# ENME472 Team 4: T-Shirt Assistant
# Final Report

December 9, 2019

*I pledge on my honor that I have not given or received any unauthorized assistance on this assignment/examination.*

*We certify that every team member completed their fair share of work to the satisfaction of the signatory.*

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# I. Executive Summary

The simple act of getting dressed in the morning is something most people take for granted. Yet for elderly people it is a daily challenge they must overcome due to the loss of mobility that comes with age. Often the elderly are unable to dress themselves on their own without the assistance of a nurse or other caretaker.  According to the U.S. Census Bureau by 2030 the nation's 65 and older population will increase by twenty percent and by 2050, there will be over 83.7 million elderly persons in the U.S. alone [1]. The United States' quickly growing eldelry population means more and more people will require assistance simply getting dressed.

Our team decided to pursue creating a solution to the difficulties elderly people have in putting on t-shirts. The team conducted a patent study, benchmarking analysis and competitive advantage analysis which identified a need in the market for a device that helps the elderly put on a simple t-shirt since there are not currently any products on the market that satisfy the elderly's need for assistance in putting t-shirts on specifically. The team also decided to create a device that allows the elderly to put on their existing t-shirts, instead of having to buy new t-shirts especially designed for the elderly with low mobility. The following report documents the team's journey through the problem identification and concept generation phases and the project's result to date.

The team conducted interviews and sent a survey to narrow down the problem and define the customer's requirements. Four face-to-face interviews were conducted at from three assisted living homes, and an online survey was conducted resulting in eight responses. From there the team generated a house of quality and over sixty initial design concepts both stemming from customer requirements. The team selected five potential concepts to pursue and a pugh chart was used to select the top three concepts taking cost, quality and performance factors into account. This pugh chart resulted in three concepts to pursue as a solution to the challenge of assisting the elderly with putting on t-shirts. The first solution is a device that pulls the t-shirt onto the user following a similar motion to a garage door. The second solution is a set of motorized armatures that help move the user's arms to make it easier for them to put their t-shirts on. The third solution is a motorized cable system that pulls the t-shirt over the user. The team then moved on to utilize the Analytical Hierarchy Process to select a final design concept. Based on the AHP the team decided to move forward with the belt arm puller concept. More information on the designs and concept selection process are found in the concept selection process sections of this report.

After selecting a final design concept the team moved forward with the embodiment design process. The team determined the product architecture, making key design changes based upon findings unearthed during the AHP pairwise ranking and began further design work. An initial prototype was constructed and tested in order to gain insight into the existing design. The team took lessons learned from the prototype to help drive final product design.

The team continued to finalize design details and constructed a second prototype iteration to conduct further testing. The team successfully built an automated prototype that was tested on users from 5'6" to 6'5" in height. Test results revealed a 70% success rate for the product for users regardless of their height differences. Mean time for the product to put a t-shirt on a user was approximately 28 seconds. During unsuccessful trials, mean time to failure was 16 seconds. The team is satisfied with product results and gathered data to be used in future prototypes.

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# II. Market Analysis Information

## General Need for Product

The problem that our team has chosen to pursue is the issue of elderly people being unable to easily put on shirts due to various conditions of old age including but not limited to: arthritis, stiff bones and joints, and lumbar/spinal pains. The elderly often struggle with mobility and can have trouble with being flexible enough to wiggle their way into a shirt that fits their size. Our product design aims to help these people by creating a device that allows the elderly to more easily put on shirts while minimizing the amount of movement and effort needed. In this way we hope to provide the elderly with a quick and easy way to put on their shirts, without the need to alter the shirts they choose to wear.

Our team investigated the struggles for elderly persons in completing everyday tasks, and set us in motion to look deeper into these issues. After further researching this and narrowing down our topic range, our team came to a consensus and agreed to pursue the issue of elderly people struggling to put on shirts. Several different factors influenced this decision, with one major factor being a team member whose mother works in a nursing home and has direct exposure to this problem in her everyday life. From this we could potentially gather data and relevant information to this project as necessary. As a result, we felt more comfortable overall continuing to pursue this project topic. Another major factor that influenced this decision came from our team's discussion of feasibility and overall relevance to our individual lives. The team decided that this project topic certainly presents possible solutions and is a common one present in the daily lives of many elderly persons. As such, there is also a sizable market demand for such a product to be put in place. This demand reflects the overall relevance to our team and to the daily lives of many citizens, as well as the feasible success of such a product entering the market. From these conclusions, our team ultimately decided to pursue the project topic of helping the elderly put on t-shirts.

## Description and Estimation of Market Size

The target market for the T-Shirt Assistant product are elderly and users with physical disabilities. The product uses automation to lift users' arms up vertically, have the t-shirt fall over their head, and then lower the arms while pulling the t-shirt on. This product is beneficial for people who have strength and flexibility issues. The team's interviews with elderly caretakers at nursing homes have shown that the most difficult part of putting a shirt on the elderly is lifting up their arms. This product effectively addresses this problem through automation, making the task easy for the elderly to do without caretaker assistance.

According to Maryland Census data, there are more than 1.2 million individuals in the state [2]. Many elderly individuals struggle daily with the task of putting on a t-shirt. The team predicts that the product will sell successfully to elderly individuals. The team also believes that the product will sell to nursing homes so that it can be placed in patients' rooms. This will save time for caretakers and provide more independence to patients.

## Benchmarking on Competitive Products

The team completed a function structure (Figure 5.0A) from which key performance characteristics and functions were determined. The key functions are as follows:

- Position t-shirt
- Position user's arms
- Move t-shirt on to user

In conducting a benchmarking study, the team found no products on the market to help assist the elderly put on t-shirts, and no products that meet any of the performance criteria listed above.. Most of the products are simple, cheap, and have no mechanical systems. While they make it easier to fasten buttons or zippers, the user still requires some fine motor skills to use the products. The team intends to create a mechanical solution to help people put on t-shirts which requires little to no user effort. Since nothing like this exists, the competitive products are not good alternatives to the team's intended solution. The team will need to meet the functions listed above to solve the issue of assisting the elderly put on t-shirts.

Many adaptive clothing products exist that contain velcro or magnetic fastening to allow an easier dressing experience. With magnetic fastening, the user would not need to pull the garment over his or her head, but could step into the garment instead. These products saturate a market of products that are meant to replace the elderly person's existing garments with clothes that are easier to don. There are several shirts, pants, and other pieces of clothing that features similar designs. Other products exist that help the elderly put on dress shirts by helping assist buttoning up shirts. There are also many products that help the elderly put on pants and socks. The closest related products currently on the market and their associated descriptions are below:

**Miracle Dressing Aid - $79.00**

The product shown below in Figure 2.0 is the most direct competitor to our product since it helps users put on t-shirts. The advantages of this product are that it is simple and multifunctional to help put of various pieces of clothing. The price point is also lower than our estimated cost. The disadvantages of this product are that it is not automated and may be difficult for some elderly people to use. To put the t-shirt on, users must lift the entire product over their head, which may be impossible. Based on our interviews with elderly caretakers, lifting up arms is the most difficult part of the dressing process. Therefore, for users who lack strength and flexibility, the Miracle Dressing Aid is impossible to use.

**Figure 2.0. Miracle Dressing Aid [3]**

**Ring Zipper Pull - $11.00**

The product shown in Figure 2.3 has a small snap hook attached to a metal ring. Users can snap the hook to their zippers, and pull the ring to zip their clothing. This product has no mechanical systems. The device could be difficult for elderly people to use. Attaching the hook to a zipper requires fine motor skills and strength that users may not have. The user still has to pull the zipper by themself, and detaching the snap hook from the zipper needs fine motor skills.

**Figure 2.3. Ring Zipper Pull [4]**

**Adaptive Sports Shirt for Men - $46.48**

The product shown in Figure 2.4 is a piece of adaptive clothing, which is made to be easier to put on for elderly or disables users. The front of the shirt is button-up and the back has hidden snaps that can be undone to separate the shirt into two pieces. The user can put the shirt on from the front and close the snaps on the back of the collar. This product requires that the user buy new clothes, which can be expensive and undesirable. There are no mechanical systems and it still requires user effort to fasten snaps and buttons.

**Figure 2.4. Adaptive Sports Shirt for Men [5]**

## Patent Study

The team utilized the United States Patent and Trademark Office website as well as Google Patent Search in order to find domestic and international patents related to the problem of helping disabled and elderly persons to put on shirts. Searching for keywords such as elderly, clothing aid, and dressing helped the team locate several relevant patents and find patent classifications useful in location other patents. An initial search was completed which resulted in promising results from the following patent categories:

**A47G 25/90**: Devices for domestic use for assisting in putting-on or pulling-off clothing

**A47G 25/80:** Devices for putting-on or removing boots or shoes, e.g. boot-hooks, boot-jacks

Further related patents were selected from these categories. The Google patent search also resulted in several patents from other countries and patent organizations such as the World Intellectual Property Organization and the Japenese Patent Office. The team collected several patents that were deemed relevant to the issue that elderly people have difficulty putting on shirts. The patents found in the patent study are described below:

**Patent No:  US 9445680 B2**

**Device for facilitating self-dressing [11]**

Publication Date: 2016-09-20

Inventors: Sheri Bean Denise, Richard May

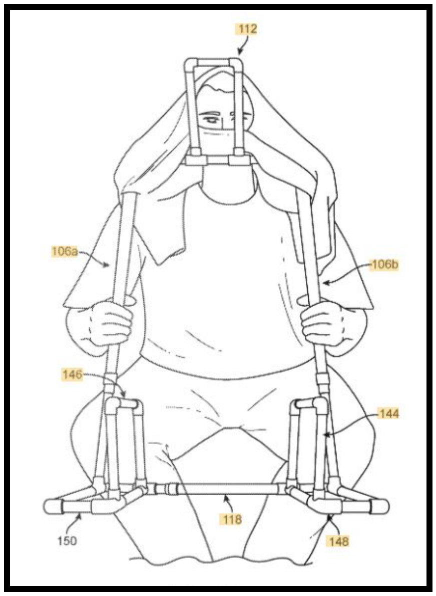



**Figure 2.5. Device for facilitating self-dressing [11]**

This patent is for a particular device that intends to provide aide in self dressing for various articles of clothing shown in figure 2.5. It gives additional stability to the user and is capable of holding clothes in a fashion that should allow individuals to more easily maneuver into them. The product is made of PVC piping and two couplers positioned on the lateral sections of the frame to allow for adjustable lengths in a specific regions to account for different sizes of clothing and people. It is constructed in a way to include a base that can hold the device itself upright, as well as handles to easily pick up and move the device overhead. This device allows a user to mount clothing to it to hold the proper openings wide and then lift the device above or below the users body to help put on the articles of clothing.

**Patent No: WO2012034561A2**

**A Two-Part Clothing for a Disabled Person [6]**

Publication Date: 2012-3-22

Inventor: Claude Teisen-Simony

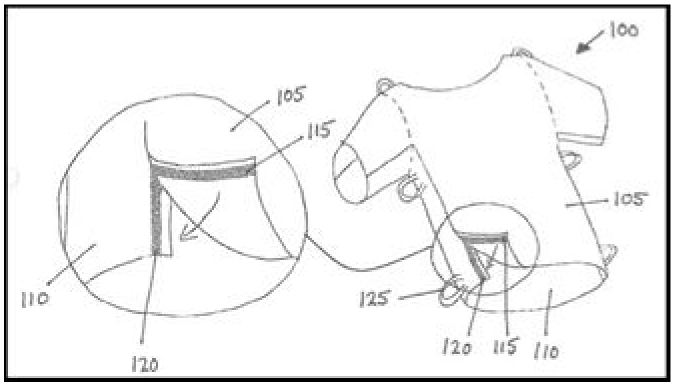



**Figure 2.6. A Two-Part Clothing for a Disabled Person [6]**

Teisen-Simony's patent is for a two-part clothing item. The first part (105) has a first fastening side (115) and the second part (110) has a second fastening side (120). The types of fasteners described in the patent are buttons, zippers, studs, magnetic strips, hooks, or other similar fasteners. The two parts of the clothing can be fully separated from each other.

The clothing in this patent can be put on in two pieces so that the user does not have to put anything over their head, or through their arms or legs. This makes it much easier for users who are elderly or disabled to put clothes on. Users will only need to put each side of the clothing on the front and back of their body, and then fasten them together. If the fasteners are magnetic, very little additional effort from the user is required.

While it is easier for the user to physically put the clothing on themselves, fastening the two pieces of clothing may be difficult for some users. The elderly may have hand tremors or loss of fine motor skills which make it impossible for them to fasten buttons, zippers, or hooks together. If the fasteners are magnetic, separating the magnets may be difficult when the user needs to adjust or take off the clothing. Additionally, this two-part clothing requires the user to buy completely new clothes. Users will not be able to wear their preferred clothes.

**Patent No: US20070095866A1**

**Dressing Aids [7]**

Publication Date: 2007-05-03

Inventor: Walter Zumbach

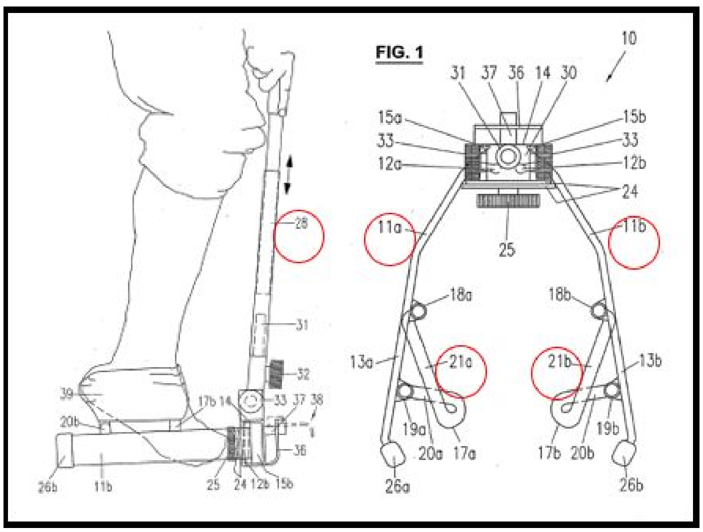



**Figure 2.7. Dressing Aids [7]**

This device widens the opening of things like socks without the need for the user to bend down and do it with his/her hands. The user folds the edges of a sock over members (21a) and (21b). Then the user puts the device on the ground while the sock is attached and pushes down on (28). This action opens legs (11a) and (11b) up therefore increasing the sock opening. The result is that the user can easily slide their foot in the sock.

The greatest strength is its simplicity and lack of expensive mechanisms. This is very important because we know that the elderly do not have high income and our product needs to be cheap to manufacture and maintain. Another benefit would be how easy it is to operate the device. Elderly might have difficulty learning how to work with new devices and that might frustrate them. Our solution also needs to be intuitive for the elderly. They need to learn how to use it in a few seconds.

One weakness of the device is that the mechanical advantage of the legs and rod cannot be great. The user needs to push down on the rod in order to use the device. If the user has back and wrist issues this product cannot be used. Another disadvantage is the volume it takes. Senior citizens usually do not live in big places and space might be an issue. Our proposed design needs to occupy the smallest footprint possible in order to completely satisfy the user requirements.

**Patent No:  US20180008075A1**

**Sleeve Puller [8]**

Publication Date: 2018-01-11

Inventor: Thelma L. Laughlin

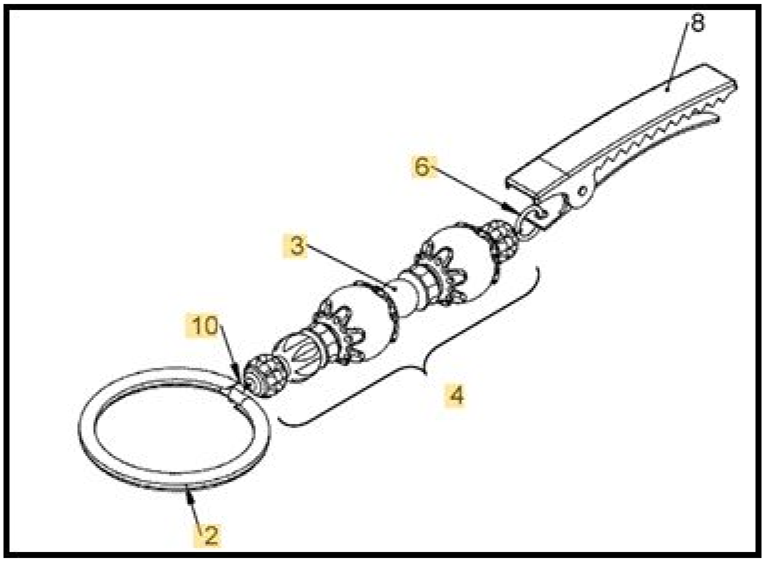



**Figure 2.8. Sleeve Puller [8]**

Laughlin's patent is for a mechanical sleeve puller device that assists a person with disabilities or otherwise physical impairments to put on an upper garment such as a shirt, coat, sweater or other garments that must go over the arms. The idea is that the device would attach to the shirt and the other end would interface with the person. This would allow the person to more easily insert their arms correctly into the sleeves of their garment. The device is comprised of a clip at one end (8) and a ring at the other (2) with a retracting device (4) and a cord (10) connecting the clip to the ring. The clip attaches to the sleeve and the ring to the finger of the user, allowing the user to pull the sleeve down without bunching.

The strengths of this device are that it is compact, and the concept for use is easy to understand. It simply clips onto the thing you want to pull (the sleeve) and you pull on the other end. It is easy to install, and theoretically easy to use. Both are important aspects in considering a product aimed to help the elderly and the physically impaired.

There are great weaknesses in this design. Particularly, the product is aimed at those who lack the dexterity required to put on their own shirts. Yet, this product requires an even higher level of dexterity, and requires a high level of finger strength in order to install the alligator clip (8) and loop fingers into the ring (2). Although a user could take their right hand to clip onto their left sleeve (and vice versa) this device still requires finger strength and dexterity, the same skills it’s users may be lacking.

**Patent No: JP3182255U**

**Undressing Aid [9]**

Publication Date: 2013-03-14

Inventor: 幸生 太田

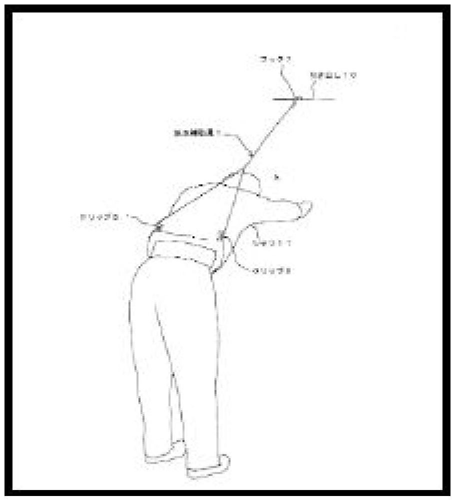


**Figure 2.9. Undressing Aid [9]**

As seen in the above figure is a man using the undressing device to take off his shirt. The function of the product is to help people whom have difficulty taking off their shirts, whether it be due to disability, old age, wet clothing, or no access to assistance from others – that is, it allows people with these issues to operate on a more independent level. The device itself is approximately 5 ft in length and requires assembly to two objects – the shirt that the customer is trying to remove as well as a door or frame that the device can hook onto. The components include a primary frame that branches out to two, with clamps attached at the base of the fork. These clamps are used on the left and right backside of the article of clothing while the header hook attaches to a door or some other available frame. After the 3 parts are in place, the consumer need only to stick their arms out and walk backward as the shirt pulls in the opposite direction and comes off of the user.

With regards to strengths of the product, the first one that comes to mind is simplicity. The product is easy to put together and easy to operate. However, there are many weaknesses that become apparent purely by looking at the several visuals alongside the patent. First off, not many elderly would be able to reach around their backside and set those two clamps in place. With age comes limited flexibility and so this may be very difficult for potential customers. Secondly, after the device is setup the customer is required to hold their arms out and move backward. A large portion of the product’s customers may not be able to extend their arms at this type of length due to weakness or upper body injuries. Lastly and more fundamentally, the user would likely be required to stand up and lean forward while backing up, which requires hand eye coordination as well as abdominal, back, neck, and arm strength. Customers of this product more than likely do not have this kind of strength or mobility and so the creators of the product fail to understand characteristics of their customers.

**Patent No: US 10,016,082 B1**

**Garment Removal Apparatus and Method [10]**

Publication Date: 2018-07-10

Inventor: Merker; Stephen L.

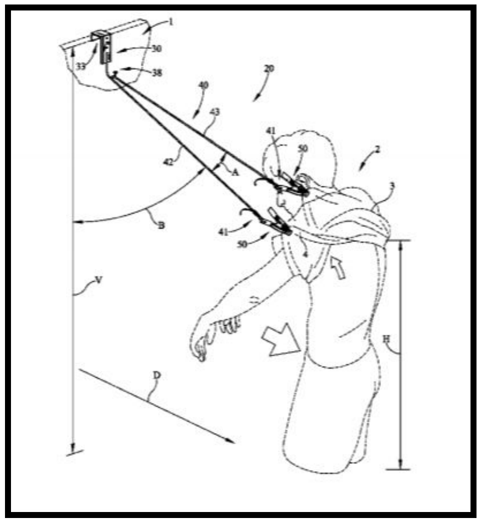


**Figure 2.10. Garment Removal Apparatus and Method [10]**

The Garment Removal Apparatus and Method is a patent that is meant to help a user remove a garment from the upper body. It is comprised of a system that attaches to a fixed point, such as a wall, and cables that attach to the user’s garment. The user then moves away from the apparatus and the mechanism progressively removes the garment from the user. The apparatus is specifically designed for users who are recovering from surgery and other health and medical conditions that limit upper body mobility for use in hospitals, assisted living homes and other similar medical facilities.

The advantage of this design is that it is easy to use. All the user has to do is clip the device to their garments and move backwards. The device does the rest. The device is also robust and reliable in design since it is so simple, there are only three real components. Since it is so simple it is likely also cheap to manufacture.

There are also several disadvantages to this design. First, the apparatus assumes the user has mobility of their lower body since they need to move away from the fixture in order to take their upper garment off. Many of the users in the patent's described target market have lost mobility which is the reason they need this very device. Also, the apparatus assumes the user will be able to clip the device to their upper garments, another task that requires strength, mobility and dexterity. If the user had enough strength, mobility and dexterity to utilize this apparatus, it is possible they may not need this device. The product may work for those recovering from shoulder surgery who may have finger strength, lower body mobility and dexterity, but may not work for the elderly who do not possess the same strength, mobility and dexterity.

**Patent Study Learning Outcomes**

After conducting a patent study the team has found that there are many patents for helping the elderly and disabled put on and take off clothes. There were several interesting and unique designs to help solve the issue of the elderly needing assistance to put on clothes.

However, the designs are very simplistic and revolve around a few common themes such as a two-part shirt, some sort of frame that helps widen the garment, and a cable and hook or clamp that allow a garment to be more easily pulled off. These designs are all very simplistic, and many require a great deal of dexterity, mobility and finger strength to operate. The team did not find any device that are t-shirt specific.

These insights from the patent study have driven design decisions in the concept generation process to specifically focus on a device that helps those with limited dexterity, finger strength and mobility to specifically assist in putting on t-shirts.

## Opportunities for Competitive Advantage

As seen from the above benchmarking and patent study, there are not many devices readily available that effectively help the elderly put on shirts. Some products like the adaptive sport shirt make it easier for nurses or family members to help and elderly person get dressed, but do not allow an elderly person to get dressed on their own.The team hopes to seize an opportunity for competitive advantage by providing a product that gives the elderly the freedom of dressing themselves unassisted.

Interviews (Appendix 1) and customer surveys (Appendix 2) indicate that there is a market for individuals who struggle to put on t-shirts. There currently does not exist a product that helps the elderly put shirts such as t-shirts on which means the team has a unique opportunity to be first to market in the creation of such a device. Casual shirts are a staple of the wardrobe for most people, and the team will provide a solution that assists in putting on the elderly's t-shirts. A key takeaway interviews were a lack of arm mobility, so the team is aiming to address assisting the elderly who have mobility since there are not competitive products that help the elderly be more mobile.

Many of the current products also still require a great deal of dexterity to operate. The elderly have rapidly decreasing levels of dexterity, meaning that many of these products only help alleviate the issue at hand, not eliminate it. The team will focus on providing a solution that does not require fine motor skills and dexterity.

The current products also suggest purchasing new adaptive easy to dress clothing designed for senior citizens. The team will seize a competitive advantage by working with the user's existing wardrobe so that they can continue to enjoy the freedom of wearing their own clothing. These new adaptive garments also often require the assistance of a caretaker to secure the cloths. The team hopes to provide an assistance free aid to the dressing process.

# III. Problem Identification

## Problem Statement

In the DC Metropolitan area, there are 91,319 individuals who are 65 years old or older [12]. This demographic is particularly subjective to physically debilitating diseases like arthritis, joint locking, Alzheimer's disease, and dementia. These diseases greatly restrict the daily lives of senior citizens. Our team aims to improve the lives of elderly people by assisting them in a stressful daily activity: putting on a t-shirt in the morning. With our project, our team hopes to improve the lives of the elderly while minimizing effects on the environment, society, or the health and safety of the user.

Our team conducted four interviews (Appendix 1) with elderly caretakers and received 8 survey results (Appendix 2). Three in person at different nursing homes with 24/7 caregivers, and one over the phone interview with a physical therapist. The survey results came from an online google survey that we sent to our family and friends to answer about their experience with elderly relatives or friends. The nursing homes we went to were specifically for patients with Alzheimer's disease or dementia.

The team had a phone interview with physical therapist Morgan Cole to get general knowledge of the physical problems elderly people face as they get older. She told us that common physical ailments that prevent senior citizens from dressing themselves are Parkinson's disease, strokes, or upper body joint/muscle injuries. She also told us that as you get older, your balance and fine motor control get much worse and injuries heal much slower. Because of this, many elderly people get dressed sitting down to eliminate the risk of falling down.

The caregiver's for these people dress them everyday, sometimes 3-4 times a day. All of the caregivers were very familiar with the process of getting on a shirt, and were used to many different types of shirt-alternatives. Residents wore under-shirts that button up from the back so that they can put it on while laying down in bed. Most residents were dressed in button down shirts or dresses (90% of the patients were women). The caregiver's typically avoided using t-shirts at all because it was too hard to take them on and off of the patients. When asked why this was the case one of the caregivers at Cedar Creek Nursing Homes (Hillwood House), Hilda, said that "their range of motion is limited and they do not have good motor control". Another caregiver at Cedar Creek (Auxiliary House), Omie Huggins, stated that injuries can make it almost impossible to put on t-shirts, and it can even be difficult with assistive clothing that opens from the back. We also asked the caregivers what they thought would be most helpful for them in putting any kind of shirt on an elderly person, and certain tricks they use. All three caregivers suggested something that can support the user's arms out in front of the in a slightly bent position. Cristine Mkirema, also from Cedar Creek Memory Homes, said that having the users arms out in front of them and completely parallel to the floor would be optimal, but Omie Huggins said that having the arms bent with the user's hands close to their shoulders would be optimal. Depending on our final concept selection, we will likely have the user's default position be one of the two suggested by Cristine and Omie.

Due to the nature of the problem our team is attempting to solve, these effects of implementation should be minimal. Putting on clothes in one's own home has very little effect on the environment, due to being inside; and society, due to being in one's home. Health and Safety is however a potential area of interest when examining the impacts related to the implementation of the product. The elderly are prone to experiencing a variety of health related conditions and as such these need to be accounted for when developing a new product. The product must satisfy the needs of our problem while remaining safe to be handled and used by elderly persons. During our interviews with experienced senior care providers we learned what was most important to ensure best practices for safety, functionality, and user satisfaction. The device must move slowly and be responsive to user input in order to avoid rotating joints or limbs too far and causing an injury. The device should support the user's arms and allow him/her to hold them in front of their bodies in an elevated position while expending minimal effort. The device should also support the user's posture and ensure they are comfortable and stable in a seated position. The size, weight, shape, and external physical features of the final product must be taken into consideration as to not present any danger or harm to a user.

After speaking with the caregivers, we learned that most people require some assistive care starting in their 80's. This reduces our market size to the 70,245 individuals between 65 and 80 years of age [12]. This age range would be the best estimate, considering that somewhere in this age range is where adults are most likely to require extra help with some daily functions while still being able to remain mostly independent. In order to come up with a worst estimate, it is necessary to look within our best market estimate of 70,245 people. Using this number, we subtract the percentage of people nationwide who have long term care arrangements or suffer from physical disabilities nationwide to gain a more accurate estimate. These people are not included in our market, since we want independent individuals to be able to use our device autonomously. Nationwide, 17.7 million individuals were caregivers of an older adult in 2011. If we remove this percent from our best estimate, we are left with 66,445. From this, we found that approximately 29% of these older adults live alone [12]. Taking this into consideration, our estimate shrinks by approximately 20,000 people. Thus, we are left with 46,074 people. This is our worst estimate of market size and demand.

A potential organization that could be involved in the implementation, qualification, distribution, or funding of our teams product is the Department on Aging and Community Living. This is a department of the D.C. government, and in order to receive funding our team would have to submit an application for a grant. This application would require us to come up with a budget and list what we plan to spend the money from the grant on.

A potential stakeholder in our team's project idea could be the Caregiver Action Network. This is a non-profit organization that provides resources for professional/spousal caregivers, and they are a potential source of customer requirements due to their first hand knowledge of the difficulties the elderly face.

## Cause-and-Effect Diagram

To determine the problem scope, the team began by creating a cause and effect diagram shown below in Figures 2.11A and 2.11B.

