Design of an Arm Rotation Assistive Device

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Abstract

People with limited arm function due to health issues such as stroke, cerebral palsy, or muscular disease often have difficulty completing activities of daily living (ADLs), such as feeding themselves and brushing their teeth, without assistance. The goal of this project is to design and manufacture a device that assists those with limited arm function in completing ADLs. Such a device must support the user's arm weight and assist with vertical and horizontal motion. Our final design accomplishes the desired horizontal motion through a three bar link system and the vertical motion is achieved through two hinging bars that are actuated by elastic resistance bands. After building our design and testing elastic band resistance, we found that our device successfully achieves the desired motions, though a few key improvements would significantly boost the device's competitive edge with other products on market.

Acknowledgements

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Introduction

This project focuses on the design, production, and analysis of an assistive device to aid a person with the rotation and lifting of a weak arm. This device would be used to support, not rehabilitate, a person's ability to perform basic activities of daily living (ADL) such as feeding themselves or brushing their teeth. People who need this device or could benefit from it include, but are not limited to, those with reduced muscle strength. This can be caused by cerebral palsy, stroke, muscular disease, neurological disease, or injury but the most common of these is stroke. In the United States alone more than 700,000 people suffer a stroke each year, with 80% of survivors experiencing some form of arm weakness (National Institute of Neurological Disorders and Stroke, 2014). As a result of this, many stroke victims struggle to live independently and require a second party caregiver to assist with daily tasks. The goal of this project is to design a device to assist in lifting and rotating an arm of a person who requires physical assistance.

Background

In order to understand the scope of the project we conducted thorough background research. We first researched medical conditions which result in limited arm mobility in order to pinpoint the range of motion and type of physical assistance that the product must provide. Using this information we determined the device must assist motions of activities of daily living (ADLs) which are the daily tasks required to live independently. To ensure the device can assist ADLs, we researched the specific arm motions required for various tasks like brushing teeth, eating, and combing hair. Lastly, we researched existing products on the market, specifically looking at what these products can achieve, what their shortcomings are, and how they compare to the functional requirements.

Prevalence

There are a variety of medical events that can affect an individual's arm motion. A severe case is monoplegia, or paralysis of a single limb, which most commonly affects an arm. This type of paralysis is most frequently the result of a stroke, but is also found in individuals who suffer from brain injury, multiple sclerosis, motor neuron disease and more (Monoplegia, 2017). In the United States alone according to the National Institute of Neurological Disorder and Stroke (NINDS), 700,000 people will suffer from a stroke this year with about 80% of the survivors experiencing some degree of monoplegia (Post-Stroke Rehabilitation, 2019). Limited arm motion is not exclusive to extreme cases of arm paralysis, but can also be an effect of muscle atrophy or spasticity which is caused by a multitude of medical conditions such as ALS, muscular dystrophy, and neuropathy (Eske, 2019), and can create severe arm weakness. In both cases, whether it is individuals with no movement in their arms, or those with weakened strength in their upper limbs, completing daily tasks by themselves become more difficult.

Activities of daily living (ADLs) are key life tasks that are routine aspects of self-care (Edemekong, 2019). In order to live independently individuals need to be able to perform the functions of eating, bathing, getting dressed, transferring, and toileting, without assistance. While the inability to execute these ADLs is most prevalent in the elderly, the loss of arm function or strength can have a severe impact on an individual's ability to complete these tasks at any age.

Mental Health and Activities of Daily Living (ADLs)

Research suggests that there is a strong correlation between physical ability and mental health. This is important because the distinct concept relating quality of life, disability, and depression plays a large role in the need for available assistive devices. Several researchers have consistently reported findings showing that those who suffer from physical illness for an acute period of time at any age are prone to high psychological distress. Furthermore, longitudinal studies have presented significant data proving that chronically physically disabled people are extremely likely to experience social isolation and depression (Turner, 1988). Physical disabilities, such as a weak arm, often contribute to feelings of frustration and unhappiness when they interfere with ADLs. The inability to complete repetitive, necessary tasks each day is a constant reminder of a person's disability and dependence on others. One study quantified the depression of post-stroke patients, concluding that there was "a significant relation between the patient's level of depression and Barthel score [The Barthel scale is an ordinal scale used to measure performance in activities of daily living. Each performance item is rated on this scale with a given number of points assigned to each level or ranking], with those with impaired

ADL having more major depression than those with minor depression” (Asa Franzén-Dahlin, 2005).

Taking into account the significant impact of physical disability on mental health, one of the goals of our arm rotation assistive device is to improve the quality of life of the user by making ADLs more effortless and less stressful.

Arm motions of ADLs

The upper-limb provides a wide range of motion and multiple degrees of freedom through each joint, which makes it difficult to identify the exact motions required to perform every activity of daily life. To help determine the types of arm motions involved in performing ADLs, we looked into a study conducted on ten able-bodied men performing three tasks: eating with a spoon, eating with a fork, and drinking from a handled cup. Through this study it was determined that there are three shoulder joint rotations, one elbow joint rotation, and a forearm joint rotation needed to successfully perform this task. The motion required for the feeding tasks were found to be 5° to 45° shoulder flexion (Figure 1), 5° to 35° shoulder abduction (Figure 1), 5° to 25° shoulder internal rotation (Figure 2), 70° to 130° elbow flection (Figure 3), and 40° forearm pronation to 60° forearm supination (Figure 4) (Safaee-Rad & Shwedyk & Quanbury & Cooper, 1990).

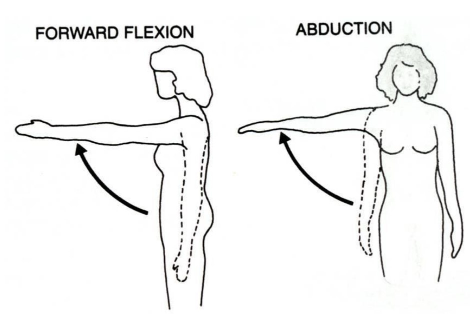


Figure 1. Shoulder Flexion and Abduction

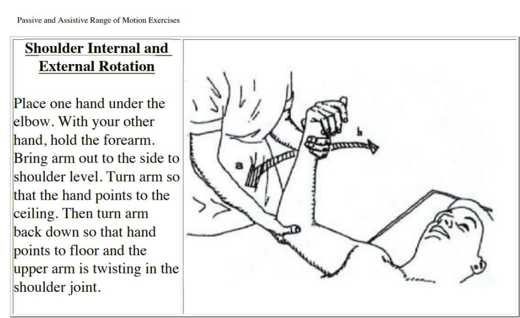
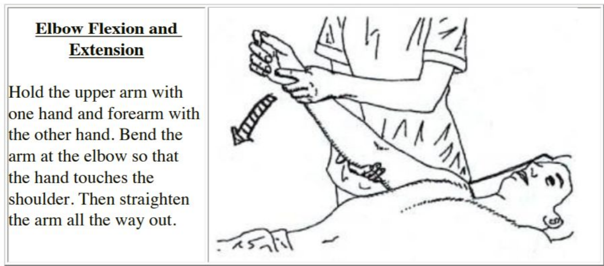


Figure 2. Shoulder Internal Rotation



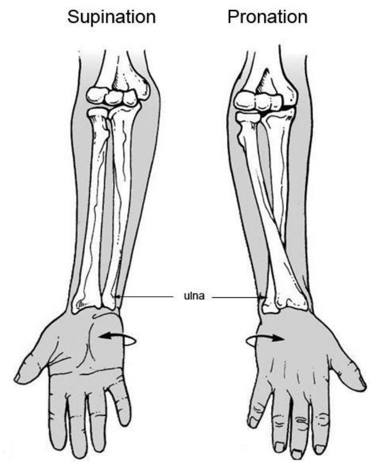


Figure 3. Elbow Flexion and Extension *Figure 4. Forearm Supination and Pronation*

Existing Products

There are a multitude of existing products available to assist in ADLs. These range from task-specific products like robotic feeders to rehabilitation devices to dynamic arm supports. Our project is to design an arm rotation assist device that will be capable of assisting a variety of ADLs and which aligns closely with some of the existing dynamic arm support technologies.

Largely due to the adjustability and functionality ranges of these existing devices, they tend to be expensive when purchased without insurance. For example, Performance Health sells an anti-gravity arm mobility aid, the JAECO/Rancho Multilink Mobile Arm Support, shown in figure 5, that can be adjusted to fit the right or left arm and can be mounted to either a wheelchair or table. However, because of this adjustability, the company sells the product in three parts: the wheelchair or table mount ($485 and $199 respectively), the forearm support ($264), and the multilink anti-gravity support which comes in ‘standard’ for $156 or ‘elevating’ for $724 (Feeders & Arm Supports, n.d.). Saebo, another assistive device supplier, sells an anti-gravity arm mobility aid, shown in Figure 6, that costs $1,999 for its mini version and does not list a price for the standard version (SaeboMAS, n.d.).

Figure 5: Performance Health's JAECO/Rancho Multilink Mobile Arm Support

Figure 6: Saebo Mobile Arm Support (SaeboMAS)

Many of these devices are complex and bulky, requiring a company representative to deliver and set up the device. Requiring a third party for set up and delivery contributes largely to the high price of the product and lessens the feeling of independence the device is meant to promote. A bulky device brings more attention to the user and often limits the user's mobility.

Based upon our research on existing products, there are a variety of product characteristics that would set our design apart and meet the needs of people with weak arms. These include but are not limited to, low cost, simple assembly, and compact design.

Existing Patents

There are a plethora of existing patented products that are designed to assist weak arms. Utilizing patent research has been essential to the design process as we legally can not infringe on patent rights. Many existing products describe themselves as “rehabilitation devices”. This terminology differs greatly from our design goal in creating an assistive device. We are not attempting to rehabilitate people who suffer from a lack of rotative motion in their arms. Instead, our design is aimed to make activities of daily living easier. One of these comparable devices with patented technology is called “Adaptive arm device” (Hoffman 2012) which is shown in figure 7 below. This device is used mainly to assist a person with tremors to complete activities of daily living. It can be mounted to either a table or a wheelchair using an anchor mechanism that has a rod and a screw. The motion of this patented device also uses five separate axes that each dictate the motion of the members as shown in the figure below.

