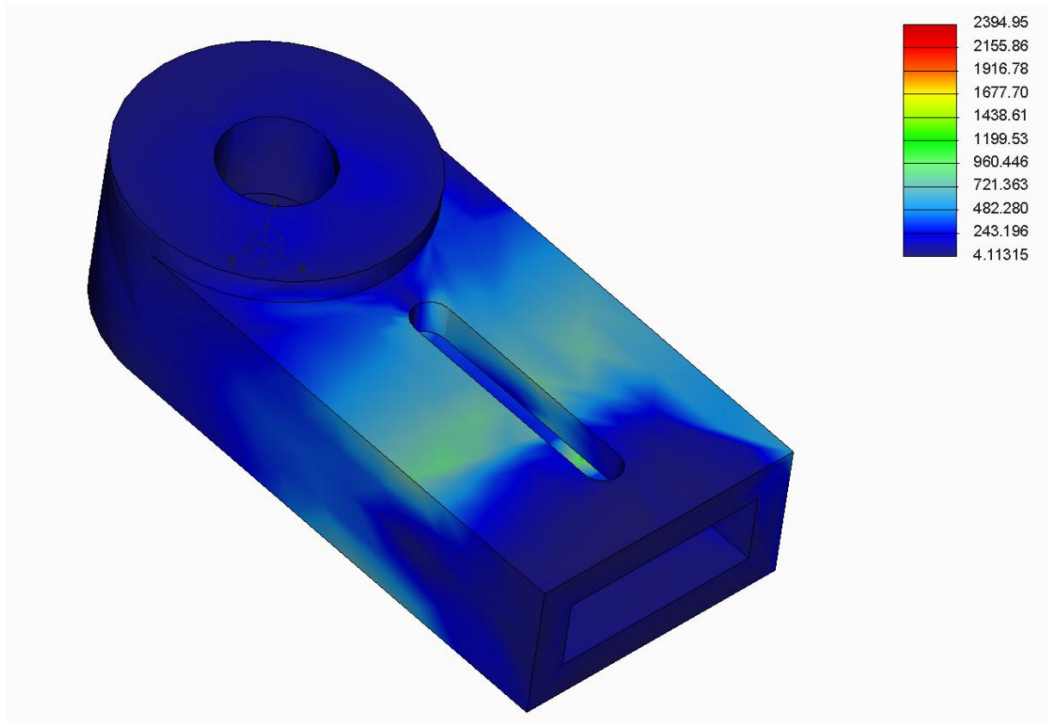
Part 3



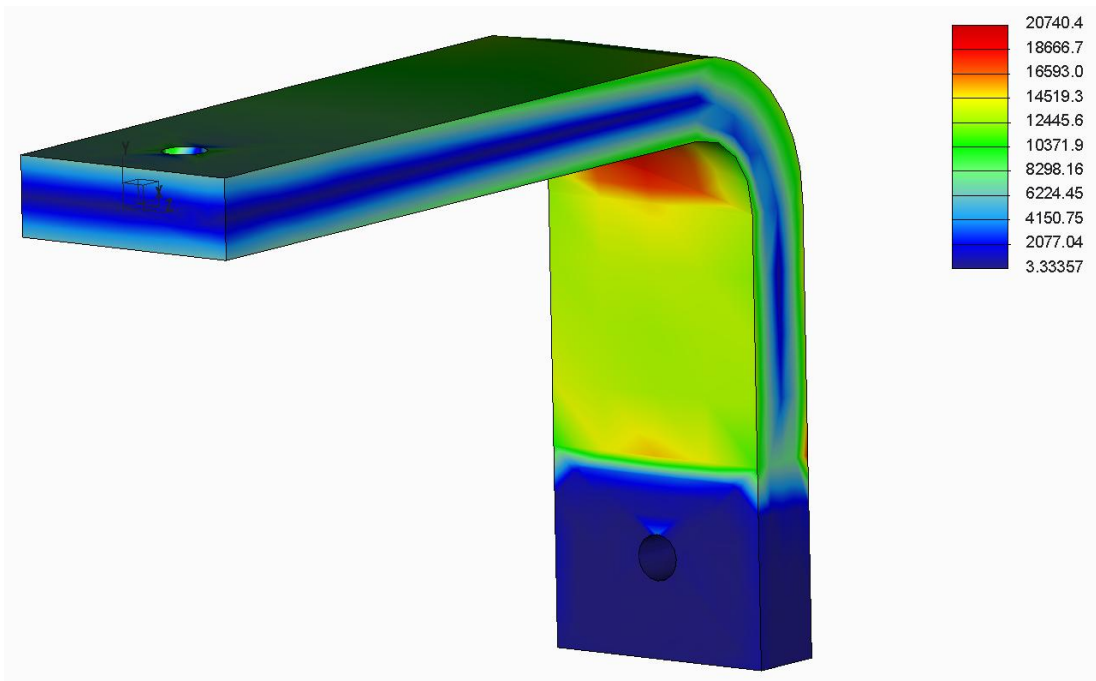
Part 4



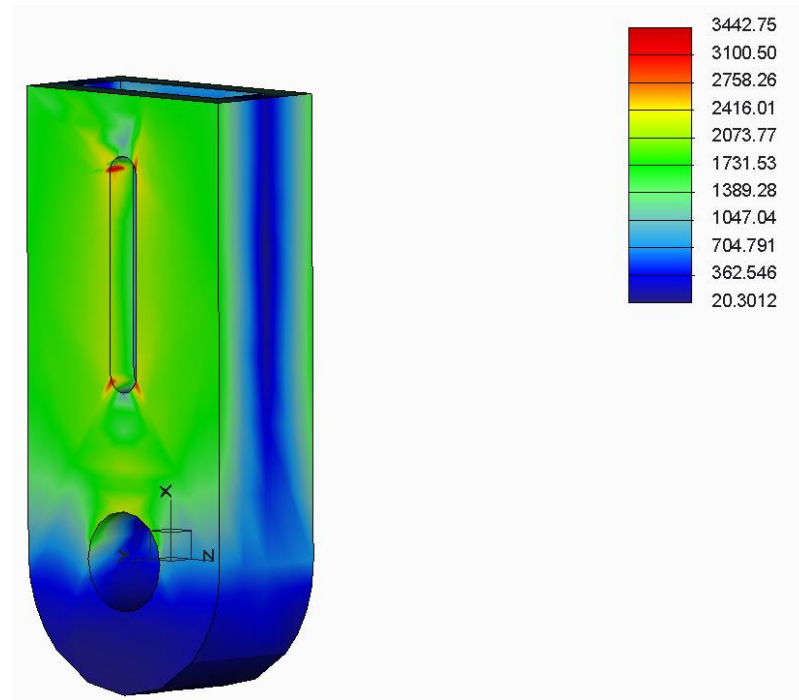
Part 5



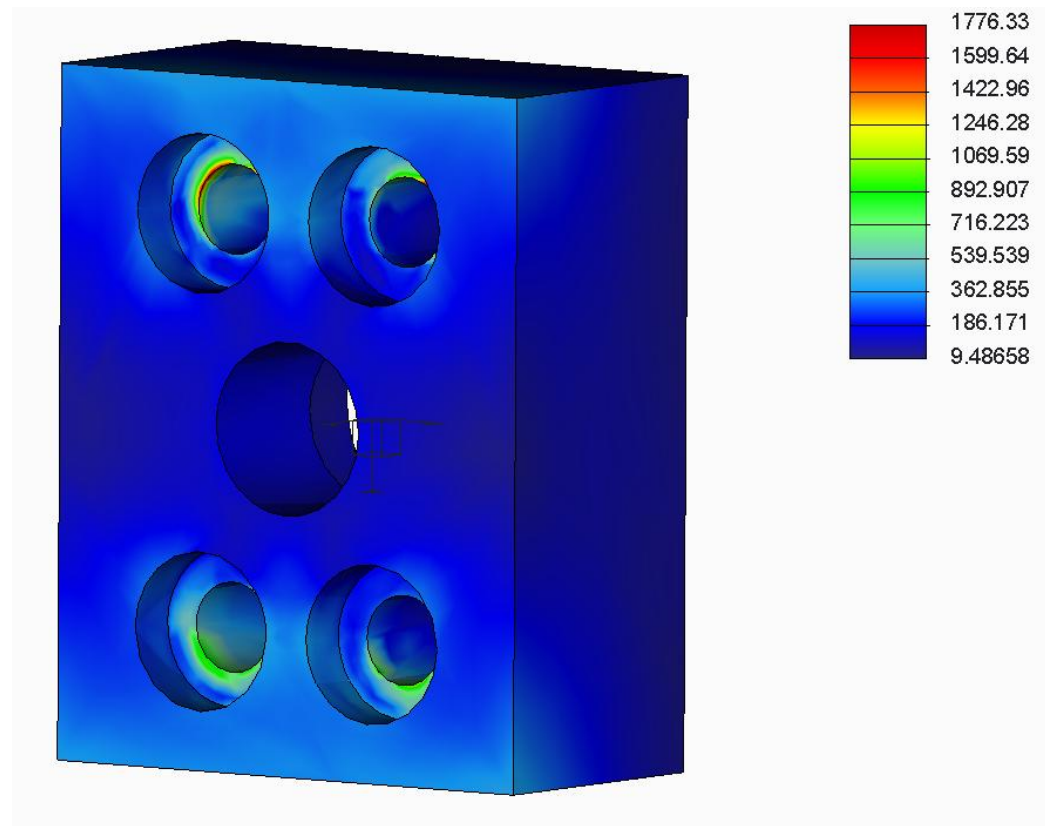
Part 6



Part 7



Part 8



Appendix G: Fastener Analysis Calculations

FASTENER ANALYSIS: Adjustment Screw

Given:

Major Diameter $d := 0.1969\text{in}$ Yield Strength $\sigma_t := 10100\text{psi}$
 Number of threads per inch $N := 31.75 \frac{1}{\text{in}}$

Solution:

Determining properties

Find the minor diameter. M5 Low head socket head cap screw

$$d_r := d - \left(\frac{1.299038}{N} \right) \quad d_r = 0.156\text{in}$$

Find the pitch diameter

$$d_p := d - \left(\frac{.649519}{N} \right) \quad d_p = 0.176\text{in}$$

Find the tensile stress area

$$A_t := \left(\frac{\pi}{4} \right) \cdot \left(\frac{d_p + d_r}{2} \right)^2 \quad A_t = 0.022\text{in}^2$$

Determining fastener axial stress failure

Force required to fail axially

$$F := \sigma_t \cdot A_t \quad F = 2.192 \times 10^3 \cdot \text{lbf}$$

Finding the design force with a safety factor of 3

$$F_{\text{des}} := \frac{F}{3} \quad F_{\text{des}} = 730.509\text{lbf}$$

Determining thread shear failure

Known properties

Shear strength $\tau_s := 9570\text{psi}$

Area factor for thread-stripping area $w_o := .88$

Pitch $p := \frac{1}{N}$

Find the shear area

$$A_s := \pi \cdot d_r \cdot w_o \cdot p \quad A_s = 0.014\text{in}^2$$

Force required to fail single thread through shear

$$F_s := \tau_s \cdot A_s \quad F_s = 1.3 \times 10^3 \cdot \text{lbf}$$

Finding the design shear force with a safety factor of 3

$$F_{s\text{des}} := \frac{F_s}{3} \quad F_{s\text{des}} = 433.275\text{lbf}$$

Determining length of engagement

$$L_e := \frac{2A_t}{\frac{1}{2} \cdot \pi \cdot (d - .649519p)} \quad L_e = 0.157 \text{ in}$$

Number of threads engaged

$$\text{Threads} := L_e \cdot N \quad \text{Threads} = 4.971$$

Total shear force required to fail all threads through shear

$$F_{s_{\text{tot}}} := \text{Threads} \cdot F_s \quad F_{s_{\text{tot}}} = 6.462 \times 10^3 \cdot \text{lbf}$$

Finding the total design shear force with a safety factor of 3

$$F_{ts_{\text{des}}} := \frac{F_{s_{\text{tot}}}}{3} \quad F_{ts_{\text{des}}} = 2.154 \times 10^3 \cdot \text{lbf}$$

FASTENER ANALYSIS: Shoulder Screws

Given:

Major Diameter	$d := 0.3937 \text{ in}$	Yield Strength	$\sigma_t := 15950 \text{ psi}$
Number of threads per inch	$N := 16.93 \frac{1}{\text{in}}$		

Solution:

Determining properties

M10 Shoulder Screws

Find the minor diameter.

$$d_r := d - \left(\frac{1.299038}{N} \right) \quad d_r = 0.317 \text{ in}$$

Find the pitch diameter

$$d_p := d - \left(\frac{.649519}{N} \right) \quad d_p = 0.355 \text{ in}$$

Find the tensile stress area

$$A_t := \left(\frac{\pi}{4} \right) \cdot \left(\frac{d_p + d_r}{2} \right)^2 \quad A_t = 0.089 \text{ in}^2$$

Determining fastener axial stress failure

Force required to fail axially

$$F := \sigma_t \cdot A_t \quad F = 1.416 \times 10^4 \cdot \text{lbf}$$

Finding the design force with a safety factor of 3

$$F_{\text{des}} := \frac{F}{3} \quad F_{\text{des}} = 4.718 \times 10^3 \cdot \text{lbf}$$

Determining thread shear failure

Known properties

$$\text{Shear strength} \quad \tau_s := 95700 \text{psi}$$

$$\text{Area factor for thread-stripping area} \quad w_o := .88$$

$$\text{Pitch} \quad p := \frac{1}{N}$$

Find the shear area

$$A_s := \pi \cdot d_r \cdot w_o \cdot p \quad A_s = 0.052 \text{in}^2$$

Force required to fail single thread through shear

$$F_s := \tau_s \cdot A_s \quad F_s = 4.953 \times 10^3 \cdot \text{lbf}$$

Finding the design shear force with a safety factor of 3

$$F_{s_{\text{des}}} := \frac{F_s}{3} \quad F_{s_{\text{des}}} = 1.651 \times 10^3 \cdot \text{lbf}$$

Determining length of engagement

$$L_e := \frac{2A_t}{\frac{1}{2} \cdot \pi \cdot (d - .649519p)} \quad L_e = 0.318 \text{in}$$

Number of threads engaged

$$\text{Threads} := L_e \cdot N \quad \text{Threads} = 5.384$$

Total shear force required to fail all threads through shear

$$F_{s_{\text{tot}}} := \text{Threads} \cdot F_s \quad F_{s_{\text{tot}}} = 2.667 \times 10^4 \cdot \text{lbf}$$

Finding the total design shear force with a safety factor of 3

$$F_{ts_{\text{des}}} := \frac{F_{s_{\text{tot}}}}{3} \quad F_{ts_{\text{des}}} = 8.889 \times 10^3 \cdot \text{lbf}$$

FASTENER ANALYSIS: Flange Screws

Given:

$$\text{Major Diameter} \quad d := 0.1969 \text{in} \quad \text{Yield Strength} \quad \sigma_t := 15000 \text{psi}$$

$$\text{Number of threads per inch} \quad N := 31.75 \frac{1}{\text{in}}$$

Solution:

Determining properties

M5 Metric Flange Button Head

Find the minor diameter.

$$d_r := d - \left(\frac{1.299038}{N} \right) \quad d_r = 0.156 \text{ in}$$

Find the pitch diameter

$$d_p := d - \left(\frac{.649519}{N} \right) \quad d_p = 0.176 \text{ in}$$

Find the tensile stress area

$$A_t := \left(\frac{\pi}{4} \right) \cdot \left(\frac{d_p + d_r}{2} \right)^2 \quad A_t = 0.022 \text{ in}^2$$

Determining fastener axial stress failure

Force required to fail axially

$$F := \sigma_t \cdot A_t \quad F = 3.255 \times 10^3 \cdot \text{lbf}$$

Finding the design force with a safety factor of 3

$$F_{\text{des}} := \frac{F}{3} \quad F_{\text{des}} = 1.085 \times 10^3 \cdot \text{lbf}$$

Determining thread shear failure

Known properties

Shear strength $\tau_s := 9570 \text{ psi}$

Area factor for thread-stripping area $w_o := .88$

Pitch $p := \frac{1}{N}$

Find the shear area

$$A_s := \pi \cdot d_r \cdot w_o \cdot p \quad A_s = 0.014 \text{ in}^2$$

Force required to fail single thread through shear

$$F_s := \tau_s \cdot A_s \quad F_s = 1.3 \times 10^3 \cdot \text{lbf}$$

Finding the design shear force with a safety factor of 3

$$F_{s_{\text{des}}} := \frac{F_s}{3} \quad F_{s_{\text{des}}} = 433.275 \text{ lbf}$$

Determining length of engagement

$$L_e := \frac{2A_t}{\frac{1}{2} \cdot \pi \cdot (d - .649519p)} \quad L_e = 0.157 \text{ in}$$

Number of threads engaged

$$\text{Threads} := L_e \cdot N \quad \text{Threads} = 4.971$$

Total shear force required to fail all threads through shear

$$F_{s_{\text{tot}}} := \text{Threads} \cdot F_s \quad F_{s_{\text{tot}}} = 6.462 \times 10^3 \cdot \text{lbf}$$

Finding the total design shear force with a safety factor of 3

$$F_{ts_{\text{des}}} := \frac{F_{s_{\text{tot}}}}{3} \quad F_{ts_{\text{des}}} = 2.154 \times 10^3 \cdot \text{lbf}$$

FASTENER ANALYSIS: M6 socket head cap

Given:

Major Diameter $d := 0.2362 \text{ in}$ Yield Strength $\sigma_t := 10100 \text{ psi}$

Number of threads per inch $N := 25.4 \frac{1}{\text{in}}$

Solution:

Determining properties

Find the minor diameter. M6 Low head socket head cap screw

$$d_r := d - \left(\frac{1.299038}{N} \right) \quad d_r = 0.185 \text{ in}$$

Find the pitch diameter

$$d_p := d - \left(\frac{.649519}{N} \right) \quad d_p = 0.211 \text{ in}$$

Find the tensile stress area

$$A_t := \left(\frac{\pi}{4} \right) \cdot \left(\frac{d_p + d_r}{2} \right)^2 \quad A_t = 0.031 \text{ in}^2$$

Determining fastener axial stress failure

Force required to fail axially

$$F := \sigma_t \cdot A_t \quad F = 3.105 \times 10^3 \cdot \text{lbf}$$

Finding the design force with a safety factor of 3

$$F_{\text{des}} := \frac{F}{3} \quad F_{\text{des}} = 1.035 \times 10^3 \cdot \text{lbf}$$

