Project Number: AHH-0601

Design of Trans-humeral Prosthetic Mounting System for Use in High Load Activities

A Major Qualifying Project
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by

Bethany Corliss

Dave Giebenhain

Richard Gilley

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Approved:

Professor Allen H. Hoffman, Major Advisor

Professor Holly K. Ault, Co-Advisor

ABSTRACT

High load activities are difficult for trans-humeral amputees due to inadequate mounting methods. The goal of this project was to design, analyze, and manufacture an upper arm exoskeleton for trans-humeral prostheses to allow one to perform high load activities. The prosthesis attachment connects the prosthetic limb to the mechanism transferring loads to a custom vest. Tests have been formulated to confirm functionality of the design. From those tests and problems encountered throughout the design process, recommendations have been made.

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1.0 INTRODUCTION

The loss of an upper extremity limb, either from a birth defect or a traumatic amputation, is a devastating experience for one to go through. An individual may experience many different emotions from depression and hopelessness to feelings of frustration and impatience from not being able to complete tasks as fast. The majority of amputees eventually accepts of the loss of the limb and gain the ability to move on.

Functionality of the lost limb can be regained with the use of a prosthetic device. For the more active individual desiring more functionality, powered devices are available. For the individual looking for an aesthetically pleasing limb and less functionality, passive devices are available.

The harnessing system used to mount the device to the residual limb limits the extent of overall function. The majority of active prostheses are designed to only withstand minimal loadings in conjunction with basic daily activities. Passive prosthetic limbs, functioning primarily to appear as a natural limb, are not mounted in such a way to withstand any load bearing activities.

The primary ways of attaching a prosthetic limb to the upper body is by suction and with harnesses. These methods are rather inadequate for high load bearing activities and can often impeded the range of motion of the user. Therefore, some other means of supporting the prosthetic limb is needed.

The goal of this Major Qualifying Project is to design, analyze, and manufacture an upper arm exoskeleton for trans-humeral prostheses to allow the user to carry out high load activities with the prosthesis. It is desirable to keep the device as discrete as possible and to have a full anatomical range of motion. In addition, the device will be easy to don and doff, and be comfortable for both male and female users as outlined in the design specifications.

2.0 BACKGROUND

In order to efficiently draft practical and effective design solutions, preliminary research was deemed necessary. First, an overview of the human body was conducted, and then specifically focused on the bones, muscles, and biomechanics of the shoulder joint. The potential users of transhumeral prostheses were identified in order to determine the candidates for the device. Also, a variety of prostheses and harnessing systems were surveyed to learn about the existing equipment with which the device might interface. Finally, other current technology was also examined to obtain ideas for future concepts.

2.1 Terms and Definitions

The structure and functions of the human body are very complex, with various appendages and movements. Thus it is necessary to define some universal terms that are used to effectively describe the location and shape of different features as well as the way in which they move.

When describing relative locations in the body, the body is considered in the *anatomical position* standing upright with the feet together, arms by the sides, and the palms facing forward. Just like mechanical models, the body is divided into three planes. The *transverse* plane is horizontal, cutting the body into cross sections. The *sagittal* plane is vertical and divides the body into right and left sides. When a sagittal plane passes through the navel, it divides the body into two approximately equal and mirror image parts, it is called the *median* plane. The *frontal* plane is also vertical, but it connects the symmetric parts that the median plane separates. The orientations of the planes relative to the body are shown in Figure 1.

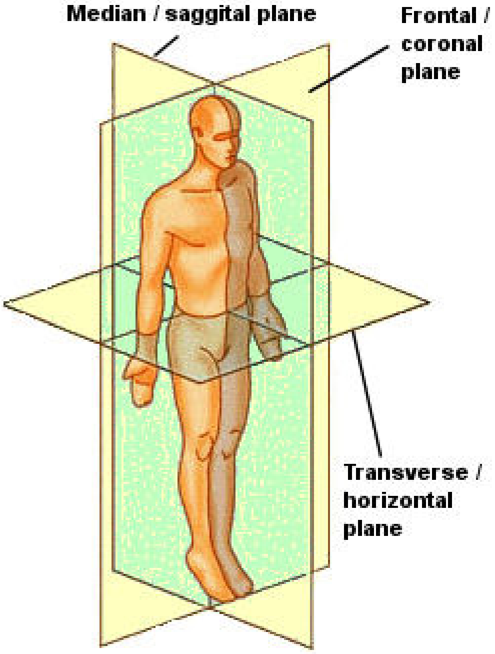


Figure 1 - Planes of the body ("Anatomy - The Joints")

The location of different landmarks can be described in comparison to these planes. Features above a transverse plane are considered *superior* to those which are below or inferior to it. Areas in the front of a frontal plane are *anterior* to those behind or *posterior* to it. Parts closer to the median plane are *medial* compared to those that farther from it, or *lateral*, and those in between are considered intermediate.

Specific aspects of the body can also be described by their position compared to one another. With regards to the extremities, localities closer to the point of attachment to the body are *proximal* to those that are farther away, or *distal*. Finally, the body’s surface is said to be superficial to that which lies deep, or within it.

These terms have been defined for when the body is in the anatomical position; however the human body rarely assumes this stance in daily living. Thus, its actual position can be described by using these planes and terms to relate the differences in positioning (Marieb, 1997).

2.2 Shoulder

The upper extremity is designed for grasping, carrying, and moving objects. The joints of the arm allow the hand to move through a large volume of space. The shoulder joint connects the arm to the body, and it is because of its design that the arm is able to obtain such a large range of motion.

2.2.1 Shoulder Joint

The shoulder joint is composed of three bones: the clavicle, scapula, and humerus, as shown in Figure 2. The scapula is a large, flat triangular bone that lies in the frontal plane. It extends approximately from the second to seventh rib vertically and laterally covers the posterior surface of the rib cage from just lateral of the spinal column to the rib cage's lateral boundary. Its lateral edge is nearly vertical and is comparatively thicker than the majority of the bone since it is the site of attachment of several muscles. The posterior surface has a spine protruding across the width of the bone, starting one-third of the way from the superior end of the medial border ending in the superior lateral corner as the acromion process of the scapula. Anterior to the acromion is another process called the coracoid process, which extends anteriorly and laterally. Inferior to the acromion on the lateral face is the glenoid surface, a shallow cavity that accepts the end of the humerus. The posterior and anterior faces of the scapula are shown in Figures 3 and 4, respectively.

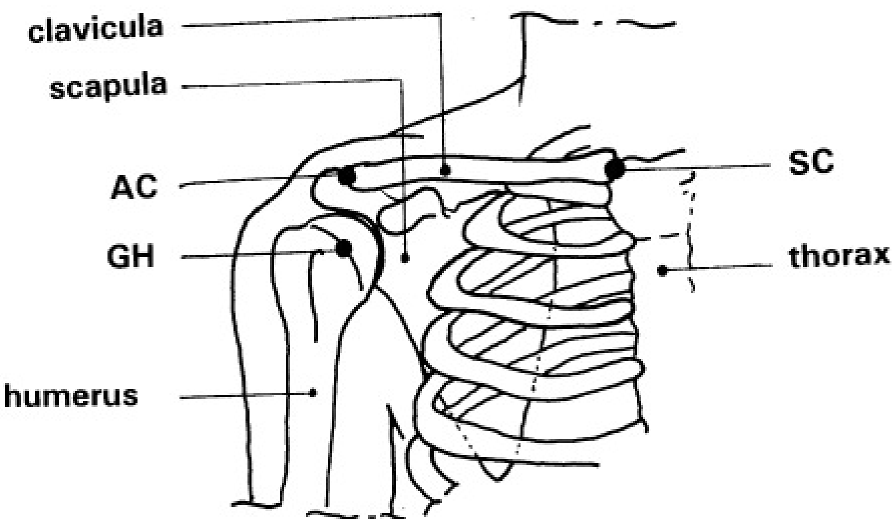


Figure 2 - The shoulder mechanism consists of the following skeletal entities: the thorax, clavicula, scapula, and humerus; and the following joints: the sternoclavicular joint (SC), acromioclavicular joint (AC) and glenohumeral joint (GH). Between thorax and scapula a scapulothoracic gliding plane is present (Carr, 1996)

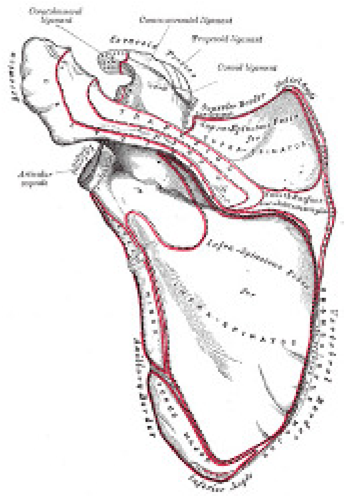


Figure 3 - Posterior view of left scapula ("Scapula.")

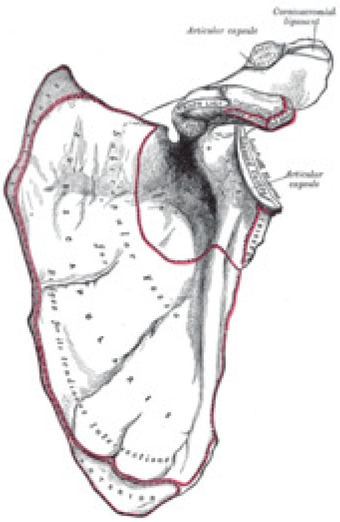


Figure 4 - Anterior surface of left scapula ("Scapula.")

The clavicle provides the connection of the shoulder joint to the trunk. It is a relatively cylindrical bone and lies horizontally across the front of the thorax above the top rib. Its medial end articulates with the sternum and its lateral end with the acromion of the scapula. The positioning of this bone allows the arm to be moved in front of the trunk. The bone has a slight S shape in the transverse plane that allows it to better transfer loads carried by the arm to the axial skeleton (Gray's Anatomy, 1995).

The humerus is the long bone of the upper arm. Its proximal end forms the large humeral head which lies in the glenoid cavity. The humeral head glides across this surface as the upper arm moves through its range of motion. The head is angled 35-40° to the posterior with respect to the long axis of the humerus. The shoulder joint is designed to provide maximum mobility and this angle helps stabilize the glenohumeral joint. Laterally to the head is a large protrusion where the greater and lesser tubercles are found. Of these nodules, the greater is located on the lateral surface and the lesser on the anterior surface of the tubercle (Carr, 1996).

2.2.2 Shoulder Musculature

Several muscles are attached to the bones that create the shoulder girdle to produce motion and to stabilize the joint. When considering the motion at a joint, specific terms are used to describe the movements unambiguously. *Flexion* decreases the angle of the joint in consideration, and applied to the shoulder, the arm would move from the person's side to above the head with its path of motion through the sagittal plane. *Extension* is the opposite motion, bringing the arm back down through the same path. *Adduction* moves the limb towards the median plane of the body, and *abduction* away from it. When the shoulder makes these motions, it has already been flexed so that it is positioned in the transverse plane, and its path of motion is also in this plane. Lastly, *rotation* is when the bone moves around its long axis; with respect to the shoulder, the humerus rotates around its long axis. It is the combinations of these movements that give the shoulder such a large range of motion, as described in Section 2.2.3 (Marieb, 1997).

The muscles of the shoulder can be divided into three categories according to their origin. The muscles either originate on the spinal column, the rib cage, or the scapula. In general, muscle contraction draws the limb on which it works towards the site of the muscle's origin. The strategic placement of each muscle in the shoulder joint allows the body to control movement of the arm through the full range of motion. Table 1 organizes the muscles into these three groups and delineates the origin, insertion, and action of each. Figures 5 and 6 show the origins and insertions of each fascicle of the muscles.

Table 1 - Muscles of the shoulder categorized by the structure from which they originate (Table compiled from information in Gray's Anatomy, 1995)

Muscle	Origin	Insertion	Action
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
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	
Infraspinatus	Intermediate posterior surface of scapula	Greater tubercle of humerus	
Teres minor	Intermediate inferior border of the scapula	Greater tubercle of humerus	
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

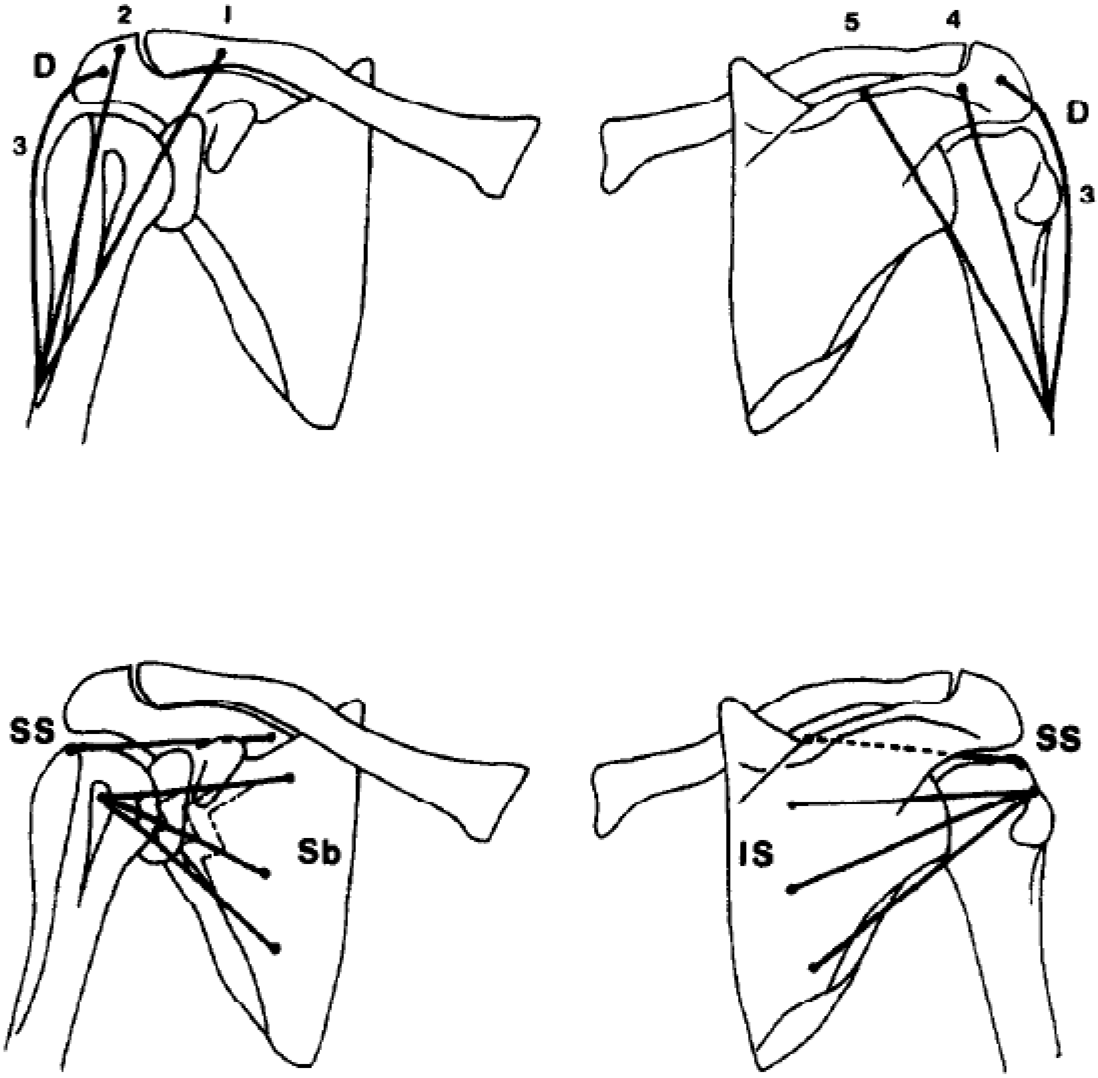


Figure 5 - Anterior and posterior views of the right shoulder girdle illustrating the disposition and attachments of the fascicles of deltoid (D), supraspinatus (SS), subscapularis (Sb) and infraspinatus (IS). (Johnson, 1996)

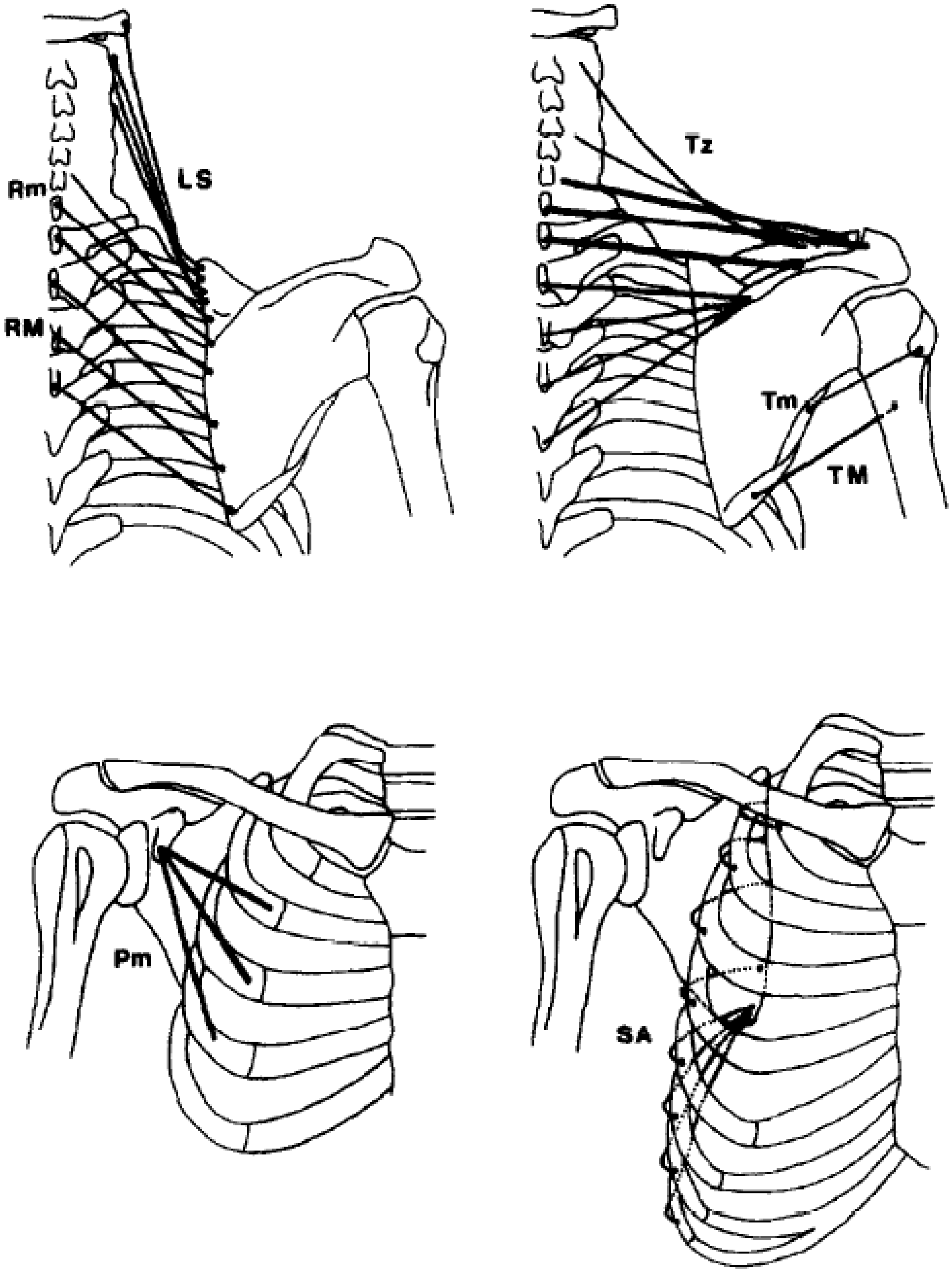


Figure 6 – Posterior and anterior views of the trunk and right shoulder girdle illustrating the disposition and attachments of the fascicles of levator scapulae (LS), rhomboid minor (Rm), rhomboid major (RM), trapezius (Tz), teres minor (Tm), teres major (TM), pectoralis minor (Pm) and serratus anterior (SA) (Johnson, 1996).

The trapezius, levator scapulae, rhomboids, and serratus anterior work together to rotate the scapula through various angles. As a result, depending on which combinations of muscles are contracting, several of these muscles are involved in opposite motions of the scapula. The teres minor, supraspinatus, infraspinatus and subscapularis form the rotator cuff which keeps the head of the humerus in the ideal position in the glenoid cavity for rotation and limits the head's translational movement. These four muscles work together to counter the actions of larger muscles in order to keep the humerus in place (Gray's Anatomy, 1995). The stability of the shoulder is also aided by the intra-articular pressure which is kept at negative 4 mm Hg. When these factors are disrupted from normal, the humeral head can dislocate anteriorly (Carr, 1996). Figure 7 shows the lateral face of the scapula including the connective tissue that stabilizes the shoulder.

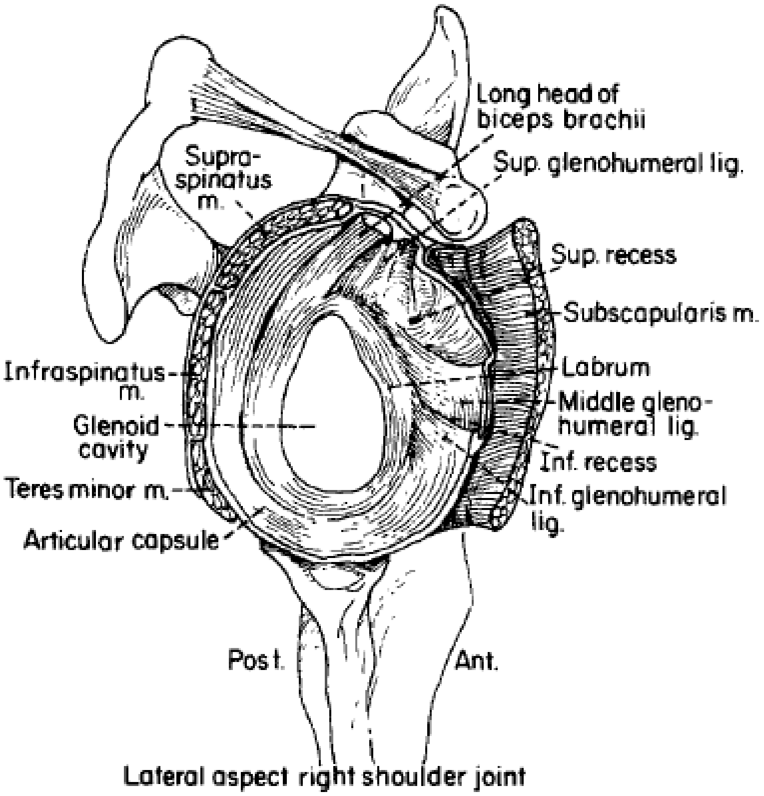


Figure 7 - A schematic diagram of the gleno-humeral ligaments and muscular stabilizers of the gleno-humeral joint (Klein Breteler, 1999).

2.2.3 Shoulder Biomechanics

The shoulder design can be mathematically analyzed similarly to a mechanical joint or linkage. The joint at which the humerus articulates with the glenoid cavity can be simulated by a ball and socket joint. The glenoid cavity is rather shallow which allows for greater mobility (Carr, 1996). Rundquist, et al, (2003) measured the range of motion of the humerus during flexion and abduction, its internal and external rotation while the arm vertically by the side and also while it is abducted 90º to the body in the frontal plane. They also determined the abduction of the scapular plane, which while at rest is 40º from the frontal plane, rotated around a vertical axis. The subjects were instructed to move the limb to maximize the angle in each of these directions, and the averages among all the trials of the subjects are shown in Table 2.

Table 2 - Motion Relative to the Trunk and Scapula as a Percentage of Normal (adapted from Rundquist, 2003). ER indicates external rotation, IR indicates internal rotation.

	Relative to Trunk		Relative to Scapula	
Motion	Mean ± SD	Range	Mean ± SD	Range
Flexion	116.9±22.1	80–165	70.5±16.4	41–102
Abduction	98.4±25.0	57–134	46.4±18.9	27–89
Scapular plane abduction	113.4±18.7	80–145	61.7±17.0	38–97
ER1*	4.5±12.3	−19 to 20	34.7±15.8	14–64
ER2†	33.5±15.5	8–54	45.3±18	15–70
IR1*	54.3±13.6	39–73	10.3±16.2	−18 to 29
IR2†	17.8±17.9	0–50	−6.4±16.6	−29 to 20

***ER1 and IR1 performed with the humerus adducted at the side. †ER2 and IR2 performed with the humerus abducted to as close to 90° as possible. Negative values indicate that a neutral position was not attained.**

The movements of the scapula are not as straightforward as those of the humerus. Fayad and colleagues defined the motion of the scapula when the arm is raised from the side in both the frontal and sagittal planes. The subjects raised their arms at two self-selected speeds, “slow” and “fast” to see if speed of the humerus has an effect on the motion of the scapula. In addition, the position of the scapula was also noted at 60º, 90 º, and 120 º in both planes. The resulting motion of the scapula can be seen in the plots in Figure 8. It is evident that the speed at which the tasks are accomplished has little effect. Protraction and retraction are the equivalent of internal and external rotation around the vertical axis. Medial and lateral rotation of the scapula occurs around an axis perpendicular to the scapular plane pointing forward. The tilt of the scapula is measured with respect to an axis placed through the spine of the scapula. The data show that the scapula protracts as the humerus is extended from 60º and 90º, and retracts to its starting position once the humerus is at 120 º. It does not rotate more than 5 º in either direction. The scapula rotates laterally as the humerus is raised in both the sagittal and frontal planes, and medially as it returns to its original position. The scapula passes through a range of about 30º in each direction. Finally, the scapula tilts posteriorly as the arm rises and anteriorly as it is lowered, approximately 10º in each direction. The pattern of motion for each of the three scapular movements in each plane is comparable, although its starting positions differ slightly between planes.

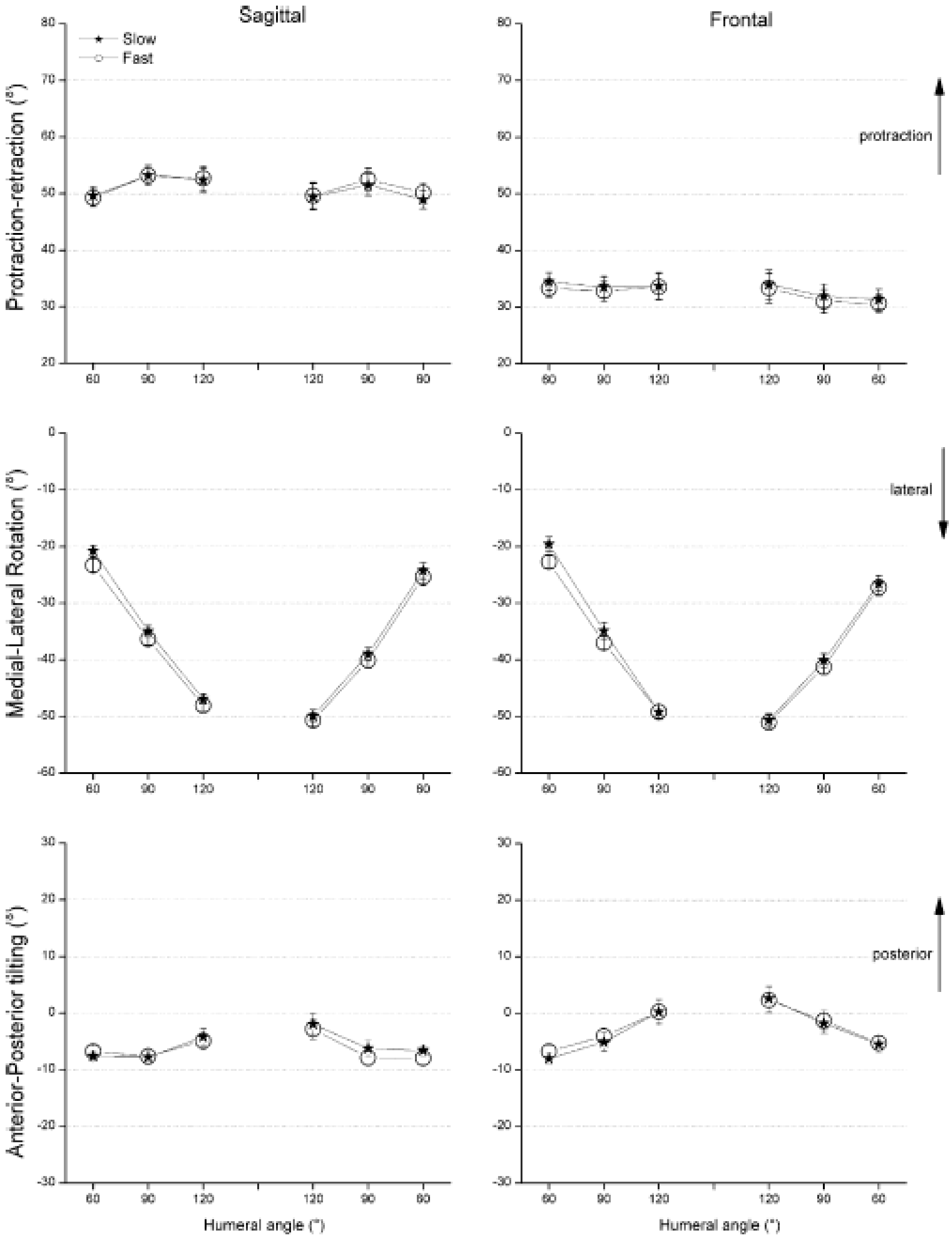


Figure 8 - Mean scapular rotations and standard error of the mean for slow and fast arm movements in the sagittal (left) and the frontal (right) plane (Fayad, 2006).

The geometric parameters of the clavicle, scapula, and humerus were measured in a study by Breteler, et al. (1999). They dissected cadavers to determine the mass, as well as location of the center of mass of each bone relative to the origin which was placed centered between the jugular notch, the superficial indentation at the anterior base of the neck, and the seventh cervical vertebra. The Y-axis extends vertically up from this point, the X-axis points perpendicular to it to the person's right, and the Z-axis is perpendicular to both X and Y pointing back. The location of the origin at the jugular notch is shown in Figure 9. The location of the center of mass in each segment was used in equations developed in a previous study, to generate the moment of inertia of the body part (Klein Breteler, 1999). The data collected are recorded in Table 3.

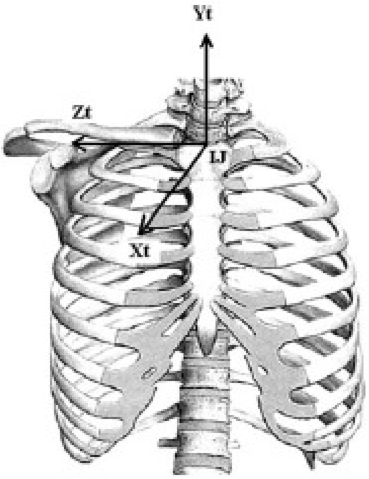


Figure 9 - Local coordinate systems of the thorax (adapted from Fayad, 2006)

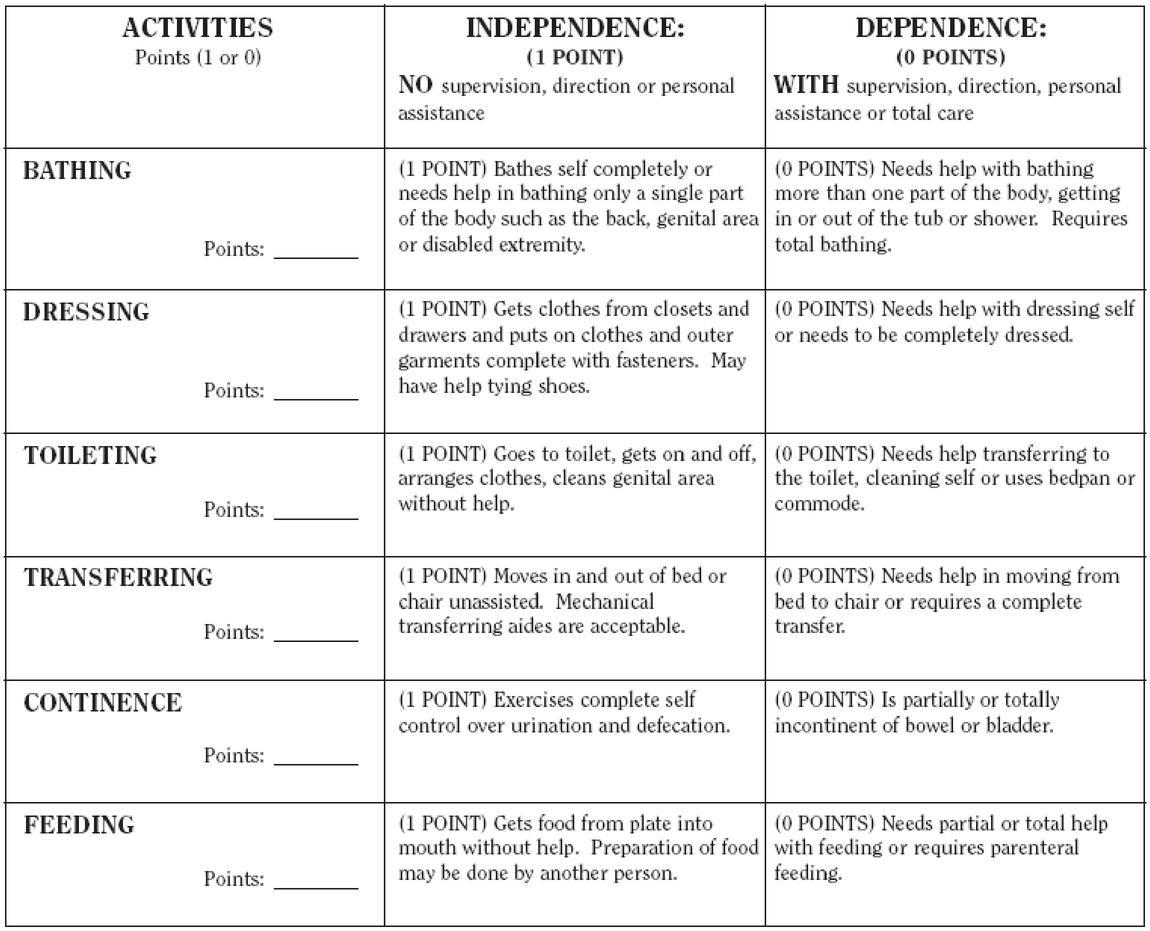
Table 3 - Segment moment of inertia (kg m2) about a transversal axis I5, and about a longitudinal axis I- (Hinrichs, 1985), mass of the body segments (kg) and the positions of the mass centers (cm) (Klein Breteler, 1999).

Body segment	I_t	I_l	mass	X	Y	Z
Thorax	—	—	—	0	– 13.93	6.80
Clavicula	0.001	0.003	0.156	8.44	1.22	6.80
Scapula	0.007	0.007	0.704	11.87	– 2.53	11.74
Upper arm	1.320	0.199	2.052	17.44	– 13.31	8.74
Forearm	0.612	0.091	1.093	18.69	– 43.84	12.21
Hand	0.064	0.019	0.525	21.45	– 61.09	11.78

2.2.4 Common Shoulder Movements

The previous described ranges of motion and other geometric data pertain to individuals with a full functioning limb. The ranges of motion noted in the above Table 2 are maximums in each direction. As it is ideal to possess such unrestricted mobility of the upper arm, it is not, however, mandatory to accomplish every day activities. According to the National Center of Health Statistics (2004), activities of daily living are defined as "activities related to personal care and include bathing or showering, dressing, getting in or out of bed or a chair, using the toilet, and eating." The Katz Index of Independence in Activities of Daily Living, Table 4, is an assessment sheet used to determine the level of self-sufficiency based on their ability to complete such common tasks. The index also describes what each activity entails. The index is often used to assess the elderly, but can be generally applied to evaluate any person.

Table 4 - Katz Index of Independence in Activities of Daily Living (Shelky, 1998).

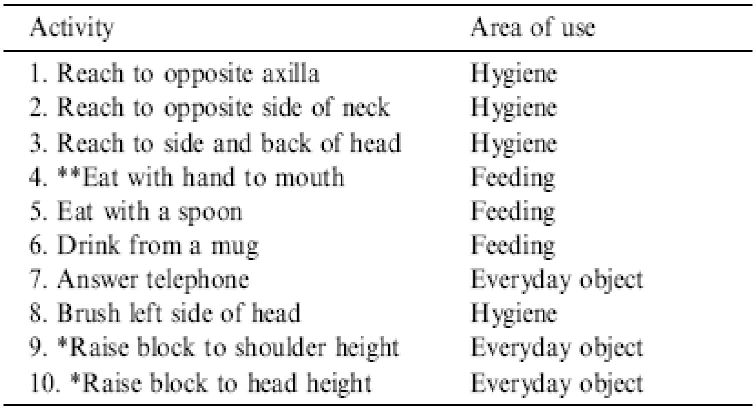


ACTIVITIES Points (1 or 0)	**INDEPENDENCE:** **(1 POINT)** **NO** supervision, direction or personal assistance	**DEPENDENCE:** **(0 POINTS)** **WITH** supervision, direction, personal assistance or total care
BATHING Points: ________	(1 POINT) Bathes self completely or needs help in bathing only a single 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 the 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.

Murray and Johnson defined the specific arm motions necessary to carry out these activities. They conducted a study in which ten male subjects repeatedly completed the tasks listed in Table 5 and the angle of shoulder flexion, abduction and internal rotation were measured. The maximum and minimum range of motion in each of these directions is recorded in Table 6. The axes from which the angles are referenced are arranged with their origin at the humeral head. Unlike previously described in Section 2.2.3, the Z-axis extends vertically up from this point, the X-axis points perpendicular to it to the person's right, and the Y-axis is perpendicular to both X and Z pointing forward. Because of this difference in reference point, the relative magnitudes of the angles differ from those mentioned in Table 2. Also, the value of internal rotation attained in Murray and

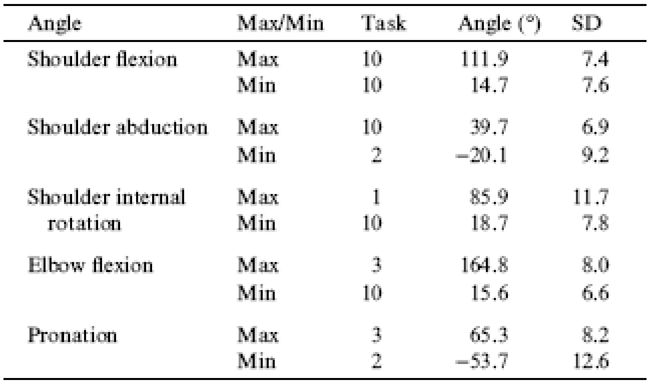
Johnson's study may be greater than that deemed maximum by Rundquist because Murray and Johnson's subjects were allowed to move their arm through any planes to accomplish the tasks, whereas Rundquist restricted his subjects to either the sagittal or frontal plane. As a result, more motion is allowed when the arm is allowed to move freely. Overall, the activities in which the arm is elevated to shoulder-height or above require the most movement in the shoulder.

Table 5 - Upper limb activities performed in the study (Murray, 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

Table 6 - Maximum ranges of motion at the elbow and shoulder for all tasks and the tasks at which they occurred (Murray, 2004).



Angle	Max/Min	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

The subjects in this study all had healthy, normal limbs. The range of motion, as well as the path of motion, for those with a prosthesis may differ from that of an unafflicted person. Nevertheless, prosthetics are designed to minimize the amount of inhibition or change to any aspect of normal motion, especially pertaining to the activities of daily living. The design of our transhumeral prosthesis support system will have the same ideals.

2.3 Trunk

While understanding the structure and motion of the shoulder is essential to design a mount that will least inhibit natural movement, it is also important to consider the trunk as well. Since the shoulder attaches the arm to the trunk, and is itself a small region in comparison, the loads applied to the prosthesis may be transmitted through the mount to the trunk. Thus, its bulk anatomy should also be identified.

The thoracic region is the upper portion of the trunk. It is supported by the spinal column down the center of the back, and is given its shape by the rib cage. The ribs attach to the spinal column at the posterior of the thorax and to the flat sternum at the anterior. They protect the lungs and heart, and a layer of muscle, at most, lies between the ribs and the skin. As previously described, the clavicle and the scapula reside in the thoracic cavity, and are the physical connection between the arm and trunk.

Inferior to the thorax is the abdomen which contains the digestive organs, kidneys, and liver, among other organs. However, unlike the thorax, the abdomen does not contain a sturdy structural enclosure. The abdomen is supported by the spinal column also, and its inferior boundary is composed of the load bearing pelvic girdle (Marieb, 1997).

2.4 Potential Candidates for Device

Since the purpose of apparatus designed in this project is to support a transhumeral prosthesis during load bearing activities involving the effected limb, the population using the device is limited to those with transhumeral prostheses. Such prostheses are used to replace the missing limb in both congenital and acquired conditions.

2.4.1 Congenital Conditions

Congenital limb abnormalities have had a steady incidence rate of 26 newborn babies per 100,000 live births in the United States between the years 1988 and 1996. Of those newborns, 58.5% suffer from deficiencies in the upper limb. One of the more common cases of congenital limb abnormalities is limb reduction deficit, in which the baby is born missing a portion of a limb. Its severity can be as trivial as a missing finger or as serious as missing both arms. Several possible factors that may cause a child to be born with a deformed limb include maternal diabetes or infection, maternal congenital defects, and maternal exposure to legal and illegal drugs such as diet pills, alcohol, and marijuana (Froster, 1993). The condition might be genetic as well. Past congenital deformities have been linked to the use of thalidomide tranquilizers by the mother during pregnancy. Thalidomide drugs were banned worldwide in 1961 due to these implications. Also, the radiation from the 1986 explosion in Chernobyl, Russia has had lingering effects and may be the cause of some birth defects. Those with a transverse deficiency, missing a limb beyond a certain point, could be candidates for a transhumeral prosthesis, and thus our device (Shelky, 1998).

2.4.2 Upper-Limb Amputations

According to the National Health Interview Survey conducted in 1996, about 1.8 million people living in the United States have suffered from an amputation. A statistic from 1993 estimates the incidence rate of amputations to be approximately 6 per 100,000 per year in the United States (Dillinham, 1998). There are several medical conditions that may require that a portion or all of a limb is removed. The survey also recorded trends that developed between the years of 1988 and 1996. The majority (82%) of the amputations during this time period were due to vascular disease, mainly from complications in diabetes. However, only 3% of these occurred in the upper extremity. In addition, the presence of bone or muscle cancer in a limb may demand that the limb be removed, and 23.9% of these operations affected the upper limb. Injuries sustained during traumatic events, often involving motor vehicles and farm equipment, may also necessitate amputation, 68.6% of which are of the upper extremity. Data have shown that males have been at a much greater risk for amputations due to vascular disease and trauma than have women.

2.5 Prosthetics

A prosthesis is an artificial device attached externally to the body which is responsible for the restoration of congenital and/or acquired neuromuscular and musculoskeletal dysfunctions that occur with the absence or loss of a limb (Orthotic & Prosthetic Rehab Center, 2000). A prosthesis can provide an amputee the ability to perform everyday activities that would otherwise not be possible. Prosthetic limbs can also boost moral in a patient after the shock of a lost limb.

Upper-extremity prosthetic limbs in particular present numerous problems for users and designers alike. The prosthesis must be able to replicate the complex motions of the shoulder and elbow. In addition, the motions of the hand and wrist must be replicated in order for the amputee to perform daily activities. The arm is also one of the most visible limbs of the body. Therefore, if the user is to be comfortable wearing the prosthesis, it must be somewhat cosmetically pleasing. A fine line needs to be drawn between function and appearance, which is usually up to the user or designer of the prosthesis. The addition of a prosthetic limb to the body takes time and a significant amount of training for a person to start gaining back functionality of the arm. One has to get used to the cables and wires responsible for movement and the weight difference between the prosthetic limb and a natural limb(Stark, 2001).

The multitude of variations present in the selection and design of prosthetics make it a complex process. Therefore, there are many different types of limbs available to an amputee based on location of the amputation, desired need of the prosthesis, and funding for the prosthesis. Prosthetic limbs can be divided into two main groups. Passive, or cosmetic prostheses, are those that do not have active grip and are used more for appearance (Farnsworth, 2004). Active prostheses, most commonly known as body-powered and myoelectric, are those that maintain active grip and movement of the arm.

2.5.1 Active Prosthetics

Of the two main types of prosthetics, active are the most common, as they enable the user to carry out many tasks as if they still had use of a natural hand, forearm, and elbow. There are numerous different types within active prosthetics, but the two main sub categories are body powered and myoelectric. Body powered prostheses utilize the user's body motion to power the device while myoelectric prostheses are powered by some kind of motor and battery source and controlled via electrical signals emitted by the user's muscles.

2.5.1.1 Body Powered Prostheses

Body powered prostheses, sometimes called conventional prostheses, are the simplest type of active prosthetics. The layout of the active element of all body powered prostheses is essentially the same – a harness worn around the users mid section (Figure 10) is connected to the terminal device via a flexible cable.

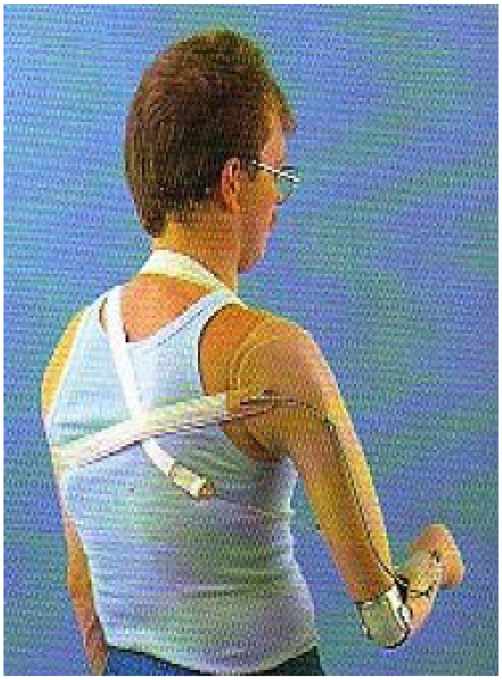


Figure 10 - Body Powered Prosthesis Harness (Ritchie, David, 2006)

The user actuates the terminal device by implementing a gross body movement, which in turn directs the harness to pull the cable it's connected to. The extent to which the terminal device is opened or closed depends on the amplitude of the user's body movement input. Although the general layout is very similar in these prostheses, the harness designs can differ significantly in order to accommodate for specific users' abilities to perform different gross body movements. There are harnesses that can take advantage of any one of the four movements: glenohumeral flexion, scapular abduction or adduction, shoulder depression or elevation, or even chest expansion. These prostheses generally allow for only glenohumeral flexion and biscapular abduction, but depending on the level of amputation some can even incorporate an artificial elbow joint. ("Prosthetic Options", 2006)

The simplicity of the body powered prostheses gives it a lot of advantages in the prosthetics market. In one case, a boy with a learning disability and low muscle development could not operate any of the prostheses on the market very well. In 1998, a new prosthesis was designed with his case in mind. New features implemented included the utilization of a pull switch incorporated into the cable control to be actuated with his remaining arm. A firm pull on the switch would open the terminal device while a slight pull closed it. Another part of the design was the removal of the elbow activated by a spring loaded cable. The elbow would now function simply by supporting the forearm with a table or his legs and locking it into position with his other hand. Essentially, the prosthesis was designed to be more dependent on his remaining natural hand. The result was an extremely user friendly design that even allowed the boy to carry a lunch tray with ease, open and close containers, and even type on a computer (Vacek, 1998). These same design principles could be applied to the development of this project. The fact that most amputees do still have one natural arm and hand to use in actuating the device could greatly reduce the complexity of the design.

Another benefit of these designs is that since they require body movement to operate, the user receives sensory feedback in the form of pressure from the harness which indicates the position of the prosthesis – something most other designs are unable to achieve. The simple design also lends itself to allow for the use of extremely durable materials which reduce maintenance costs and can withstand just about any situation or environment. Even though most body powered prostheses are just for general daily use activities, numerous specialized designs have been made as a result of their durability. Specific examples include fishing, swimming, and many ball sports ("Prosthetic Options", 2006).

However, like all things, body powered prosthetics have their disadvantages. One of the main drawbacks is the uncomfortable harness. In order for the device to work properly, it must be tight fitting. Another result of the tight harness is restricted movement which limits the functional workspace of the user. Wearers of body powered prosthetics also complain about the aesthetics – generally the devices are very mechanical looking, making them very noticeable to others. Worst of all, the number of body powered prosthesis candidates is limited in that the user must have sufficient residual limb length, musculature, and range of motion ("Prosthetic Options", 2006).

One prosthesis that seems to be improving on, but still retains most of the characteristics of body powered prosthesis is the AdVAntage Arm. The manufacturer specifies that it is "a body powered upper arm prosthesis designed to improve upon and overcome the major limitations of conventional prostheses". One area the AdVAntage arm improved upon was the range of motion. The excursion of the elbow ranges from 20 to 148 degrees when measuring the angle from the axis of the humerus. It can also be operated at 58 degrees above the horizontal. This is of importance because its range encompasses the range of motion of almost all body powered prostheses and should be accommodated for in the final design of this project. Another design feature of the AdVAntage arm is its cable material, Spectra 1000, which has high strength, and low friction. If the final design were to incorporate any type of cable this gives an idea of what to use, as few materials incorporate both of these properties (Cupo, 1998).

2.5.1.2 Myoelectric Prostheses

For the amputees that are unable to use body powered prostheses, myoelectric prosthetics (Figure 11) are a great option. These designs are more complex in theory, but the operation itself is simple.

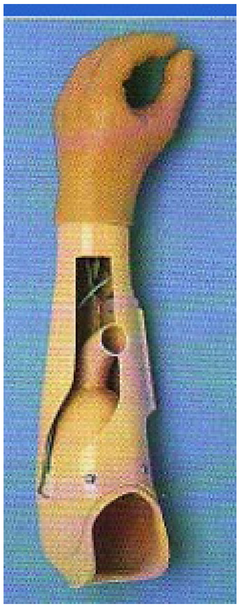


Figure 11 - Myoelectric Prosthesis (Ritchie, 2006)

There are electrodes on the limb end of the prosthesis that harvest electrical signals that the muscles transmit (EMG). Those signals are then amplified and sent to a control unit which can interpret them into movement of the prosthesis via electric motors connected to the hands, wrists, and elbows. Flexing different muscles in the residual limb sends different electrical signals, which are then interpreted to move different parts of the prosthesis (Ritchie, 2006).