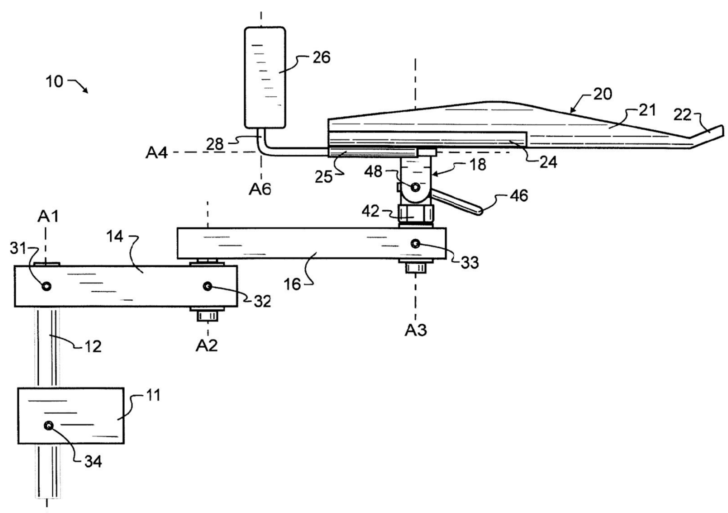


Figure 7: Image of the patented Adaptive Arm device, showing the five separate axes of movement

As previously mentioned, Saebo also offers a device that is used to assist individuals with ADLs; the design is shown in figure 8 and is also patented (Berglund 2003). This device helps users with things like feeding themselves and brushing their teeth. However, like the previously mentioned patented design, it is meant to help people who have more arm function than our intended users. This arm support was created utilizing a pulley mechanism as a tensioner. Furthermore, while this product is transportable, it is not attachable to a table or a wheelchair.

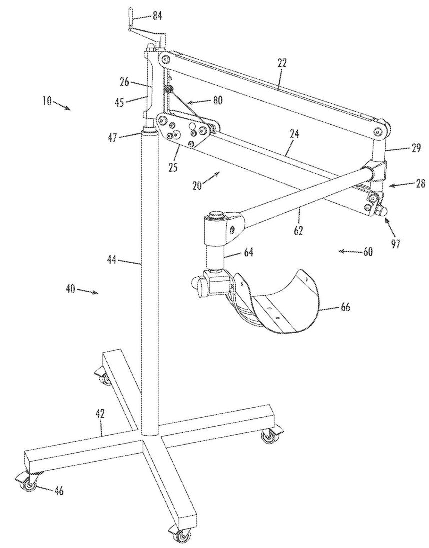


Figure 8: Image of the patented Sabeo device with labels for the different members

Although there are many patented products in this market space, our design is not modeled after one specific product nor does it utilize all of the components of a singular patented product. Instead, we took inspiration from these existing devices to create a device that fits our functional requirements and does not infringe on any patented rights.

Federal Guidelines

Although there are many federal guidelines for medical devices, there are less for assistive devices. Many of these federal guidelines protect American's use of assistive technologies in both public and private settings. For example, the Americans with Disabilities Act protects an individual's right to choose the device that best assists them in their mobility.

However, the Food and Drug Administration (FDA) has guidelines for upper extremity prosthesis including a simultaneously powered elbow and/or shoulder with greater than two simultaneous powered degrees of freedom and controlled by non-implanted electrical components. Although this type of device is not exactly what we have designed for, it is helpful to look at the criteria by which this device had to meet in order to become approved by the FDA. These guidelines provide some important requirements that we will keep in mind during the design process including, but not limited to, utilizing flame retardant materials and providing clear documentation, device assembly instructions, patient fitting instructions, and device maintenance instructions (CFR, 2018).

Functional Requirements

In order to create a design we first created a list of functional requirements that we wanted our product to meet. Ultimately we decided on twelve of these requirements which we used as a rubric to which we could uphold our design. These requirements are oriented around adaptability, manufacturability, ergonomics, spatial constraints, and arm motion.

1. Must support the arm of males in the 40+ age range
2. Must support an arm of length between the 5th and 95th percentile for men in the 40+ age range
3. Must assist in elbow flexion and extension and shoulder flexion and abduction
4. Must support at least 90% of the user’s arm weight
5. Must achieve motion in three dimensions
6. Materials and mechanisms must comply with federal standards
7. Must cost less than $400 to make here at WPI
8. Must support either left or right arm disabilities
9. Must be able to attach to a variety of surfaces
10. Can be assembled within 5 minutes using common household tools
11. Must occupy less than 24” x 24” x 24” spatial volume when in use
12. Must fit into a 18” x 18” x 18” box for packaging and mailing purposes

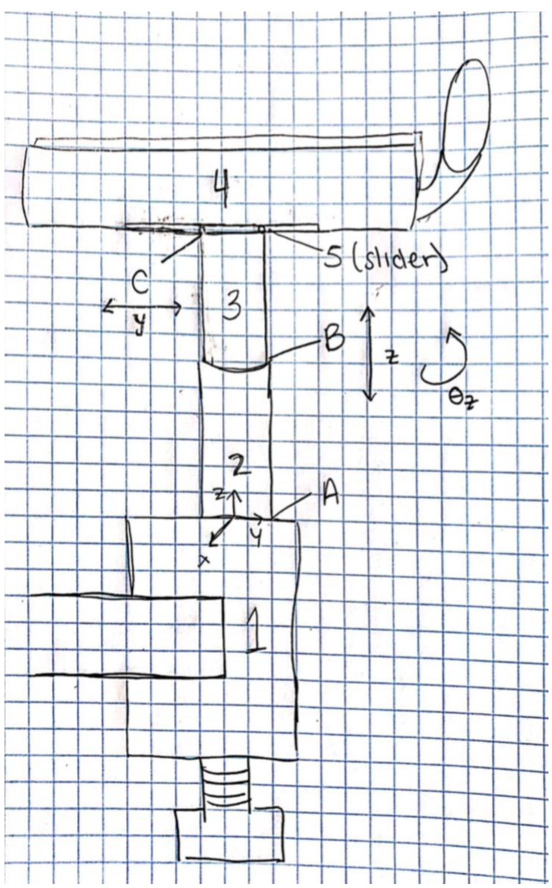
Design Process

We followed the engineering design process to come up with a design that meets all of our functional requirements. The process includes defining the problem, researching existing solutions, conceptualizing innovative solutions, selecting the design, prototyping, testing, and ideating. In this section we discuss our approach in the design process.

Design Concepts

In order to achieve our functional requirements, we created two main designs for our product. The first conceptual design we came up with was a slider and spring mechanism. This design is mounted to a table by a C-clamp. Attached to the C-clamp by a pin joint is a rod that rotates about the Z axis and can be extended in the positive Z direction using a either a motor-actuated or spring actuated elevation mechanism not shown in Figure 9. A slider mechanism is rigidly connected to the top of the rod, and is capable of extending in the X-Y plane in order to provide three-dimensional range of motion. The arm support is mounted to the slider mechanism on the top of the rod.

The second conceptual design we created was a three bar linkage system that is actuated by an elastic band. The three bar linkage accounts for motion in the horizontal plane. In addition, this design includes a forearm support that will be ergonomic and will take into consideration the comfort of the user. This design concept can be seen in Figure 10 below.



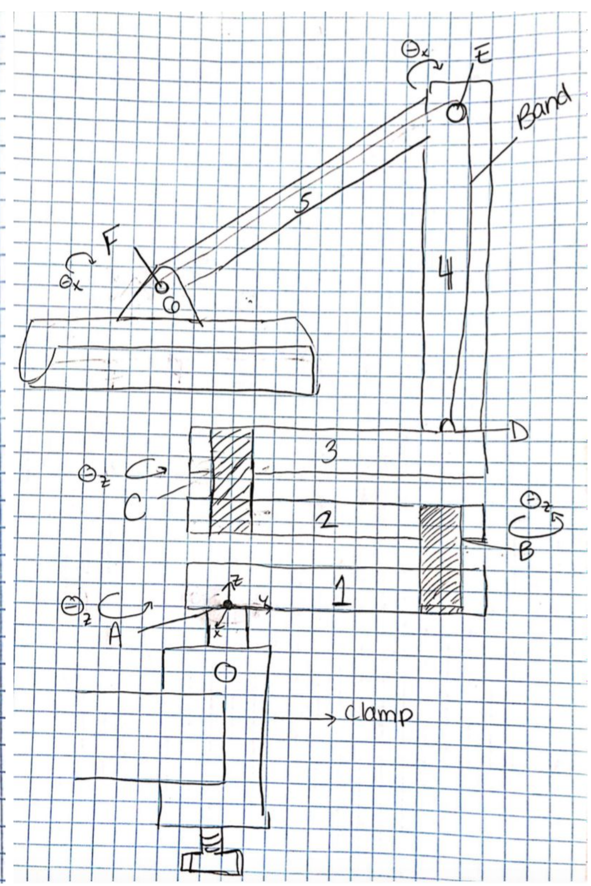


Figure 9: Slider and Spring *Figure 10: Three Bar Linkage*

Design Selection

After attempting to come up with more designs, we found that each design consisted of the same main components: a vertical motion actuation method, a horizontal motion mechanism, an attachment mechanism, and a forearm support. In order to decide on a design, we created multiple decision matrices, one for each main design component. An example matrix for actuated method can be seen below in figure 11. Actuation was one of the major decisions we had to make since it would have the greatest effect on cost and performance. We had come up with four different methods of actuation including a spring, elastic, pulley, and a motor. We compared each of these methods to different criteria. These included cost, adjustability, support capability, and maintenance. We weighed each on a scale from 1 to 5. With 1 being poor and 5 being very good. We then totalled up all the weighted scores to get the final column of the chart. From this matrix we found that the Elastic had the highest score, thus we decided to use an elastic band as the actuation method in our prototype.

	Cost	Adjustability	Support Capability	Maintenance	Total Weighted Score
Weight of Criteria	5	4	5	3	
Spring	4	3	4	4	64
Elastic	5	5	4	4	77
Pulley	3	4	4	3	60
Motor	2	5	5	3	64

*Scored on a scale of 1 (Not good) to 5 (very good)

Figure 11: Decision matrix used to determine actuation method

For the other design components, we selected a 3-bar linkage system as the horizontal motion mechanism, a C-clamp as the method of attachment to the required surface, and a forearm support with a one sided elbow hook. The rest of the matrices can be found in Appendix I.

3D Modeling

Using our decision matrices, we were able to move forward with the design process. We selected our mechanism of actuation and each component of the design, then used the computer aided design software Solidworks to create a model of the device. We also used Solidworks to make adjustments until we obtained desirable dimensions that would work for our concept and motion. After multiple iterations and force analysis calculations, we have our complete design concept that can be seen in the figures below. From this model we created ASME standard drawings (American Society of Mechanical Engineers) as well as used it to manufacture our machinable parts. This model will also be the basis to any iterations.