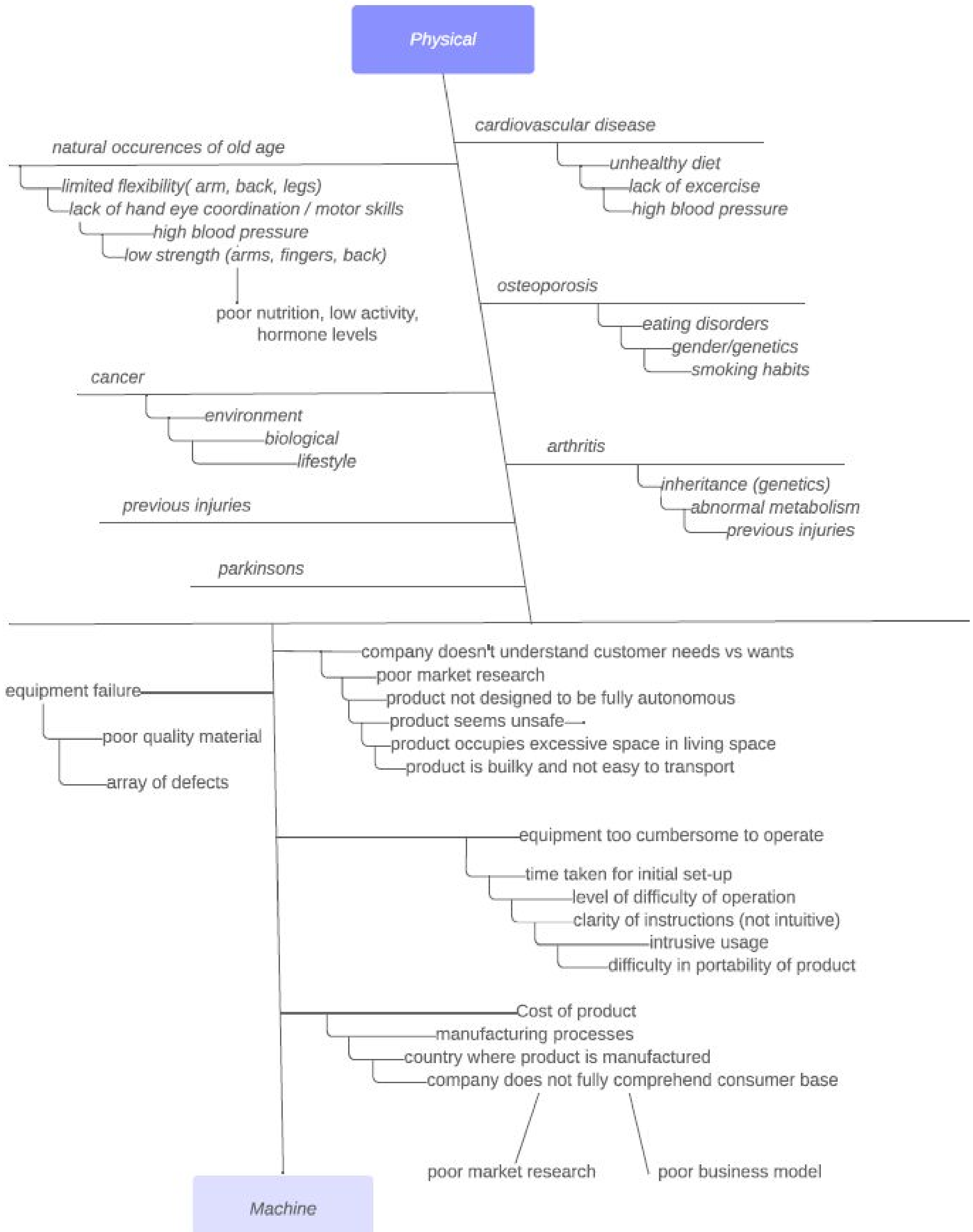



**Figure 2.11A. Cause and effect diagram created by the team (left half).**

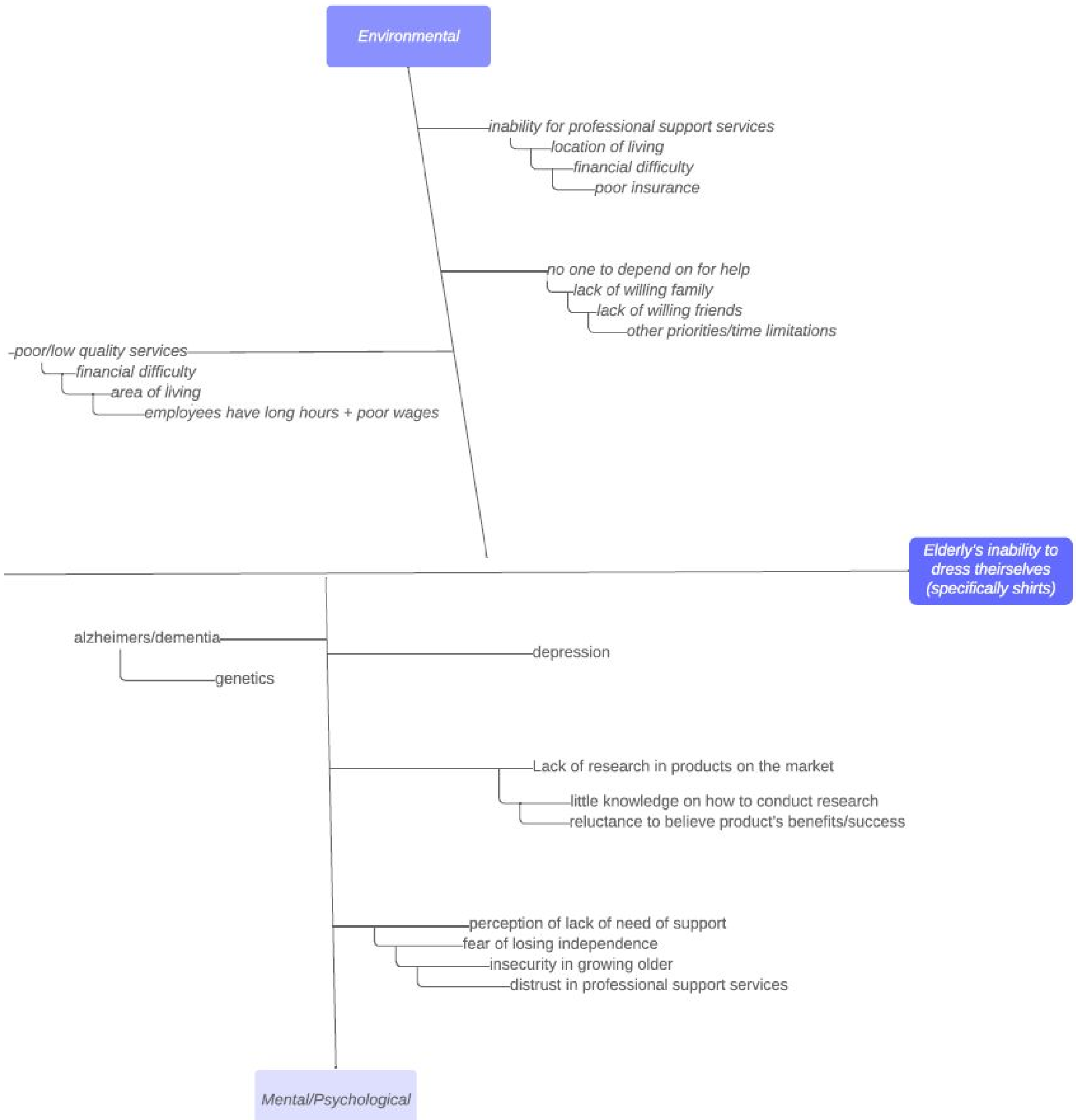



**Figure 2.11B. Cause and effect diagram created by the team (right half).**

The cause and effect diagram shown in Figures 2.11A and 2.11B was created by splitting up the problem into four causal categories: physical, psychological, environmental, and machine. As the problem we are solving is related most to movement, the physical causal categories is the most comprehensive. A variety of diseases can lead to elderly having immense trouble putting upper garments of clothing on; this includes cardiovascular disease, osteoporosis, arthritis, and parkinsons. These debilitating diseases are sometimes genetic but often due to a patient's lifestyle. Unhealthy diets, lack of exercise, and high blood pressure can weaken one's ability to be productive and get through the day. One very fundamental bone of the physical section is 'natural occurrences of old age', which is most relevant to the problem we are trying to solve. In putting on clothing, it is necessary that the patient has a certain level of flexibility, hand eye coordination, and strength. If sufficient ability does not exist in these categories, a person will ultimately be unable to put clothing on. We are consequently seeking to develop a device that can aid a person in flexibility and strength.

The 'Machine' category is also worth delving a bit deeper into. From the patent study and other market research that the group has conducted, we have been able to identify a variety of weaknesses in products currently being sold to our target customers. What we have found is that many products cost too much, are too cumbersome to operate, or do not adequately solve the customers needs for a system that pro.

In taking a broader look at the entire fishbone diagram, it is vital to identify repeat causes that may in reality serve as a root cause to the problem we are working to solve. Moreover, we must weigh causes against one another and identify characteristics that must be prioritized in the product. From the diagram, we can conclude that customers are likely looking for a low-cost product that does not require an incredible amount of strength or flexibility to operate, which in turn provides a substantial level of independence in solving the problem of getting dressed.

## Physics of the Task

One incredibly vital and apparent factor is weight due to the fact that our group is seeking to create a portable device - this will hopefully occupy a small footprint and serve to be more versatile. Moreover, these two attributes will make the product more compelling to our target market, thus increasing the number of customers. Our target market is composed of patients who have difficulty performing physical tasks, such as moving heavy objects from one location in their home to another. In addition to the operation of the device, the set-up of the product proves weight to be a crucial issue. There is a high probability that the elderly will purchase the product on their own and so setting it up for use will be their responsibility as well. The most simplistic device without any electrical power supply requires a series of linkage and mounting mechanisms. The number of linkages and the chosen material will largely affect the overall performance. However, for the purpose of this report, we assume that the linkages are made from PVC pipes with a diameter of two inches and a wall thickness of 0.154 inch. There will be anywhere from 5 to 10 linkages comprising the device. We are going to make the assumption that each linkage will be sized similar to body parts of our users such as forearm, waist and spine. Based on the patents similar to our products which used PVC piping to build the product we proceed to estimate weight based on that. Without loosing solution neutrality, PVC is a good option for estimation since there are options that are heavier such as steel and lighter such as certain types of wood. the device will have approximately a total of 10 feet in PVC tubing. Based on available PVC tubing in the market correspond to ten pounds in tubing alone. This estimate is based on a worst case scenario and more research is needed for Interim Report 2.

If we choose to pursue an electrically powered device as our final solution, the weight of the motors and batteries must be considered. Considering a worst case scenario, our device needs to compensate for the loss of strength in all joints in the arm for both the left and right side of the body, resulting in a 4 motor device. Based on a study by the National Institute of Health, the average human in their 20's can exert about 30 N.m of torque using their elbows depending on the angle of the elbow [13]. In order to restore the physical ability of the elderly, a motor capable of producing at least 30 N.m is needed. Based on the available options, one such motor rated at 35W runs at 10RPM, produces 33.42 N.m, and weighs about 550g**.** The implementation of four motors will add about four pounds to the total weight. Assuming that the motors are DC powered, we are required to introduce a battery pack. Adding 8 of 18650 Li-ion batteries that are capable of producing the 24V required will yield a weight equal to 8 ounces (or half a pound). Considering the miscellaneous wiring, mounting brackets, and control systems, the total weight will be approximately 22 pounds. Although this is a rough estimate and more research is needed to ensure that our market is capable of moving 22 pounds around, this is an indication that the design of a portable device is possible. In future section of concept generation, our team does not have to be limited to stationary solutions.

There are also mechanical modes of failure that can occur in our product that our design needs to address. Our device must transfer forces internally as well as manage external forces; The device will need to be able to lift the users arms and/or the t-shirt in order to manipulate them so that the shirt can be put on. Based on a very coservative estimate, arms are about 10% of the total body weight. Assuming the average weight of our user is 300 pounds, our design will need to be able to lift 30 pounds for three feet (conservative estimate) without any deflection.

That monuevour corresponds to addition of about 150 joules to the potential energy of the arms and holding that state for a period of time. The product also needs to perform this operation many times during its lifespan without any failures. The proposed limit for the design is well within the capabilities of the components currently available in the market. Thus we can proceed with the product design process.

## Human Factors Consideration

Since our product closely interacts with the human body, all aspects of the anthropological characteristics must be considered. Our device interacts both with the shirts and the upper body but because shirts have already been designed based on ergonomics of the body, we will need to focus only on the body. One of the essential body dimensions is the length of the arm. Based on the U.S. Anthropometric Data [14],the 50th population percentile has: an arm length of 30.7 inches from the back of the shoulder, an elbow-to-fist length of 14.5 inches, a mid shoulder height of 23.3 inches, and a waist to shoulder height averaging 13.8 inches (13, 23). These values are all needed for the design of a product that seamlessly interacts with the body.

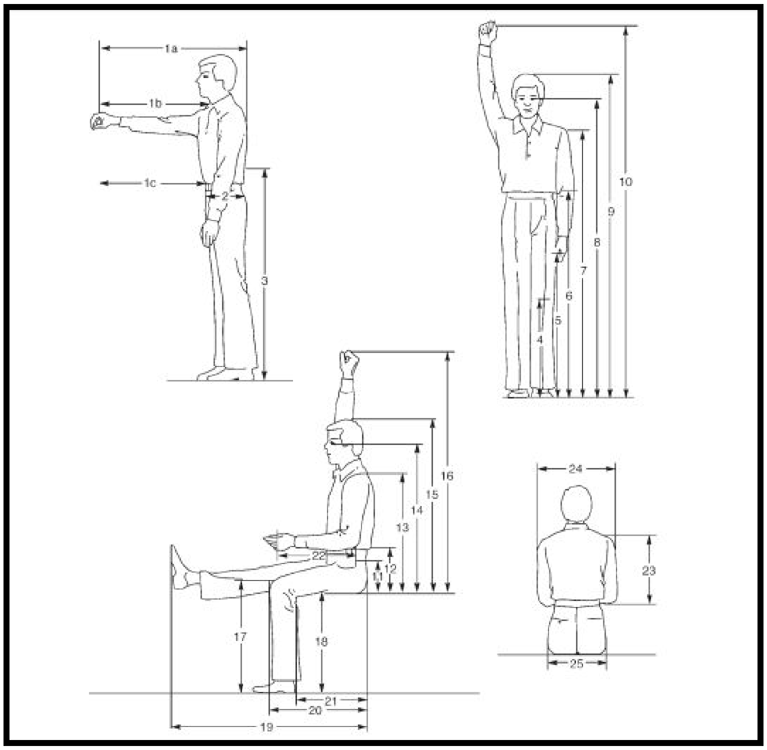



**Figure 3.1. Human body dimensions [14]**

Figure 3.1 above shows relevant human body dimensions. Besides the physical aspect of the human body, cognitive aspect plays an important role in designing our device. One of the mentioned CR has been that the product needs to be easy to operate. There are not many resources to evaluate the cognitive ability of our customers to help us design the user interface or operation and so we are going to leave this part open ended to address after the completion of prototype one. During prototyping, various user interfaces are going to be presented and the one with the most positive feedback will be chosen. Fundamentally, based on the survey results collected from our interviews, considering the cognitive ability of our users must be a priority. We need to ensure that our final design addresses this point and that the product will operate with minimal cognitive effort.

## Quantifiable Design Problem Criteria and Constraints

The product is intended to be used in private houses and apartments for elderly who are not living in hospitals or adult care facilities. This environment is generally free of major temperature fluctuations and is shielded from natural elements, such as extensive sun exposure and wind. Based on a study conducted by national laboratory of the U.S. Department of Energy, Office of Energy Efficiency & Renewable Energy, the mean indoor temperature of residencies in the US is 70 ± 0.1°F in winter and 74.9 ± 0.1°F in the summer [15]. Assuming a conservative margin of error, our design will take into account a 20°F temperature differential during the operation of our device in its life cycle.

Without any major thermal stresses on the device, no sources of vibration from the environment are expected. The only mechanical source of stress is due to operational conditions and stems from the device-user interaction which has been addressed in the previous section.

One of the mentioned customer requirements is decibel level; according to OSHA, any noise level under 80dbs has no exposure time limit. This implies that the user can be operating our product in their home environment for as long as needed. However, this decibel level may be uncomfortable for some elderly and so we are going to target a 60dbs noise level during our devices operation (this corresponds to the sound of a conversation).

Durability is another demand of our customers - our device needs to operate without failure over its intended life cycle. In order to plan a full life cycle product plan more customer research is needed. Based on the available customer research and engineering estimation, the user will use our device up to twice a day. if there are motors actuating the device, they will be operating for about two minutes each day and will rotate 720° (four 180° rotation for completing the task and returning to the rest position). We design the product for a ten year product life. We choose the lifecycle to be considerably long because the intention of this project is not to generate money knowing our customers have below average income. If that was not the case, then the life cycle would have been chosen to be much less that ten years to prompt repurchasing of the same product after it fails. Thus our motors need to be operational for about 7300 rotations under high torque low RPM environment. Any motors chosen for the application needs to undergo reliability testing to ensure overall durability of the device.

As mentioned before, the main goal of this project is to help the elderly and not to be profitable. In order to bring the cost down, the initial cost as well as the maintenance cost must be minimized. While there is no similar product on the market, our closest competitors, shown in the competitor benchmarking section, are offering one unique solution in the range of $11-$47. The most optimistic estimate for a product would have a minimum number of parts and a short amount of time needed to produce it. The shorter the time, the lower the labor, tooling and overhead cost per product. A solution made out of 10 feet of PVC piping as mentioned in the previous section will cost about $33 in raw material alone. Assuming an hour of manual labor at $15/hr for manufacturing and a minimal $5 tooling/equipment cost, the total cost will amount to $53 pre overhead. At a very optimistic 20% overhead, the product will cost at least $63. This is already move expensive than any other solution on the market. On the other side of the spectrum, a solution that requires a frame, motors, sensors and microcontrollers can cost upwards of $100. A more complicated solution will need more time for manufacturing and assembly. A couple of hours amounting to about $60 in labor can be expected. Because of a low production volume, tooling cost per product will be high and anywhere between $5-$20 depending on the tooling needed. A typically large overhead of 50% associated with start-ups can be expected as well yielding a final solution costing approximately $300. In general, our solution will be more expensive than anything else currently on the market. However, the mentioned price range is competitive compared to medical assistive products that can cost in the thousands of dollars.

# IV. House of Quality

## Customer Requirements

According to the team's interview results (Appendix 1) and survey results (Appendix 2), the team determined that the following customer requirements are necessary for the design:

- Autonomous / Promotes user independence
- Adjustable for different size shirts
- Energy efficient
- Reliable
- Lightweight
- Quick to assemble
- Easy to use
- Affordable
- Portability
- Aesthetics
- Durable
- Compact size
- Safe
- Quiet
- Ergonomic
- Instructions

## Engineering Characteristics

Accordingly, the team developed the following engineering characteristics.

- Power requirements
- Material durability
- Weight
- Physical Footprint / Volume
- Decibel output
- Mean time to assemble
- Reset time
- Number of steps to use
- Adjustable
- Number of users required to operate
- Material roughness
- Strength-Weight ratio
- Operating cost
- Capital
- Manufacturing cost
- Probability of failure / Breakdown / Injury to consumer
- Mean time to successfully operate

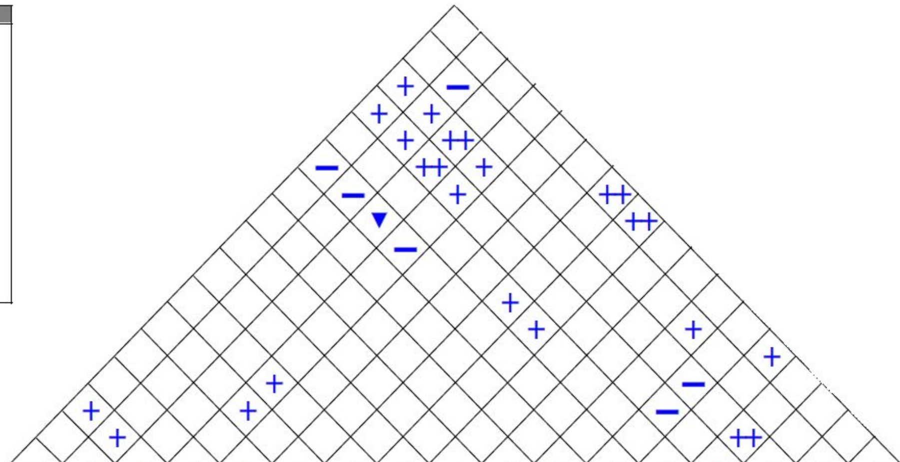
## Constraints

In developing the house of quality, we have successfully created a set of engineering characteristics to pair with the customer requirements (CTQ’s). In doing so, we must explore various types of design constraints before moving ahead with a final concept later on. When analyzing our House of Quality, one must note that if an EC column contains many relationships, it is in reality a cost, reliability, or safety item (i.e. a constraint that we are trying to identify).The most prominent constraint that many groups will face is cost. Whether it be manufacturing cost for us or the capital cost / operating cost for the consumer, our team of engineers must be able to develop a product that is both profitable and affordable to our consumer base.

We must recognize spatial constraints, as our product is to be used inside of the consumer’s home. It must be able to get through one’s front door and occupy a relatively small volume in average-sized households. We will determine approximate sizes of each of the parts in order to ensure each part satisfies the product design specifications. What is necessary to consider is the safety of our customers. In doing so, we must comply with the United States Consumer Product Safety Commission. Our final product will likely involve motors, actuation, and an interface between the product itself and the consumer. It is our duty as engineers to ensure that what we build and sell to the public will not put anyone in harm's way by injury.

# House of Quality and Interpretation

| Legend | | |
|---|---|---|
| Θ | Strong Relationship | 9 |
| O | Moderate Relationship | 3 |
| ▲ | Weak Relationship | 1 |
| ++ | Strong Positive Correlation | |
| + | Positive Correlation | |
| − | Negative Correlation | |
| ▼ | Strong Negative Correlation | |
| ▼ | Objective Is To Minimize | |
| ▲ | Objective Is To Maximize | |
| X | Objective Is To Hit Target | |



| Row # | Max Relationship Value in Row | Relative Weight | Weight / Importance | Demanded Quality (a.k.a. "Customer Requirements" or "Whats") / Quality Characteristics (a.k.a. "Functional Requirements" or "Hows") | Power requirements | Material durability/hardness | Weight | Physical Footprint/Volume | Decibel output | Mean Time to Assemble | Reset time | # of steps to use | Adjustable | Number of Users Required to Operate | Material roughness | Strength-Weight Ratio | Operating Cost | Capital Cost | Manufacturing Cost | Probability of Failur/Breakdown/Injury to Consumer | Mean Time to Successfully Operate |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Column # | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |
| | | | | Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x) | X | ▲ | ▼ | ▼ | ▼ | ▼ | ▼ | ▼ | X | X | X | ▲ | ▼ | ▼ | ▼ | X | ▼ |
| 1 | 9 | 8.2 | 9.0 | Lightweight | | O | Θ | O | | ▲ | ▲ | ▲ | ▲ | | | | | | | | O |
| 2 | 9 | 7.3 | 8.0 | Quick to assemble | | | ▲ | O | | Θ | O | O | ▲ | O | | | | | | | ▲ |
| 3 | 9 | 8.2 | 9.0 | Easy to use (does not require significant flexability, strength, motor skills) | ▲ | | ▲ | ▲ | | O | O | Θ | O | O | | O | | | | O | ▲ |
| 4 | 9 | 7.3 | 8.0 | Affordable | | ▲ | ▲ | O | | Θ | Θ | ▲ | O | O | | | Θ | Θ | Θ | | |
| 5 | 3 | 9.1 | 10.0 | Autonomous / Promotes User Independence | ▲ | ▲ | O | O | ▲ | | | | ▲ | | ▲ | ▲ | | | | | |
| 6 | 9 | 2.7 | 3.0 | Portability | | | ▲ | O | | O | O | O | O | Θ | | O | | | | | |
| 7 | 9 | 3.6 | 4.0 | Aesthetic | | O | Θ | Θ | | | | | ▲ | | | | | ▲ | O | | |
| 8 | 3 | 6.4 | 7.0 | Durable | | O | | O | | | | | ▲ | ▲ | O | ▲ | | | | ▲ | |
| 9 | 9 | 6.4 | 7.0 | Compact size | | Θ | O | O | | | | | ▲ | | O | ▲ | | ▲ | | | |
| 10 | 9 | 7.3 | 8.0 | Safe | | | | | | | | | Θ | | | O | | | | Θ | |
| 11 | 9 | 3.6 | 4.0 | Quiet | O | ▲ | O | O | O | | | | | ▲ | Θ | O | | | | | |
| 12 | 9 | 8.2 | 9.0 | Adjustable for different size shirts | ▲ | | ▲ | | Θ | | | | | | | | | | | | |
| 13 | 1 | 6.4 | 7.0 | Ergonomic | | ▲ | | | | | | | | | | | | | | | ▲ |
| 14 | 9 | 6.4 | 7.0 | Reliable | | O | | | | | | | ▲ | | | ▲ | ▲ | | | Θ | |
| 15 | 3 | 2.7 | 3.0 | Energy Efficient | O | | O | ▲ | | | | | | | | ▲ | O | ▲ | ▲ | | |
| 16 | 9 | 6.4 | 7.0 | Instructions | | | | | | Θ | | ▲ | ▲ | | | | | | | O | Θ |
| | | | | Target or Limit Value | | | | | | | | | | | | | | | | | |
| | | | | Difficulty (0=Easy to Accomplish, 10=Extremely Difficult) | 3 | 2 | 6 | 8 | 4 | 2 | 8 | 7 | 1 | 3 | 2 | 1 | 3 | 6 | 4 | 2 | 6 |
| | | | | Max Relationship Value in Column | 3 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 3 | 9 | 9 | 9 | 9 | 9 |
| | | | | Weight / Importance | 44.5 | 157.3 | 205.5 | 196.4 | 93.6 | 229.1 | 128.2 | 125.5 | 173.6 | 102.7 | 80.0 | 96.4 | 80.0 | 78.2 | 79.1 | 172.7 | 103.6 |
| | | | | Relative Weight | 2.1 | 7.3 | 9.6 | 9.1 | 4.4 | 10.7 | 6.0 | 5.8 | 8.1 | 4.8 | 3.7 | 4.5 | 3.7 | 3.6 | 3.7 | 8.0 | 4.8 |

**Figure 4.1. House of Quality created by the team.**

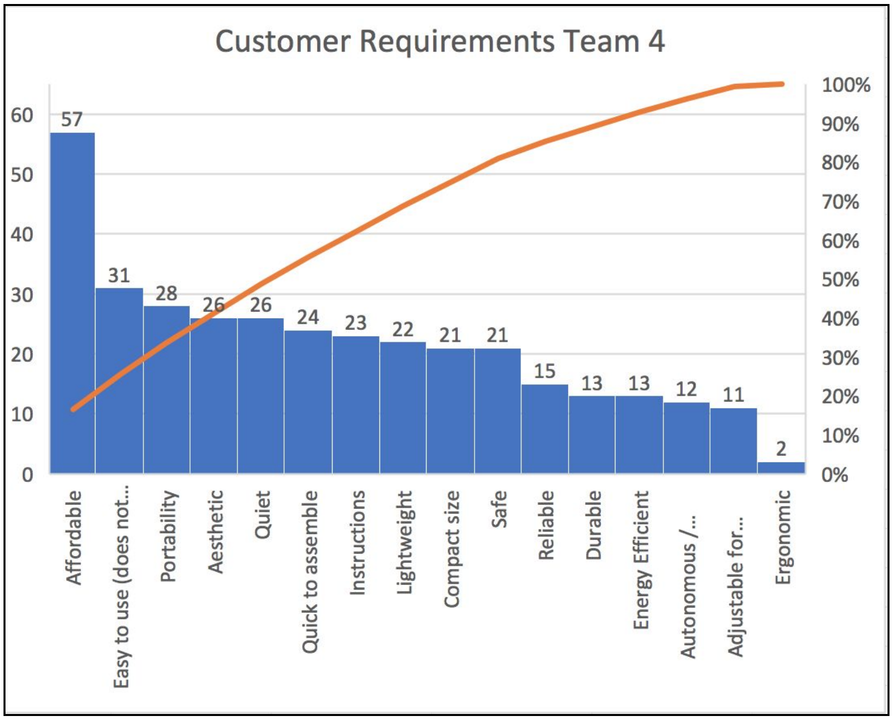



**Figure 4.2. Customer Requirements Pareto Chart.**

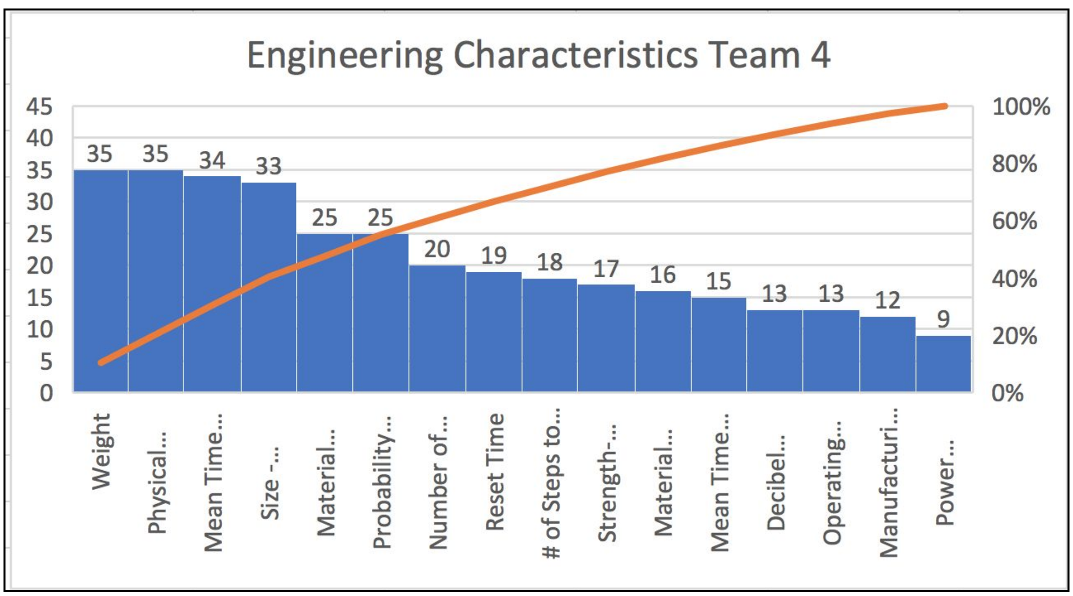



**Figure 4.3. Engineering Characteristics Pareto Chart.**

Figure 4.1 above shows the team's house of quality and Figures 4.2 and 4.3 show Pareto charts. When analyzing the house of quality, it is critical to identify key engineering characteristics. While 'physical footprint' has the most number of relationships with our set of customer requirements, 'mean time to assemble' contains the most number of strong relationships with the set. It is consequently important for our team to realize that when designing a product to help elederly, we must adhere to what our consumers believe to be critical to quality (CTQ) of our type of product. In further analyzing, we can see that decibel level and operating cost contain the fewest number of relationships with the customer requirements. That being said, if we were to create a subset of engineering characteristics and prioritize them from critical to 'add ons', decibel level and cost would be at the lower end of this list. We are aiming to create a product that promotes autonomy while also not being easily noticed sitting in a patient's home.