This advanced prosthesis design has countless benefits. First and foremost, since it has all the same joints as a real arm with electric motors to move them, myoelectric prostheses are easier to use, have a more natural response, and a freer range of motion along with less effort for actuation. The use of motors also allows for a stronger pinch force than is possible with the body powered prostheses. Another advantage is that the terminal device (Figure 12) is often interchangeable. A mechanic, for instance, could replace his normal hand device with one more suited for holding tools. Lastly, the myoelectric prostheses are more humanlike and less noticeable to others. They do not require the strap that body powered prostheses do, and they usually have a “skin” over all the mechanicals and electronics so it appears as a real arm ("Prosthetic Devices: using cybernetic devices to enhance human mobility”, 2006).

Figure 12 - Myoelectric Terminal Device ("Myoelectric Prosthetics")

Unfortunately, myoelectric prosthetics are not the answer to all transhumeral amputees. The two biggest problems are that they are prohibitively expensive for many prosthesis users, and due to the complexity of the design, the devices do not stand up to much abuse. The heavy duty materials, motors, and electronics also make myoelectric prostheses significantly heavier than other options, which can be a burden to many ("Prosthetic Devices: using cybernetic devices to enhance human mobility", 2006).

One of the most popular of myoelectric devices on the market is the Boston Arm, which holds the title of "The world's most powerful elbow". Despite its prominence in the marketplace, it does share many of the same features as less successful prostheses. Although lighter than most at only 3.5 pounds, it has a minimum coupling collar length of 2.80 inches, a maximum forearm circumference of 9.25", a forearm ranging in length from 8.5 – 14.5 inches, and a center of mass at 3.5 inches from the rear housing ("Upper Limb Prosthetics Technology", 2006). These will all be useful parameters to design around in the development of this project.

The prominence of myoelectric prostheses has led to the development of a new and even more advanced type of prosthesis. Instead of using external electrodes to collect EMG signals, electrodes are being wired directly to nerves that were once connected to the arm. This enables the user to simply think about what he wants to do with the arm, and it will respond accordingly. A man named Jesse Sullivan (Figure 13) is in the process of testing such a device. Recently, pressure sensors have even been implemented with this design to permit Jesse to feel what he is touching (Dyer, 2005).

Figure 13 - Robotic Prosthesis (Dyer, 2005)

2.5.2 Passive Prosthetics

A passive prosthesis functions mainly as a cosmetic limb. Those who do not carry out an active life style or prefer a more aesthetically pleasing prosthesis would be strong candidates for such a device. A passive prosthesis can add symmetry to the human body, thus eliminating the appearance of a lost limb. The addition of a limb can also even out the weight distribution of the upper body by adding weight to one side. The addition of weight to the side of the lost limb aids in realigning the spinal cord which can help to eliminate future back problems of the amputee (Benchmark Medical, 2006). Materials such as flexible latex, silicone, and PVC allow skilled artisans to construct passive prosthetic limbs that appear real to the untrained eye (Fraser, 1999). These limbs do not require a significant amount of harnessing to hold in place, are very durable due to few moving parts, require little maintenance, and are lightweight when compared to a powered prosthesis (Benchmark Medical, 2006).

The main limitation behind the passive prosthesis is that the user has no active grip. The hand is pre-positioned in one place, and can only be changed by force with the opposing arm assuming it is still functional. Users of this device can still perform bi-manual activities. Objects can be pushed or pulled, held in place, and stabilized.

There are many users of the passive prosthesis who use it as a secondary device. Active prosthetics may be used for a majority of the time to perform basic daily activities. The passive prosthetic can then be put in place when the user does not require the active functions and would like the lighter weight, comfort, and aesthetically pleasing options. Examples of situations described by amputees are social situations and times of relaxation (Farnsworth, 2004).

2.6 Limits of Existing Technology

The average human adult arm is approximately 5.1% of a persons total body weight. The upper arm is comprised of 54.9%, forearm 33.3%, and hand 11.8% of the total weight of the arm. Therefore, a person weighing around 170 pounds would have arms over 8.7 lbs each (Kroemer, 1989). The majority of prosthetic limbs weigh less than this. For example, the Utah Arm weighs 3 lbs with the arm in place (Motion Control, Inc, 2006). The problem is that the weight of a prosthetic limb, several pounds less than an actual arm, is still difficult for an upper arm amputee to bear for extended periods of time. The method of attachment for a prosthesis is not comparable to the mounting of a human arm to the body. The human arm is attached and supported by muscle fibers, ligaments, and skeletal structure. The shoulder is designed to support the arm for extended periods of time, whereas the supporting system of a prosthesis is not. It does not have the same natural feeling.

One of the most important parts of a prosthetic limb is the socket. This is the area of contact between the prosthesis and the body. The mounting location for the prosthesis is different for each person due to body size, shape of the residual limb, and location of the amputation. A person can only fully benefit from their prosthesis if it is as comfortable as it is functional.

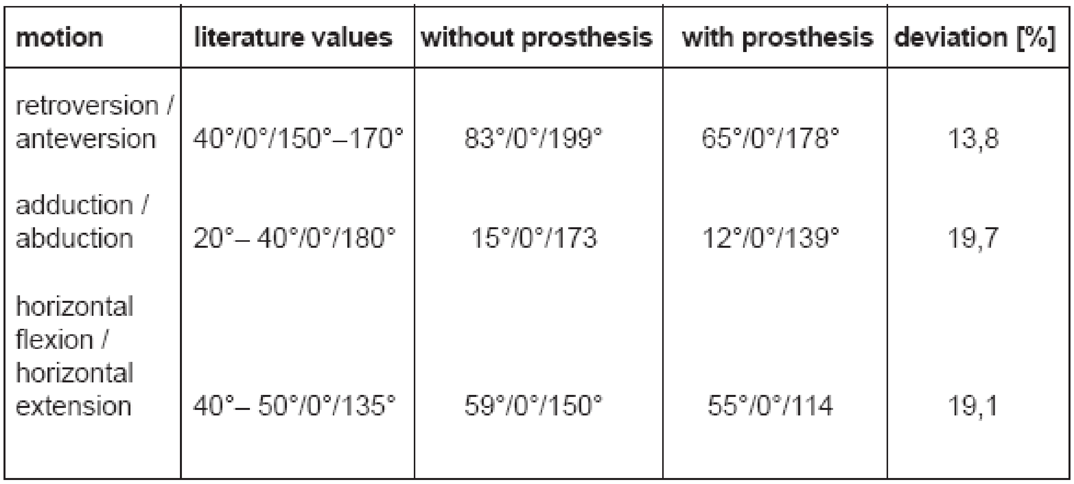
Many prostheses are held on by a suction system. Air is removed from the interface between the socket of the prosthetic limb and residual limb. This creates a vacuum and consequently the limb is held in place. It is essential that the suction remain constant throughout the entire range of motion of the arm (Farnsworth, 2004). The suction method of suspension is only applicable to basic daily activities that do not put extra forces onto the prosthetic limb. Any load bearing or forceful activities may cause the prosthetic limb to separate from the residual limb of the body.

Other methods of suspending the prosthesis to the body are with the use of straps, belts, and corsets. These methods provide a secure foundation for the prosthesis, but they can be extremely uncomfortable to the user. The rubbing of the straps and belts can cause skin irritation, abrasion, and sweating. Corsets and torso mounts can cause the individual to sweat excessively as well as cause discomfort to the body of the user.

A prosthetist, Tim Curran, from Hanger Orthapedic Group, Inc. provided some information with respect to the limits of prosthetic limbs in load bearing cases. He stated that there is basically no limit on load bearing activates for an amputee when a comparison is made between pre-amputation and post-amputation. He described a situation in which an amputee had the need to support axial loads of 100 lbs. That amputee could be provided with a specific harnessing system that would allow him to carry out such activities. He then describes that this would be difficult due to the fact that the majority of prosthetic limbs have a much lower load rating and would most likely break or become damaged in such a situation. Certain myoelectric prostheses can only support 20-33 lbs. A specific prosthesis would have to be designed for the special harness. There is a chance that the new prosthesis would not be as functional as a regular myoelectric prosthesis. Sacrifices would have to be made in exchange for a more robust harnessing system that supports heavier loads (Previous MQP, 2006). The website for the Utah Arm states that their arm can withstand a load of up to 50 lbs in the locked position with the arm at 90 degrees flexion without the forearm extension installed (Motion Analysis, Inc., 2006).

The range of motion of a prosthetic device is crucial to functional operation. An amputee with a prosthesis will not retain the range of motion similar to that of a natural arm. The harnessing system of the device is the limiting factor that causes the reduction. A study was done to measure the mobility of a shoulder joint using a shoulder joint simulator called IKARUS. The range of motion was measured for a natural arm, arm with a body powered prosthesis and harness, and values were compared to those found in some unmentioned literature. The values can be seen in Table 7.

Table 7 - Range of Motion of Arm With and Without Prostheses (Bertels, 2001; Debrunner, 1994)



motion	literature values	without prosthesis	with prosthesis	deviation [%]
retroversion / anteversion	40°/0°/150°–170°	83°/0°/199°	65°/0°/178°	13,8
adduction / abduction	20°– 40°/0°/180°	15°/0°/173	12°/0°/139°	19,7
horizontal flexion / horizontal extension	40°– 50°/0°/135°	59°/0°/150°	55°/0°/114	19,1

As can be seen in the table, the range of motion of the arm with the prosthesis is significantly less than the arm without the prosthesis.

The ideal system would include a comfortable yet stable support system to harness the prostheses to the body without sacrificing range of motion. A device that would also enable the use of an existing prosthesis for load bearing activities would be beneficial as well.

2.7 Analogous Systems

Information regarding prosthetics and the limits of current technology will only give a small part of the knowledge needed in designing a prosthesis supporting system. There are many other designs to look at which perform similar functions and would aid in gaining an understanding of what needs to be implemented and what does not.

2.7.1 Exoskeletons

Since it is likely that the supporting system to be designed will be connected externally to the body and prosthesis, looking at the design of different types of exoskeletons could prove to be very beneficial. Various exoskeleton designs that were examined include those of orthotics, insects, superhumans, and pressure suits.

2.7.1.1 Orthotics

The world is filled with different types of orthotics that can aid in a patient's limb recovery. In terms of this project, these devices are useful in that many of them incorporate different variations of exoskeletons to accomplish their purpose. One such device is described in the US Patent 5662594 – the Instant Invention (Figure 14).

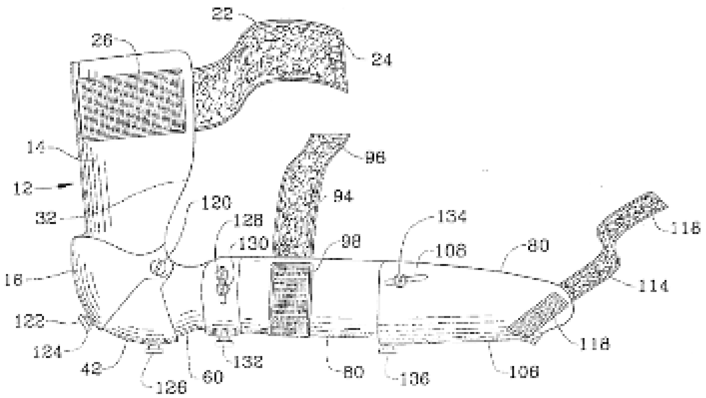


Figure 14 - Exoskeletal Orthosis (Rosenblatt, 1997)

The Instant Invention is an exoskeletal orthosis connecting from the humerus to the wrist that has lockable joints to restrict movement in any plane the user desires. For instance, to restrain elbow flexion and excursion, item number 120, a securing screw, can be locked. The resulting friction between item 18 and 42 makes the joint impossible to move. Forearm rotation can also be restrained utilizing a combination of securing screws, items 128 and 130, and a slot (within item 80). Numerous other degrees of freedom can be restrained as well using equivalent methods in different locations. The idea is to restrict movement which can keep an injury from healing much like a cast does but without immobilizing more than is necessary. This project could utilize a similar joint locking exoskeleton device, only applying the technology to the shoulder joint, which could increase the load capacity in certain arm positions such as straight out from the body. The main difference would be that joints could be easily locked and unlocked in only a few seconds by hand instead of utilizing a permanent locking system requiring tools for adjustment (Rosenblatt, 1997).

Two good examples of shoulder orthoses can be seen in Table 8.

Table 8 – Shoulder Orthoses

Name of Shoulder Orthoses	Characteristics	Diagram

Prototype Arm I Exoskeleton with Scapula Motion for Shoulder Rehabilitation (Carignan, 2005)	Arm exoskeleton for treating shoulder pathology, intended to have 5 active degrees of freedom	
Prototype Arm II Exoskeleton with Scapula Motion for Shoulder Rehabilitation (Carignan, 2005)	Arm exoskeleton for treating shoulder pathology, intended to have 5 active degrees of freedom, more kinematic changes implemented when compared to first prototype	

The two shoulder rehabilitation prototypes are complex devices that required a significant amount of kinematic analysis and design. The designs of the two prototype exoskeletons are good examples that show how important it is to reduce the degrees of freedom of a device. Designing around the necessary degrees of freedom will make the device simpler and require less moving parts.

There were two major issues that arose during the design of the devices. The first issue was trying to simulate the motions of the shoulder joint, and the second was determining the placement of the shoulder singularity. The first motion analyzed was shoulder depression and elevation since this commonly occurs when someone shrugs or when the glenohumeral joint is rotated. This analysis aided in meeting their goal of having scapulothoracic motion (Carignan, 2005).

To solve the problem of placing the singularity, the design team had to figure out a way of simulating the shoulder as a ball and socket joint without actually using one in the exoskeleton. The designers described the interference that would exist between the robotic ball and socket joint and the human ball and socket. To solve the problem, they used 3 "serially connected" pin joints. The 3 pin joints somewhat replicated the motion of the ball and socket, but with different kinematics (Carignan, 2005). The forearm joint was easier to design since it only required a single pin joint. The serially connected joint can be seen in Figure 15.

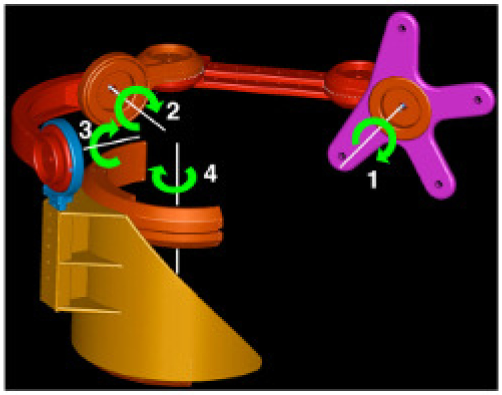


Figure 15 - Serially Connected Joint of Prototype Shoulder Orthosis (Carignan, 2005)

2.7.1.2 Arthropods

Sometimes the best engineering designs have already been engineered by nature. Evolution has refined the design of insect and other arthropod exoskeletons for thousands of years, which makes them a prime candidate for study in the process of creating an artificial exoskeleton. The exoskeletons of arthropods only allow one degree of freedom per joint. Figure 16 is a good example of this and shows how a cockroach's leg uses single DOF joints for its complex mobilization. The joint connecting the coxa and metathorax allows the arthropod to change its body position either up or down. The three remaining pin joints connecting the other leg segments are knee like in their operation, and work together to allow for almost any type of cockroach movement.

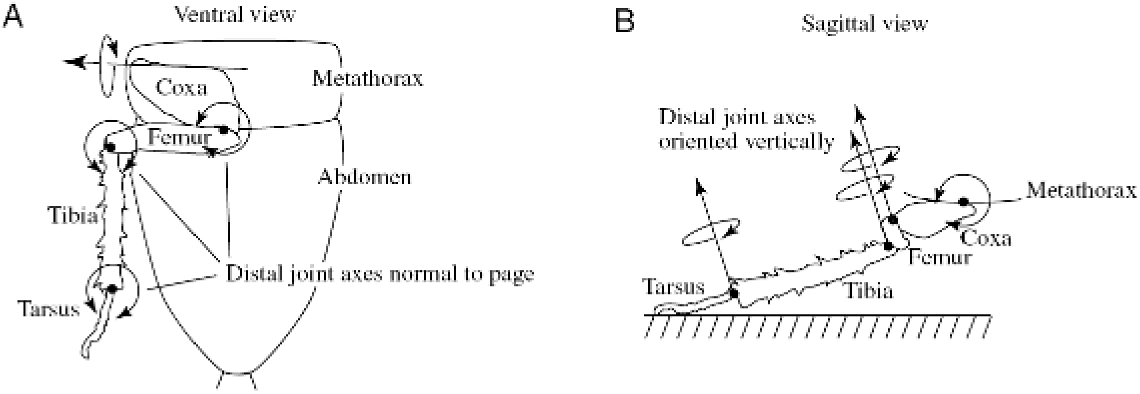


Figure 16 – Joints of a cockroach leg from two different views (Dudek, 2006)

Because arthropods and vertebrates have such different skeletal systems, it would make sense that their muscular systems also differ to the same extent. However, although there are differences, the overall idea is essentially the same - pairs of muscles antagonize each other through a system of rigid levers. The main difference is that the muscles lie within the skeleton rather than outside. Other variations include how nerve impulses actuate the muscles and the fact that vertebrates have primarily smooth muscle whereas arthropods have entirely striated due to its responsiveness needed for things like flight (“The Arthropods”, 2006).

2.7.1.3 Superhumans and Space Suits

Many different sects in society have taken note that exoskeletons could provide significant advantages in terms of load bearing and protection qualities. As a result, many different exoskeleton designs have been created in order to expand the normal range of human ability. While the device to be created within this project is not designed to grant its user superhuman abilities, many design features such as mounting systems and kinematics will be similar. Although concentrating on the lower part of the body rather than the arm, the BLEEX project at the University of California – Berkeley, figure 17, is an excellent example of a body mounted exoskeleton.

Figure 17 – BLEEX Superhuman Exoskeleton (Chu, 2002)

As would be expected in such a design, kinematics were of the utmost importance. The BLEEX team of engineers decided not to model the kinematics of the exoskeleton exactly like a human leg. The main reason behind this decision is that only users with the exact leg dimensions of the device would be able to operate it. To accommodate for multiple users, BLEEX is rigidly fixed to the operator only at the hip and foot. Fixing at any more locations would result in the machine imposing high loads onto the human at those points due to kinematic differences (Chu, 2002).

It is easiest to explain the kinematics and 7 degrees of freedom of the BLEEX exoskeleton by starting at the top and working down. Figure 18 shows the device's hip section.

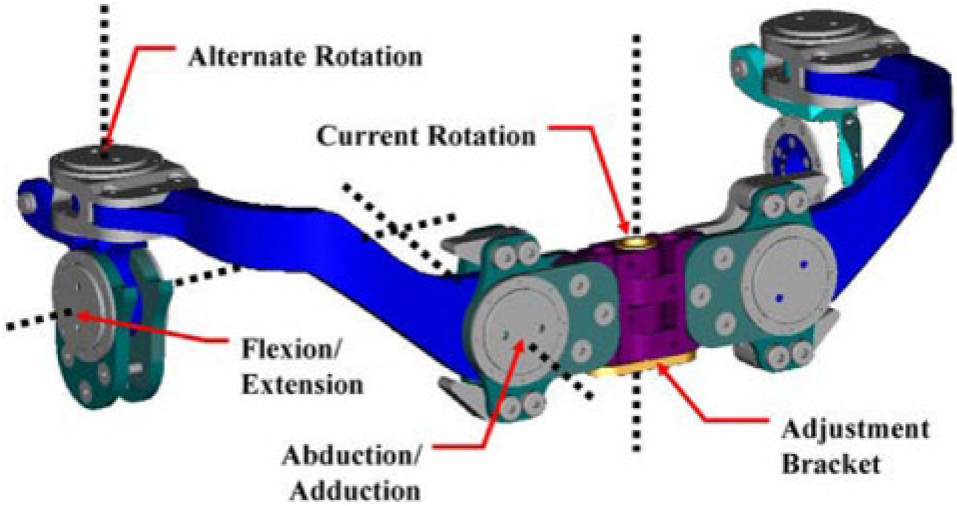


Figure 18 – BLEEX Hip (Chu, 2002)

The hip rotation joint for each leg was chosen to be a single axis behind the user's back. The alternate hip rotation joint located just outside the hip was only implemented for testing purposes, but is a viable alternative. The hip abduction/adduction and hip flexion/extension joints' axes pass through the human hip to replicate its motion exactly.

The next joint down from the hip is the knee. This is another joint in the BLEEX design that differs from its human counterpart. A human's knee contains complex motion in which the center of rotation moves as the knee flexes. This exoskeleton simplifies the knee joint to a simple pivot joint.

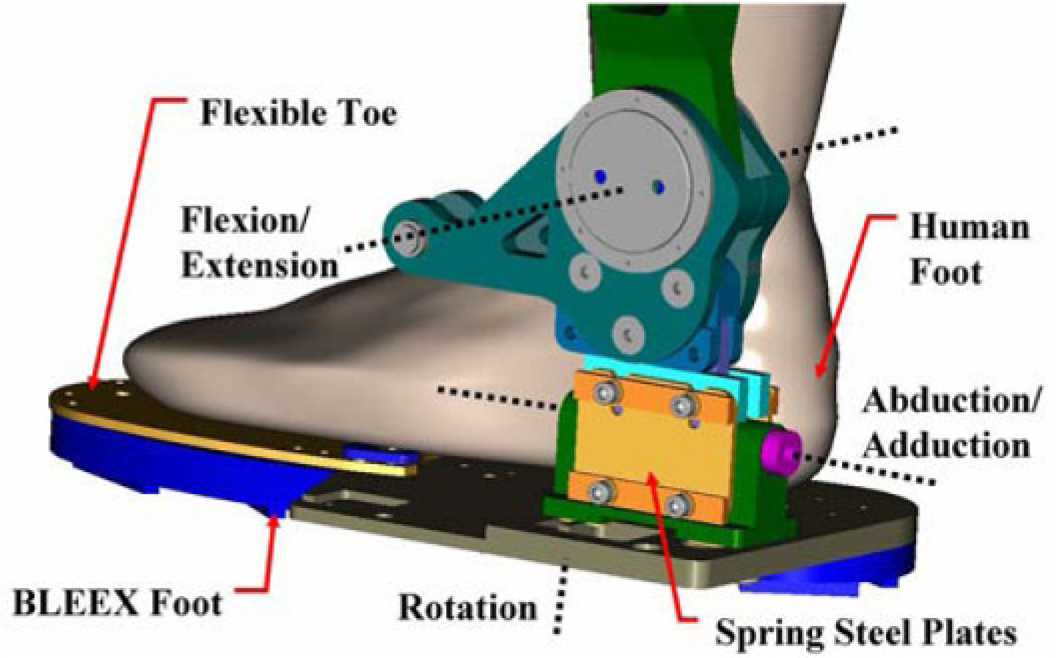


Figure 19 – BLEEX Ankle (Chu, 2002)

The final significant section of the machine is the ankle, which can be seen in Figure 19. In this part of the exoskeleton, the only joint to replicate the human's exactly is the ankle's flexion/extension, as its axis passes through the human joint's axis. The abduction/adduction and rotation form a plane outside the foot (Chu, 2002).

Space suits are another form of exoskeleton worn by humans to enable otherwise impossible actions. Above an elevation of approximately 63,000 feet human blood begins to boil due to the low pressure. Because of this, space suits must be pressurized to keep this phenomenon from occurring. However, without a proper structure, the suit would balloon out, constraining the user's movements. The incorporation of an "exoskeleton" within the suit stops this from happening. These exoskeletons always follow a number of key guidelines. The most important of these is that the volume must be kept constant. Since the suit is pressurized, any change in volume would require work from the user. The space exoskeletons achieve this goal usually by using rigid joints that roll using bearings (“Space Suit”, 2006). This idea could easily be integrated into the device to be designed. Even if only used at atmospheric pressure, the use of bearings would aid in reducing the friction in the joints.

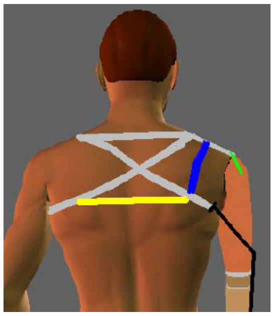
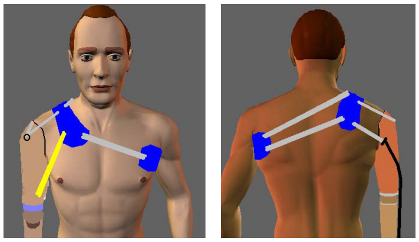
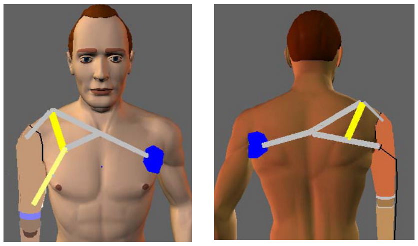
2.7.2 Harnessing Systems

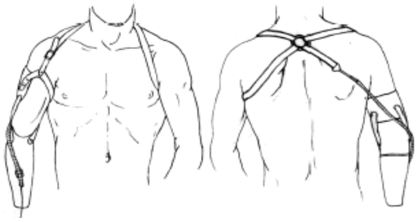
The job of a harness is to support, attach, or suspend an appendage or object to the body. When designing a harnessing system, the goal is to achieve comfort, support, and the ability to don and doff easily. Prostheses harnesses have the purpose of attaching and supporting the prosthetic limb to the body. Body powered harnesses have the additional responsibility for movement of the prosthetic limb. Shoulder orthosis harnesses are used to rehabilitate different parts of the upper body.

2.7.2.1 Upper-Extremity Prostheses Harnesses

There are numerous options available to harness a prosthesis to the body. The options are based on the location of the amputation, intended use of the prosthesis and desired comfort level. Most harnessing systems consist of the same basic parts. There is usually a loop that wraps under the opposing arm, which is known as an axilla loop. There is also a suspension strap that wraps over the shoulder and attaches to the prosthesis. For body powered prostheses, there is always a cable attachment strap that allows for operation of hand grip. Each harnessing system suits different users and is suitable for different tasks. Some of the basic systems are displayed in Table 9.

Table 9 - Prosthesis Harnessing Options (Body Power Harness Fundamentals, 2006)

Name of Harnessing System	Characteristics of Harness	Diagram
Trans-humeral Figure of Eight Harness	Cross back strap, or Z strap, axilla loop (anchor point, under natural arm), cable attachment strap and a suspension strap (grey), cable (black)	
Trans-humeral with Shoulder Saddle	Suspends over the shoulder and under the opposing arm, dual straps around back, axilla loop (blue, under natural arm)	
Trans-humeral Strap Saddle	Similar to the shoulder saddle, wraps under the opposing arm, uses a strap on the shoulder rather than padding, axilla loop (blue, under natural arm)	
Fillauer Trans-humeral Harness	This harness eliminates buckling, keeps the axilla strap low (thick white harness), and is compatible with body powered or external powered prostheses	
TES Belt	Firmly secured to the arm, elastic strap, has a lateral suspension strap	

Name of Harnessing System	**Characteristics of Harness**	**Diagram**
German Trans-humeral Harness	Axilla suspension strap, cable attachment strap, made of elastic material	
O-ring Harness	Uses many of the basic concepts behind the figure of eight harness, but straps in back are connected with an O-ring, still uses the cable attachment strap	

Most harnessing systems tend to be uncomfortable to wear due to the sensitive areas of contact. They are also difficult to don and doff, especially with one functioning limb. If the harness is not cleaned on a regular basis, then it will begin to emit unpleasant odors (Plettenburg, 1998).

2.7.2.2 Shoulder Orthoses

Upper-extremity orthoses are used primarily for rehabilitation purposes. They are also known as braces, supports or splints. When a person has a trauma related injury or undergoes a surgical procedure, an orthosis is often needed to aid in the healing process (Upper Extremity Orthoses). Orthoses can also be used to correct a muscle weakness or deformity and can even shift weight to another area of the body. Other candidates for an upper-extremity orthosis are those with neurological problems, brain injuries, multiple sclerosis, cerebral palsy, spinal cord injuries, peripheral nerve injuries, and those with certain cases of arthritis (Bertini, 2006). They work by either restricting or assisting a part of the body to attain the desired outcome. Like prostheses, they can be custom fit and adapted to individual users.

Upper-extremity orthoses not only work on functioning limbs, but have the ability to be used on prosthetic limbs. The orthesis can aid in the rehabilitation of secondary conditions either caused by the use or improper use of a prosthetic limb (Bedotto, 2005). Different shoulder orthoses are shown in Table 10.

Table 10 - Shoulder Orthoses

Name of Shoulder Orthoses	Characteristics	Diagram
Shoulder Orthosis (OrthoRehab, Inc.)	Designed to offer support for clavicle fractures, acromio/clavicular problems and postural dysfunctions, supports the forearm/elbow for better alignment of the glenohumeral joint	
Shoulder Immobilizer (OrthoRehab, Inc.)	For rehabilitation of the shoulder joint following rotator cuff surgery, keeps the GH (shoulder) joint in an internally rotated position, uses a Figure of Eight design with a sling	

3.0 GOALS

Using the background, goals were set for the completion of the project. In order to achieve the final goal, a number of performance specifications must be met.

3.1 Goal Statement

The goal of this Major Qualifying Project is to design, analyze, and manufacture an upper arm exoskeleton for trans-humeral prostheses to allow one to perform high load activities including high moments about the humeral and elbow axes. It is desirable to keep the device as discrete as possible and to have a full anatomical range of motion. In addition, this device will be easy to don and doff, and be comfortable for both male and female users as outlined in the design specifications.

3.2 Performance Specifications

Before anything can be designed, performance specifications must be devised to guide the process. The specifications that the design concepts and, eventually, the final design will achieve are separated into five different categories: key performance, safety, user friendliness, reliability, and cost – all of which have an integral part in the success of the final product. Every requirement, regardless of its category, should be defined using specific, measurable quantities, in order to allow for verification upon production.

3.2.1 Key Performance

Key performance specifications are defined as specifications which are absolutely integral to the design. These types of specifications include accommodation for various prostheses, work required from the user for proper function, stability, range of motion, load distribution on the body, and load capacity

- Accommodate all types of existing commercially available transhumeral prostheses
    - Passive
    - Body-Powered
    - Myoelectric
- Required physical characteristics for ease of functionality
    - Device must weigh less than 8 pounds
    - Device must not bind or seize in any kinematic position
- Stability
    - Device must not slip of shift position on the body while holding a 10 pound object in the terminal device and moving it through the device's entire range of motion
- Range of motion
    - The device must not impede the range of the user's normal post amputee motion
- Load distribution
    - Device must not have loads higher than 6 psi acting on any part of the user's body under the load conditions specified below

- Load capacity
    - The device must be able to sustain 60 pounds axially
    - The device must be able to sustain 30 ft-lb about any axis

3.2.2 Safety

As with any device designed for use by a human, safety is of the utmost importance. Specific safety factors to be considered are sharp edges, pinch points, and areas which could produce sores on the user's body.

- Edges
    - The device must not be able to puncture skin or clothing
- Pinch points
    - The device must not have any exposed joints or areas that could pinch the user
- Pressure sores
    - Pressure of the device on the body must not exceed 6 psi at any location

3.2.3 User Friendliness

Performance specifications regarding user friendliness are not quite as crucial as safety, but are absolutely necessary in designing a successful product or device. Certain considerations include adjustability, ease of donning and removal, irritation, and aesthetics.

- Adjustability
    - The device must be able to accommodate both males and females falling within the 5th – 95th percentile in terms of arm and torso circumferences

- Ease of don/doff
    - The average user should be able to put on or take off the device within two minutes without aid
- Irritation
    - Any material contacting the skin should be non abrasive and breathable
- Aesthetics
    - The device should protrude from the body no more than 3 inches at joints and 2 inches in all other areas

3.2.4 Reliability

Reliability specifications also must be integrated for a design to be successful. These factors include fatigue, shock, and weather resistance as well as the ability to be washed.

- Fatigue resistance
    - The device must have a lifetime of at least 3 years
- Shock resistance
    - The device must withstand a drop test from 5 feet off the ground
- Weather resistance
    - The device must be able to withstand a spray test lasting one minute
    - The device must be able to withstand temperatures ranging from -30 degrees Fahrenheit to 115 degrees Fahrenheit
- The device must be washable with household cleaning products

3.2.5 Cost

In order to be competitive in the prosthetic attachment market, cost specifications must be taken into account. Specific considerations include material selection, manufacturing processes, and maintenance expenses.

- Materials
    - The total cost of materials cannot exceed $400 per unit
- Manufacturing processes
    - The total cost of the manufacturing including raw material, processing, and labor cannot exceed $400 per unit
- Maintenance
    - Materials to maintain the device cannot exceed $100 per year
    - Maintenance of the device must be simple enough to be performed by any prosthetist

4.0 EVOLUTION OF DESIGN

The Evolution of Design section represents the complete design process of the trans-humeral prosthetic mounting system from early on in the concept stage through design selection. Numerous design concepts were created that had potential of solving the problem at hand. A decision matrix, based on our performance specifications, was used to eliminate non-feasible concepts. The selected concepts were further refined and then analyzed. Following the analysis, potential for redesign was seen, thus leading to the current final design.

4.1 Design Concepts

The trans-humeral prosthetic mounting system will consist of three main subassemblies that are connected to achieve the desired project goal. The three subassemblies are the prosthesis attachment, torso mount, and mechanism. A general description of the three subassemblies is outlined below.

4.1.1 Torso Mount

The torso mount acts as the interface between the body of the person and the mechanism of the mounting system. The torso mount must be comfortable to wear and also be strong enough to withstand the loads transmitted by the mechanism.

I. Side Torso

The side torso mounting concept, shown in Figure 20, will be used to keep the mechanism securely mounted to the torso of the amputee while remaining comfortable during use. There are two options for the construction of the side torso mount. The first option is to make it from a plastic material molded specifically to each different user. The second option is to make it out of a more flexible material with a skeletal structure for rigidity. This would somewhat resemble sports equipment padding, but would be much stronger. This would make it somewhat adjustable for male and female users. The inside surfaces of the torso mount will be padded for a comfortable fit as well.

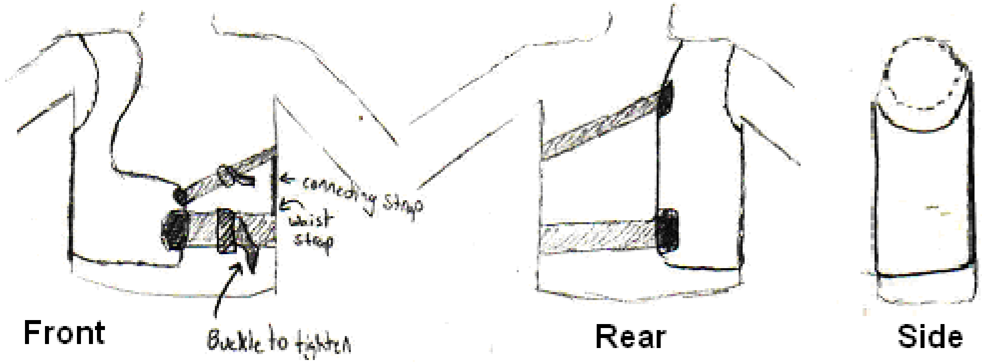


Figure 20 - Side torso mount concept, front, rear and side views.

There will be a system of straps used to keep the torso mount securely attached to the body. The primary strap will be a waist strap made from one to two inch nylon strapping. Buckles will be used similar to those in backpacks to secure the strapping. A secondary strap will be placed slightly above the waist strap and will travel from the front of the torso, under the opposing arm, to the upper back. A small connection strap will also be placed between the primary strap and the secondary strap to keep the secondary strap from contacting the arm pit area of the opposing functional arm. The amount and placement of the straps can be modified easily, but the basic concept is of a torso side mount. The mechanism will be attached to the side torso mount in the shoulder area. A thicker or more reinforced insert may have to be incorporated into the design for a solid and sturdy mount.

The amputee will have to place the prosthetic limb through the arm hole in the torso mount. The opposing arm will have to be used to place the straps and connect the buckles. To remove the side torso mount, the buckles will have to be unclipped and the opposing arm will have to be used to work the prosthetic limb out of the arm hole.

II. Full Back Vest

The full back vest torso mount concept is somewhat similar to the side torso mount but covers the entire back area rather than just half. The full back vest torso mount is pictured in Figure 21.

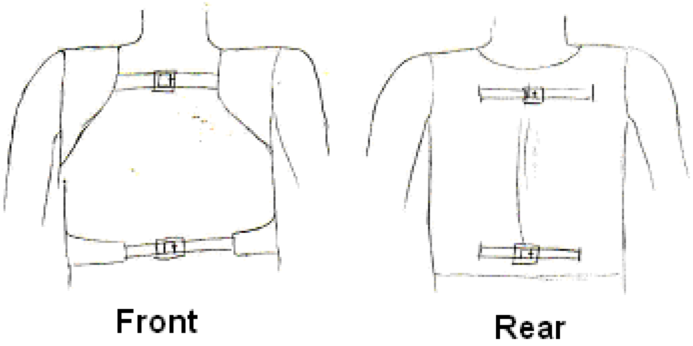


Figure 21 - Full Back Vest Concept

The portion of the vest that covers the shoulder is approximately two inches wide so that when its lateral edge is directly superior to the axilla, the medial edge is not interfering with the neck. The two sides are connected by an adjustable strap that clips together anterior to the superior sternum. The region on top of which the mechanism is attached is reinforced with a rigid material such as hard plastic or metal. The medial edges of the portions of the vest that covers the shoulder descend down the anterior surface then curve laterally under the axilla, much like the straps on a backpack. This edge, which has now become the lateral border of the vest, continues vertically down from the axilla to just above the pelvic girdle where it extends medially along the anterior surface of the body as a wide, 3 inch long tab. The medial edges of the tabs from each side are connected by another pair of adjustable straps which clip together inferior to the naval.

Posteriorly, the shoulder regions are connected with a sheet of fabric much like the back of a shirt. To allow for adjustability and secure fitting for each individual person, two adjustable straps are located on the posterior surface of the vest, at the same distance from the superior surface of the person's shoulders as their anterior counterparts. The straps should be adjusted for a snug but comfortable fit so the load can effectively be transferred to the internal boney structures. The vest as a whole is made of a sturdy fabric and the shoulder regions as well as the pelvic tabs are padded where they cross over the bones.

III. Rigid Shoulder Insert

The interface between the mechanism and the torso mount will be a rigid shoulder insert. This rigid shoulder insert will be incorporated into the torso mount and will provide a solid foundation for connection of the mechanism. The insert will have to be placed in the torso mount in such a way that the axis through the mechanism will be inline with the center of the shoulder joint. The rigid insert will be made out of a metal such as aluminum or steel and will be shaped to fit over the shoulder. A soft padding material will be placed on the inside surface of the rigid insert to reduce any possible discomfort. There will be enough material on this rigid insert to allow the mechanism to be bolted to it in some fashion.

4.1.2 Mechanisms

The primary responsibility of the mechanism is to connect the prosthesis attachment to the torso mount while retaining as much of a full anatomical range of motion as possible. The mechanism must also withstand the high loads and high moments placed on it during use.

I. Strings

This mechanism connects the torso mount and the prosthesis attachment with a pair of cords, as shown in Figure 22. The cords would be made of a flexible but sturdy, wear resistant material that will not stretch. An end of Cord 1 is looped around a ring attached to the anterior surface of the prosthesis mount near the axilla and would be fastened with a ferrule. The cord is fed through a ring located on the anterior surface of the body mount near the axilla and is guided over the superior contours of the shoulder by rollers/pulleys. On the superior posterior surface of the body mount, the cord is looped through another ring, and then terminates with a ferrule on a fourth ring located on the lateral posterior surface of the prosthesis mount. A similar arrangement of rings guides Cord 2, connecting the body and prosthesis mounts with its ends terminating on the body mount.

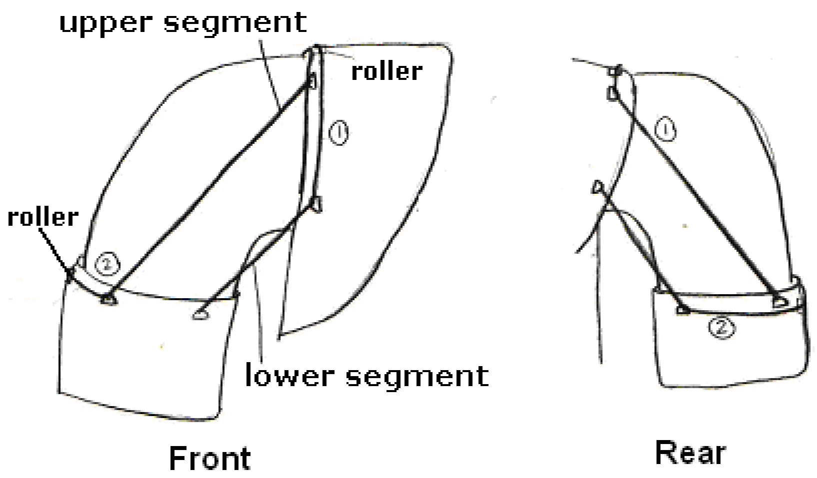


Figure 22 - Strings Concept

When the body is in the anatomical position, visually each cord and set of rings appears to contain an upper and a lower segment of the cord, both of which traverse the gap between the body mount and prosthesis mount. Each of the lower segments connects a pair of rings that are closer to the axilla, whereas the endpoints of the upper segments are more superior and lateral than those of the lower segment. The positioning of the rings in this way allows the two segments of a certain string to reciprocate during arm motions. When the arm is flexed, the lower segment of Cord 1 shrinks, providing slack for the length of the upper segment of Cord 1 to grow to accommodate for this motion. Likewise, the upper segment of Cord 2 grows as the shoulder flexes, taking length from the lower segment of Cord 2. The positioning of the rings allows the two segments of each cord to compensate similarly in extension, abduction, adduction, and other positions in between.

II. Rear/Front Scapula Mount

The rear scapula mount mechanism, displayed in Figure 23 concept is composed of four main sections. The first, A, is a simple quarter circle bar. One end is attached via a pin joint to the torso mounting structure in such a way that the axis is coincident to the shoulder's abduction/adduction axis. The bar then curves over the shoulder and is then connected via another pin joint to a straight bar, part B. The axis of the pin connecting these two parts is coincident with the shoulder's flexion/extension axis. Part B then runs along the user's humerus until it connects to a circular joint, part C. The center of the circular joint is along the humeral rotational axis. Connected to the other end of part C is another straight bar, part D. This bar extends along the humerus and serves as the mounting point for the prosthesis attachment design. Each joint mentioned can be locked in order to restrict movement of the mechanism.

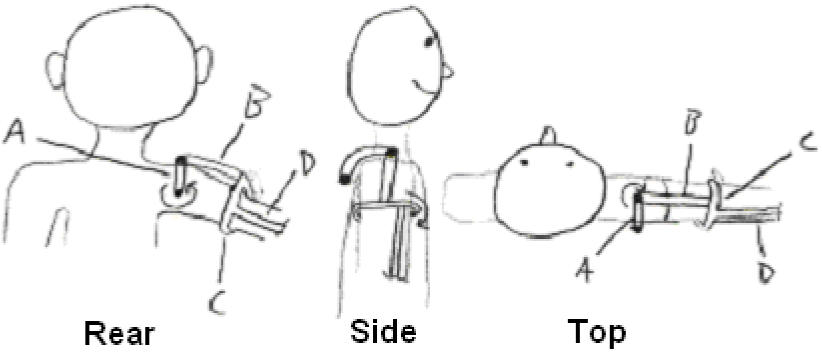


Figure 23 - Rear Scapula Mount Concept

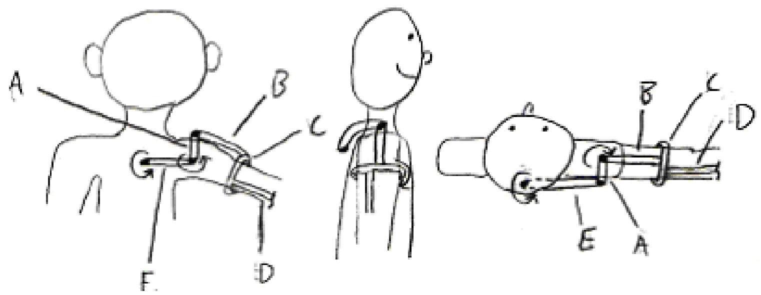
Once attached to the torso mounting structure and the prosthesis, the rear scapula mount concept achieves its goal in a fairly simple manner. The pin joints and the circular joint all have their axes aligned with the shoulder's three rotational axes. As a result, the mechanism can be moved along with any shoulder movement performed by the user.

Also, the fact that the mounting point to the torso support structure is on the shoulder itself, scapula motion is already taken into account and does not need to be replicated by the mechanism. The lockable joints allow for the user to transform the free moving mechanism into a rigid structure, allowing for loads to be transferred to the body rather than the junction point of the humerus and prosthesis, which results in higher load capacities.

A slight variation to the rear scapula mount concept is a front scapula mount. Part A from Figure 23 would curve from the chest to the top of the shoulder rather than from the back to the top of the shoulder. The rest of the mechanism would remain the same.

III. Five Degree of Freedom

The five degree of freedom mechanism seen in Figure 24 is also very similar to the rear and front scapula mount concepts. The main difference is an additional joint and bar. Instead of the mechanism connecting to the torso mount structure with bar A, it connects via bar E. Bar E connects to the torso using a U joint. The other end of bar E connects to bar A using a pin joint. The rest of the design is identical to the rear scapula mount mechanism.



Rear Side Top

Figure 24 - 5 degree of freedom concept, front, side and top views

The usage of the five degree of freedom mechanism is identical to the rear scapula mount mechanism with one exception – bar E and its U joint connection incorporates scapula motion into the mechanism. With two more degrees of freedom from the U joint comes two additional rotation locks. Although there is added complexity to this design, it could be beneficial in that the load can be transferred to the center of the back rather than the shoulder, allowing it to be distributed about the body more effectively.

4.1.3 Prosthesis Attachment

The prosthesis attachment is responsible for connecting the prosthetic limb to the mechanism of the mounting system. The prosthesis attachment must have a connection to the prosthesis that is secure and does not slip.

I. Pins

The pin concept for prosthesis attachment is quite simple. Pictured in Figure 25, it consists of two rings rigidly connected to the mechanism. Each ring is actually split in half with a hinge connecting the two semicircles on one end and a locking mechanism on the other end.

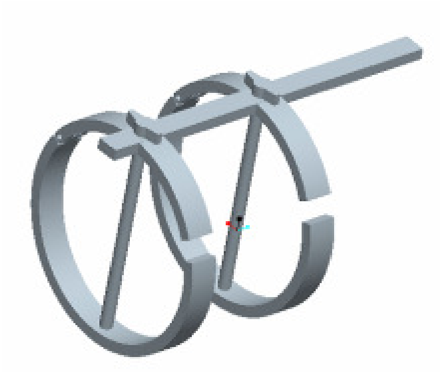


Figure 25 - Pin Attachment Concept

The usage of the pin concept is simple. Once positioned on the prosthetic arm, the rings of the concept can be locked around the prosthesis. The pins on the inner side of each ring would fit into custom made holes in the user's prosthesis to prevent rotation and translation apart from the mechanism's movements, essentially connecting the prosthesis to the mechanism rigidly.

II. Ratcheting Strap

A cuff open on both ends is lined with a high friction material on the inside surface. This cuff serves as the attachment interface between the mechanism and the prosthesis. The user is able to slide the cuff over the prosthesis and any of its protrusions since the cuff is not a complete closed circle. The cuff is made out of a soft material with an inner skeletal structure for support. A padded ratchet strap, similar to those in Figure 26, would connect the two ends of the cuff and allow the user to effectively tighten the cuff around the prosthesis to hold the mechanism in place. The high friction material helps to achieve this and the ratchet provides mechanical advantage to facilitate its tightening. The ratcheting straps would have to be connected to bars coming off the mechanism in some fashion.

Figure 26 - Ratcheting straps concept

III. Screw Clamps

The screw clamp prosthesis attachment concept consists of two screw clamps and a clamping pad, arranged as in Figure 27. The clamping pad will be attached to the mechanism. Two bars coming off the mechanism would make a good attachment point for the clamping pad. The two screw clamps will provide a clamping force around the prosthetic limb, keeping the attachment in place during use. A material with a high coefficient of friction, such as a non-slip liner, will be placed on the inside of the clamping pad. In the event of high loads and torques, the material will prevent the prosthesis attachment from slipping on the surface of the prosthetic limb.

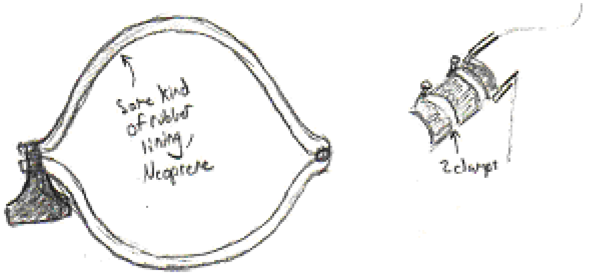


Figure 27 - Screw Clamps Concept

The screw clamp concept will be relatively easy to don and doff. The clamps can be tightened and loosened by turning a thumb screw with the opposing arm. The screw clamps are hinged, allowing easy removal, but may be more difficult to put on due to the difficulty of lining the clamps back up with one hand. If slippage is noticed between the prosthetic limb and the clamping pad, the clamps can easily be tightened.

IV. Velcro

The Velcro prosthesis attachment concept consists of at least two Velcro straps and a clamping pad similar to the screw clamp concept, drawn in Figure 28. The clamping pad will be attached to the specific mechanism used. The Velcro straps will provide the necessary clamping force to keep the mechanism attached to the prosthesis. As in the previous concept, a material with a high coefficient of friction will be placed on the interior lining of the clamping pad to aid in restricting motion. The two Velcro straps will be similar to those used on a wrist orthosis or cast. They are strong and provide a significant amount of clamping force.

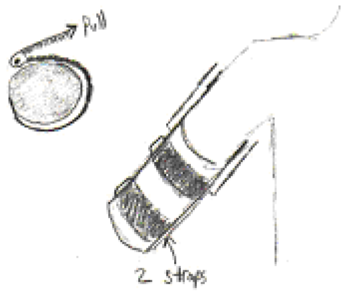


Figure 28 - Velcro concept for prosthesis attachment

This attachment concept will be easy to don and doff. The Velcro can be attached and removed with the opposing arm. The only difficult part will be keeping the clamping pad in line as the Velcro is being tightened.

V. Climbing Harness

The climbing harness prosthesis attachment, sketched in Figure 29, will be similar to that of the main waist strap on a climbing harness. It will consist of the two straps and a clamping pad similar to the two previous designs. The clamping pad will be connected to the mechanism. The prosthesis attachment will keep the mechanism attached to the prosthetic limb. Similar to the other concepts, a material with a high coefficient of friction will be placed on the inner surface of the clamping pad to reduce the chance of slippage between the prosthetic limb and the prosthesis attachment.