Determining thread shear failure

Known properties

$$\text{Shear strength} \quad \tau_s := 95700 \text{psi}$$

$$\text{Area factor for thread-stripping area} \quad w_o := .88$$

$$\text{Pitch} \quad p := \frac{1}{N}$$

Find the shear area

$$A_s := \pi \cdot d_r \cdot w_o \cdot p \quad A_s = 0.02 \text{in}^2$$

Force required to fail single thread through shear

$$F_s := \tau_s \cdot A_s \quad F_s = 1.928 \times 10^3 \cdot \text{lbf}$$

Finding the design shear force with a safety factor of 3

$$F_{s_{des}} := \frac{F_s}{3} \quad F_{s_{des}} = 642.532 \text{lbf}$$

Determining length of engagement

$$L_e := \frac{2A_t}{\frac{1}{2} \cdot \pi \cdot (d - .649519p)} \quad L_e = 0.186 \text{in}$$

Number of threads engaged

$$\text{Threads} := L_e \cdot N \quad \text{Threads} = 4.72$$

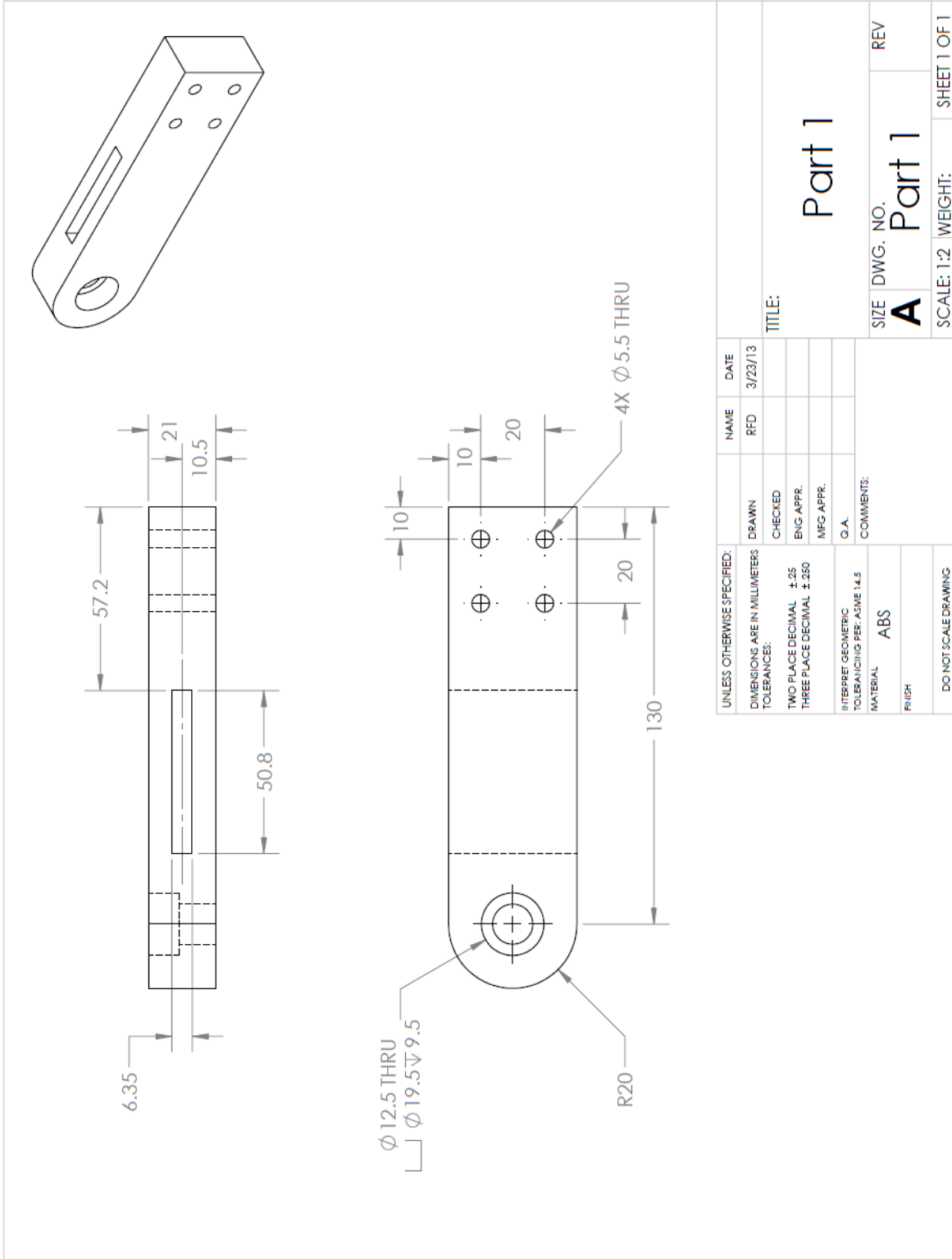
Total shear force required to fail all threads through shear

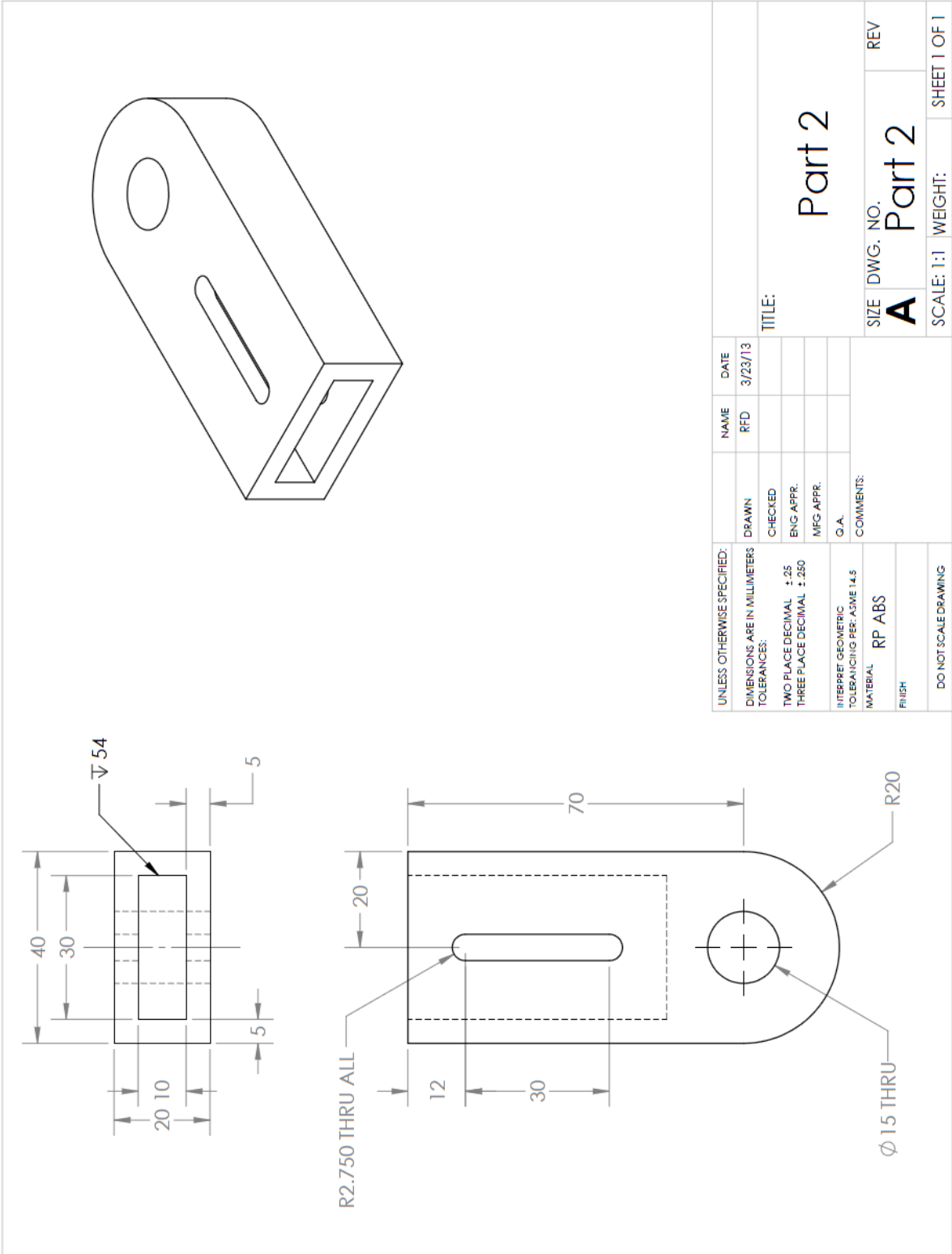
$$F_{s_{tot}} := \text{Threads} \cdot F_s \quad F_{s_{tot}} = 9.099 \times 10^3 \cdot \text{lbf}$$