We are confident that the list of engineering characteristics and customer requirements is adequate. There are enough relationships, as well as strong correlations, and so this is indicative that we have successfully created a subset of characteristics that we will aim to reproduce in our product. It is necessary that we realize that the product development process is ever-changing - if our group finds out that customers are seeking a device with one particular characteristic that we have not yet explored, we would conduct further research to implement it in our product.

## Decision Characteristics

A fundamental decision characteristic that will set our product apart from competitors will be performance. We plan on drastically improving the process of elderly getting dressed through an efficient product that will be intuitive, easy to use, and quick. Moreover, we plan on creating a reliable product that will need minimal to zero maintenance and have a product life that will provide consumers with the support they need for as long as they need.

A decision characteristic that our group first conceived of was a product that promoted the elderly's independence; that is, a product that would be fairly autonomous and need little human intervention aside from a few control buttons. In creating a list of decision characteristics, what inevitably gets brought up is cost. While this was spoken above as a constraint, it is important to recognize that if we fail to produce an affordable product, we essentially fail in solving the problem being addressed. The point is not to help elderly at one end of the financial spectrum but instead to aid a variety of people – whether they be poor or wealthy, injured or old, in a nursing home or living by themselves. We must work in reducing the capital cost of the product as well as the operating cost (which must be addressed when calculating the amount of power required to operate the final product).

## Group Signoff

*We certify that every team team member contributed to the house of quality portion of the design analysis and that all signatories approve of the presented results.*

Hirbod Akhavan-Taheri

Charlie Benamram

Chad Cartwright

Graham Clifford

Conrad Hong

Mark Vulcan

# V. Conceptual Design Process

## A. Set of Five Feasible Concepts

In order to aid in concept generation the team created a function structure (Figure 5.0A.) for a device that assists the elderly in putting on a t-shirt. This function structure is a solution neutral representation of the intended behavior of the team's device. From the function structure, key functions were selected and imported into morphological chart (Figure 5.0B).

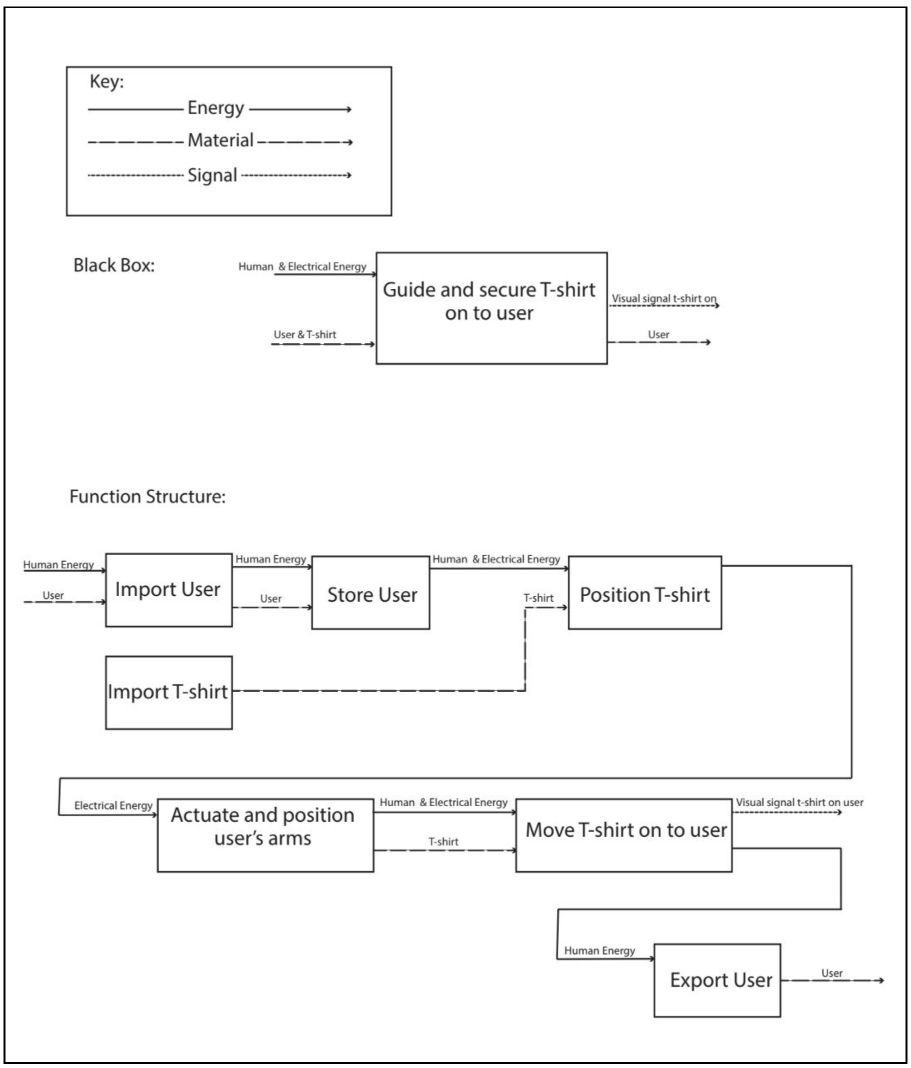



**Figure 5.0A. Function structure created by the team to assist in ideation.**

| Subprobem Solution Concepts | | | |
|---|---|---|---|
| **Import T shirt** | **Position T Shirt** | **Actuate and position user's arms** | **Move T shirt on to user** |
| Place into device | T-shirt held over user | User positions own arms | User pulls T-shirt down |
| Attach hanger with t-shirt to device | **User positions with their arms while in device*** | **Motorized armature actuates and positions users arms** | **Motorized Armature moves t-shirt on to user** |
| **User brings with them into device** | User's arms moved to position T-shirt | Handles attached to cables | Belt, cables and clips pull shirt down |
| Give user t-shirt externally | Optical sensor with placement device | Horizontal handlebar externally controlled | Shirt slid through frame |
| Device incorporated with T-shirt | T-shirt placed in rails/frame | External Assistance | External assistance |

* Multiple concepts utilize this solution concept

Key:

T-Shirt Hanger Concept

Horizontal T-Shirt Puller Concept

Shirt Ring Concept

**Belt Arm Puller Concept**

Arm-Lifty Upper Concept

**Figure 5.0B. Morphological chart created by team to assist in concept generation**

The morphological chart allowed the team to synthesize possible solutions for each individual function, then combine them to form concepts. 60 initial concepts were generated by the team, ten per person. Function solutions for the team's final concept are bolded in the above function structure. From the original 60 concepts the team narrowed the ideas to the five feasible concepts listed below:

## 1. T-Shirt Hanger Device

The sketches for this product are shown below in Figures 5.1 and 5.2. This device consists of two main sub-systems. The easily detachable three-piece hanger and the frame. The User needs to put the shit on the hanger and attach the clips (7) through the sleeves on the hanger. Then, he/she needs to sit underneath the hanger on a chair and activate the linear actuator (4) by pressing on one of the switches (8) to lower the hanger onto him/her. Then the user grabs onto the handles (6). Lastly the user activates the device using the feet activated switches (8) and the two motors (1) start to retract two pieces of the hanger with them forcing the user's arms through the sleeves (shown in Fig. 2).

The main advantage of this concept is simplicity. The design is based on existing products and no complicated approach to solving the problem is introduced. Another benefit is that a set of hangers can be purchased to replace the existing hangers. This way a shirt can be quickly and easily be loaded in the device straight from the wardrobe.

The major weakness of the concept is the lack of detailed control of the process. The motion of pulling the hanger through the sleeves while the user is holding on to them can be dangerous for the user. More testing is required to make sure this specific motion is applicable to all the users. Another disadvantage of this design could be characterized as the amount of time needed for set-up and reassembly of the hanger.

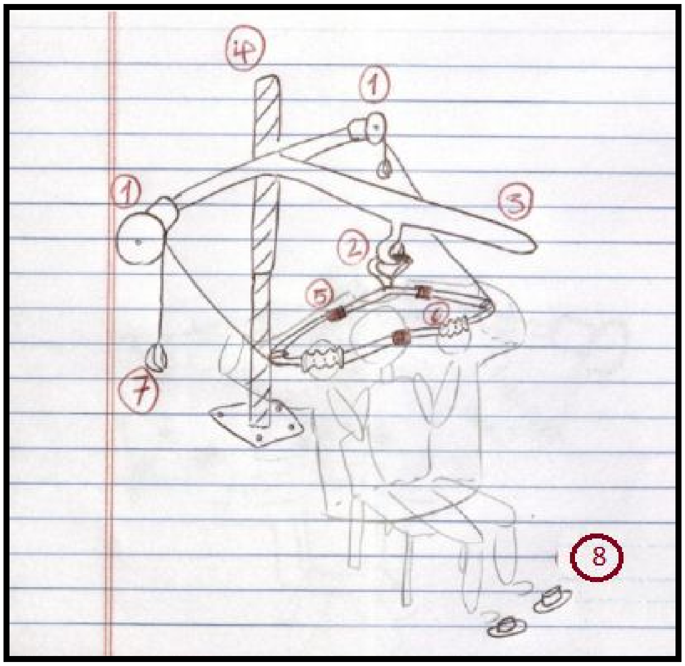



Figure 5.1. Numbered Sketch.

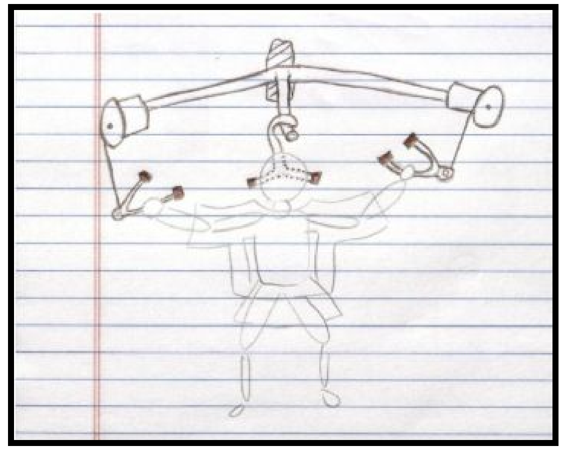


Figure 5.2 Design Sketch.

Parts List

| Part # | Part Name | Quantity |
|---|---|---|
| 1 | AC powered motor | 2 |
| 2 | Three-piece hanger | 1 |
| 3 | T-Shaped frame | 1 |
| 4 | Vertical linear actuator | 1 |
| 5 | Magnet | 6 |
| 6 | Handles mounted on the hanger | 2 |
| 7 | Mountain climbing style clips attached to the motors | 2 |
| 8 | Foot activated switches | 2 |

## 2. Horizontal T-Shirt Puller

The sketches for this product are shown below in Figures 5.3 - 5.5. This product is a horizontal t-shirt puller. The user can pull a chair behind the product and adjust the height of the product to be slightly above their head at sitting height, from 4 to 6 feet. The user can then push a button on the motor, hold their arms out horizontally, and lean forward. The puller assembly (shown above) will pull the t-shirt along a horizontal track and through their head and arms. After the t-shirt is on, the user can pull downward on the t-shirt to easily detach it from the device, and pull the t-shirt down to their waist.

This device functions by using a motor (1) to wind up a cable (2). The motor is operated by a button that the user can press. The cable has one end fixed to the t-shirt holding bar (3) and the other end fixed to a spool connected to the motor. The t-shirt holding bar is an H-shaped bar and each of the four ends is attached to a sliding t-shirt clip (4). The center point of this H-shape has a hinge that allows it to bend while sliding across the curved rails (5). The sliding t-shirt clips connect the ends of the t-shirt to the product and slide across the curved rails. The curved rails attach to the mounting poles (7), which are height adjustable poles that hold the puller assembly out horizontally in the air. The motor support bar (6) connects the mounting poles together and support the motor. The connection bar (8) connects the far ends of the mounting poles. The base plates (9) hold up the mounting poles and support the weight of the product.

This concept is feasible because some elderly users lack the ability to hold their arms up vertically, but they can hold them out horizontally. Instead of putting the t-shirt over their head, this device slides the t-shirt vertically on the user, which prevents the user from having to make difficult movements.

This concept has several important advantages. It is easy for the user to operate and understand. It requires minimal effort and little strength exertion from the user. The design is relatively simple and the product is unlikely to malfunction or need repair. The product accommodates a wide range of elderly users with the ability to hold their arms out horizontally but not vertically. Additionally, the product never makes contact with the user so there are no safety issues.

The disadvantages of this product are that it is very large and will take considerable time to build. It will likely be heavy and expensive. Adjusting the height of the device may be difficult for some users with limited strength, but this only has to be done once. The product may also be difficult for elderly users to move if necessary. Additionally, it may be aesthetically displeasing to have it in a room.

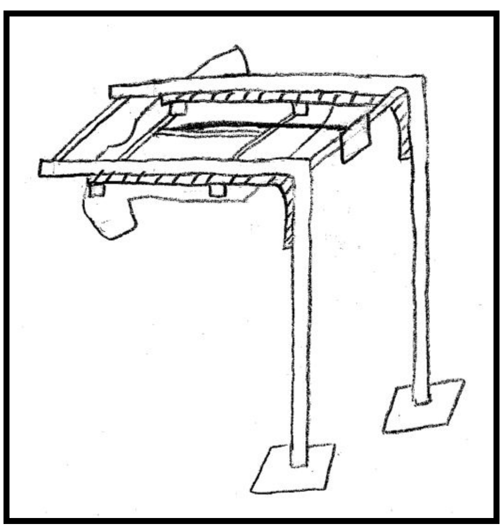


**Figure 5.3. Design Sketch with T-shirt.**

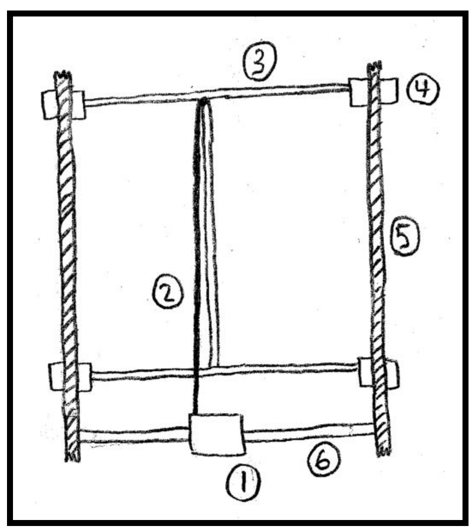



**Figure 5.4. Top View Sketch of Puller Assembly.**

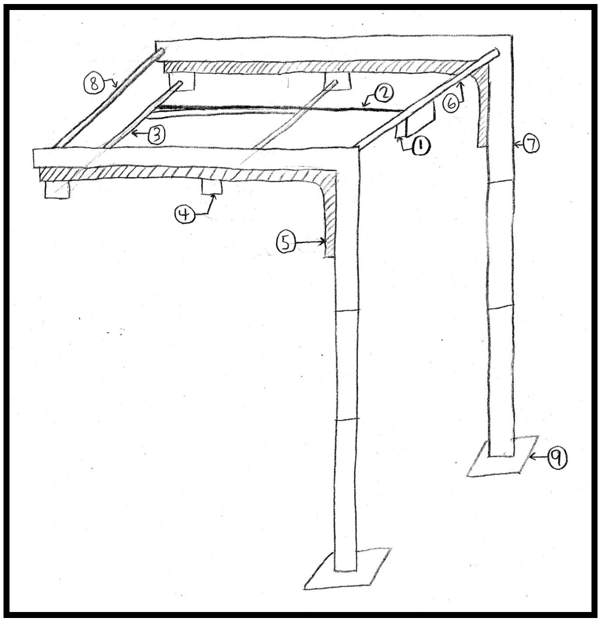



**Figure 5.5. Detailed Design Sketch of T-shirt Puller.**

Parts List

| Part # | Part Name | Quantity |
|---|---|---|
| 1 | Motor | 1 |
| 2 | Cable | 1 |
| 3 | T-shirt holding bar | 1 |
| 4 | Sliding t-shirt clip | 4 |
| 5 | Curved rail | 2 |
| 6 | Motor support bar | 1 |
| 7 | Mounting poles | 2 |
| 8 | Connection bar | 1 |
| 9 | Base plate | 2 |

## 3. Shirt Rings

The sketch for this product is shown below in Figure 5.6. This concept is an automated adjustable ring or strap with a “velcro-like” material around the exterior surface outer belt material (3). This ring fits into the openings of a T-shirt and sticks to the fabric material in order to hold the shirt open wide. This aims to help elderly persons more easily maneuver themselves within a shirt by making the opening easy to locate, as well as providing more stable points for users to grasp when handling the shirt. The inside of the belt is made of a different inner belt material (2) that is comfortable for users to handle. The ring itself can automatically adjust to a variety of sizes using the aluminum belt buckle (3) with a sensor which can determine when the appropriate size has been met. The sensor provides data to a small motor (4) which automatically adjusts the ring size to match the t-shirt. This allows the ring to accommodate different sizes of shirts and people accordingly.

Our team considered this product as a possible alternative due to its fundamentally different approach and perspective on solving the problem. The rings act as a small portable device which can aide a user in getting into the shirt, rather than helping the shirt be forcefully put on the user. In this way the shirt still has to be put on by the user on their own, but it would help with those who simply struggle with minor physical limitations such as joint stiffness.

The strengths associated with this product include its size and shape. The rings are adjustable to accommodate a large variety of people, and are both compact and lightweight. The rings’ functionality is also quite intuitive, making usage swift and easy to comprehend. In this way the rings become an overall simple and easy product to introduce into a market.

The weaknesses on the other hand include users not being capable of being provided physical support in mobility. This means that users who have more extensive physical limitations on their range of motion will not be provided enough support that may be necessary from this product. This design also requires the user to purchase multiples of the same product in order to account for multiple holes in a shirt. Having multiple small rings as a single product could serve to harm the product's success on the market, as well as make it easier for users to misplace them.

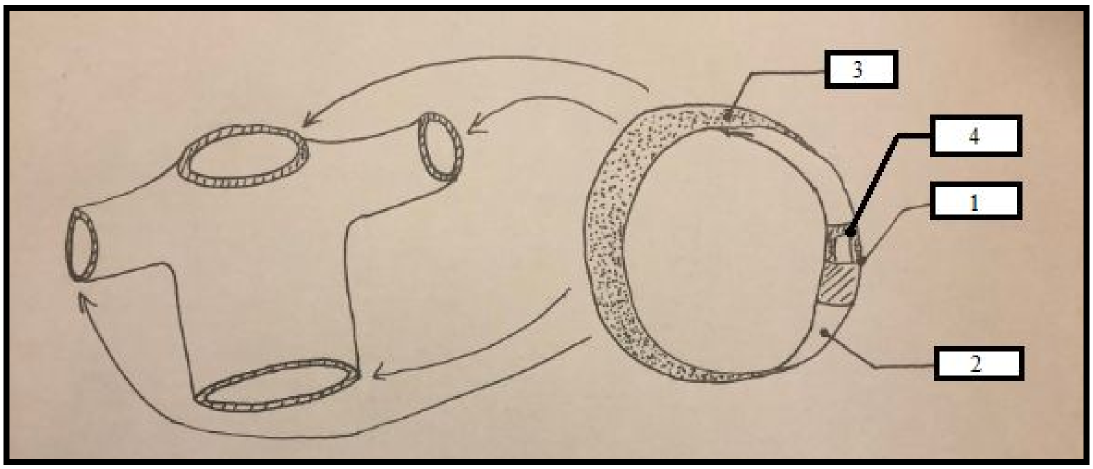



**Figure 5.6. Design Sketch of Shirt Rings.**

Parts List

| Part # | Part Name | Quantity |
|---|---|---|
| 1 | Aluminum Belt Buckle | 1 |
| 2 | Inner Belt Material | 1 |
| 3 | Outer Belt Material | 1 |
| 4 | Small Motor | 1 |

## 4. Belt Arm Puller

The sketch for this product is shown below in Figure 5.7. This device consists of a belt (4) that wraps around the user's waist and two motorized armatures attached to a rigid frame (1). The armatures have handles (2) on the end for the user to grip and two pivot points where motors (3) would actuate. The user would don the belt, or have the belt put on them and put their hands on the handles. The device would then help position their arms through a T-shirt, and lower their arms and t-shirt, then would detach from the user.

The strengths of this design are that it assists a user in helping to move their arms in ways that they may no longer be able to on their own in order to help facilitate putting a t-shirt on. It is fairly simple in design consisting essentially of just four motors, armature, handle and frame. It relies only on the user's own body to help put the shirt on, so is a fairly compact device.

The weakness of this design it is difficult to ensure that this device is lightweight enough for a user who struggles to put a t-shirt on. It may also be hard to find motors that provide enough torque to move a user's arms. It also does not automatically import the shirt, the user must bring the shirt with them and pre-insert their arms into the arm openings.

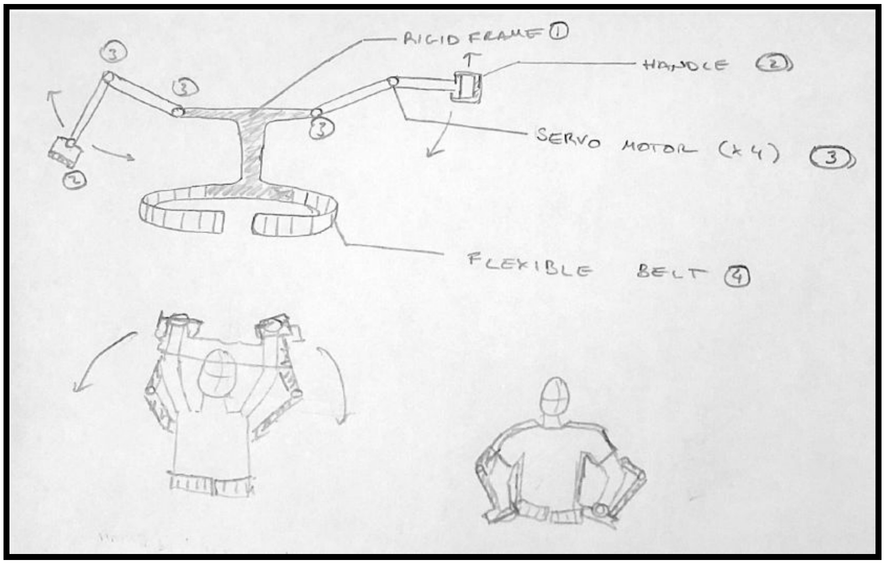



**Figure 5.7. Design Sketch of Belt Arm Puller.**

Parts List

| Part # | Part Name | Quantity |
|---|---|---|
| 1 | Rigid Frame | 1 |
| 2 | Handle | 2 |
| 3 | Servo Motor | 4 |
| 4 | Flexible Belt | 1 |

## 5. Vertical Arm Lifter

The sketch for this product is shown below in Figure 5.8. This device is meant to assist in lifting one's arms while putting on a shirt in a sitting position. The device can attach to the arms of a chair using the four clamps (1). It should be positioned over and around the user when in use. It is motorized (4), and the motor is controlled by the user stepping on a button at their feet (5). The user should thread their arms through the arms holes of the shirt first, then grab the arm bar (2) using their hands, and then allow the bar to be moved up and over their head along the arm bar track (3).

The strengths of this design are that it simplifies and shortens the total process by having the user put their arms through the shirt in their lap. The user is required to sit down to use the device, which decreases the likelihood of failure. The device's movement is totally controlled by the user, and there is a low amount of steps required to complete the design's process.

The weaknesses of this design are that it is potential difficult for one person to set the device up by themselves. It could potentially be difficult for an elderly person to hold on to the arm bar while it is being raised above their head.

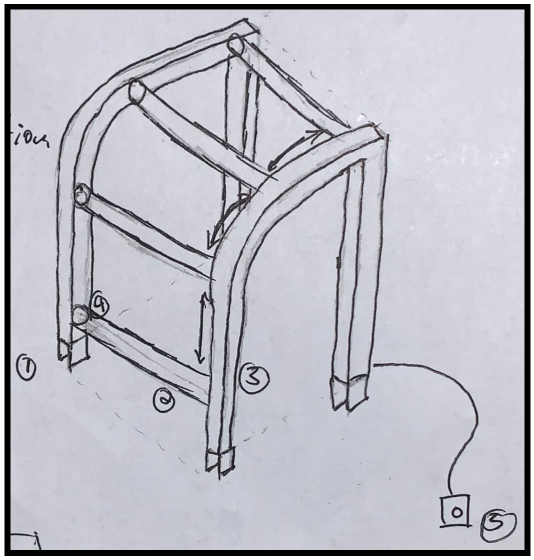


**Figure 5.8. Design Sketch of Vertical Arm Lifter.**

Parts List

| Part # | Part Name | Quantity |
|---|---|---|
| 1 | Chair Clamp | 4 |
| 2 | Arm Bar | 1 |
| 3 | Arm Bar Track | 2 |
| 4 | Motorized Wheel | 2 |
| 5 | Push-Button Switch | 1 |

# B. Concept Selection Process

## Pugh Chart

The team created the pugh chart shown below in Figure 5.9 to begin the concepts selection process. It was used to narrow down our design to the best three concepts.

| | | Base | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|---|
| | Weight | (Laughlin's Sleeve Puller) | Arm Lifty-Upper | Horizontal T-Shirt Puller | Belt Arm Puller | Split Hanger | Shirt O Rings |
| Cost | 3 | 0 | -1 | -1 | -1 | -1 | +2 |
| Power Requirements | 2 | 0 | +1 | +1 | -1 | +2 | +2 |
| Durability | 5 | 0 | 0 | +2 | 1 | +1 | -1 |
| Weight | 4 | 0 | +1 | -2 | -1 | +1 | +2 |
| Physcial Footprint | 5 | 0 | 0 | -2 | +1 | -1 | +2 |
| Decibel Output | 3 | 0 | 0 | 0 | 0 | +2 | +2 |
| Mean Time Initial Assembly | 4 | 0 | -1 | -1 | +2 | +2 | +2 |
| Reset Time | 4 | 0 | +2 | +1 | +1 | -2 | -2 |
| # Steps to Use | 5 | 0 | +1 | +1 | +2 | -1 | -2 |
| Level of Autonomy | 4 | 0 | +2 | +1 | +2 | +2 | -2 |
| Mean Time to Operate | 4 | 0 | +1 | +2 | +2 | +1 | -1 |
| Shirt Size Adjustable | 5 | 0 | -1 | +2 | +2 | +2 | +1 |
| Material Roughness | 2 | 0 | 0 | +1 | 0 | +2 | -2 |
| Probability of Failure | 5 | 0 | -1 | +1 | 0 | -1 | +1 |
| | | | | | | | |
| | | | | | | | |
| S+ | - | +0 | +31 | +55 | +53 | +53 | +52 |
| S- | - | -0 | -17 | -25 | -9 | -18 | -39 |
| S | - | 0 | 15 | 3 | 10 | 0 | 0 |
| | | | | | | | |
| **Totals:** | | 0 | +14 | +30 | +44 | +35 | +13 |

**Figure 5.9. Pugh chart created by the team to score feasible concepts.**

The team's task was to narrow down 60 concepts down to 5 that we thought could efficiently solve the problem in a new and innovative way. That being said, an initial meeting was held for all 6 of us to explain to the rest of the group their individual 10 concepts. The meeting was largely productive as we were able to narrow down the total number to approximately 30, as we all agreed many concepts would not be feasible due to lack of time, skills, or money. Afterwards, each individual team member worked to sift through the remaining 30 and rank their top 5-6 concepts. We separately analyzed the feasibility of each individual concept and reported to the next meeting with a list worth delving into a bit deeper. Fortunately enough, a majority of the concepts that were chosen actually overlapped among our team members and so picking the final 5 was fairly easy.