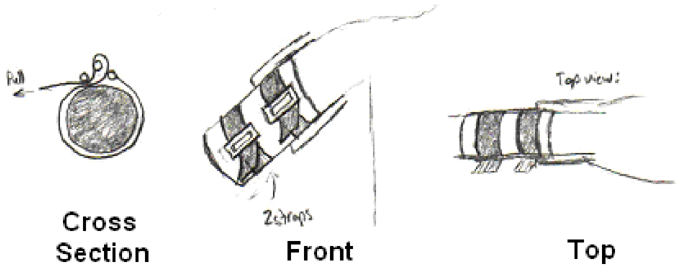


Figure 29 - Climbing harness concept for prosthesis attachment

The climbing harness concept is a variation of prosthesis attachment similar to the others. The clamping pads will be placed over the prosthetic limb and the straps will be tightened down with the opposing arm. The mechanism used to secure the harness straps may be difficult to operate with one hand since the strap has to be looped through several metal rings.

4.2 Decision Matrix

Choosing which concept to bring to the final design stage can seem like a daunting decision, but it can actually be made into a simple, logical conclusion through the usage of a decision matrix. A decision matrix works by giving each performance specification a weight in proportion to its importance and multiplying it by the rating each concept receives in that category. Whichever concept has the highest sum of those products is the best and should be brought to final design.

4.2.1 Matrix Organization

In order for a decision matrix to operate effectively, the weights of each performance specification must be designated carefully. First, each specification category will be given a weight, and thereafter, each individual specification within the category will be given a weight. The five categories are key performance, user friendliness, reliability, safety and cost. Since there are five total, each would receive a weight of .2 if all categories were equally important. Therefore, if a specification category is weighted greater than .2, it is considered of greater than average importance, and vice versa. Both key performance and user friendliness have weights of .25. These are of greater importance than the rest because these are the specifications that would set the design apart from what is already available on the market. Reliability is weighted at the average of .2 since this device will have a reasonably high initial price, and as such, it is important that it lasts a long time. Safety is ranked at a below average .15 because the device is not seen as potentially dangerous. Cost is also considered slightly less important than average with a .15 weight since, even with a high price, it is only paid once initially.

4.2.2 Design Selection

The mechanisms and prosthesis attachments were placed into the decision matrix. The torso attachments were not placed in a decision matrix due to their similarities and the fact that both would perform almost equally. The individual specifications, within the specification categories (specification categories in bold), were each given a value. A value was assigned by the project group members after a consensus was reached. These values were then averaged and weighted according to the decision matrix. The values from all of the weighted specification categories were added together for all of the concepts. It was then possible to see which concept scored the highest overall and for each of the specification categories. The decision matrices can be seen in Appendix A.

For the prosthesis attachment, it was determined that the ski binding/ratcheting mechanism concept would be the most suitable. The score it received was a .88/1. The next highest score was the pin concept, which received a .86/1. The two prosthesis attachments were both good concepts that had potential, but it was decided that the ski binding concept would be the one designed further. Even though the pin concept would be the most secure form of attachment to the prosthesis, it would require the prosthetic limb be altered. Holes would have to be drilled into the limb to allow the pins to go through. These alterations to a prosthetic limb would prove to be difficult and most users would be unlikely to do it. There is a possibility to design a prosthetic limb specifically for this mounting method, but the price would be increased significantly as a result.

For the mechanism, it was determined that the strings concept would be most suitable for further design based on its decision matrix score of .92/1. The rear scapula mount had the second highest score of .80/1. It was decided that both concepts would be designed further since the strings concept was a relatively new idea that had not been studied before. The rear scapula mount concept incorporated a few ideas that had been studied before; therefore we were more confident with its success.

5.0 FINAL DESIGN

The components of the trans-humeral prosthetic mounting system will be described in detail individually and as a complete working system. The final design is made up of three sub-assemblies - the prosthesis attachment, the mechanism, and the torso mount. Dimensioned drawings of each part and complete assembly drawings are included in Appendix B.

5.1 Parts & Assembly

The assembly of the device as a whole is very important as it would otherwise not work correctly. First, the mechanism sub-assembly must be created. An exploded view of all the parts needed for this process is shown in Figure 30.

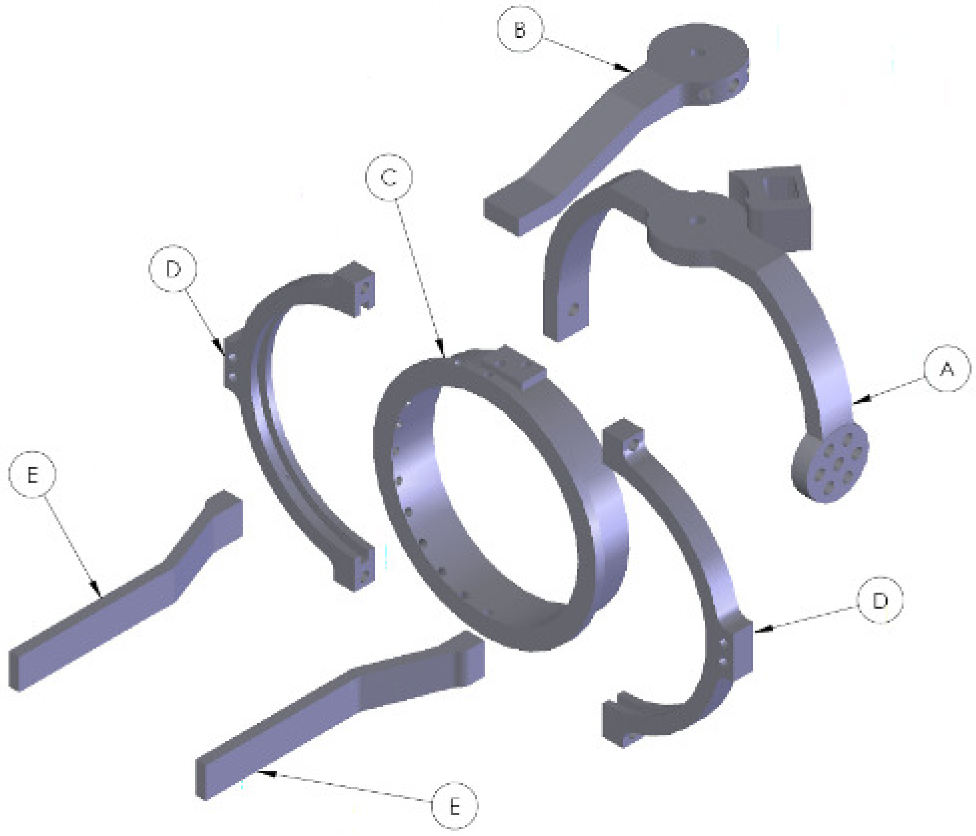


Figure 30 - Exploded Mechanism Sub-Assembly

The assembly process begins with screwing the two prosthesis attachment bars (parts E) to their respective outer ring pieces (parts D), making a rigid connection. Those two outer ring pieces are then screwed together around the inner ring (part C) to create a rotational joint. Following this, the top of the inner ring is screwed to the end of the humeral bar (part B). That piece is then connected via a pin joint to the top of the shoulder arch (part A), completing the mechanism sub-assembly. The final assembly should resemble Figure 31.

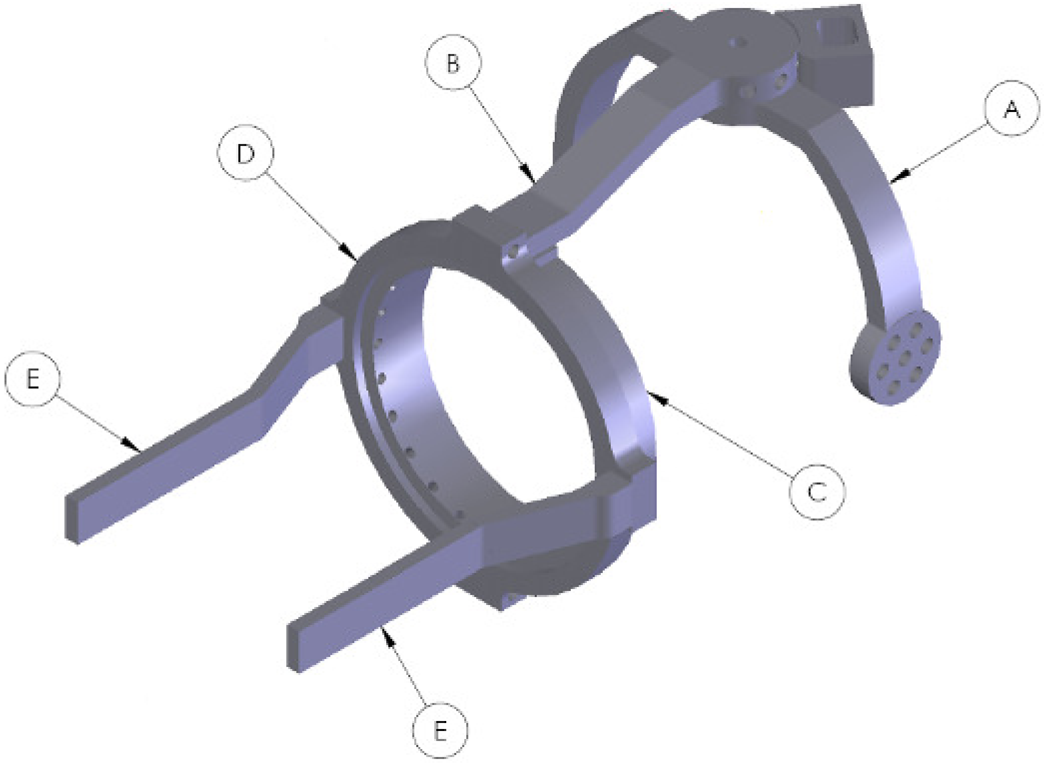


Figure 31 - Mechanism Sub-Assembly

The next sub-assembly, the torso mount, is really a single complex part. The details will be summarized in the manufacturing section, but it is essentially a semi-rigid canvas vest with a rigid shoulder insert.

The final sub-assembly is the prosthesis attachment. It consists of two teethed straps, two ratcheting locks, canvas, and a sheet of rubber. The two straps will be connected to the outside of the canvas sheet on one end opposite the two ratcheting locks on the other end. The sheet of rubber will be sewn to the inside of that canvas sheet.

With the all three sub-assemblies finished, the main assembly can be completed. The prosthesis attachment connects to the prosthesis attachment bars of the mechanism sub-assembly. This is done using rivets along the length of the prosthesis attachment's canvas piece on both sides. On the other end of the mechanism sub-assembly, the shoulder arch connects to the torso mount's rigid insert via pin connections.

5.2 Operation

Having completed the assembly of the device, it is essential to know how it works. The first point of operation would be for the user to don the device. This is done by simply putting on the torso mount like any other type of vest and tightening the straps. The user's prosthesis is inserted through the prosthesis attachment sub-assembly and is clamped down via the teethed straps and ratcheting locks. The combination of those clamping forces and the high coefficient of friction that the rubber on the inside the prosthesis attachment provides keeps the prosthesis rigidly connected to the rest of the device.

With the device donned, the user can utilize it for its intended purpose – carrying out high load activities without worry of the prosthesis disconnecting from the body. The first step in this process is the user positioning his arm in the desired position in which the loads will be applied. For example, if he wants to lift an object straight out in front of him, he will need to extend his arm and prosthesis out in front of his body. The device can achieve almost any position that the body can as it has the following joints: the rotational joint provided by the rings allows the mechanism to replicate rotation about the humeral axis, the pin joint between the top of the shoulder arch and the humeral bar replicates abduction and adduction, and the pin joint between the torso mount and shoulder arch replicates flexion and extension.

The next step is for the user to lock out any joints that may move as a result of applying the load. Using the previous example of holding an object straight out in front of the body, the user would have to lock out the flexion/extension joint and possibly the rotation around the humeral axis depending on if the object's center of mass lies off the humeral axis. Since there are no significant forces acting horizontally on the device the abduction/adduction joint does not need to be locked out. In fact, the user would most likely want to leave it unlocked so he could still utilize that motion while carrying the object. All three of the arm's rotational joints are lockable. The rotation about the humeral axis can be locked out via a set screw like pin that threads through the outer ring into one of many holes in the inner ring. The inner ring features so many holes in order to accommodate for a number of different positions to be locked in. The abduction/adduction joint can be locked in a similar way; a pin located on the top of the shoulder arch can be inserted into one of a number of different holes in the humeral bar. Flexion/extension is locked out using a pin located on the lower front end of the arch.

Locking out the correct joints will transform the previously body-following mechanism into a rigid structure. The loads imposed on the prosthesis will then be translated through the mechanism directly to its connection on the other end – the torso mount. The torso mount is designed to take those loads imposed on it and distribute them about the user's entire torso.

5.3 Stress Analysis

In order to ensure that the parts are sufficiently designed for safety and ease of use, they must be fully analyzed before they are ready to be manufactured. Throughout the original design of each part, careful consideration was taken to align the necessary holes, shafts, and axes of linked parts to guarantee a kinematically correct mechanism. Therefore, further kinematic analysis of the design is unnecessary. However, it must still be proven that while undertaking the worst possible conditions, none of the mechanism's components will fail.

The first step in carrying out the aforementioned analysis was determining the worst case condition that the device as a whole would be required to undertake. There were four loading situations that caused concern – bending moments, torsional moments, axial forces, and shear forces. A simple qualitative study of these various loading conditions produced five possible worst case conditions to be analyzed quantitatively. Free body diagrams were drawn for each of the following five situations, and the stresses on each part were analyzed using MathCAD, as shown in Appendix C.

The first of the five positions, which can be seen in Figure 32, has the user's humerus straight down at his side with his elbow bent 90 degrees and therefore extending his forearm out in front of him.

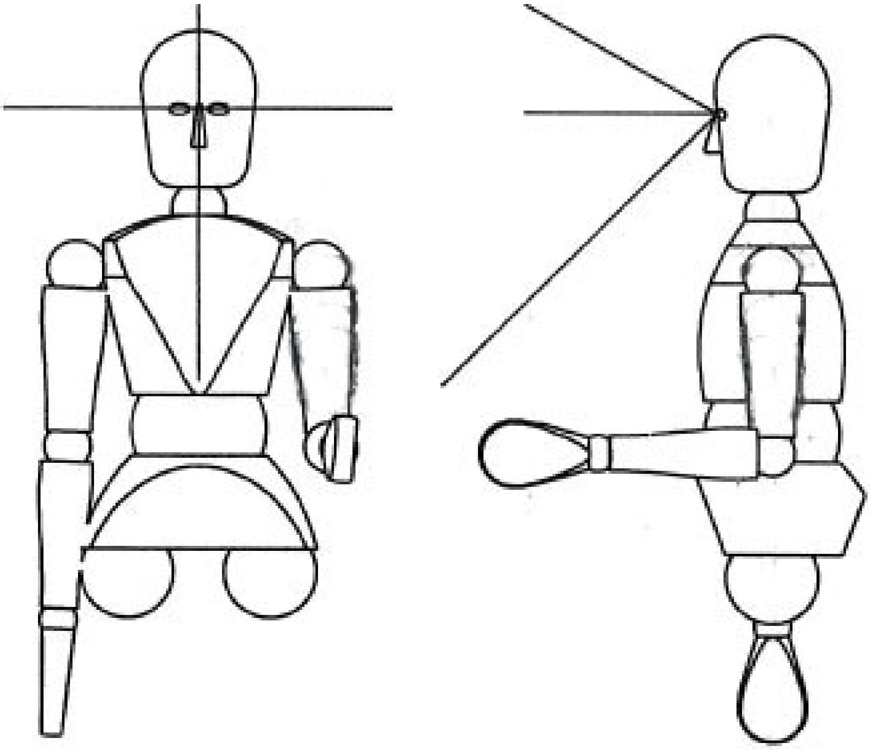


Figure 32 - Position 1

He is also holding a twenty-five pound object in his terminal device. To eliminate redundancy, it should be noted that all of the five positions have the user holding a twenty-five pound weight in his hand. There are two reasons this position was chosen to be included in the quantitative loading analysis – the straight down humerus would maximize axial forces along the humerus and the forearm facing forward increases the offset of the force and therefore increases the bending moment within the mechanism.

The next position has the user's humerus directed straight out laterally with the elbow bent in such a way that the forearm is directed straight forward as shown in Figure 33.

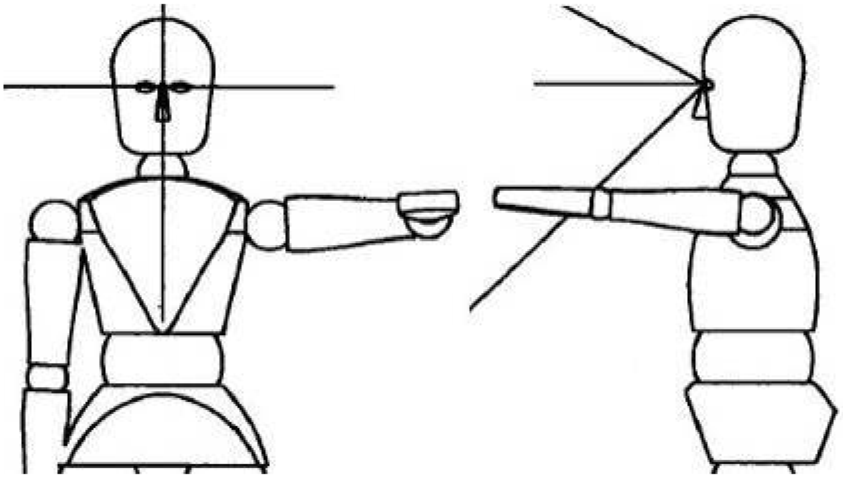


Figure 33 - Position 2

The humerus at the horizontal will impose shear stresses and a bending moment, and the offset created by the forward facing forearm will add a significant twisting moment.

The third position, which can be seen in Figure 34, has the entire arm extended laterally.

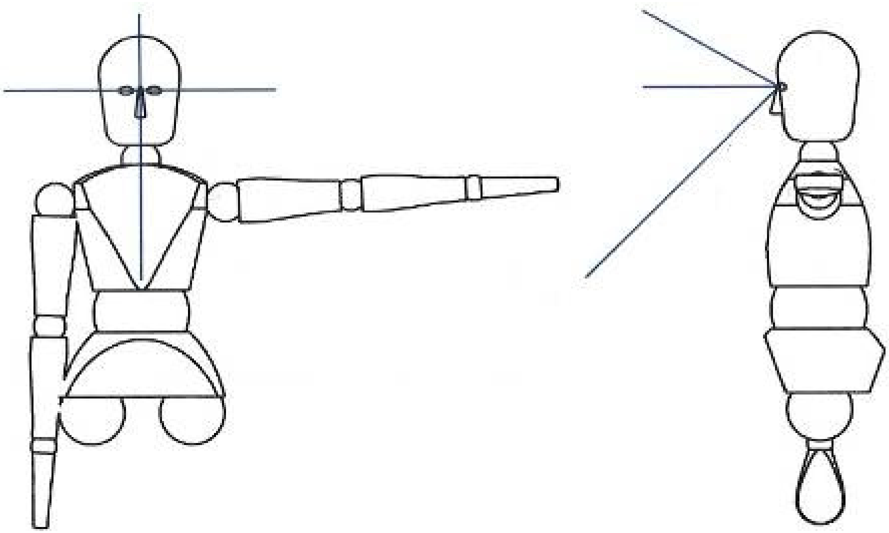


Figure 34 - Position 3

This is the position that will impose shear stresses along with a high bending moment.

The fourth position is very similar to the second position. The humerus is extended straight forward with the arm bent 90 degrees directing it inward across the chest, as shown in Figure 35. This position imposes shear stresses and a bending moment along with a high twisting moment.

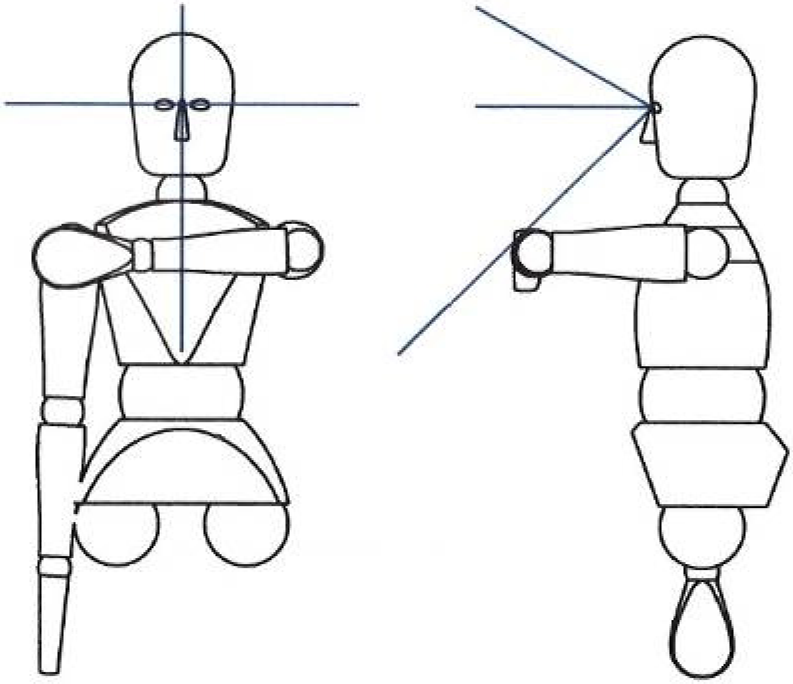


Figure 35 - Position 4

The fifth position is the most similar to the third position. It creates shear stress and a high bending moment; both of which are created by having the user's entire arm extended straight forward, pictured in Figure 36.

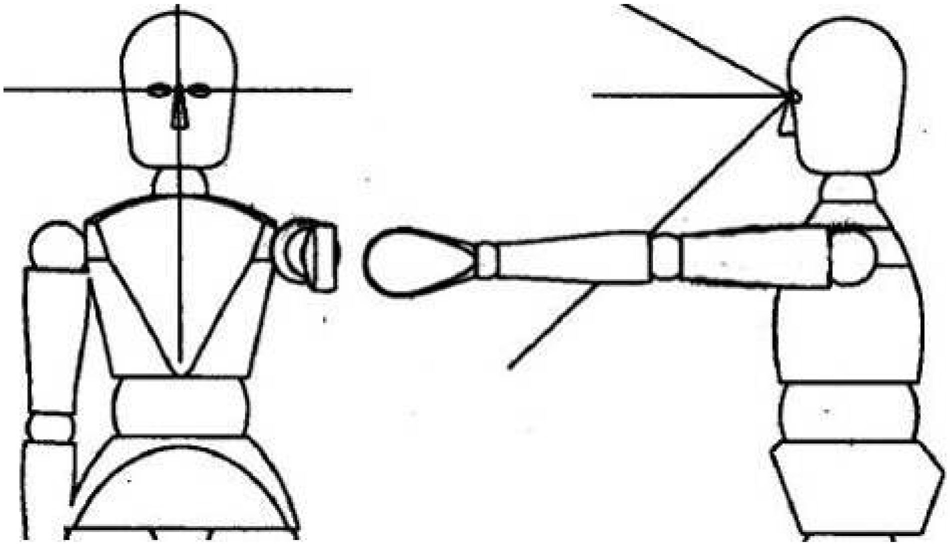


Figure 36 - Position 5

After quantitatively analyzing the loading conditions on each of the mechanism's parts for all five positions, it was clear that two of the five positions would impose the highest stresses on the mechanism. The second position has a maximum shear force of 25 lbs along the entire mechanism, a bending moment of 325 lb*in, and a torsional moment of 375 lb*in. Position five imposes a maximum shear force of 25 lbs along the entire mechanism as well, but with a bending moment of 700 lb*in and a torsional moment of 62.5 lb*in. Since position two has the highest twisting moment, it will be referred to as the "high twisting moment position" from now on. Position five will then be referred to as the "high bending moment position".

Although two positions have been analyzed quantitatively for their particular loading situations, the effect those conditions have on the mechanism's parts' integrity is still unknown. In order to find this information, the loads must be translated to stresses. There are a number of different types of stresses, but calculating each on its own would prove to be extremely time consuming. Because of this, the Von Mises stress was chosen to be the only stress in the analysis. The Von Mises stress is simply a scalar function of the components of the stress tensor effectively giving the overall magnitude of the stress. The function used in calculating this is stress shown in Figure 37, where σ_1, σ_2, and σ_2 are the principal stresses.

$$\sigma_v = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2}}$$

Figure 37 - Von Mises Stress Equation

Due to the complex geometry and loading conditions involved in calculating the Von Mises stresses, closed form solutions do not exist, and simplifying the geometry would result in inaccurate estimates. As a result, a finite element analysis program must be used. Although there are many available, most are prohibitively expensive and require a great amount of skill to master. Taking those factors into account, COSMOSWorks, a SolidWorks FEA package, was chosen to aid the analysis since it was available to students at no cost and is easy to use – especially in applying combined and distributed loads.

With the means to find the stresses that each part of the mechanism could realize under the worst possible conditions, there needs to be some sort of metric with which to compare those stresses. Since the yielding of any part will change its shape permanently, it is the primary concern in the analysis. As a result, the maximum Von Mises stress calculated will be compared to the yield strength of the parts' material, alloy steel, which is about 90,000 psi. Also, since even small deflections could greatly hinder the kinematics of the mechanism, they will be analyzed as well.

Also, a safety factor of three was chosen to be instituted for the design of this mechanism. For components whose failure could result in a significant financial loss, serious injury, or death often have a safety factor of around four. Since none of those situations apply to our device, its safety factor can afford to be lower. However, since it is still relevant to keep the device reliable, the safety factor of just under four was chosen. Therefore, the relevant stress to compare the maximum Von Mises stress to is 30,000 psi (yield strength / safety factor).

For the individual parts of the mechanism, the analysis outlined in this section will start at the bars connected to the prosthesis mount, move along the arm, and finish at the shoulder arch. Both the high twisting moment and high bending moment situations were tested for each condition. Also, although the reason for analyzing each condition is that the mechanism has a high load imposed upon it in a particular direction, all other loads were still considered in the analyses due to the compounding stresses that would result.

The first part of the mechanism analyzed was the bar connected to the prosthesis mount on one end and the outer ring on the other. The only boundary condition imposed was a fixed restraint on the face that connects to the outer ring to simulate their rigid connection. That constraint can be seen in Figure 38 as the green arrows.

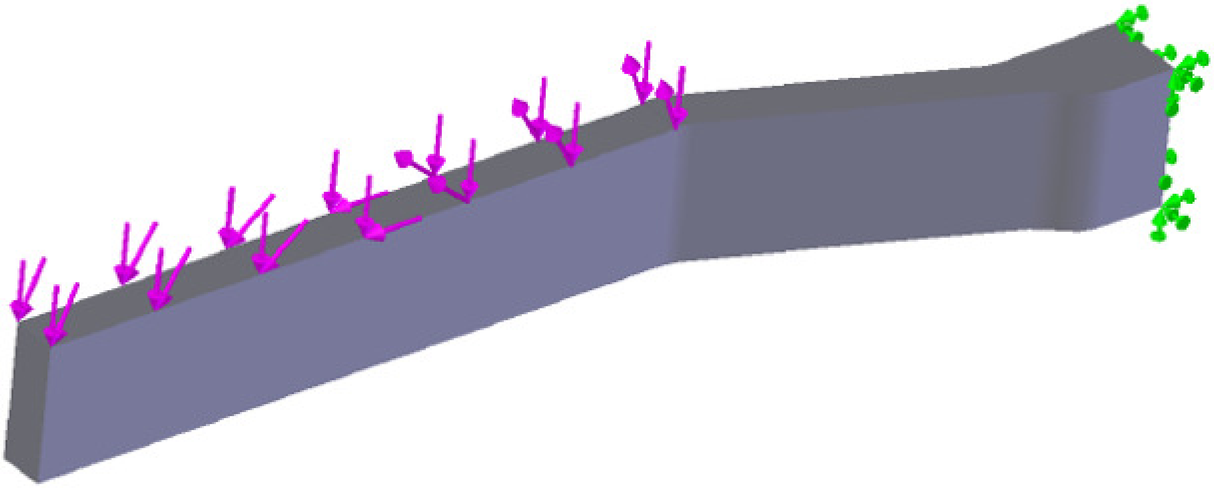


Figure 38 - Prosthesis Attachment Bar Boundary Constraints (green) and Applied Loads (Purple)

The force resulting from the twisting moment was defined as a downward acting distributed force on the top side of the straight section of the bar since this is where the prosthesis will be attached and therefore where the forces will be in reality. The bending moment was also placed on the same face as the twisting moment, but defined as a torque around an axis placed across the midpoint of the straight section of the bar. The final load imposed on this bar is simply the downward force resulting from the weight of the prosthesis. This was defined as a distributed downward force on the same face as the previous two loads. The purple arrows in Figure 38 represent the distributed torques and loads. The high bending situation produced the highest stresses in the bar, so its results are outlined in Figure 39.

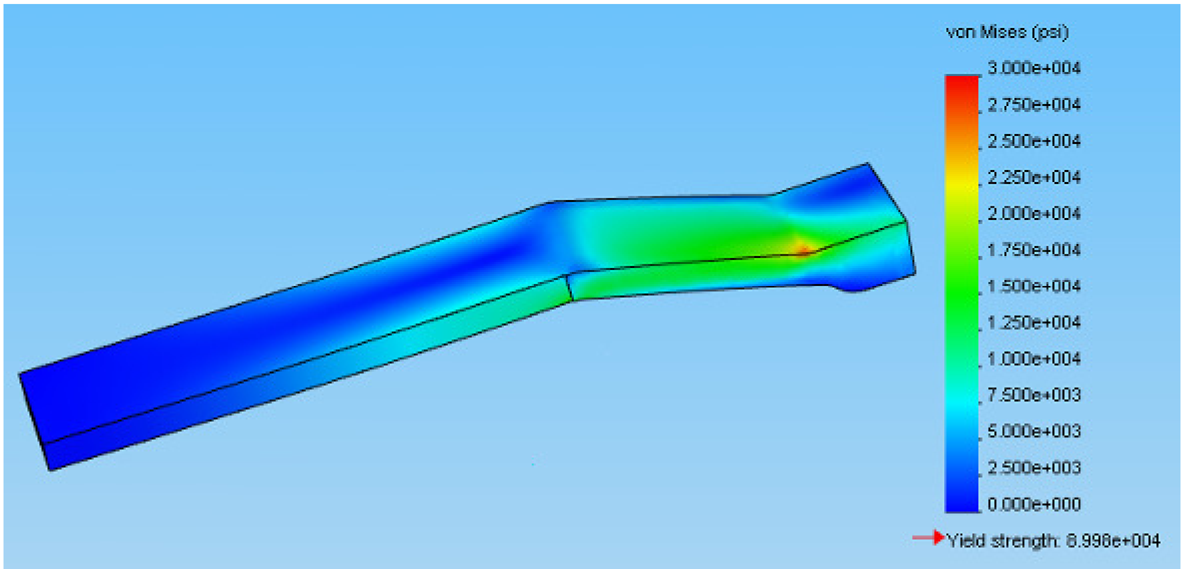


Figure 39 - Resultant Prosthesis Attachment Bar Von Mises Stresses in Worst Case Conditions

The maximum stress induced was 27,043 psi, giving the bar an acceptable minimum safety factor of 3.3 given the part's material of alloy steel. The maximum displacement is .022 inches in the vertical direction which will not hinder the function of the device at all since this part has no effect on kinematics.

Since the bar previously analyzed connects to the outer ring, it was the next part in the analysis. The outer ring is a relatively complex part, and as such, it required four separate boundary conditions. The first restrained the inner surface of the ring's groove from translating in any direction around the part's center axis which represents the forces that the outer surface of the inner ring's lip would provide. The next two boundary conditions were applied to the ring groove's walls to restrain each of them from translating along the part's axis. Those boundary conditions are also a representation of the forces that the inner ring's lip would provide. The last condition applied was fixing the location of the hole that goes in the radial direction through the ring characterizing the set screw that will be threaded into it in the final assembly. Those boundary constraints are represented as the green arrows in Figure 40.

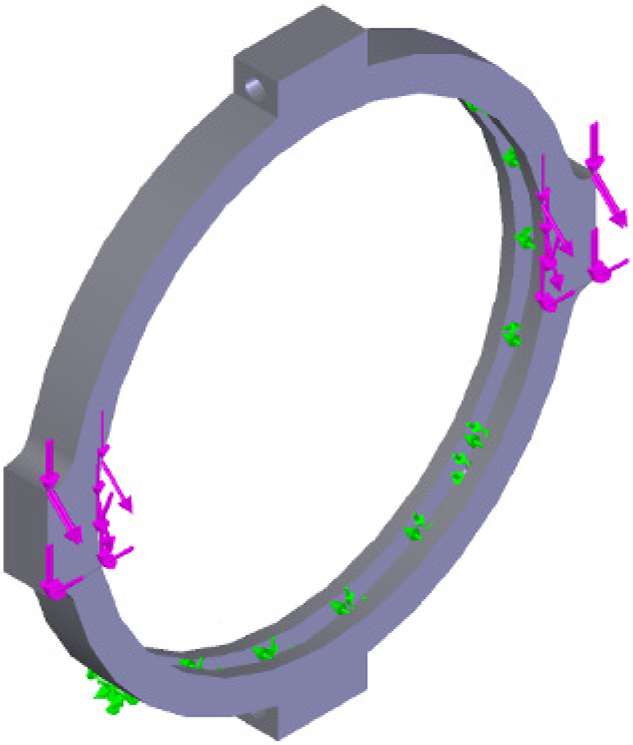


Figure 40 - Outer Ring Boundary Constraints (green) and Applied Loads (Purple)

The applied loads to this particular analysis are all the results of the forces applied by the prosthesis mount bars. Two distributed vertical forces were applied on their respective mounting locations (one for each bar) to represent the shear forces from the prosthesis mounting bars. The remaining load placed in the model was a distributed torque on the mounting locations about a horizontal axis going across the middle of the part to represent the imposed bending moment. Those loads are represented by purple arrows in Figure 40. The high bending moment situation produced the highest stresses within the part, and its results are overviewed in Figure 41.

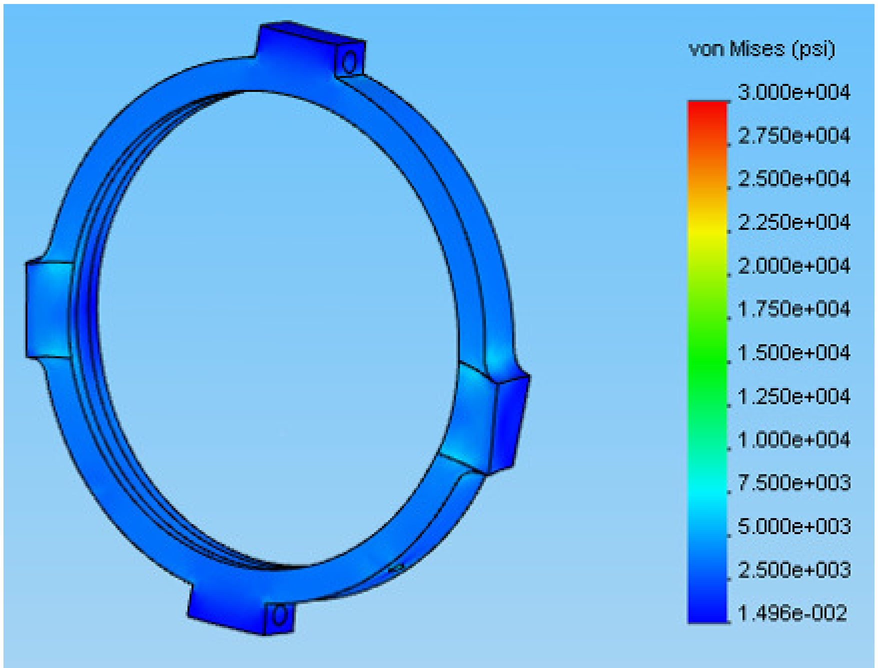


Figure 41 - Resultant Outer Ring Von Mises Stresses in Worst Case Conditions

The highest stress within the part under this particular condition is only 8609 psi, giving it an extremely conservative safety factor of about 10. The low stresses are most likely a result of the large areas on which the boundary conditions are defined. The highest displacement is .00086” vertically. Like the bars, this will not adversely affect the performance. That displacement would likely reduce this part’s ability to rotate around the inner ring, but the device is designed to be locked under high loading conditions, so it is not an issue.

Moving along the mechanism toward the shoulder, the next part in the assembly is the inner ring. The only restraint needed for this piece is fixing the top surface that bolts to the humeral bar which is represented in Figure 42 as green arrows.

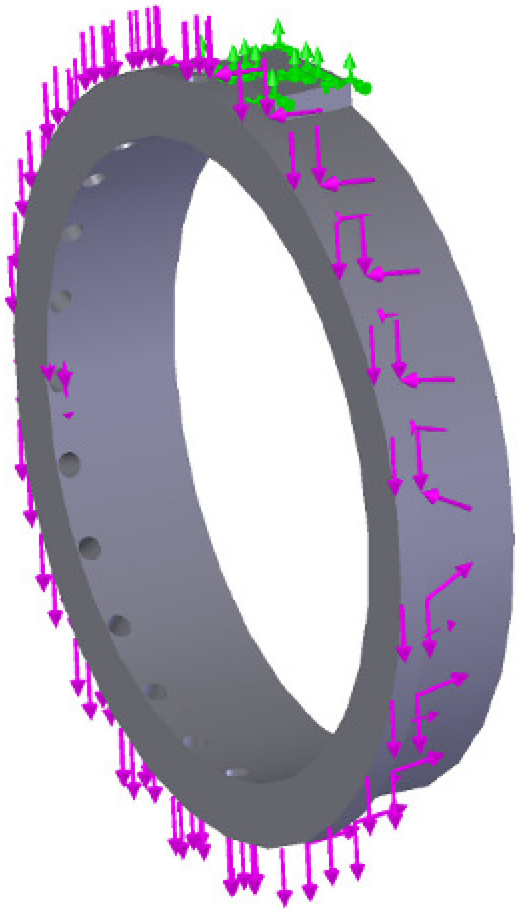


Figure 42 - Inner Ring Boundary Constraints (green) and Applied Loads (Purple)

There are three separate loads involved in this analysis. The first is the bending moment, which was applied as a distributed torque on the shorter side of the ring's lip about an axis going horizontally across the middle of the part. The twisting moment was represented by a torque applied on one of the ring's radial hole's surfaces about the axis going through the center of the ring. The reason for the load applied to the hole's surface is to characterize the effect that the set screw will have on the ring during the actual use of the design. The final load added to the model is a downward vertical load placed on the outer surface of the ring to represent the vertical forces placed on it by the outer ring. Those loads can be seen as the purple arrows in Figure 42. Unlike the previous two parts, the high twisting moment situation resulted in the highest stresses, which are shown in Figure 43.

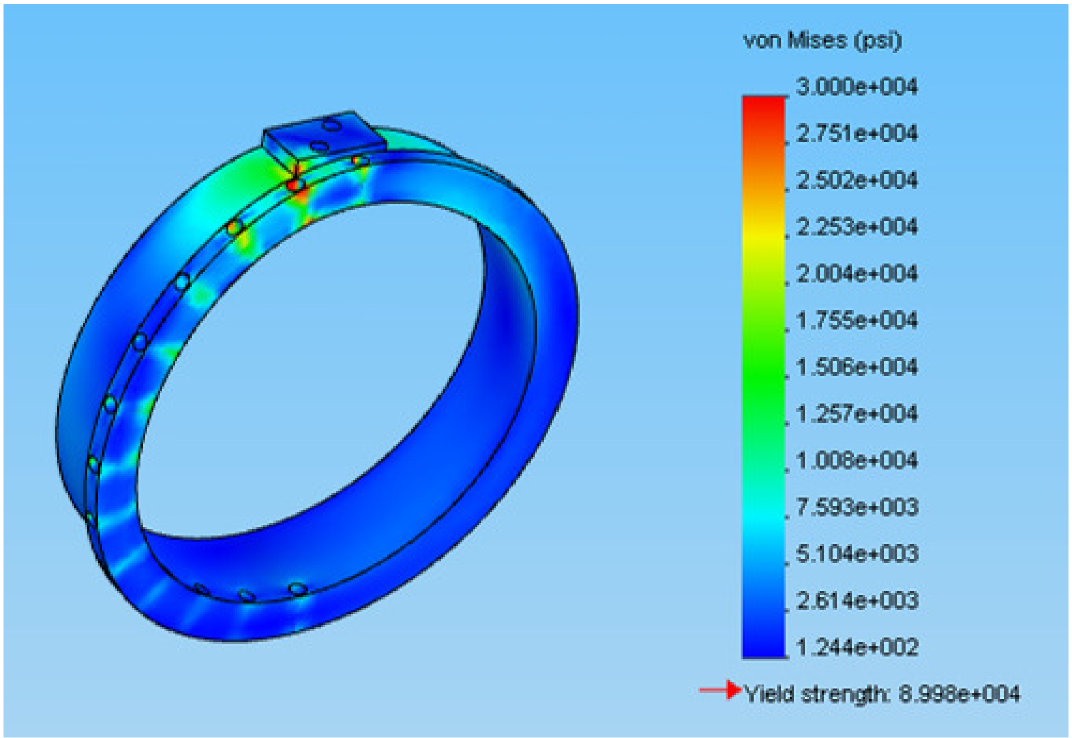


Figure 43 - Resultant Inner Ring Von Mises Stresses in Worst Case Conditions

The highest overall stress realized within the inner ring is 54,720 psi. Although it is significantly higher than the safety factor allows (30,000), those high stresses occur only in a location where yielding would not affect the part's performance. That particular location is in the very thin wall of one of the radial holes, as represented by the dark red area in Figure 43. In reality, those walls are not required to be there and are only present to remove the sharp edges that would exist without them. They do carry a load, but do not help significantly in reducing the load elsewhere in more critical areas. Even so, a stress of 54,720 psi still achieves a safety factor of 1.6. The part actually achieves a safety factor of 5 or greater in all other locations. The largest displacement is approximately .017 inches horizontally toward the bottom of the ring. However, the same argument made for the outer ring could be applied to this situation – the part is not meant to function as a bearing under high load, so deformation is not a critical factor.

Since the inner ring is connected to the humeral bar, it was the next to be analyzed. The boundary condition in place for the inner ring's analysis is simply fixing the bottom circular surface since it is what will be connected to the shoulder arch which can be seen as green arrows in Figure 44.

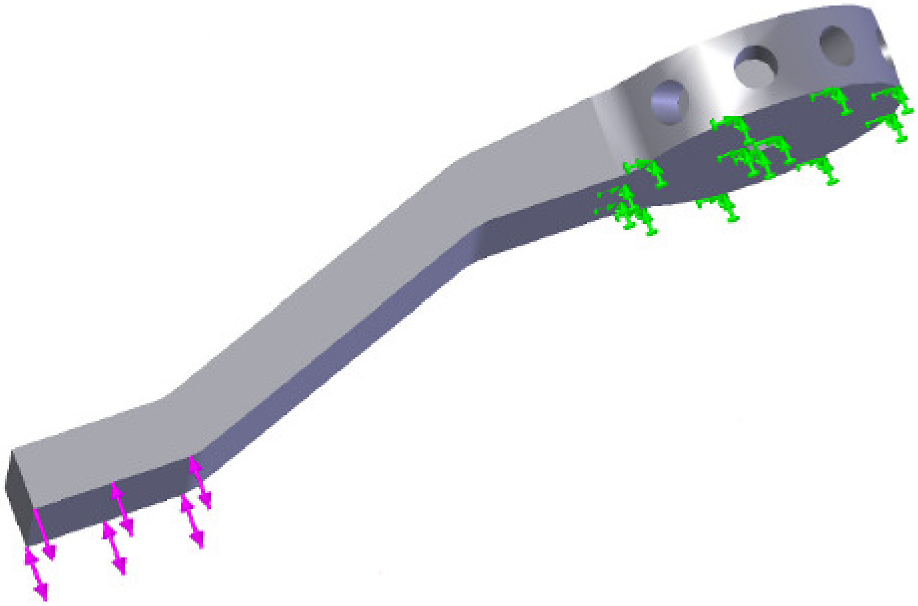


Figure 44 - Humeral Bar Boundary Constraints (green) and Applied Loads (Purple)

The bending moment was placed on the bottom square surface of the bar as a distributed torque about an axis located in the middle of that same surface. The twisting moment was placed on the same surface as a distributed torque about an axis perpendicular to and on the midpoint of the one used for the bending moment torque. The downward vertical load was simply placed as a distributed force on the same face. The applied loads are represented by purple arrows in Figure 45. The situation inducing the highest stresses was the high bending moment situation. The results can be seen in Figure 45.

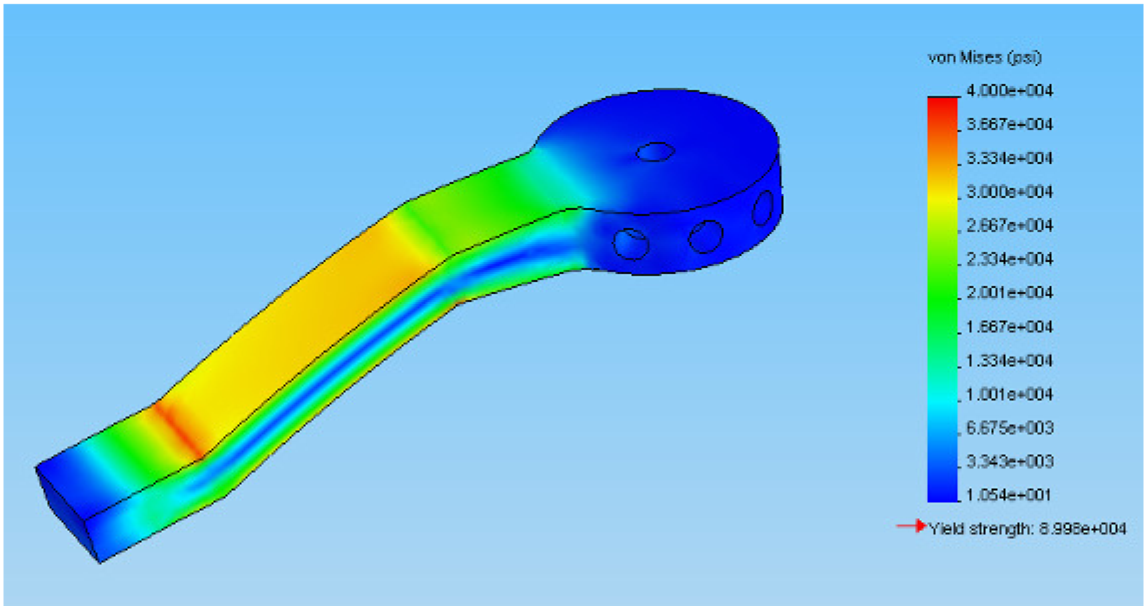


Figure 45 - Resultant Humeral Bar Von Mises Stresses in Worst Case Conditions

The highest stress within the part was found to be 38,365 psi. Since a large surface was subject to stresses higher than the normal chart maximum of 30,000 psi, a higher maximum on this chart scale was used to show the distribution more clearly. Although this is greater than the stress associated with a safety factor of 3, the difference is minimal and occurs only in two small locations – small portions of the inside surfaces of the two angles. Even then, the safety factor is 2.3. The rest of the part assumes a safety factor of at least 3. The largest displacement that could possibly occur in the humeral bar is .039 inches vertically. That displacement, although noticeable, should not have any adverse effects on the functionality of the mechanism. It may slightly misalign the ring assembly from its axis, but those rings are not designed to move under these particular loading situations.

The last part in the analysis is the shoulder arch. The final connection is at the torso mounted vest in two separate locations, so there had to be two separate boundary constraints. The first boundary constraint fixed the surface of the circular end of the arch that has the seven holes in it, since under test conditions it will be static. The other boundary constraint defines the hole on the other arm of the arch as a hinge, allowing it to rotate about its own axis but unable to translate. Those boundary constraints are represented by green arrows in Figure 46.

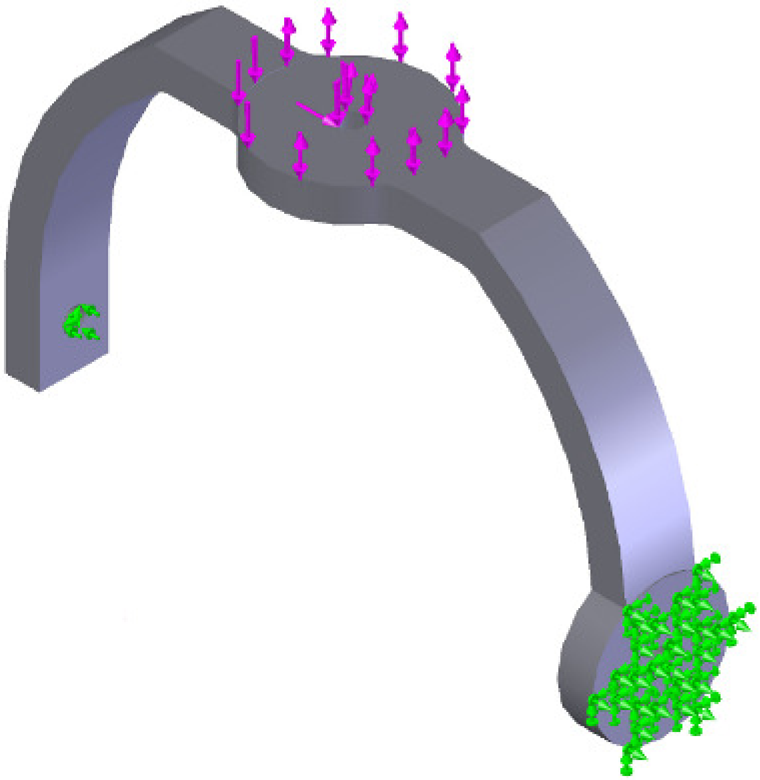


Figure 46 - Shoulder Arch Boundary Constraints (green) and Applied Loads (Purple)

Like most the other parts, there were three separate loads applied – the bending moment, twisting moment, and vertical force. The bending moment was represented as a distributed torque on the top circular face about an axis on that same surface along the length of the part and intersecting the middle. The bending moment was also placed as a distributed torque on the same surface, but on an axis perpendicular to and bisecting the bending moment axis. The downward vertical load was defined on the same surface as a distributed force. Those loads are shown on as purple arrows in Figure 46. The bending moment situation resulted in the highest stresses, as outlined in Figure 47.