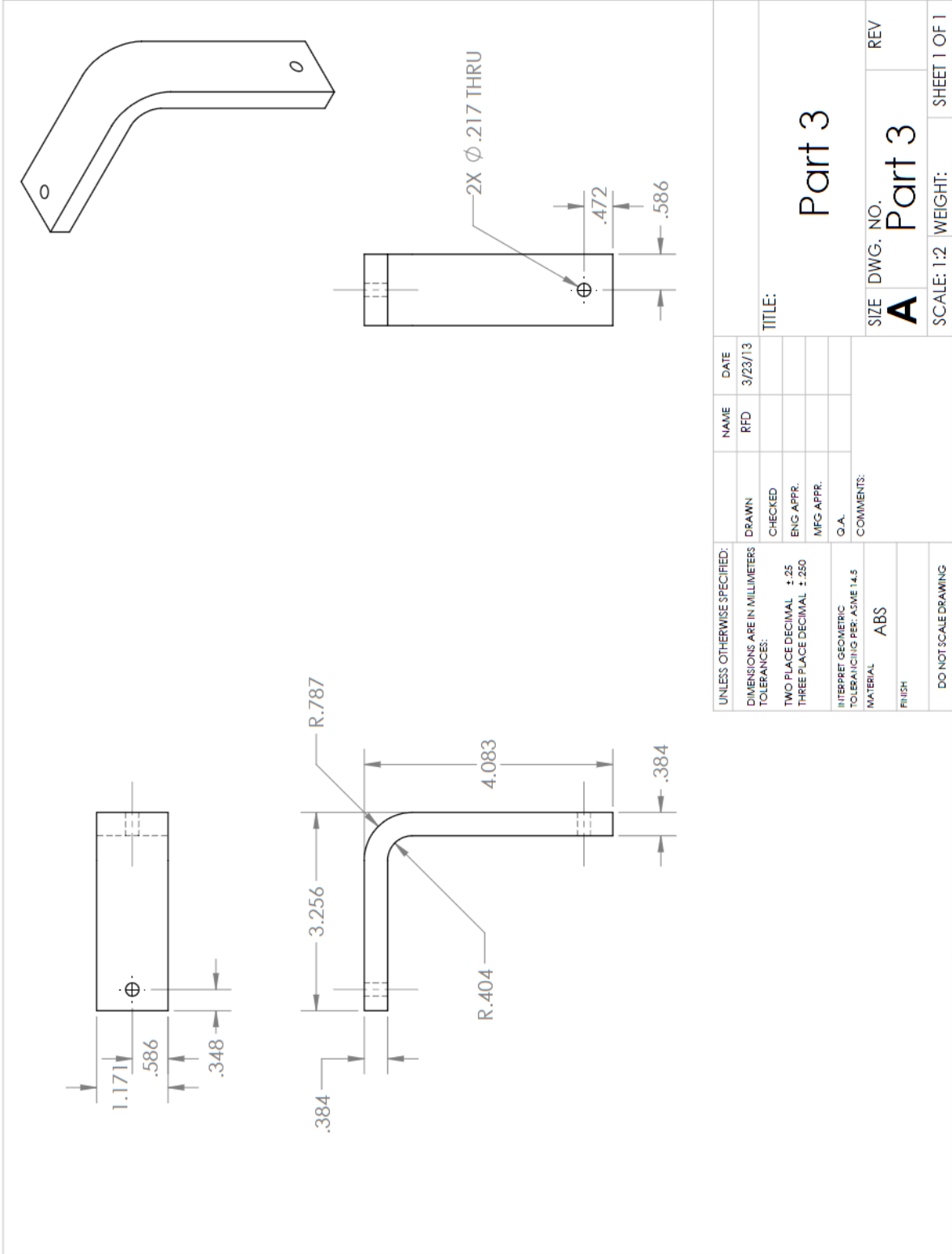
Finding the total design shear force with a safety factor of 3

$$F_{ts_{des}} := \frac{F_{s_{tot}}}{3} \quad F_{ts_{des}} = 3.033 \times 10^3 \cdot \text{lbf}$$

Appendix H: Part Drawings





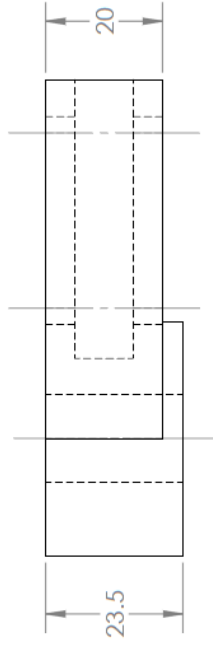
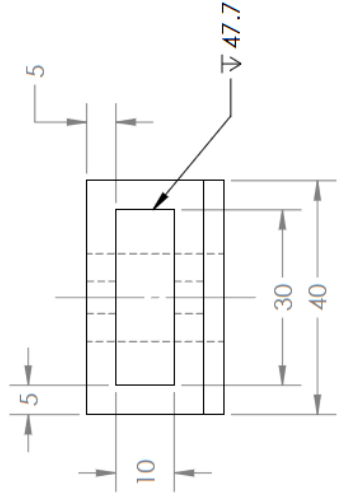
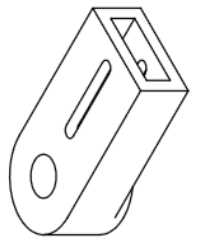
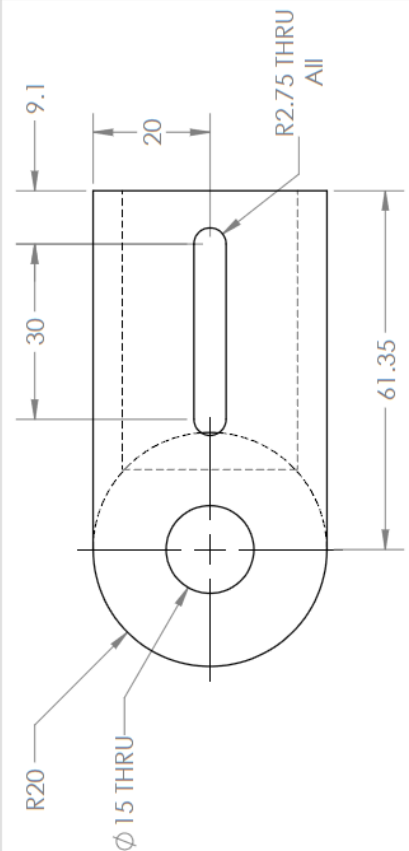


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DIMENSIONS ARE IN MILLIMETERS		RFD	3/23/13
TOLERANCES:		DRAWN	
TWO PLACE DECIMAL ±.25		CHECKED	
THREE PLACE DECIMAL ±.250		ENG. APPR.	
INTERPRET GEOMETRIC TOLERANCING PER: ASME 14.5		MFG APPR.	
MATERIAL ABS		Q.A.	
FINISH		COMMENTS:	
DO NOT SCALE DRAWING			

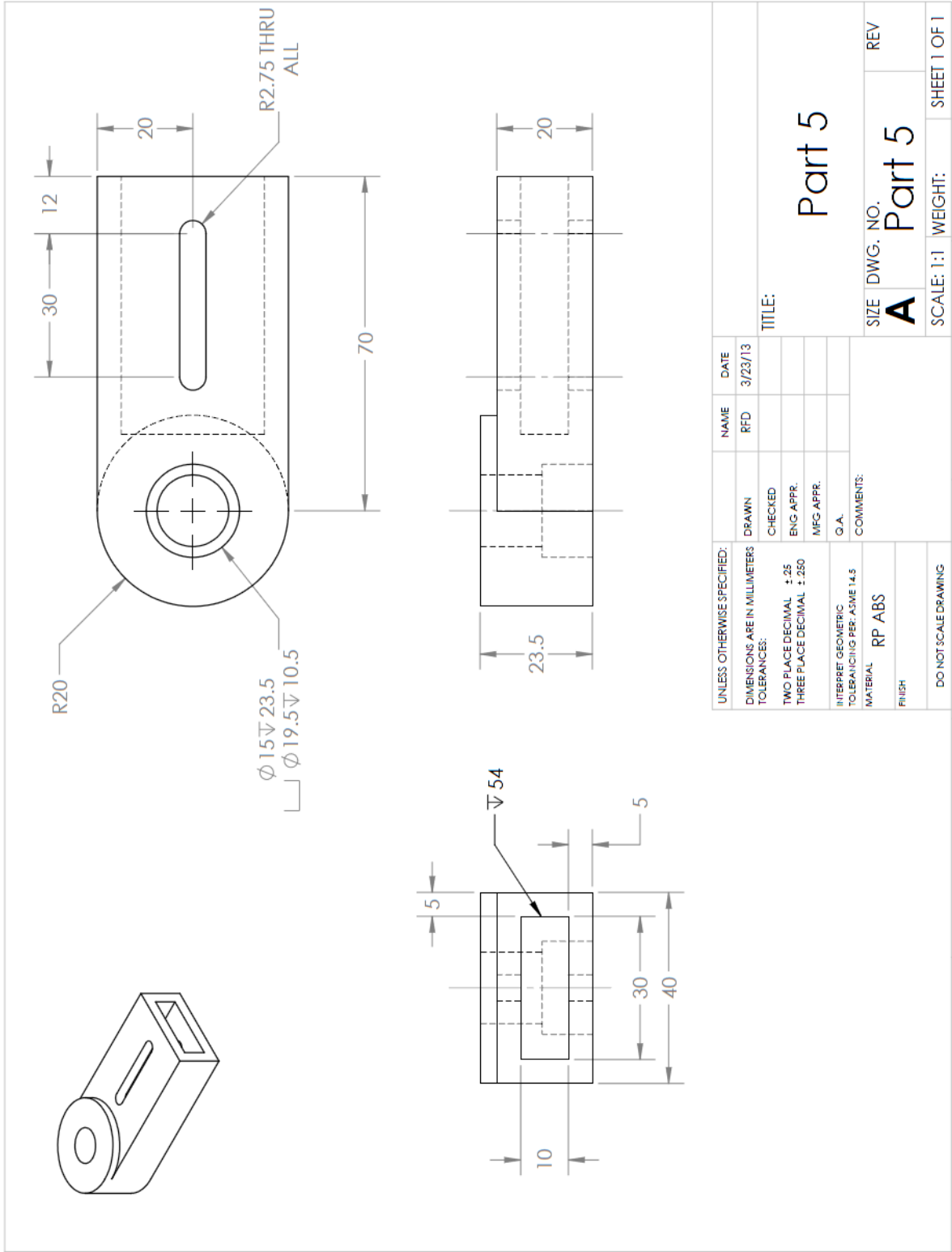
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SIZE DWG. NO. REV
A Part 3 REV