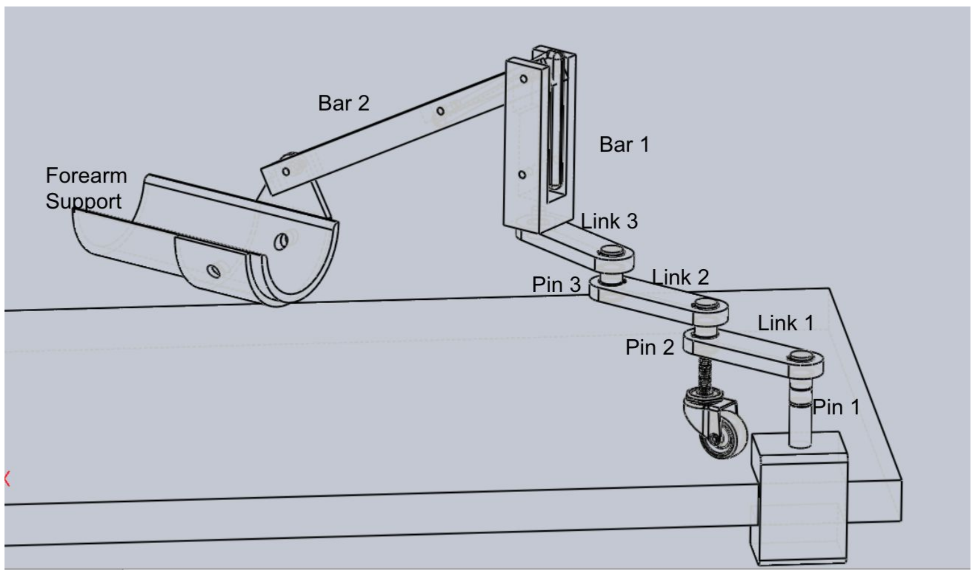


Figure 12: Wire frame view of design concept

Detail Design Description

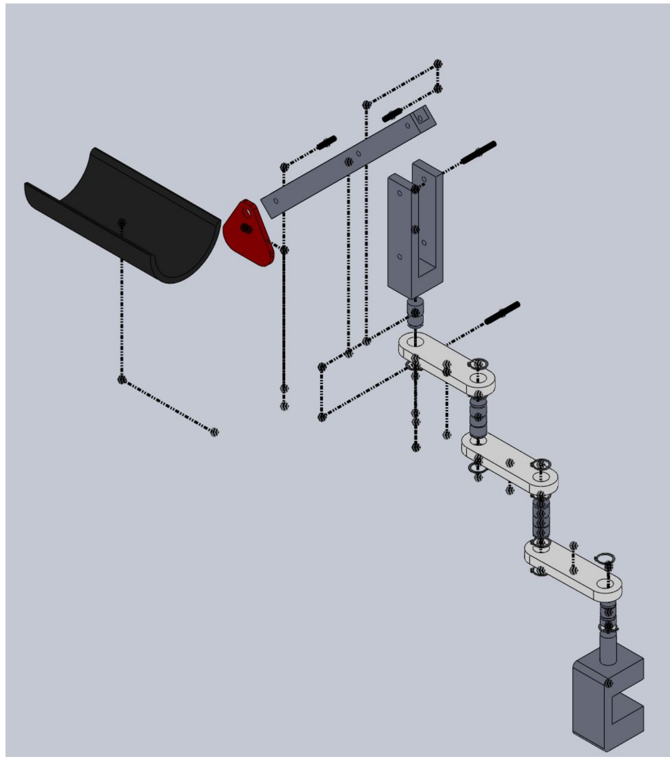


Figure 13: Exploded view of assembly

The final iteration of the arm support design is pictured above in Figures 12 and 13. It consists of a steel C clamp that is adjustable and attaches to standard tables and surfaces. The linkage system is made up of three links that are connected by steel pins, which are contained by retaining rings. The top link is connected to the vertical bar through a press-fit steel pin in the bottom of the bar. The arm support bar is connected to the vertical bar by a top pin that allows for vertical motion of the arm. The arm support bar is connected to a triangular attachment plate with a pin. This plate is attached to the forearm support. The elastic bands are stretched from the bottom of the vertical bar to the top of the arm support bar by being wrapped around removable pins. The elastic band is not pictured. Engineering drawings of our final design can be found in Appendices 8-17.

Analysis of Materials and Dimensions

To ensure that our final design and prototype meet our functional requirements, we needed to decide on materials and dimensions for each design component. The following sections discuss the rationale for each of our material and dimension choices.

Materials

For our design, we chose our materials based on strength, durability, function, and cost. The majority of our parts were made either from Aluminum 6061 or 4140 Alloy Steel. The following section describes our decision process for materials.

<u>Aluminum 6061</u>

The three links and two bars were made out of the aluminum. We selected aluminum 6061 for these parts because the material has a high yield strength of 276 MPa. With this yield strength we knew this material could withstand the amount of force that would be applied to these parts. A complete force analysis for this material can be found in the following section. The material properties for this material can be seen in Appendix II. Furthermore, this material is cost effective; for the raw aluminum stock used to make the links and two bars, we spent $110.61.

<u>Steel</u>

For our pins, we chose hardened 4140 alloy steel. After speaking with laboratory staff in Washurns shops, we determined that this material would work best for machining in the lathe and would best fit the design functionality by withstanding potentially high stresses and reducing wear and tear from aluminum-aluminum interactions. In addition to the pins, we created our custom C-Clamp using this steel.

<u>PVC Pipe</u>

For the forearm support we utilized a combination of different materials. For the main holding piece we used a 5-inch PVC pipe. This material was highly accessible for free at Washburn Shops. The curve size of this PVC pipe was able to comfortably fit a human forearm.

Adhesive Foam

For the inside of the forearm support we purchased latex free adhesive foam. This foam will make the support more comfortable and easy to clean for the user. We planned to adhere this to the PVC pipe using velcro which will allow for easy removal.

Resistance Bands

With the help of the decision matrices, we decided upon elastic band resistance as the actuation method for our device. These bands are far cheaper than many of the other actuation methods and can allow for easy adjustment in resistance level with the addition of more bands. For our device we purchased resistance bands that are conventionally used for exercise purposes. Further explanation on the performance of this material can be seen in the Virtual Testing Section of this paper.

Dimensions

One of our functional requirements was that our device would fit into a 24” x 24” x 24” box for packaging and mailing processes. We wanted to keep this in mind when deciding the design component dimensions. Knowledge of the desired function of our device and the anatomy of the 5th to 95th percentile of males' arm lengths and weights also had an impact on our dimension decisions. A table of the final design’s dimensions can be found in Appendix III.

Analysis

From the free body diagram of our selected design shown in figure 14, we see that the first joint, connecting pin 1 and link 1, bears the highest stress and moment. To ensure that this joint or the first link does not fail, we calculated the effects of the worst-case load applied to the mechanism. We did this to ensure the device does not sink to an uncomfortable level for the user or does not break when in use.

The worst-case loading was assumed to take place when the mechanism is fully extended and the arm is elevated to the maximum angle between bars 1 and 2, as shown in figure 14.

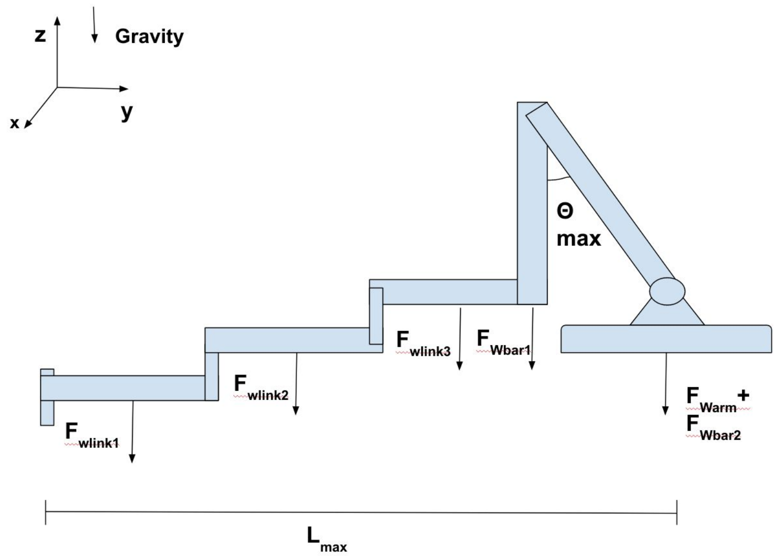


Figure 14: Free Body Diagram

Deflection

To calculate the deflection, we utilized the following equation:

$$\delta \;=\; F a^2(3L - a)/6EI$$

Where F is the applied force at distance a, from pin 1, L is the total length of the fully-extended mechanism, E is the material's elastic modulus, and I is the moment of inertia of the link. Since there are loads acting at various locations along the length L, we utilized the principle of linear superposition and summed up the deflections that resulted from each force. In the end we found that the deflection on link 1 was .019 mm, on link 2 was .017 mm, and on link 3 was .017 mm. This results in .052 mm vertical displacement which is insignificant to the user. The calculations can be found in Appendix IV.

Shear Stress

The maximum shear stress on link one can be found with the equation for rectangular cross sections:

$$\tau_{max} = 3V_{max}/2A$$

Where V_{max} is the maximum shear force on the link and A is the link's cross-sectional area. To find V_{max} we utilized the principle of linear superposition and found the maximum internal shear force acting on the mechanism. From this we see that V_{max} acts on link one. From this $V_{max.,}$ we calculated the maximum shear stress and compared it to the material's shear strength. In conclusion, τ_{max} is .309 MPa, which is less than Aluminum 6061's shear strength (207 GPa), so link one, nor any of the other links, will fail under worst-case loading. The calculations can be found in Appendix V. The following figure X shows the plot of the shear stress as a function of distance from the clamp.

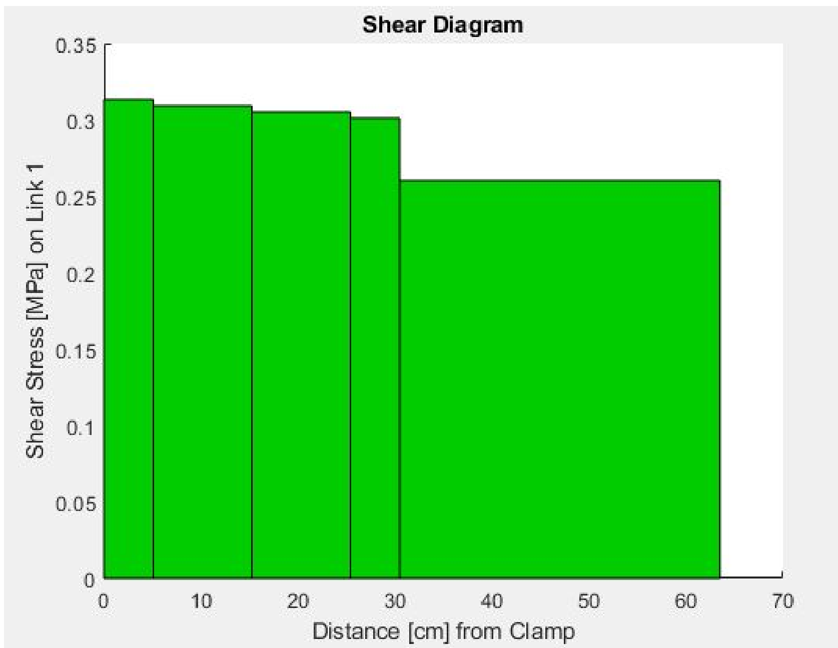


Figure 15: Plot of Shear Stress versus Distance from Clamp

Tear Out

In our design, there are two pins that will experience the greatest amount of force. These can be seen in figure 14 th free body diagram above and are pin 1 and the top pin. In order to see if these pins will experience tear out we utilized the following equation:

$$\boldsymbol{\tau}Tear= F/2A$$

Where F is the force being applied onto the pin, and A is the area of tear out. Area of tear out is described best in the image in figure 16 below from Norton's Machine Design. For the top pin this equation becomes:

$$\tau_{Tear} = F/4A$$

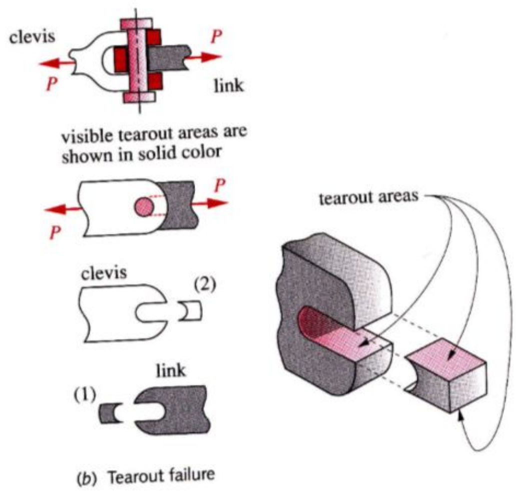


Figure 16: Tear out area from Norton's Machine Design

We used this second equation because at this spot the force is acting on two areas. Through our analysis of pin 1 we found that the τ_{Tear} at this site would be $2.058*10^5$ Pa. This is far lower than the shear strength of the aluminum material that we used in our design which has a shear strength of 207 Gpa. The top pin goes through both bar 1 and bar 2. Thus we analyzed the possibility of tear out at both of these sites. Through bar 1 the τ_{Tear} is $1.71*10^5$ Pa and the τ_{Tear} of bar 2 is $4.81*10^5$ Pa. These are also lower than the shear strength of the aluminum we are using which is at 207 Gpa. Thus we concluded that these two pins will not experience tearout. A complete analysis can be found in Appendix VI.

Manufacturing

After conducting our analysis and finalizing our design, we began the manufacturing process. Our manufacturing process was on schedule, however, unfortunately due to unexpected circumstances our access to the machine shop and the necessary tools was cut short. We were able to manufacture the majority of the parts needed for our device. Our manufacturing process took place mostly using Washburn Machine Shops on campus.

Material Availability at WPI

At the beginning of the manufacturing process we met with lab staff at Washburn Shops. We discussed our design constraints and drawings and determined the feasibility of manufacturing with the available machinery. In addition, we discussed the availability of material at WPI. We chose the mini-mill and the lathe to machine our parts as they work well with our materials: Aluminum 6061 stock and hardened 4140 Alloy Steel. These materials and the majority of the materials for the device were not readily available at WPI. Instead, we ordered these materials from third party vendors, namely Amazon.com and Mcmaster-Carr. PVC pipe was available at WPI for free. After this preliminary discussion we were able to establish a strategy and sequence of how we wanted to complete the manufacturing process.

Strategy and Sequence of Manufacturing

To begin manufacturing we started by machining the least complicated part of the assembly in order to familiarize ourselves with the machines. The first parts manufactured were the three links. Most of the machines used in the manufacturing of the device were CNC machines. Before machining we first created a file utilising a CAM software available at WPI called Esprit. The Esprit program was able to simulate the stock, tools, tool paths, and operations that we would be using on the real machine to manufacture our device components. For the three links we had a stock material of aluminum 6061 which was machined on a Haas Mini-mill using a range of tools which can be seen in Table 1 below. We utilized Washburn Shop staff in order to ensure the safety of all team members and maintain the integrity of the machinery. After the first link was finished, the manufacturing process was much faster for link 2 and link 3. The same Esprit file and machine tools could be used for all of the links. Machining in the mill resulted in sharp edges on each of the links which could be dangerous for the user. We smoothed the edges of each link with metal files to avoid this problem.

There was no clamp that could be purchased that met our design needs. We needed our clamp to have a bar coming out of it in order to attach the rest of our assembly to the table. Thus we had to manufacture our own clamp. The clamp we manufactured is a sliding T bar in order to allow users to use the device in different locations to meet our functional requirements. As well as has a steel rod coming out from the side of the clamp in order for the linkage system and pins to be attached. The clamp we manufactured has a holding capacity of 3,500 lbs. This capacity far exceeds the holding capacity needed for our device and the users arm.

Next, we worked on the machining of bar 1. For this bar we followed the same process as we did for the links by creating an Esprit file then using the Mini-mill. The types of tools and operations we used can be seen in Table 1 below. The final piece that was machined in the mini-mill was bar 2. This bar was by far the most challenging up to that point in the process. One of the main issues in manufacturing this bar was that the material stock length required to machine it was too long for the mini-mill. When setting our work offsets on the mini-mill, we realized that the probe in the x direction was having difficulty reaching each end of the bar to locate the origin of the stock. In order to resolve this issue, we had to relocate the vice in the machine a few inches in the negative x direction so that the probe was able to reach both ends of the bar. An additional issue that arose from the length of the bar was during the pocketing operations. The bar was overhanging the clamp, vice, and parallels by a few inches on each side, which caused a lot of chatter during the pocketing operation (it functioned like a tuning fork with a high pitch resonating from the shape). Finally, drilling the holes in the side of the bar once it was flipped on its side was not completely successful. The initial peck for the tool to locate the hole location was successful, however the force of the drill when going all the way down through the material caused it to rise off the parallels at a slant. Due to the safety concerns this raised, we decided the best way to make the holes was to use a drill press instead.

The final step was to manufacture the four unique pins from steel each with four stepped diameters. For stock material we used 4140 hardened alloy steel to be machined on the CNC Lathe in Washburn shops. However, this process revealed many issues. Just like for the other parts, we created an Esprit file detailing the tools and sequencing that we wanted the lathe to perform. After probing and calibrating the lathe and loading the tools we machined the first pin. Immediately after machining we knew the pin was not machined correctly One of the 4 grooved stepped diameters was missing from the pin. This was odd considering the Esprit file accounted for that fourth diameter. After speaking to lab staff we came to the conclusion that the probe on the machine itself was bent. This was then causing the stock material to be pushed back into the machine causing the dimensions to be inaccurate as the computer program was no longer aware of where the operations were happening in reference to the actual stock. This was not an issue that we as a team could solve. We also had sacrificed a large portion of our stock material attempting to find solutions to this issue. As a team we came up with a list of solutions in order to overcome the issue at hand and had decided to try and use a manual metal lathe to create our pins using an outside machine shop.

Tools Used on Haas Mini Mill	Operations used on Mill
½" Endmill	Facing
¼" Endmill	Pocketing
⅜" Endmill	Contouring
3" Round Insert Facemill	Tapping
	Drilling
	Roughing

Table 1: Tools and Operations we used during manufacturing on the Haas Mini Mill

Tools used on Lathe	Turning Operations on Lathe
Square Grooving tool	Facing
Cutoff Tool	Cutoff
35 degree insert	Contouring Cycle
55 degree insert	

Table 2: Tools and Operations we used during manufacturing on the Haas Lathe

Assembly

One of our functional requirements was that this device could be assembled in under five minutes using common household tools. After preliminary assembly testing throughout the manufacturing process, we found that link 1 and pin 1 can easily and quickly be attached to the C clamp using a small bolt wrench. The other pins can also be quickly and easily assembled without any tools. Furthermore, bar 1 and bar 2 can also be attached without any tools. The most difficult and time consuming part to assemble is the resistance band. We did not design for enough space to fit the band in easily. This would likely cause assembly to be longer than 5 minutes and make it more difficult for a single person to assemble the device.

Testing

A major part of the design process is testing and ideation. In order to quantify a design's (or design component's) functionality or ensure that a design meets specifications, prototype testing must be completed. The results of those tests provide insight regarding how the design can be improved in future ideations. The following section details both the testing we have completed on our design and the required testing that still must be done to ensure the design meets our functional requirements.

Completed Testing

The first part of our mechanism we decided to test was the resistance bands. The purpose of this test was to confirm that our actuating mechanism successfully raised bar 2. In order to accomplish this we cut and attached a 3 lb resistance band to bar 1 and bar 2. By doing this test we realized that the 3 lb resistance band selected did not have a high enough resistance to raise bar 2 over the force of gravity. We then laid bar 1 down horizontally eliminating the need for the resistance band to fight against the force of gravity. This resulted in bar 2 raising. This test proved that a higher resistance elastic could raise the weight of the long bar and the user's arm, though the dimensioning of the elastic band grove's would prevent the required band size from being attached to the mechanism.

Required Testing

The following sections discuss the testing that still must be completed in order to ensure the design meets functional requirements and works efficiently and smoothly for the user.

Resistance Band Testing

The elastic resistance bands require more testing to improve the functionality of the device. Testing to find the spring constants of different bands, would allow us to find the correct band weight that could assist the users arm up to 90% of their arm weight. After some rudimentary testing we know that to attain this information it would be necessary to test bands weighted at 30, 40, 50 and 60 lbs. These high resistances would allow us to manipulate the bands, by cutting them in half vertically and horizontally, to fit our mechanism and quantify how much the bands resistance the bands supply after such manipulation. An example test involves attaching one side of the band to an elevated hook and attaching known weights to the other end. During this test we would measure the elastic stretch of the band and observe for any signs of failure with the added weight. This test would provide the spring constant of the band after whatever form of manipulation was used. With the known spring constant of the bands, we would be able to calculate whether or not that band can support the weight of both the device and the user's arm, and if not, would allow us to quantify how much more resistance would be required.

Additional Testing

Once the elastic band types and resistances are determined, the next tests required would assess the performance of the final device with respect to the functional requirements. Most importantly, we would test the device to confirm that it assists the ADL of feeding oneself. This test would show if the device is capable of supporting, lifting, translating, and rotating the desired arm weight and length as well as provide insight on how comfortable the arm support is for the user. Another test would be to measure the time it takes for a non-team member to assemble the entire device. This would allow us to determine if our device is easy to assemble for those unfamiliar with the components and if it can be done in under 5 minutes as the functional requirements mandate. Finally, since we wanted our device to work on a multitude of surfaces including a kitchen table, bathroom countertop etc., we would test the attachment mechanism, the device's functionality, and the ease of assembly on these different surfaces.

Conclusion and Recommendations

At the conclusion of this project, we reflected on the design's overall success in meeting the desired functional requirements. The following section details our conclusions and recommendations for future work.

Does our Design Satisfy the Functional Requirements?

To assess the success of our final design, we reflected on the original functional requirements. Overall, the device satisfies the functional requirements, with a few exceptions. First, the device is not able to easily attach to a table with a common c-clamp. This is because the rest of the device must be removed before loosening or tightening the c-clamp, which is not an easy task. Instead, we designed a new clamp that is capable of being adjusted without removing the rest of the device, but this is not a "common" clamp as stated in the functional requirements. Second, the device as detailed in our design drawings cannot be assembled within 5 minutes using common household tools. This is largely because of the elastic bands, which are difficult to attach when extended. Lastly, since we were unable to finish building and testing the device, we are unsure if the device fulfills the requirement to support at least 90% of the user's arm rate. While we can quantify how much resistance the bands would need to meet this requirement, the size limitations on the band could prevent the use of such a high-resistance band.