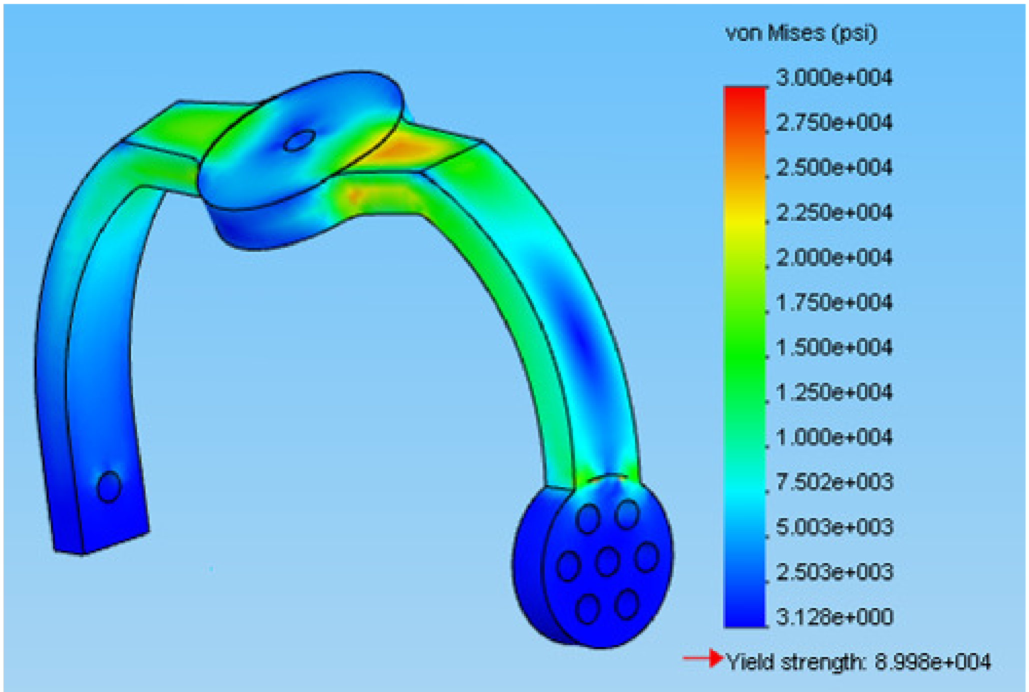


Figure 47 - Resultant Shoulder Arch Von Mises Stresses in Worst Case Conditions

The highest stress within the part is 25,663 psi, which is well under the prescribed maximum stress, giving it a minimum safety factor of 3.5. The maximum displacement is .010 inches vertically. Although unmeasured, it also seems as though the top surface of the shoulder arch has deformed to a significantly high angle (.46 degrees). This displacement and angle would surely misalign the rings from their axis, but as mentioned in the humeral bar’s analysis, a misalignment under loading conditions would not affect performance as long as no yielding occurs. If no yielding occurs, the alignment would be regained upon unloading and the rings would be free to rotate again. It is also possible that the shoulder abduction/adduction axis would become misaligned by the angle under deformation. However, since the humeral bar is connected to the top of the shoulder arch at such a proximity to the body's joint, there won't be a significant distance between the axes at the point of rotation.

Overall, analyzing the stress of the individual parts in the mechanism has given considerable assurance that the final product will work as intended. Although some parts contained higher stresses than they should have as prescribed by the safety factor and material, those high stresses were either concentrated in very small areas or were in non-critical areas of the part. Even if those locations were critical to the functionality of the part, they would still not result in the yielding of the part. The lowest safety factor for the humeral bar is 2.3, which is still acceptable by industry in cases where the failure of such a part would not result in a large financial loss or human injury.

5.4 Fastener Analysis

The primary attachment method for the mechanism parts is standard steel socket head cap machine screws. Socket head cap machine screws allow for easy assembly/disassembly with a standard Allen wrench and are widely available for replacement. All fasteners will be threaded into tapped holes in 1018 carbon steel or standard grade steel nuts. To ensure that the fasteners and mating materials do not fail during use, a full analysis was completed. Analyses were performed to show the following:

- Fasteners will not fail
- Thread pullout will not occur in tapped holes and fastener threads will not strip

- Shear tear-out will not occur

The fasteners are chosen individually for each attachment point based on size limitations and expected loading conditions.

The locations of each fastener relative to the assembly can be seen in Figure 48.

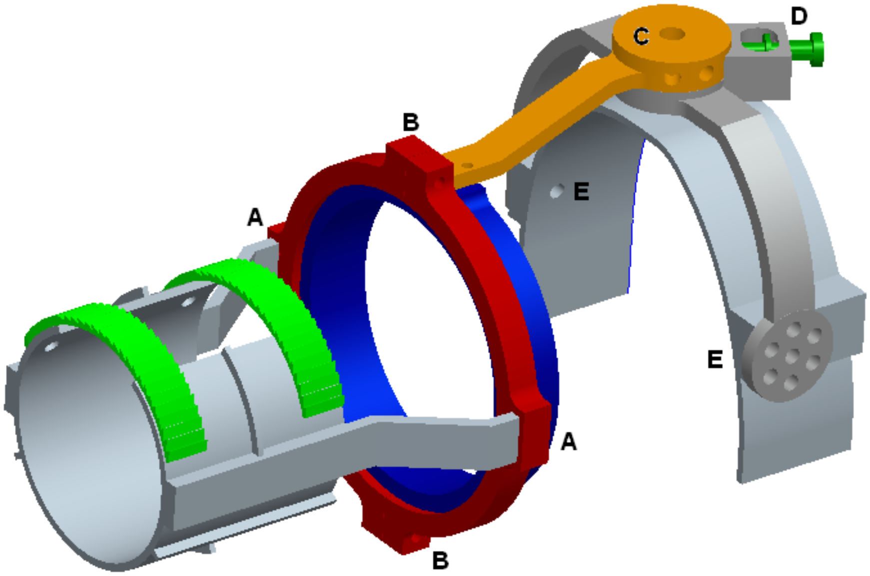


Figure 48 - Device fastener locations, labeled with letters

5.4.1 Fastener Failure

The first analysis shows that the fasteners themselves will not fail in tension. The results can be seen in Table 11.

Table 11 - Fastener failure in tension, locations and forces shown

Location	Fastener Description	Force (lb) to Fail Fastener	Wish Safety Factor of 3 (lb)
A	10-32 UNF Machine Screw	900	300
B	12-24 UNC Machine Screw	1087	362.3
C	1/4-28 UNF Machine Screw	3350	1121

Forces listed in Table 11 are tensile forces. A safety factor of 3 was applied as specified within the design specifications. The mechanism will not see forces of such high magnitudes at each particular location. At location A, there are 2 fasteners, thereby doubling the required force to cause failure. However, it is unlikely that the loads are equally distributed. Even so, one fastener is sufficient. The calculations of these forces can be found in Appendix E.

5.4.2 Thread Pullout

The second analysis performed was a thread pullout analysis. Thread pullout occurs when the threads on the outside of a screw or on the inside of a tapped hole or nut fail. If a nut or tapped hole fails, the threads will strip at the major diameter. If the fastener fails, the threads will strip at the minor diameter (Norton, 827). Failure of the tapped hole was chosen for this analysis due to the fact that it is of a weaker material in most situations. Calculations for this type of failure assume that one thread is taking the entire load. Based on this assumption, the force to strip one thread was found with a safety factor of 3 applied. These values can be seen in Table 12.

Next, the recommended Length of Engagement (LOE) for each fastener/tapped hole combination was found. Using the LOE and the threads per inch of the fastener, the actual number of threads in contact was found. The force to cause complete thread pullout was then calculated based on the force to fail a single thread and the total number of threads in contact. These values can be seen in Table 12.

Table 12 - Thread Stripping/Pullout

Location	Fastener Description	LOE	# Threads	Force to Strip 1 Thread (lb) with safety Factor of 3	Force to Strip LOE Threads
A	10-32 UNF Machine Screw	0.15	4.8	49927	240000
B	12-24 UNC Machine Screw	0.163	3.9	72125	281000
C	1/4-28 UNF Machine Screw	0.2	5.7	77759	445000

As can be seen from Table 12, the required force to cause thread pullout will never be exceeded even at the most extreme loading conditions. The human body would be unable to experience such forces as well. The calculations of these values can be found in Appendix E.

5.4.3 Shear Tear-out

The final fastener analysis done was a shear tear-out analysis. Shear tear-out occurs when the material around the fastener fails before the fastener does. This usually occurs when a hole is placed to close to the edge of the part, as can be seen in Figure 49.

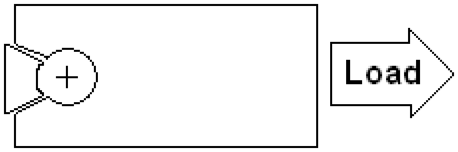


Figure 49 - Shear Tear-out, hole placed too close to edge

For the mechanism, the worst case scenarios were found for areas where shear tear-out could possibly occur. The areas in question were those that had a thin wall of material between the fastener and edge of the part. The results from the calculations can be seen in Table 13.

Table 13 - Shear Tear-out

Location	Description	Force to Cause Tear-out, Safety Factor of 3 (lb)
A	10-32 machine screw, bar	309400
A	10-32 machine screw, outer ring	781300
C	1/4 in. Lock Hole, Top of Shoulder Arch	282000
D	1/4 in. Lock Pin and Spring Holder	317333
E	1/4 in. Lock Pin, Front of Shoulder Arch	557000

As can be seen from the calculations, the likelihood of shear tear-out occurring is very unlikely. The calculations of these values can be found in Appendix E.

5.5 Torso Mount

The torso mount must effectively secure the mechanism to the body. While doing so, it should distribute the loads applied to the mechanism to the torso in a way that is comfortable to the user. These tasks are accomplished by the vest design. The vest is made of two layers of duck fabric, chosen for its strength and low shear due to its tight weave. Sandwiched between the two layers are pieces of ¼" ionomer foam strategically placed and shaped to provide both rigidity and comfort. Assuming that the right arm is the one with the prosthesis, the metal shoulder arch is sewn in place at the right shoulder of the vest. The vest is fastened to the user by two waist straps and three shoulder height straps.

The torso mount is bounded by two sets of identical fabric pieces sewn together to form a two layered vest. Between the layers, the vest is composed of strategically placed foam pieces. These provide semi-rigid support in the necessary regions, as well as cushioning over bony areas of the body. Also, the metal shoulder arch is secured into place over the shoulder of the affected arm. It is fastened with two waist straps that travel within sleeves around the user's abdomen. It also has three upper straps that effectively join the two opposing shoulder pieces. Details as to its construction are contained in Chapter 6, Manufacturing.

5.6 Mechanism

After a thoroughly examining the results of the stress analysis for each part within the mechanism, the fine details of each part can be completed. These decisions include hole placement, thread types, and adding or removing material in certain places to reduce both stress and weight. Although many of the specifics will be discussed in this section, full detailed drawings can be found in Appendix B.

Before continuing to the specifics of each part, there are two design decisions that were made for all the different parts. The first was the choice of alloy steel for the material. Alloy steel has two enormous advantages – it is both inexpensive and strong. Aluminum was also strongly considered but was ruled out since it had a lower strength to weight ratio. Although it is significantly lighter than steel, it would require more material to make it as strong in addition to being considerably bulkier. The other design choice made for all parts was to add fillets and rounds to any sharp edges or corners to reduce the stress concentration factors.

5.6.1 Prosthesis Attachment Bar

The prosthesis attachment bar has two main functions – attach to the prosthesis attachment sub-assembly on one end and attach to the outer ring on the other. Since the prosthesis attachment sub-assembly is about 3.5 inches long, the prosthesis attachment bar should have a straight feature at least that long so the load can distribute along it. This feature is shown as section A in Figure 50.

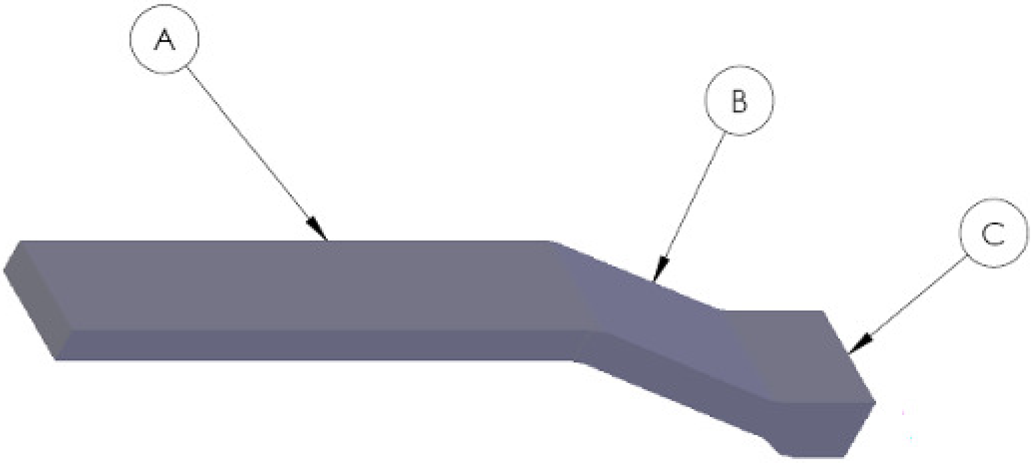


Figure 50 - Prosthesis Attachment Bar Design Feature Overview

The distance between the two opposing prosthesis attachment bars must also be able to properly accommodate the majority of the prosthetics. From previous research, 4.25 inches has been found to be a good choice for that particular distance. The other end of the bar connects to the outer ring. Since the outer ring has a different diameter than the previously selected distance between the two bars, there must be some sort of step to account for the difference in distances. After the straight section of the bar where the prosthesis attachment connects an angle was incorporated to allow both main functions to be met as can be seen in section B of Figure 50. Finally, in order to achieve the actual connection between the prosthesis attachment bar and outer ring, two threaded holes have been drilled on that end’s face (section C of Figure 50). Screws will join the two parts using those holes. Fillets were also added in any sharp corners of the part to reduce stress concentration factors.

5.6.2 Outer Ring

The outer ring serves three main purposes. The first is to connect to the prosthesis attachment bar. As mentioned in the previous section, these rings are joined together using two screws for each outer ring and prosthesis attachment bar pair. In order to accommodate these screws, each outer ring has two clear holes drilled with the same spacing as the threaded holes in the prosthesis attachment bar as can be seen in section A of Figure 51.

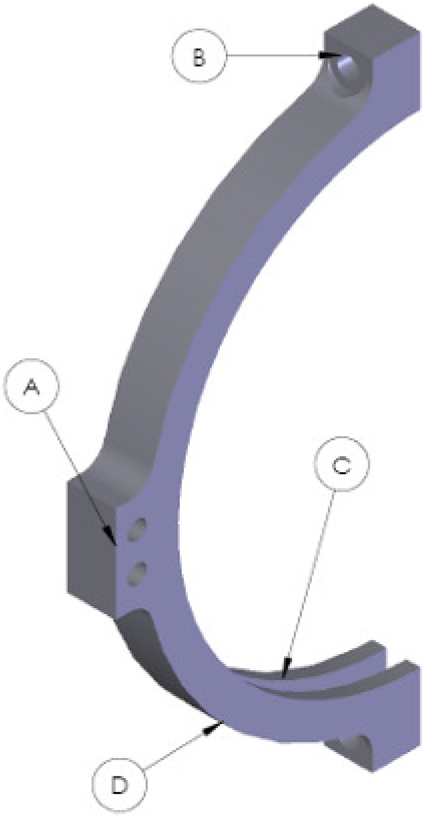


Figure 51 – Outer Ring Design Feature Overview

The next function is for one outer ring to connect to the other around the inner ring. One of the rings has clear holes drilled through each of its ends. The other outer ring has two threaded holes in the same location. There is also a groove cut out to accommodate for the lip on the inner ring. The holes and groove are shown as sections B and C respectively in Figure 51. The two outer rings are placed around the inner ring and joined together using screws through the holes on the ends of the rings. The last function incorporated into the outer rings is a threaded hole through the outside of the rings. Although it can't be seen clearly in Figure 51, it is through the curved edge near section D. A set screw can be threaded through this hole and into a pocket built into the inner ring, restricting any rotation about the ring's central axis.

5.6.3 Inner Ring

The inner ring also provides three main functions. The first is simply to hold the outer ring in place using the lip extending from its main body as seen as feature A of Figure 52.

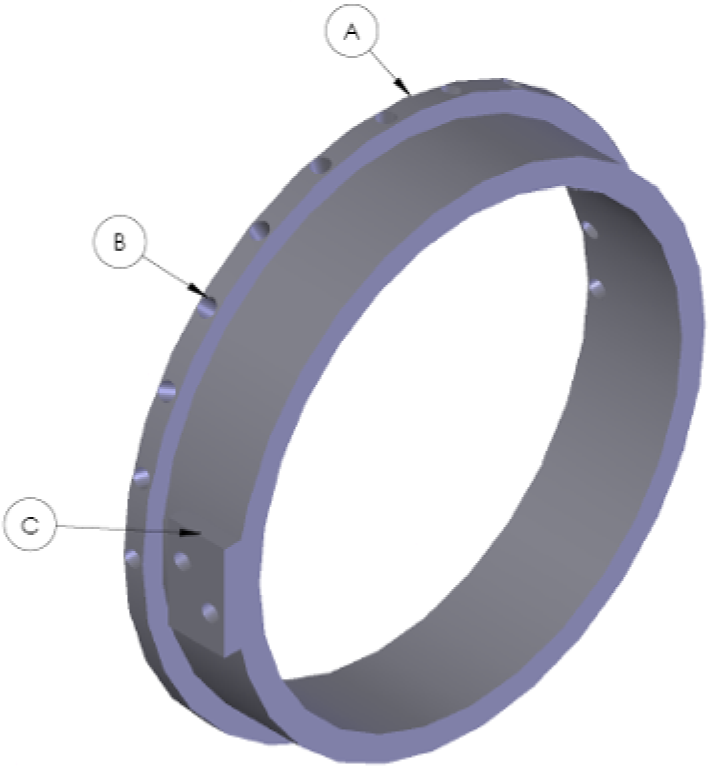


Figure 52 – Inner Ring Design Feature Overview

The feature for the next function is part of the outer ring's function of restricting rotational movement about the ring's central axis. The inner ring's lip has holes drilled into its outside edge every fifteen degrees to provide set screw inserting location, allowing the ring rotation to be locked at any interval of fifteen degrees. One of those holes is labeled as feature B in Figure 52. The last significant function of the inner ring is to connect to the humeral bar. This is achieved by incorporating a flat surface on the top of the ring with two threaded holes drilled into it. This can be seen as section C of Figure 52.

5.6.4 Humeral Bar

The humeral bar is an essential part in that it has three important functions. The first is attaching to the inner ring via a flat section shown as section A in Figure 53 with two clear holes in it. Two screws are inserted into those holes and threaded into the inner ring to secure it.

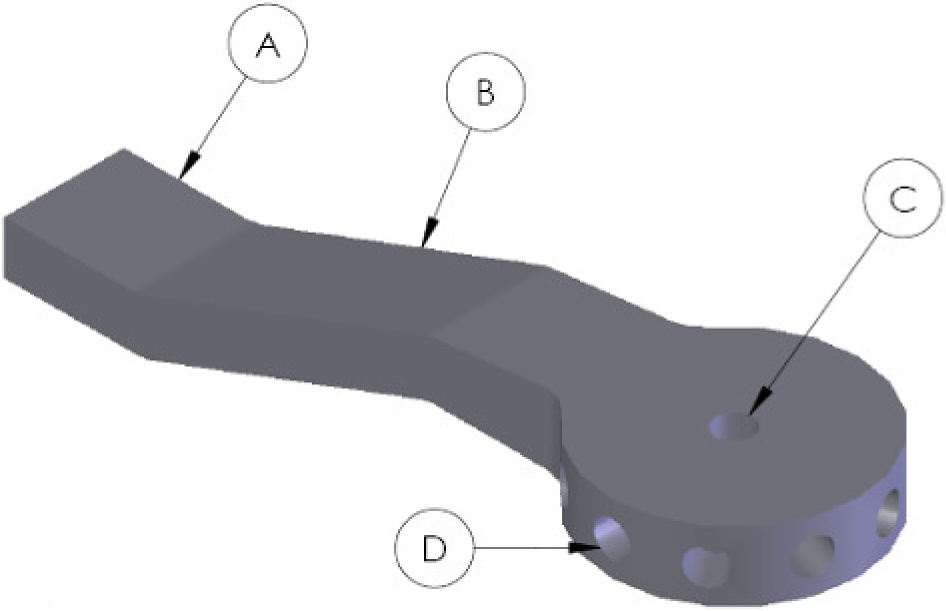


Figure 53 - Humeral Bar Design Feature Overview

The next important feature is connecting to the shoulder arch via another flat section with one clear hole in it shown as feature C in Figure 53. Only one hole is used because in addition to connecting the two parts, it also serves as a hinge joint. Because the ring has to be in a particular location due to kinematic constraints, and the top of the shoulder arch is at a different level, the two flat sections of the humeral bar must be joined by an angled section (section B in Figure 53). The final function is locking that hinged joint. This is done by drilling holes into the circular side of the flat section that joins with the shoulder arch. One of those holes is feature D in Figure 53. Similar to the inner ring, a pin can be inserted into these drilled holes to restrict the rotation.

5.6.5 Shoulder Arch

The shoulder arch provides three main functions – connecting to the humeral bar, connecting to the torso mount, and locking the rotational movement between the arch and the torso mount. To achieve the first function described, a simple pin is inserted through the humeral bar and a hole in the top of the shoulder arch (feature A in Figure 54), defining their connection as a hinge.

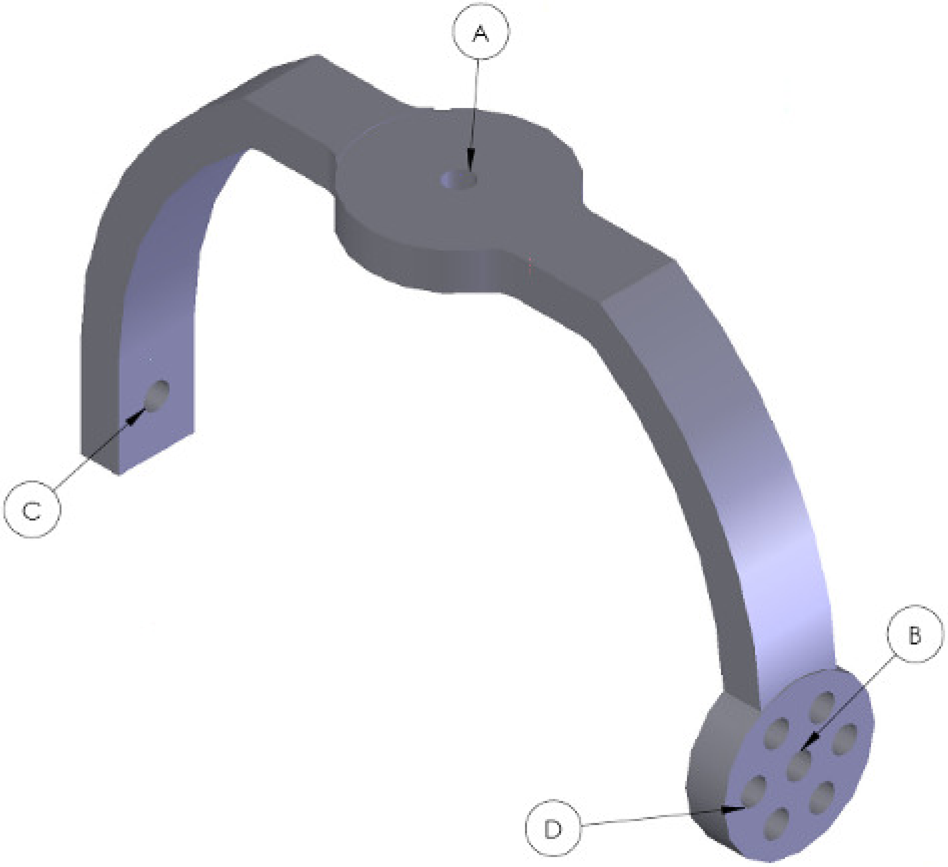


Figure 54 – Shoulder Arch Design Feature Overview

To connect the shoulder arch to the torso mount, one pin is inserted through the center hole on the end with the circular feature (feature B of Figure 54), and another is inserted into the hole on the other end of the arch (feature C of Figure 54). The other ends of those pins go through a hole in the rigid shoulder insert of the torso mount. Finally, to restrict rotation between the arch and torso mount, a set screw can be threaded into any one of the other holes in the circular feature on the end of the shoulder arch arm. One example of those holes is feature D in Figure 54. The end of the screw that goes through the arch intersects with a hole in the rigid insert, locking the two parts together.

5.7 Prosthesis Attachment

The prosthesis attachment is responsible for securing the mechanism to the prosthetic limb. Loads are transmitted through the prosthetic limb to the prosthesis attachment and ultimately to the vest. To don the device, the user will insert the prosthetic limb through the arm hole of the vest, rings and finally the prosthesis attachment. To secure the prosthesis attachment in position, the user will tighten down two ratcheting straps using the opposing arm. To doff the device the user has to release the ratcheting straps and pull the prosthetic limb out of the prosthesis attachment, ring, and finally the vest.

The two bars of the mechanism act as the base of the prosthesis attachment. The bars can be seen in Figure 55, labeled by E.

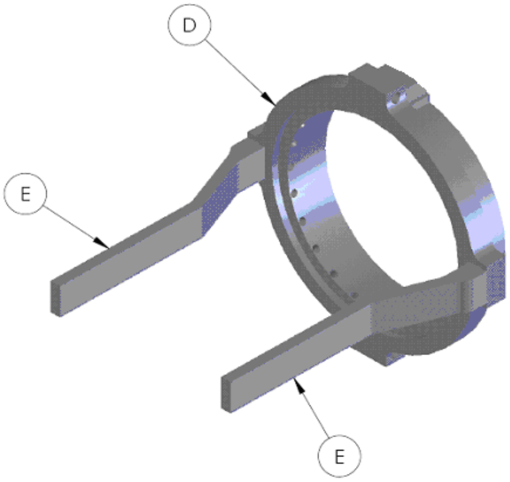


Figure 55 - Mechanism bars acting as base of prosthesis attachment, designated by letter E

An outer shell constructed from cotton duck fabric wraps around the exterior surface of the prosthetic limb. Secondary pieces of fabric encase the two aluminum bars to the outer shell. A cross section of the prosthesis attachment can be seen in Figure 56. To ensure the bars do not slide within the fabric shell, rivets are used to connect the bars to the fabric.

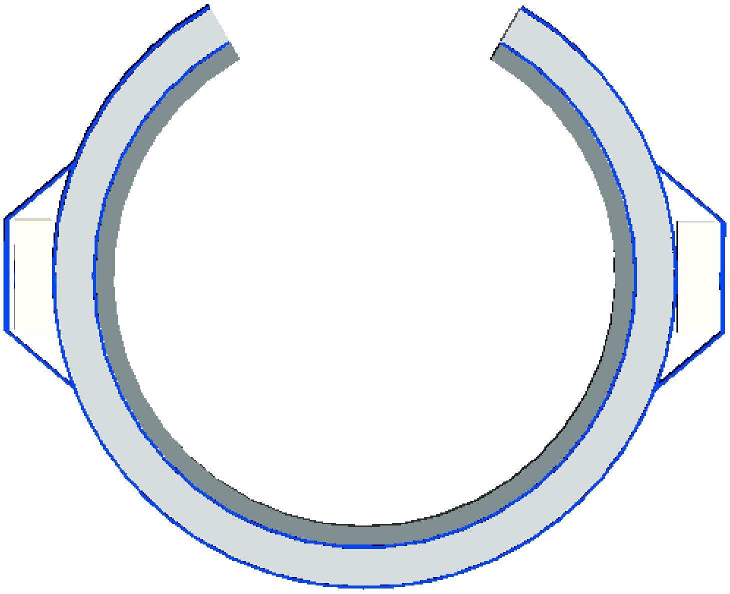


Figure 56 – Cross-section of fabric orientation around mechanism bars, fabric in blue, ionomer foam in light gray, neoprene foam in dark gray

The interior of the prosthesis attachment shell is lined with a layer of ionomer foam. A layer of neoprene foam having a high coefficient of friction is placed on the innermost surface that comes in contact with the prosthetic limb. This ensures that the prosthesis attachment will not slide or rotate on the surface of the prosthetic limb during use. The interior lining can be seen in Figure 56 in dark gray.

Two ratcheting straps are used to keep the interior lining of the prosthesis attachment pressed firmly against the surface of the prosthetic limb. The ratcheting straps are 1” wide and can be adjusted in 1/8” increments. The strap is made out of DuPont Super Tough Nylon. The ratcheting straps can be seen in Figure 57.

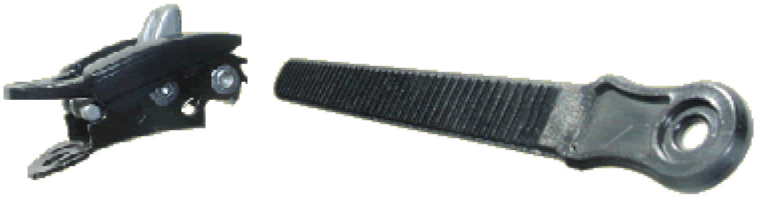


Figure 57 - 1" Ratcheting Strap and Ratchet

The ratcheting straps will be fastened to the sides of the outer shell using rivets. The ratchet and strap wrap around opposing sides of the outer shell and meet on the top surface. A picture of the prosthesis attachment with the ratcheting straps can be seen in Figure 58.

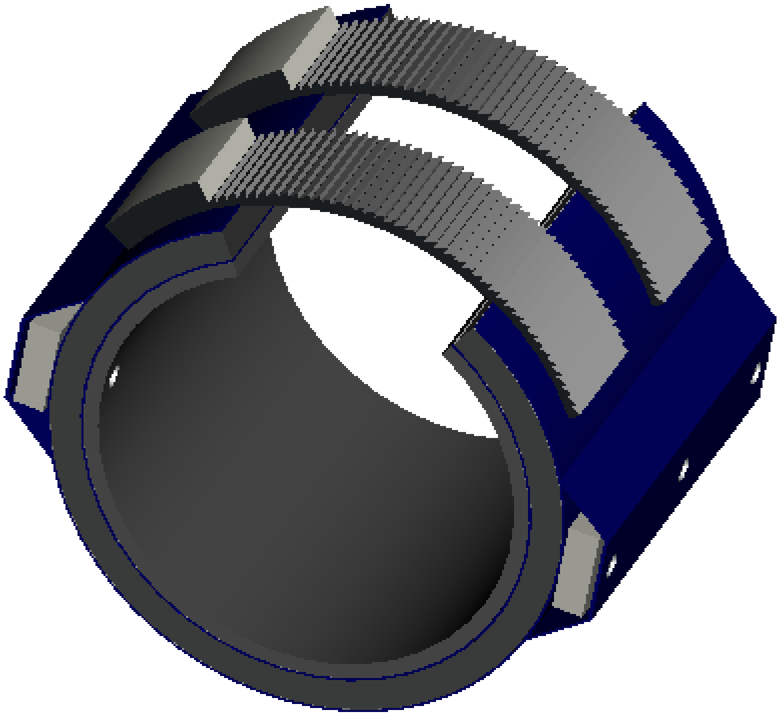


Figure 58 - Cross-Section of Prosthesis Attachment with Ratcheting Straps

A top view of the prosthesis attachment can be seen in Figure 59.

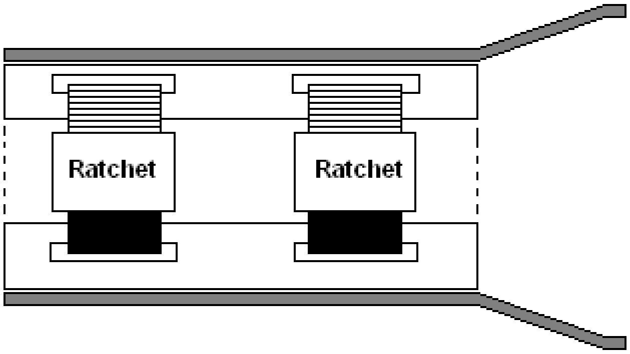


Figure 59 – Prosthesis attachment top view, bars in gray

If a situation arises where the prosthesis attachment is too big for a particular user, an insert can be placed in between the prosthesis attachment and limb to take up the gap. This insert will have to be securely fastened to either the prosthetic limb or prosthesis attachment to avoid slippage.

5.8 Strings Design

The strings concept described in Section 4.1.2.I was also further developed and analyzed in order to discover the design that provides optimal performance. This design would be used in conjunction with the torso attachment and prosthesis attachment described in Sections 5.3 and 5.5, respectively.

5.8.1 Detailed Design

The shoulder attachment for the strings design consists of a metal frame on which the strings will be mounted, and the shoulder attachment described in the exoskeleton design. The string mount is composed of a semicircle arc with outer radius 2.75in of 0.13in thick and 1.5” deep piece of material. Each end of the arc extends straight 1” tangent to the arc. This piece is welded to the exoskeleton’s shoulder attachment so that the ends of the tangent extensions are 1.2in vertically above the ends of the exoskeleton’s attachment. Face A of the string mount in Figure 60 is in line with Face B of the exoskeleton’s attachment Figure 61. The strings are then mounted onto the outer edge of the face opposite to Face A at the positions show in Figure 62. A rivet holds the ends of a string at P3 and P7, while another string will run over pulleys located at P1 and P5. The positions of these points are shown in Figure 63.

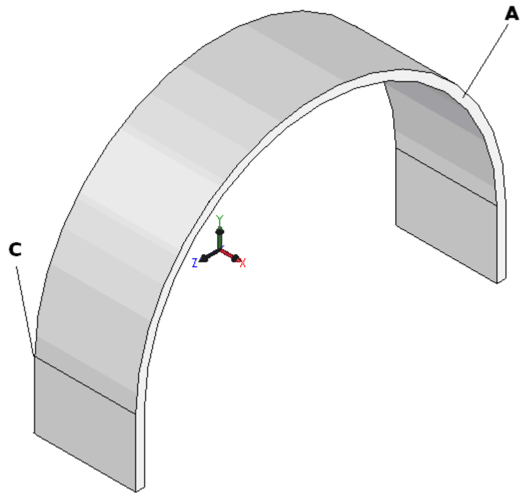


Figure 60 – Strings mount for the shoulder attachment.

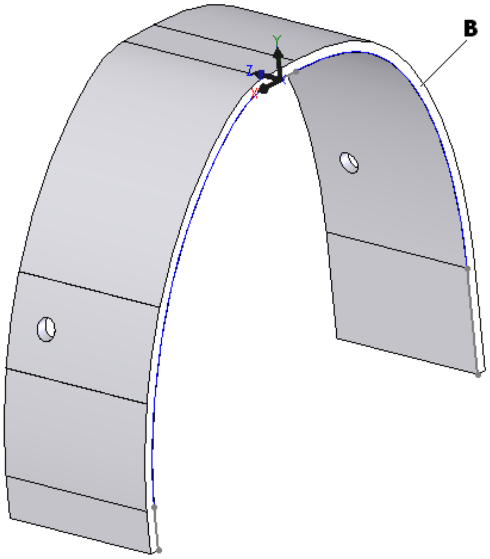


Figure 61 – Shoulder attachment from the exoskeleton design.

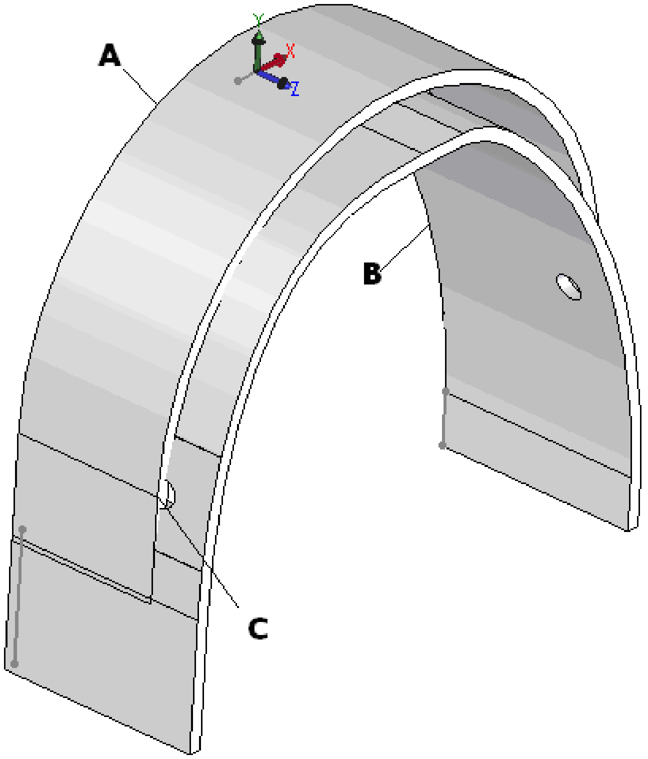


Figure 62 – Final assembly of shoulder attachment for strings design.

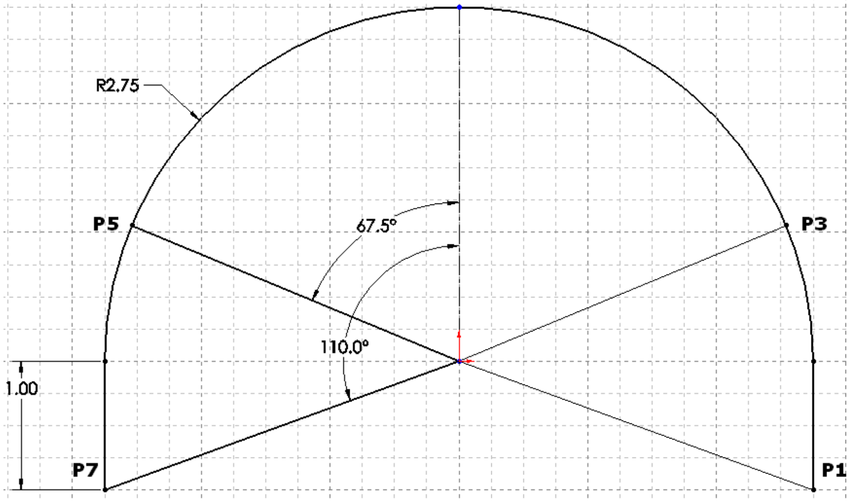


Figure 63 – Location of the strings on the shoulder attachment.

The prosthesis attachment is the same as that used in the exoskeleton design, except the bars are replaced by mountings for the strings. The mountings are placed on the outer edge of the proximal end of the ring in the locations shown in Figure 64. A rivet fastens the ends of a string at P2 and P6, while a pulley guides the other string at P4 and P8.

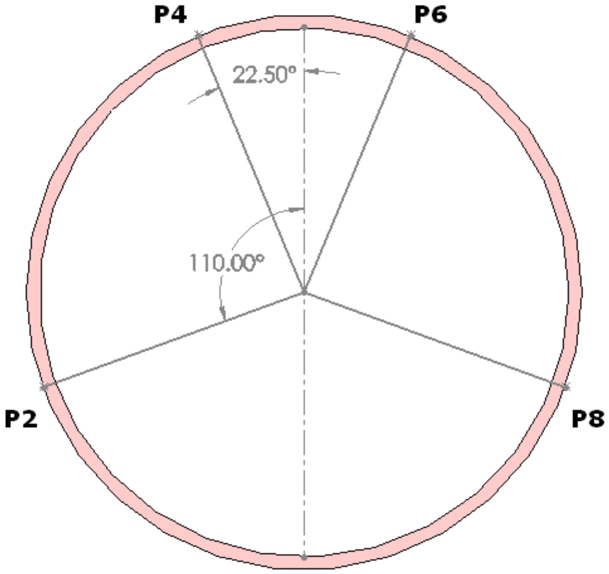


Figure 64 – Location of string mountings on the humeral ring, viewed distally from the shoulder.

Two strings connect the two attachment devices. One string starts at P3, travels over the pulleys at P4 and P8, then terminates at P7. Likewise, the other string begins at P2, goes around the pulleys at P1 and P5, and ends at P6. The material for the strings, pulleys, and rivets were chosen for their ability to sustain the loading conditions specified in the performance specifications. The overall layout of the strings device with strings is shown in Figure 65.

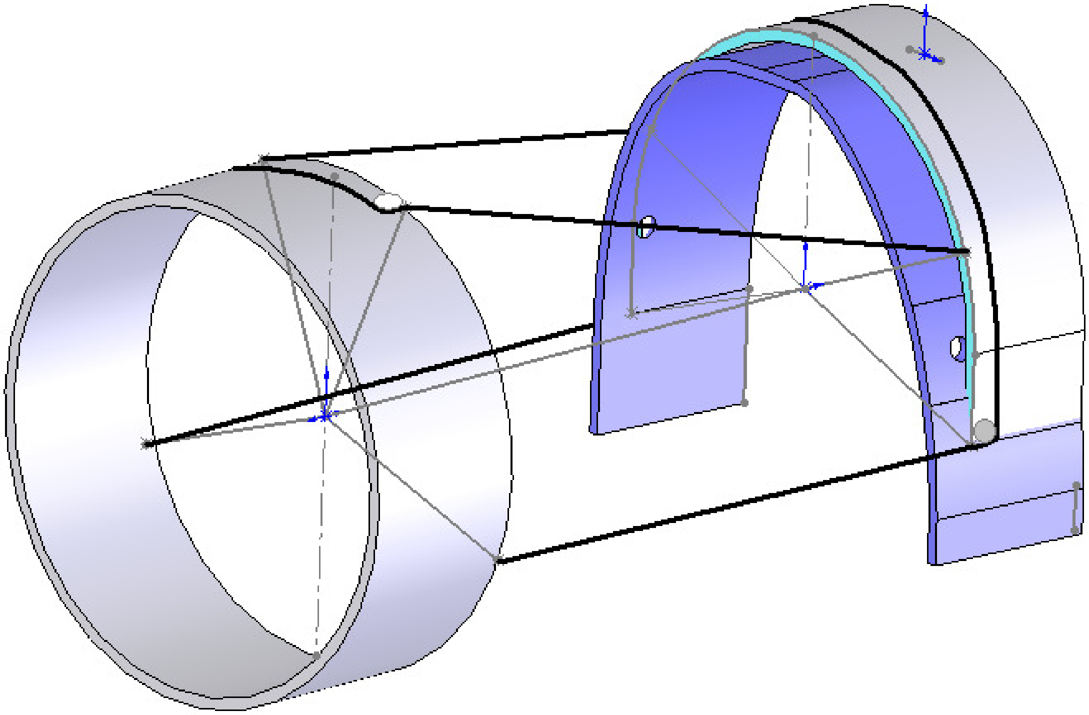


Figure 65 – Total mounting system for strings design.

5.8.2 Functionality

The shoulder attachment is placed so that the center of the arc of the string mount is coincident with the center of the humeral head. Point C is located at the end point of the semicircle on the outer edge of the face opposite Face A. A line connecting Point C with the corresponding point on the other half of the semicircle passes though the center of the humeral head. As a result of the design of the exoskeleton piece and its assembly with the string mount, the shoulder attachment fits on the shoulder of the affected arm so that the midpoint of this line is coincident with the center of the humeral head. The shoulder attachment is fastened to the body with the same vest support system as used in the exoskeleton design. Since the body attachment vest is not totally rigid, the vest, as well as the shoulder attachment, is allowed to move with the body as the humerus and scapula move, allowing the shoulder attachment to stay in alignment with the humeral head. Thus, scapular motion is accounted for in the body attachment design. The prosthesis attachment is allowed to turn over the guide ring that lies within it, just as it does in the exoskeleton model.

The prosthesis attachment and the shoulder attachment are linked by two strings. Each string connects two pairs of points. Each pair consists of one point on the shoulder attachment and one point on the prosthesis attachment; one rivet and one pulley. As the arm moves, for a given string, the distance between one pair of points increases by the same amount that the distance between the other pair decreases. In this way, the sum of the distances between the pairs remains constant, and the string is always in tension. This tension pulls the prosthesis towards the stump while the arm moves through different positions. This constant force holding the prosthesis onto the stump allows the user to perform load bearing activities.

5.8.3 Analysis

In order to determine the ideal mounting positions for the strings, a CAD model was created to simulate the motion of the shoulder and prosthesis attachments relative to each other. The model can be seen in Figure 65. The model is composed of a shoulder attachment, a prosthesis attachment, and a straight link between them to simulate the humerus. The humerus link is concentric with the prosthesis attachment to simulate a snug fit of the prosthesis attachment to the prosthesis. The other end of the humeral link was fixed to the point at which the center of the humeral head was assumed to be. At this connection, the humerus is able to pivot freely at this joint to simulate the motion of a ball joint.

To understand how the string reacts to the movements, extreme positions were chosen. The CAD model was positioned to simulate the arm straight out in the frontal plane so that it is parallel to the ground; abducted with the humerus at 30^o to the vertical; adducted with the humerus at 30^o to the vertical; flexed with the humerus 30^o to the sagittal plane; and extended with the humerus 30^o to the sagittal plane.

Both the prosthesis attachment and the shoulder attachment had points corresponding to the mounting locations of the strings. The distances between the two pairs of points that belong to a single string were measured in different positions. The sum of the two distances was recorded in each arm position for each orientation of the points. The sums of the two distances for a given orientation of the points were compared. The goal was discover the orientation of the points for which there was the least difference between the sums of the distances at different arm positions. The orientation of the points relative to each other was modified in the search for this ideal situation.

The first design had the humerus concentric with the prosthesis attachment, but the ball joint was not centered in the arc that formed the shoulder attachment. Instead, the ball joint was placed superior to the center of the arc. Also, the shoulder attachment and the prosthesis attachment had different radii. The points were rearranged several times, and the smallest difference between the sums in the different arm positions was 1.23in. Because of the layout of the strings, each string crosses the gap between the shoulder attachment and the prosthesis attachment twice. As a result, since the string is essentially folded in half, an overall difference in length of 1.23in means a net difference of 0.61in distance between the two attachments.

The second design tested kept the same dimensions as the original, but now placed the center of the humeral head at the center of the shoulder attachment arc. Of the different string orientations tested with this design, the least difference in sum was 0.75in, for a net change in distance between the two attachments of 0.38in.

The final design attempted kept the humeral head at the center of the shoulder attachment arc, and also equalized the radii between the shoulder attachment arc and the prosthesis attachment ring. The best orientation found with this set up showed a total difference in sum of 0.39in, for a net difference in distance between the two attachments of 0.20in. The greatest sum in this case is for when the arm is flexed at 30^o to the sagittal plane. Because the second set of points is arranged symmetrically on both attachments, the same is the case for the other string when the arm is extended at 30^o to the sagittal plane. See Table 14 for final results of calculations.

Table 14 - Distances between pairs of points in different humeral positions.

abd/add	*Pair*	90.00	ABD	ADD
	P12	180.06	*202.39*	*158.42*
	P56	187.78	169.25	212.90
	TOTAL	187.78	169.25	212.90
flex/ext	*Pair*	90.00	FLEX	EXT

P12	180.06	*129.82*	*239.00*
P56	187.78	242.49	123.35
TOTAL	367.84	372.31	362.35

As the symmetry in the design increased, the differences in the sums decreased, approaching the "ideal" situation in which there is no change in the sums as the arm moves through its full range of motion. Although this ideal situation was never obtained, the final design came relatively close to it. Since the total sum in these positions is 14.66in at its greatest, the difference in the sums only accounts for 2.68% of the total length. This same percentage can be applied to the net difference with respect to the change in distance between the prosthesis attachment and the shoulder attachment. The net difference in distance of 0.30in and its corresponding percentage of change are small enough that they can be considered negligible.

When the humerus is either flexed or extended at 30^o to the sagittal plane, one string is at the maximum length, as previously asserted. It is at this position as well that the other string is at the minimum length measured, of the five arm positions tested. So it can be seen that when one string is at its loosest, the other is at its tightest, reassuring that tension is holding the prosthesis on. This situation provides more proof that 0.30 in. net change in distance is negligible because one string compensates for the other.

Free body diagrams of the arm straight out in the frontal plane so that it is parallel to the ground are shown in Appendix D. In this position, the strings are angled down from the prosthesis attachment, so a component of their tension force is in the same direction as the applied weight W. Thus, a resultant force and moment must be exerted by the prosthesis on the prosthesis attachment to counteract the imbalance in forces applied by the weight of the load and the strings.

The case in which the arm is adducted straight down and supporting a load was also considered. Appendix D also shows the free body diagrams for this situation viewed from above and from the side.

6.0 MANUFACTURING

The device contains many components that are either manufactured by the group members or by the WPI Washburn Shops. The vest and prosthesis attachment are completely manufactured by the group members, whereas the mechanism is manufactured mostly by the WPI Washburn Shops. The raw materials were all acquired from outside sources. The manufacturing process is described in detail below.

6.1 Budget

The materials used for manufacturing the vest, mechanism and prosthesis attachment are listed in Table 15. The supplier, part number, description of the part and cost are all included as available.

Table 15 – Budget Outline

Supplier	Part #	Description	Qty	Unit Price	Sub Total	Shipping
McMaster	86205K63	Ionomer Foam, 1/4" x 48" x 76"	1	$32.72	$32.72	
McMaster	8643K844	Polyurethane Foam Sheet	2	$18.71	$37.42	
McMaster	2172T21	Foam Selector Pack	1	$37.50	$37.50	
M2 Intl.	10RPS	10" Padded Ratchet Strap	2	$34.00	$68.00	$15.00
Home Depot		1/8" x 2" x 48" Flat Plate Steel	1	$8.03	$8.03	
Home Depot		1/8" x 1" x 3' Angled Steel Bar	1	$7.28	$7.28	
McMaster	3510T11	3/4" x 10' Nylon Webbing	10	$0.37	$3.70	
McMaster	3510T13	1-1/2" x 10' Nylon Webbing	10	$0.62	$6.20	
Jo-Ann Fabrics		Linen	6	$4.19	$25.14	
Jo-Ann Fabrics		Duck Fabric	3	$6.99	$20.97	
Jo-Ann Fabrics		McCall's Vest Pattern	1	$6.30	$6.30	
Jo-Ann Fabrics		Upholstery thread	2	$2.09	$4.18	
Jo-Ann Fabrics		Pattern Ease	1.5	$1.99	$2.99	

Jo-Ann Fabrics		Machine needles, size 18	1	$2.29	$2.29	
Jo-Ann Fabrics		Machine needles, size 16	1	$2.19	$2.19	
Strap Works	SRBSA	3/4" Side Release Buckle	1	$0.77	$0.77	$4.80
Strap Works	SRBSA	1-1/2" Side Release Buckle	2	$1.51	$3.02	
McMaster	8570K11	Neoprene Foam Rubber	1	$13.06	$13.06	
Strap Works	SRBSA	3/4" Side Release Buckle	3	$1.02	$3.06	$4.80
Home Depot		5/32" x 1/4" Alum Rivets	1	$4.94	$4.94	
Home Depot		5/32" x 1/2" Alum Rivets	1	$4.94	$4.94	
Home Depot		3/16" Washers for Rivets	1	$1.69	$1.69	
Jo-Ann Fabrics		3/4" x 3' Nylon Webbing	1	$0.89	$0.89	
Ace Hardware		Pliobond glue	1	$4.50	$4.50	
				Total Cost:	$326.38	

6.2 Design for Manufacturability

The goal of design for manufacturability is to make the components simpler and manufacturing processes more efficient. CNC machines are used to do the majority of the machining due to the complexity of the mechanism parts. To ensure that the mechanism parts are produced accurately and in a timely fashion, several modifications are made.