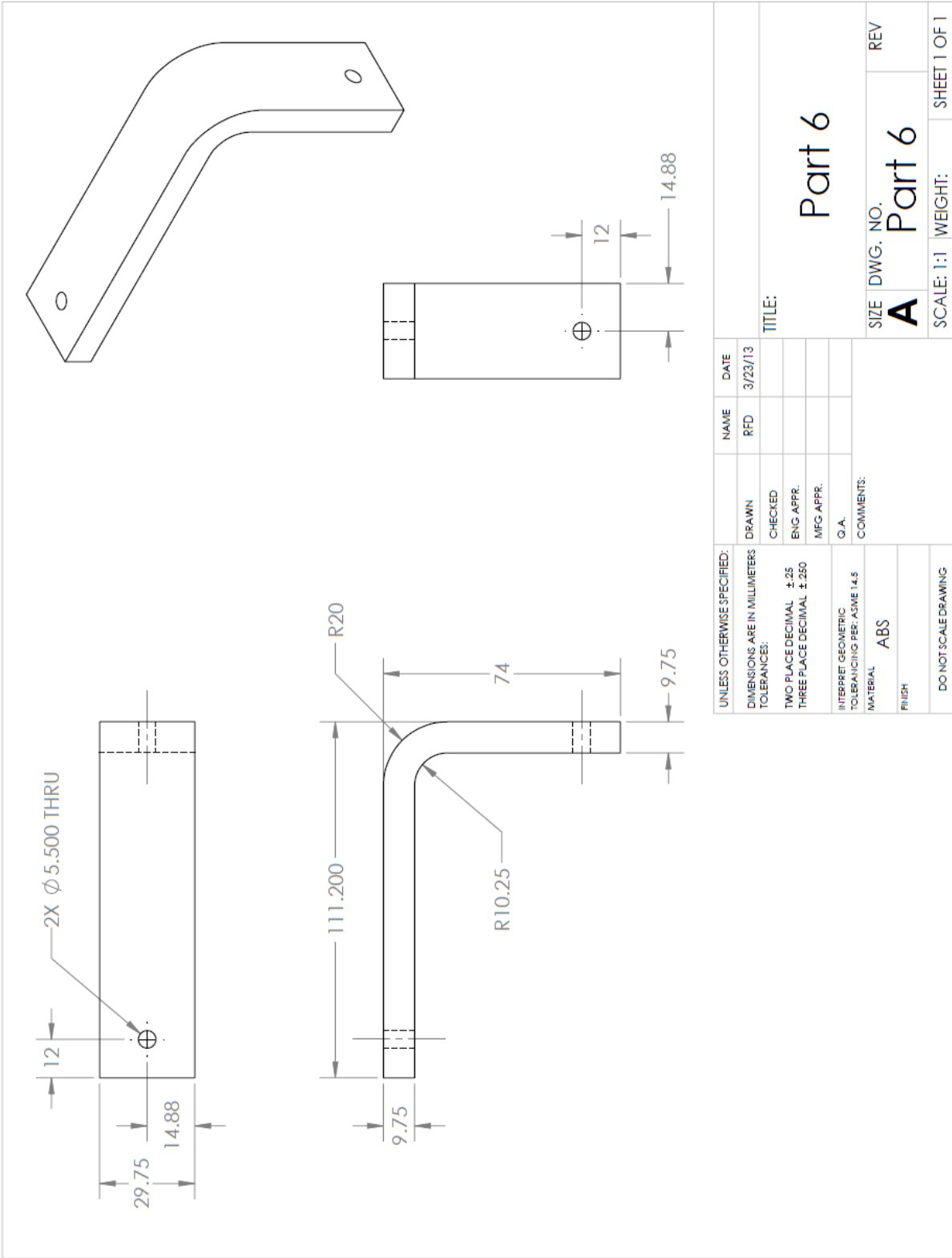
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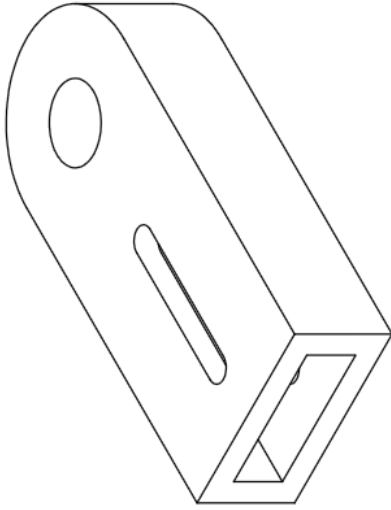
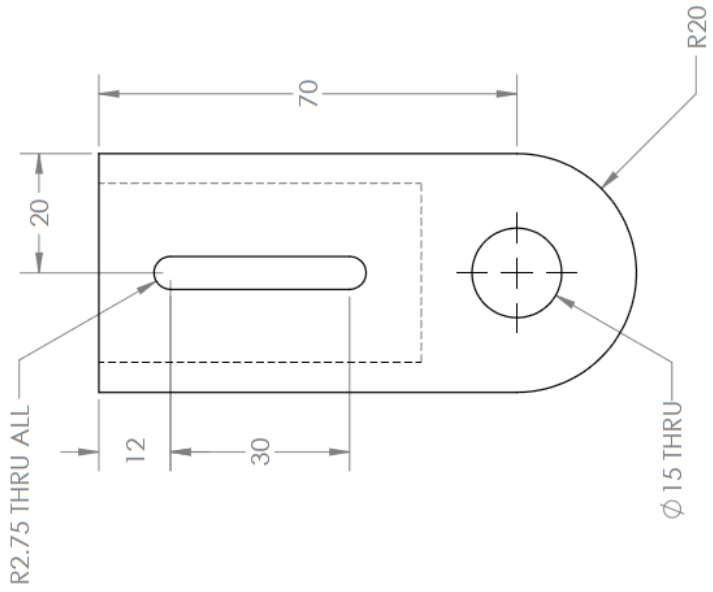
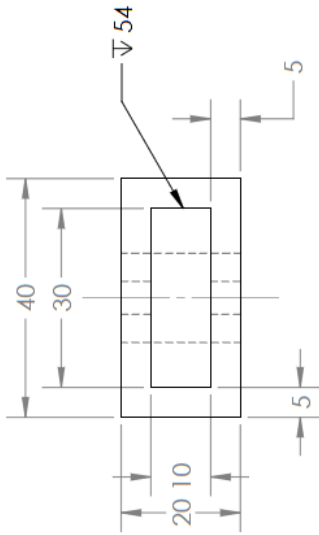


UNLESS OTHERWISE SPECIFIED:		NAME	DATE
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TOLERANCES:		DRAWN	
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THREE PLACE DECIMAL ±.250		ENG APPR.	
		MFG APPR.	
		G.A.	
INTERPRET GEOMETRIC TOLERANCING PER: ASME 14.5		COMMENTS:	
MATERIAL: RP ABS			
FINISH:			
DO NOT SCALE DRAWING			
TITLE: Part 4			
SIZE	DWG. NO.	REV	
A	Part 4		
SCALE: 1:1	WEIGHT:	SHEET 1 OF 1	

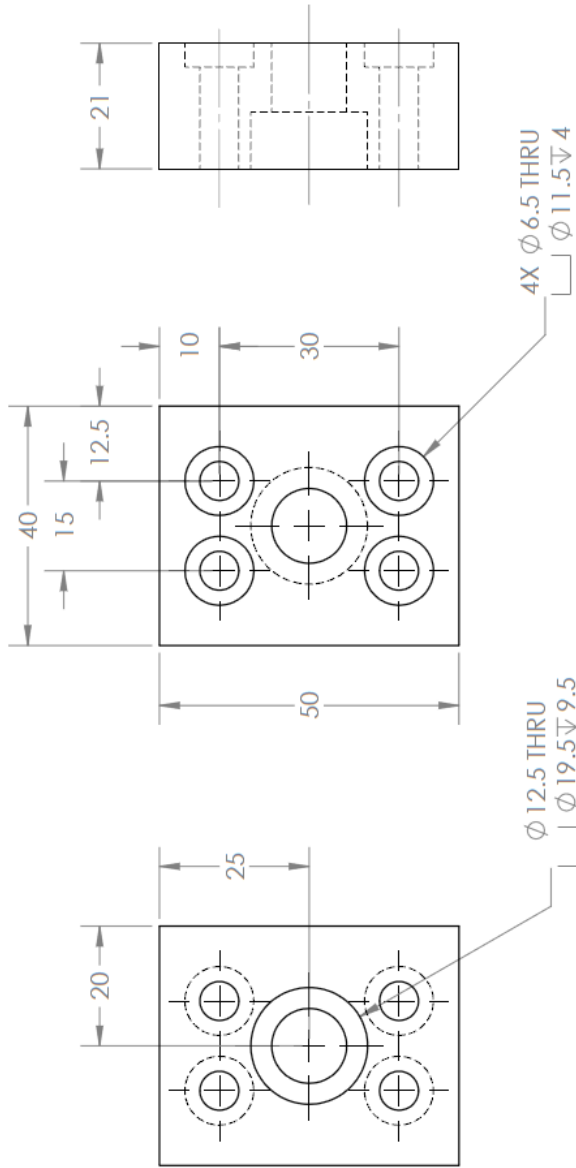
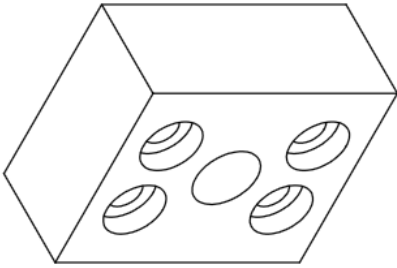


UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN MILLIMETERS		RFD	3/23/13
TOLERANCES:		DRAWN	CHECKED
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THREE PLACE DECIMAL $\pm .250$		MFG APPR.	
INTERPRET GEOMETRIC TOLERANCING PER: ASME Y14.5		G.A.	
MATERIAL		COMMENTS:	
FINISH		RP ABS	
DO NOT SCALE DRAWING			

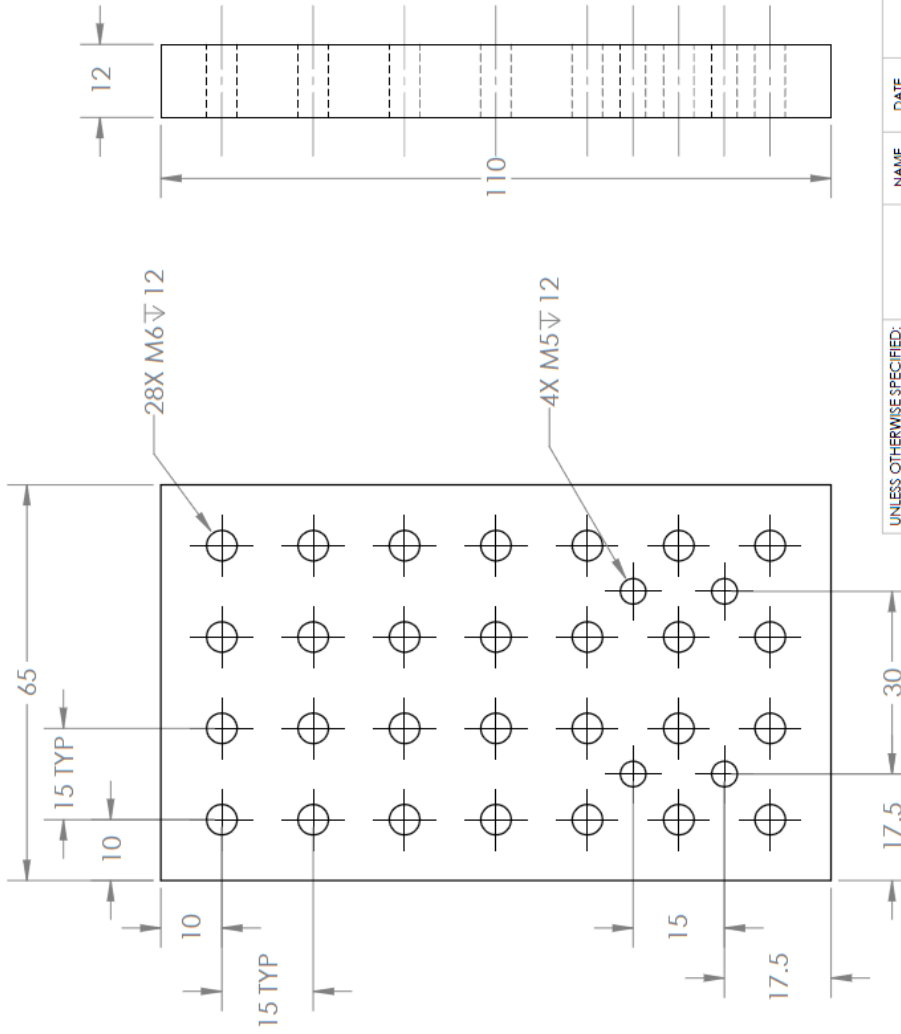
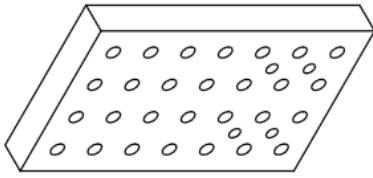




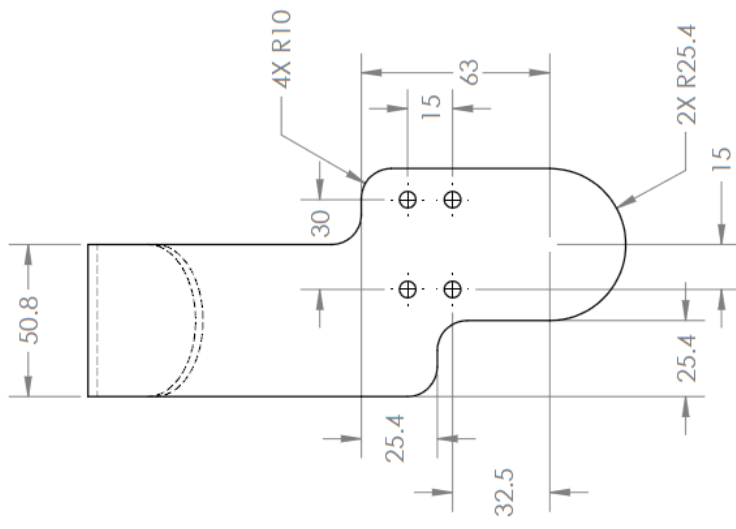
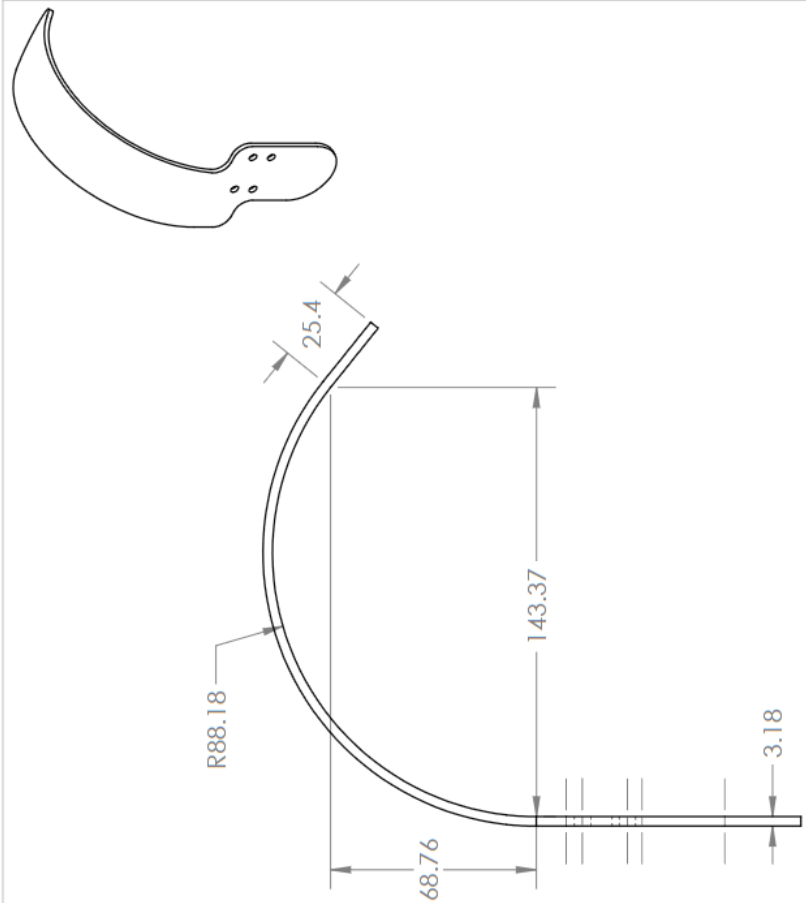
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DRAWN		RFD	3/23/13
CHECKED			
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THREE PLACE DECIMAL ±.250 MFG. APPR.			
O.A.			
INTERPRET GEOMETRIC TOLERANCING PER: ASME 14.5		COMMENTS:	
MATERIAL RP ABS			
FINISH			
DO NOT SCALE DRAWING			
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SIZE	DWG. NO.	REV	
A	Part 7		
SCALE: 1:1	WEIGHT:	SHEET 1 OF 1	



UNLESS OTHERWISE SPECIFIED:	NAME	DATE
DIMENSIONS ARE IN MILLIMETERS	RFD	3/23/13
TOLERANCES:		
TWO PLACE DECIMAL ± .25		
THREE PLACE DECIMAL ± .250		
INTERPRET GEOMETRIC TOLERANCING PER ASME 14.5		
MATERIAL		
FINISH		
DO NOT SCALE DRAWING		
TITLE: Part 8		
SIZE	DWG. NO.	REV
A	Part 8	
SCALE: 1:1	WEIGHT:	SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN MILLIMETERS		RFD	3/23/13
TOLERANCES:		DRAWN	
TWO PLACE DECIMAL \pm .25		CHECKED	
THREE PLACE DECIMAL \pm .250		ENG APPR.	
		MFG APPR.	
		G.A.	
INTERPRET GEOMETRIC TOLERANCING PER: ASME 14.5		COMMENTS:	
MATERIAL		ALUMINUM	
FINISH			
DO NOT SCALE DRAWING			
TITLE:		Part 9	
SIZE	DWG. NO.	REV	
A	Part 9		
SCALE: 1:2		WEIGHT:	SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN MILLIMETERS	DRAWN	RFD	3/23/13
TOLERANCES:	CHECKED		
TWO PLACE DECIMAL ±.25	ENG APPR.		
THREE PLACE DECIMAL ±.250	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER: ASME 14.5	G.A.		
MATERIAL	COMMENTS:		
FINISH	ABS		
DO NOT SCALE DRAWING			

TITLE:		Part 10	
SIZE	DWG. NO.	REV	
A	Part 10		
SCALE: 1:5	WEIGHT:	SHEET 1 OF 1	

Appendix I: Test Subject Testing Procedures

Follow the order of this handout for testing test subjects

General Data

- Camera recording unnecessary.
- Acquire brief measurements and demographic data.
 - Name
 - Gender
 - Handedness
 - Height
 - Shoulder width
 - Upper Arm length
 - Lower Arm length
 - Hand length

Range of Motion Angles

- Camera recording unnecessary, pictures will suffice.