Our device did successfully achieve motion in 3 dimensions, cost less than $400 to make at WPI, and support an arm length of a 40+ year old male in the 5th to 95th percentile. Overall our device did achieve its main goal of being able to assist in the lifting and rotating of a weakened arm, though a few key improvements would significantly boost the device's competitive edge with other products on market.

Strength and Weaknesses of Final Design

While the conceptual design of our device is very strong, meaning it is capable of assisting those with weakened arms complete ADLs at a low price point, there were a few specific design choices that resulted in weaknesses in our final prototype. One weakness is the attachment mechanism of the elastic bands. While most of the device is easy to assemble with common tools, the elastic bands are quite difficult to attach due to their resistance. With our design, the elastic bands must first be looped through one pin which is then screwed into place. Then, the band must be stretched and looped around a second pin which is then screwed into place. Attempting to loop the stretched elastic band over the second screw is quite difficult, especially at high resistances.

A second design flaw is the dimensions of the groove in which the elastic bands sit. In the design phase, we assumed we would be able to obtain an elastic band of small diameter and high resistance. However, after manufacturing the device with the small depth and width dimensions of the groove, we had difficulty finding an elastic band that had the required resistance and which fit within the groove. A deeper and wider groove would have allowed for more options for elastic band materials and resistances as well as elastic band attachment mechanisms. Since the grooves were so small, we were unable to find a clasp small enough to allow for multiple bands (adjustable resistance) to fit in the groove and therefore had to rely on "looping" the bands around the pin.

The last major design flaw was the lack of a locking mechanism in the original design. We realized, albeit a little late, that once the elastic bands are attached to the mechanism, the forearm support will be elevated when the device is not in use. This makes it difficult for the user to get their weak arm into the forearm support when they want to use the device. To combat this, we came up with a chain and clasp locking mechanism. This means that the user must lock the device in place prior to removing their arm from the forearm support, which is easy to forget.

Recommendations

Though our device was successful in its ability to help a person complete ADLs, there are several key design changes that would improve its overall function and boost its competitive success if it were to go to market. Additionally, there are various tactics we would adopt if we had the chance to start the project over from scratch that would further bolster the success of this project.

<u>Design Changes</u>

1. Elastic Band Attachment Mechanism

A major design change we recommend is a new elastic band attachment mechanism. With the current design, the elastic bands are meant to be either looped or hooked around the pins on both the vertical and horizontal bars. Once the band is secured around one pin, it must then be stretched to be secured around the other. As the bands have enough resistance to lift an arm, this stretching is not an easy task when trying to assemble the mechanism or adjust the resistance level. We recommend a new design for this system that allows the user to more smoothly and effortlessly attach the elastic bands.

2. Locking Mechanism

   We recommend a locking mechanism be included in the design of the device. With the current design the forearm support will raise without any arm weight in it due to the high resistance of the bands needed for actuation. Thus it would be impossible for the user to get their arm into the device unless it is locked into place. We recommend a design including a locking mechanism to ensure the safety of the user as well ease of use of the device.

3. Pin and Link Dimensions

   We recommend that the dimensions of the pins and links be changed in order to make them standard. During the manufacturing process it was difficult to machine the unique parts. By changing the dimensions of the pins and links to common dimensions, the manufacturing process becomes simpler and quicker as the parts can be ordered. Furthermore, it also allows the opportunity to order replacement parts if the device needs maintenance.

4. Elastic Band Groove Dimensions

   Another recommendation would be to widen and deepen the groove dimensions of bar 1 and bar 2. We originally assumed we would be able to buy resistance bands of small thickness, but that was not the case. The original small dimensions made it difficult to fit a band of the required resistance and made assembly difficult. Furthermore, the grooves could not fit multiple resistance bands which is required to make the device adjustable for users with differing arm weights or abilities. We recommend making the dimensions of the grooves of bar 1 and bar 2 larger in order to make assembly of the resistance bands easier as well as to allow for additional bands for adjustability.

Design and Manufacturing Process Changes

1. We would design for easy manufacturability by using common pins and links.
   By not using commonly dimensioned pins and links, we tacked on additional manufacturing time as well added additional opportunity for manufacturing errors. If we were to start over we would pay greater attention to the Design for Manufacture and Assembly (DFMA) guidelines in order to lead to an easier manufacturing process.
2. We would test the elastic actuation with a small prototype early on.
   By testing the elastic actuation method earlier on we would have additional time to determine the right band necessary for actuation. In addition, earlier testing could have demonstrated the need to redesign the grooves in bar 1 and bar 2 to make them larger before manufacturing them.
3. In the ideation phase, we would reflect frequently on our functional requirements.
   Reflecting more consistently and frequently on our functional requirements could have improved manufacturing decisions as well as enabled us to deliver the best product possible for consumers.

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Appendices

Appendix I: Decision Matrices

Forearm Support Design				
	Cost	Adjustability (2 =not arm specific; 1=arm specific)	Mobility	Total
weight	4	4	5	
elbow pad	5	2	3	**43**
One sided elbow hook	5	1	4	**44**
Forearm + upper arm support	3	2	3	**35**

horiztonal motion decision matrix						
	Degrees of Freedom	Complexity	Cost	Motion Smoothness	Functionality	Total Score
Weight	4	2	1	3	5	
3 bar linkage	3	1	1	3	3	**39**
Slider	1	2	2	1	2	23
Hinge	1	3	3	1	2	26

Clamp type					
	Adjustability	Ease of set up	Portability	Support Capacity	Total Weighted Score
Weight of Criteria	5	4	3	5	
Clamp to table	5	5	3	5	79
Clamp to body	5	3	5	2	62
clamp to wheelchair	3	4	4	3	58

Appendix II: Mechanical Properties of Aluminum 6061

Mechanical Properties			
Hardness, Brinell	95	95	AA; Typical; 500 g load; 10 mm ball
Hardness, Knoop	120	120	Converted from Brinell Hardness Value
Hardness, Rockwell A	40	40	Converted from Brinell Hardness Value
Hardness, Rockwell B	60	60	Converted from Brinell Hardness Value
Hardness, Vickers	107	107	Converted from Brinell Hardness Value
Ultimate Tensile Strength	310 MPa	45000 psi	AA; Typical
Tensile Yield Strength	276 MPa	40000 psi	AA; Typical
Elongation at Break	12 %	12 %	AA; Typical; 1/16 in. (1.6 mm) Thickness
Elongation at Break	17 %	17 %	AA; Typical; 1/2 in. (12.7 mm) Diameter
Modulus of Elasticity	68.9 GPa	10000 ksi	AA; Typical; Average of tension and compression. Compression modulus is about 2% greater than tensile modulus.
Notched Tensile Strength	324 MPa	47000 psi	2.5 cm width x 0.16 cm thick side-notched specimen, K_t = 17.
Ultimate Bearing Strength	607 MPa	88000 psi	Edge distance/pin diameter = 2.0
Bearing Yield Strength	386 MPa	56000 psi	Edge distance/pin diameter = 2.0
Poisson's Ratio	0.33	0.33	Estimated from trends in similar Al alloys.
Fatigue Strength	96.5 MPa	14000 psi	AA; 500,000,000 cycles completely reversed stress; RR Moore machine/specimen
Fracture Toughness	29 MPa-m½	26.4 ksi-in½	K_{IC}; TL orientation.
Machinability	50 %	50 %	0-100 Scale of Aluminum Alloys
Shear Modulus	26 GPa	3770 ksi	Estimated from similar Al alloys.
Shear Strength	207 MPa	30000 psi	AA; Typical

Appendix III: Dimensions device parts

Pins	Length: 1.8 in max Pin Height between Links: 0.2 Calerance: 0.1 Diameter: .75
Links	Thickness:0.5 in Length: 4 in
Clamp + Rod	3 in max height
Forearm Support	9-11 in
Bar 1	6 in
Bar 2 (connected to forearm support)	13.41 in

Appendix IV: Deflection Analysis

Deflection(cm)

$$d1 := 100(Fwfs + Fwfa + Fwbar2)\cdot\frac{afs^2\cdot(3\cdot L - afs)}{6\cdot E_1\cdot I_1} = 0.016$$

$$d2 := 100\cdot Fwbar1\cdot\frac{awbar1^2\cdot(3\cdot L - awbar1)}{6\cdot E_1\cdot I_1} = 6.471\times 10^{-4}$$

$$d3 := 100\cdot Fwlink3\cdot\frac{awlink3^2\cdot(3\cdot L - awlink3)}{6\cdot E_1\cdot I_1} = 5.157\times 10^{-5}$$

$$d4 := 100\cdot Fwlink2\cdot\frac{awlink2^2\cdot(3\cdot L - awlink2)}{6\cdot E_1\cdot I_1} = 1.969\times 10^{-5}$$

$$d5 := 100\cdot Fwlink1\cdot\frac{awlink1^2\cdot(3\cdot L - awlink1)}{6\cdot E_1\cdot I_1} = 2.314\times 10^{-6}$$

$$Deflection1 := d1 + d2 + d3 + d4 + d5 = 0.017$$

$$Deflection2 := d1 + d2 + d3 + d4 = 0.017$$

$$Deflection3 := d1 + d2 + d3 = 0.017$$

Appendix V: Shear Stress Calculation

Maximum shear stress (Pa)

$$\tau 1 := 100^2(\mathrm{Fwfs} + \mathrm{Fwfa} + \mathrm{Fwbar2})\cdot\frac{3}{2\cdot c_1} = 2.603 \times 10^5$$

$$\tau 2 := 100^2(\mathrm{Fwbar1})\cdot\frac{3}{2\cdot c_1} = 3.633 \times 10^4$$

$$\tau 3 := 100^2(\mathrm{Fwlink3})\cdot\frac{3}{2\cdot c_1} = 4.041 \times 10^3$$

$$\tau 4 := 100^2(\mathrm{Fwlink2})\cdot\frac{3}{2\cdot c_1} = 4.037 \times 10^3$$

$$\tau 5 := 100^2(\mathrm{Fwlink1})\cdot\frac{3}{2\cdot c_1} = 4.037 \times 10^3$$

$$\tau\mathrm{max} := \tau 1 + \tau 2 + \tau 3 + \tau 4 + \tau 5 = 3.087 \times 10^5$$

Appendix VI: Tearout Analysis

Tearout Analysis

Pin 1

$$t := 0.0127\mathrm{m}$$

$$\mathrm{Fpull} := 99.581\mathrm{N}$$

$$d := 0.01905\mathrm{m}$$

$$\mathrm{Atear} := d\cdot t = 2.419 \times 10^{-4}\,\mathrm{m}^2$$

$$\tau\mathrm{tear} := \frac{\mathrm{Fpull}}{2\cdot\mathrm{Atear}} = 2.058 \times 10^5\,\mathrm{Pa}$$

This is far lower then the yield strength of the aluminum we are using (207 Mpa) meaning that tearout would not occur at this point