All edges with an interior angle of less than 180 degrees have a radius of at least ¼” added. CNC machines commonly use round end mills and are unable to cut such angles. This operation can be seen in Figure 66.

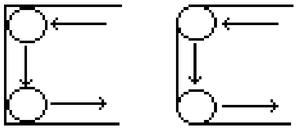


Figure 66 – Left – Corners without radius, Right – Corners with ¼” radius added

Simplification of parts is a key concept of design for manufacturability. It ultimately leads to a reduction in cost and improvements in quality. The preliminary design of the shoulder arch part of the mechanism was a single piece. The machinist said that it was too difficult and time consuming to machine as designed. Following the advice of the machinist, the shoulder arch was redesigned a first time as an assembly of 3 separate pieces that are fastened together. The assembly of parts can be seen in Figure 67 for the first redesign. The parts had to be redesigned a second time to allow for easier fixturing in the CNC machine. The curves on the two arch side pieces were removed. The arch side pieces can be seen in Figure 68.

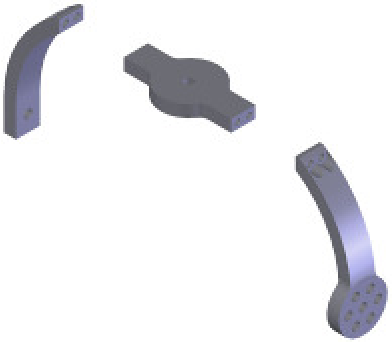


Figure 67 - Shoulder arch redesigned for easier manufacturing as an assembly of 3 pieces

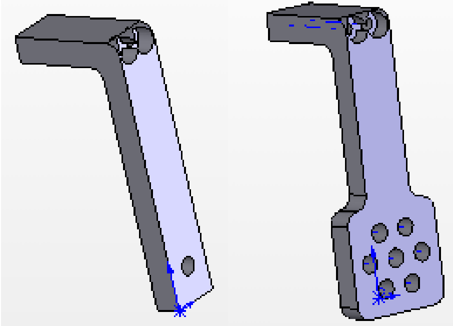


Figure 68 - Shoulder Arch side parts redesigned for easier fixturing in CNC machine

This method is acceptable for prototyping purposes. However, if the part is to go into production, it will be produced as a single piece as originally designed.

The humeral bar was also redesigned for easier manufacturing. The machinist could not fixture the part properly as designed given the time constraints for machining. To make the fixturing easier, the single bar was made into two separate parts. These two parts are fastened together by a single machine screw. The assembly of the humeral bar parts can be seen in Figure 69.

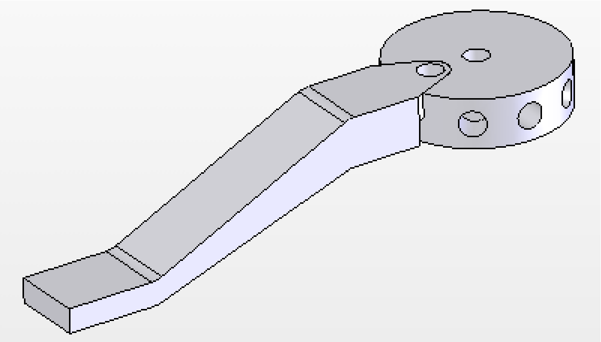


Figure 69 - Redesign of humeral bar into two separate components for easier manufacturing

Tolerances are added to the parts prior to manufacturing. Proper tolerances ensure easy assembly and disassembly of mating parts and sliding between bearing surfaces. The area where tolerancing is critical occurs at fastening and bearing locations of two or more parts. Therefore, tight tolerances are avoided to make sure parts function properly.

The device conforms to a few of the basic principles of design for manufacturability. Adopting these principles makes the manufacturing process easier and cheaper due to the limited budget and time available. The principles of design for manufacturability will ensure marketability of the device in the event that it is successful.

6.3 Vest

6.3.1 Prototype I

The original basis for the design of the vest was pattern 8285D size medium by McCall's. However, 1" was added to the perimeter of the pieces in order to accommodate foam and any other material that would be added. This first prototype was constructed out of cotton linen fabric because it is less expensive and easier to work with than the Duck fabric chosen for the final product. During the modifications, Richard Gilley acted as the model subject to whom the vest was fit. The vest was then donned on the subject to whom the vest would be tailored. While he was wearing it, the vest was marked with the locations the foam and straps, as well as the actual outline of the vest in the front. The vest was then cut and sewn so the front resembled the final design, as shown in Figure 70. Also, two 1¾” tailored button holes aligned vertically on each half of the front of the vest were created, leading into a sleeve that was sewn on the inside of the front layer. These aspects will unobtrusively guide the 1½” waist straps around the waist and allow the user to tighten them at the outside front of the vest.

Figure 70 – Design of the front of the vest from the disassembled Prototype I. The right border accommodates the specific fit to the subject. The tailored button holes are also visible.

The vest was placed on the subject and fit to his torso by making two vertical darts in the back and one vertical dart under each arm, as can be seen in Figures 71 and 72. The darts were sewn into the vest and the product was checked for fit on the subject. Since the fit was satisfactory, this prototype could be successfully be used as a basis for a second prototype. So this vest was cut along all seams, and one piece from the back and one from the front were chosen to be the patterns for the next prototype in order to keep symmetry. The outline of the pieces was traced on to Pattern Ease interface to make new pattern pieces, shown in Figure 72.

Figure 71 – Half of the back of disassembled Prototype I. The curvature on the left border and the removed strip of fabric in the center achieve the tailored fit to the subject.

Figure 72 – Pattern pieces resulting from Prototype I.

6.3.2 Prototype II

The new pattern pieces were translated onto the cotton linen fabric again. The pattern pieces also served as a guideline for the shapes of the foam inserts. The front and back pattern pieces were attached as if they were sewn at the shoulder seam and the perimeter was traced onto the foam to provide the a basic shape. The piece of foam was then put over the shoulder of the subject and overlapped under the arm along the torso in order to fit it to the body. The overlap was outlined then cut, and the two edges were hand sewn together with an overhand stitch. The piece of foam for the opposite shoulder was shaped in a similar way, using the outline of the top portion of the front and back patterns. The foam piece to cover the opposite hip was shaped as a semi-oval with dimensions to fit the subject. The three foam pieces are displayed in Figure 73. The vest was sewn together, and the foam pieces and metal shoulder arch correctly positioned. The large foam piece was machine sewn into the fabric along the front middle edge. After the shoulder arch was put into place, and stitches through both the fabric and the foam were taken to hold the arch in place. Hand stitches were also used to tack the foam to the opposite shoulder of the vest. A piece of $^{5}/_{8}$” ribbon was sewn into the both of the shoulder portions of the foam in the front to simulate the straps that would be there in the final product. Likewise, two sets of ribbons were sewn in to shoulder foams in the back as well.

Figure 73 - Clockwise from upper left, the large foam piece for the affected side, the smaller foam piece for the opposite shoulder, and the foam piece for the hip. On the large foam piece, the top two edges were uncut while the vest was intact. Note the seam under the arm hole and the removed triangle for fitting on the right border.

The subject donned the vest, positioning the hip foam over his hip bone, and secured it to himself using his belt and one of the 1½" ribbons around his waist. The donned vest can be seen in Figure 74. The top three ribbons were also tied to tighten the fit. The larger foam piece gapped in the back over his shoulder blade so a triangle was cut out of the foam and the exposed edges were sewn together to improve the fit. Afterwards, the vest was cut open and the foam and shoulder arch were removed. The large foam piece was cut across the shoulder and opened up to make a stencil for the final product.

Figure 74 - The subject wearing Prototype II.

6.3.4 Final Prototype

To create the final vest, the same pattern pieces were used in the creation of the final product. The tailored button holes and the sleeves for the straps were replicated in this vest. The foam pieces from the previous prototype were used as stencils to shape the new pieces. The large foam piece was held into place around the subject, and the side under his arm along his torso was heated with a hair drier until the curved surface felt soft. It was then allowed to cool in this position, helping it to assume the curvature permanently. The top edges were hand sewn together with an overhand stitch and the foam was reapplied to the subject. This junction was held into place with the desired curvature, blow dried, and allowed to cool. The metal shoulder arch was correctly positioned over the shoulder foam and super-glued into place. The seam was then sewn around the foam, and both the foam and the shoulder arch were sewn into the fabric. The opposite shoulder piece and the hip piece were also heated and allowed to cool in their curved states, then sewn into their respective positions in the vest. Now that all of the foam is situated correctly, the two front $^{5}/_{8}$” straps and four back $^{5}/_{8}$” straps that connect the two shoulder pieces were sewn into the vest and through the foam. Finally, the two 1½” straps were threaded through the button holes and sleeves. All straps were cut excessively long to allow for adjustments in the buckles.

The final product can be seen in a front view in Figure 75. The right shoulder area is featured in Figure 76, displaying the shoulder arch and the foam piece sewn into the fabric. The region of the vest that contains the waist and hip straps is magnified in Figure 77. Finally, the strap sleeves and the darts can be seen clearly in the back of the vest in Figure 78.

Figure 75 - Front view of the final vest.

Figure 76 - Close up on the right shoulder (the affected side). Note how the metal shoulder arch and the foam are secured into place with stitching.

Figure 77 - Close up of the abdominal portion of the vest. Note the nylon straps exiting the sleeves and tailored button holes.

Figure 78 - Back of the vest displaying the strap sleeves and the darts.

6.4 Mechanism

The mechanism components are all manufactured by CNC mills at the WPI Washburn Shops. CNC machines are required because of the complexity of the parts. In order to properly assemble and operate the mechanism without binding, the tight tolerances must be maintained.

Steel is the preferred material for the actual mechanism; however, the prototype mechanism is machined from aluminum. The allotted time and machinability of the metal are primary factors in the decision to use aluminum.

The basic procedure for manufacturing involves transferring CAD files to CAM files and generating NC code for the CNC machines to interpret. Following machining, the parts are deburred and assembled to check for proper clearances and operation.

6.5 Prosthesis Attachment

The prosthesis attachment is made primarily out of the same materials as the vest. The duck fabric is strong and durable enough for the intended application. The main components used to manufacture the vest are:

- Heavy-duty cotton duck fabric, navy blue
- ¼” Ionomer foam
- Heavy-duty thread
- 1/8” Neoprene foam with high coefficient of friction on surface

The fabric and ionomer foam are cut from previously designed patterns. Button style holes are added to the fabric first. Two are added on each side. This is where the ratcheting straps will feed through. The ionomer foam is then formed with a hairdryer to produce a circular piece consistent with the dimensions of a prosthetic limb. The outside surface of the ionomer foam is heated and allowed to cool while being held in its desired shape. The ¼” ionomer foam is then placed within the cut fabric pieces. The fabric is sewn shut around the ionomer foam creating a shell. The material with a high coefficient of friction is then glued on the inside of the fabric shell. The order of layers can be seen in Figure 79.

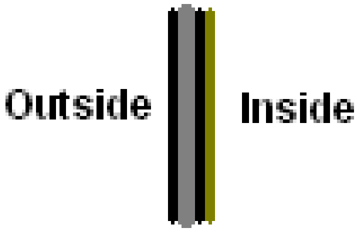


Figure 79 - Order of materials: black is fabric, gray is ionomer foam, brown is high friction neoprene foam

Bar sleeves are made by sewing a layer of fabric to the main body of the prosthesis attachment. A cross section of the material layers and fabric encasing the aluminum bars can be seen in Figure 80.

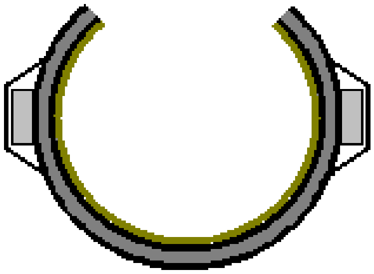


Figure 80 - Cross section of prosthesis attachment showing encased aluminum bars, black is fabric

Holes are made through the four layers of the fabric and foam shell for the connection of the ratcheting straps with rivets using an industrial hole punch. Holes are also made along both sides of the shell to allow connection to the bars of the mechanism using rivets. The rivet locations, bar sleeves, and button holes can be seen in Figure 81.

Figure 81 - Prosthesis attachment showing locations of bar sleeve, button holes, and rivets

The final prosthesis attachment can be seen in Figure 82.

Figure 82 - Final prosthesis attachment strapped to a glass to simulate prosthesis

Assembly of Prosthesis Attachment Components

The main components of the prosthesis attachment that are assembled together are:

- The prosthesis attachment shell, consisting of 4 layers
- 1” Ratcheting straps and ratchets
- 5/32” x ¼” aluminum rivets

The ratcheting straps are inserted at the top of the prosthesis attachment through the button holes and fed through the shell till the holes of the straps line up with the holes through the shell. Two rivets are inserted to secure the straps to the prosthesis attachment shell. The strap with the teeth wraps around one side, and the strap that has the ratchet attached without teeth wraps around the opposite side. The two straps meet at the top. The straps are hidden under the top layer of fabric but above the ionomer foam. A detailed top view picture can be seen in Figure 59 in Section 5.7, Final Design and Analysis. The shell and straps are inserted over the two bars of the mechanism and are secured with rivets through the previously manufactured holes.

7.0 TESTING PROCEDURES

We will perform several tests to evaluate the design with respect to each of our design specifications. The full attainable range of motion using the device will be measured with and without loads. At the same time, we will check that all the parts of the device move smoothly. The comfort and stability of the device while worn will be evaluated by several subjects of varying body size and build. Also, the structural integrity of the device will be assessed under a variety of conditions.

The full loading capacity of the device will not be physically tested, however. The detailed design specifies that the device be made of steel, giving it a safety factor of 3. A safety factor of this magnitude virtually eliminates the possibility that the device would fail due to loading. Also, the prototype was fabricated out of aluminum to facilitate manufacturing, and thus has different physical properties than the actual device would. Therefore, the device will be tested with a reduced loading to verify that it functions as designed.

The majority of the tests involve a test subject answering a number of questions about the device. In order to gain enough experience and knowledge of the device in order to properly answer the questions, the test subject will go through the following procedure: don the device, move his arm through its entire range of motion, pick up a ten pound weight and go through the entire range of motion again, and finally doff the device.

7.1 General Characteristics

The weight of the entire device will be measured. Also, overall dimensions of the assembled device will be taken, including measurements in its most compact and extended positions.

7.2 Range of Motion

Several tests will be conducted to evaluate the range of motion of the device. The first test conducted will be to measure the achievable angles at each joint of the mechanism. The vest will be strapped to several test subjects and measurements will be taken. The vest will then be strapped to a bench and measurements will be taken for comparison.

The next test conducted will require the test subject to move the device through its full range of motion, first unloaded, and then loaded with a 5 lb weight. A questionnaire will be provided asking the test subject to rate the range of motion of the device using a 5 point Likert scale.

While moving the device through its full range of motion, the user should also note any observations of binding or locking up on the questionnaire. The questionnaire can be found in Appendix F.

7.3 Comfort and User Friendliness

The opinions of several test subjects concerning the device's ease of use and comfort will be considered in unloaded and loaded situations with the arm in various positions.

The test subject will first don the device. A questionnaire will be provided asking the test subject to rate certain aspects of the device using a 5 point Likert scale. Space will be provided for any additional comments.

The comfort of the vest will then be evaluated in several positions. An unloaded test will be conducted first followed by the same test with the addition of a 5 lb weight. A questionnaire will be provided asking the test subject to rate the comfort of the device in certain locations using a 5 point Likert scale. The specific locations considered are the shoulder and waist/strap area. Space will be provided for any additional comments. The testing questionnaire can be found in Appendix G.

7.4 Strength Testing

Although the prototype being tested is not constructed out of the material specified in the final design, alloy steel, it is still necessary to see how the device reacts under load. Each of the five "worst case" arm positions that were analyzed previously will be tested using a load of ten pounds. Since the mechanism is designed to transfer all the loads to the user's body using locking joints, a mock arm need not be placed in the device. The shoulder arch will be fixed to a bench, the joints will be locked in the positions specified by the five "worst case" scenarios, and the loads will be applied directly to the prosthesis attachment. The five worst case scenarios can be seen in Section 5.3, Analysis. In each of the tests, the deflection of the prosthesis attachment will be recorded in the form provided in Appendix I. The torque required to move any joints that do not need to be locked for a certain position will also be recorded in Appendix H to determine if the non-locked joints will be operable by the user.

8.0 RESULTS

After completion of the testing, results would be compiled. Due to time constraints and problems with the machining facility, parts were not machined on time. This greatly limited the amount of testing that could be performed. The results that could be obtained are summarized below.

8.1 General

The general results consist of the weight and overall dimensions of the device. The weight and overall dimensions of the mechanism were obtained through SolidWorks. The weight of the mechanism does not include the weight of the fasteners. These are assumed to be less than a ¼ lb. The vest was weighed using a hanging scale and the prosthesis attachment was weighed using a generic kitchen scale. Overall dimensions were obtained using a standard tape measure. The results are summarized in Table 16.

Table 16 - General weight and overall dimension results for device

	Vest	Mechanism	Prosthesis Attachment
Weight (lbs.)	2.50	4.64	0.28
Overall Dim. (LxWxH) (in.)	12.50 x 7.50 x 16.50	13.10 x 6.75 x 7.00	3.25 x 4.50 x 4.50

8.2 Comfort

Due to the machining problems, the only comfort test that could be completed was the unloaded test. The vest was put on a user and the 7 different positions specified in the testing protocol were applied. The average response to the comfort questionnaire was 3.8 out of 5 on the Likert scale, 1 being unbearable, and 5 being barely noticeable.

9.0 DISCUSSIONS

Although the tests conducted produced only a fraction of the results that were expected, it does not take away from the fact that the overall quality of the design can be evaluated and discussed. In chapter three, the goal of the design was outlined - to design, analyze, and manufacture an upper arm exoskeleton for trans-humeral prostheses to allow the user to perform high load activities. Five categories of task specifications were created to guide the design in order to help achieve the goal – key performance, safety, user friendliness, reliability, and cost. Those same five categories will be used to discuss the final design to help conclude whether or not the original goal was achieved.

9.1 Key Performance Specifications

The first category of task specifications that will be discussed is key performance specifications. The first specification outlined in this category was that the device must be able to accommodate all types of prostheses, which includes passive, body powered, and myoelectric. The final design surely meets this objective. The prosthesis attachment subassembly simply grips to the prosthesis using force and friction and uses adjustable straps to allow for different sized prostheses.

The next task specification dealt with the required physical characteristics. The mechanism part could not weigh more than eight pounds. Weighing the prosthesis attachment sub-assembly and analyzing the CAD assembly model of the mechanism sub-assembly, the total would be slightly less than five pounds. The other part of this specification is that the mechanism cannot bind or seize in any position. Given that the three axes of the mechanism align with the ball and socket joint of the body's shoulder, the mechanism will move fluidly along with the arm in any position. However, it is possible that the axes do not align perfectly. That possibility will be discussed later in the report.

The third sub-category of key performance specifications is stability. The device must not slip or shift position on the body while holding a ten pound object in the terminal device and moving it through the entire range of motion. This specification does not entirely apply since for many positions the device is only designed to bear load when certain joints are locked. Therefore, one could not move the device through the entire range of motion while bearing that load. However, it could be modified to say that the device must not slip or shift position on the body while holding a ten pound object in a stationary position. In that case, it could be said reasonably that the device would most likely achieve this. The vest is form fitting and strapped tightly to the body. The mechanism is a rigid structure, and the prosthesis attachment will be gripping the prosthesis very tightly. The end result would be a very stable structure.

One of the most important categories of key performance specifications is range of motion. The metric outlined in chapter three states that the device must not impede the normal range of motion of a trans-humeral prosthesis user. As mentioned previously, given that the mechanism joints' axes are aligned with the shoulder joint, it is capable of perfectly following human arm movement. Since prosthesis users would generally have a more limited range of motion than that of a person with a fully functioning arm, it could be concluded that the device would not have a problem replicating that motion as well.

The final key performance category is load distribution. The first sub-task is that the device must be able to sustain a 25lb load in any direction or position. This is difficult to say without a final version of the design. Even if the prototype were available to test, it is constructed from aluminum, a weaker metal than the design material of alloy steel. Basing a conclusion on the stress analysis of the parts in COSMOSWorks would suggest that the device would easily handle that load, especially with the incorporated safety factor of three. The other sub-task of load distribution specifications is that the device must not impose any loads higher than 6psi on any part of the body. Unfortunately, this would be difficult to estimate without actually testing the prototype. However, it is probable that carrying the maximum design load of 25lbs would produce higher pressure points on the body than 6psi. Under normal, non loaded circumstances, and when the user is bearing lighter loads, it is feasible that there would not be any pressure points on the body.

9.2 Safety

The next main category of task specifications are safety specifications. There are not as many sub requirements in this area as key performance, but they are important nonetheless. The first task was to design the mechanism in a way that it is not able to puncture skin or clothing. As with many of the specifications, it is hard to make any real conclusions without testing. Since the mechanism in no way contacts the skin, it will most likely not be able to puncture it. Clothing could possibly get caught in the joints and tear. The device does not have any sharp features and is not a subject of worry.

The next safety task specification was that the device must not have any exposed joints or areas that could pinch the user. As mentioned previously, the mechanism does not contact the skin in any way, so it would most likely not pinch the skin. Also, as stated before, loose clothing could get pinched in the joints.

The last area of interest in terms of safety is pressure sores. This is essentially a repeat of the key performance sub-category of load distribution, but it applies to safety as well. Pressure of the device on the body must not exceed 6 psi at any location. As stated previously, pressures of this magnitude are likely when the device is bearing high loads, but under normal use they are unlikely since the loads will be distributed throughout the body via the vest.

9.3 User Friendliness

The third category of task specifications revolves around user friendliness. With a user friendly device, users would be more apt to use the device and wear it for extended periods of time. The first important sub-category is adjustability. The device must be able to accommodate both males and females falling within the 5th – 95th percentile in terms of arm and torso perimeters. In retrospect, that is an extremely large number of people to accommodate. With the current design, it would most likely not fit that large of a range. Extremely large biceps would not fit within the mechanism's rings, and the prosthesis attachment would not be able to tighten enough around extremely small prostheses.

Another sub-category of user friendliness is the ease of which someone can don and doff the device. The average user should be able to put on or take off the device within two minutes without aid. This requirement is probably met by the current design. The vest takes only about 20 seconds to don, and the prosthesis attachment takes approximately 15 seconds to tighten onto a prosthesis. Given the added complexity of guiding the prosthesis through the mechanism and prosthesis attachment while donning, one could expect to add another minute or so at maximum, giving the total donning time of about a minute and a half. Removing the device would take even less time.

The next area of interest is irritation. Any material contacting the skin should be non abrasive and breathable. The neoprene lining on the prosthesis attachment only contacts the prosthesis. The only part of the device contacting any part of the body is the vest, which is made of breathable canvas, meeting the requirement.

The last important area regarding user friendliness is aesthetics. The device should protrude from the body no more than 3 inches at joints and 2 inches in all other areas. Although this needs to be tested in order to be sure that the requirement is satisfied, it is unlikely that the device would protrude more than 2 inches in any area including the joints.

9.4 Reliability

The next significant category of task specifications is reliability – important for any device to be successful. Unfortunately, even with a prototype built, reliability would be extremely hard to test. As a result, no conclusions will be drawn as to whether or not the device would satisfy the requirements, but design considerations that would help achieve the specifications will be outlined. The first sub-category of reliability is fatigue resistance. The device must have a lifetime of at least three years. The vest is constructed from high strength canvas, and the mechanism is made of alloy steel which is highly resistant to deformation of any kind. Those materials were also chosen to satisfy the next requirement of shock resistance. The device must withstand a drop test from five feet off the ground.

Weather resistance is the next reliability category. The device must be able to withstand a spray test lasting one minute. Although the canvas vest is not waterproof, becoming wet does no damage and it can easily dry. After prolonged use in the rain, there is a chance of rusting the steel parts of the mechanism. The device must be able to withstand temperatures ranging from -30 degrees Fahrenheit to 115 degrees Fahrenheit. Almost none of the materials used in the device (canvas, foam, steel, and neoprene) would be susceptible to damage enduring that range of temperature. The plastic straps on the prosthesis attachment could become brittle at the lower end of that range, but being that they were designed originally for snowboard bindings, they would most likely endure a significant amount of abuse even at -30 degrees Fahrenheit.

The final category within reliability is the device's ability to be cleaned. It must be washable using only household cleaning products. Although the vest can be worn like any other vest, it cannot be cleaned in a washing machine due to the steel shoulder insert. It could, however, be hand washed without any problem. The same procedure would be used for cleaning the prosthesis attachment. As for the mechanism, any household product such as 409 or soapy water would do just as long as the parts are dried afterward.

9.5 Cost

The final category of task specifications is cost. Like all products, prosthesis aides must be priced to compete in the marketplace. Cost must be controlled in every aspect of the design, or the final retail price would rise as well. The first sub-category of cost is materials. The total cost of materials cannot exceed $400 per unit. The final design is most likely just under this number. The steel will be the most expensive material by far coming in at approximately $200 to $300. The prosthesis attachment and vest material cost would be about $50 total. The total then comes in under $400 by about $50. Buying in bulk, as one would in an actual manufacturing process, the prices would come down even more.

The next cost category is the manufacturing processes. The total cost of the manufacturing including raw material, processing, and labor cannot exceed $400 per unit. This is extremely hard to judge, as one would need specific quotes for a number of different processes. CNC machining each part for every device would be extremely cost prohibitive and would also produce a significant amount of scrap metal. Some type of casting would be the most appropriate for this application. The cost would depend entirely on what type of casting done and also the quantity produced due to the high initial cost of the molds. The vest and prosthesis attachment sub-assemblies would also need to be manufactured. This could also range from a single manual worker to a large automated plant. The conclusion would be that the price of the manufacturing processes could range anywhere from thousands of dollars per unit to well under $100.

The final sub-category within cost is the maintenance costs. Materials to maintain the device cannot exceed $100 per unit per year. The final design would likely achieve this requirement, as the only real maintenance costs that could be expected are regular lubrication of the joints and any regular cleaning the user would want to perform. Maintenance of the device must be simple enough to be performed by any prosthetist. The simplicity of the device would not even require a skilled prosthetist. As mentioned before, the only real maintenance necessary would be the lubrication of the joints.

10.0 CONCLUSIONS

The absence of a functional limb, acquired as either a birth defect or amputation, can significant affect the affected person’s ability to independently complete tasks of daily living. Prosthetic limbs have been developed to help the afflicted person regain desired features of the missing limb, such as aesthetics, basic function, or function for more extreme athletic activities. However, the extent to which to prosthesis can be used is often limited by insufficient mounting in the form of suction or harnessing. In the case of a transhumeral prosthesis, secure mounting is difficult to achieve without impeding on the user’s natural range of motion at the shoulder. The motion of the shoulder joint is more complex than a simple ball-and-socket joint due to scapular motion, which significantly increases the range of motion in all planes. As a result, it is difficult to effectively model the shoulder.

The goal of this project is to design, analyze, and manufacture an upper arm exoskeleton for trans-humeral prostheses to allow one to perform high load activities including high moments about the humeral and elbow axes. Several design specifications were formulated to guide the design process. The device should be able to bear applied loads while minimizing limitations to the range of motion at the shoulder. The device should be safe and minimize the negative effects on the user. It should be comfortable, easy to use, and aesthetically pleasing. It should be reliable, yet low in cost.

After extensively researching human anatomy and other parallel systems occurring in nature, as well as current technology pertaining to exoskeletons and harnessing, several concepts were drafted. Each concept included a prosthesis attachment, a torso attachment, and a mechanism connecting the two. The concepts for each of these three components were evaluated methodically using a design matrix to rank them based on the design specifications.

The final chosen design is composed of the optimal version of each component. The torso attachment takes the form of a full back vest with a steel arch located over the effected shoulder for mounting of the mechanism. The mechanism is an effective compilation of steel linkages in the form of a shoulder arch, humeral bar, inner and outer rings, and the prosthesis attachment bars. The arrangement of these components generates three single degree of freedom joints to simulate the three degrees of freedom of the ball-and-socket joint. The scapular motion is accounted for in the way that the mechanism is mounted directly at the shoulder and does not impede this aspect of the joint. The mechanism is connected to the prosthetic arm via the adjustable prosthesis attachment. After analyzing the mechanism in COSMOSWorks, the mechanism as design meets the task specifications for stress, including a safety factor of three.

Optimal materials for each component were chosen with their function and the design specifications in mind. The vest is composed of duck cloth enclosing strategically placed pieces ionomer foam and the steel shoulder arch, and is secured with nylon straps. The mechanism is machined out of aluminum instead of the specified steel to facilitate its manufacturing. Several of the parts were redesigned for this same reason. The humeral attachment is constructed of the ionomer foam enclosed in duck cloth, and is fastened with ratchet straps.

A protocol for testing the prototype was devised based on the design specifications. The general dimensions and weight would be measured of the mechanism as a whole. The achievable angles of a full range of motion would be measured of the device independently, while strapped to a user unloaded, and while strapped to a user with a 5 lb weight. The ease with which the vest is donned and doffed, as well as its comfort unloaded and loaded, would be evaluated on a 5 point Likert scale. Improvised strength tests were devised to test the function of the aluminum while loaded.

Due to an overload of requests to the machine shop this year, our prototype was not completely constructed. However, some basic aspects could be assessed. The overall dimensions of the mechanism are 13.1” x 6.75” x 7.00”, and it weighs 4.64 lbs. Based on this information and logically reasoning, the design specifications were reconsidered and it was decided that our final design met many of them.

Although our testing data is limited, some recommendations for future work became evident where the design fell short of the design specifications. The vest which was composed of several pieces of foam could be made of one large piece that is molded to the user’s torso to transfer the loads from the mechanism to the body more effectively. More research might be put into the mechanism to redesign it to better simulate the structure and motion of the shoulder. The prosthesis attachment could be made more adjustable, and could be fixed to the prosthesis using a rigid connection to better transfer the loads.

11.0 RECOMMENDATIONS

In many design projects, the outcomes are not always what are expected. The analysis, testing, and results can provide important insight into the overall design of the device. From this information, one can extract the potential weaknesses of the device as well as improvements that can be made. The weaknesses can be analyzed to find possible solutions. Improvements can lead to future work to make the device as functional as possible. Recommendations are outlined below for each of the three subassemblies.

11.1 Prosthesis Attachment

11.1.1 Adjustability

The current prosthesis attachment is designed around a 50th percentile male body. It is unlikely that a person with a body type smaller or larger than this will be able to comfortably fit their prosthetic limb into the sleeve. This is mainly due to the fact that a prosthetic limb is made proportional to the body size of the user. It is recommended that the prosthesis attachment be modified or redesigned in a way to allow adjustability for users of different body sizes. One possible solution is to modify the outer rings at the attachment point of the bars. Slots could be added to the outer rings allowing the bars to move closer together or further apart depending on the particular user of the device. The current design and a redesign with slots can be seen in Figure 83. The user would have to tighten down 4 screws after they size the prosthesis attachment to their prosthetic limb.

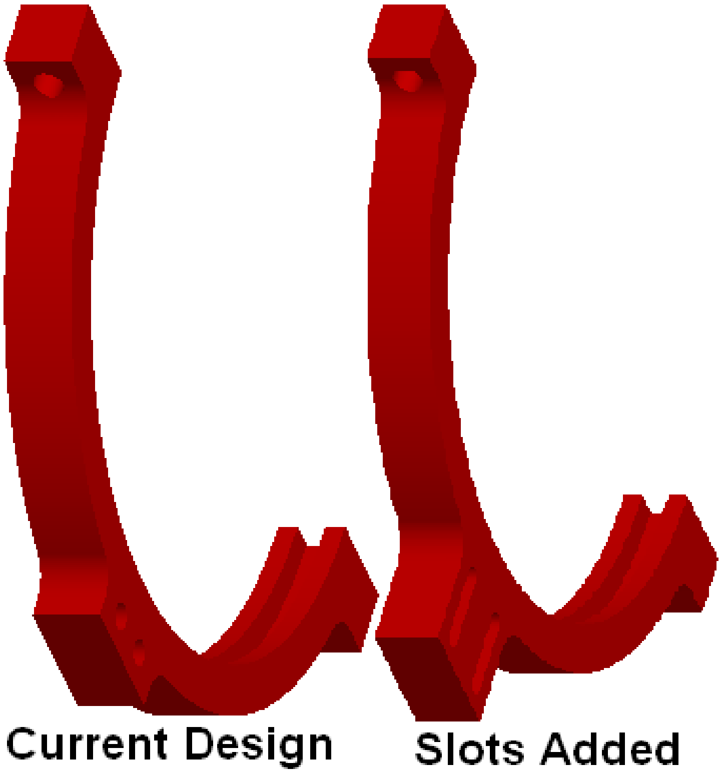


Figure 83 - Current outer ring design and outer ring with slots added for adjustability

11.1.2 Rigid Attachment System

The effectiveness of the attachment system was never tested. In theory the neoprene interior lining of the prosthesis attachment will hold the prosthetic limb in place for the specified loading conditions. However, to be on the safe side, it is recommended that a rigid attachment system be used to ensure that the prosthetic limb stays connected to the device at all times. The prosthetic limb would have to be modified for the insertion of pins or fasteners. During the design phase, a pin attachment method was proposed. This method was not selected for final design because the team felt that amputees would be unlikely to modify their prosthetic limb. Prosthetic limbs are expensive and most would be hesitant to drill holes without knowing how the device works. The ratcheting strap design was chose because it is less invasive.

11.2 Mechanism

11.2.1 Shoulder Joint Replication

The primary focus of the analysis and testing was based on a single mechanism design. It is recommended that other ways of replicating the shoulder's joint are researched. New designs may prove to meet or surpass the design specifications set forth for the current device.

11.2.2 Shoulder Anatomy

The current method of attaching the mechanism to the rigid steel insert of the vest is by trial and error. The goal is to have the 3 axes of the mechanism joints intersect at the center of the ball and socket joint of the shoulder. The vest and mechanism are placed on the user's body, not connected initially. The user will move their arm until a position is found where the mechanism moves fluidly with the user's arm. This position will be marked on the rigid steel insert of the vest and the metal attachment pieces will be welded in place. It is recommended that more research be conducted on the shoulder's anatomy so that better assumptions can be made as to the location of the mechanism's arch on the shoulder. The trial and error process currently used is unsatisfactory and time consuming.

11.2.3 Bearings

The current design is crude and simple. Holes are drilled in two pieces of metal to make a joint. A nut and bolt are placed through the two drilled holes to finish the joint. This simple joint will work for prototyping purposes to verify that the kinematics work correctly and that the device is sized correctly. However, there is a chance that binding will occur due to friction from the metal surfaces in close contact. It is recommended that roller bearings are used at the pin joints to allow for smoother motion of the mechanism during high load activities. This would be a simple redesign that would greatly improve the operation of the device.

11.2.4 Part Coating

The final device is to be manufactured from steel. Steel tends to rust easily when exposed to the elements. The user has the ability to use the device outside and therefore can expose the steel parts to rain and humid conditions. Rust formation has the potential to hinder the performance of the device. The critical areas that rust could possibly have an effect on are the rings and joints of the mechanism. It is recommended that the device be coated to deter the formation of rust. Possible solutions are powder coatings or epoxy based liquid coatings. It should be noted that thinner coatings placed on a bearing surface would be likely to wear off after time whereas a thicker bronze insert would not. The rings could be modified for bronze inserts on the bearing surfaces as well.

11.3 Vest

11.3.1 Continuous Foam

The vest is currently made from several pieces of ionomer foam. The pieces are sewn through the canvas material of the vest in many places. One piece, over the shoulder with the rigid steel insert, is made from two pieces sewn together. The sewn foam piece can be seen in Figure 84.

Figure 84 - Ionomer foam pieces sewn together creating a weak construction

It is recommended that a single piece of foam is used rather than several smaller pieces. The benefits of using a single piece of foam rather than several pieces by themselves or sewn together would be a better distribution of the loading over the user's body. It was also noticed that the junction of the sewn piece was weaker and tended to bend easily when compared to a solid piece. The single foam piece could also be molded to the person's body for a better fit. This would effectively distribute the loads more efficiently and would provide additional comfort for the user of the device.

11.4 Recommendations for the Strings Design

Further research on the strings model was discontinued due to time constraints and higher priority tasks. However, investigating the strings model has revealed that there are some benefits to this nontraditional design. Since its function is mainly to keep the prosthesis attached to the stump rather than support the entire load, its profile is less obtrusive and bulky. The device would be lighter weight with the heaviest components being the humeral and torso attachments. Its lightness gives the wearer a more natural feel since much of the load is transferred to the prosthesis and the stump. As a result, the wearer has better proprioception, and is able to sense what the limb is doing and how the stump and the prosthesis are reacting to various movements and loads.

For these reasons, researching this design further would be valuable. The manner in which the loads are distributed to the prosthesis, stump, torso, and device should be ascertained. According to the free body diagrams in Appendix D, the angles that the strings create with both the humeral and the torso attachments necessitate the presence of additional forces from the prosthesis and torso to establish equilibrium. Thus, it is important to calculate these forces in order to determine the response of the prosthesis, stump, torso, and device under various loading conditions. A MathCAD program could be written accomplish this. The program should calculate the angle of each string as the arm moves through the allowed range of motion. Subsequently, it would determine the tension in each string, as well as the resulting force from the body or prosthesis on the device in order to establish equilibrium. The resulting forces and moments would give insight as to how the prosthesis, device, and body will react. For example, if there is a large moment around a certain axis, the device exerts an undesirable torque the prosthesis, the prosthesis may torque on the arm, or both. The way in which the forces caused by the torque are distributed on the body would be of interest when evaluating the comfort of the device.

The completed analysis of the design shows that in a given position the sum of the distances between the two sets of points differ slightly in length. The calculations thus far have assumed that the strings connecting the humeral and torso attachments at these points are always taught. The actual device must accommodate the longer length to allow movement in all directions. As a result, in certain positions, one string will have slack while the other is taught. In other positions, neither string would be taught if the distance between the two coordinate systems remains constant. However, in practice, this would likely not be the case. Applied loads with components that points away from the humeral head would possibly cause the device to shift to a new position that would cause both strings to be taught. Analysis is needed to see how much the device might shift as the arm moves through the allowed range of motion, as well as in which direction the shift occurs. These shifts might change the angles of the strings and the ways in which the forces are distributed to the body and prosthesis.

Once it is determined whether or not the loads applied to the body and prosthesis through the prosthesis are acceptable, another computer program could be developed in order to easily fit the device to a specific client. This program would essentially perform an analysis on the SolidWorks model that has been performed manually in Excel already. The distance between the humeral head and the prosthesis attachment would be an adjustable variable in the program and would depend on the certain client. The radii of the humeral and torso attachments would also be adjustable as would the location of the points on both the attachments. The program would determine the ideal location of the points as well as the length of the strings for a given humeral length.

To increase the device's adjustability, the humeral and torso attachments could be made in a few set sizes, each of which could be fitted to a range of clients. The string fasteners could be attached for each client based on the results of the latter program. Depending on fasteners used, pulleys and anchors could either be welded to the exact position stipulated by the program, or set into pre-made holes in the body attachments near the desired location. The latter method would allow universal models to be manufactured, but analysis would need to be done to see how the inaccuracy of the string locations affects range of motion.

APPENDIX A – Decision Matrix

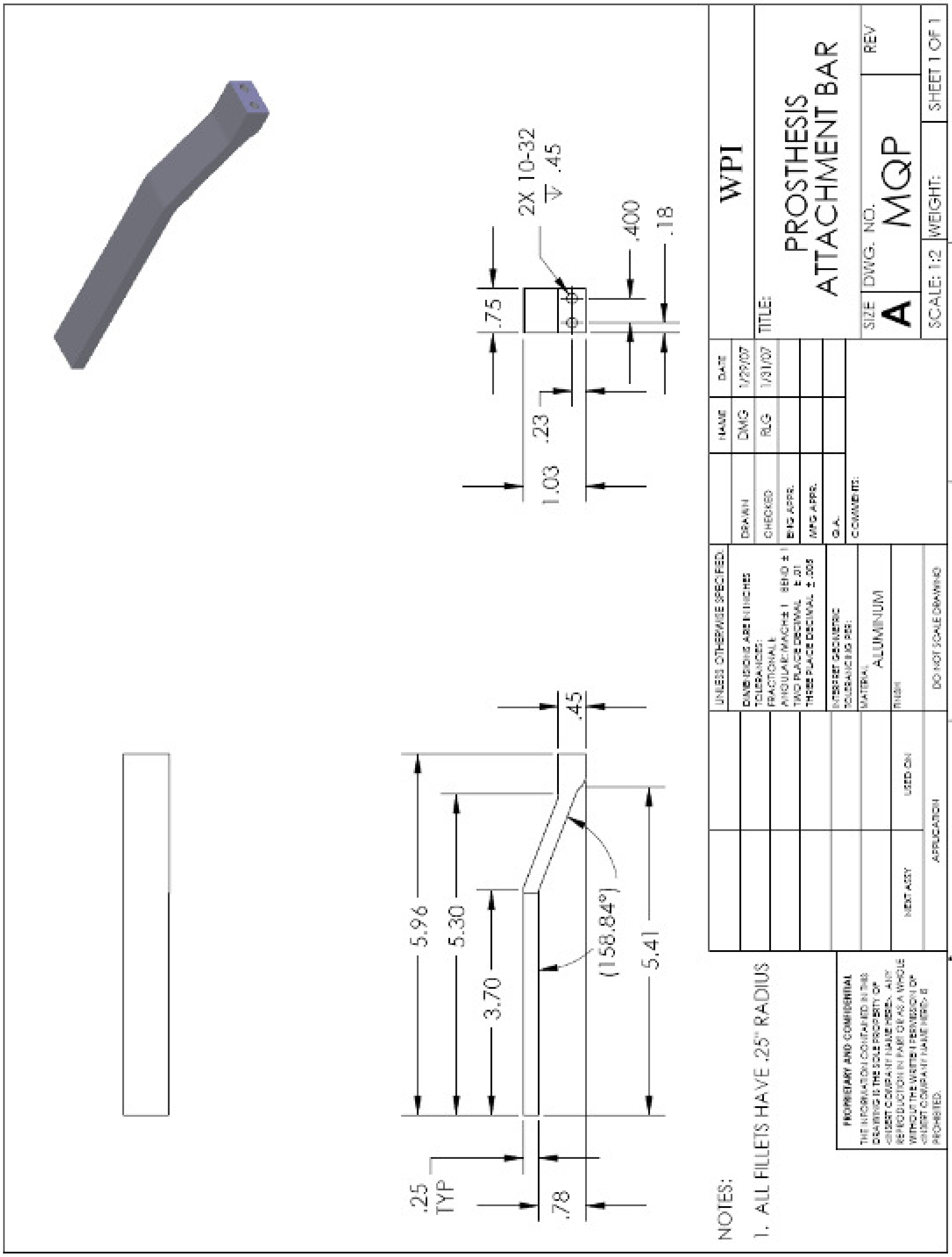
Prosthesis Attachment Decision Matrix

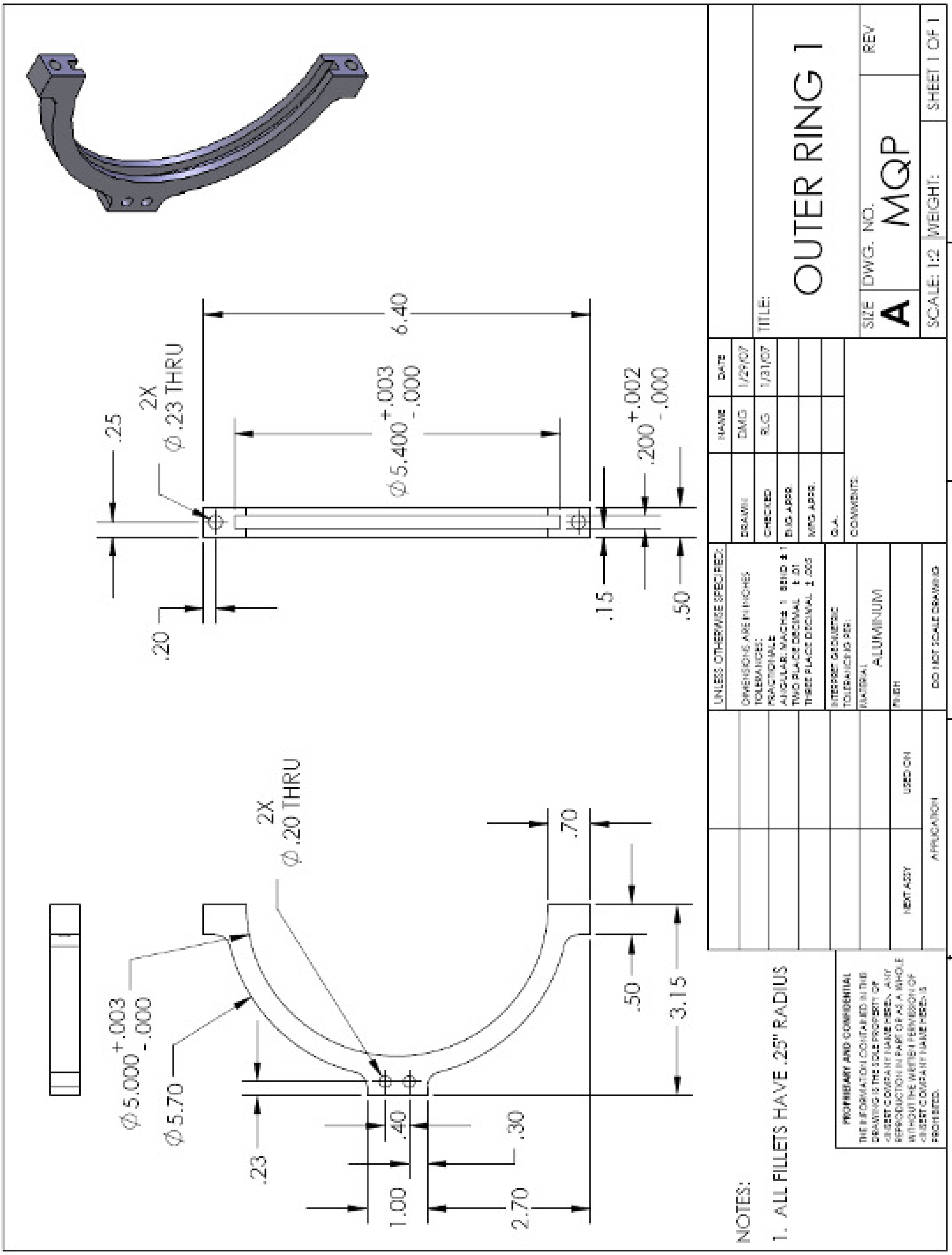
	Weight	Ski Binding	Pin	Pressure	Screw Clamps	Velcro	Climbing Harness
Key Performance	**0.25**	**0.23**	**0.22**	**0.20**	**0.21**	**0.21**	**0.19**
Accomodation		1.00	0.80	1.00	1.00	1.00	1.00
Required Work		0.80	0.90	0.80	0.65	0.70	0.70
Stability		0.90	0.85	0.70	0.85	0.85	0.70
Load Capacity		0.90	0.90	0.75	0.90	0.80	0.70
Total	1	0.90	0.86	0.81	0.85	0.84	0.78
Safety	**0.15**	**0.12**	**0.13**	**0.14**	**0.11**	**0.15**	**0.14**
Edges		0.85	0.85	0.95	0.70	1.00	0.90
Pinch Points		0.70	0.85	0.90	0.70	0.95	0.90
Total	1	0.78	0.85	0.93	0.70	0.98	0.90
User Friendliness	**0.25**	**0.23**	**0.21**	**0.21**	**0.19**	**0.23**	**0.23**
Adjustability		0.90	0.75	0.95	0.90	0.95	0.95
Ease of Don/Doff		0.95	0.85	0.85	0.70	0.90	0.85
Aesthetics		0.85	0.95	0.70	0.70	0.90	0.90
Total	1	0.90	0.85	0.83	0.77	0.92	0.90
Reliability	**0.20**	**0.18**	**0.18**	**0.17**	**0.17**	**0.16**	**0.16**
Fatigue		0.85	0.85	0.70	0.80	0.70	0.70
Shock		0.90	0.90	0.90	0.85	1.00	1.00
Weather		0.90	0.90	0.90	0.85	0.70	0.70
Washable		0.90	0.90	0.90	0.90	0.70	0.70
Total	1	0.89	0.89	0.85	0.85	0.78	0.78
Cost	**0.15**	**0.14**	**0.13**	**0.08**	**0.12**	**0.11**	**0.11**
Materials		0.90	0.80	0.40	0.75	0.80	0.80
Maintenance		0.90	0.90	0.70	0.80	0.60	0.60
Total	1	0.90	0.85	0.55	0.78	0.70	0.70
Grand Total		**0.88**	**0.86**	**0.80**	**0.80**	**0.84**	**0.81**

Mechanism Decision Matrix

	Weight	Rear Scapula Mount	Front Scapula Mount	5DOF Exo	Strings
Key Performance	**0.25**	**0.20**	**0.20**	**0.18**	**0.24**
Required Work		0.60	0.80	0.40	0.95
Range of Motion		1.00	0.80	1.00	1.00
Total	1	0.80	0.80	0.70	0.98
Safety	**0.15**	**0.14**	**0.12**	**0.11**	**0.14**
Edges		0.90	0.80	0.70	1.00
Pinch Points		0.90	0.80	0.70	0.90
Total	1	0.90	0.80	0.70	0.95
User Friendliness	**0.25**	**0.20**	**0.18**	**0.17**	**0.22**
Adjustability		0.90	0.70	0.90	0.95
Ease of Don/Doff		0.75	0.90	0.50	0.90
Aesthetics		0.75	0.60	0.60	0.80
Total	1	0.80	0.73	0.67	0.88
Reliability	**0.20**	**0.16**	**0.16**	**0.14**	**0.18**
Fatigue		0.80	0.80	0.60	0.80
Shock		0.80	0.80	0.80	1.00
Total	1	0.80	0.80	0.70	0.90
Cost	**0.15**	**0.10**	**0.10**	**0.08**	**0.13**
Materials		0.70	0.70	0.50	0.90
Manufacturing		0.70	0.70	0.50	0.90
Maintenance		0.60	0.60	0.50	0.80
Total	1	0.67	0.67	0.50	0.87
		0.80	**0.76**	**0.66**	**0.92**