The user completes these steps without the prototype device.

- Ask user to raise arm forward, with elbows locked, to maximum flexion position take picture.
 - Return to neutral position.
- Ask user to raise arm backward, with elbows locked, to minimum flexion position and take picture.
 - Return to neutral position.
- Ask user to raise arm to shoulder height then move arm left to maximum abduction position and take picture.
 - Return to neutral position.
- Ask user to raise arm to shoulder height then move arm left to minimum abduction position and take picture.
 - Return to neutral position.

Activities of Daily Living Testing

- Camera recording necessary.

The user completes these steps without the prototype device.

- Instruct subject to stand in designated area and to not move feet for the duration of the test.

Standing only tests:

- *Hygiene*
 - Ask test subject to reach to opposite axilla (armpit) with right arm.
 - Ask test subject to reach to opposite side of neck with right arm.
 - Ask test subject to reach to side and back of head with right arm and without crossing body.
- *Everyday Object*
 - Hand 5lb weight to test subject.
 - Ask test subject to raise 5lb weight to shoulder height with arm straight.
 - Ask test subject to raise 5lb weight to head height with arm straight.

Sitting tests:

- Place chair and stool in designated positions for testing, instruct test subject to sit down without moving feet. **Request that all actions are done with right hand.**
- *Feeding*
 - Place apple on stool on designated mark.
 - Ask test subject to pick up apple and move it towards the mouth as if about to bite. Instruct test subject to not eat or bite apple.
 - Remove apple and replace with spoon.
 - Ask test subject to pick up spoon and move it towards the mouth as if about to eat.
 - Remove spoon and replace with mug.
 - Ask test subject to pick up coffee mug and move it towards the mouth as if to drink.
- *Everyday Object*
 - Remove mug and replace with cellphone.
 - Ask test subject to pick up cellphone and move it towards the ear as if to answer.

User dons device

- Assist the test subject in donning the prototype device and adjust accordingly.
- Confirm that prototype can properly adjust to test subject.
- If not take note of where adjustment is inadequate.

User answers “Donning” and “Neutral Position” questionnaire sections

Activities of Daily Living Testing

- Camera recording necessary

The user completes these steps with the prototype device.

- Instruct subject to stand in designated area and to not move feet for the duration of the test.

Standing only tests:

- *Hygiene*
 - Ask test subject to reach to opposite axilla (armpit) with right arm.
 - Ask test subject to reach to opposite side of neck with right arm.
 - Ask test subject to reach to side and back of head with right arm and without crossing body.
- *Everyday Object*
 - Hand 5lb weight to test subject
 - Ask test subject to raise 5lb weight to shoulder height with arm straight.
 - Ask test subject to raise 5lb weight to head height with arm straight.

Sitting tests:

- Place chair and stool in designated positions for testing, instruct test subject to sit down without moving feet. **Request that all actions are done with right hand**
- *Feeding*
 - Place apple on stool on designated mark.
 - Ask test subject to pick up apple and move it towards the mouth as if about to bite. Instruct test subject to not eat or bite apple.
 - Remove apple and replace with spoon.
 - Ask test subject to pick up spoon and move it towards the mouth as if about to eat.
 - Remove spoon and replace with mug.
 - Ask test subject to pick up coffee mug and move it towards the mouth as if to drink.
- *Everyday Object*
 - Remove mug and replace with cellphone.
 - Ask test subject to pick up cellphone and move it towards the ear as if to answer.

Range of Motion Angles

- Camera recording unnecessary, pictures will suffice.

The user completes these steps with the prototype device.

- Ask user to raise arm forward, with elbows locked, to maximum flexion position take picture.
 - Return to neutral position.
- Ask user to raise arm backward, with elbows locked, to minimum flexion position and take picture.
 - Return to neutral position.
- Ask user to raise arm to shoulder height then move arm left to maximum abduction position and take picture.

- Return to neutral position.
- Ask user to raise arm to shoulder height then move arm left to minimum abduction position and take picture.
- Return to neutral position.

User answers “Activities of Daily Living Testing” questionnaire section.

User doffs device.

- Assist the test subject in doffing the prototype device.

User answers “Doffing” questionnaire section.

Appendix J: Test Subject Consent Form

Informed Consent Agreement for Participation in a Research Study

Investigators: Rich Downey, Nikole Dunn, Adam Hoyt

Contact Information: richdwny4564@wpi.edu, nikole_dunn@wpi.edu, adamh@wpi.edu

Title of Research Study: Shoulder Mount for a Wearable Arm Orthosis

Sponsor: WPI (MQP)

Introduction

You are being asked to participate in a research study. Before you agree, however, you must be fully informed about the purpose of the study, the procedures to be followed, and any benefits, risks or discomfort that you may experience as a result of your participation. This form presents information about the study so that you may make a fully informed decision regarding your participation.

Purpose of the study:

We wish to test the user comfort and functionality of our shoulder mount prototype. This prototype is the combination of a mechanism and a vest that you will wear. One part of the mechanism is embedded within the vest and the rest attaches to the vest via an embedded piece. The ultimate purpose of this device is to allow a user to wear a powered, upper-limb orthosis. The combination of the shoulder mount and a powered arm orthosis would aid persons with permanent and long-term disabilities by improving their functional independence. Our work only tests the shoulder mount itself.

Procedures to be followed:

We wish to have you wear the device and complete specific tasks to confirm functionality. You will wear the vest, and the mechanism will be attached to your upper arm by using a strap with Velcro. The testing procedures you will be asked to follow include: recording basic information including name, age, handedness, height, and arm length; measurement of maximum and minimum shoulder/arm positions; and basic shoulder/arm movements to mimic activities such as eating, drinking, answering a cell phone, and self-care. These tasks will require very little effort. Your participation will last for a total of about 30 minutes. We will take photographs and record video of you performing these procedures.

Risks to study participants:

There is some possibility of minor discomfort due to the vest that you will wear and the Velcro strap that will attach your upper arm to the device.

Benefits to research participants and others:

There is no direct benefit to you.

Record keeping and confidentiality:

Records of your participation in this study will be held confidential so far as permitted by law. However, the study investigators, the sponsor or it’s designee and, under certain circumstances, the Worcester Polytechnic Institute Institutional Review Board (WPI IRB) will be able to inspect and have access to confidential data that identify you by name. Any publication or presentation of the data will not identify you. However, signing this form indicates that you do agree to allow use of photographs and video of you, obtained in this study, in future publications and presentations associated with this research.

Compensation or treatment in the event of injury:

In the unlikely event of physical injury resulting from participation in the research, you understand that medical treatment may be available from WPI, including first aid emergency care, and that your insurance carrier may be billed for the cost of such treatment. No compensation for medical care can be provided by WPI. You further understand that making such medical care available, or providing it, does not imply that such injury is the fault of the investigators. You do not give up any of your legal rights by signing this statement.

For more information about this research or about the rights of research participants, or in case of research-related injury, contact:

Please refer to the contact information provided at the top of this form. You may also contact the chair of the WPI Institutional Review Board (Professor Kent Rissmiller, Tel. 508-831-5019, Email: kjr@wpi.edu) or WPI’s University Compliance Officer (Michael J. Curley, Tel. 508-831-6919, Email: mjcurley@wpi.edu).

Your participation in this research is voluntary.

Your refusal to participate will not result in any penalty to you or any loss of benefits to which you may otherwise be entitled. You may decide to stop participating in the research at any time without penalty or loss of other benefits. The project investigators retain the right to cancel or postpone the experimental procedures at any time they see fit. Data obtained in this experiment will become the property of the investigators and WPI. If you withdraw from the study, data already collected from you will remain in the study.

By signing below, you acknowledge that you have been informed about and consent to be a participant in the study described above. Make sure that your questions are answered to your satisfaction before signing. You are entitled to retain a copy of this consent agreement.