Vertical Bar 1

$Fpull2 := 210.55N$

$t2 := 0.01143m$

$$d2 := \frac{(0.01905m)}{\cos(.785)} = 0.027\,m$$

$$Atear2 := d2 \cdot t2 = 3.078 \times 10^{-4}\,m^2$$

$$\tau tear2 := \frac{Fpull2}{4 \cdot Atear2} = 1.71 \times 10^{5}\,Pa$$

We divided by 4 as the force is acting on two areas and typicallyit is already 2*Atear

This is far lower then the shear strength of the aluminum we are using (207 Mpa) meaning that tearout would not occur at this point

Pin 5 Top Pin:

$Fpull3 := 210.55N$

$t3 := 0.00508m$

$$d3 := \frac{(0.1524m)}{\cos(.785)}$$

$$Atear3 := d3 \cdot t3 = 1.094 \times 10^{-3}\,m^2$$

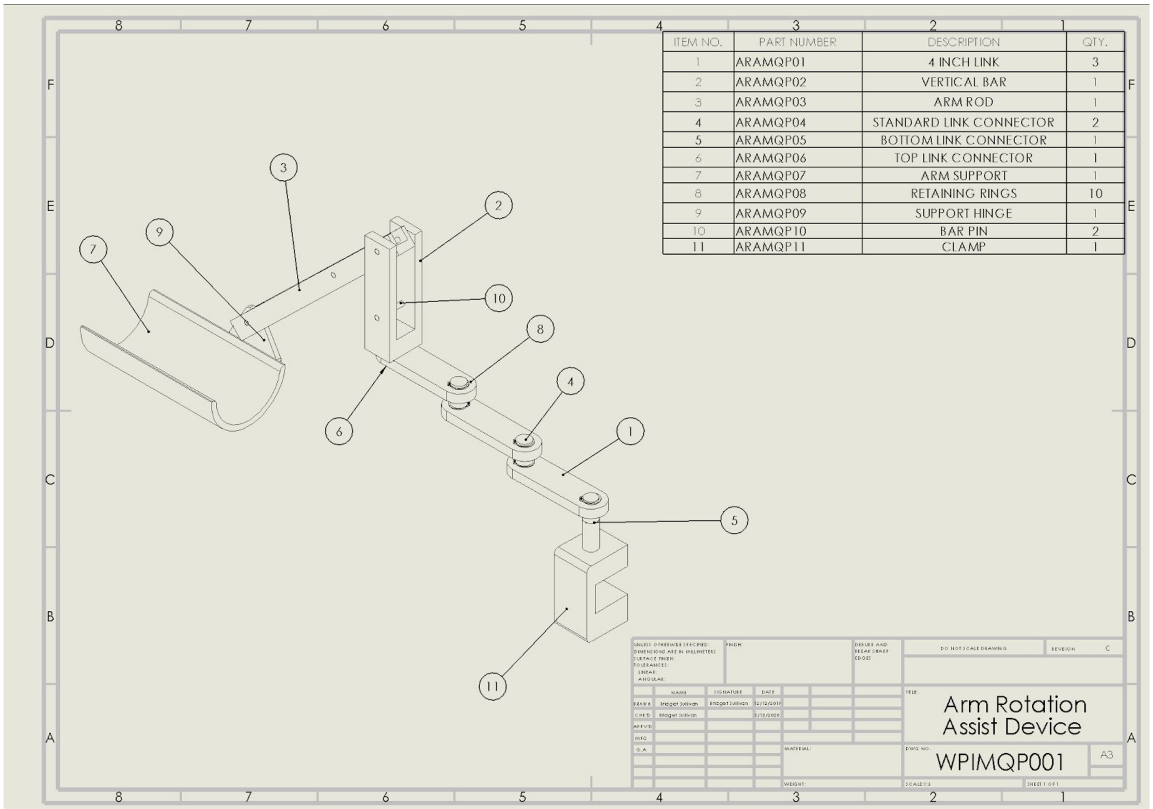
$$\tau tear3 := \frac{Fpull3}{4 \cdot Atear3} = 4.81 \times 10^{4}\,Pa$$

This is far lower then the shear strength of the aluminum we are using (207 Mpa) meaning that tearout would not occur at this point

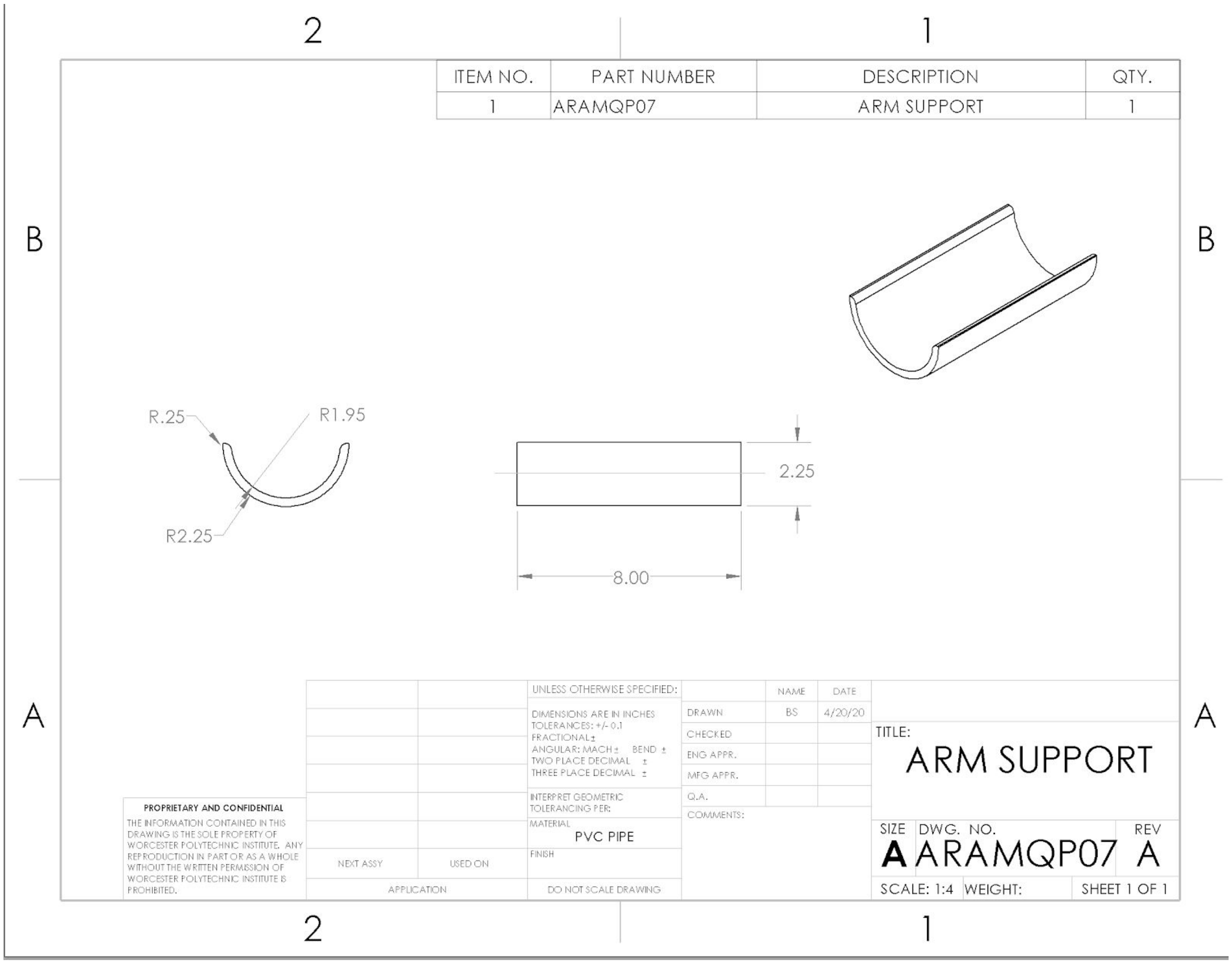
Appendix VII: Budget

Item Name	Link to Website	Price	Ordered? Y/N	Recieved? Y/N
Multipurpose 6061 Aluminum for links	https://www.mcmaster.com/8975k78-9140T159	$27.85	Y	Y
Multipurpose 6061 Aluminum for vertical bar	https://www.mcmaster.com/8975k262-8975K312	$47.24	Y	Y
Multipurpose 6061 Aluminum for rod 5	https://www.mcmaster.com/9008k46-9008K464	$35.52	Y	Y
C Clamp, Steel Sliding T Handle	https://www.mcmaster.com/5027a12	$27.04	Y	Y
Hardened 4140 alloy steel multipurpose for pins	https://www.mcmaster.com/8935k36-8935K431	$17.21	Y	Y
hooks	https://www.mcmaster.com/3961t15	$10.43	Y	Y
elastic bands	https://www.amazon.com/FlexBand-Micro-Band-lb-Resistance/dp/B00391YXKU	$6.94	Y	Y
retaining rings x3packs	https://www.mcmaster.com/91590a128	$22.50	Y	Y
small binding barrel and screw x3	https://www.mcmaster.com/99637a306	$4.66	Y	Y
longer binding barrel and screw x2	https://www.mcmaster.com/99637a309	$5.73	Y	Y
Foam for forearm support	Amazon Foam Latex Free	$11.03	Y	Y
Polyurethane Cord 7/32"	https://www.mcmaster.com/elastic-banding%2Felastic-cord-and-fittings/	$6.90	Y	Y
Loop Fittings for elastic cord 7/32" to 1/4" cord	https://www.mcmaster.com/2095n11	$6.56	Y	Y
Theraband Resistance Band Loop Set	Therabands	$15	Y	Y
Hardened 4140 alloy steel multipurpose for pins	https://www.mcmaster.com/8935k36-8935K431	$17.21	Y	N
smaller barrel screw for forearm support 1"	https://www.mcmaster.com/99637a306	$1.91	Y	N
metal plate for forearm support	https://www.mcmaster.com/8809t63	$12.94	Y	N
one size down retaining rings just incase?	https://www.mcmaster.com/91590a127	$13.94	Y	N
400 lbs. Capacity Zinc Plated Steel Tie-Down Ring (order 2)	https://www.mcmaster.com/3076t34	$3.09	N	
Powder-Coated Steel Carabiner (order 2)	https://www.mcmaster.com/3079t21	$3.38	N	
Budget:	$1,200			
	Total Spent:	$297.08		
	Money Left:	$903		