With regards to the Pugh Chart (Figure 6.1) and the criteria used in this part of the concept selection process, we extracted the engineering characteristics from the previously developed House of Quality. The weight of each individual criterion was decided amongst the team (using our vision for the end product) but more importantly from our surveys – these interviews provided our group with distinct criteria that would be necessary in developing a product capable of solving the problem.

In choosing a baseline product to compare to, it was necessary for our group to use already-conducted market research from the patent study homework. Having each conducted significant research on the market and potential competitors, we had a total of 6 products to compare our concepts with. However, we wanted to choose a baseline that would be competitive. That being said, we chose the baseline product to be Laughlin's Sleeve Puller – an electromechanical device that, to some extent, solves the problem we are addressing.

With regards to rating each concept against the base and criteria, we needed to meet amongst ourselves and discuss the specifics of the concept a bit more in depth. For example, with the Shirt O Rings:

While the product involved no electrical components (less expensive) and would be made of Velcro (very lightweight), it ended up scoring very poor against Laughlin's product in the efficiency criterion: reset time, # steps to use, and level of autonomy. In discussing this product, we collectively realized that while it would be easy to design, Laughlin's Sleeve Puller would outperform us due to being easier to use.

With regards to the scoring itself, each concept was rated on a scale of -2 (largely underperforming against the baseline) to +2 (outperforming). From researching different types of scoring methods used in Pugh Charts, we agreed this one would efficiently allow us to describe the concept's potential performance level.

## Analytic Hierarchy Process

After selecting the top three feasible concepts from the team's initial concepts, the team utilized the Analytical Hierarchy Process (AHP) to assist in selecting a final concept to pursue. The AHP is a decision making process that allows the team to help select among a number of alternatives and take multiple criteria into account to make a selection of the single best concept to pursue. The team first set a goal for the product to help an elderly user put on a t-shirt and identified the top three concept alternatives selected from the Pugh Chart. The top three alternative concept results were the Horizontal T-shirt Puller, the Belt Arm Puller and the Split Hanger. From there the team selected selected six criteria, based upon engineering characteristics used in the HOQ and pugh chart to evaluate and made pairwise comparisons as a group ranking the importance of the criteria compared to each other. Figure 5.10 below shows the initial setup and pairwise comparisons and rankings determined by the team.

| | Physical Footprint | Mean Time to Successfully Operate | Cost | Number of Steps to Use | Power Required | Level of Automation |
|---|---|---|---|---|---|---|
| **Physical Footprint** | 1.00 | 5.00 | 3.00 | 9.00 | 1.00 | 7.00 |
| **Mean Time to Successfully Operate** | 0.20 | 1.00 | 5.00 | 5.00 | 1.00 | 1.00 |
| **Cost** | 0.33 | 0.20 | 1.00 | 3.00 | 5.00 | 3.00 |
| **Number of Steps to Use** | 0.11 | 0.20 | 0.33 | 1.00 | 5.00 | 7.00 |
| **Power Required** | 1.00 | 1.00 | 0.20 | 0.20 | 1.00 | 9.00 |
| **Level of Automation** | 0.14 | 1.00 | 0.33 | 0.14 | 0.11 | 1.00 |

**Figure 5.10.** Initial AHP Pairwise Comparisons

After conducting the first couple steps of the AHP process the team created a weighted matrix based upon the initial pairwise comparison in order to determine weights for each of the criteria. Then, the team moved on to compare the alternative concept pairwise with respect to each criterion. This resulted in twelve matrices, two per criterion, with one comparison matrix and one normalized comparison that determines the weight of each concept with respect to the criterion.  Figure 5.11 below shows the output of the twelve matrices that summarizes the obtained weights for each criterion and concept.

| | Physical Footprint | Mean Time to Successfully Operate | Cost | Number of Steps to Use | Power Required | Level of Automation |
|---|---|---|---|---|---|---|
| **Horizontal T-Shirt Puller** | 0.08 | 0.09 | 0.07 | 0.21 | 0.20 | 0.07 |
| **Belt Arm Puller** | 0.49 | 0.67 | 0.64 | 0.55 | 0.60 | 0.64 |
| **Split Hanger** | 0.44 | 0.24 | 0.28 | 0.24 | 0.20 | 0.28 |

**Figure 5.11.** Table summarizing concepts vs criterion weights

After weights were obtained, the team aggregated the weights for each concept. Aggregating the weights for each concept outputted the results as seen in Figure 5.12 below. The aggregated weights indicated to chose the Belt Arm Puller concept.

| | Aggregate Weight |
|---|---|
| **Horizontal T-Shirt Puller** | 0.115 |
| **Belt Arm Puller** | **0.575** |
| **Split Hanger** | 0.310 |

**Figure 5.12.** AHP Aggregated Weights

Finally, consistency is checked confirming that the pairwise comparisons throughout the AHP process are consistent. Following the results from the AHP reveals that the Belt Arm Puller is the best concept to move forward with based upon the team's valuation of the pairwise comparisons. Based upon the results of the Pugh chart above and the AHP process, the team has decided to move forward with the Belt Arm Puller as the final concept selection. The full AHP including consistency checks is included as appendix 4 of this report.

## Group Signoff

*We certify that every team team member contributed to the concept select portion of the design analysis and that all signatories approve of the presented results.*

Hirbod Akhavan-Taheri

Charlie Benamram

Charlie B

Chad Cartwright

Graham Clifford

Conrad Hong

Conrad Hong

Mark Vulcan

Mark Vulcan

## C. Final Concept Sketch and Description

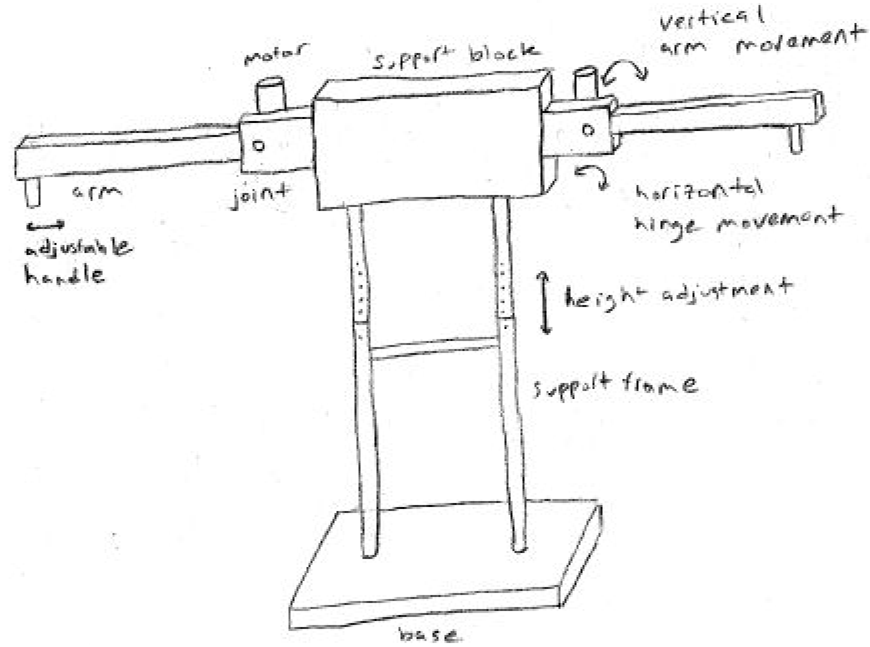



**Figure 5.13. Final Concept Sketch of T-Shirt Assistant**

As a result of the AHP process, the team made several modifications to the selected concept. The main modification is that the product is supported by a base on the floor and held up by a support frame. The product will be set up directly behind a chair so it can be used while the user is sitting down. The original design, the "Belt Arm Puller" was strapped to the user by a belt. The team changed this design so that elderly users would not have to hold the weight of the product with their backs. Additionally, a floor supported product is more stable. The second major change is that we added a horizontal degree of freedom using a hinge attached to the product arm, allowing it to rotate 90 degrees horizontally. The arm is also motorized to move 180 degrees vertically and be controlled by the user. In the "Belt Arm Puller" design, the product has two vertical degrees of freedom, one at the user's shoulder and another at the user's elbow. We changed this because based on our testing, it is beneficial for users to be able to move their arms horizontally and vertically while putting on a shirt. Additionally, we made the handle and support frame adjustable to accommodate for varying user arm lengths and heights, respectively.

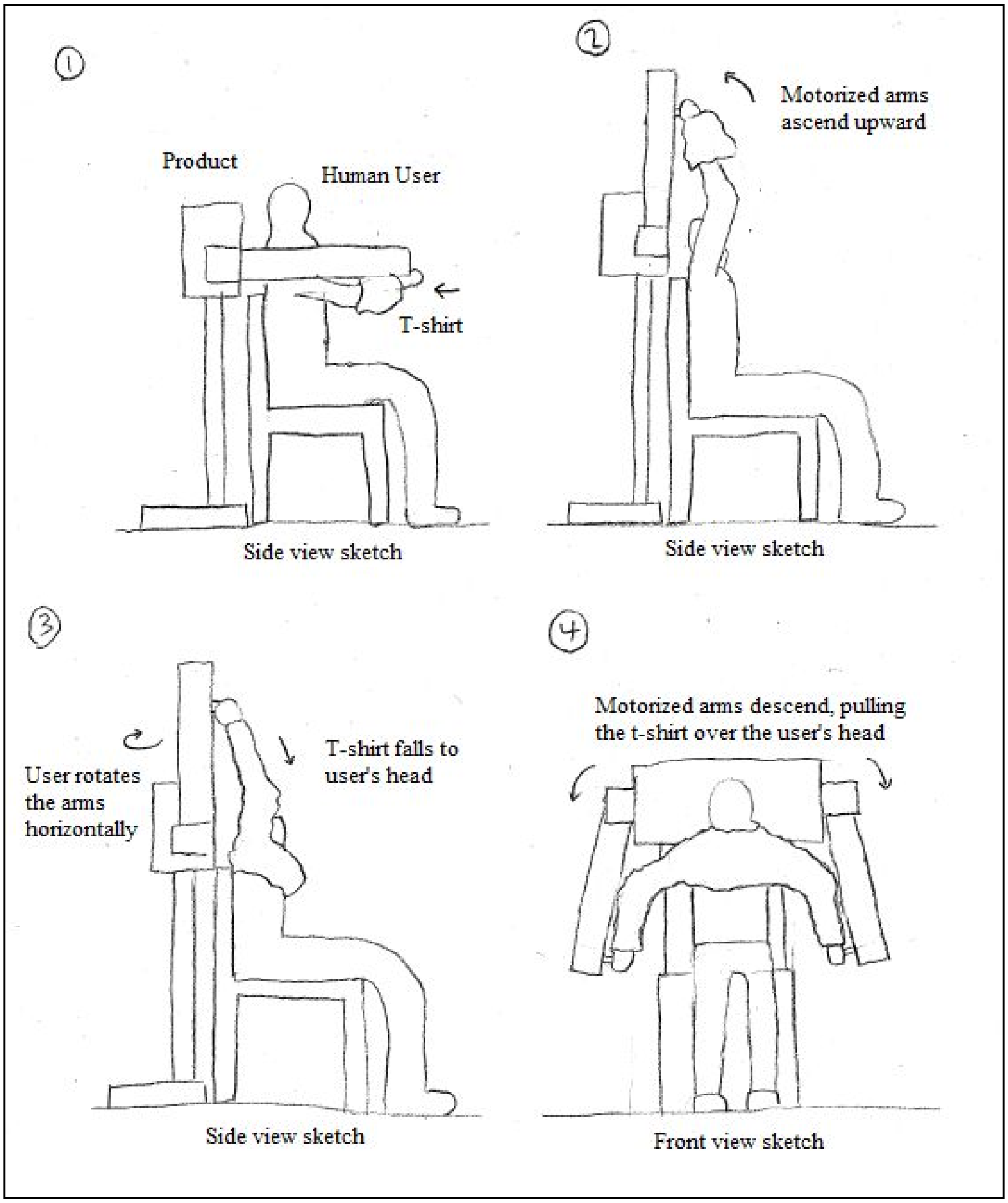



**Figure 5.14. Steps to Use the T-Shirt Assistant**

Figure 5.13 shows the steps that the user will take while operating the final T-Shirt Assistant product. Step (1) shows a side view of the human user sitting in a chair that is directly in front of the product. The user begins by putting the  shirt over their arms and holding their arms out vertically. The user grips the handle. Step (2) shows the motorized arms ascending upward in front of the user to the fully vertical position. Step (3) shows the t-shirt falling down to the user's head due to gravity. The user then turns the handles 90 degrees horizontally to rotate the arms outward. Step (4) shows a front view. This sketch shows the motorized arms descending fully downward. Since the arms have been rotated outward in the previous step, they descend at the sides of the user instead of the front. This forces the shirt fully over the user's head as shown in the sketch.

# VI. Embodiment Design Process

## Product Architecture

### General Product Layout

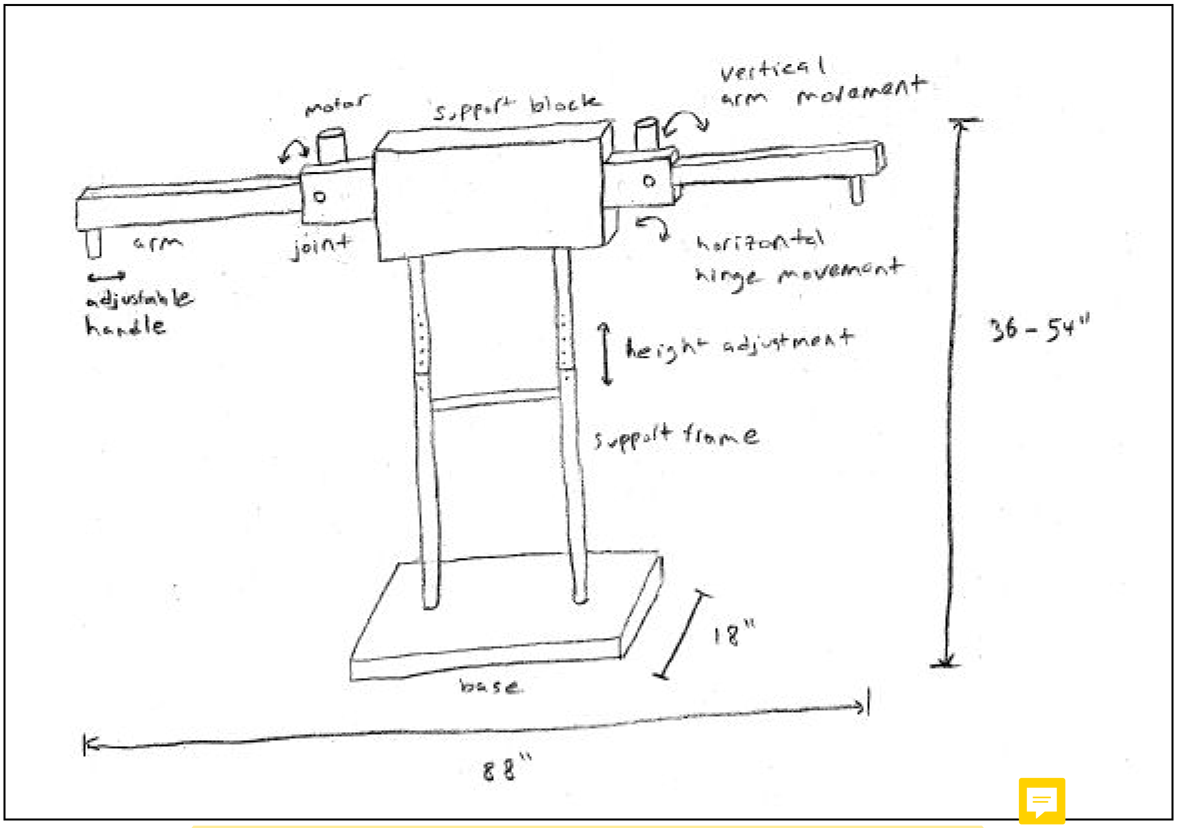



**Figure 6.1A. General Product Layout of T-Shirt Assistant**

The T-Shirt Assistant is designed to be set up behind a chair. It is supported by a base on the floor. A height adjustable support frame is connected to the base and allows the product to adjust from 36"-54" in total height. This height range is sufficient for any user and chair size. A support block is connected to the top of the support frame and houses the electronic components of the product. A standard door hinge is connected to each side of the support block, allowing the arms to move 90 degrees in the horizontal plane. The hinge is connected to a metal joint (bracket), which supports a gearbox and motor. The device arms are supported by a shaft that goes through the metal joint. The arms are motorized, user controlled, and can move 180 degrees vertically. A handle extends from the bottom surface of the arms and is adjustable to slide across the full length of the arms. This allows the product to accommodate users with all arm lengths. The overall width of the product is 88", which is sufficient for any user wingspan.

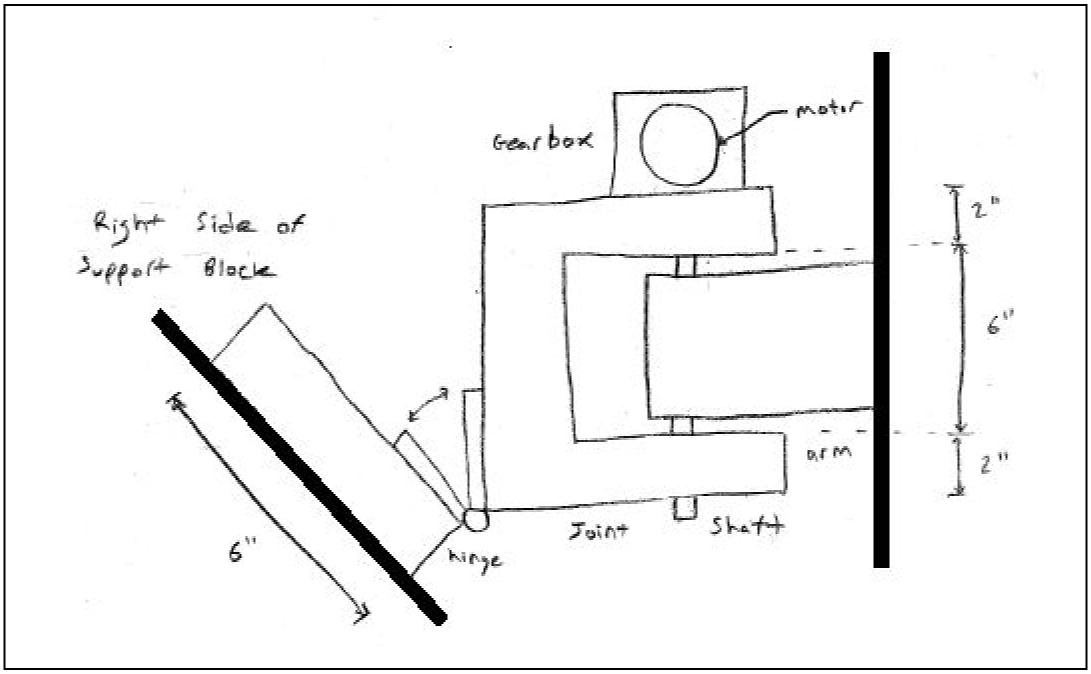



**Figure 6.1B. Product Arm and Joint Assembly Top View**

The product arm and joint (bracket) assembly is shown in Figure 6.1B. The boundaries are shown by the thick lines at the sides of the sketch. The right side of the support block is shown on the far left of the picture. A standard door hinge connects the support block to a metal joint, allowing 90 degrees of horizontal rotation. The product arm is connected to the metal joint by a shaft and can rotate 180 degrees vertically. The gearbox and motor are connected to the shaft. The rotation of the motorized arm is operated by a human user via a nunchuck controller.

## List of Subsystems

### 1. Structural Subsystem

The structural subsystem includes the base, support frame, support block, joint (bracket), and arm modules. This subsystem is designed to provide structural support for the product and be adjustable for users of all heights and arm lengths.

### 2. Mechanical Subsystem

The mechanical subsystem includes the shafts, motors, hinges, and gearbox modules. This subsystem allows the device arms to rotate 180 degrees vertically using a motor controlled by the user, and 90 degrees horizontally using force exerted on the hinge by the user.

### 3. Electrical Subsystem

The electrical subsystem includes the power supply, microcontroller, and all other electrical modules in the product. This subsystem gives the human user control over the motorized arm actuation and powers the motors.

## List of Modules

### 1. Support Frame Module

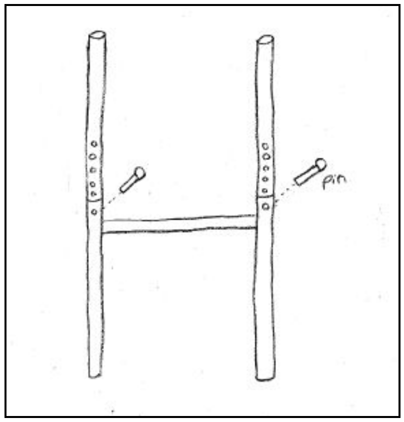



**Figure 6.2A. Support Frame Assembly**

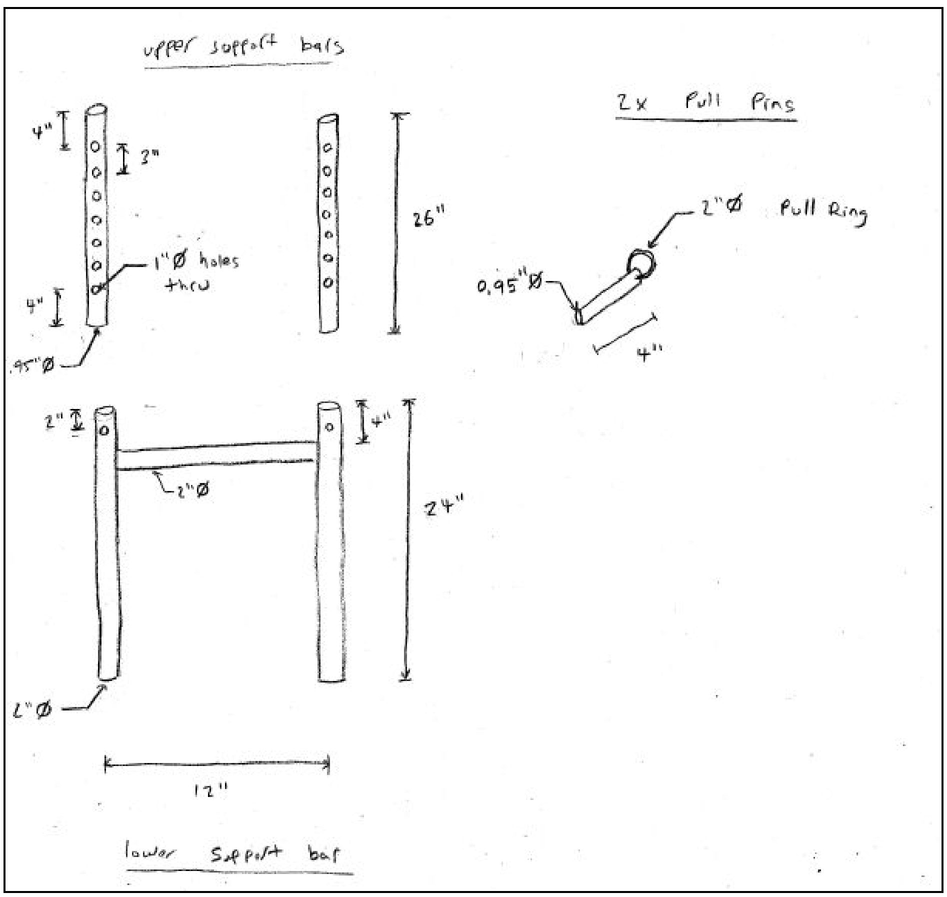



**Figure 6.2B. Support Frame Exploded View**

The support frame module is mounted to the product base and supports the weight of the product. Figure 6.2A shows the assembled support frame and Figure 6.2B shows the components. The lower support bar connects to the base. The two upper support bars slide into the lower support bar, and are pinned in place. There are seven holes to place the pin into, allowing the support frame to be height adjustable from 26" to 48".

**2. Base Module**

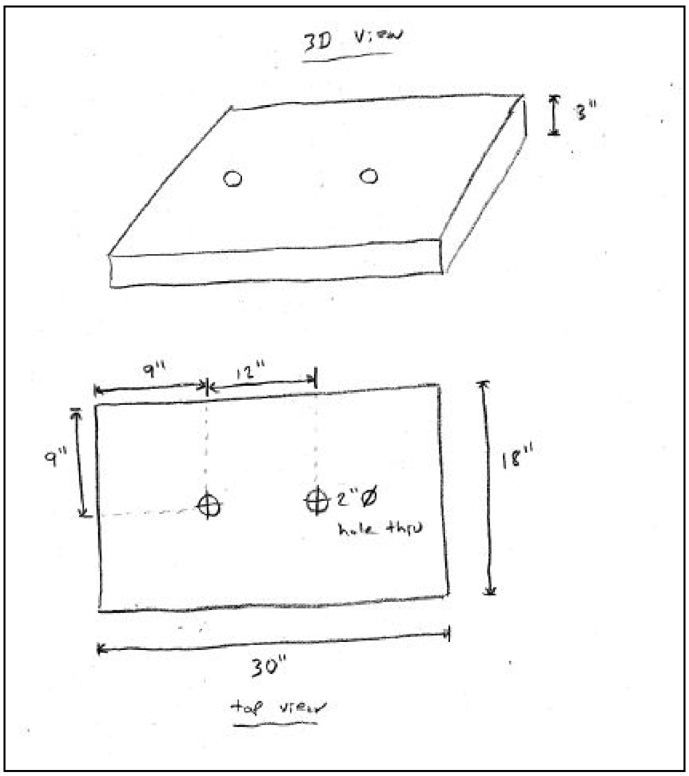



**Figure 6.3. Base 3D View and Top View**

The base module sits on the floor and holds up the support frame. It is 3" thick and has two holes going through it that the support frame slides into. The depth of the base is 18" to prevent the product from tipping over easily.

### 3. Support Block Module

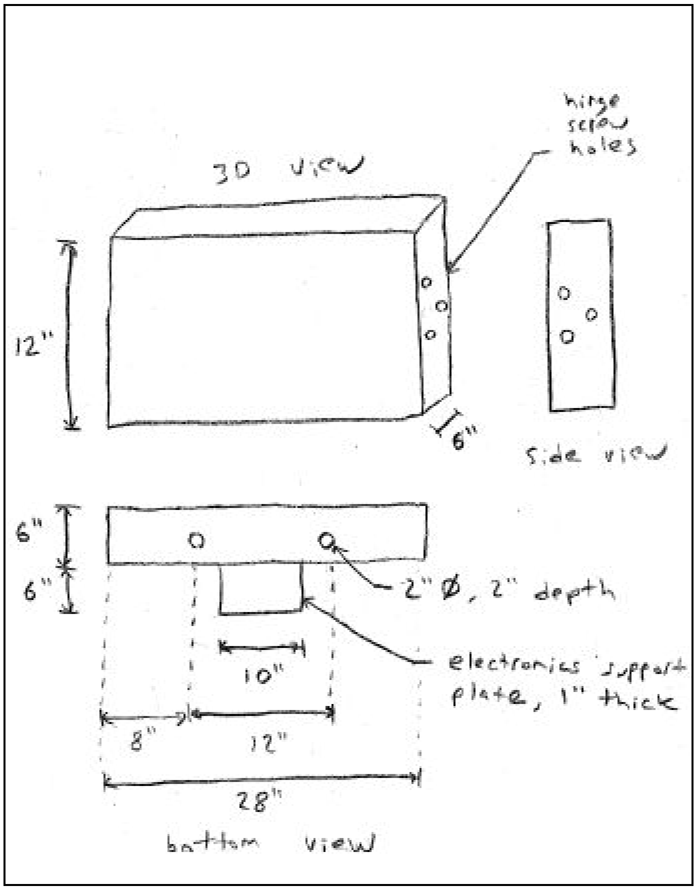



**Figure 6.4. Support Block 3D View and Bottom View**

The support block module is held up by the support frame. It has two holes on the bottom surface that the support frame fits into. There are three holes on each side of the block that hinges are bolted into. The hinges connect the metal joints to the support block. Electronic components are housed on the back of the support block.

## 4. Joint and Shaft Assembly Module

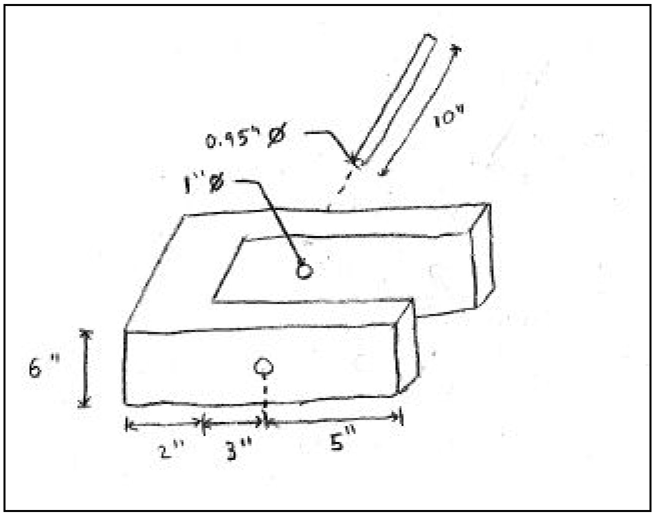



**Figure 6.5. Joint and Shaft Assembly**

The joint (bracket) and shaft assembly support the weight of the product arm, gearbox, and motor. Referring to Figure 6.5, a standard door hinge is fixed to the left side of the joint, and allows the joint to rotate 90 degrees horizontally. The joint is 8" in depth and a 10" shaft goes through it. A gearbox is attached to the back side of the shaft, and the gearbox holds up the motor. The product arm is connected to the joint by the shaft, and is able to rotate 180 degrees. The shaft will also have several bearings allowing it to rotate the arm.