Study Participant Signature

Date: _____

Study Participant Name (Please print)

Signature of Person who explained this study

Date: _____

Appendix K: Comfort and User-Friendliness Questionnaire

Name: _____

Comfort and User-Friendliness Questionnaire

Donning

How difficult is it to don the device?	1	2	3	4	5
	Extremely	Somewhat	Neutral	Not Very	Not at All
How difficult is it to fasten the straps?	1	2	3	4	5
	Extremely	Somewhat	Neutral	Not Very	Not at All

Neutral Position

How noticeable is the device?	1	2	3	4	5
	Extremely	Somewhat	Neutral	Not Very	Not at All

Activities of Daily Living Testing

Hygiene

How difficult is it to reach left armpit?	1	2	3	4	5
	Extremely	Somewhat	Neutral	Not Very	Not at All
How difficult is it to reach left side of neck?	1	2	3	4	5
	Extremely	Somewhat	Neutral	Not Very	Not at All
How difficult is it to reach left side of head?	1	2	3	4	5
	Extremely	Somewhat	Neutral	Not Very	Not at All
How difficult is it to reach back of head?	1	2	3	4	5
	Extremely	Somewhat	Neutral	Not Very	Not at All

Feeding

How difficult is it to eat with hand to mouth?	1	2	3	4	5
	Extremely	Somewhat	Neutral	Not Very	Not at All
How difficult is it to eat with spoon?	1	2	3	4	5
	Extremely	Somewhat	Neutral	Not Very	Not at All
How difficult is it to drink from mug?	1	2	3	4	5
	Extremely	Somewhat	Neutral	Not Very	Not at All

Everyday Object

How difficult is it to answer a telephone?	1	2	3	4	5
	Extremely	Somewhat	Neutral	Not Very	Not at All
How difficult is it to raise weight to shoulder height?	1	2	3	4	5
	Extremely	Somewhat	Neutral	Not Very	Not at All
How difficult is it to raise weight to head height?	1	2	3	4	5
	Extremely	Somewhat	Neutral	Not Very	Not at All

Doffing

How difficult is it to unfasten the straps?	1	2	3	4	5
	Extremely	Somewhat	Neutral	Not Very	Not at All
How difficult is it to doff the device?	1	2	3	4	5
	Extremely	Somewhat	Neutral	Not Very	Not at All

Appendix L: Prototype Weight & Dimension Data

Weight Measurements

	Trial #	Recorded Weight (lbs)	Weight Difference (lbs)	Total Average Weight (lbs)
Test Subject Alone	1	185.0	0.0	
	2	185.0	0.0	
	3	185.0	0.0	
Test Subject w/ Device & Vest	1	188.4	3.4	Entire Device 3.4
	2	188.4	3.4	
	3	188.4	3.4	
Test Subject w/ Mechanism Only	1	186.4	1.4	Mechanism 1.4
	2	186.4	1.4	
	3	186.4	1.4	
Test Subject w/ Vest Only	1	187.0	2.0	Vest 2.0
	2	187.0	2.0	
	3	187.0	2.0	

Dimensions

	Length (z)	Width (x)	Height (y)
Maximum Adjustment	203 mm	200.0 mm	282 mm
Minimum Adjustment	173 mm	170 mm	252 mm
Extends Beyond Shoulder	3.5"	3.75"	4.25"

Appendix M: Range of Motion Angle Measurements

Test Subject #1	Shoulder Flexion			Shoulder Abduction		
	Unrestricted	W/ Device	Required for ADLs (Murry & Johnson, 2004)	Unrestricted	W/ Device	Required for ADLs (Murry & Johnson, 2004)
Maximum	137°	95°	111.9°	98°	32°	39.7°
Minimum	-51°	-24°	14.7°	-39°	-40°	-20.1°
Maximum w/ Vest Compliance	-	119°	-	-	-	-
Total Range of Motion	188°	119°	97.2°	137°	72°	59.8°

Test Subject #2	Shoulder Flexion			Shoulder Abduction		
	Unrestricted	W/ Device	Required for ADLs (Murry & Johnson, 2004)	Unrestricted	W/ Device	Required for ADLs (Murry & Johnson, 2004)
Maximum	138°	91°	111.9°	74°	30°	39.7°
Minimum	-55°	-12°	14.7°	-33°	-17°	-20.1°
Maximum w/ Vest Compliance	-	117°	-	-	-	-
Total Range of Motion	193°	103°	97.2°	107°	47°	59.8°

Test Subject #3	Shoulder Flexion			Shoulder Abduction		
	Unrestricted	W/ Device	Required for ADLs (Murry & Johnson, 2004)	Unrestricted	W/ Device	Required for ADLs (Murry & Johnson, 2004)
Maximum	157°	93°	111.9°	104°	46°	39.7°
Minimum	-40°	-20°	14.7°	-25°	-28°	-20.1°
Maximum w/ Vest Compliance	-	135°	-	-	-	-
Total Range of Motion	197°	113°	97.2°	129°	74°	59.8°

Test Subject #4	Shoulder Flexion			Shoulder Abduction		
	Unrestricted	W/ Device	Required for ADLs (Murry & Johnson, 2004)	Unrestricted	W/ Device	Required for ADLs (Murry & Johnson, 2004)
Maximum	158°	90°	111.9°	98°	42°	39.7°
Minimum	-62°	-30°	14.7°	-36°	-20°	-20.1°
Maximum w/ Vest Compliance	-	145°	-	-	-	-
Total Range of Motion	220°	120°	97.2°	134°	62°	59.8°

Test Subject #5	Shoulder Flexion			Shoulder Abduction		
	Unrestricted	W/ Device	Required for ADLs (Murry & Johnson, 2004)	Unrestricted	W/ Device	Required for ADLs (Murry & Johnson, 2004)
Maximum	158°	91°	111.9°	93°	38°	39.7°
Minimum	-44°	-12°	14.7°	-44°	-41°	-20.1°
Maximum w/ Vest Compliance	-	139°	-	-	-	-
Total Range of Motion	202°	103°	97.2°	137°	79°	59.8°

Test Subject #6	Shoulder Flexion			Shoulder Abduction		
	Unrestricted	W/ Device	Required for ADLs (Murry & Johnson, 2004)	Unrestricted	W/ Device	Required for ADLs (Murry & Johnson, 2004)
Maximum	169°	96°	111.9°	110°	33°	39.7°
Minimum	-64°	-45°	14.7°	-54°	-39°	-20.1°
Maximum w/ Vest Compliance	-	138°	-	-	-	-
Total Range of Motion	233°	141°	97.2°	164°	72°	59.8°

Appendix N: Unaltered ADL Testing Data Including Comments

Female 25%	Completion		Adaptive Learning	Comments
	Natural	Orthosis		
Touch Armpit	✓	✓	✗	
Touch Neck	✓	✓	✗	
Touch Back of Head	✓	✓	✓	Moved head farther forward so did not have to bring arm as high.
Lift Weight Shoulder Height	✓	✓	✗	
Lift Weight Head Height	✓	✓	✗	
Eat Apple	✓	✓	✗	
Eat Spoon	✓	✓	✗	
Drink Mug	✓	✓	Maybe	Kept right arm more vertical and tucked closer to torso when wearing the device.
Answer Phone	✓	✓	✗	

Female 50%	Completion		Adaptive Learning	Comments
	Natural	Orthosis		
Touch Armpit	✓	✓	✗	
Touch Neck	✓	✓	✗	
Touch Back of Head	✓	✓	✓	Head slightly bent arm at an angle closer to body facing front more than side
Lift Weight Shoulder Height	✓	✓	✗	
Lift Weight Head Height	✓	✓	✗	
Eat Apple	✓	✓	✗	
Eat Spoon	✓	✓	✗	
Drink Mug	✓	✓	✗	
Answer Phone	✓	✓	✗	

Female 75%	Completion		Adaptive Learning	Comments
	Natural	Orthosis		
Touch Armpit	✓	✓	✗	
Touch Neck	✓	✓	✗	
Touch Back of Head	✓	✓	✗	
Lift Weight Shoulder Height	✓	✓	✗	
Lift Weight Head Height	✓	✓	✗	
Eat Apple	✓	✓	✗	
Eat Spoon	✓	✓	Maybe	Arm is lower than with out orthosis slightly different angle.
Drink Mug	✓	✓	✗	
Answer Phone	✓	✓	✗	

Male 25%	Completion		Adaptive Learning	Comments
	Natural	Orthosis		
Touch Armpit	✓	✓	✗	
Touch Neck	✓	✓	✗	
Touch Back of Head	✓	✓	✓	Arm is at a significantly different angle(both front and side) and the head has been moved farther forward
Lift Weight Shoulder Height	✓	✓	✗	
Lift Weight Head Height	✓	✓	✗	
Eat Apple	✓	✓	✗	
Eat Spoon	✓	✓	✗	
Drink Mug	✓	✓	✗	
Answer Phone	✓	✓	✗	

Male 50%	Completion		Adaptive Learning	Comments
	Natural	Orthosis		
Touch Armpit	✓	✓	✗	
Touch Neck	✓	✓	✗	
Touch Back of Head	✓	✓	✓	Angled head forward and to the side so did not have to raise arm as much, arm angled further forward.
Lift Weight Shoulder Height	✓	✓	✗	
Lift Weight Head Height	✓	✓	✗	
Eat Apple	✓	✓	✗	
Eat Spoon	✓	✓	✗	
Drink Mug	✓	✓	✗	
Answer Phone	✓	✓	✓	Arm at slightly different angle, more vertical closer to body, angled further forward from side view

Male 75%	Completion		Adaptive Learning	Comments
	Natural	Orthosis		
Touch Armpit	✓	✓	✗	
Touch Neck	✓	✓	✗	
Touch Back of Head	✓	✓	✗	
Lift Weight Shoulder Height	✓	✓	✗	
Lift Weight Head Height	✓	✓	✗	
Eat Apple	✓	✓	✗	
Eat Spoon	✓	✓	✗	
Drink Mug	✓	✓	✗	
Answer Phone	✓	✓	✗	