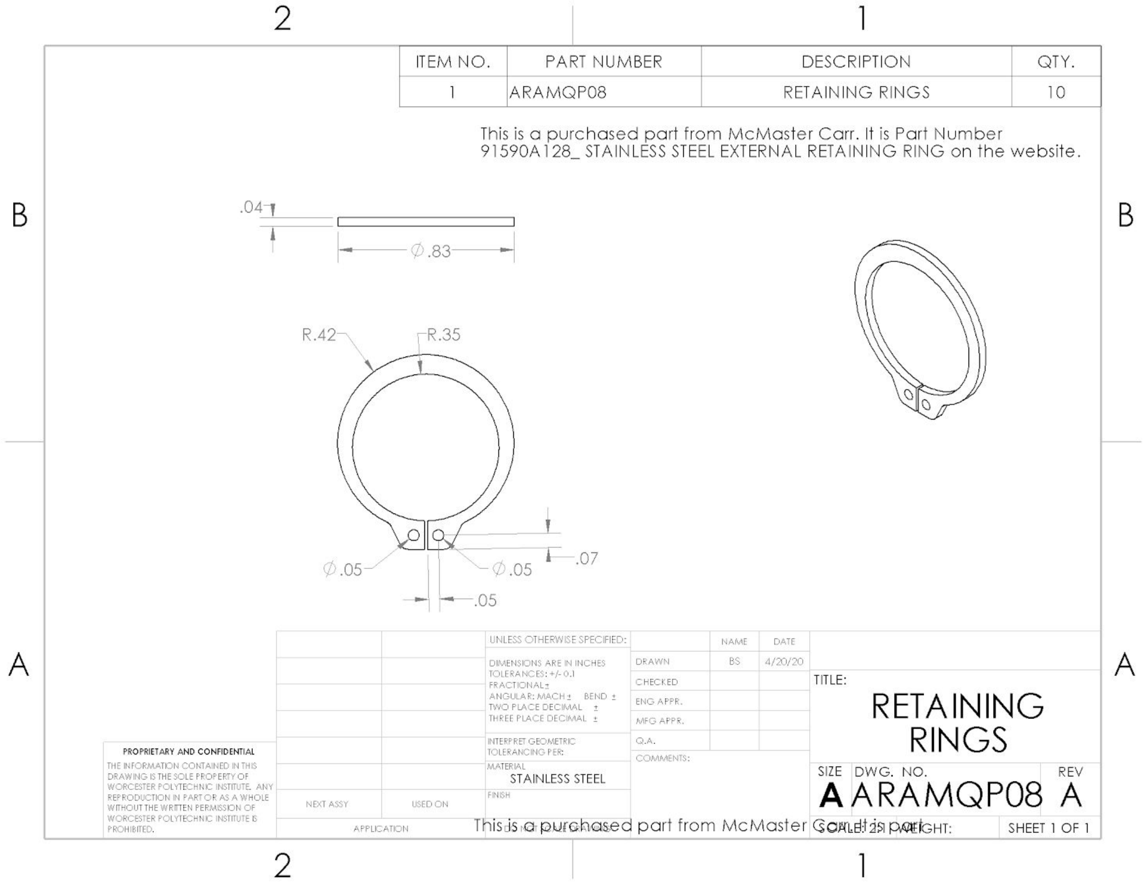
Appendix VIII: Assembly Drawing



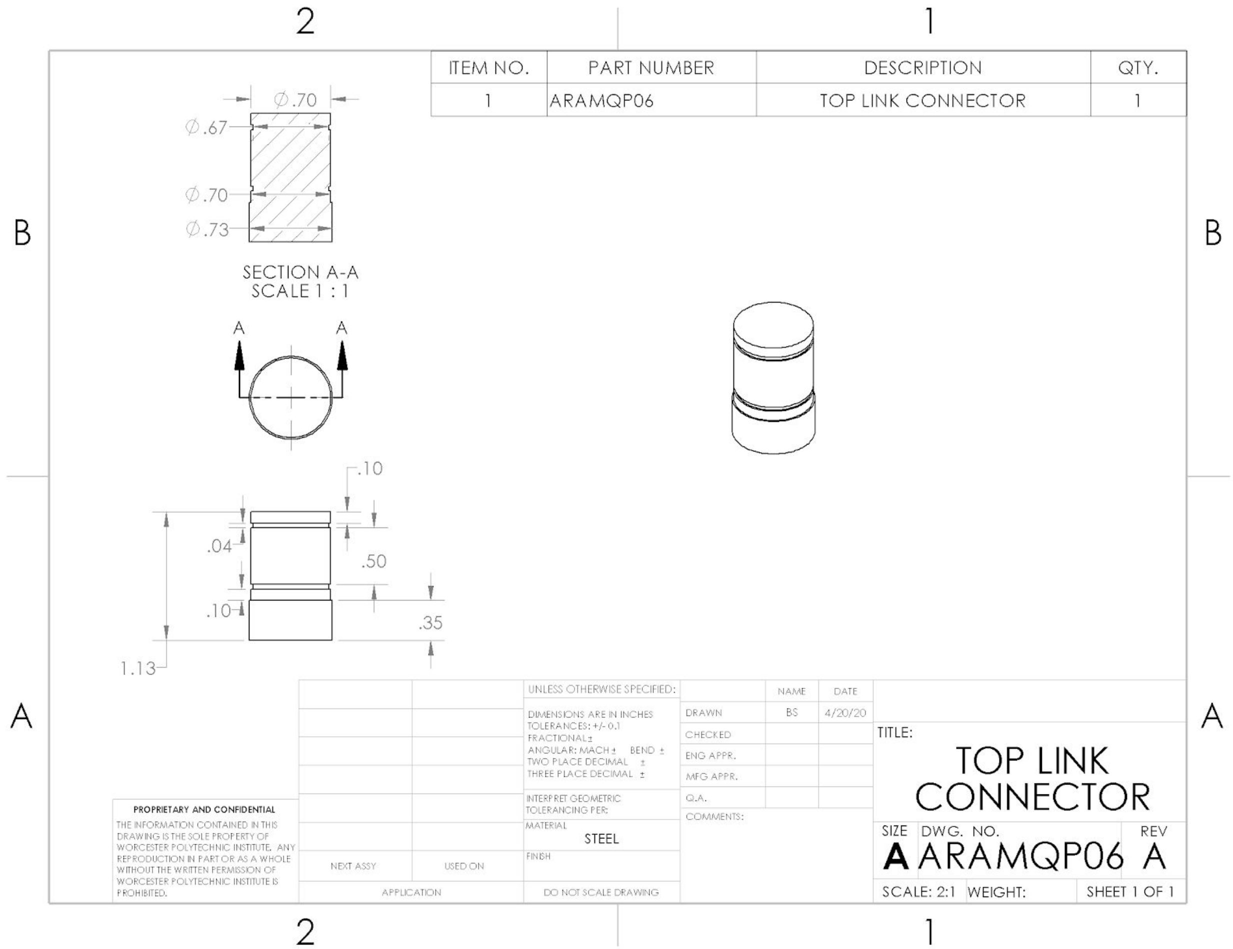
Appendix IX: Arm Support Drawing



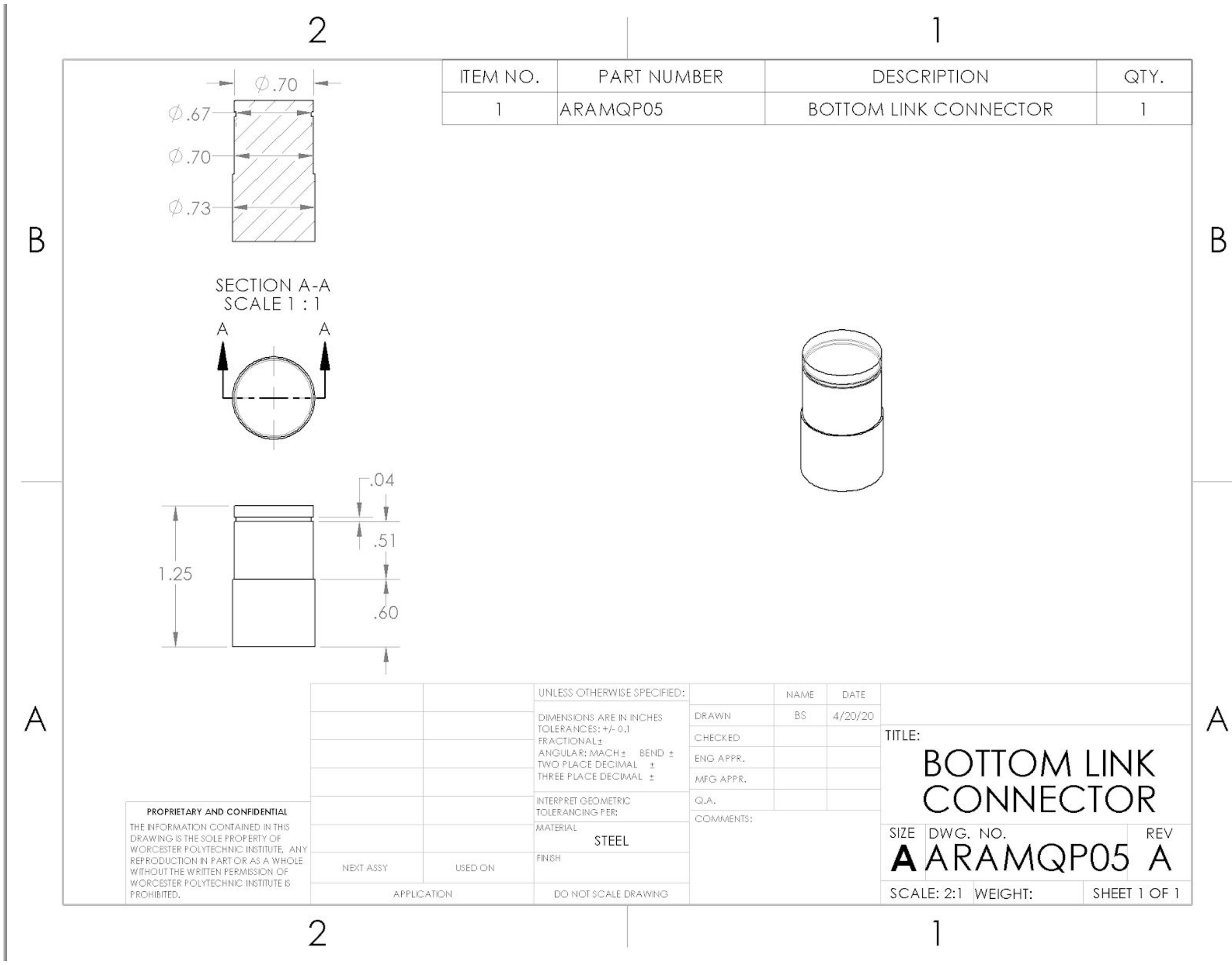
Appendix X: Retaining Ring Drawing



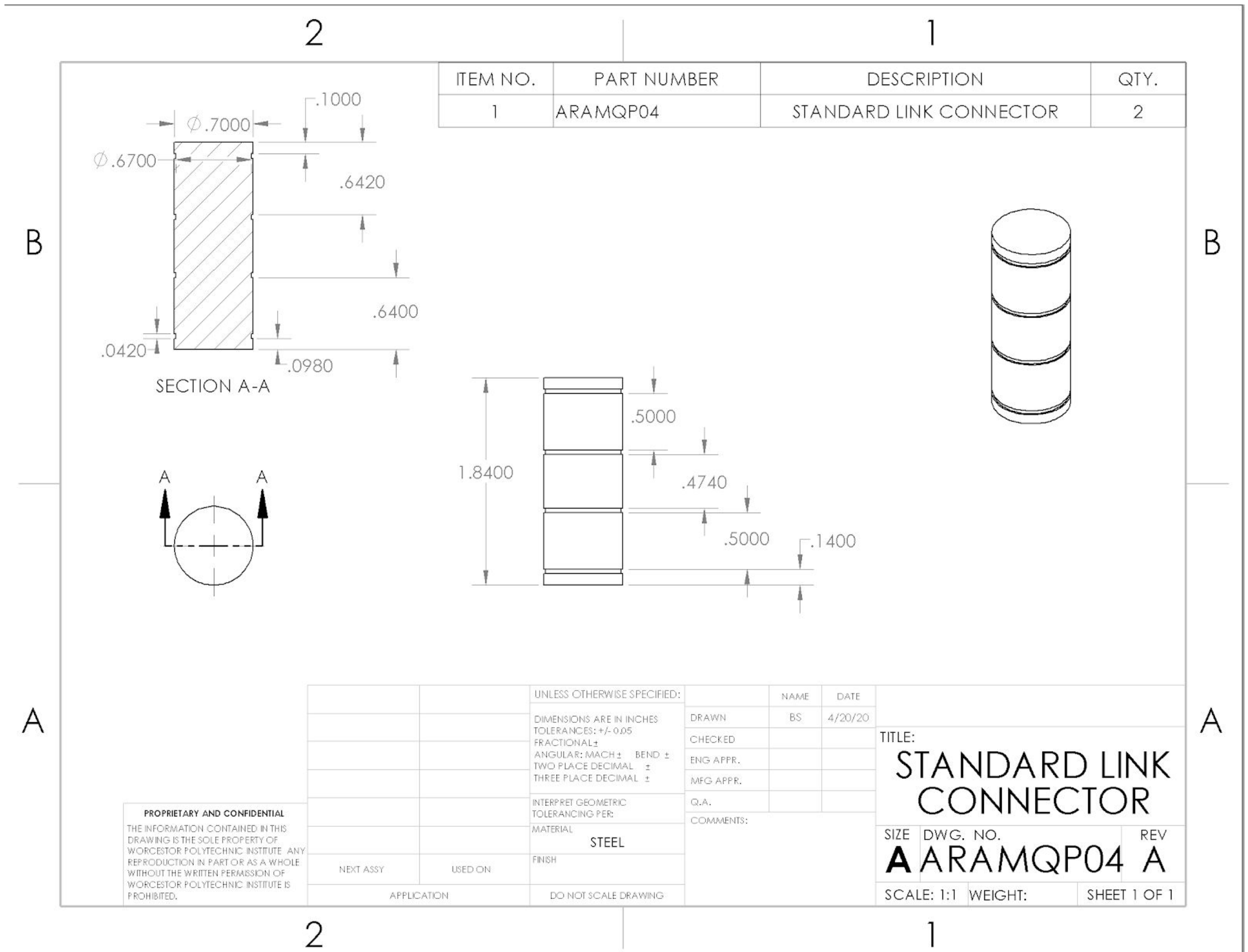
Appendix XI: Top Link Connector Drawing