APPENDIX B – Dimensioned Drawings




2X
Ø .23 THRU
.25
Ø 5.400 +.003 -.000
6.40
.200 +.002 -.000
.15
.50
.20
2X
Ø .20 THRU
.70
.50
3.15
Ø 5.000 +.003 -.000
Ø 5.70
.23
.40
.30
1.00
2.70
NOTES:
1. ALL FILLETS HAVE .25" RADIUS
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± 1 BEND ± 1
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
ALUMINUM
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
NAME
DATE
DRAWN
DMG
1/29/07
CHECKED
RJG
1/31/07
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
OUTER RING 1
SIZE
A
DWG. NO.
MQP
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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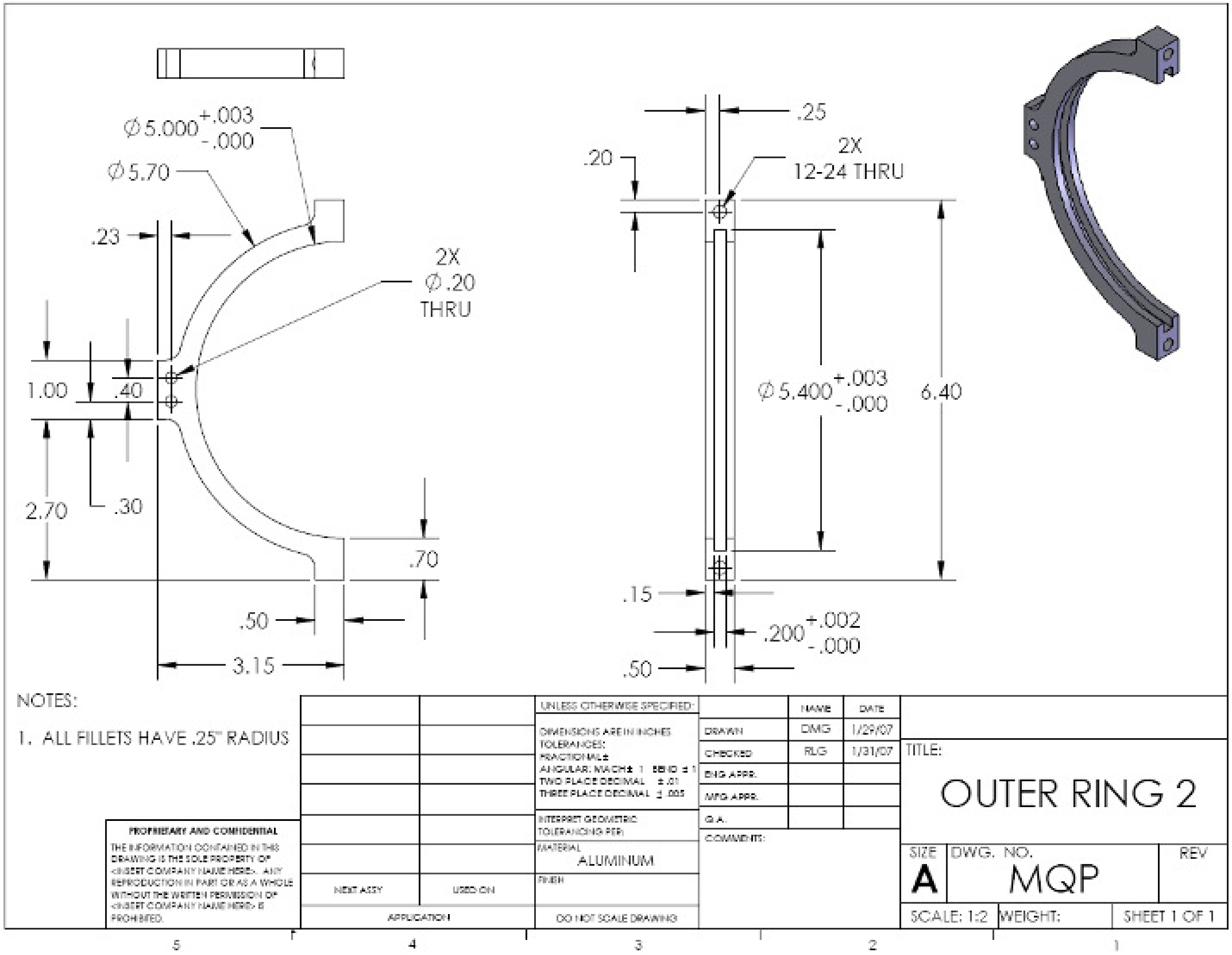
5
4
3
2
1


Ø5.000 +.003 -.000
Ø5.70
.23
2X
Ø.20
THRU
1.00
.40
.30
2.70
.70
.50
3.15
.25
.20
2X
12-24 THRU
Ø5.400 +.003 -.000
6.40
.15
.200 +.002 -.000
.50
NOTES:
1. ALL FILLETS HAVE .25" RADIUS
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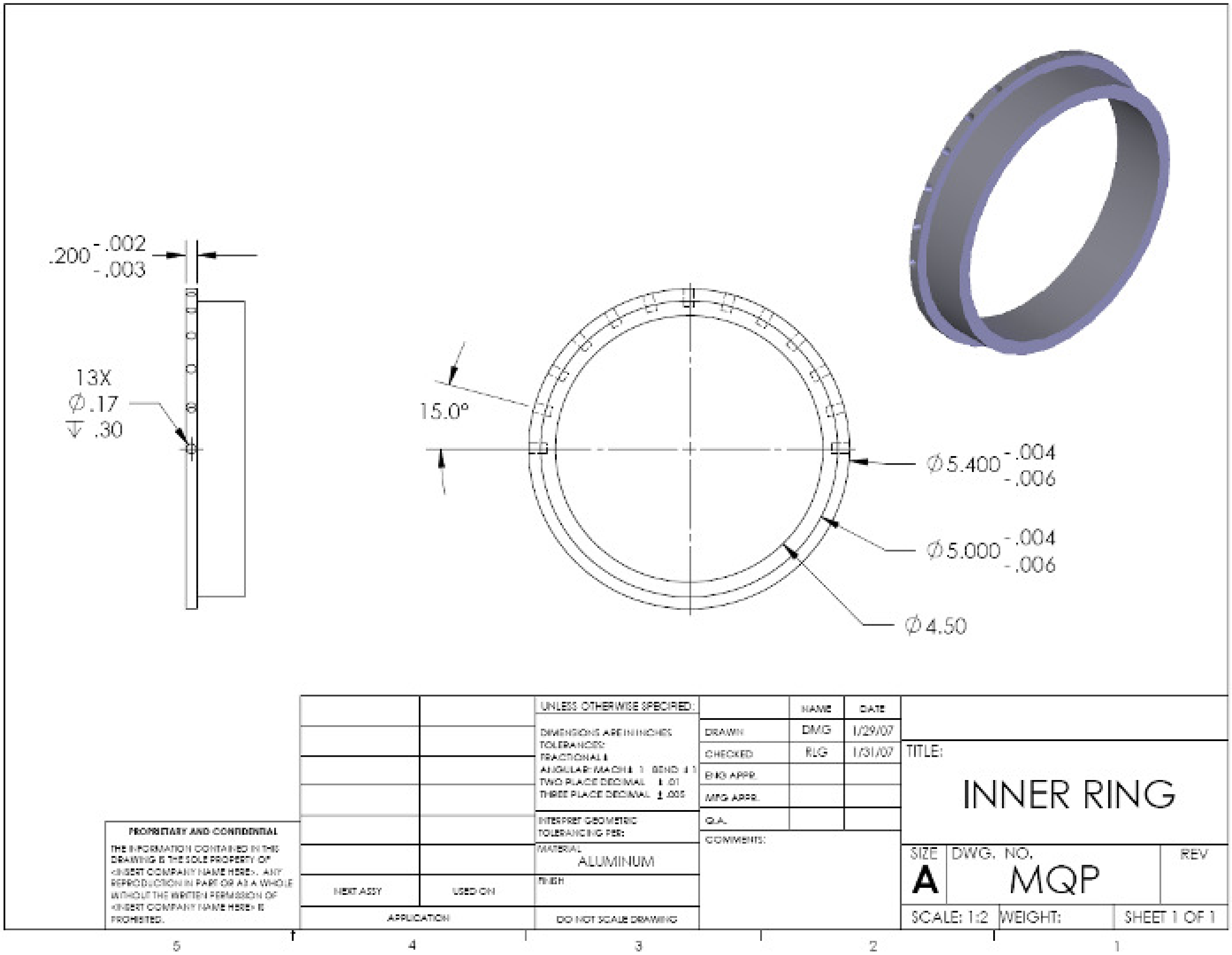
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± 1 BEND ± 1
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
ALUMINUM
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
DMG
1/29/07
CHECKED
RLG
1/31/07
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
OUTER RING 2
SIZE
A
DWG. NO.
MQP
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1


.200 -.002 -.003
13X
⌀.17
↧ .30
15.0°
⌀5.400 -.004 -.006
⌀5.000 -.004 -.006
⌀4.50
PROPRIETARY AND CONFIDENTIAL
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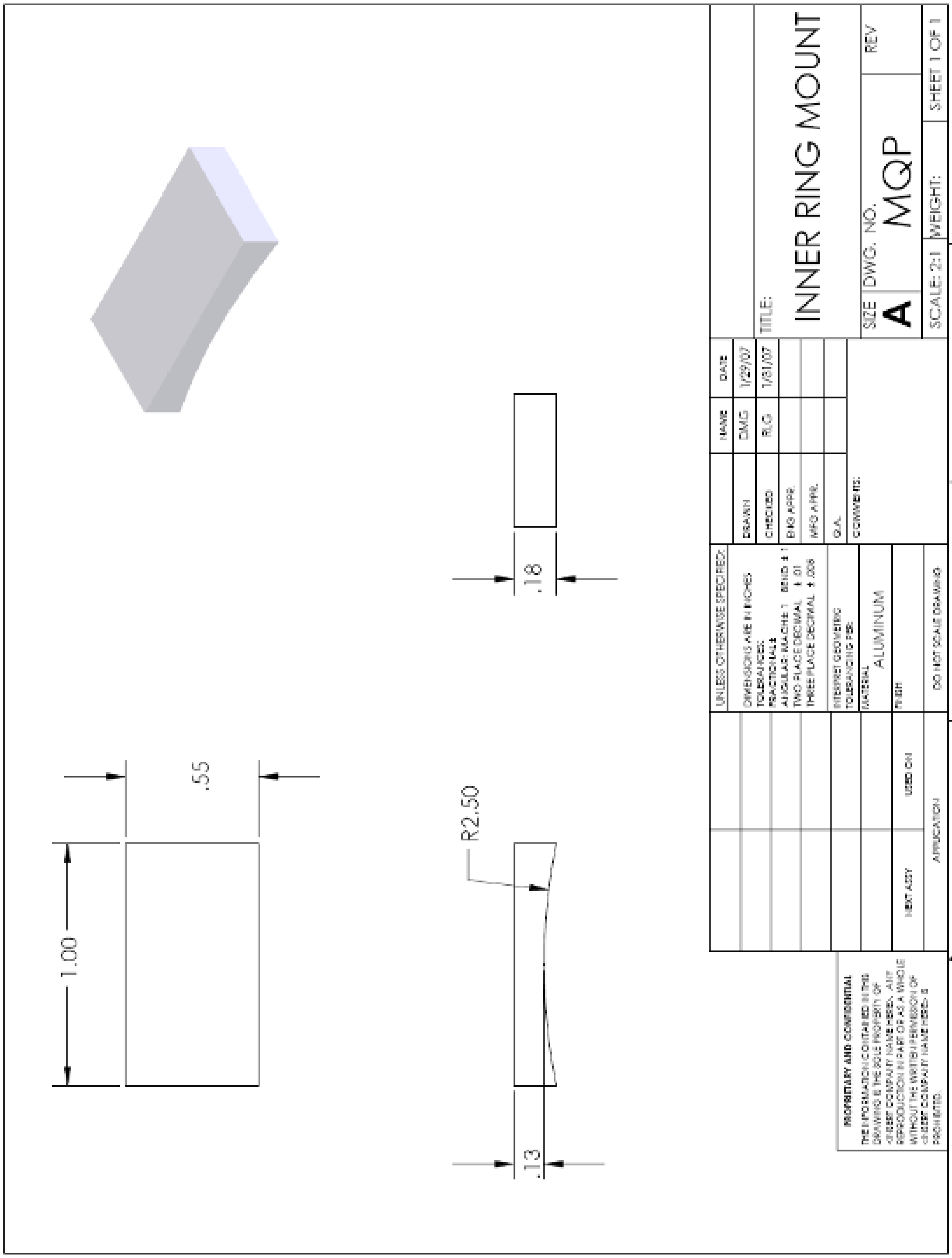
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± 1 BEND ± 1
TWO PLACE DECIMAL ± .01
THREE PLACE DECIMAL ± .005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
ALUMINUM
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
DMG
1/29/07
CHECKED
RLG
1/31/07
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
INNER RING
SIZE
A
DWG. NO.
MQP
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1


1.00
.55
R2.50
.18
.13
TITLE:
INNER RING MOUNT
SIZE
A
DWG. NO.
MQP
REV
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1
NAME
DATE
DRAWN
DMG
1/29/07
CHECKED
RLG
1/31/07
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± 1 BEND ± 1
TWO PLACE DECIMAL ± .01
THREE PLACE DECIMAL ± .005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
ALUMINUM
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
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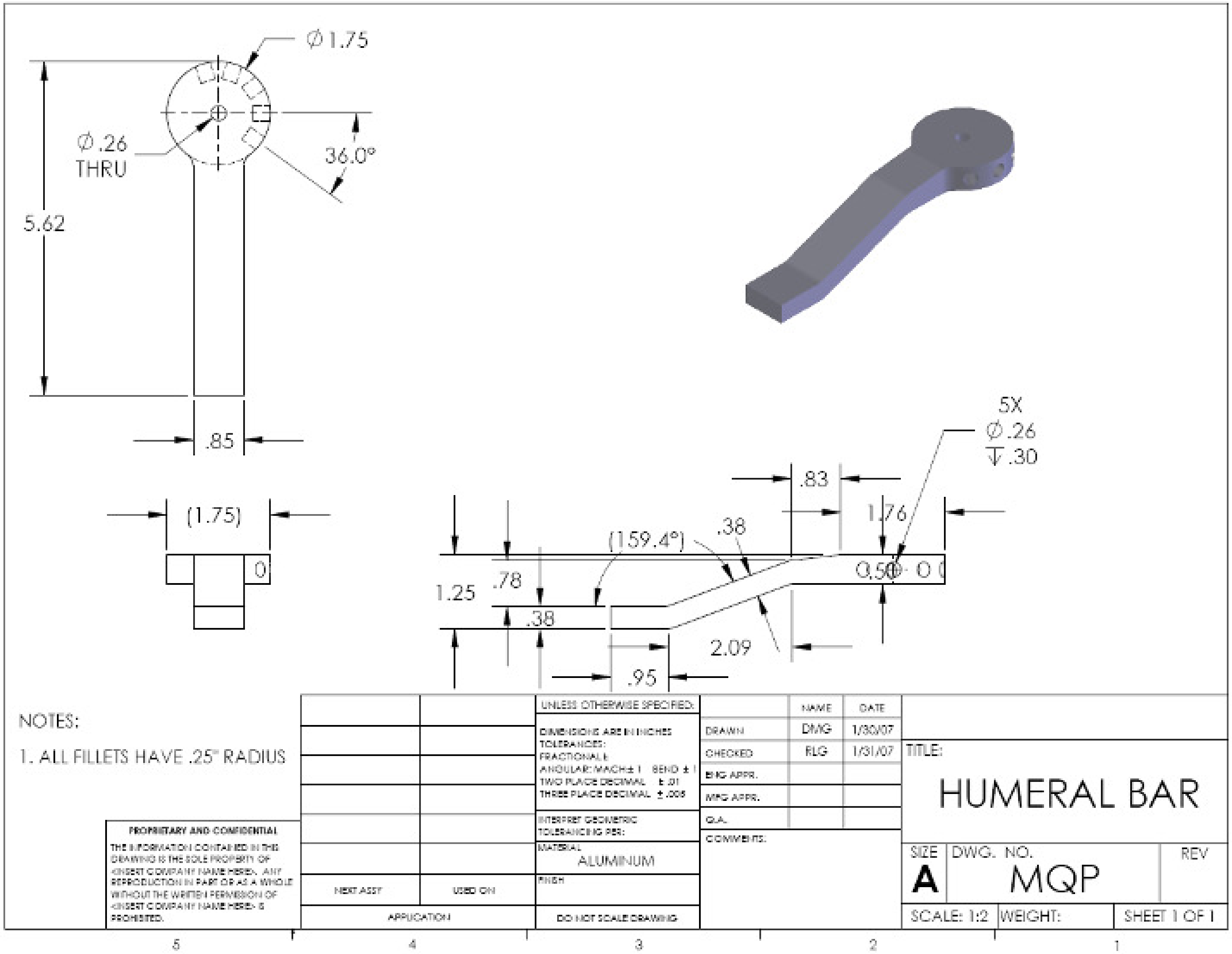
1
2
3
4
5


Ø1.75
Ø.26
THRU
36.0°
5.62
.85
(1.75)
0
5X
Ø.26
↧.30
.83
1.76
.38
(159.4°)
0.50
1.25
.78
.38
2.09
.95
NOTES:
1. ALL FILLETS HAVE .25" RADIUS
PROPRIETARY AND CONFIDENTIAL
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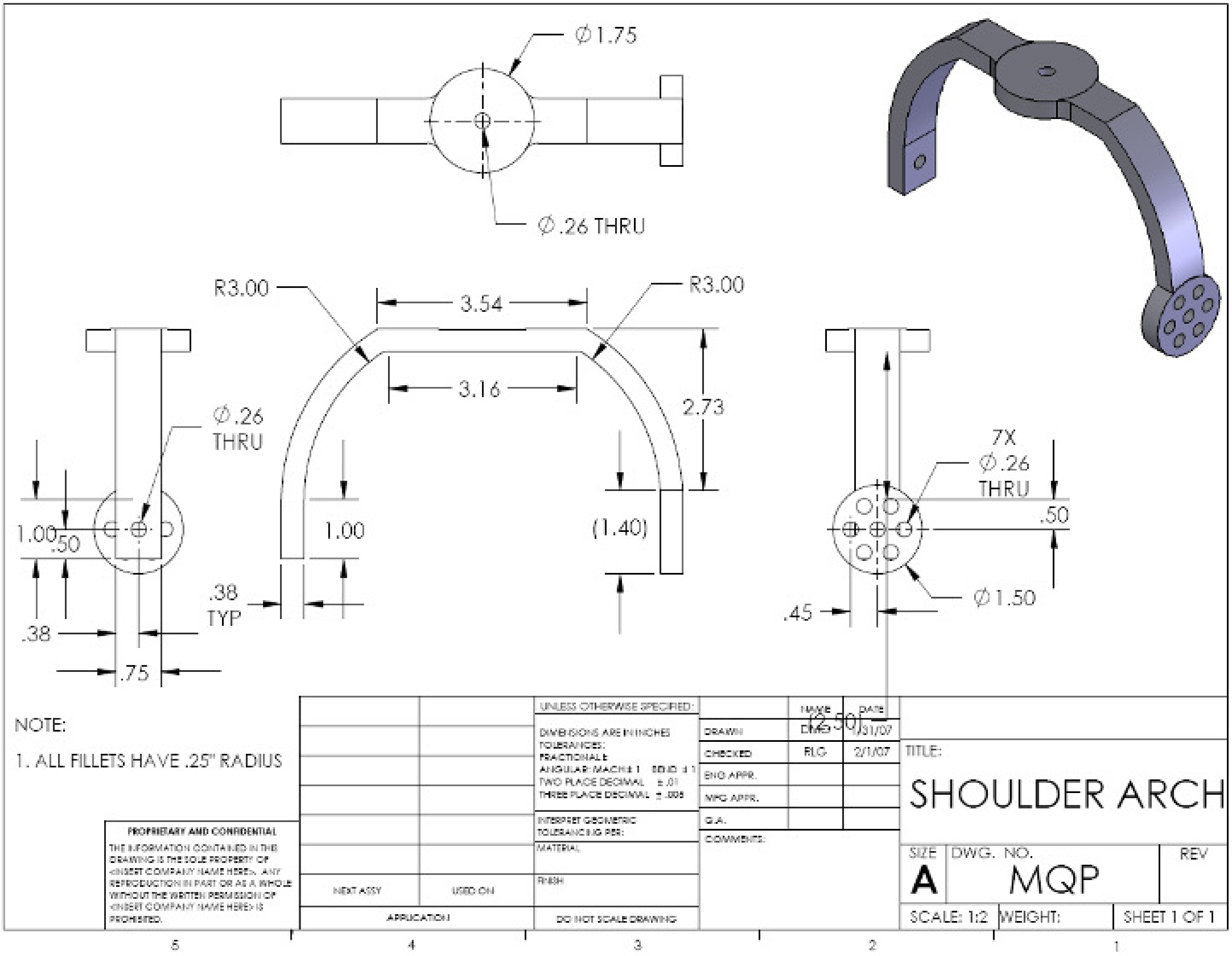
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± 1 BEND ± 1
TWO PLACE DECIMAL ± .01
THREE PLACE DECIMAL ± .005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
ALUMINUM
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
DMG
1/30/07
CHECKED
RLG
1/31/07
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
HUMERAL BAR
SIZE
A
DWG. NO.
MQP
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1


Ø1.75
Ø.26 THRU
R3.00
3.54
R3.00
3.16
2.73
Ø.26
THRU
1.00
.50
1.00
(1.40)
.38
TYP
.38
.75
7X
Ø.26
THRU
.50
Ø1.50
.45
(2.50)
NOTE:
1. ALL FILLETS HAVE .25" RADIUS
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.
NEXT ASSY
USED ON
APPLICATION
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± 1 BEND ± 1
TWO PLACE DECIMAL ± .01
THREE PLACE DECIMAL ± .005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
DMG
1/31/07
CHECKED
RLG
2/1/07
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
SHOULDER ARCH
SIZE
A
DWG. NO.
MQP
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1

APPENDIX C – Free Body Diagrams & MathCAD Programs

Map of Free Body Diagram Points

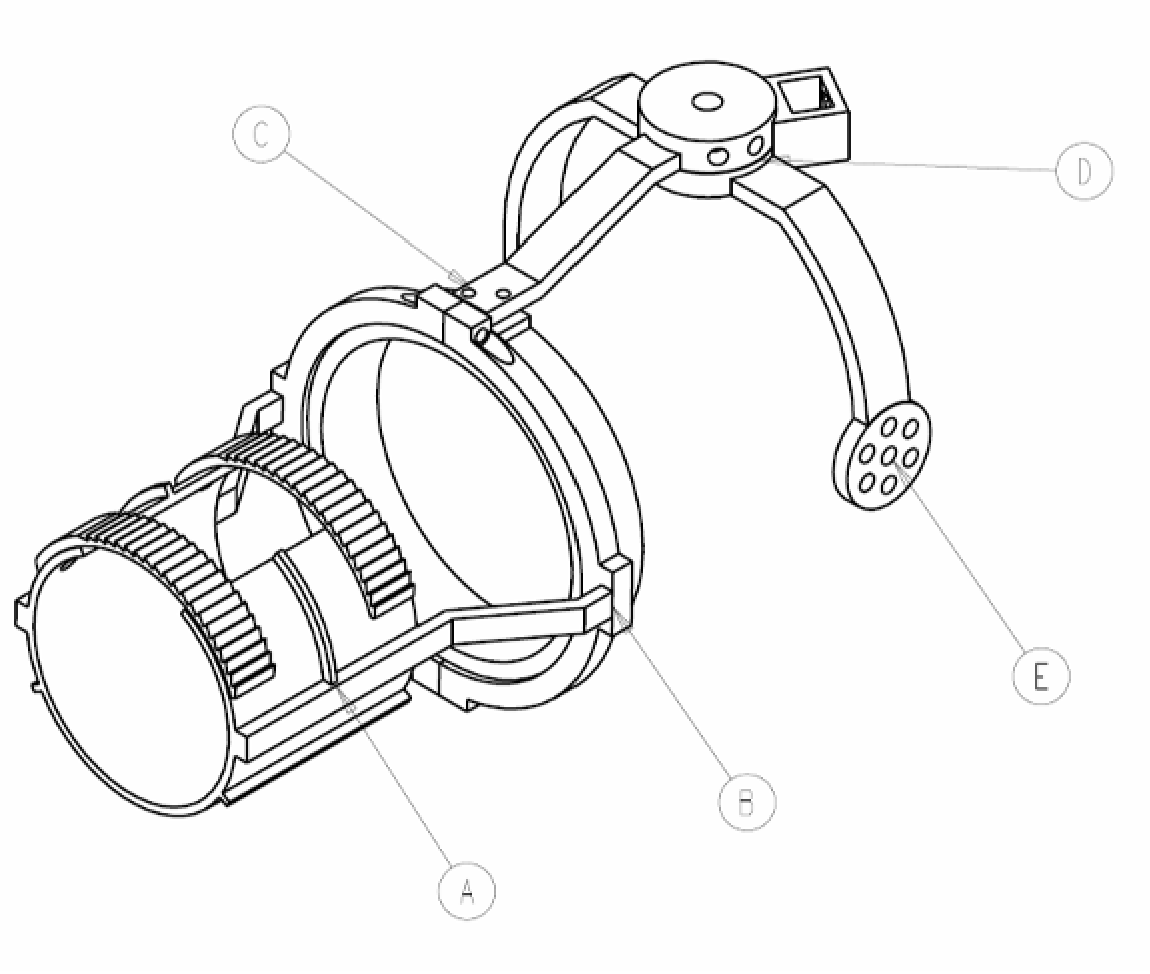
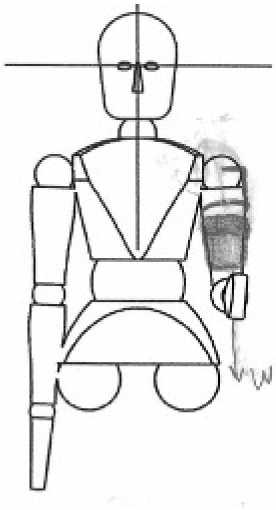
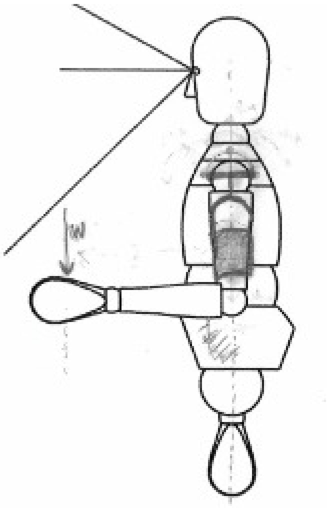


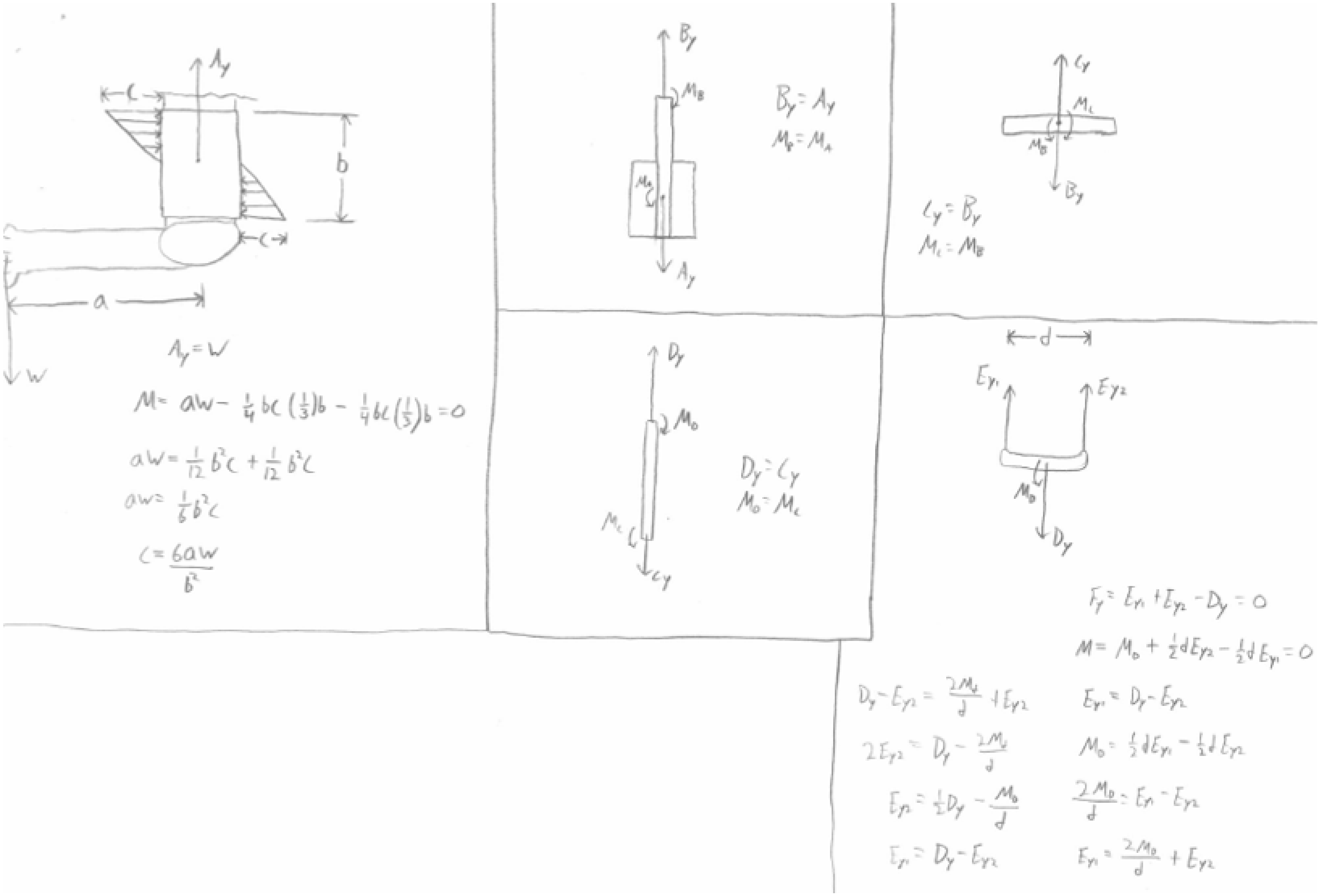
Figure 85 - Map of Free Body Diagram Points

Position 1





Side View



$$A_y = W$$

$$M = aW - \frac{1}{4}bc\left(\frac{1}{3}\right)b - \frac{1}{4}bc\left(\frac{1}{3}\right)b = 0$$

$$aW = \frac{1}{12}b^2c + \frac{1}{12}b^2c$$

$$aw = \frac{1}{6}b^2c$$

$$c = \frac{6aw}{b^2}$$

$$B_y = A_y$$

$$M_B = M_A$$

$$C_y = B_y$$

$$M_C = M_B$$

$$D_y = C_y$$

$$M_D = M_C$$

$$F_y = E_{y1} + E_{y2} - D_y = 0$$

$$M = M_D + \frac{1}{2}dE_{y2} - \frac{1}{2}dE_{y1} = 0$$

$$E_{y1} = D_y - E_{y2}$$

$$M_D = \frac{1}{2}dE_{y1} - \frac{1}{2}dE_{y2}$$

$$\frac{2M_D}{d} = E_{y1} - E_{y2}$$

$$E_{y1} = \frac{2M_D}{d} + E_{y2}$$

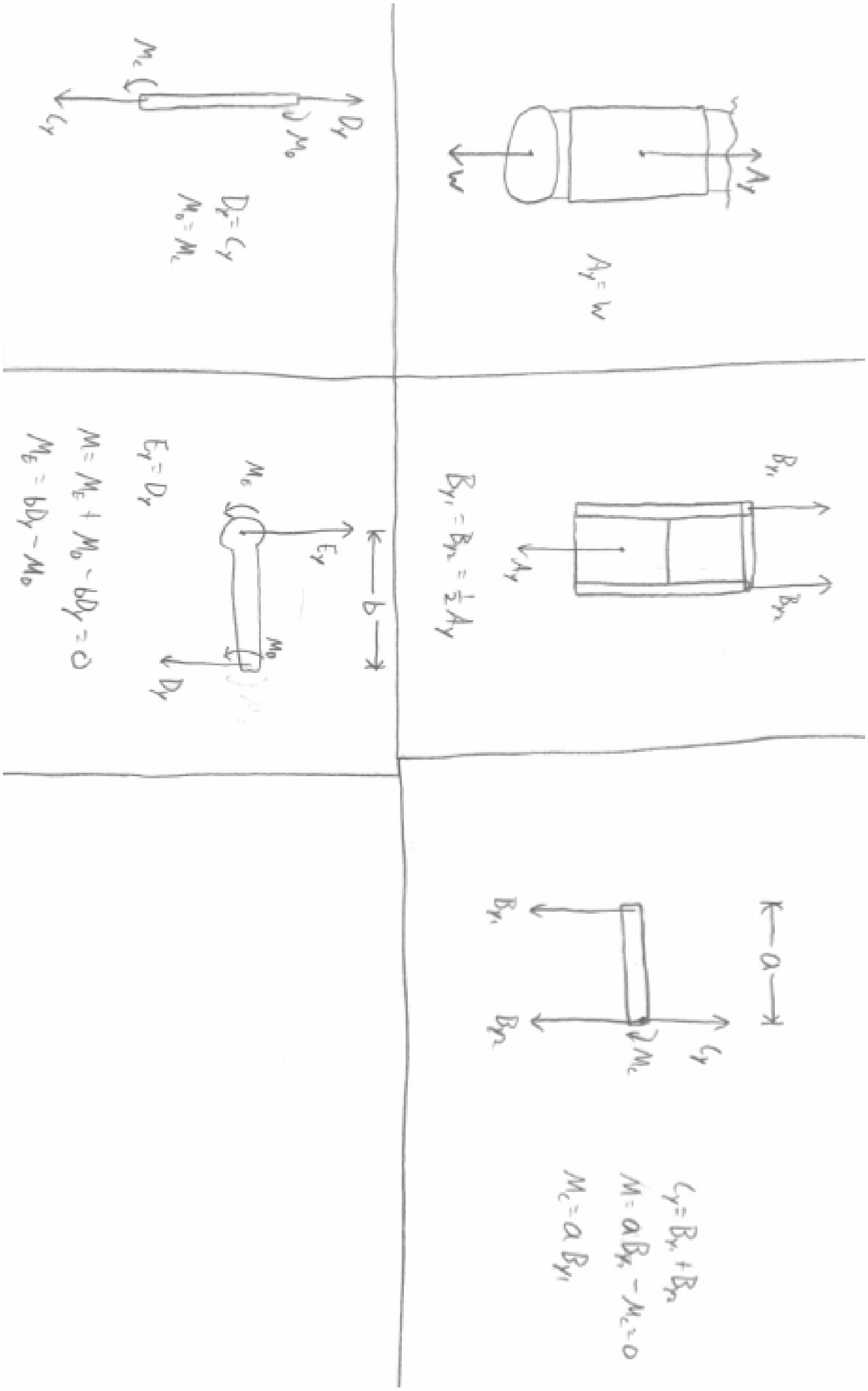
$$D_y - E_{y2} = \frac{2M_D}{d} + E_{y2}$$

$$2E_{y2} = D_y - \frac{2M_D}{d}$$

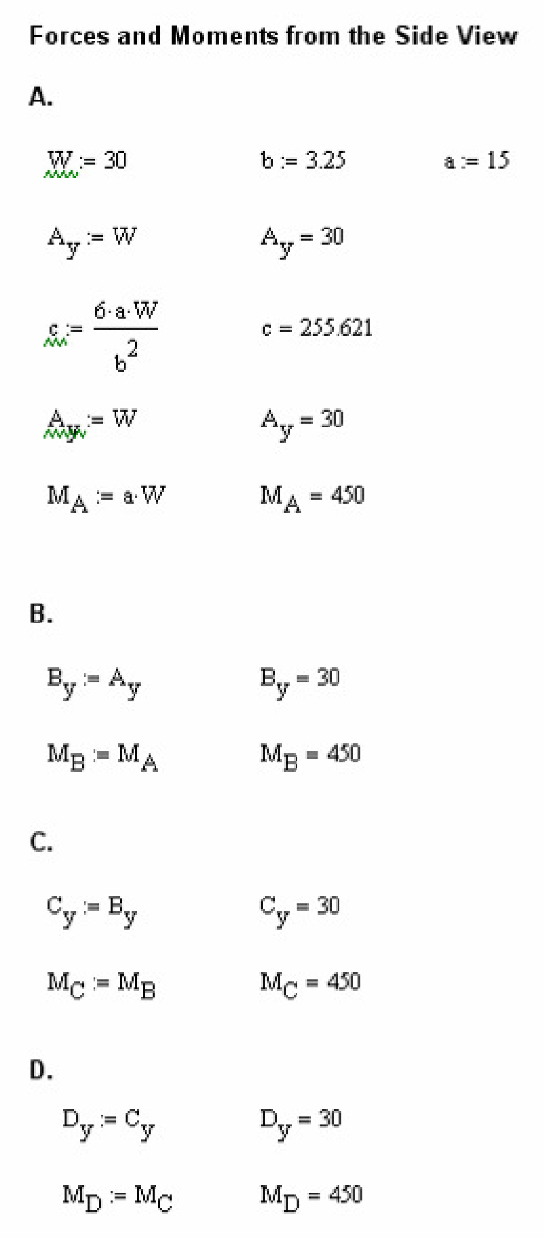
$$E_{y2} = \frac{1}{2}D_y - \frac{M_D}{d}$$

$$E_{y1} = D_y - E_{y2}$$

Front View


A_y
W
$A_y = W$
B_{y1}
B_{y2}
A_y
$B_{y1} = B_{y2} = \frac{1}{2} A_y$
a
C_y
M_c
B_{y1}
B_{y2}
$C_y = B_{y1} + B_{y2}$
$M = aB_{y1} - M_c = 0$
$M_c = a B_{y1}$
D_y
M_D
M_c
C_y
$D_y = C_y$
$M_D = M_c$
b
E_y
M_E
M_D
D_y
$E_y = D_y$
$M = M_E + M_D - bD_y = 0$
$M_E = bD_y - M_D$

MathCAD Program



Forces and Moments from the Side View

A.

$W := 30$ $b := 3.25$ $a := 15$

$A_y := W$ $A_y = 30$

$c := \frac{6 \cdot a \cdot W}{b^2}$ $c = 255.621$

$A_y := W$ $A_y = 30$

$M_A := a \cdot W$ $M_A = 450$

B.

$B_y := A_y$ $B_y = 30$

$M_B := M_A$ $M_B = 450$

C.

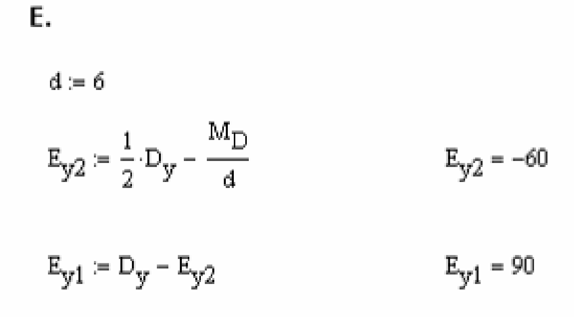
$C_y := B_y$ $C_y = 30$

$M_C := M_B$ $M_C = 450$

D.

$D_y := C_y$ $D_y = 30$

$M_D := M_C$ $M_D = 450$

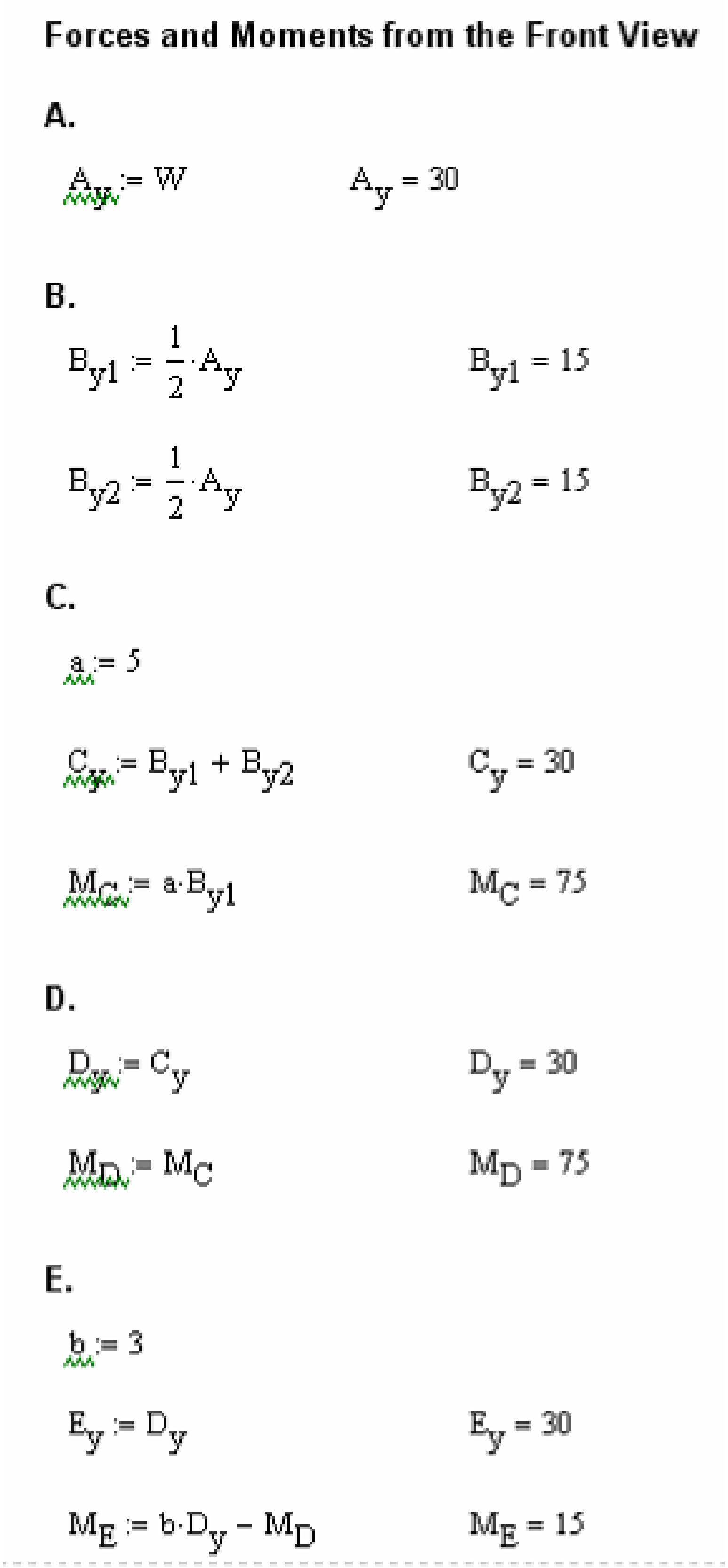


E.

$d := 6$

$E_{y2} := \frac{1}{2} \cdot D_y - \frac{M_D}{d}$ $E_{y2} = -60$

$E_{y1} := D_y - E_{y2}$ $E_{y1} = 90$



Forces and Moments from the Front View

A.

$A_y := W$ $\quad A_y = 30$

B.

$B_{y1} := \frac{1}{2} \cdot A_y$ $\quad B_{y1} = 15$

$B_{y2} := \frac{1}{2} \cdot A_y$ $\quad B_{y2} = 15$

C.

$a := 5$

$C_y := B_{y1} + B_{y2}$ $\quad C_y = 30$

$M_C := a \cdot B_{y1}$ $\quad M_C = 75$

D.

$D_y := C_y$ $\quad D_y = 30$

$M_D := M_C$ $\quad M_D = 75$

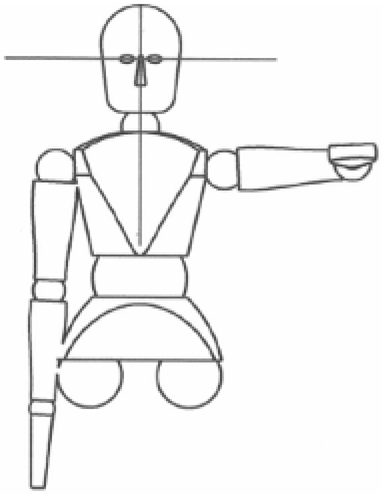
E.

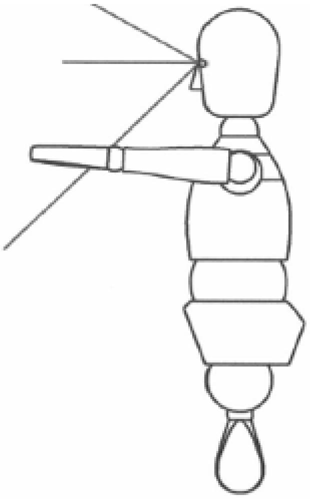
$b := 3$

$E_y := D_y$ $\quad E_y = 30$

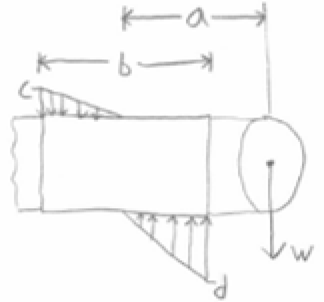
$M_E := b \cdot D_y - M_D$ $\quad M_E = 15$

Position 2





Front View



$F_y = \frac{1}{2}(\frac{1}{2})bd - \frac{1}{2}(\frac{1}{2})bc - w = 0$

$\frac{1}{4}b(d-c) = w$

$d - c = \frac{4w}{b}$

$M = \frac{1}{2}(\frac{1}{2})bc(\frac{1}{3})b + \frac{1}{2}(\frac{1}{2})bd(\frac{1}{3})b - aw = 0$

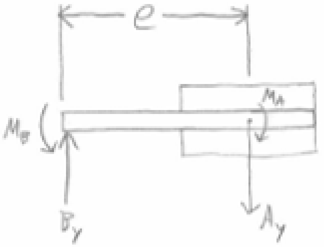
$\frac{1}{12}b^2c + \frac{1}{12}b^2d = aw$

$c + d = \frac{12aw}{b^2}$

$2d = \frac{4w}{b} + \frac{12aw}{b^2}$

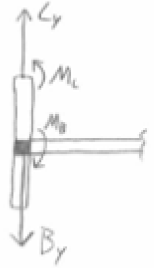
$d = \frac{2w}{b} + \frac{6aw}{b^2}$

$c = d - \frac{4w}{b}$



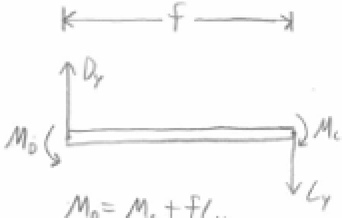
$B_y = A_y$

$M_B = M_A + A_y e$



$M_C = M_B$

$C_y = B_y$



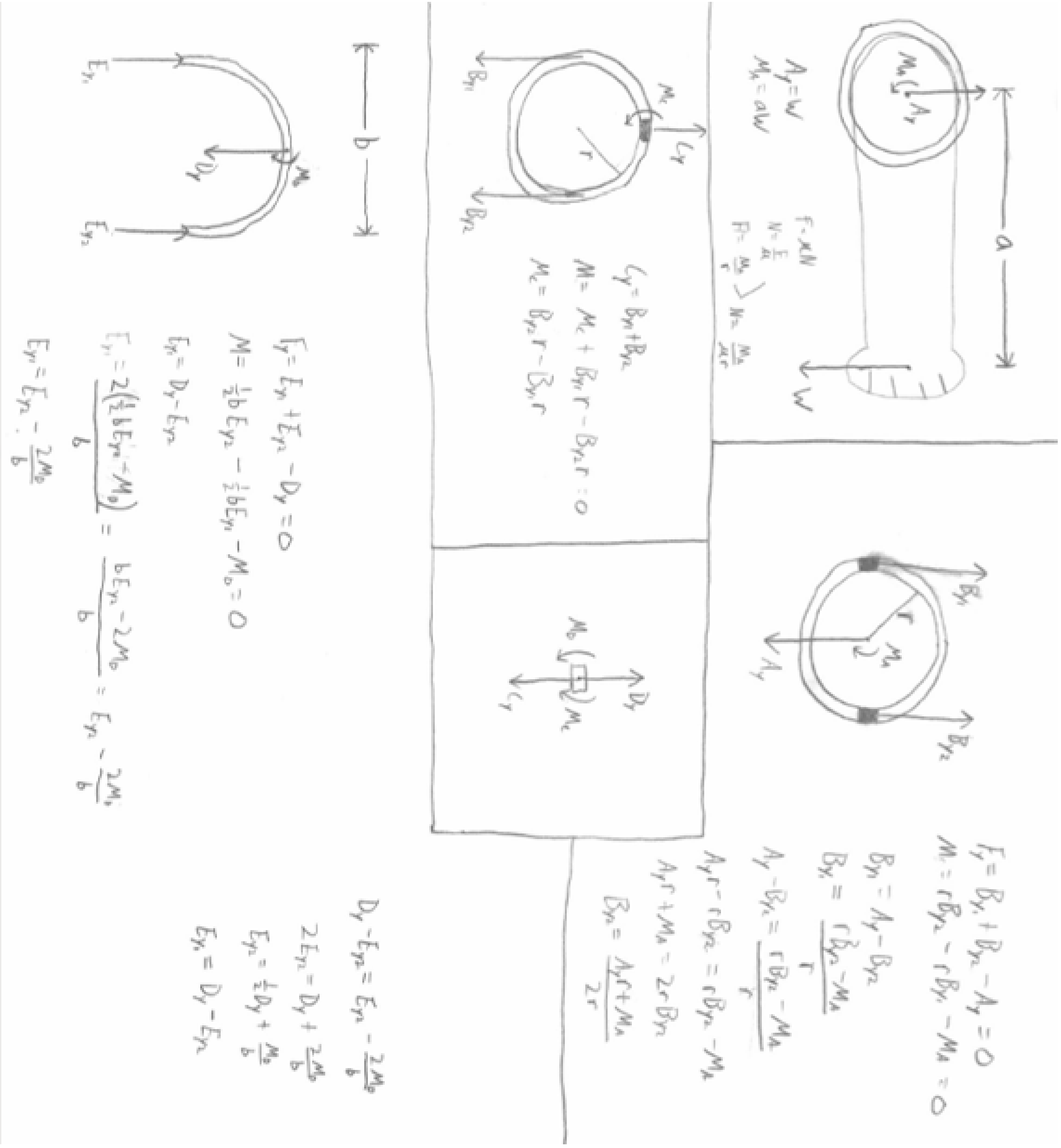
$M_D = M_C + fC_y$

$D_y = C_y$

$M_E = M_D$

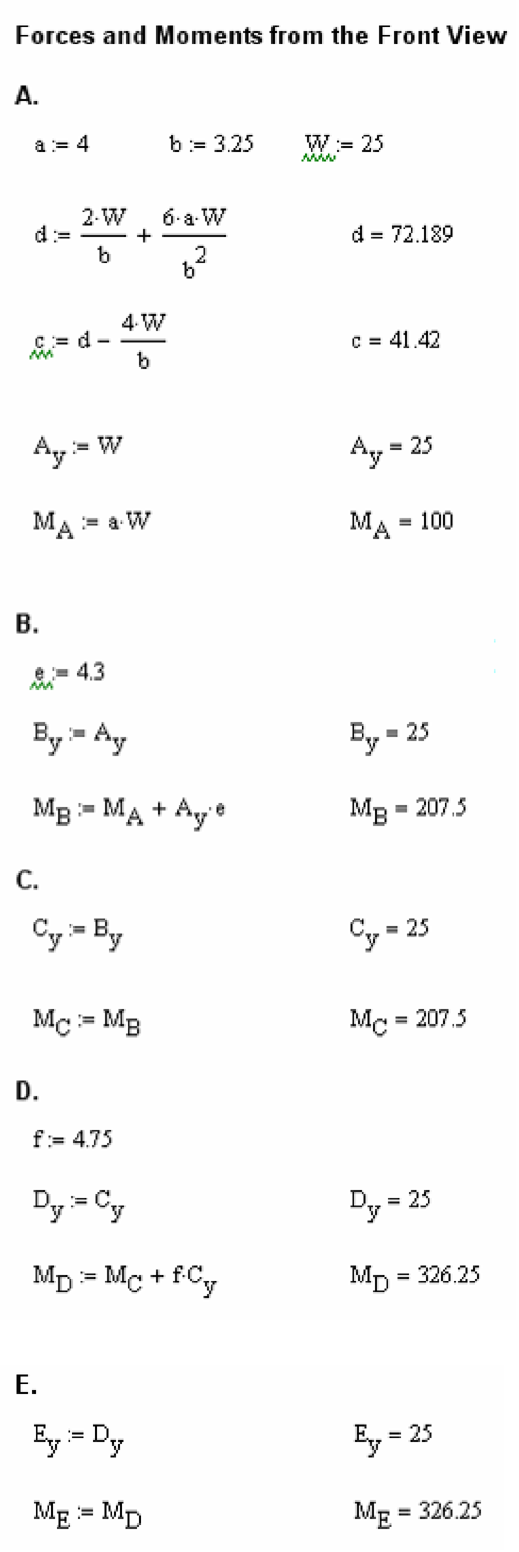
$E_y = D_y$

Side View



a
M_A
A_y
W
$A_y = W$
$M_A = aW$
$F = \mu N$
$N = \frac{F}{\mu}$
$F = \frac{M_A}{r}$
$N = \frac{M_A}{\mu r}$
B_{y1}
B_{y2}
r
M_A
A_y
$F_y = B_{y1} + B_{y2} - A_y = 0$
$M = rB_{y2} - rB_{y1} - M_A = 0$
$B_{y1} = A_y - B_{y2}$
$B_{y1} = \frac{rB_{y2} - M_A}{r}$
$A_y - B_{y2} = \frac{rB_{y2} - M_A}{r}$
$A_y r - rB_{y2} = rB_{y2} - M_A$
$A_y r + M_A = 2rB_{y2}$
$B_{y2} = \frac{A_y r + M_A}{2r}$
M_c
C_y
r
B_{y1}
B_{y2}
$C_y = B_{y1} + B_{y2}$
$M = M_c + B_{y1} r - B_{y2} r = 0$
$M_c = B_{y2} r - B_{y1} r$
D_y
M_D
M_c
C_y
b
M_D
D_y
E_{y1}
E_{y2}
$F_y = E_{y1} + E_{y2} - D_y = 0$
$M = \frac{1}{2}bE_{y2} - \frac{1}{2}bE_{y1} - M_D = 0$
$E_{y1} = D_y - E_{y2}$
$E_{y1} = \frac{2(\frac{1}{2}bE_{y2} - M_D)}{b} = \frac{bE_{y2} - 2M_D}{b} = E_{y2} - \frac{2M_D}{b}$
$E_{y1} = E_{y2} - \frac{2M_D}{b}$
$D_y - E_{y2} = E_{y2} - \frac{2M_D}{b}$
$2E_{y2} = D_y + \frac{2M_D}{b}$
$E_{y2} = \frac{1}{2}D_y + \frac{M_D}{b}$
$E_{y1} = D_y - E_{y2}$

MathCAD Program



Forces and Moments from the Front View

A.