### 5. Arm Assembly Module

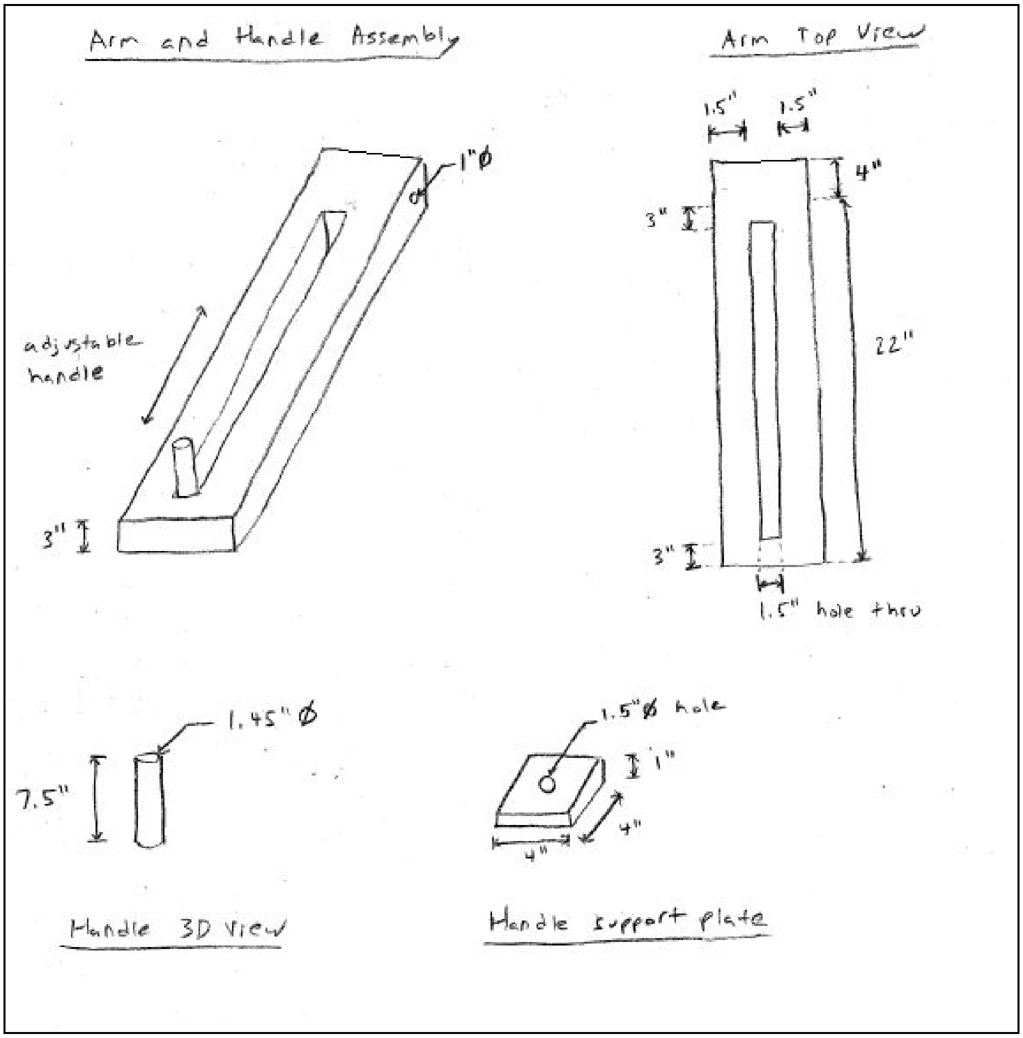



**Figure 6.6. Arm and Handle Views**

The arm module is connected to the metal joint by the shaft. There is a slot cut through the length of the arm that the handle fits into. The handle is attached to the handle support plate, which can be moved across the length of the arm and tightened into place based on the arm length of the user. The total length of the product arm is 26", which can accomodate the arm length of any human user.

### 6. Gearbox, Motor, and Hinge Modules

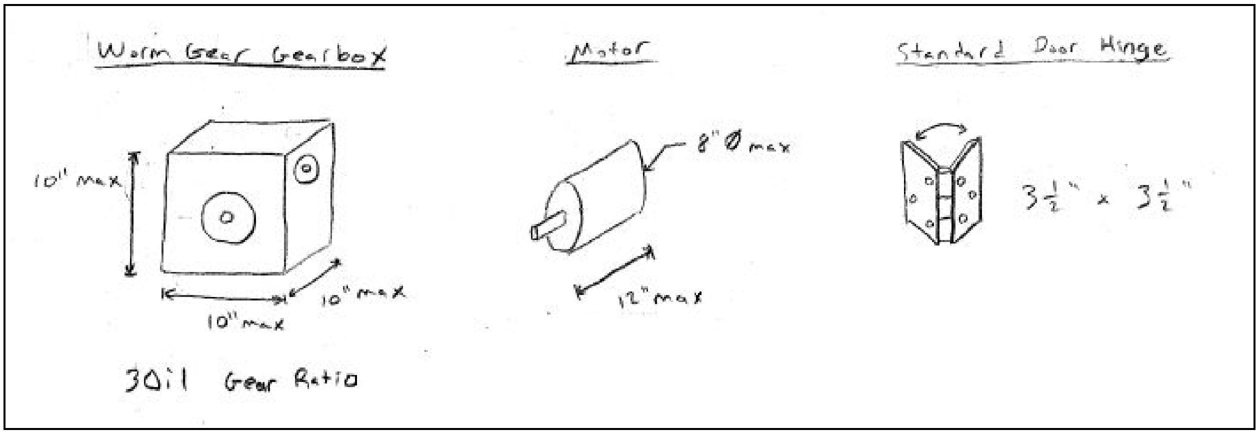



**Figure 6.7. Gearbox, Motor, and Hinge**

The product features several standard parts and some are shown in Figure 6.7. Standard parts include two 30:1 gear ratio worm-gear gearboxes, two NEMA 23 motors, two 3.5" x 3.5" door hinges, a power supply, bolts, and fasteners. The worm-gear gearbox is connected to the motor and joint and shaft assembly.

## Interfaces

The product base and support frame are press fitted together. The support block is press fitted on the support frame. The hinges are bolted to the sides of the support frame, and the joints (brackets) are bolted to the other end of the hinges. The arms are connected to the joints using shafts. The motors are screwed into gearboxes, and the gearboxes are screwed in the sides of the joints and connected to the shafts. The handles on the arms are able to slide and tighten based on user preferences. The support frame has a pin on each side so that it is height adjustable.

# Configuration Design

## Product Arm Torque Requirements

Assuming 15 lbs maximum weight of a person's arm, maximum user arm length of 2.5 ft, and 10 lb weight of the product arm centered at 1.25 ft from the end of the arm:

$$15\ lbs\ \times 2.5\,ft\ +\ 10\ lbs\ \times 1.25\,ft\ =\ 50\,ft \cdot lbs$$

The NEMA 23 motor provides 3 Nm of torque:

$$3\ N \cdot m =\ 2.21\ \ ft \cdot lbs$$

$$50\,ft \cdot lbs\ /\ 2.21\ \ ft \cdot lbs\ =\ 22.6$$

$$22.6\ \times 1.33\ safety\,factor\ = 30$$

Therefore, the team selected the NEMA 23 motor with a 30:1 gear ratio to meet the torque requirements for actuating the product's arms.

## Manufacturing Considerations

Based on the team's material and manufacturing analysis shown in the section below, the team selected AISI 1018, a low carbon steel, as the material for all structural parts. Therefore, the base, support frame, support block, joint (bracket), arms, and handles will all be made of AISI 1018. This steel is inexpensive, strong, and weldable. Thus, it is a good choice for structural material. All structural components must be made custom for the T-Shirt Assistant product, either in a company facility or by a supplier. The dimensions and configurations of all custom parts are shown in the above product architecture section.

The standard parts used in this product include two NEMA 23 stepper motors, two NEMA 23 30:1 worm gear gearboxes, one 24V power supply, one microcontroller, and all other electronic components. These parts are all mass produced and will be ordered from suppliers. A summary of parts, quantities, materials, and manufacturing is provided in the table below.

**Parts List, Materials, and Manufacturing**

| Part | Quantity | Material | Manufacturing |
|---|---|---|---|
| Base | 1 | AISI 1018 | Custom |
| Support Frame | 1 | AISI 1018 | Custom |
| Support Block | 1 | AISI 1018 | Custom |
| Joint (Bracket) | 2 | AISI 1018 | Custom |
| Shaft | 2 | AISI 1018 | Custom |
| Arm | 2 | AISI 1018 | Custom |
| Handle | 2 | AISI 1018 | Custom |
| NEMA 23 Stepper Motor | 2 | Varies | Ordered from supplier |
| Nema 23 30:1 Worm Gear Gearbox | 2 | Varies | Ordered from supplier |
| EAGWELL 24V Power Supply | 1 | Varies | Ordered from supplier |
| 18 AWG 3-Prong Power Cord | 1 | Varies | Ordered from supplier |
| Arduino UNO | 1 | Varies | Ordered from supplier |
| Bearings and Fasteners | 10+ | Varies | Ordered from supplier |

## Material and Manufacturing Process Selection Analysis

The bracket which attaches the arms to the product is the most critical part of the entire design as well as the part which is under the most stress. A failure of this bracket will be catastrophic and not only will cause the product to be inoperable, it can lead to injuries for the user. Henceforth, the most important requirement for the part is that the von-mises stress cannot exceed the yield strength under any circumstances. While the part cannot yield under stress, it cannot exceed deflection limits too. Exceed deflection limits will not cause a catastrophic failure, but it will drastically hamper the operation of the device due to tight tolerances of connected parts (two hinges at each end).

The goal for material selection of this particular part will be to maximize Young's modulus which directly corresponds to minimum deflection. Our targeted product life is going to be five years and 2400 cycles. Every component needs to not exceed it's fatigue limit including the brackets. In order to ensure our expected product life expectancy, we will consider materials which have high fatigue life. Similar to any other parts that are in contact with humans, it needs to be safe to contact and free of sharp edges and burs. The part must not cause any skin irritations or be a safety hazard for the user. Since the product is designed for the costumer market, it needs to be aesthetically pleasing.

A general industrial design needs to be performed on the product which can directly affect the material selection and design of the parts to a certain extent. This criteria however is less important compared to others mentioned above. Our product will be used in a temperature and moisture controlled environment of a house or an apartment. Therefore, the brackets will not be exposed to any excessive sun radiation, acids, oils or chemical gases. Based on that, we are not concerned with material compatibility with environmental factors. Finally, the overall cost of manufacturing and assembly must be as low as possible to maximize the profit.

In order to determine the range of yield strength needed to ensure that our product will not exceed it during the operation, we calculate the maximum stress possible on the part:

The moment of inertia of the bracket in the direction of applied force will be as follows:

$$I = \frac{1}{12}bh^3 = 0.25$$

The maximum applied moment will be:

$$M = 30 \times 4 = 120\ lb - in$$

Thus, based on moment of inertia and max moment, the maximum stress is:

$$\sigma = \frac{M \times Y}{I} = \frac{120 \times 0.5}{0.25} = 240 PSI$$

With a safety factor of 3, our final max stress in the part will be 720PSI. Based on the Ashbey chart, we need to be in the highlighted range (720PSI=5MPa) in figure 6.8.

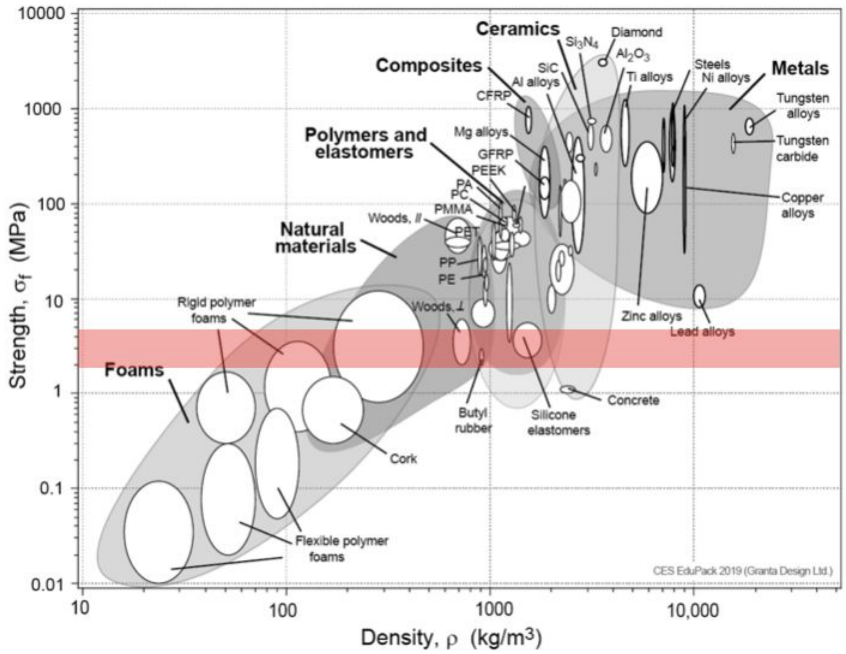



**Figure 6.8. Strength v. Density**

Certain types of wood, polymers and all types of metals will satisfy our main constraints of strengths. In order to proceed with the material selection process we move on to considering material stiffness and total deflection under loading. We use the CES database to look at the material that have a young's modulus greater than 10^6 psi and less than 1.5*10^7 psi while costing the least amount of money to keep the manufacturing cost as low as possible.

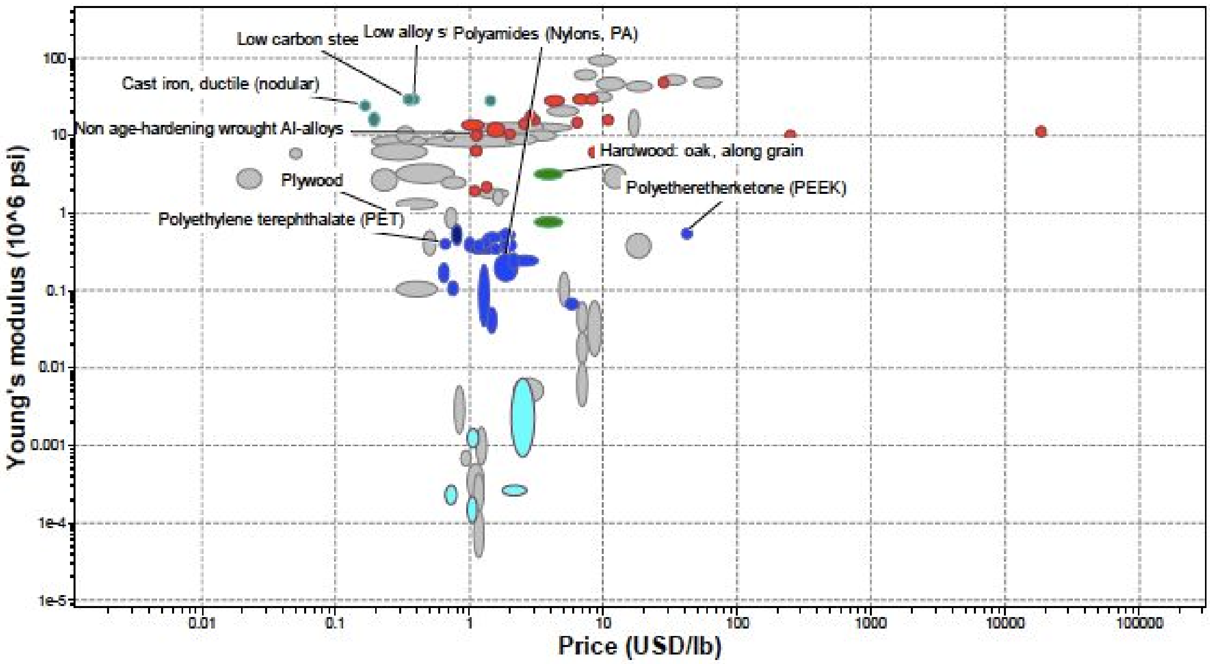



**Figure 6.9. Young's Modulus v. Price**

Although polymers and natural wood (blue and light green) satisfies our yield strength requirements, they do not provide the needed young's modulus to ensure limited deflection under normal operation. Thus based on cost and stiffness, we are going to focus on the metal family of materials, both ferrous and non-ferrous sub-group. The next important criteria is going to be fatigue life. Considering fatigue life at 10^7 cycles we can see that steels in particular, low carbon steel can satisfy all of our constraints so far. Although Age-Hardened Al alloys is not as resistant to fatigue stress, it still can withstand 10+ Ksi at 10^7 cycles which more that needed.

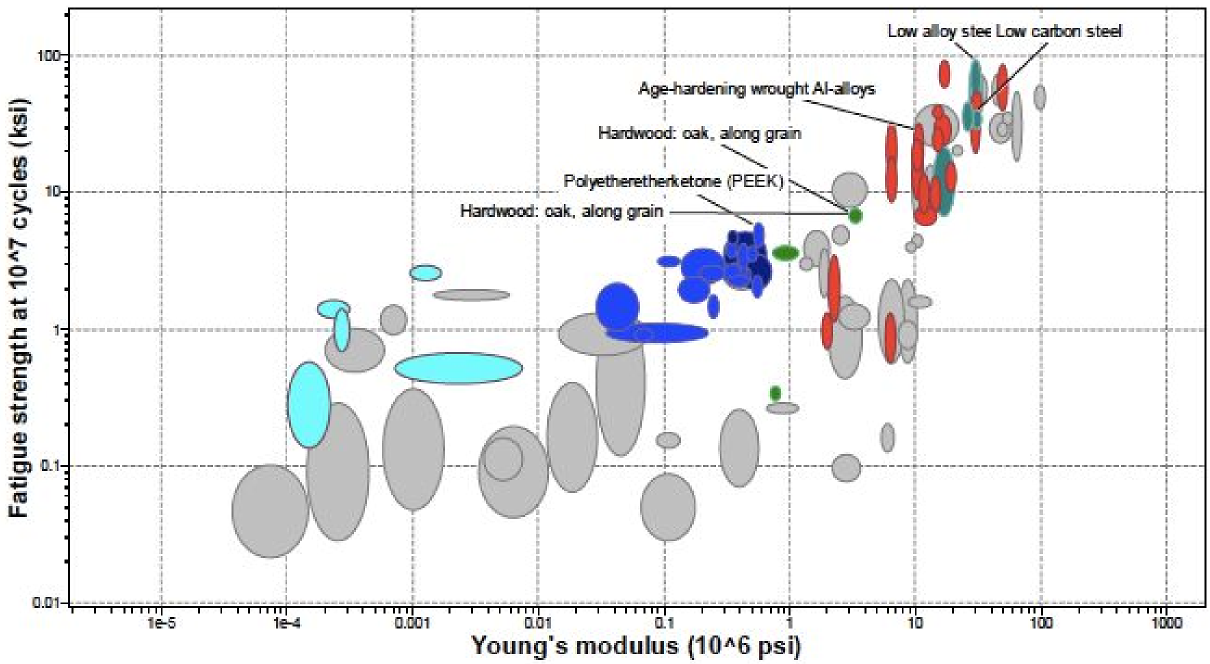



**Figure 6.10. Fatigue Strength v. Young's Modulus**

In conclusion, Age-hardening wrought Al alloys and low carbon steel are the two materials which meet are most critical requirements. In the second stage of material selection secondary criteria such as manufacturing cost and material availability are examined.

In line with the US Department of Interior, as of 2018 Aluminum has become part of the critical mineral list shown in the following graph. There is a nation-wide initiative to reduce dependence of Aluminum in the internal markets of the US which can potentially pose a national security threat. On the other hand, the US is not dependent on foreign sources of steel and can supply the internal need. Although our brackets do not require much raw material based on their size and our planned manufacturing capacity, we are still going to choose steel despite low production volume. Choosing Aluminum now and then optimizing the part over the next ten years based on aluminum properties might become challenging if the supply of aluminum becomes scarce. Thus we are planning to choose steel as our material of choice due to less risk of shortage after optimizing the part over the next ten years.

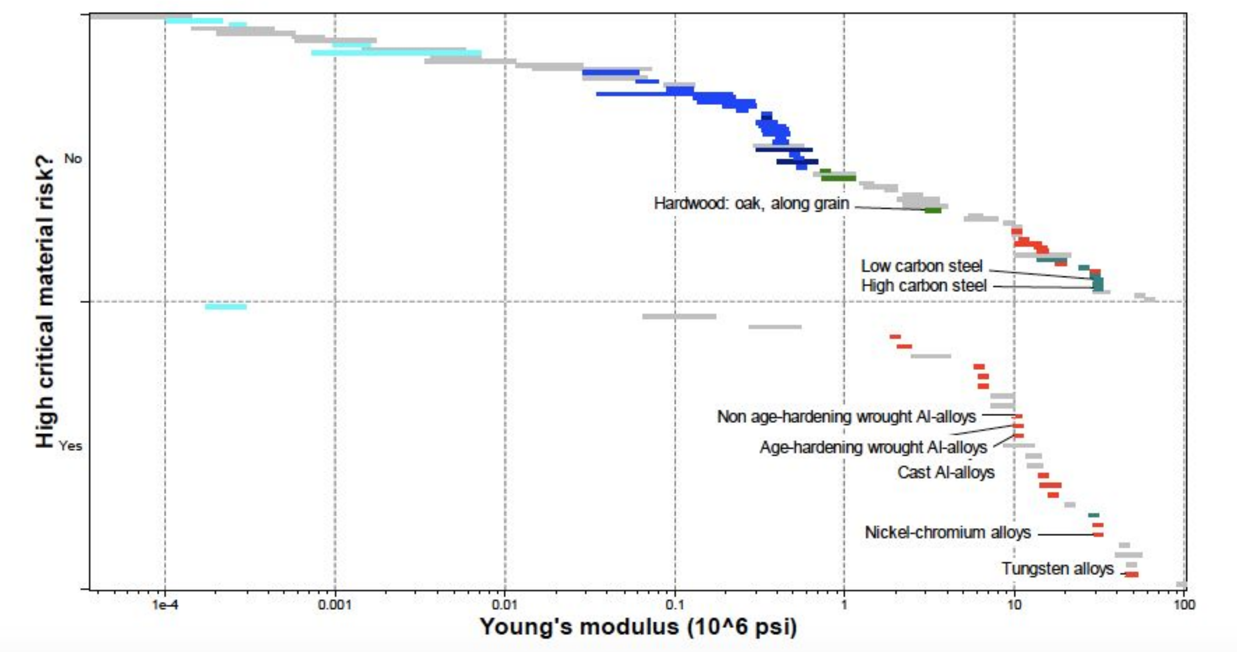



**Figure 6.11. High Critical Material Risk v. Young's Modulus**

During cost comparison, we can see that Al alloys cost between $1.08 and 1.16$ per pound[1] while low carbon steel costs between $0.34 and $0.354 per pound[2]. The raw material cost of steel is one third that of Al alloys which suggest that using steel over aluminum will reduce the overall cost of the profit which will maximize the profit. On the other hand, manufacturing cost of steel will slightly be higher than aluminum due it its higher material harness (113-168 HV for low carbon steel and 83-116 HV for cast AL-alloys). Even with the difference in material hardness, that will not compensate for the three times higher cost of the raw material.

[1] Estimated based on market values as of 11/13/2019 in the US
[2] Estimated based on market values as of 11/13/2019 in the US

While steel is the material of choice over aluminum in our case, there are some trade-offs associated with it. Overall weight of the device is not a high on the customer requirements or engineering characteristics list, but it does matter. The weight of the bracket directly affects the ease of moving the product in an indoor environment. Aluminum has a density of about 0.1 lb/in^3 while low carbon steel has a density of 0.28 lb/in^3. This indicates that using steel will increase the overall weight of the product compared to Al alloys.

We are estimating an initial market size of 600,000 customers in the United States. We will slowly ramp-up production from 100 units to 10,000 units per year for later stages of the company. Based on the materials selected and manufacturing capacity, we are considering conventional machining and forging as our manufacturing method for the brackets.

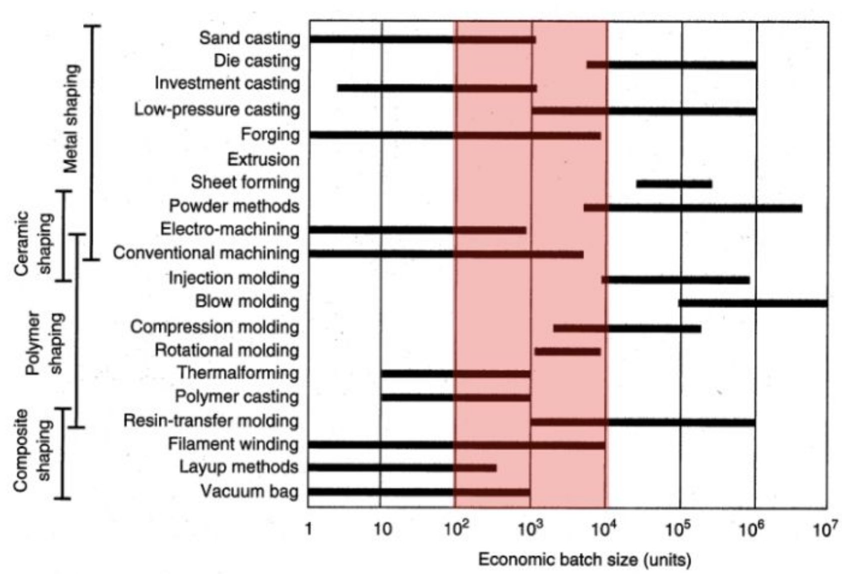



**Figure 6.12. Economic Batch Size for Material Shaping**

## Human Factors Analysis

In performing a quantitative human factors analysis, we must determine if our product fits into one of the four provided categories: manual operation, human powered devices, wearable products, and reduction in cognitive or physical effort. Being that the ‘Belt-Arm Puller’ is a wearable product that aims to reduce the consumer’s requirement for cognitive and strength to put on a shirt, it is required that we conduct a sufficient human factors analysis.

First with regards to manual operation, our consumer population will be lifting a t-shirt above their head with help from our product. Using the Liberty Mutual Manual Materials Handling Tables, we will very conservatively that a shirt weighs one pound. If we assume average hand distances (10”), an average lifting distance of 20”, and a frequency of lift approximately once every 8 hours,  we see that more than 90% of either the male or female population is capable of doing this. Given that in 2017 15.6% of the American population was 65 or older, we see that manual operation of our device will not significantly preclude any subset of our intentional consumer base. Furthermore, it is noted by LMMMHT that designing manual tasks for greater than 75% of the population will offer the best protection from manual handling injuries.

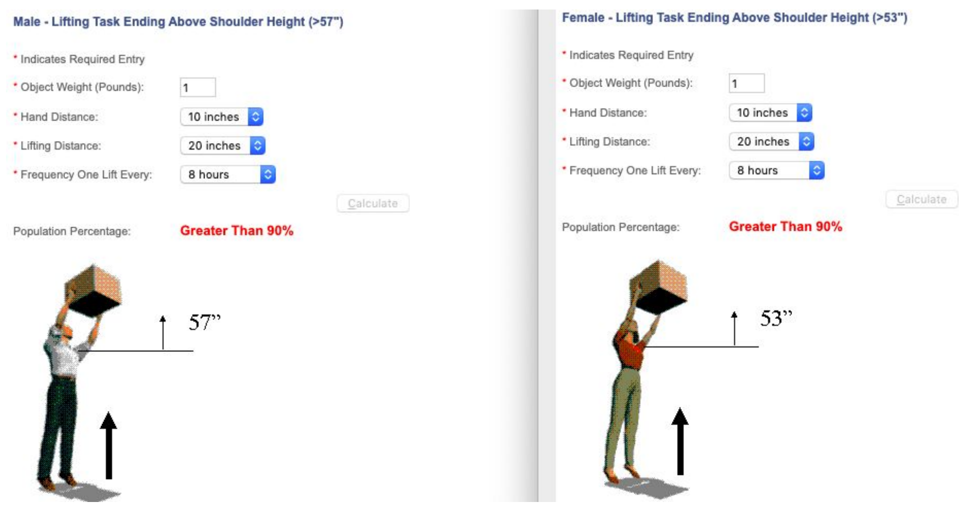



**Figure 6.13: Lifting Task Population Percentage**

As you can see from our final concept selection and prototype, the final product will be wearable. That being said, anthropometric characteristics should be explicitly defined (as they are in the preliminary human factors section from IR1) in addition to product specifications for the human-machine interface:

Two motorized armatures part of the rigid frame are attached to the customer via gripping handles for the left and right hands. This minimal interaction ensures the highest aspect of safety in that the user can let go of the armatures whenever they deem necessary. Furthermore, it ensures a high level of comfort in that the consumer will feel freedom to move as they please without a robot being latched onto their body.

A task analysis detailing the steps associated with achieving the goal of putting on a shirt must be analyzed for our proposed design.