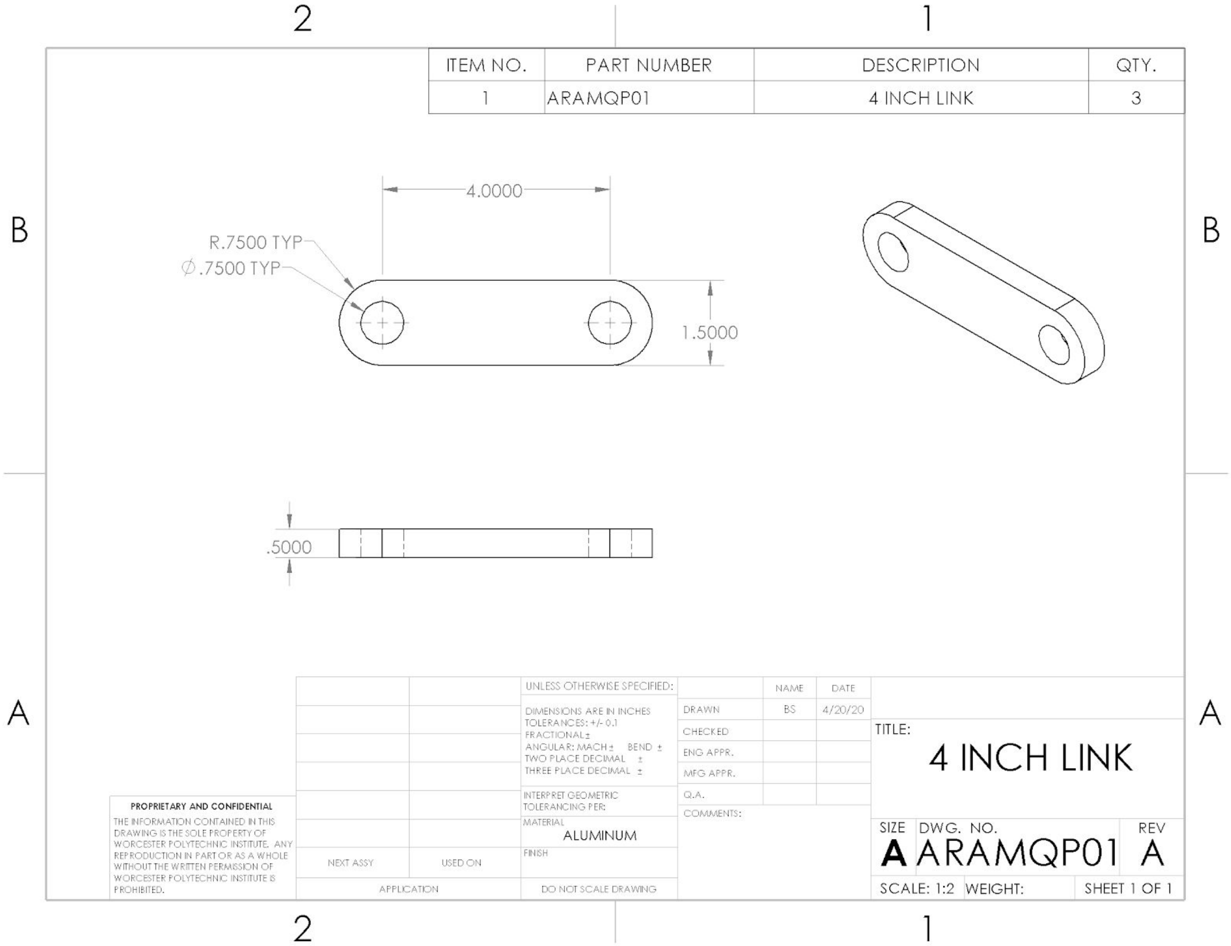
Appendix XII: Bottom Link Connector Drawing



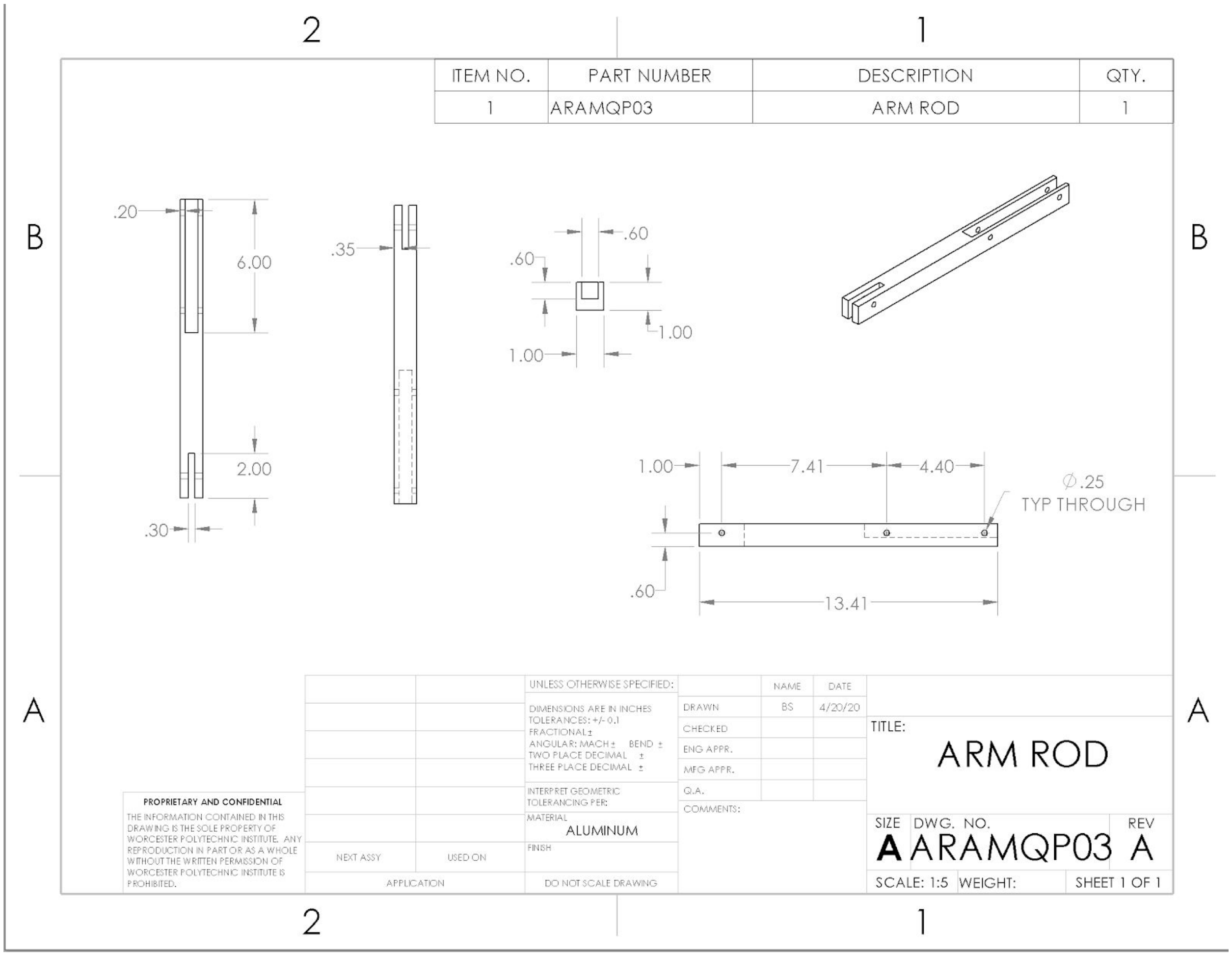
Appendix XIII: Standard Link Connector Drawing



Appendix XV: 4 Inch Link Drawing



Appendix XVI: Arm Rod Drawing



Appendix XVII: Vertical Bar Drawing