$a := 4$ $b := 3.25$ $W := 25$

$d := \frac{2 \cdot W}{b} + \frac{6 \cdot a \cdot W}{b^2}$ $d = 72.189$

$c := d - \frac{4 \cdot W}{b}$ $c = 41.42$

$A_y := W$ $A_y = 25$

$M_A := a \cdot W$ $M_A = 100$

B.

$e := 4.3$

$B_y := A_y$ $B_y = 25$

$M_B := M_A + A_y \cdot e$ $M_B = 207.5$

C.

$C_y := B_y$ $C_y = 25$

$M_C := M_B$ $M_C = 207.5$

D.

$f := 4.75$

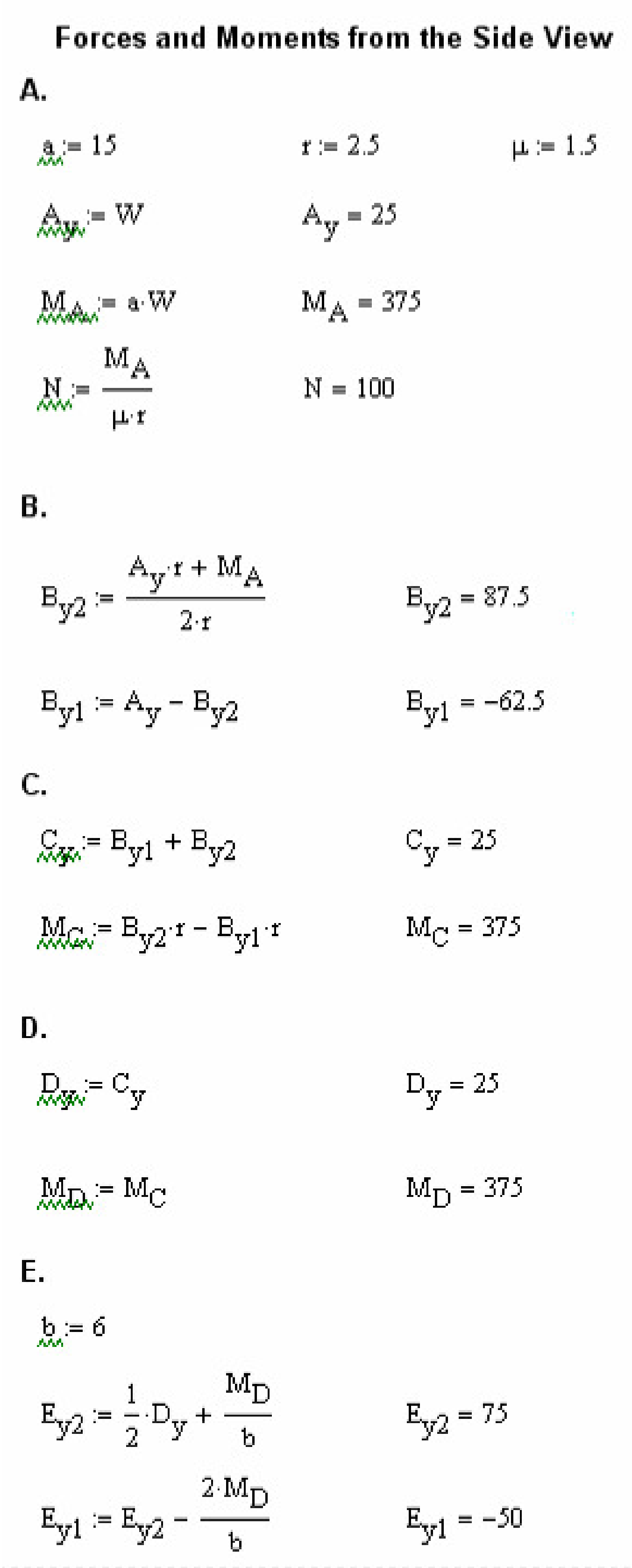
$D_y := C_y$ $D_y = 25$

$M_D := M_C + f \cdot C_y$ $M_D = 326.25$

E.

$E_y := D_y$ $E_y = 25$

$M_E := M_D$ $M_E = 326.25$



Forces and Moments from the Side View

A.

$a := 15$ $\quad r := 2.5$ $\quad \mu := 1.5$

$A_y := W$ $\quad A_y = 25$

$M_A := a \cdot W$ $\quad M_A = 375$

$N := \frac{M_A}{\mu \cdot r}$ $\quad N = 100$

B.

$B_{y2} := \frac{A_y \cdot r + M_A}{2 \cdot r}$ $\quad B_{y2} = 87.5$

$B_{y1} := A_y - B_{y2}$ $\quad B_{y1} = -62.5$

C.

$C_y := B_{y1} + B_{y2}$ $\quad C_y = 25$

$M_C := B_{y2} \cdot r - B_{y1} \cdot r$ $\quad M_C = 375$

D.

$D_y := C_y$ $\quad D_y = 25$

$M_D := M_C$ $\quad M_D = 375$

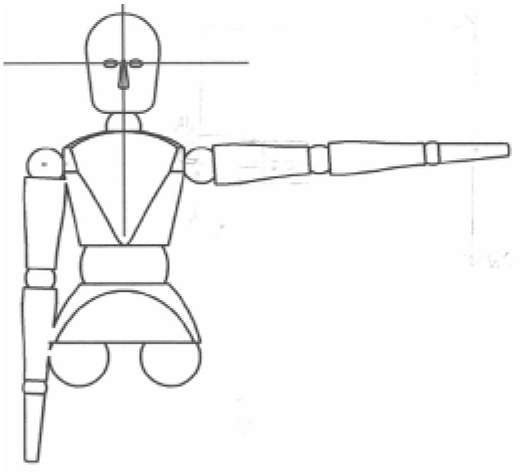
E.

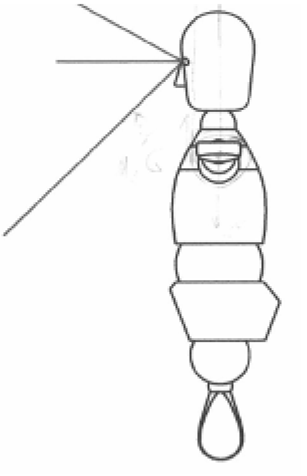
$b := 6$

$E_{y2} := \frac{1}{2} \cdot D_y + \frac{M_D}{b}$ $\quad E_{y2} = 75$

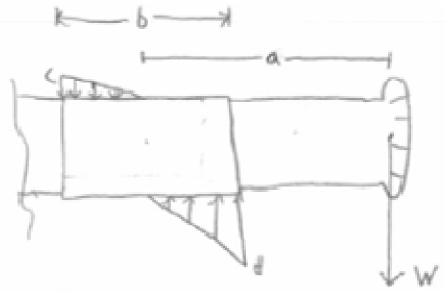
$E_{y1} := E_{y2} - \frac{2 \cdot M_D}{b}$ $\quad E_{y1} = -50$

Position 3





Front View



$F_y = 0 = \left(\frac{1}{2}\right)\left(\frac{1}{2}\right)bd - \frac{1}{4}bc - w$

$\frac{1}{4}bd - \frac{1}{4}bc = w$

$d = \frac{4w}{b} + c$

$M = \frac{1}{4}bd\left(\frac{1}{3}b\right) + \frac{1}{4}bc\left(\frac{1}{3}b\right) - aw = 0$

$\frac{1}{12}b^2d + \frac{1}{12}b^2c = aw$

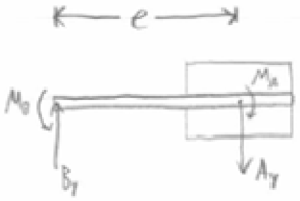
$d = \frac{12aw}{b^2} - c$

$\frac{12aw}{b^2} - c = \frac{4w}{b} + c$

$2c = \frac{12aw}{b^2} - \frac{4w}{b}$

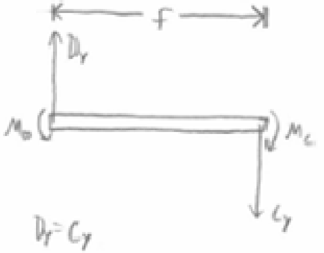
$c = \frac{6aw}{b^2} - \frac{2w}{b}$

$d = \frac{4w}{b} + c$



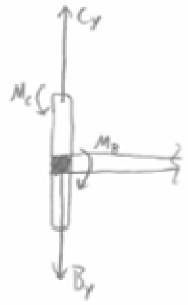
$B_y = A_y$

$M_B = M_A + eA_y$



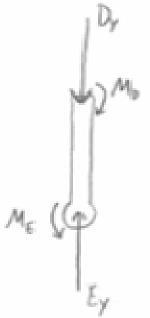
$D_y = C_y$

$M_D = M_C + fC_y$



$M_C = M_B$

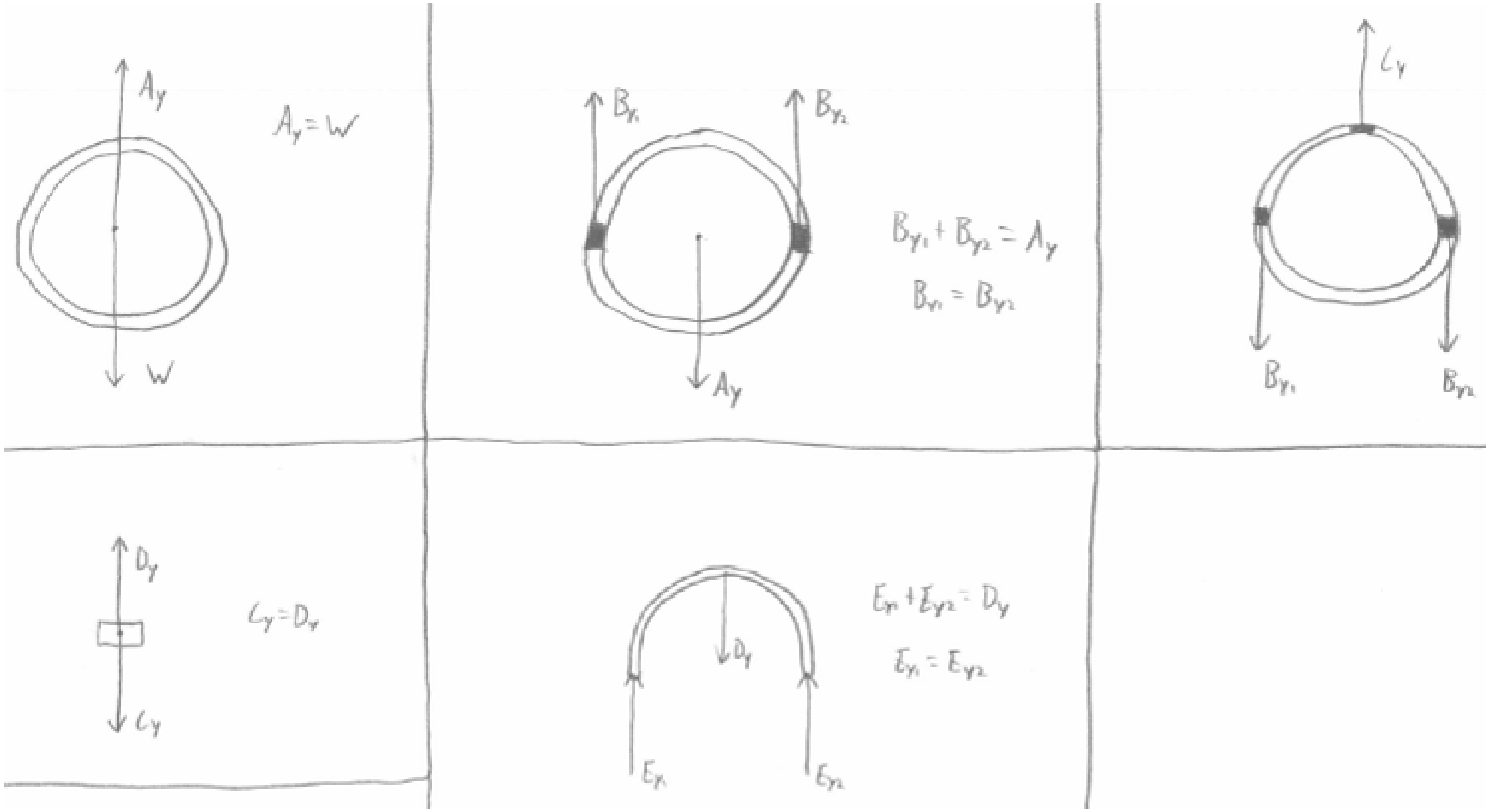
$C_y = B_y$



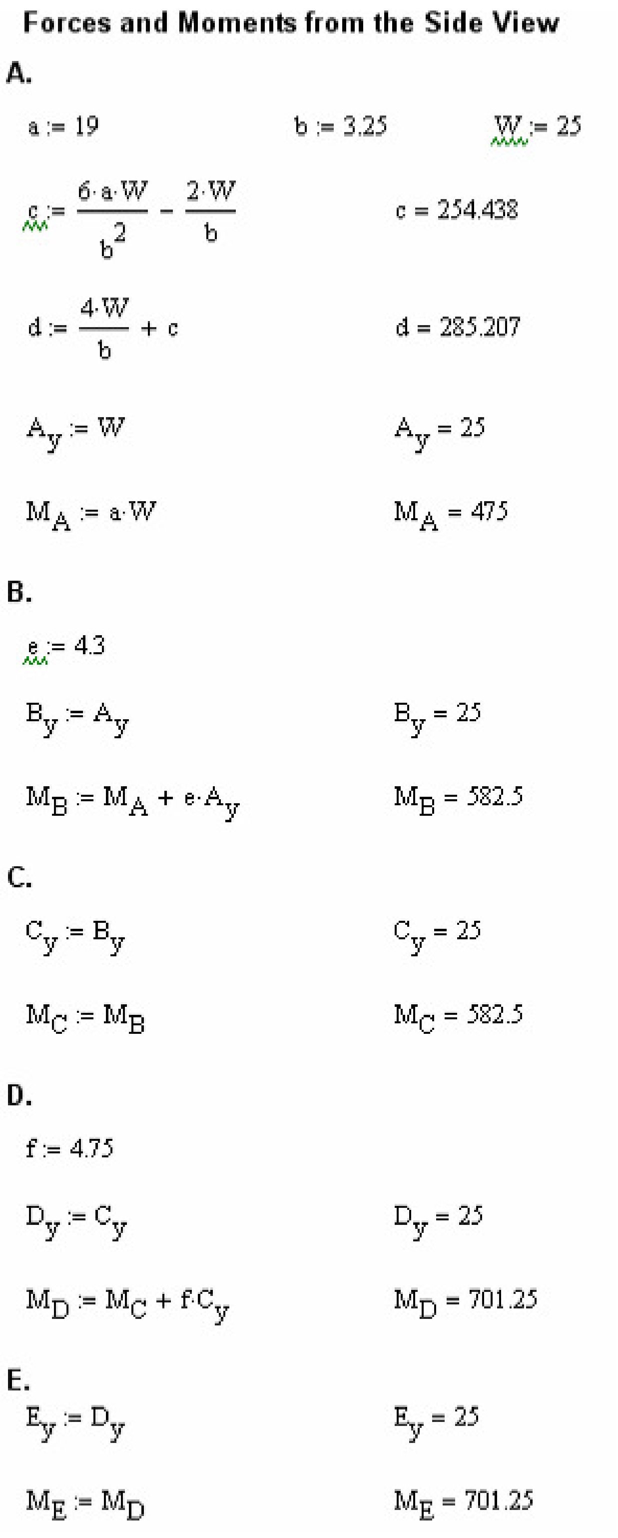
$E_y = D_y$

$M_E = M_D$

Side View


A_y
W
$A_y = W$
B_{y1}
B_{y2}
A_y
$B_{y1} + B_{y2} = A_y$
$B_{y1} = B_{y2}$
C_y
B_{y1}
B_{y2}
D_y
C_y
$C_y = D_y$
D_y
$E_{y1} + E_{y2} = D_y$
$E_{y1} = E_{y2}$
E_{y1}
E_{y2}

MathCAD Program



Forces and Moments from the Side View

A.

$a := 19$ $\quad b := 3.25$ $\quad W := 25$

$c := \frac{6 \cdot a \cdot W}{b^2} - \frac{2 \cdot W}{b}$ $\quad c = 254.438$

$d := \frac{4 \cdot W}{b} + c$ $\quad d = 285.207$

$A_y := W$ $\quad A_y = 25$

$M_A := a \cdot W$ $\quad M_A = 475$

B.

$e := 4.3$

$B_y := A_y$ $\quad B_y = 25$

$M_B := M_A + e \cdot A_y$ $\quad M_B = 582.5$

C.

$C_y := B_y$ $\quad C_y = 25$

$M_C := M_B$ $\quad M_C = 582.5$

D.

$f := 4.75$

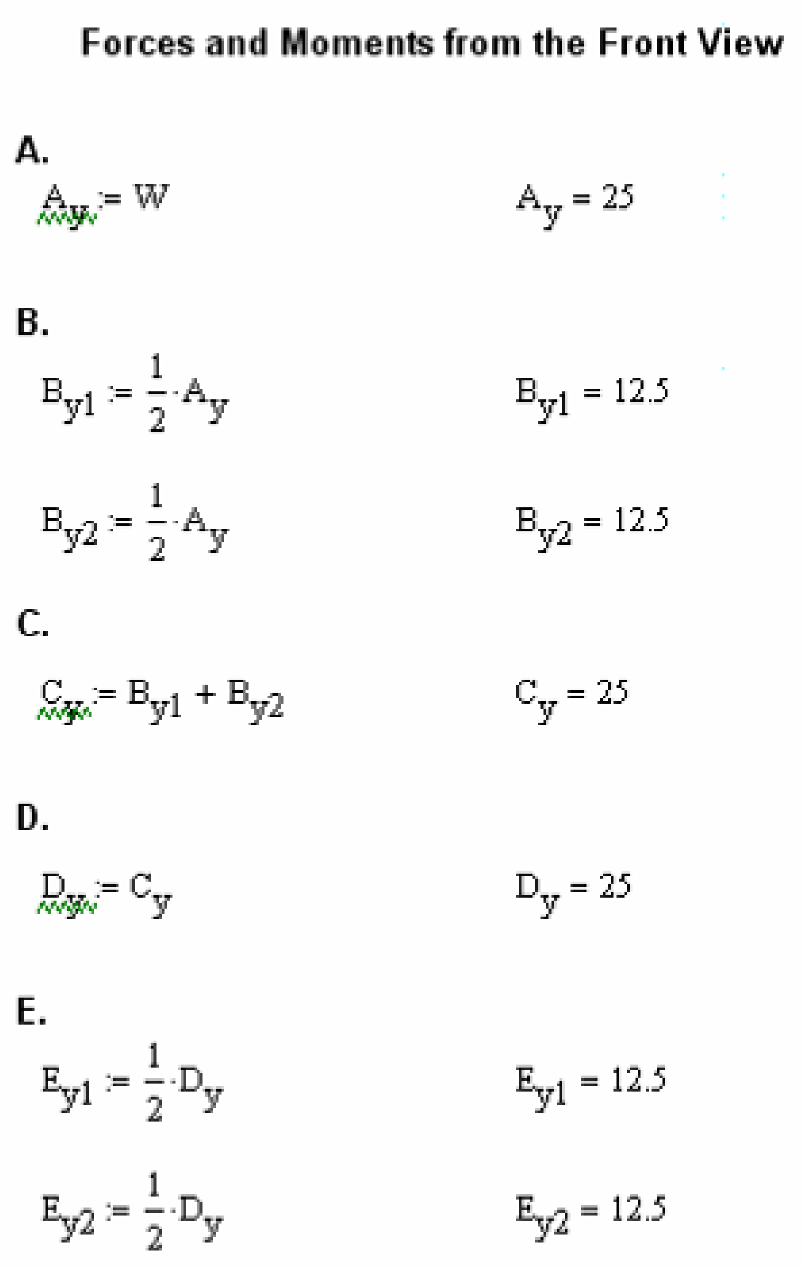
$D_y := C_y$ $\quad D_y = 25$

$M_D := M_C + f \cdot C_y$ $\quad M_D = 701.25$

E.

$E_y := D_y$ $\quad E_y = 25$

$M_E := M_D$ $\quad M_E = 701.25$



Forces and Moments from the Front View

A.

$A_y := W$ $A_y = 25$

B.

$B_{y1} := \frac{1}{2} \cdot A_y$ $B_{y1} = 12.5$

$B_{y2} := \frac{1}{2} \cdot A_y$ $B_{y2} = 12.5$

C.

$C_y := B_{y1} + B_{y2}$ $C_y = 25$

D.

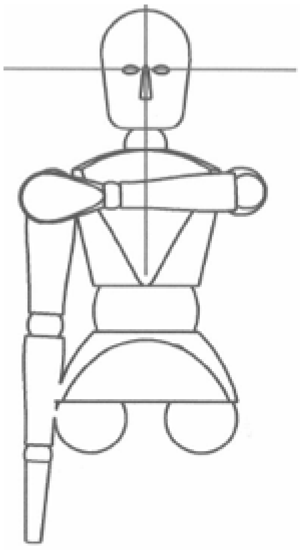
$D_y := C_y$ $D_y = 25$

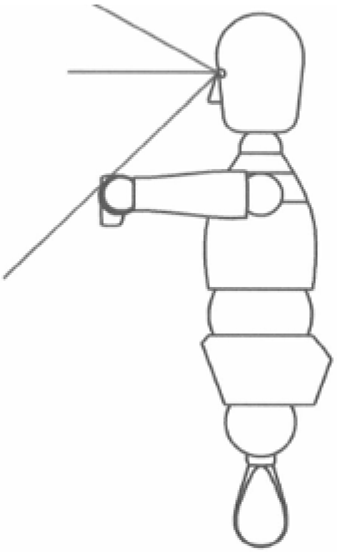
E.

$E_{y1} := \frac{1}{2} \cdot D_y$ $E_{y1} = 12.5$

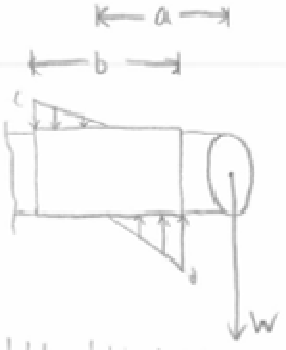
$E_{y2} := \frac{1}{2} \cdot D_y$ $E_{y2} = 12.5$

Position 4





Side View



$F_y = 0 = \frac{1}{4}bd - \frac{1}{4}bc - w = 0$

$d = \frac{4w}{b} + c$

$M = 0 = -\frac{1}{4}bd(\frac{1}{3})b + \frac{1}{4}bc(\frac{1}{3})b - aw$

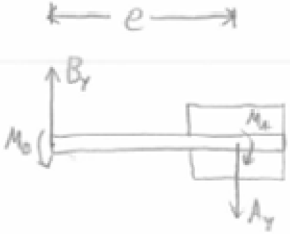
$\frac{12aw}{b^2} -$ [illegible] $= d$

$\frac{4w}{b} + c = \frac{12aw}{b^2} - c$

$\frac{4w}{b} - \frac{12aw}{b^2} = 2c$

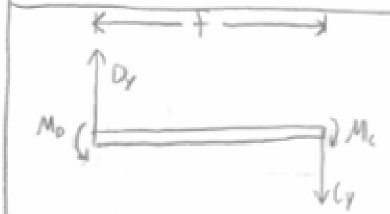
$c = \frac{6aw}{b^2} - \frac{2w}{b}$

$d = \frac{4w}{b} + c$



$B_y = A_y$

$M_B = M_A + eA_y$

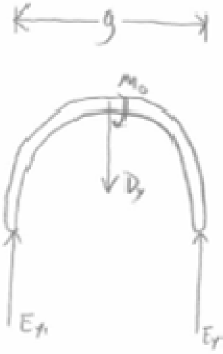


$D_y = C_y$

$M_D = M_C + fC_y$

$C_y = B_y$

$M_C = M_B$



$F_y = E_{y1} + E_{y2} - D_y = 0$

$E_{y1} = D_y - E_{y2}$

$M = \frac{g}{2}E_{y2} - \frac{g}{2}E_{y1} - M_D = 0$

$E_{y2} - E_{y1} = \frac{2M_D}{g}$

$E_{y1} = E_{y2} - \frac{2M_D}{g}$

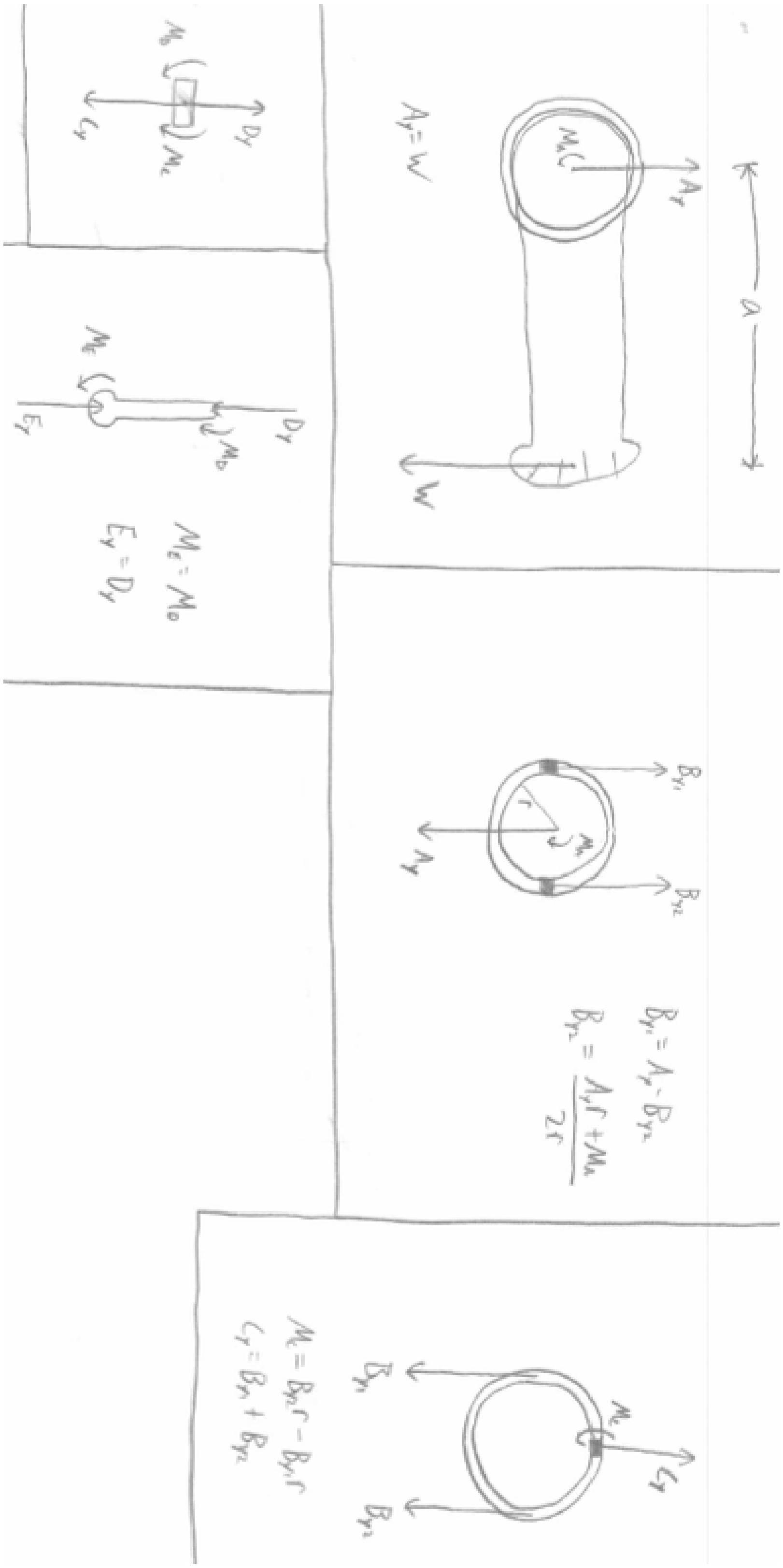
$E_{y2} - \frac{2M_D}{g} = D_y - E_{y2}$

$2E_{y2} = D_y + \frac{2M_D}{g}$

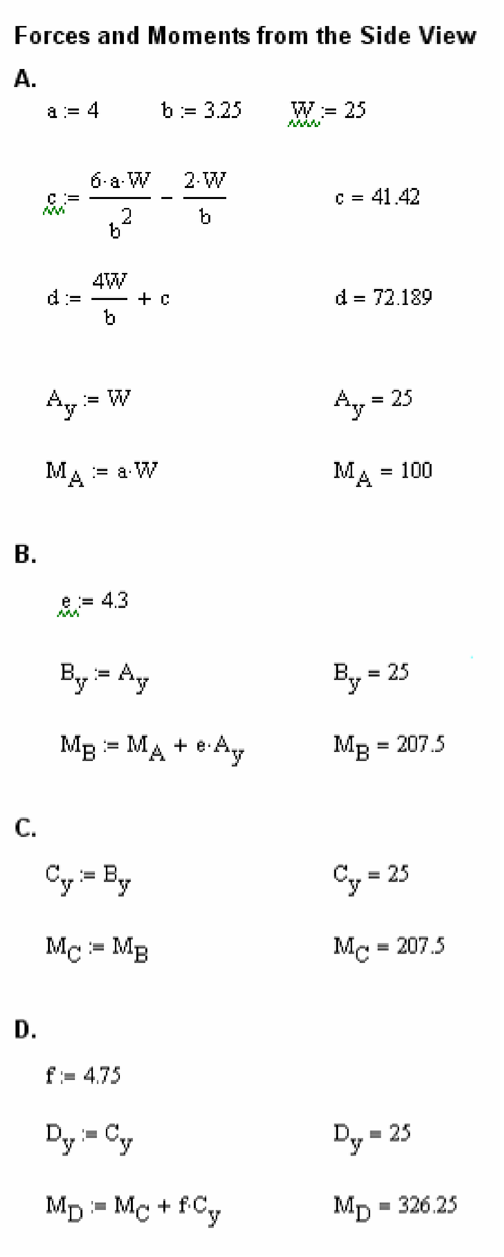
$E_{y2} = \frac{1}{2}D_y + \frac{M_D}{g}$

$E_{y1} = D_y - E_{y2}$

Front View


M_D
M_C
C_y
D_y
M_A
A_y
a
W
$A_y = W$
M_E
E_y
D_y
M_D
$M_E = M_D$
$E_y = D_y$
B_{y1}
B_{y2}
r
M_A
A_y
$B_{y1} = A_y - B_{y2}$
$B_{y2} = \frac{A_y r + M_A}{2r}$
B_{y1}
B_{y2}
M_C
C_y
$M_C = B_{y2} r - B_{y1} r$
$C_y = B_{y1} + B_{y2}$

MathCAD Program



Forces and Moments from the Side View

A.

$a := 4$ $b := 3.25$ $W := 25$

$c := \frac{6 \cdot a \cdot W}{b^2} - \frac{2 \cdot W}{b}$ $c = 41.42$

$d := \frac{4W}{b} + c$ $d = 72.189$

$A_y := W$ $A_y = 25$

$M_A := a \cdot W$ $M_A = 100$

B.

$e := 4.3$

$B_y := A_y$ $B_y = 25$

$M_B := M_A + e \cdot A_y$ $M_B = 207.5$

C.

$C_y := B_y$ $C_y = 25$

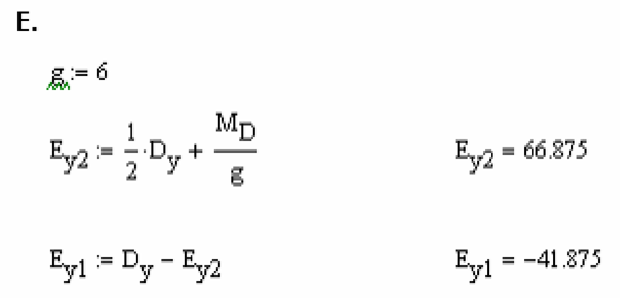
$M_C := M_B$ $M_C = 207.5$

D.

$f := 4.75$

$D_y := C_y$ $D_y = 25$

$M_D := M_C + f \cdot C_y$ $M_D = 326.25$

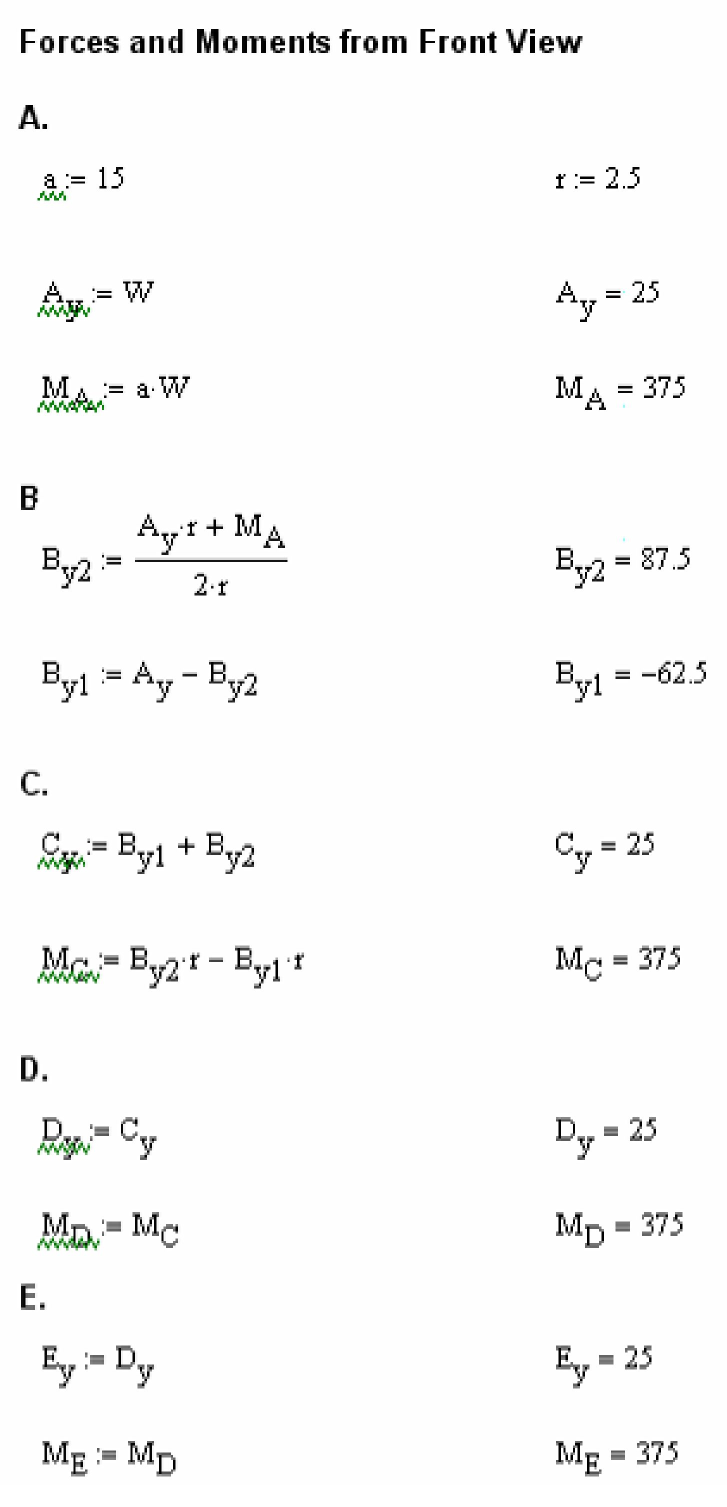


E.

$g := 6$

$E_{y2} := \frac{1}{2} \cdot D_y + \frac{M_D}{g}$ $E_{y2} = 66.875$

$E_{y1} := D_y - E_{y2}$ $E_{y1} = -41.875$



Forces and Moments from Front View

A.

$a := 15$ $\qquad$ $r := 2.5$

$A_y := W$ $\qquad$ $A_y = 25$

$M_A := a \cdot W$ $\qquad$ $M_A = 375$

B

$$B_{y2} := \frac{A_y \cdot r + M_A}{2 \cdot r} \qquad B_{y2} = 87.5$$

$B_{y1} := A_y - B_{y2}$ $\qquad$ $B_{y1} = -62.5$

C.

$C_y := B_{y1} + B_{y2}$ $\qquad$ $C_y = 25$

$M_C := B_{y2} \cdot r - B_{y1} \cdot r$ $\qquad$ $M_C = 375$

D.

$D_y := C_y$ $\qquad$ $D_y = 25$

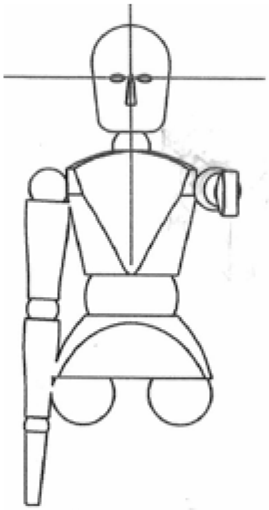
$M_D := M_C$ $\qquad$ $M_D = 375$

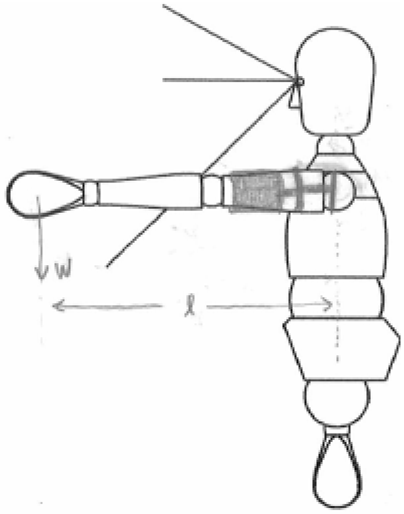
E.

$E_y := D_y$ $\qquad$ $E_y = 25$

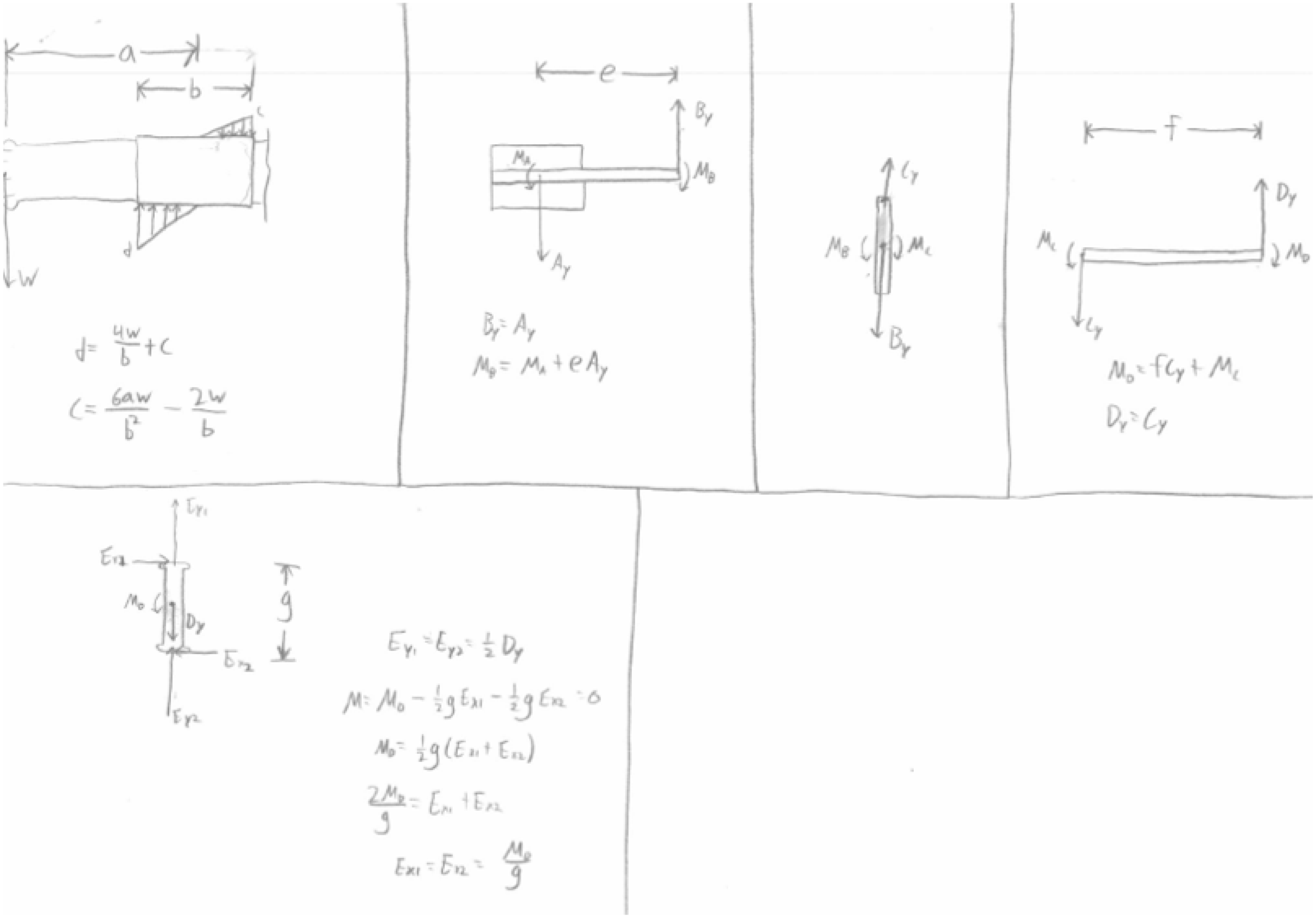
$M_E := M_D$ $\qquad$ $M_E = 375$

Position 5





Side View



$d = \frac{4w}{b} + c$

$c = \frac{6aw}{b^2} - \frac{2w}{b}$

$B_y = A_y$

$M_B = M_A + eA_y$

$M_D = fC_y + M_C$

$D_y = C_y$

$E_{Y1} = E_{Y2} = \frac{1}{2} D_y$

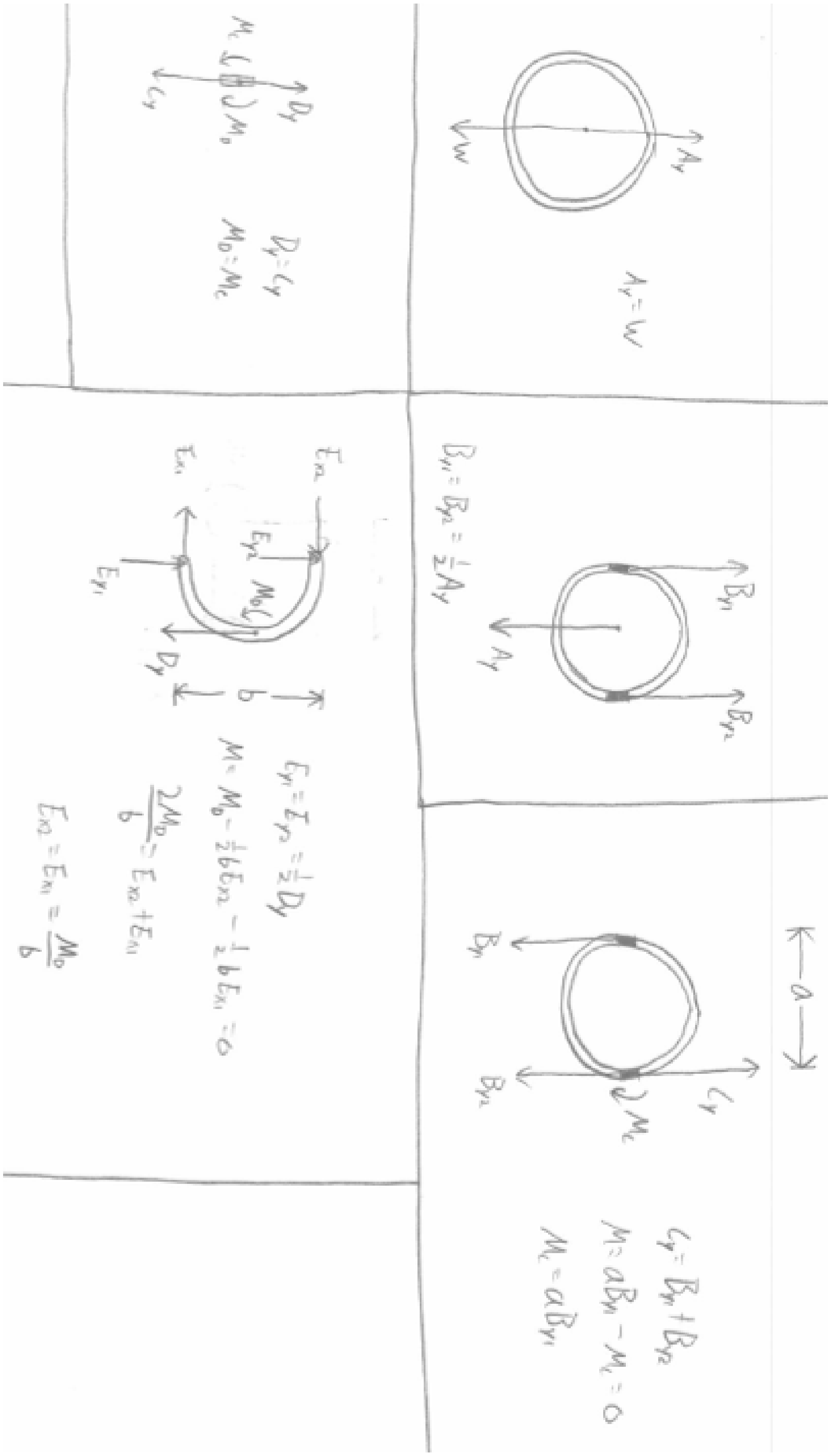
$M = M_D - \frac{1}{2} g E_{X1} - \frac{1}{2} g E_{X2} = 0$

$M_D = \frac{1}{2} g (E_{X1} + E_{X2})$

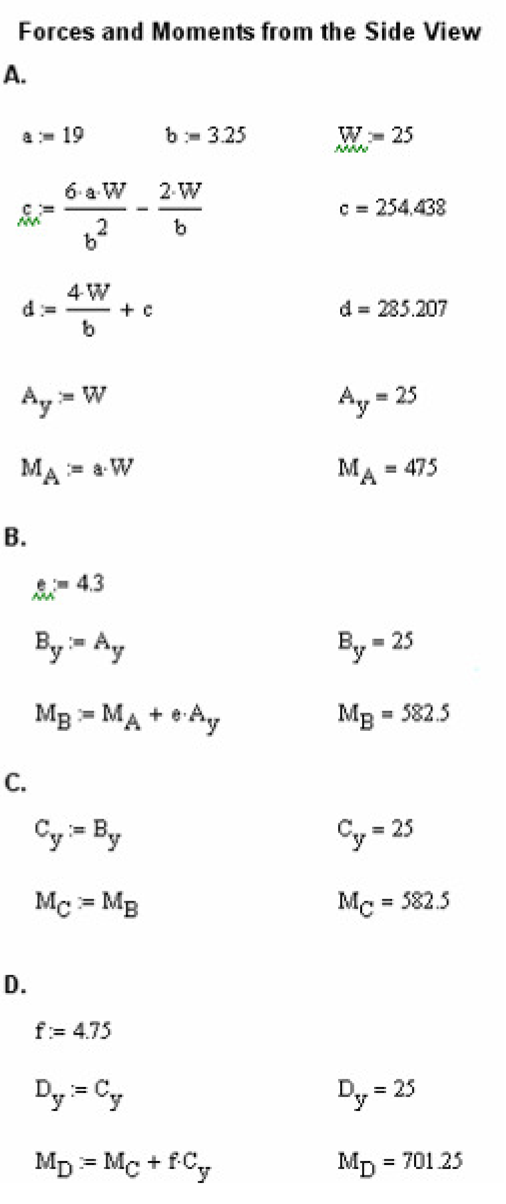
$\frac{2M_D}{g} = E_{X1} + E_{X2}$

$E_{X1} = E_{X2} = \frac{M_D}{g}$

Front View


A_y
W
$A_y = W$
B_{y1}
B_{y2}
A_y
$B_{y1} = B_{y2} = \frac{1}{2}A_y$
a
C_y
M_c
B_{y1}
B_{y2}
$C_y = B_{y1} + B_{y2}$
$M = aB_{y1} - M_c = 0$
$M_c = aB_{y1}$
D_y
M_c
M_D
C_y
$D_y = C_y$
$M_D = M_c$
E_{x2}
E_{y2}
M_D
E_{x1}
E_{y1}
D_y
b
$E_{y1} = E_{y2} = \frac{1}{2}D_y$
$M = M_D - \frac{1}{2}bE_{x2} - \frac{1}{2}bE_{x1} = 0$
$\frac{2M_D}{b} = E_{x2} + E_{x1}$
$E_{x2} = E_{x1} = \frac{M_D}{b}$

MathCAD Program



Forces and Moments from the Side View

A.