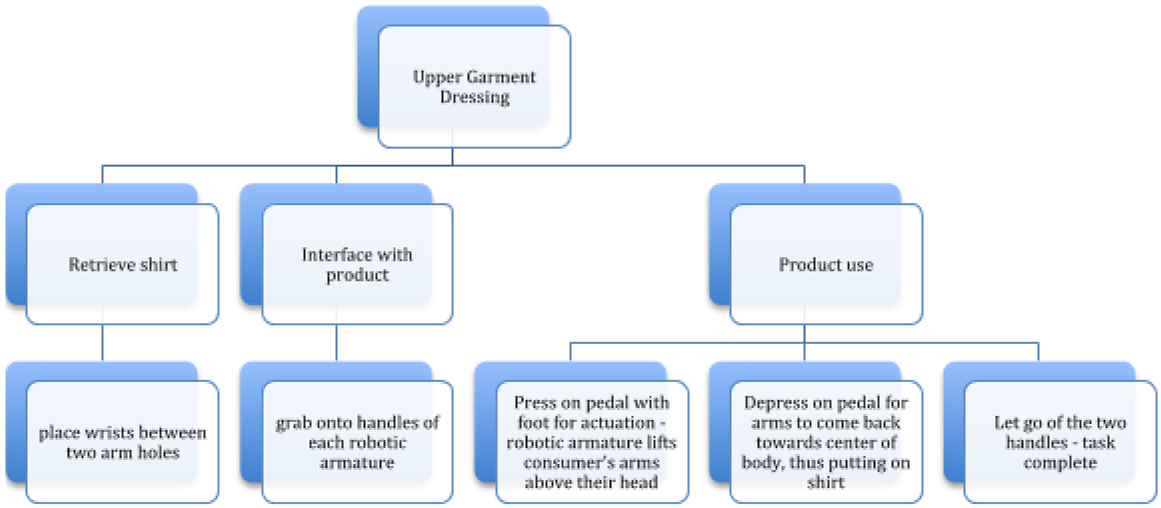



**Figure 6.14: Task Analysis For T-shirt Assistance Device**

With regards to prototyping, we are required to perform a usability test with at least 5 users with similar characteristics as the end user population. Our test aims to validate data from the software analysis / paper checklist used earlier in the design process.

# Failure Modes and Effects Analysis

| Potential Failure Mode | SEV | OCC | Cause of Failure | DET | Effects of Failure | RPN | Percentage |
|---|---|---|---|---|---|---|---|
| Device not adjusted properly for user. | 3 | 4 | User incorrectly adjusts device for themselves. | 7 | Process fails, user must restart. | 84 | 21 |
| Device experiences structural failure. | 10 | 2 | Large magnitude force is applied to device in unforseen way. | 10 | Device is destroyed, injury likely caused to user. | 200 | 52 |
| Device functions properly but user cannot complete process. | 2 | 5 | Shirt is improperly sized for user. | 10 | Process fails, user must restart. | 100 | 26 |
| | | | | | Total: | 384 | |

**Figure 6.15: Failure Modes and Effects Analysis**

Using the FMEA chart above, it is possible to determine critical to function parts and assemblies. The three failure modes are: the user did not adjust the device properly prior to use, the structure of the device itself fails during use, and the device works properly but the t-shirt process fails anyway. The first failure mode is caused solely by the user. If the device is not adjusted properly, then the user's arms will not have the correct positioning necessary to complete the process and put on the shirt. This might be avoided by adding a warning label or reminder somewhere on the outside of the device reminding the user to adjust it properly before use. The second failure mode would be caused either due to excessive wear on the devices parts and subsystems over time, or an unexpectedly large force is applied to a critical position on the device. This might be avoided by calculating potential number of cycles the devices components can undergo before excessive danger to the user becomes present. It is difficult and not practical to design for random, large forces being put on the device since we are only able to design for intended use of the product. The third and final mode is caused by the t-shirt choice of the user. If the shirt is too small or too large for the user's body type, even the correct adjustment and positioning of the devices subsystems will not be enough to prevent the process from failing. This case could also fall under un-intended use of the product, as our team has assumed the user wears proper and well-fitted clothes.

## Social and Environmental Design Considerations

Our product offers something that is going to be priceless for our customers, a restored dignity. When people age, naturally they will become more reliant on others for their basic needs. A fruitful life and years of contribution to society makes it difficult for individuals to ask for help for mundane tasks, such as putting on a t-shirt. Our product is going to offer the elderly a higher quality of life in restoring their dignity. This kind of social impact cannot be quantified in any type of engineering analysis, especially cost analysis.

Another major factor that simply cannot be represented quantitatively, but was extensively considered, is our product's CO2 footprint on the environment. We have actively made design decisions to ensure minimal negative environmental impacts. In order to reduce the effect of transportation of our raw materials and pre-made parts, we are planning to manufacture the product in Maryland, USA and source from vendors, which are on average 200 miles away from the College Park area. Although voluntarily limiting our supply chain to a relatively small area will increase our cost and limits our design and manufacturing flexibility, it drastically reduces our CO2 footprint on the environment. Due to our planned low volume of production, we are also going to utilize light goods vehicle instead of larger multi-axle trucks which would impact the environment in a more negative way. Based on the proposed supply-chain our total CO2 footprint is going to be about 10lb, which is negligible compared to other factors.

Aside from transportation, the sources of our parts and raw material have a large impact on our overall CO2 footprint. Our product is largely made from Li-on batteries, plywood, aluminum and steel using forging and extrusion methods, as broken down in the following tables. In order to reduce our CO2 footprint, we will collect products that are past their 5-year life cycle and recycle the metals as well as downcycle the wooden parts.

| Component | Material | Recycled content* (%) | Part mass (lb) | Qty. | Total mass (lb) | Energy (kcal) | % |
|---|---|---|---|---|---|---|---|
| **Bracket** | Low carbon steel | Typical % | 20 | 1 | 20 | 4.6e+04 | 8.4 |
| **Wood** | Plywood | Virgin (0%) | 30 | 1 | 30 | 8.4e+04 | 15.4 |
| **Al** | Non age-hardening wrought Al-alloys | Typical % | 30 | 1 | 30 | 4.2e+05 | 76.2 |
| Total | | | | **3** | **80** | **5.5e+05** | **100** |

*Typical: Includes 'recycle fraction in current supply'

| Component | Process | Amount processed | Energy (kcal) | % |
|---|---|---|---|---|
| **Bracket** | Forging | 20 lb | 6.3e+03 | 16.8 |
| **Al** | Extrusion, foil rolling | 30 lb | 3.1e+04 | 83.2 |
| Total | | | **3.7e+04** | **100** |

**Figure 7.1. Material Comparison**

Currently, our CO2 footprint estimate due to raw materials is about 380lb in the 5-year life span. This is the main source of our products footprint.

Overall the breakdown of our product’s environmental impact is as follows[3]:

[3] We are assuming 20 watts of power rating used in north America in 360 days per year at 0.005 hours a day for product life of five years.

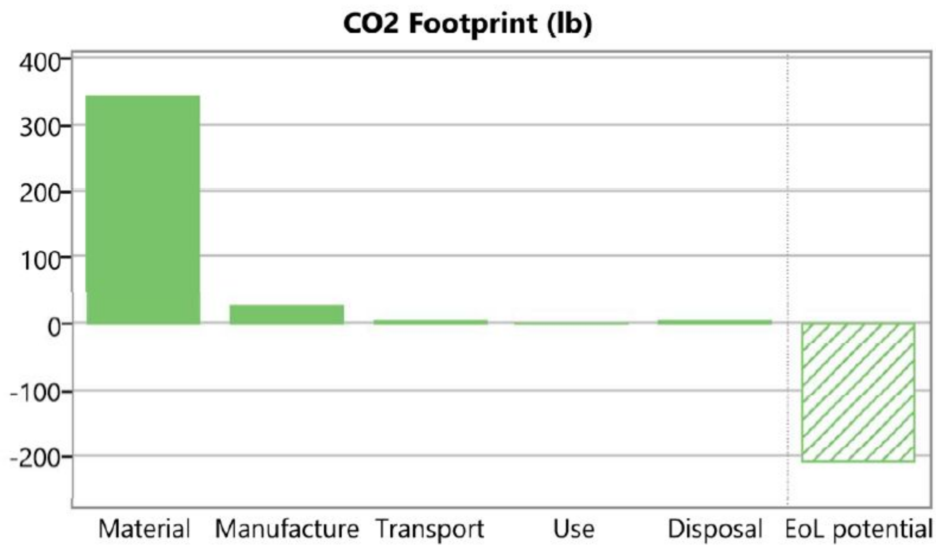



**Figure 7.2. Carbon Footprint**

Figure 7.2 shows the carbon footprint of the product. By reusing plywood, aluminum and steel (increase recycle content to 90%+) and then remanufacture our batteries and plywood after the product life-cycle, we can reduce our total produce energy consumption by 98% percent as well as our CO2 footprint. The wooden and metal parts are not going through high levels of stress and after five years, repurposing them is indeed feasible. Not only that will help conserve the environment, the low CO2 footprint can become a selling point and attract more customers. Our adjusted CO2 footprint projection can be seen in the following graph[4] (Figure 7.3).

[4] Product (1) refers to our product after logistical modifications

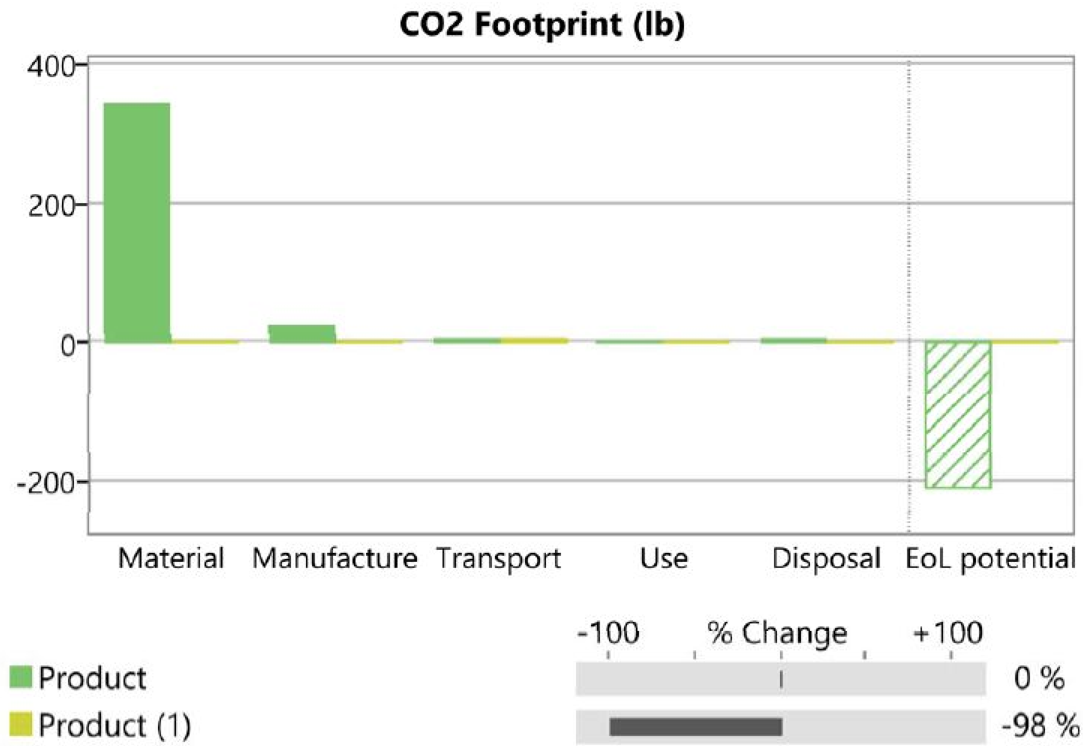



**Figure 7.3. Carbon Footprint (2)**

## Parametric Design

To begin the parametric design process, it is important to first specify the design problem. In our case, the design problem is to design a device that efficiently, safely, and cost effectively assists users in lifting in their arms above their heads to put on a t-shirt. Every attribute of the design that contributes to solving our design problem is a solution evaluation parameter (SEPs). The SEPs of the design that contribute to the efficiency of the design are the power requirements, the weight of the device - especially the arm mechanism, and the mean time to successfully complete the process. Next, the SEPs that contribute to the safety of the device are the probability of process failure and adjustability of the device. Finally, the SEPs of the device that contribute to the cost effectiveness are the weight, material, and manufacturing processes.

In order for the operation of the device to be efficient, it is important to choose a motor that is able to raise the arms of the device at a slow but reasonable pace. It is also important to minimize the dimensions of all structural elements of the device to ensure that the weight of the device is minimized. With this in mind, we dimensioned our device to minimize the physical footprint of each subsystem while still ensuring user comfort and structural integrity. Due to the nature of our device, our team determined that the subsystem most-likely to fail during operation will be the connection between the motor shaft and the arm of the device. FEA analysis was conducted to observe the Von Mises stresses, max principal stresses, and maximum displacement of the arm of the device during operation. The inner diameter of the motor shaft hole on the arm was fixed, and a load of 220 N or ~50lbs was put on the bottom of the handle facing downwards.

The results can be seen below:

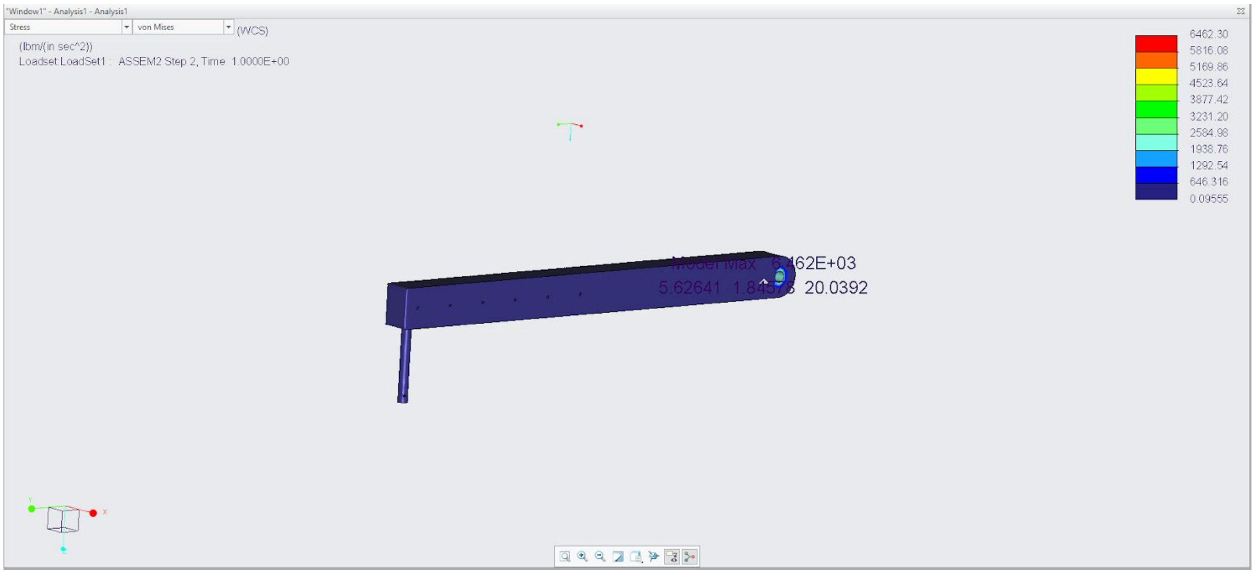



**Figure 6.15: Von Mises Stress During Operation of Device**

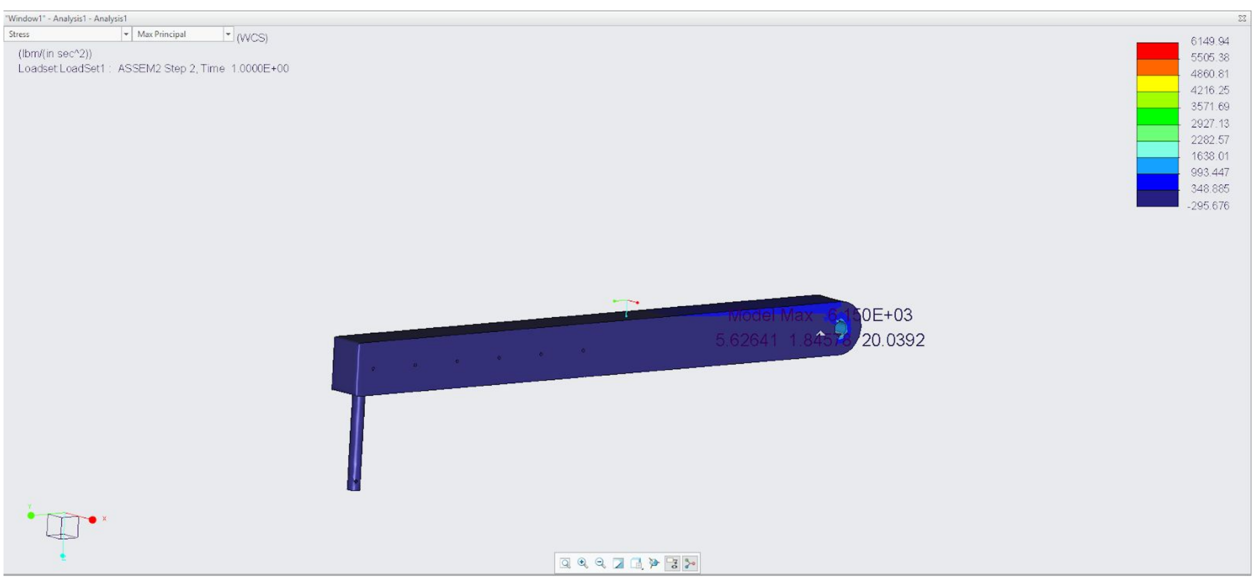



**Figure 6.16: Max Principal Stress During Operation of Device**

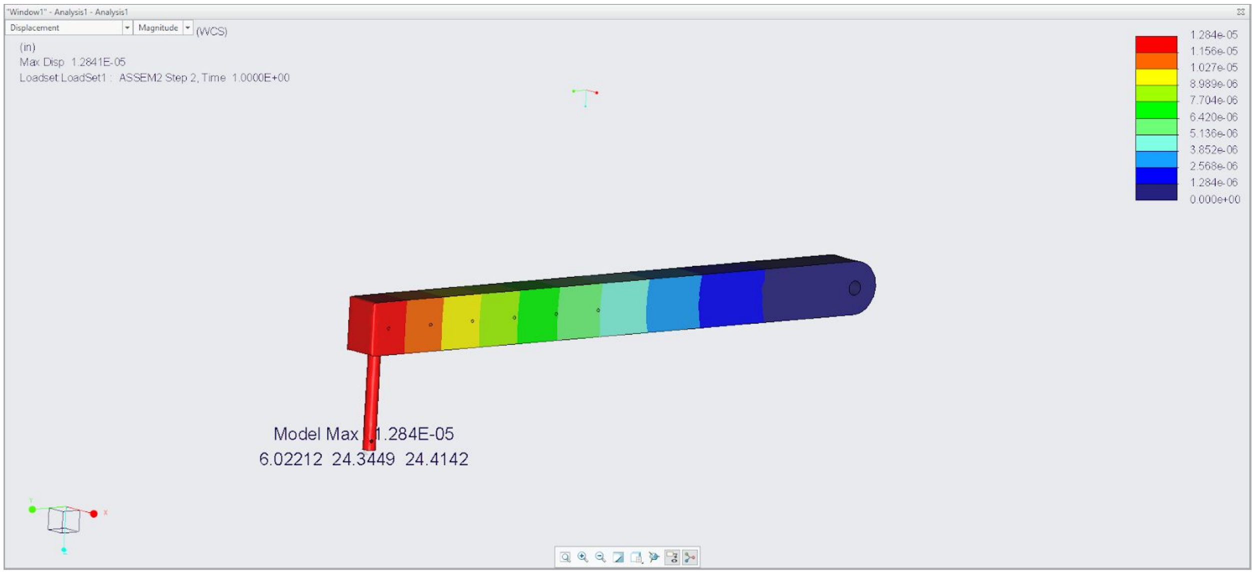



**Figure 6.17: Max Displacement During Operation of Device**


**Figure 6.18: FEA Setup**

See Figure 6.15. The Von Mises stress is at a maximum in the motor-shaft hole at the rear of the arm. It reaches a maximum value of 6,462 $lbm/in * s^2$, or 44.7 $MPa$. The minimum shear strength of steel is about 200 $MPa$, which gives our design a safety factor of 4.5. This should be more than sufficient. The maximum principal stress during operation will reach a value of 6150

$lbm/in * s^2$ , or 42.4 MPa. The minimum yield strength for steel is around 295 MPa, which gives our design a safety factor of 6.95. This should also be sufficient. The maximum displacement at the end of the arm is 1.28E-05 *in*, which will be unnoticeable by any user.

There are four positions on the device where dimension tolerances must be calculated. They are where the upper and lower support legs connect to the back plate and base plate, respectively; where the handle connects to the arm, where the handle pin connects to the arm, and where the motor shaft connects to the arm. Using an engineering tolerance calculator found online, these tolerances should be +/- 9.8E-04 *in*, +/- 7.1E-04 *in,* +/- 4.7E-04 *in,* and +/- 7.1E-04 *in*, respectively.

Our team attempted to optimize our design while in the process of designing it, and thus we do not have a repertoire of alternative designs. Reducing dimensions further than we already have would result in issues with structural integrity, aesthetics, or safety of the user.

In order to ensure the safety of our users, our team implemented a responsive user-operated control system. While not implemented in CAD models, a Wii nunchuk will be attached to the right arm of the device on the handle. This will allow the user to control the speed and movement of the device to the fullest extent possible. In addition, we designed our product to be fully adjustable to account for all body types. Each support leg is adjustable vertically, the back plate is wide enough for users in the 99th percentile for shoulder width, and the handle position on the device arm is able to be adjusted to account for all arm lengths. These features should ensure the safety of the user to the maximum extent.

# VII. Manufacturing and Cost Analysis

## Manufacturing

To manufacture the final product, minimum amount of initial investment is expected, therefore, no major capital purchase is feasible due to lack of initial funding. Henceforth, the majority of the processes are going to be carried out manually instead of being automated using machinery. This approach will increase the cost of the device initially. In later stages of the manufacturing process, capital investments will replace the labor cost with equipment cost and lower the overall production cost. In addition, our team has made the conscious decision to accept higher production costs in trade-off for minimal environmental impacts of manufacturing and operation of our device. Out team has attempted to source the parts from a 200 miles radius from College Park, MD to minimize the $CO_2$ production during the transportation of the raw material and an increase in the cost instead. In the cost-analysis of the product, major capital costs associated with facilities and testing equipments are ignored. No warranty cost has been performed to simplify the analysis. Furthermore, there are no expected R&D costs during the first year of operation due to the fact that most of the R&D has been done during this project. For the purposes of this report the cost associated with testing and rework has been omitted as well. A planned 1000 products manufacturing per year is expected. It will be assumed that the yield is 100% during the manufacturing process to simplify the analysis. The general outline of the manufacturing process can be seen in the following diagram, Figure 7.1.

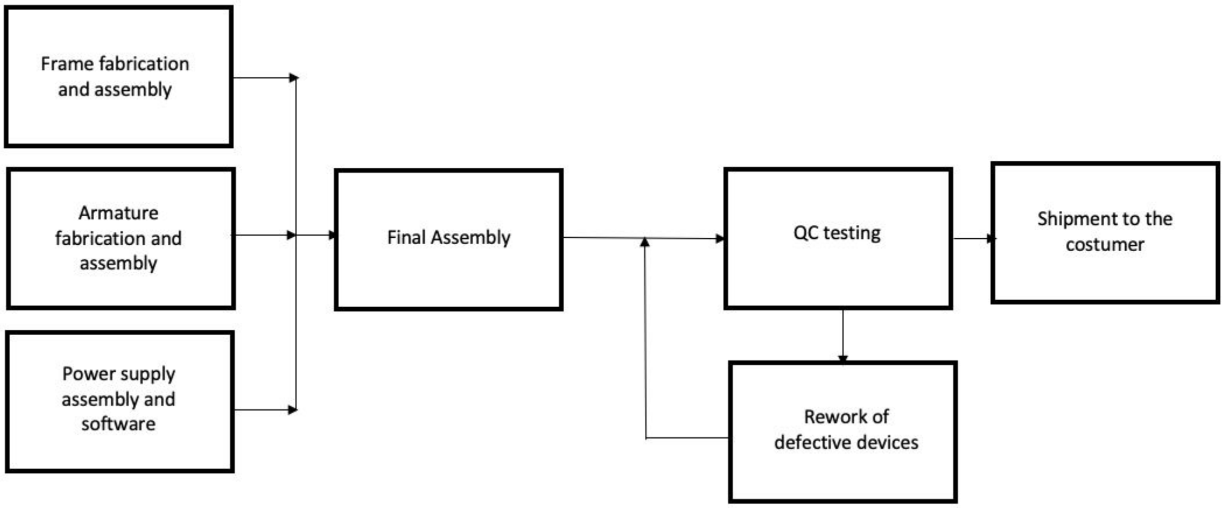



**Figure 7.1. Outline of Manufacturing Process**

There are three main subsystems that comprise the product, the frame, armature and the electrical power system. Each needs a different manufacturing approach and production line. Lastly, all the three subsystems will be assembled on a single line. After the final assembly, a quality control testing will be performed for each device and in the case of nonconformance, a rework will be performed on defective devices. After the QC step, the product will be packaged and shipped to the customer based on their preferred shipment method.

## Cost Analysis

The frame is made from 6061-T6 1” 16GA aluminum tubing 12 feet in total, purchased in bulk from local vendors in the mid-Atlantic region in order to minimize the CO2 impact during the transportation. The material will be sourced from TW Metals based in North Carolina at $193.08 for pre-cut tubing, 12 feet in total. Each section will be cut, bent and taped based on our requirements. Assuming a 35% discount rate for bulk purchasing, the total raw material cost of the frame comes out to be $125.502. In the second stage of the manufacturing each pre cut tubing is manually welded together. Assuming a burden rate of 0.85 and 0.5 hour of operation per frame per welder and a $19.89 per hour labor rate according to the Bureau of Labor Statistics [23] the labor cost is estimated to be $18.398 per frame. There needs be an additional purchase of a welding machine. Planning to purchase the Eastwood TIG 200 AC/DC Welder at $649.97 and manufacturing 1000 devices per year, the equipment cost is planned to be $0.65 plus a $0.01 of recurring cost of purchasing argon gas for the welding machine per frame. In total, a cost of **$146.05** is expected for the frame.

The next sub-system is the armature assembly which is the most expensive and complicated part of the device. It is comprised of directly purchased assembly of NEMA 23 stepper motor and driver, worm gearbox, 360W power supply and 18 AWG 3 Conductor 3-Prong Power Cord assemblies. These parts require no additional post processing on our part. Which lowers the assembly part. A detailed price breakdown is provided below in Figure 7.2.

| Part | Qty | Unit Cost | Extended Cost (Unit Cost x Units) |
|---|---|---|---|
| STEPPERONLINE 1 Axis CNC Kit 3Nm(425oz.in) Nema 23 Stepper Motor & Driver | 2 | $69.05 | $138.10 |
| Worm Gear Speed Reducer NEMA23 Stepper Gearbox (30:1) | 2 | $65.00 | $130.00 |
| EAGWELL 24v 15a DC Universal Regulated Switching Power Supply 360w | 1 | $24.68 | $24.68 |
| 18 AWG 3 Conductor 3-Prong Power Cord with Open Wiring, 10 Amp Max, 6 ft Replacement Power Cord with Open End, Pigtail Open Cable | 1 | $8.99 | $8.99 |

**Figure 7.2. Product Component Prices**

In total there is a $301.77 cost associated with the power and actuation unit. Assuming a 35% bulk purchasing discount rate, the total cost is estimated to be **$196.15**.

The next two critical parts of the power and actuation subassembly are casted and machined low carbon steel brackets attached to two adjustable telescopic PVC arms bolted to the handlebars. For the adjustable arms, we are planning to source Adjustable-Length Shipping Tube Clear, Round, 1.46" ID, 14"-24" Inside Length from McMaster-Carr (2108T76) at the price of $4.00 Each. These prefabricated adjustable tubes will drastically reduce manufacturing cost and lead-time. By aiming for a production volume of 1000 units per year and a 35% discount rate for bulk purchasing, the total cost of the PVC pipes will be $5.2 per unit. The most critical costume manufactured part of the sub-assembly will be shoulder joints. By using the service from on-demand manufacturing companies such as Xometry the cost per part when ordering 100 parts will be $48.26 per joint. The material is specified to be Steel 4140 and CNC machined. There would be no additional bulk purchasing discount as it has already been applied by Xometry. The parts will be sourced from China using economy shipping and with a 30 days lead-time. More details can be found from the following real time quote submitted by Xometry in Figure 7.3.


**Figure 7.3. Shoulder Joint Cost**

Thus, the total cost of joints will be $96.52 per product. Finally, there will be miscellaneous cost associated with percurrent of joints and fasteners to make the assembly of all the parts of the subsystem possible. There is an estimated $5 cost associated with the purchase of raw miscellaneous parts. In total there will be a **$302.87** cost in attaining the raw and the prefabricated parts. The next step of manufacturing of the armature subsystem is the assembly. Through the experience our team has gained in the assembly of the armature, the assembly is highly labour intensive while it requires not specialized tooling or machinery. According to the Bureau of Labor Statistics, the average salary of an expired assembler is $19.89 per hour [23]. Assuming a two hour required time for assembly, the total labor cost for the subsystem is going to be **$39.78.**

The third and final subsystem is the power and electronics subsystem. There are no raw material and part purchase necessary in this step as all the necessary parts have already been acquired in the previous section along with the stepper motors. However assembling the unit and installing the pre programmed operating software is highly critical. According to the Bureau of Labor Statistics, the median salary of electricians in 2018 was $26.53 per hour [24]. Hiring an experienced electrician in the 75th percentile will demand roughly $30 per hour salary. There are no tooling or machinery associated with assembly of this subsystem. Through experience, there will be an hour of manual labor needed to install the software and assemble the power unit to the frame. In conclusion, there will be a **$30.00** cost associated with the power unit.

After manufacturing and assembling each subsystem, the final step before packaging and shipment will be the final assembly of the entire device. As it was realized through trial and error in prototype manufacturing process, no equipment, tooling or specialized facility is needed for the final assembly. The job can be done by an experienced assembler in less than an hour. Total cost of final assembly is estimated to be **$19.89** [23]. During the first step of final assembly, the armature subsystem needs to be bolted to the frame using the aforementioned hinges in the configuration shown below in Figure 7.4.

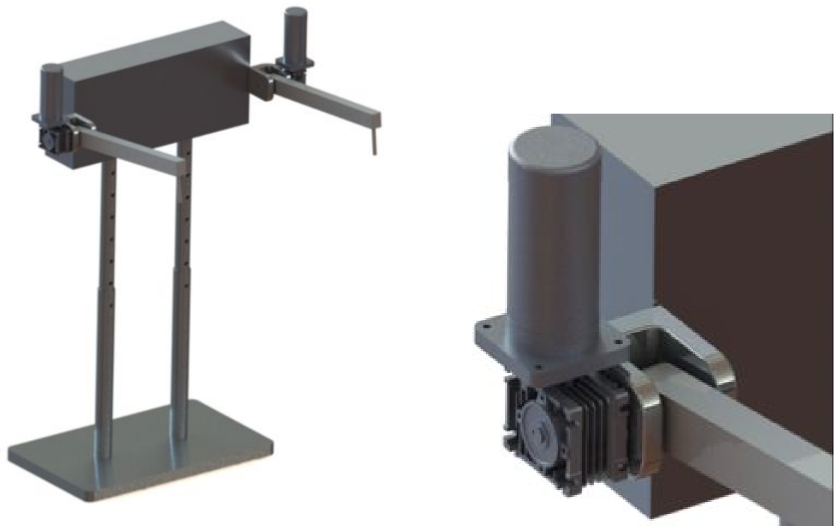


**Figure 7.4. Product CAD Assembly**

In the second and final step of the assembly, the power unit is attached to the back of the frame as shown below in Figure 7.5 and needed connections are attached to make the device operable.

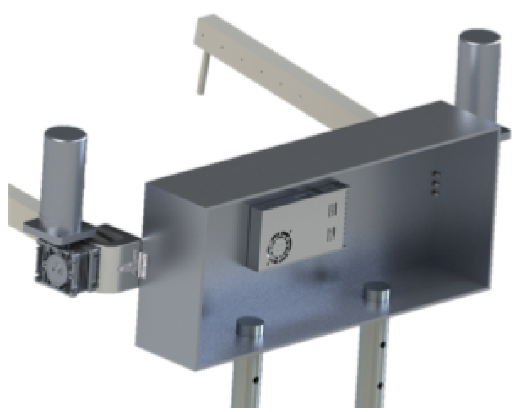


**Figure 7.5. Back View of Product CAD Assembly**

After final assembly There would be packaging and shipment offered through UPS or FedX to our customers. The cost associated with shipment is not going to be covered by the company and will be handled by the customer separately. The total estimated cost of the final assembly is going to be **$539.** After applying an 85% overhead cost to the direct costs, total cost of the product before applying the profit margin will be **$997.** Assuming a 10% profit margin to remain competitive with other similar products, the final cost of the device will be **$1099.** As mentioned before the cost will go down after establishing supply-chain relation with the vendors and through attracting investments while automating the manual process of manufacturing.

## Quality Plan

Quality of the design has been ensured through methodical material selection process and generated engineering drawings containing geometric tolerancing and dimensioning. The material has been selected to meet our engineering requirements and ensure quality. tolerancing and dimension has been established to meet our device functional requirements. In addition, tolerancing and material of a few components have been thoroughly tested during the prototyping phase to examine our quality expectations. In the next phase of the quality assurance phase, sample parts made from chosen material and within specified tolerances will be examined to ensure design quality for the final product. Every incoming part out of ten will be destructively tested to ensure material conformation to ASME and ASTM standards. Because of our low volume of production, it will be feasible to validate each critical part (the shoulder joint) using CMM. Then, we are going to be comparing the results to specified tolerances and dimensions produced by the engineering team.

After assembly, each device will be tested for functionality before shipment. If a device failed, rework will be done on the device and then retested to keep the yield as high as possible. Due to low number of individual parts, individual subsystems will not be tested to expedite the manufacturing and keep the cost as low as possible. In addition every month, accelerated life-cycle test will be performed to measure the products reliability and ensure that the MTTF is still at 3000 cycles. No environmental or regulatory testing is needed since the device is only going to be used in controlled environments.

The result of each test will be examined against the theoretical results from simulations and testing of our prototype. A constant feedback loop will be implemented to examine each customer complaint and compliment to improve quality and design. The warranty department will handle warranty claims and if a claim is valid, the defective device will be sent to the factory for detailed analysis to make find defections and lack of quality during manufacturing.

The entire quality process will be carried out by the QA department in conjunction with supply-chain and warranty team.

# VIII. Final Product Design Specifications

The team's final product design specifications for the T-Shirt Assistant are shown below.

| | |
|---|---|
| **Product Identification**<br>● T-Shirt Assistant<br>● Product to assist the elderly in raising their arms and putting on t-shirts<br>● Motorized arms gear for torque<br>● Controlled by electronics<br>● Device assembled by caretaker and set up on floor<br><br>**Key Project Deadlines**<br>● 10/8 - Interim Report 1<br>● 10/28 - Prototype 1<br>● 11/14 - Interim Report 2<br>● 12/3 - Design Day<br>● 12/9 - Final Report<br><br>**Physical Dimensions**<br>● External dimensions 88"x18"x54" at maximum adjusted size<br>● Max load of 50lbs on arms<br>● Accommodates human users of all sizes<br><br>**Financial Requirements**<br>● Manufacturing price estimate - $997<br>● Profit margin - 25%<br>● Market price estimate- $1250<br>● Warranty - 5 year free part replacement<br><br>**Life Cycle Targets**<br>● Useful life - 5 years<br>● Shelf life - 10 years<br>● 10 years for the motor-gearbox assembly<br>● Requires assembly and source of electricity<br>● Reliability - 2400 cycles<br>● End-of-life - all steel parts and reusable electronics will be recycled | **Social, Political, and Legal Requirements**<br>● Motors controlled by user, can be stopped at any time<br>● Product is heavy and should not be assembled by the elderly<br>● Limited exposure of electrical components<br>● Complies with Consumer Product Safety Commission (CPSC)<br><br>**Manufacturing Specifications**<br>● Product structure including base, supports, brackets, arms, handles manufactured custom for this product<br>● Standard parts include motors, bolts, fasteners, gearboxes, all electronics<br>● Suppliers:<br>○ McMaster-Carr (2108T76)<br>○ TW Metals (Al tubing)<br>○ Xometry (Shoulder joint)<br>○ ToAuto (Gearbox)<br>○ STEPPERONLINE (Motor)<br>○ EAGWELL (Power supply)<br><br>**Market Identification**<br>● 49.2 million elderly in US<br>● 1.2 million elderly in Maryland<br>● 35% of elderly people have a disability<br>● No competitor dressing aid product is automated<br>● Many elderly struggle to raise their arms when putting on shirts<br>● Trademark "T-Shirt Assistant" |

# IX. Prototyping & Testing

Our team conducted testing on our final prototype in order to confirm that the machine would work for people with different body types, how long the process took to complete using the stepper motor speed we had selected, and to see how often the process would fail and why. These parameters were tested for using a single test that every member of the group took part in. Graham Clifford and Chad Cartwright were the test subjects, Mark Vulcan was the time keeper, Charlie Benamram operated the machine, Hirbod Akhavan-Taheri was the data-collector, and Conrad Hong determined if the tests were a success/fail. Conrad's failure criteria was that if the user was not able to put on the shirt safely and with little to no movement of their own body, the test was a success. If the shirt got stuck on the user's head or did not go onto the user's head in a safe, smooth manner, the test was a failure. Graham and Chad completed ten trials each, their testing data can be seen below:

| | Graham (6'5") | | | Chad (5'6") | | |
|---|---|---|---|---|---|---|
| Trial | Success/Failure | Time to Complete | Time to Failure | Success/Failure | Time to Complete | Time to Failure |
| 1 | F | | 14.1 | S | 28.9 | |
| 2 | S | 27.2 | | F | | 14.4 |
| 3 | S | 31.8 | | S | 23.6 | |
| 4 | S | 31.9 | | S | 22.6 | |
| 5 | F | | 16.4 | S | 25.8 | |
| 6 | S | 30.5 | | F | | 15.7 |
| 7 | S | 33.9 | | S | 24.1 | |
| 8 | F | | 25.4 | F | | 14.2 |
| 9 | S | 30.5 | | S | 29.8 | |
| 10 | S | 33.9 | | S | 22.4 | |

**Figure 9.1. Trial results data table**

For each trial we recorded whether or not the test was successful and the time it took for the process to end. By recording the time to complete full, successful runs we hoped to identify the mean amount of time it took to complete the process. By recording the time it took for the process to fail, we hoped to be able to identify and have evidence for a certain step in the process causing the user to fail more often. Additional data can be seen below, including averages and standard deviations.

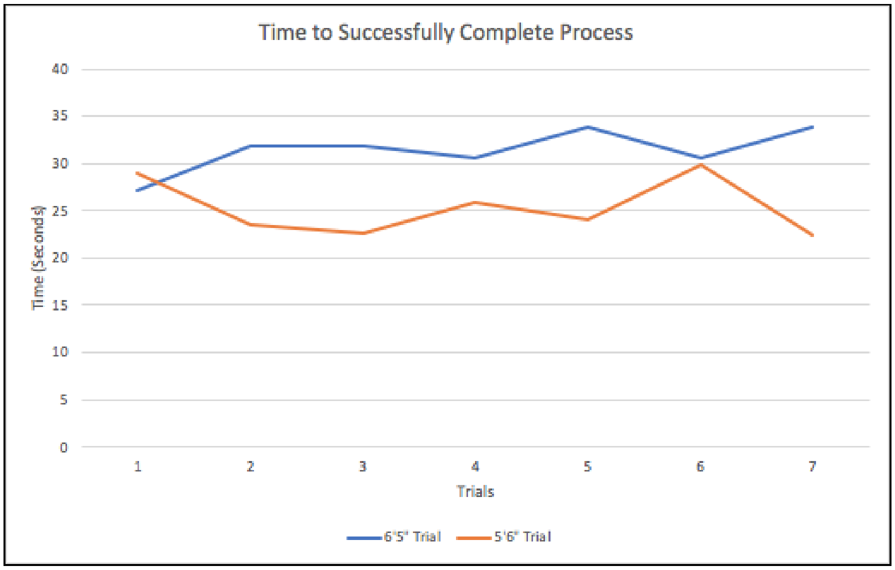



**Figure 9.2 Line graph depicting the trend of mean time to completion for Graham and Chad.**

| Mean Time to Completion (MTC) | MTC (Graham) | MTC (Chad) |
|---|---|---|
| 28.4 | 31.4 | 25.3 |
| **Standard Deviation** | **Standard Deviation** | **Standard Deviation** |
| 4.06 | 2.32 | 2.99 |

**Figure 9.3. Mean time to completion (total and individual) with standard deviations for each separate set of data.**

| Mean Time to Failure (MTF) | MTF (Graham) | MTF (Chad) |
|---|---|---|
| 16.7 | 18.6 | 14.8 |
| **Standard Deviation** | **Standard Deviation** | **Standard Deviation** |
| 4.36 | 5.97 | 0.814 |

**Figure 9.4. Mean time to failure (total and individual) with standard deviations for each separate set of data.**

**Discussion of Results**

Our test results lead to multiple key findings for our team that point to design improvements for future prototypes. The mean time to failure was 16.7 seconds, while the mean time to completion was 28.35 seconds. From this data, in addition to noting where the process would fail each time, our group determined that the device would typically fail when the user's arms were fully extended above their head. This was because the shirt would be unable to drop far enough down the user's arms and not let their head enter the bottom of the shirt. We determined that this was because the lever arm went from being a few feet (with the arms horizontal) to only an inch or two with the arms fully vertical. This made it difficult for the user to rotate the joints far enough in to allow the shirt to fall. In future iterations of our prototype, our team determined that it will be necessary to add a motor to the hinge that connects the shoulder joint with the back plate. This way, both degrees of freedom will be powered and this failure mode will be reduced significantly.

Additionally, from this test our group determined that we will not need to make the device adjustable horizontally. With the shoulder joints the same width apart for two different sized users, each user had the same failure rate and similar times to complete/fail the process. As long as the position of the handle on the arm is adjustable, along with the device being adjustable vertically to account for different chair heights, the width will not need to change.

The team's final conclusion from the prototype testing phase is that the base of the device will either need to be sufficiently wide or sufficiently narrow enough to allow 99% of household chairs to fit comfortably. The standard width of a wheelchair is 28", this is so that they can fit through standard 32” wide doorways. Our design will have to accommodate these constraints. Further testing is needed to determine the ideal width of our device in future iterations.

# X. Conclusions on Designed Product

### Results and Recommendations for Future Design

To conclude, our team is extremely confident in the potential success of the T-shirt assistant product going forward. Our end design, featuring two NEMA 23 stepper motors, a 30:1 ratio gearbox, and a versatile height adjustable base is vastly different from any other product currently on the market. As referenced earlier, our main competitor features a product by the name of the ‘Miracle Dressing Aid.’ In terms of our penetration in the medical device market, we believe we have the ability to outperform this specific competitor. The product fails to entirely dress the consumer, requires user strength to lift the product above their head, and does not feature the level of autonomy that is needed in their target population. In all, the uniqueness of our product will allow potential consumers to easily differentiate the benefits being offered as compared to other products on the market.

With regards to design analysis and decisions that helped shape our design, the interviews conducted at nursing homes largely affected the way we approached creating the product. Interviewees and employees at these homes vehemently suggested the need for a product that would lift one's arms above the head in order to complete the task – they all agreed that in the process of putting on a t-shirt, this aspect is the most difficult to achieve. That being said, we all agreed to implement handle bars that the user could grasp on to but also freely let go of in scenarios where they felt discomfort – this way we ensured a level of safety by avoiding any process where a user's wrists would be directly attached to the armatures (via Velcro straps for example). Other aspects of design analysis include hinge location as well as length of the motorized armatures. In testing our initial prototype, we learned that in order to optimize function as well as performance, it was necessary to place the hinge as close to the shoulder as possible so as to maximize the user's range of motion.

In becoming successful entrepreneurs, it is absolutely vital to point on imperfections and weaknesses in our product so as to make changes before going to market. As mentioned above, we plan on making the base height-adjustable so as to account for a larger user base. This way, users of all heights and owners of different sized chairs can easily use the product. Furthermore, with our current design, actuation of the armatures is controlled via two push buttons behind the product. This would consequently require a secondary party to control the device while the primary consumer used the product to get dressed. Going forward, we plan on wiring these push buttons through the armatures and integrate them into the handles. This would allow for an individual to operate the T-shirt assistant on his or her own as well as control movement as to their liking. Lastly, we plan on motorizing the hinges. In testing our product, we unexpectedly found that it took sufficient strength at the peak of operation (just before the user begins lowering the armatures back down) to swing the hinges outward to allow for free movement of the arms horizontally. Motorizing these hinges will optimize product performance as well as create a more autonomous experience for our target market, which is precisely what they are seeking. We believe these design refinements will sufficiently overcome any predicted failure or inadequacies the product may bear. It is imperative to note that before these plans are achieved, we are not yet ready for commercialization. With regards to profitability, more research on material costs must be done. The current design features a wooden back-plate while the future product will likely be made of aluminum, thus driving up the cost. We must submit surveys to consumers in our target market to get a more concrete idea as to what they would be willing to pay for a product without capabilities. As of now, the direct to consumer cost would be approximately $500 and so driving this down slightly may be a priority.

While the initial goal of this project was to create a device capable of putting t-shirts on, a common question received on design day was how the user would take the shirt off. As this action involves entirely different types of movements, it is something important for our group to consider going forward. The question, consequently, becomes if we can integrate more features within the current product to achieve this task of taking a shirt off or whether an entirely new product altogether is needed.

**Reflection on the Design Process**

Although the design process was an overall success, the team certainly had challenges to overcome throughout the engineering design process. From the onset, one of the biggest challenges to overcome was the selection of a problem to solve. The team came up with several ideas that were difficult to solve and likely not feasible to complete within a semester's project, but it was easier to reject topics than to come up with ideas that the whole team was passionate about. Although the team certainly feels strongly about the well-being of the elderly, it also certainly was not the team's first choice.

From there, further struggles ensued with narrowing down an idea and connecting with our intended market. The team was able to rely on four separate in-person interviews conducted with assisted living home employees and physical therapists that gave valuable insight in to the end user to define customer requirements and drive conceptual design. However the survey was more difficult to get responses to. The team was hoping for more responses, but did not get many.

The team also found several aspects of the embodiment design phases to be not useful, and completed them only to fulfill the class requirements. The house of quality was useful in documenting customer requirements and engineering characteristics, but not much else. The pugh chart was also unhelpful as the team had a good idea of what design concepts to use, and the team was confused about the restriction on combining initial design concepts. The analytical hierarchy process was a novel exercise, and something that may help make objective decisions, but, again, was not useful in terms of how much time and effort was put in to select what was already the team's top design concept.

The team also struggled with the first prototype in fabricating something between simply design concepts on paper to a final fully fleshed prototype. The first prototype the team developed gave valuable insight in to the movements required for the end product, but was not a high performing prototype. The final prototype, however, is certainly something that the team is proud of and was able to assist a user in putting a t-shirt on. From the final prototype the team was able to gain valuable insight into changes that would need to be made to the final product, such as also motorizing the second degree of freedom.