$a := 19$ $\quad b := 3.25$ $\quad W := 25$

$$c := \frac{6 \cdot a \cdot W}{b^2} - \frac{2 \cdot W}{b} \qquad c = 254.438$$

$$d := \frac{4 \cdot W}{b} + c \qquad d = 285.207$$

$$A_y := W \qquad A_y = 25$$

$$M_A := a \cdot W \qquad M_A = 475$$

B.

$e := 4.3$

$$B_y := A_y \qquad B_y = 25$$

$$M_B := M_A + e \cdot A_y \qquad M_B = 582.5$$

C.

$$C_y := B_y \qquad C_y = 25$$

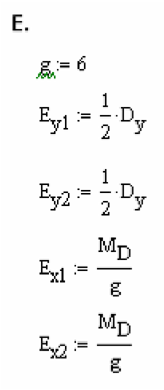
$$M_C := M_B \qquad M_C = 582.5$$

D.

$f := 4.75$

$$D_y := C_y \qquad D_y = 25$$

$$M_D := M_C + f \cdot C_y \qquad M_D = 701.25$$



E.

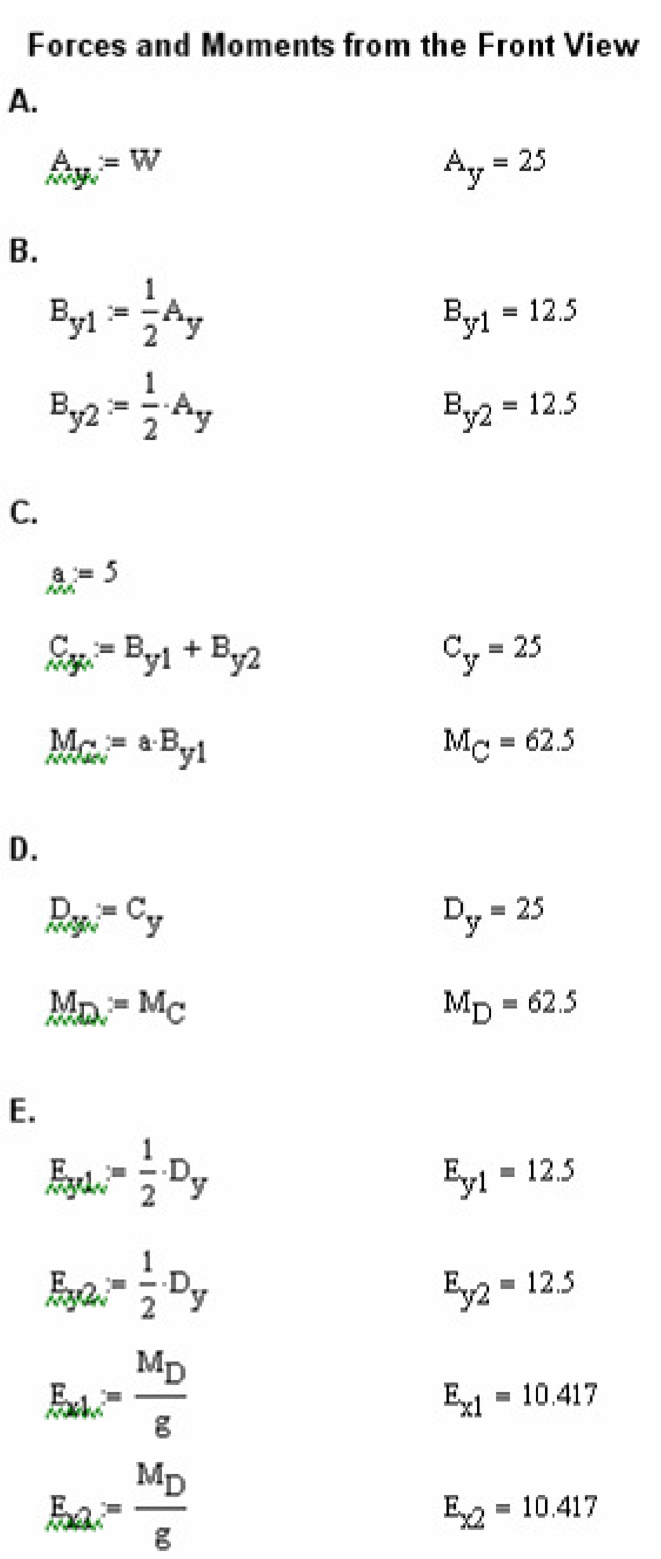
$g := 6$

$$E_{y1} := \frac{1}{2} \cdot D_y$$

$$E_{y2} := \frac{1}{2} \cdot D_y$$

$$E_{x1} := \frac{M_D}{g}$$

$$E_{x2} := \frac{M_D}{g}$$



Forces and Moments from the Front View

A.

$A_y := W$ $A_y = 25$

B.

$B_{y1} := \frac{1}{2} A_y$ $B_{y1} = 12.5$

$B_{y2} := \frac{1}{2} \cdot A_y$ $B_{y2} = 12.5$

C.

$a := 5$

$C_y := B_{y1} + B_{y2}$ $C_y = 25$

$M_C := a \cdot B_{y1}$ $M_C = 62.5$

D.

$D_y := C_y$ $D_y = 25$

$M_D := M_C$ $M_D = 62.5$

E.

$E_{y1} := \frac{1}{2} \cdot D_y$ $E_{y1} = 12.5$

$E_{y2} := \frac{1}{2} \cdot D_y$ $E_{y2} = 12.5$

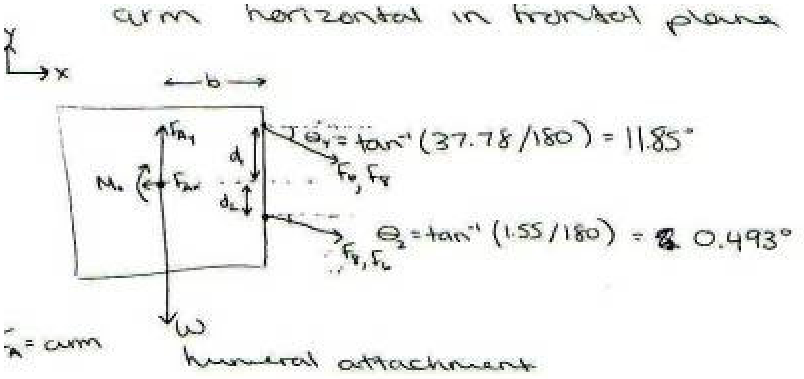
$E_{x1} := \frac{M_D}{g}$ $E_{x1} = 10.417$

$E_{x2} := \frac{M_D}{g}$ $E_{x2} = 10.417$

APPENDIX D – Strings Free Body Diagram

Free body diagram of the arm as it is extended horizontally in the frontal plane, viewed from the front.

arm horizontal in frontal plane



$d_1 = 64.53\,mm$

d_2 23.89mm

$$\Sigma F_y = 0 = -W - F_6(\sin\theta_4 + \sin\theta_2) - F_8(\sin\theta_4 + \sin\theta_2) + F_{A_y}$$

$$F_{A_y} = W + F_6(0.205 + 0.001) + F_8(0.206)$$

$$F_{A_y} = W + 0.206(F_6 + F_8)$$

$$\Sigma F_x = 0 = -F_{Ax} + (\cos\theta_4 + \cos\theta_2)(F_6 + F_8)$$

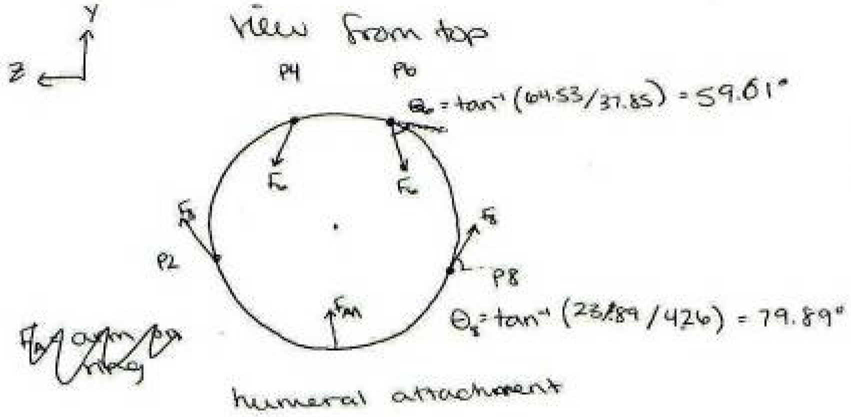
$$F_{Ax} = 1.979(F_6 + F_8)$$

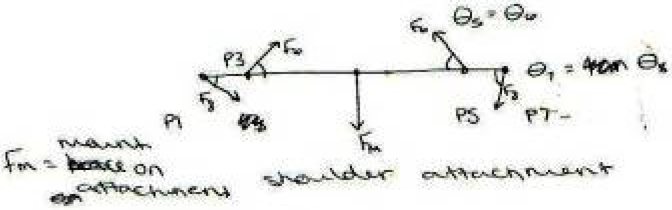
$$\Sigma M = 0 = -M_o - \underset{\cos\theta_4}{\underset{\wedge}{d_1}}(F_6 + F_8) - \underset{\sin\theta_4}{\underset{\wedge}{b}}(F_6 + F_8) + d_2\cos\theta_2(F_6 + F_8) - b\sin\theta_2(F_6 + F_8)$$

Free body diagrams of the arm as it is adducted to the side, viewed from above.

when the arm is straight down holding weight

view from top



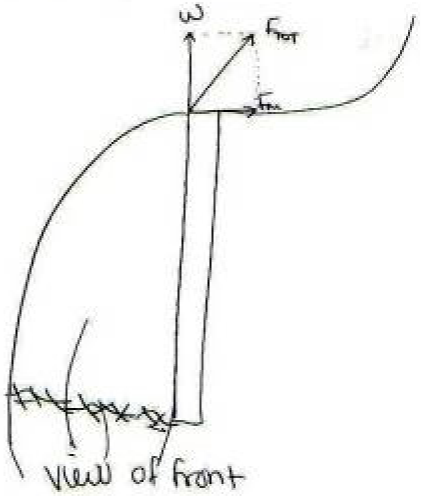


F_m = mount ~~force~~ on attachment

$$\Sigma F_y = 0 = 2F_6 \sin\theta_6 - 2F_8 \sin\theta_8 - F_m$$

$$\Sigma F_y = 0 = 1.725F_6 - 1.969F_8 - F_m$$

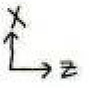
$$F_m = 1.725F_6 - 1.969F_8$$

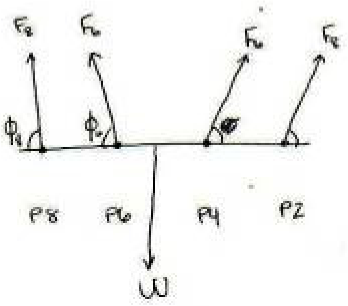


view of front

Free body diagrams of the arm as it is adducted to the side, viewed from the side.

from side, looking toward the body SOH CAH TOA





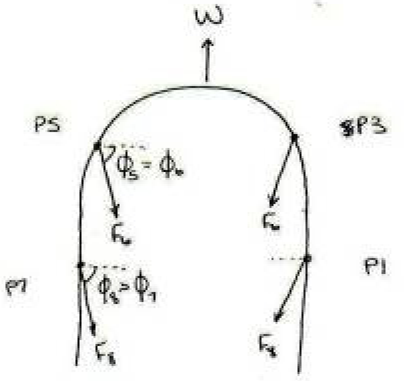
$\phi_6 = \tan^{-1}(206.75/64.53) = 72.67°$

$\phi_8 = \tan^{-1}(15456/426) = 88.42°$

$\Sigma F_y = 0 = 2F_8 \cos\phi_8 + 2F_6 \cos\phi_6 - W$

$\Sigma F_y = 1.999F_8 + 1.909F_6 - W = 0$

$W = 1.999F_8 + 1.909F_6$



APPENDIX E – Fastener Analysis

#10-32 UNF Machine Screw, Location A:

d=Major Diameter
dr=Minor Diameter
dp=Pitch Diameter
At=Tensile Stress Area
N=# of Threads per Inch

$d_{10} := .1900\,in \qquad N_{10} := 32\cdot\frac{1}{in}$

$d_{r10} := d_{10} - \frac{1.29903}{N_{10}} \qquad d_{p10} := d_{10} - \frac{.64951}{N_{10}} \qquad A_{t10} := \frac{\pi}{4}\cdot\left(\frac{d_{p10} + d_{r10}}{2}\right)^2$

$d_{r10} = 0.1494\,in \qquad d_{p10} = 0.1697\,in \qquad A_{t10} = 0.02\,in^2$

Axial Stress of 10-32 Machine Screw (To show fastener will not fail):

Yield Strength of 10-32 pan head machine screw of steel= 45000 psi

$\sigma_{t10} := 45000\frac{lb}{in^2} \qquad F_{10} := \sigma_{t10}\cdot A_{t1} \qquad F_{10} = 899.7393\,lb$

To fail a 10-32 fastener axially in tension would require 900 lb of force. With a safety factor of 3 in place, the fastener would require 300 lb of force to fail. This is much greater than any forces the fastener will experience

Shear Failure of 10-32 Machine Screw (Threads stripping/pullout):

wo= Area Factor for Thread-Stripping Shear Area, Major Diameter

As= Stripping Shear Area, for one screw thread

p= Pitch

τs= Shear Strength, 1018 steel is 80GPa or 11600ksi, with a safety factor of 3, 11600ksi/3=3,868,000psi

F= Force applied

$p_{10} := \frac{1}{N_{10}} \qquad p_{10} = 0.0313\,in \qquad w_o := .8$

$A_{s10} := \pi\cdot d_{r10}\cdot w_o\cdot p_{1} \qquad A_{s10} = 0.0129\,in^2 \qquad \tau_{s10} := 3868000\frac{lb}{in^2}$

$F_{s10} := \tau_{s10}\cdot A_{s10} \qquad F_{s10} = 4.9927\times 10^4\,lb$

For one thread to fail in a 10-32 fastener, a force of 49,927 lb would be required. This is with a safety factor of 3 already in place.

Length of Engagement:

$$Loe_{10} := \frac{2 \cdot A_{t10}}{\frac{1}{2} \cdot \pi \cdot (d_{10} - .649519 p_{10})}$$

$Loe_{10} = 0.15in$

$Threads_{10} := Loe_{10} \cdot N_{1C}$

$Total_{10} := Threads_{10} \cdot F_{s10}$

$Threads_{10} = 4.8004$

$Total_{10} = 2.3967 \times 10^{5} \, lb$

The recommended length of engagement for a 10-32 fastener is .15 inches. This is equivalent to 4.8 threads. If the force to strip the tapped hole is 49,927 lb for a single thread, then the force to fail 4.8 threads would be 2.40*10^5 lb, with a safety factor of 3 in place.

#12-24 UNC Machine Screw, Location B:

$d_{12} := .2160\,in \qquad N_{12} := 24\cdot\frac{1}{in}$

$d_{r12} := d_{12} - \frac{1.299038}{N_{12}} \qquad d_{p12} := d_{12} - \frac{.649519}{N_{12}} \qquad A_{t12} := \frac{\pi}{4}\cdot\left(\frac{d_{p12} + d_{r12}}{2}\right)^2$

$d_{r12} = 0.1619\,in \qquad d_{p12} = 0.1889\,in \qquad A_{t12} = 0.0242\,in^2$

Axial Stress of Machine Screw (To show fastener will not fail):

Yield Strength of 12-24 pan head machine screw of steel= 45000 psi

$\sigma_{t12} := 45000\frac{lb}{in^2} \qquad F_{12} := \sigma_{t12}\cdot A_{t12} \qquad F_{12} = 1.0874\times 10^3\,lb$

To fail a 12-24 fastener axially in tension would require 1087 lb of force. With a safety factor of 3 in place, the fastener would require 362.3 lb of force to fail. This is much greater than any forces the fastener will experience

Shear Failure of 12-24 Machine Screw:

wo= Area Factor for Thread-Stripping Shear Area, Major Diameter

As= Stripping Shear Area, for one screw thread

p= Pitch

τs= Shear Strength, 1018 steel is 80GPa or 11600ksi, with a safety factor of 3, 11600ksi/3=3,868,000psi

F= Force

$p_{12} := \frac{1}{N_{12}} \qquad p_{12} = 0.0417\,in \qquad w_o := .88$

$A_{s12} := \pi\cdot d_{r12}\cdot w_o\cdot p_{12} \qquad A_{s12} = 0.0186\,in^2 \qquad \tau_{s12} := 3868000\frac{lb}{in^2}$

$F_{s12} := \tau_{s12}\cdot A_{s12} \qquad F_{s12} = 7.2125\times 10^4\,lb$

For one thread to fail in a 12-24 fastener, a force of 72,125 lb would be required. This is with a safety factor of 3 already in place.

Length of Engagement:

$$Loe_{12} := \frac{2 \cdot A_{t12}}{\frac{1}{2} \cdot \pi \cdot \left(d_{12} - .649519 p_{12}\right)} \qquad Loe_{12} = 0.1628 \text{in}$$

$$Threads_{12} := Loe_{12} \cdot N_{12} \qquad Total_{12} := Threads_{12} \cdot F_{s12}$$

$$Threads_{12} = 3.9082 \qquad Total_{12} = 2.8188 \times 10^{5} \text{ lb}$$

The recommended length of engagement for a 12-24 fastener is .1628 inches. This is equivalent to 3.91 threads. If the force to strip a tapped hole is 72,125 lb for a single thread, then the force to fail 3.91 threads would be 2.81*10^5 lb, with a safety factor of 3 in place.

1/4-28 UNF Machine Screw, Location C:

$d_{.25} := .25\text{in}$ $\qquad N_{.25} := 28 \cdot \frac{1}{\text{in}}$

$d_{r.25} := d_{.25} - \frac{1.299038}{N_{.25}}$ $\qquad d_{p.25} := d_{.25} - \frac{.649519}{N_{.25}}$ $\qquad A_{t.25} := \frac{\pi}{4} \cdot \left(\frac{d_{p.25} + d_{r.25}}{2} \right)^2$

$d_{r.25} = 0.2036\text{in}$ $\qquad d_{p.25} = 0.2268\text{in}$ $\qquad A_{t.25} = 0.0364\text{in}^2$

<u>Axial Stress of Machine Screw(To show fastener will not fail)</u>:

Minimum Yield Strength of 1/4-28 (grade 5) hex head machine screw of steel= 92000 psi

$\sigma_{t.25} := 92000 \frac{\text{lb}}{\text{in}^2}$ $\qquad F_{.25} := \sigma_{t.25} \cdot A_{t.25}$ $\qquad F_{.25} = 3.3464 \times 10^3 \text{lb}$

To fail a 1/4-28 fastener axially in tension would require 3346 lb of force. With a safety factor of 3 in place, the fastener would require 1121 lb of force to fail. This is much greater than any forces the fastener will experience

<u>Shear Failure of 1/4-28 Machine Screw:</u>

wo= Area Factor for Thread-Stripping Shear Area, Major Diameter

As= Stripping Shear Area, for one screw thread

p= Pitch

τs= Shear Strength, 1018 steel is 80GPa or 11600ksi, with a safety factor of 3, 11600ksi/3=3,868,000psi

F= Force

$p_{.25} := \frac{1}{N_{.25}}$ $\qquad p_{.25} = 0.0357\text{in}$

$A_{s.25} := \pi \cdot d_{r.25} \cdot w_o \cdot p_{.25}$ $\qquad A_{s.25} = 0.0201\text{in}^2$ $\qquad \tau_{s.25} := 3868000 \frac{\text{lb}}{\text{in}^2}$

$F_{s.25} := \tau_{s.25} \cdot A_{s.25}$ $\qquad F_{s.25} = 7.7759 \times 10^4 \text{lb}$

For one thread to fail in a 1/4-28 fastener, a force of 77,759 lb would be required. This is with a safety factor of 3 already in place.

Length of Engagement:

$$Loe_{.25} := \frac{2 \cdot A_{t.25}}{\frac{1}{2} \cdot \pi \cdot \left(d_{.25} - .649519 p_{.25}\right)}$$

$Loe_{.25} = 0.2042 in$

$Threads_{.25} := Loe_{.25} \cdot N_{.25}$

$Total_{.25} := Threads_{.25} \cdot F_{s.25}$

$Threads_{.25} = 5.7176$

$Total_{.25} = 4.4459 \times 10^{5} lb$

The recommended length of engagement for a 1/28 fastener is .204 inches. This is equivalent to 5.72 threads. If the force to strip a tapped hole is 77,759 lb for a single thread, then the force to fail 5.72 threads would be 4.45*10^5 lb, with a safety factor of 3 in place.

Shear Tear-out: 10-32 Machine Screw, Threaded Hole of Bar, Location A

Effective Cross Sectional Area:

e = Edge Distance

d = Hole Diameter

t = Thickness of Material

Fshear = Shear Force Applied

$t_{10} := .5in$

$d_{10} := .1900in$

$e_{10} := .175in$

$$A_{s10} := 2\left(e_{10} - \frac{d_{10}}{2}\right) \cdot t_{10}$$

$\sigma_{10} := 11604000 \frac{lb}{in^2}$ Shear strength of steel: 11,604,000 psi

$F_{shear10} := \sigma_{10} \cdot A_{s10}$

$F_{shear10} = 9.283 \times 10^5\ lb$

Shear tearout will occur with a force equal to 928300 lb

This is a worst case scenario calculation. For shear tearout to occur in the threaded hole of the bar, a force equal to 928,300 lb would have to be seen. With a safety factor of 3 applied, this force would have to be equal to 309400 lb. There is no apparent reason to consider the possibility of shear tearout.

Shear Tear-out: 10-32 machine screw, Clearance Hole of Outer Ring, Location A

Effective Cross Sectional Area:

e = Edge Distance

d = Hole Diameter

t = Thickness of Material

Fshear = Shear Force Applied

$t_{10} := .5in$

$d_{10} := .1960in$

$e_{10} := .3in$

$$A_{s10} := 2\left(e_{10} - \frac{d_{10}}{2}\right)\cdot t_{10}$$

$\sigma_{10} := 11604000\frac{lb}{in^2}$ Shear strength of steel: 11,604,000 psi

$F_{shear10} := \sigma_{10}\cdot A_{s10}$

$F_{shear10} = 2.344\times 10^{6}\,lb$

Shear tearout will occur with a force equal to 2344000 lb

This is a worst case scenario calculation. For shear tearout to occur in the clearance hole of the outer ring, a force equal to 2344000 lb would have to be seen. With a safety factor of 3 applied, this force would have to be equal to 781300 lb. There is no apparent reason to consider the possibility of shear tearout.

Shear Tear-out: 1/4 pin, Shoulder Arch Lock, Top, Location C

Effective Cross Sectional Area:

e = Edge Distance

d = Hole Diameter

t = Thickness of Material

Fshear = Shear Force Applied

$t_{.25} := .3in$

$d_{.25} := .2570in$

$e_{.25} := .25in$

$$A_{s.25} := 2\left(e_{.25} - \frac{d_{.25}}{2}\right) \cdot t_{.25}$$

$\sigma_{.25} := 11604000 \frac{lb}{in^2}$ Shear strength of steel: 11,604,000 psi

$F_{shear.25} := \sigma_{.25} \cdot A_{s.25}$

$F_{shear.25} = 8.459 \times 10^5\ lb$

Shear tearout will occur with a force equal to 845900 lbs

This is a worst case scenario calculation. For shear tearout to occur in the lock on top of the shoulder arch, a force equal to 845,900 lb would have to be seen. With a safety factor of 3 applied, this force would have to be equal to 282000 lb. There is no apparent reason to consider the possibility of shear tearout.

Shear Tear-out: 1/4 pin, Shoulder Arch Lock, Pin and Spring Holder, Vertical Tear-out would be Worst Case, Location D

Effective Cross Sectional Area:

e = Edge Distance

d = Hole Diameter

t = Thickness of Material

Fshear = Shear Force Applied

$t_{.25} := .28\,in$

$d_{.25} := .2570\,in$

$e_{.25} := .275\,in$

$$A_{s.25} := 2\left(e_{.25} - \frac{d_{.25}}{2}\right)\cdot t_{.25}$$

$\sigma_{.25} := 11604000\,\frac{lb}{in^2}$ Shear strength of steel: 11,604,000 psi

$F_{shear.25} := \sigma_{.25}\cdot A_{s.25}$

$F_{shear.25} = 9.52\times 10^{5}\,lb$

Shear tearout will occur with a force equal to 952000 lb

This is a worst case scenario calculation. For shear tearout to occur in the locking pin spring holder of the shoulder arch, a force equal to 952,000 lb would have to be seen. With a safety factor of 3 applied, this force would have to be equal to 317333 lb. There is no apparent reason to consider the possibility of shear tearout.

Shear Tear-out: 1/4 pin, Shoulder Arch Lock, Front, Location E

Effective Cross Sectional Area:

e = Edge Distance

d = Hole Diameter

t = Thickness of Material

Fshear = Shear Force Applied

$t_{.25} := .38\,in$

$d_{.25} := .2570\,in$

$e_{.25} := .318\,in$

$A_{s.25} := 2\left(e_{.25} - \frac{d_{.25}}{2}\right)\cdot t_{.25}$

$\sigma_{.25} := 11604000\frac{lb}{in^2}$ Shear strength of steel: 11,604,000 psi

$F_{shear.25} := \sigma_{.25}\cdot A_{s.25}$

$F_{shear.25} = 1.671\times 10^{6}\,lb$

Shear tearout will occur with a force equal to 1,671,000 lb

This is a worst case scenario calculation. For shear tearout to occur in the locking pin holes of mechanism part 1, a force equal to 1,671,000 lb would have to be seen. With a safety factor of 3 applied, this force would have to be equal to 557000 lb. There is no apparent reason to consider the possibility of shear tearout.

APPENDIX F – Range of Motion Questionnaire

1 Impossible	2	3	4	5 Effortless

Unloaded Assessment					
Move the device through its full range of motion. a.) How difficult was it? Comments:	1	2	3	4	5
b.) Comments:	1	2	3	4	5
Are there any observations of binding or locking up while moving the device through its full range of motion? Comments:					
Loaded Assessment					
Strap weight to the prosthesis attachment. Move the device through its full range of motion. a.) How difficult was it? Comments:	1	2	3	4	5
b.) Comments:	1	2	3	4	5
Are there any observations of binding or locking up while moving the device through its full range of motion? Comments:					

APPENDIX G – Comfort and User Friendliness Questionnaire

The trials will begin by donning the vest and assessing the ease with which this is accomplished. Also, the general fit and feel of the vest will be evaluated.

Donning the Vest					
Put the vest on. How easy was it? Comments:	1 Extremely Difficult	2	3	4	5 Effortless
Fasten the straps. How easy was it? Comments:	1 Extremely Difficult	2	3	4	5 Effortless
Once the vest is completely secured, how comfortable is it, in general? Comments:	1 Unbearable	2	3	4	5 Barely Noticeable

The tests on the following page will evaluate the comfort of the vest with the arm in various positions. Each position will be tested with the device alone first. A 5 lb weight will then be strapped to the prosthesis attachment, and the position will be repeated. Please rate each position on a scale from 1 to 5, with 1 being unbearable, and 5 being barely noticeable. Please provide comments to describe the fit and comfort of the vest, especially comparing the weighted to the unweighted situations.

Questions b) and d) for each position mention pressure points. Pressure points are to be considered locations where concentrated pressure is applied to the body by the vest, often resulting in discomfort or pain.

1 Unbearable	2	3	4	5 Barely Noticeable

Unloaded Assessment					
Position your arm by your side in the frontal plane. a) How comfortable is the shoulder area? Comments:	1	2	3	4	5
b) Are there any pressure points in the shoulder area? Comments:	1	2	3	4	5
c) How comfortable is the waist/straps area? Comments:	1	2	3	4	5
d) Are there any pressure points in the waist/ straps area? Comments:	1	2	3	4	5
e) Are there additional areas that are particularly comfortable or uncomfortable due to the vest in this position? Comments:					
Loaded Assessment					
Strap weight to the prosthesis attachment. a) How comfortable is the shoulder area? Comments:	1	2	3	4	5
b) Are there any pressure points in the shoulder area? Comments:	1	2	3	4	5
c) How comfortable is the waist/straps area? Comments:	1	2	3	4	5
d) Are there any pressure points in the waist/ straps area? Comments:	1	2	3	4	5
e) Are there additional areas that are particularly comfortable or uncomfortable due to the vest in this position? Comments:					

1 Unbearable	2	3	4	5 Barely Noticeable

Unloaded Assessment					
Extend your arm to the side in the frontal plane. Keep your arm at shoulder height. a) How comfortable is the shoulder area? Comments:	1	2	3	4	5
b) Are there any pressure points in the shoulder area? Comments:	1	2	3	4	5
c) How comfortable is the waist/straps area? Comments:	1	2	3	4	5
d) Are there any pressure points in the waist/ straps area? Comments:	1	2	3	4	5
e) Are there additional areas that are particularly comfortable or uncomfortable due to the vest in this position? Comments:					
Loaded Assessment					
Strap weight to the prosthesis attachment. a) How comfortable is the shoulder area? Comments:	1	2	3	4	5
b) Are there any pressure points in the shoulder area? Comments:	1	2	3	4	5
c) How comfortable is the waist/straps area? Comments:	1	2	3	4	5
d) Are there any pressure points in the waist/ straps area? Comments:	1	2	3	4	5
e) Are there additional areas that are particularly comfortable or uncomfortable due to the vest in this position? Comments:					

1 Unbearable	2	3	4	5 Barely Noticeable

Unloaded Assessment					
Lift your arm above shoulder height as high as possible in the frontal plane. a) How comfortable is the shoulder area? Comments:	1	2	3	4	5
b) Are there any pressure points in the shoulder area? Comments:	1	2	3	4	5
c) How comfortable is the waist/straps area? Comments:	1	2	3	4	5
d) Are there any pressure points in the waist/ straps area? Comments:	1	2	3	4	5
e) Are there additional areas that are particularly comfortable or uncomfortable due to the vest in this position? Comments:					
Loaded Assessment					
Strap weight to the prosthesis attachment. a) How comfortable is the shoulder area? Comments:	1	2	3	4	5
b) Are there any pressure points in the shoulder area? Comments:	1	2	3	4	5
c) How comfortable is the waist/straps area? Comments:	1	2	3	4	5
d) Are there any pressure points in the waist/ straps area? Comments:	1	2	3	4	5
e) Are there additional areas that are particularly comfortable or uncomfortable due to the vest in this position? Comments:					

1 Unbearable	2	3	4	5 Barely Noticeable

Unloaded Assessment					
Extend your arm horizontally in front of you as if you were opening a door. a) How comfortable is the shoulder area? Comments:	1	2	3	4	5
b) Are there any pressure points in the shoulder area? Comments:	1	2	3	4	5
c) How comfortable is the waist/straps area? Comments:	1	2	3	4	5
d) Are there any pressure points in the waist/ straps area? Comments:	1	2	3	4	5
e) Are there additional areas that are particularly comfortable or uncomfortable due to the vest in this position? Comments:					
Loaded Assessment					
Strap weight to the prosthesis attachment. a) How comfortable is the shoulder area? Comments:	1	2	3	4	5
b) Are there any pressure points in the shoulder area? Comments:	1	2	3	4	5
c) How comfortable is the waist/straps area? Comments:	1	2	3	4	5
d) Are there any pressure points in the waist/ straps area? Comments:	1	2	3	4	5
e) Are there additional areas that are particularly comfortable or uncomfortable due to the vest in this position? Comments:					

1 Unbearable	2	3	4	5 Barely Noticeable

Unloaded Assessment					
Reach your arm across your body to the opposite shoulder. Touch your shoulder if you can. a) How comfortable is the shoulder area? Comments:	1	2	3	4	5
b) Are there any pressure points in the shoulder area? Comments:	1	2	3	4	5
c) How comfortable is the waist/straps area? Comments:	1	2	3	4	5
d) Are there any pressure points in the waist/ straps area? Comments:	1	2	3	4	5
e) Are there additional areas that are particularly comfortable or uncomfortable due to the vest in this position? Comments:					
Loaded Assessment					
Strap weight to the prosthesis attachment. a) How comfortable is the shoulder area? Comments:	1	2	3	4	5
b) Are there any pressure points in the shoulder area? Comments:	1	2	3	4	5
c) How comfortable is the waist/straps area? Comments:	1	2	3	4	5
d) Are there any pressure points in the waist/ straps area? Comments:	1	2	3	4	5
e) Are there additional areas that are particularly comfortable or uncomfortable due to the vest in this position? Comments:					

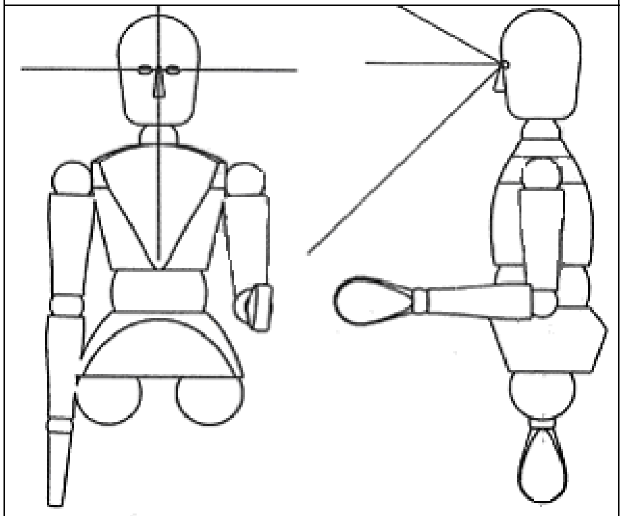
1 Unbearable	2	3	4	5 Barely Noticeable

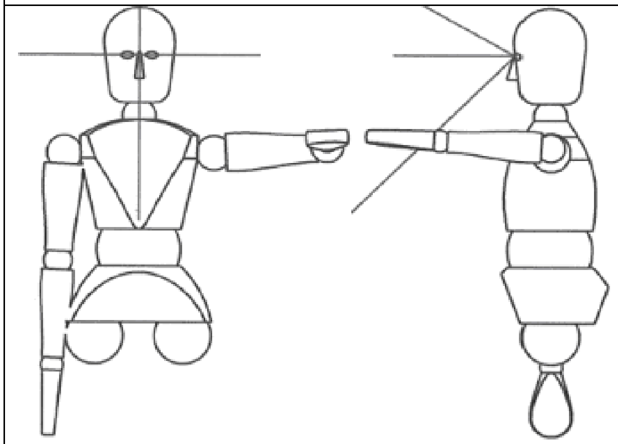
Unloaded Assessment					
Reach your arm back behind you horizontally. a) How comfortable is the shoulder area? Comments:	1	2	3	4	5
b) Are there any pressure points in the shoulder area? Comments:	1	2	3	4	5
c) How comfortable is the waist/straps area? Comments:	1	2	3	4	5
d) Are there any pressure points in the waist/ straps area? Comments:	1	2	3	4	5
e) Are there additional areas that are particularly comfortable or uncomfortable due to the vest in this position? Comments:					
Loaded Assessment					
Strap weight to the prosthesis attachment. a) How comfortable is the shoulder area? Comments:	1	2	3	4	5
b) Are there any pressure points in the shoulder area? Comments:	1	2	3	4	5
c) How comfortable is the waist/straps area? Comments:	1	2	3	4	5
d) Are there any pressure points in the waist/ straps area? Comments:	1	2	3	4	5
e) Are there additional areas that are particularly comfortable or uncomfortable due to the vest in this position? Comments:					

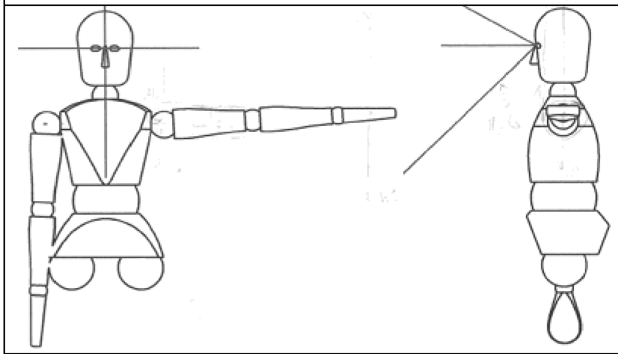
1 Unbearable	2	3	4	5 Barely Noticeable

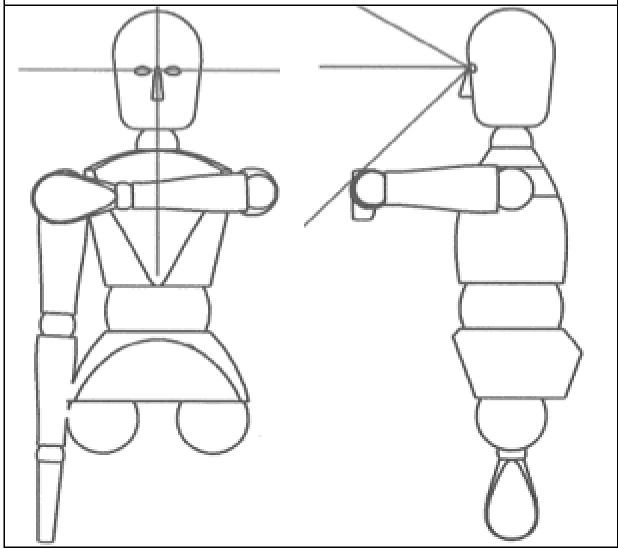
Unloaded Assessment					
Move your arm continuously through the full range of motion in all planes. a) How comfortable is the shoulder area? Comments:	1	2	3	4	5
b) Are there any pressure points in the shoulder area? Comments:	1	2	3	4	5
c) How comfortable is the waist/straps area? Comments:	1	2	3	4	5
d) Are there any pressure points in the waist/ straps area? Comments:	1	2	3	4	5
e) Are there additional areas that are particularly comfortable or uncomfortable due to the vest in this position? Comments:					
Loaded Assessment					
Strap weight to the prosthesis attachment. a) How comfortable is the shoulder area? Comments:	1	2	3	4	5
b) Are there any pressure points in the shoulder area? Comments:	1	2	3	4	5
c) How comfortable is the waist/straps area? Comments:	1	2	3	4	5
d) Are there any pressure points in the waist/ straps area? Comments:	1	2	3	4	5
e) Are there additional areas that are particularly comfortable or uncomfortable due to the vest in this position? Comments:					

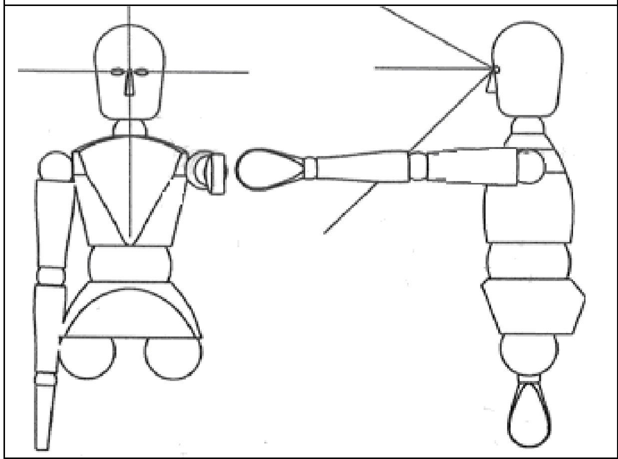
APPENDIX H – Strength Testing

Position 1	Deflections (in.)	Torque (in.-lb)
		

Position 2	Deflections (in.)	Torque (in.-lb)
		

Position 3	Deflections (in.)	Torque (in.-lb)
		

Position 4	Deflections (in.)	Torque (in.-lb)
		

Position 5	Deflections (in.)	Torque (in.-lb)
		

REFERENCES

"Anatomy - The Joints." <u>ShoppingTrolley.net</u>. 6 Oct 2006. 6 Oct 2006 <http://www.shoppingtrolley.net/anatomy-and-physiology-2b.shtml>.

Bedotto, Robert. "Testing the Whole Person: The Importance of Orthotics in the Care of Amputee Patients." In Motion 15.6 Dec 2005 21 Sep 2006 <http://www.amputee-coalition.org/inmotion/nov_dec_05/treating_the_whole_person.html>

Bertels, Thomas. "Functions of the Body Harness for Upper Extremity Prostheses." (2001) <http://www.ottobockus.com/products/upper_limb_prosthetics/triple_control_harness.pdf#search=%22%22Functions%20of%20the%20body%20harness%20for%20upper%20extremity%20prostheses%22%22>.

"Body Power Harness Fundementals." 2006. Northwestern University. 21 Sep 2006 <http://www.medschool.northwestern.edu/depts/nupoc/images/UpperExtPros/HarnessingPrinciples2.pdf#search=%22cross%20chest%20strap%20harness%20prosthetics%22>

Carignan, Craig, and Liszka, Michael. "Design of an Arm Exoskeleton with Scapula Motion for Shoulder Rehabilitation." <u>University of Maryland</u> 2005 1-8. 05 OCT 2006 <http://rtsx-kiwi.umd.edu/work/publications/2005_ICAR.pdf>.

Carr, A.. "(i) Biomechanics of shoulder stabilitynext term." <u>Current Orthopaedics</u> 10(1996): 146-150.

Chu, Andrew, and Kazerooni, H., and Zoss, Adam. "On the Mechanical Design of Berkeley Lower Extremety Exoskeleton (BLEEX)." <u>University of California</u> (2002)

Cuccurullo, Sara J.. Physical Medicine and Rehabilitaion Board Review. (2004). 21 Sep 2006 http://www.ncbi.nlm.nih.gov/books/bv.fcgi?indexed=google&rid=physmedrehab.section.8475

Cupo, Mary, and Sheredos, Saleem. "Clinical Evaluation of a New, Above-Elbow, Body-Powered Prosthetic Arm: A Final Report." <u>Journal of Rehabilitation Research and Development</u> 35.04OCT 1998 431-446. 10 OCT 2006 <http://www.vard.org/jour/98/35/4/cupo.pdf>.

Dillingham, Timothy, Liliana Pezzin, Ellen MacKenzie. "Incidence, Acute Care Length of Stay, and Discharge." <u>Archives of Physical Medicine and Rehabilitation</u> 79(1998): 279-287.

Dudek, Daniel, and Full, Robert. "Passive mechanical properties of legs from running insects." The Journal of Experimental Biology 209(2006) 1502-1515. 10 OCT 2006 <http://polypedal.berkeley.edu/twiki/pub/PolyPEDAL/BreakingNews/Dudek_JEB_06.pdf>.

Dyer, Nicole. "A Toast to the Bionic Man." Popular Science SEP 2005 06 OCT 2006 <http://www.popsci.com/popsci/medicine/6123dc8a25076010vgnvcm1000004eecbccdrcrd.html>.

"Exoskeletons: Wearable Robots." Gizmag. 2005. Gizmag. 6 Oct 2006 <http://www.gizmag.com/go/1604/>.

Farnsworth, Troy. "Enhancing Your Comfort and Function Through Upper-Extremity Socket Technology ." In Motion 14.6Dec 2004 20 Sep 2006 <http://www.amputee-coalition.org/inmotion/nov_dec_04/sockettech.html>

Farnsworth, Troy. "The Call to Arms." Active Living Magazine (2004) 20 Sep 2006 http://activelivingmagazine.com/artman/publish/article_22.shtml

Fayad, F., G. Hoffman, S. Hanneton, C. Yazbeck, M.M. Lefevre-colau, S. Poiraudeau, M. Revel, A. Roby-Brami. "3-D scapular kinematics during arm elevation: Effect of motion velocity." Clinical Biomechanics 21(2006): 932-941.

Fraser, C.M.. "Use and Training of Cosmetic and Functional Arm Prostheses." Living Skin. (1999). 20 Sep 2006 http://www.livingskin.com/function.htm

Froster, Ursula, Patricia Baird. "Maternal Factors, Medications, and Drug Exposure in Congenital Limb Reduction Defects." Environmental Health Perspectives Supplements 101(1993): 269-274.

"Glossary of Orthotic and Prosthetic Terminology." Orthotics and Prosthetics Rehabilition Engineering Centre. (2000). 20 Sep 2006 http://oandpcentre.com/glossary.htm

Gray's Anatomy. Ed. Peter Williams. New York: Elsevier Churchill Livingstone, 1995.

Johnson, G., D. Spalding, A. Nowitzke, N. Bogduk. "Modelling the muscles of the scapula morphometric and coordinate data and functional implications ." Journal of Biomechanics 29(1996): 1039-1051.

Kapandji, A. "You Said Biomechanics?." Orthapaedic. 1999. Maitrise Orthopedique. 6 Oct 2006 <http://www.maitrise-orthop.com/corpusmaitri/orthopaedic/mo64_fuzzy_mechanics/index.shtml>.

Klein Breteler, Mary, Cornelis Spoor, Frans Van der Helm. "Measuring muscle and joint geometry parameters of a shoulder for modeling purposes." Journal of Biomechanics 32(1999): 1191-1197.

Kroemer, "Engineering Anthropometry" (1989), Ergonomics, 32(7):767-784

Marieb, Elaine. Essentials of Human Anatomy and Physiology. 5th. Menlo Park, CA: The Benjamin/Cummings Publishing Company, Inc., 1997.

Motion Control, Inc. (2006) http://www.utaharm.com

Murray, Ingram, Garth Johnson. "A study of the external forces and moments at the shoulder and elbow while performing every day tasks." Clinical Biomechanics 19(2004): 586-594.

"Myoelectric Prosthetics." Fit-Well. 2005. Fit-Well. 6 Oct 2006 <http://www.fit-well.com/myopros.html>.

Plettenburg, Dick H.. "Basic Requirements of Upper-Extremity Prostheses: The Wilmer Approach." IEEE Engineering in Medicine and Biology Society 20.5(1998) 2276-2281. 21 Sep 2006

"Prosthetic Devices: using cybernetic devices to enhance human mobility." Prosthetic Devices. WordInfo. 6 Oct 2006 <http://www.wordinfo.info/words/index/info/view_unit/3396/?letter=P&spage=13>.

"Prosthetic Options." Advanced Arm Dynamics. 2006. Advanced Arm Dynamics. 6 Oct 2006 <http://www.armdynamics.com/healthC_prosthetic.html>.

Ritchie, David. "Upper Limb Prosthetics." 06 OCT 2006. University of Texas. 6 Oct 2006 <http://www.utmb.edu/footankle/powerpoint%20pdf%20files/orthotics/Upper%20extremity%20prosthetics.pdf>.

Rosenblatt, Marc. "Dynamic Exoskeletal Orthosis." freepatentsonline. 02 SEPT 1997. USPTO. 6 Oct 2006 <http://www.freepatentsonline.com/5662594.html?s_id=4891f2d1c8e3483db92fa9d3855bc849>.

Rundquist, Peter, Donald Anderson, Carlos Guanche, Paula Ludewig. "Shoulder kinematics in subjects with frozen shoulder." Archives of Physical Medicine and Rehabilitation 84(2003): 1473-1479.

"Scapula." Wikipedia. 1 Oct 2006. Wikimedia Foundation, Inc.. 6 Oct 2006 <http://en.wikipedia.org/wiki/Scapula>.

Sensenig, Andrew, and Schultz, Jeffrey. "Mechanics of cuticular elastic energy storage in leg joints lacking extensor muscles in arachnids." The Journal of Experimental Biology 206 29 OCT 2002 771-784. 06 OCT 2006 <http://www.life.umd.edu/entm/shultzlab/opiliomd/papers/ss2003.pdf>.

Shelkey, Mary, Meredith Wallace. "Katz Index of Independence in Activities of Daily Living (ADL)." Try This: Best Practices in Nursing Care to Older Adults Oct 1998: 1-2.

"Space Suit." Wikipedia. 12 Apr. 2006. 26 Apr. 2006 <http:/en.wikipedia.org/wiki/Spacesuit>.

Stark, Gerald. "Upper-Extremity Limb Fitting." Aug. 2001., Sept. 20. 2006 <http://www.amputee-coalition.org/inmotion/jul_aug_01/primer.html>.

The Arthropods. 2006. University of Alabama. 11 Oct 2006 <http://bama.ua.edu/~clydeard/bsc376/lecture29.htm>.

"Upper Extremity Orthoses." Ortho, Rehab, Inc. . 21 Sep 2006 <http://www.orthorehab.com/web2004/products_bracing_4.aspx>.

"Upper-Extremity Prosthetics." Benchmark Medical, Inc. 2006. 20 Sept. 2006 <http://www.benchmarkmed.com/orthotics/upper_prosthetics.html>.

"Upper Limb Prosthetics Technology." 2006. Liberating Technologies. 11 Oct 2006 <http://www.liberatingtech.com/>.

Vacek, Kris. "Transition to a Switch Activated, 3-S, Transhumeral Prosthesis: A Team Approach." 1998. American Academy or Orthotists and Prosthetists. 6 Oct 2006 <http://www.oandp.org/jpo/library/1998_03_056.asp>.

"Welcome to the BLEEX Project." Berkely Robotics Laboratory. 2003. UC Berkeley. 6 Oct 2006 <http://bleex.me.berkeley.edu/bleex.htm>.