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# XII. Appendix

## Appendix 1: Parts List and Bill of Materials

**Engineering Drawings:**

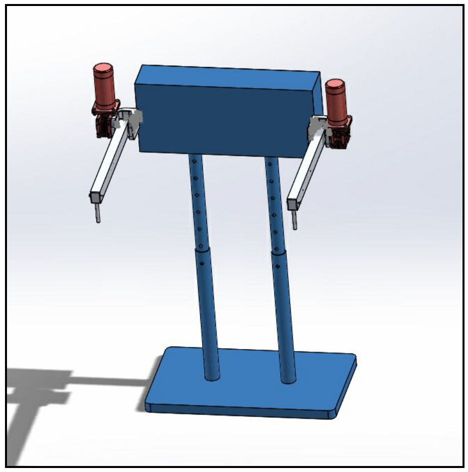

**Figure 8.1: Final Design CAD Model**

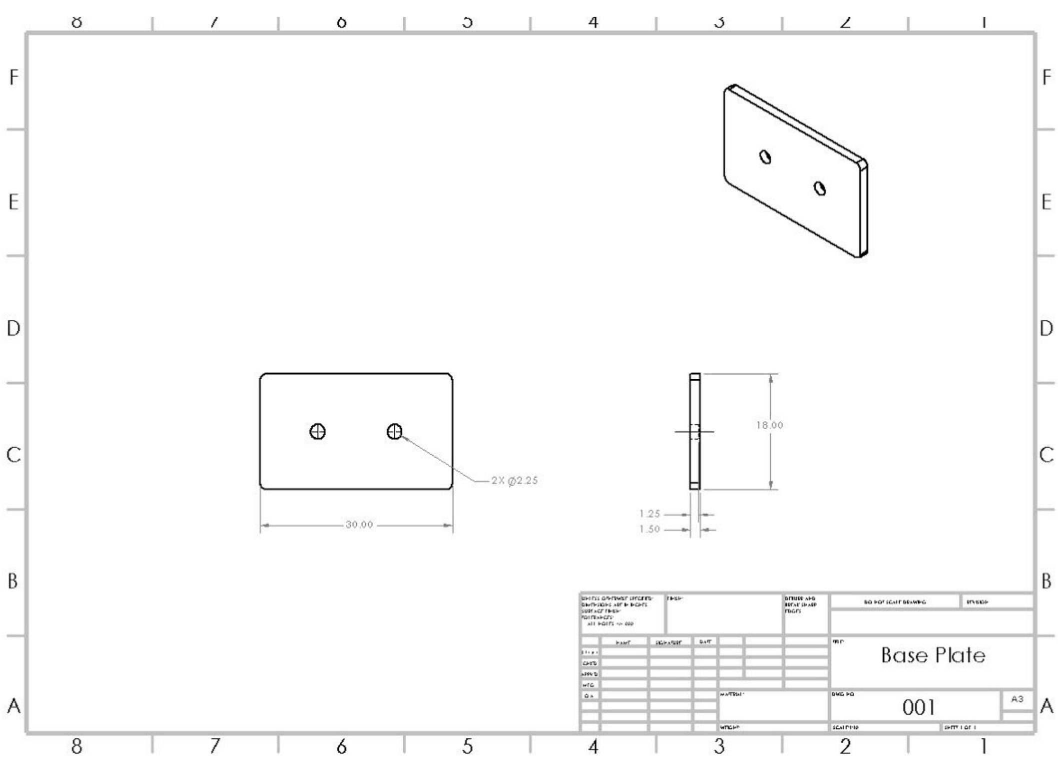


**Figure 8.2: Base Plate**

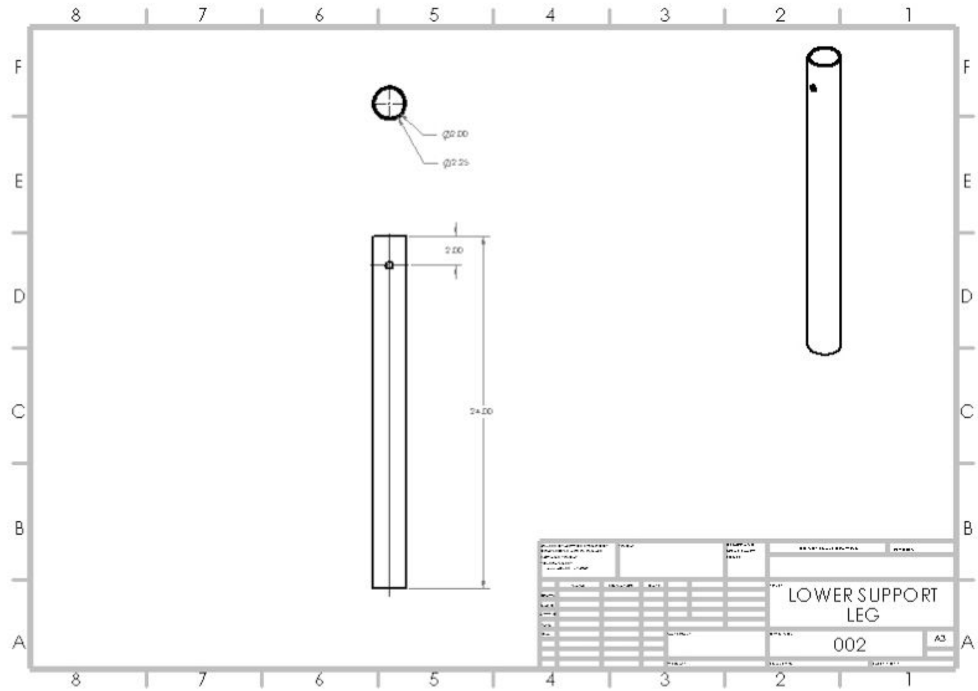


**Figure 8.3: Lower Support Leg**

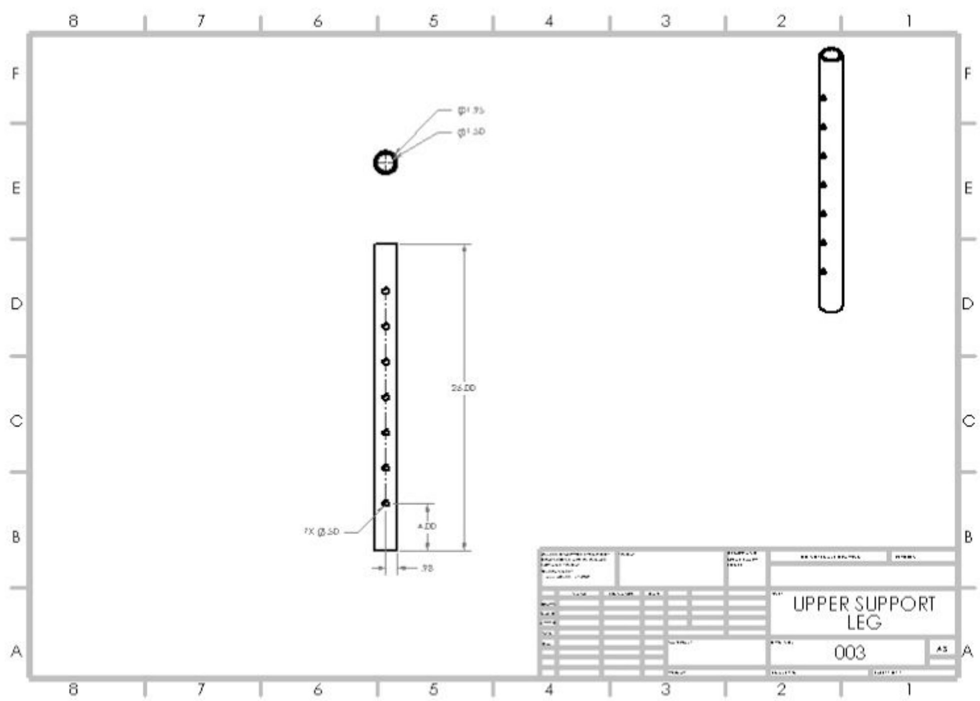


**Figure 8.4: Upper Support Leg**

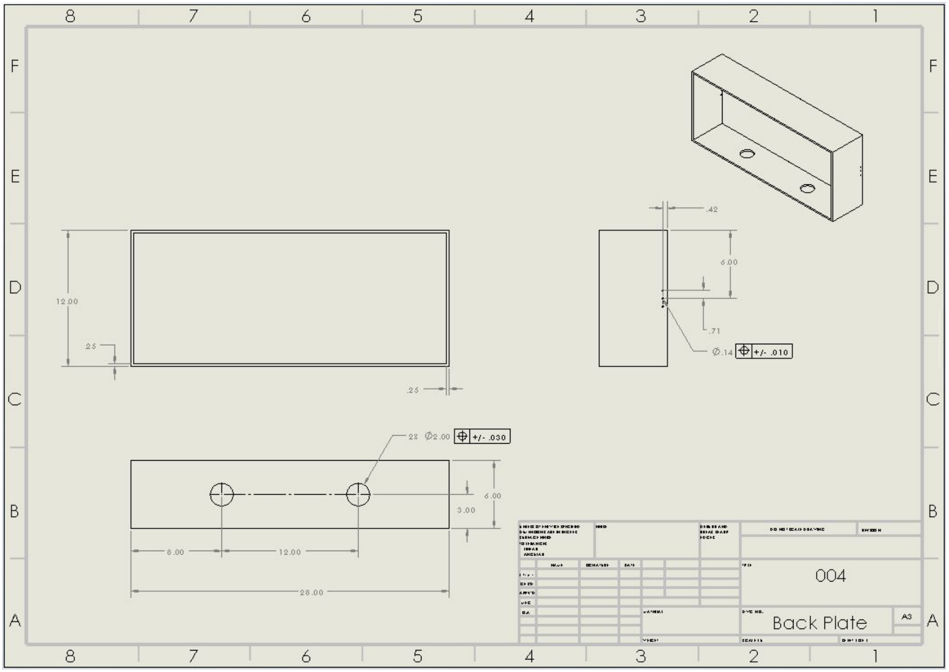


Figure 8.5: Back Plate

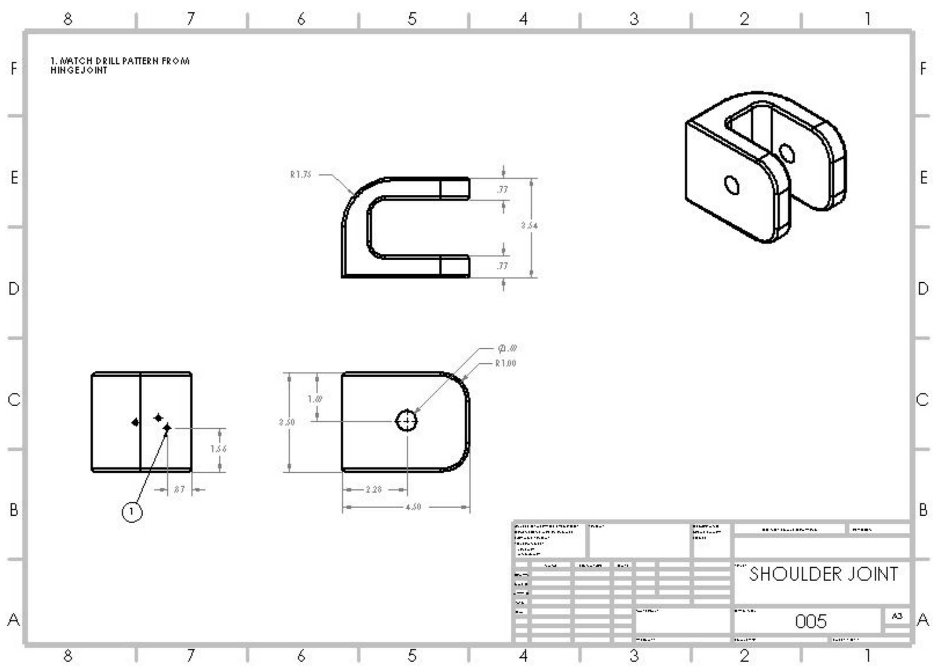


Figure 8.6: Shoulder Joint

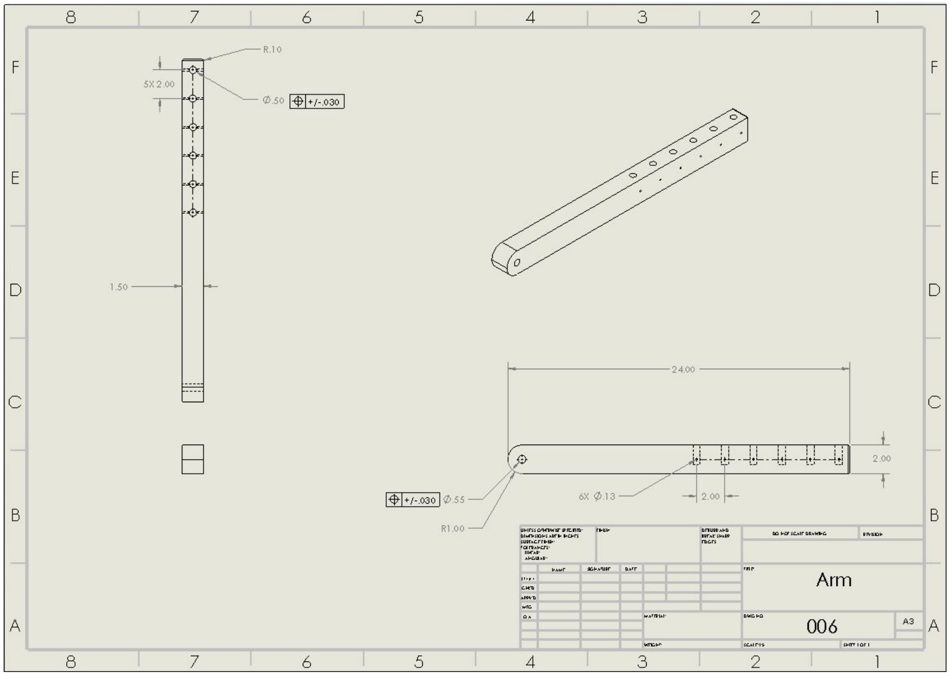


**Figure 8.7: Arm**

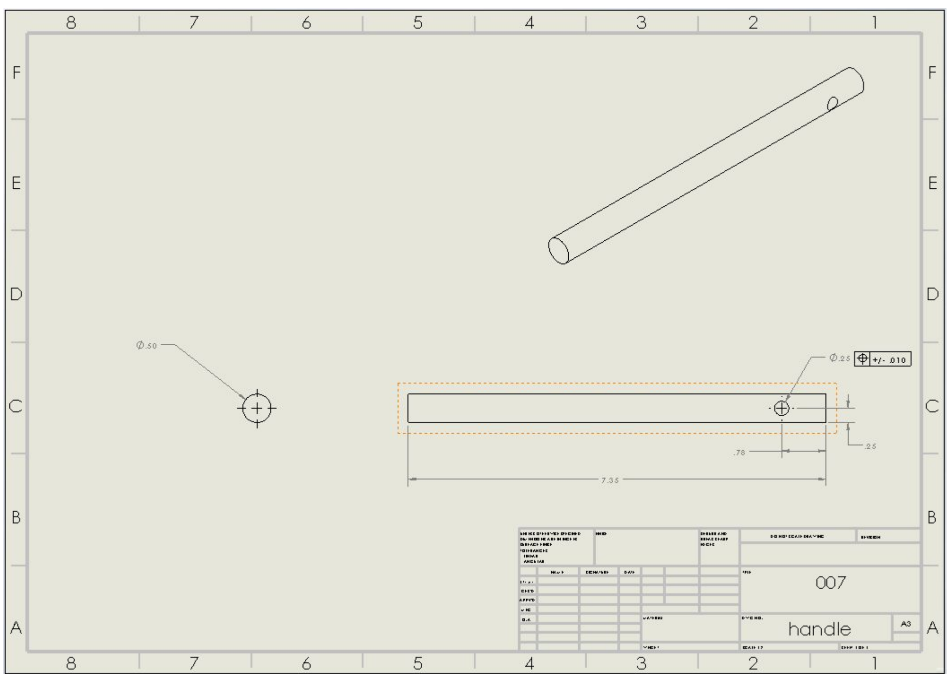


**Figure 8.8: Handle**

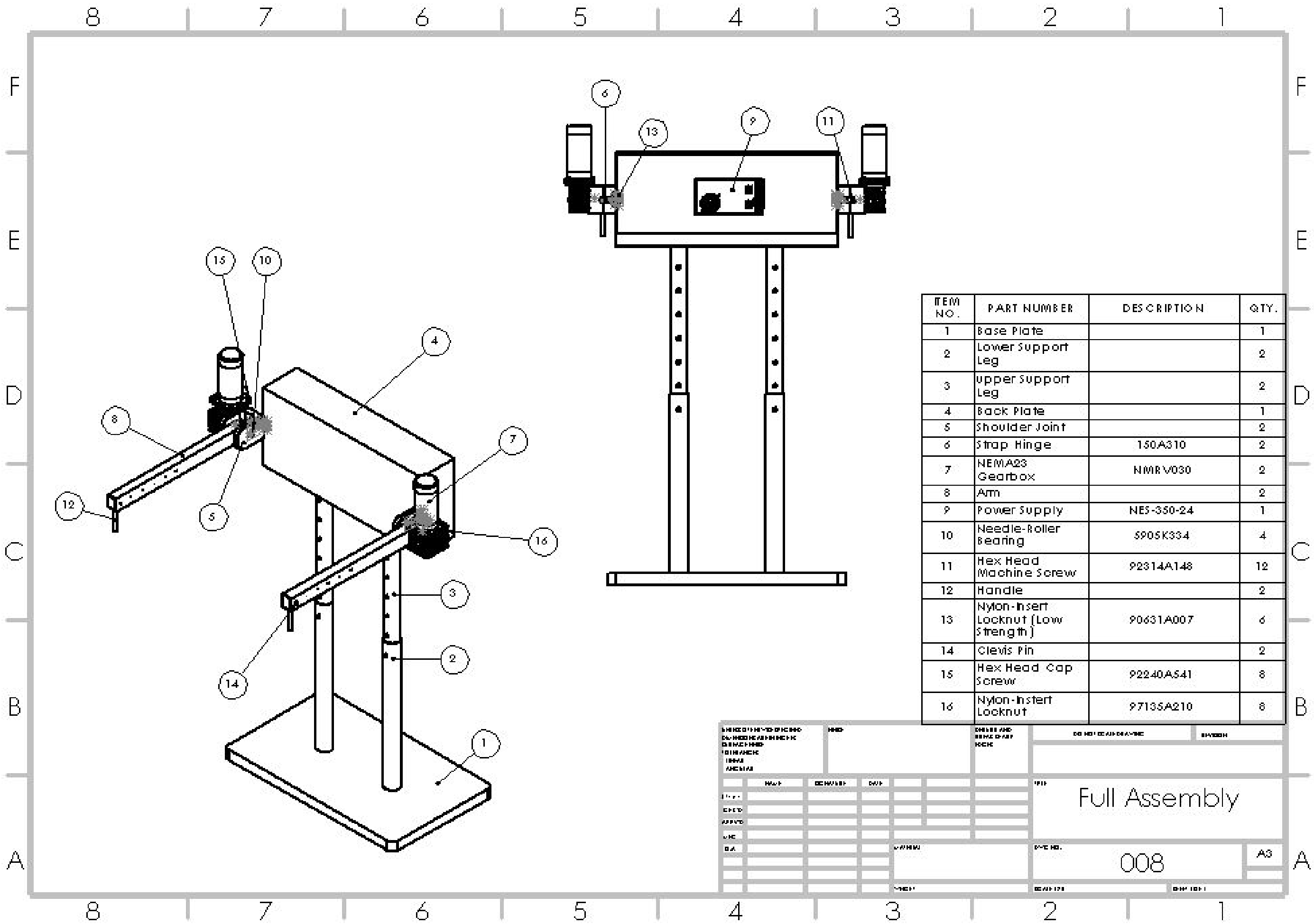


**Figure 8.9: Full Assembly Drawing**

**Bill of Materials:**

| Item No. | Part Number | Description | Material | Qty. |
|---|---|---|---|---|
| 1 | - | Base Plate | AISI 1018 Steel | 1 |
| 2 | - | Lower Support Leg | AISI 1018 Steel | 2 |
| 3 | - | Upper Support Leg | AISI 1018 Steel | 2 |
| 4 | - | Back Plate | AISI 1018 Steel | 1 |
| 5 | - | Shoulder Joint | AISI 1018 Steel | 2 |
| 6 | 150A310 | Strap Hinger | Non-custom | 2 |
| 7 | NMRV030 | NEMA23 Gearbox | Non-custom | 2 |
| 8 | - | Arm | AISI 1018 Steel | 2 |
| 9 | NES-350-24 | Meanwell Power Supply | Non-custom | 1 |
| 10 | 590K334 | Needle-Roller Bearing | Non-custom | 4 |
| 11 | 92314A148 | Hex Head Machine Screw | Non-custom | 12 |
| 12 | - | Handle | AISI 1018 Steel | 2 |
| 13 | 90631A007 | Nylon-Insert Locknut (Low Strength) | Non-custom | 6 |
| 14 | - | Clevis Pin | AISI 1018 Steel | 2 |
| 15 | 92240A541 | Hex Head Cap Screw | Non-custom | 8 |
| 16 | 97135A210 | Nylon-Insert Locknut | Non-custom | 8 |

**Figure 8.10. Bill of Materials**

**Key Sub-Assembly Views:**

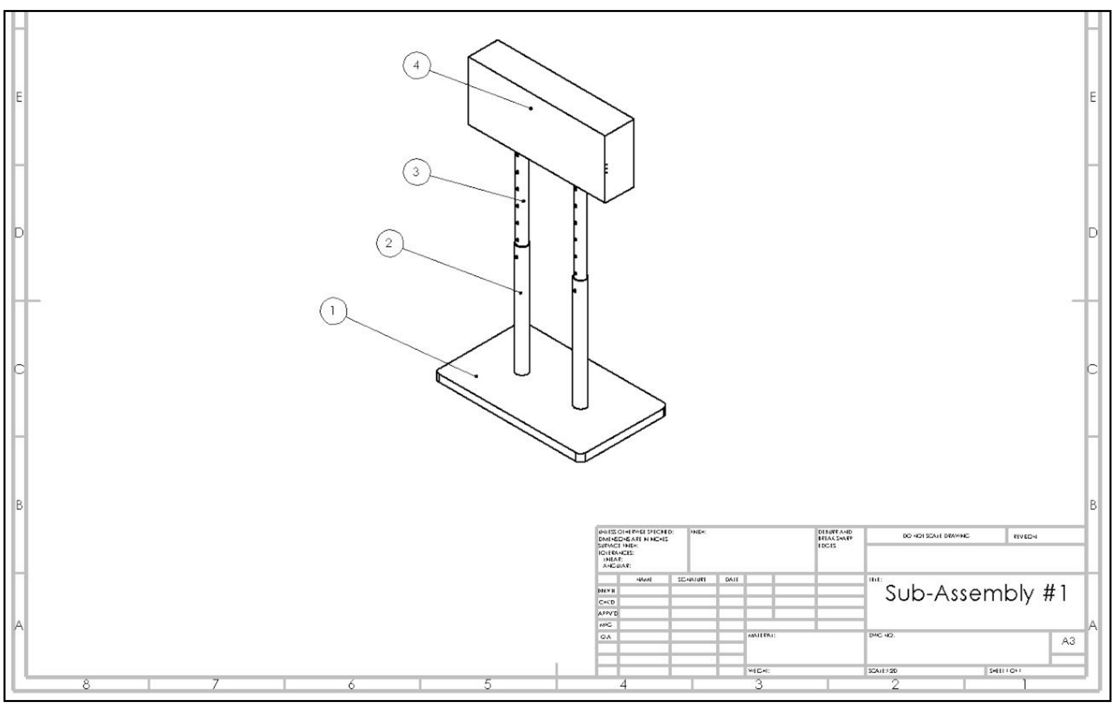

**Figure 8.11: Sub-Assembly #1**

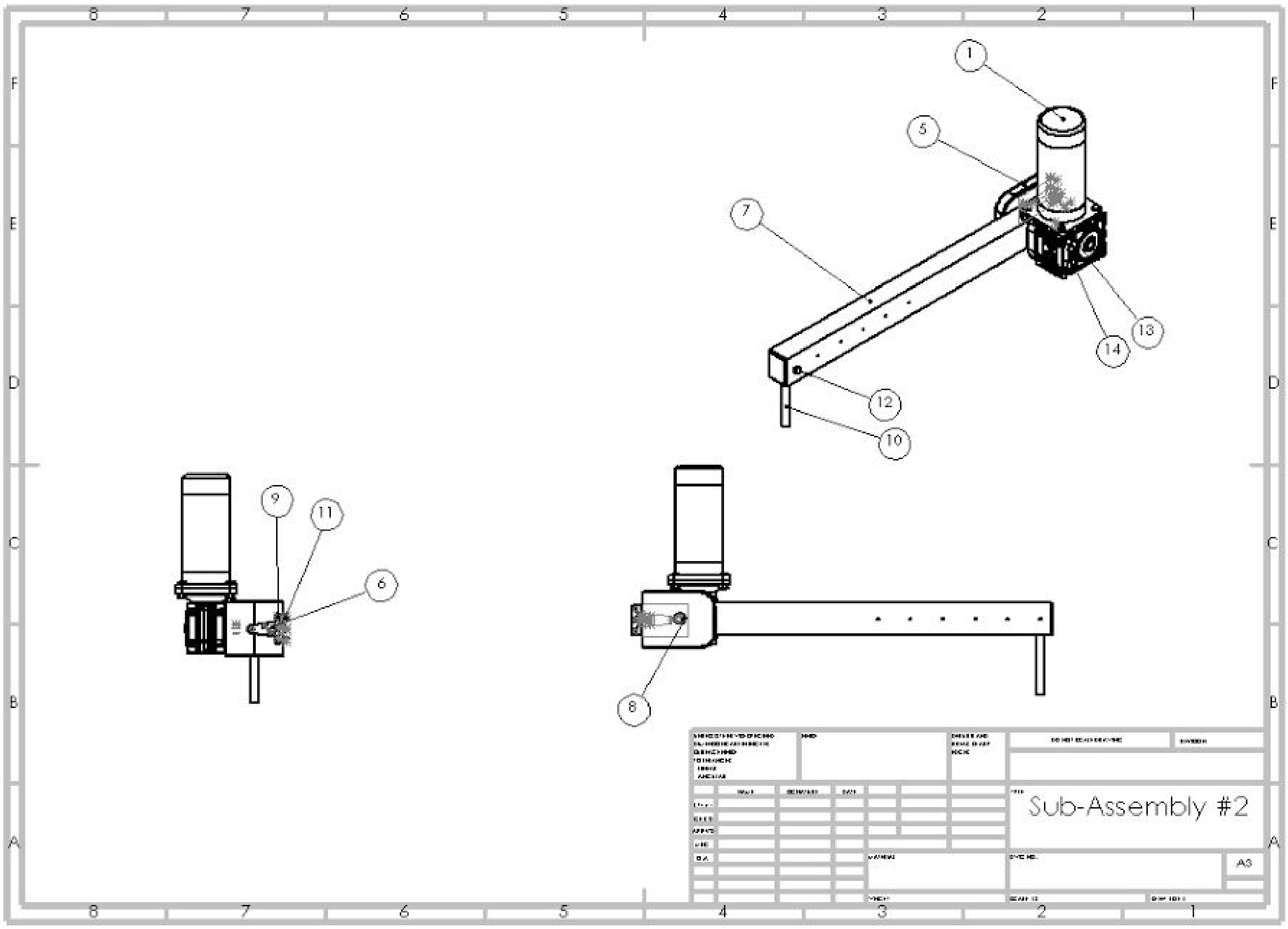


**Figure 8.12: Sub-Assembly #2**

The two key sub-assemblies in our design can be seen above. The first sub-assembly is the base plate, both upper and lower support legs, and the back plate. These parts make up the main structure and support system for our device. The second sub-assembly consists of the strap hinge, the shoulder joint, the NEMA 23 motor and gearbox, the arm, the handle, and the pin. This sub-assembly will be in motion while a user is operating the device, and it is the most important sub-assembly.

One critical aspect of our design involves the shoulder joint sub assembly. This is where the gearbox and shaft must align properly with the bearings and bearing housings residing within the shoulder joint in order to properly function. Due to the nature of the assembly, a stack-up analysis is not optimal as each part is purchased COTS in accordance with one another. In this way, the critical value is only the dimensions of the diameter and location of the through holes running through the center of the joint. As a result, we create tolerances around this feature in order to ensure that the shaft system will not fail due to misalignment or interference.

The gearbox shaft has a 0.5 inch outer diameter. For the size of the hole we are adding an extra .05 inches to the diameter in order to create a "normal fit." From this, the holes will have a +/- .010 inch tolerance on their specified center location in order to account for potential offsets between one another. At this tight range, even at the opposing extremes in dimensional allowance, the holes will still align properly in order for the bearings to be press fit properly, and to feed the shafts through the bearings.

Keeping the potential interference in mind, it is important to develop the essential tolerances for the associated features in order to minimize the amount of defective products in this area during production and assembly phases of the manufacturing process. As a result, taking this into account will help to keep this risk as low as possible.

**Note:** Please see the attached engineering drawings for the overall dimensions of the parts within the aforementioned subassembly.

# Appendix 2: Interview Results

**Cristine Mkirema - Cedar Creek Memory Care Homes [17]**

How would you describe your daily activities?

- Helping patients that are possibly aggressive when they are trying to help them.
- Primarily dealing with age group of 80-100

What are common physical problems people develop in old age?

- Weak arms/muscles is one of the first problems that start to develop, especially in people who don't exercise or move their limbs a lot.
- Joint contraction, especially elbows and fingers can become difficult.
- Stretchy clothes and clothes with buttons (maybe from the back) are easier to put on than others.

What kind of health issues do you most commonly deal with in your position?

- Alzheimer's disease and dementia.

Do many people you care for have difficulties getting dressed in the morning?

- Yes, they are totally unable to dress themselves.

What are the difficulties elderly people have putting on t-shirts specifically?

- Putting their shirt on their arms/head, lifting their limbs, coordination, balance, remembering how to do it.

Do elderly people mainly get dressed sitting down or standing up?

- Sitting down, standing up is too big of a risk to take.

What do you think would be most helpful to you when you are trying to assist a resident of the house to put on a shirt?

- It’s much easier to put your hands into something first.
- Something to elevate arms and hold them in place would be useful.
- Arms out in front parallel to the floor, or with a little bend in the elbows.

**Hilda - Cedar Creek Memory Care Homes, Hillwood House [18]**

What are common physical problems people develop in old age?

- Dementia restricts your range of motion as it gets worse
- Joints freezing.

What kind of health issues do you most commonly deal with in your position?

- Alzheimer’s disease and dementia.

Do many people you care for have difficulties getting dressed in the morning?

- Yes, they are unable to dress themselves.

What are the difficulties elderly people have putting on t-shirts specifically?

- If a patient is injured, put item of clothing on the injured arm first, and then work the rest of the shirt over the rest of the body while moving the injured limb as little as possible.
- Their range of motion is limited and they do not have good motor control.

Do elderly people mainly get dressed sitting down or standing up?

- People mainly sit down and mainly want to be sitting down.

How many times a day do you typically have to dress/undress a patient?

- Sometimes dressing and undressing 3 or 4 times a day

What do you think would be most helpful to you when you are trying to assist a resident of the house to put on a shirt?

- Something to assist with increasing range of motion.

**Omie Huggins - Cedar Creek Memory Care Homes, Auxiliary House [19]**

How would you describe your daily activities?

- Putting patients' clothes on for them: support and prop up patients arms, pull the shirt over their head and all the way down their torso.

What are common physical problems people develop in old age?

- Muscle atrophy, joint freezing, psychological problems.
- People typically start losing their functions by their 80s.

What kind of health issues do you most commonly deal with in your position?

- Alzheimer's and dementia patients, stroke victims, wheel-chair bound elderly people

Do many people you care for have difficulties getting dressed in the morning?

- None of them are able to dress themselves.

What are the difficulties elderly people have putting on t-shirts specifically?

- They just don't know how to do it or being injured can prevent it.

Do elderly people mainly get dressed sitting down or standing up?

- Sitting down is generally preferred.

How many times a day do you typically have to dress/undress a patient?

- The usual amount is two, once in the morning and once in the evening. If they spill food on themselves or something else then they have to change again.

What do you think would be most helpful to you when you are trying to assist a resident of the house to put on a shirt?

- Some device that provides weight support for elderly patients: holding arms up, holding them in a sitting position (in bed).
- Getting the second arm into the shirt when the first one is injured is tricky
- Something that keeps the arm bent in with the hand near the shoulder would be useful, I believe this will only work with a caregiver present though.

**Morgan Cole - Physical Therapist [20]**

What are common physical problems people develop in old age?

- Parkinsons, stroke, arthritis, balance problems
- Difficulty gripping and moving the shirt
- Rotator cuff injury: months of injury time

What kind of issues do you typically deal with?

- Balance issues and injury recovery

Do many people you care for have difficulties getting dressed in the morning?

- Yes, shirts are tough to put on.

Do elderly people mainly get dressed sitting down or standing up?

- Balance issues could cause people to put shirts on sitting down

# Appendix 3: Survey Results

The team distributed an online survey to student organizations, fraternities, and friends asking about the needs of their elderly relatives when putting on t-shirts. The team received 8 total responses and the results are listed below:

**Do you have a 65-80 year old relatives/friends/family friend?**

- 8 Yes, 0 No

**If yes, does this person have difficulty getting dressed?**

- 6 Yes, 2 No

**If yes, does this person have any disability(ies)?**

- Hip replacements, arthritis, osteoporosis, Altzheimers, Rotator cuff sprain

**Does this person have difficulty putting on t-shirts?**

- 6 Yes, 1 No, 1 Unsure

**If yes, what specific difficulties does this person have putting on t-shirts?**

- Moderate mid section movement limitations, lifting up arms, person is often uncooperative

# Appendix 4: Task Assignment Sheet

| Team Member | Tasks |
|---|---|
| Hirbod Akhavan-Taheri | ● Problem refinement<br>● Feasible concept 1<br>● Patent study<br>● House of quality interpretation<br>● Concept selection process criteria<br>● Manufacturing and cost analysis<br>● Social and environmental considerations<br>● Material and manufacturing process selection analysis<br>● Quality Planning<br>● Manufacturing and process cost analysis<br>● Final prototype assembly |
| Charlie Benamram | ● Problem scope<br>● Pugh chart spreadsheet & analysis<br>● Concept selection process discussion and criteria<br>● House of quality spreadsheet, constraints, decision characteristics, and interpretation<br>● Patent study<br>● Human Factors<br>● Planning for prototype and testing<br>● Final prototype assembly<br>● Conclusion results and future recommendations |
| Chad Cartwright | ● Problem definition<br>● Initial motivation for product<br>● Feasible concept 3<br>● Patent study<br>● House of quality interpretation<br>● Concept selection process criteria<br>● Final design sketch<br>● Initial prototype development<br>● CAD modeling, tolerances, and stack-up<br>● FEA, DFM, DFA, DFX<br>● Final prototype design, assembly, and testing |
| Graham Clifford | ● Problem definition<br>● House of quality spreadsheet and interpretation<br>● Interviews and surveys<br>● Feasible concept 5<br>● Patent study<br>● Concept selection process criteria<br>● Initial prototype development |

| | |
|---|---|
| | • CAD modeling, tolerances, and stack-up<br>• FEA, DFM, DFA, DFX<br>• Final prototype design, assembly, and testing |
| Conrad Hong | • Executive summary<br>• Benchmarking on competitive products<br>• Patent study<br>• Opportunities for competitive advantage<br>• Function structure and morphological chart<br>• Feasible concept 4<br>• House of quality interpretation<br>• Concept selection process criteria<br>• Analytical hierarchy process<br>• Design Day poster<br>• Final prototype electrical system<br>• Conclusion reflection on design process |
| Mark Vulcan | • Description and estimate of market size<br>• Benchmarking on competitive products<br>• Patent study<br>• Opportunities for competitive advantage<br>• Feasible concept 2<br>• House of quality interpretation<br>• Concept selection process criteria<br>• Final concept sketches<br>• Product architecture<br>• Configuration design<br>• Product design specifications<br>• Final prototype design and assembly |

# Appendix 5: Analytical Hierarchy Process Matrices

| | Physical Footprint | Mean Time to Successfully Operate | Cost | Number of Steps to Use | Power Required | Level of Automation |
|---|---|---|---|---|---|---|
| Physical Footprint | 1.00 | 5.00 | 3.00 | 9.00 | 1.00 | 7.00 |
| Mean Time to Successfully Operate | 0.20 | 1.00 | 5.00 | 5.00 | 1.00 | 1.00 |
| Cost | 0.33 | 0.20 | 1.00 | 3.00 | 5.00 | 3.00 |
| Number of Steps to Use | 0.11 | 0.20 | 0.33 | 1.00 | 5.00 | 7.00 |
| Power Required | 1.00 | 1.00 | 0.20 | 0.20 | 1.00 | 9.00 |
| Level of Automation | 0.14 | 1.00 | 0.33 | 0.14 | 0.11 | 1.00 |
| SUM | 2.79 | 8.40 | 9.87 | 18.34 | 13.11 | 28.00 |

| Key | |
|---|---|
| Equal | 1 |
| Moderate | 3 |
| Strong | 5 |
| Very Strong | 7 |
| Extreme | 9 |

| | Physical Footprint | Mean Time to Successfully Operate | Cost | Number of Steps to Use | Power Required | Level of Automation | Average |
|---|---|---|---|---|---|---|---|
| Physical Footprint | 0.36 | 0.60 | 0.30 | 0.49 | 0.08 | 0.25 | 0.35 |
| Mean Time to Successfully Operate | 0.07 | 0.12 | 0.51 | 0.27 | 0.08 | 0.04 | 0.18 |
| Cost | 0.12 | 0.02 | 0.10 | 0.16 | 0.38 | 0.11 | 0.15 |
| Number of Steps to Use | 0.04 | 0.02 | 0.03 | 0.05 | 0.38 | 0.25 | 0.13 |
| Power Required | 0.36 | 0.12 | 0.02 | 0.01 | 0.08 | 0.32 | 0.15 |
| Level of Automation | 0.05 | 0.12 | 0.03 | 0.01 | 0.01 | 0.04 | 0.04 |
| | | | | | | | 1.00 |

| Physical Footprint | Horizontal T-Shirt Puller | Belt Arm Puller | Split Hanger |
|---|---|---|---|
| Horizontal T-Shirt Puller | 1.00 | 0.14 | 0.20 |
| Belt Arm Puller | 7.00 | 1.00 | 1.00 |
| Split Hanger | 5.00 | 1.00 | 1.00 |
| Sum | 13.00 | 2.14 | 2.20 |

| Number of Steps to Use | Horizontal T-Shirt | Belt Arm Puller | Split Hanger |
|---|---|---|---|
| Horizontal T-Shirt Puller | 1.00 | 0.14 | 0.33 |
| Belt Arm Puller | 7.00 | 1.00 | 3.00 |
| Split Hanger | 3.00 | 0.33 | 1.00 |
| Sum | 11.00 | 1.48 | 4.33 |

| Mean Time to Successfully Operate | Horizontal T-Shirt Puller | Belt Arm Puller | Split Hanger |
|---|---|---|---|
| Horizontal T-Shirt Puller | 1.00 | 0.14 | 0.20 |
| Belt Arm Puller | 7.00 | 1.00 | 3.00 |
| Split Hanger | 5.00 | 0.33 | 1.00 |
| Sum | 13.00 | 1.48 | 4.20 |

| Power Required | Horizontal T-Shirt | Belt Arm Puller | Split Hanger |
|---|---|---|---|
| Horizontal T-Shirt Puller | 1.00 | 0.33 | 1.00 |
| Belt Arm Puller | 3.00 | 1.00 | 2.00 |
| Split Hanger | 1.00 | 0.50 | 1.00 |
| Sum | 5.00 | 1.83 | 4.00 |

| Cost | Horizontal T-Shirt Puller | Belt Arm Puller | Split Hanger |
|---|---|---|---|
| Horizontal T-Shirt Puller | 1.00 | 0.33 | 1.00 |
| Belt Arm Puller | 3.00 | 1.00 | 3.00 |
| Split Hanger | 1.00 | 0.33 | 1.00 |
| Sum | 5.00 | 1.67 | 5.00 |

| Level of Automation | Horizontal T-Shirt | Belt Arm Puller | Split Hanger |
|---|---|---|---|
| Horizontal T-Shirt Puller | 1.00 | 0.14 | 0.20 |
| Belt Arm Puller | 7.00 | 1.00 | 3.00 |
| Split Hanger | 5.00 | 0.33 | 1.00 |
| Sum | 13.00 | 1.48 | 4.20 |

| Physical Footprint | Horizontal T-Shirt Puller | Belt Arm Puller | Split Hanger | Avg |
|---|---|---|---|---|
| Horizontal T-Shirt Puller | 0.08 | 0.07 | 0.09 | 0.0781663 |
| Belt Arm Puller | 0.54 | 0.47 | 0.45 | 0.4865579 |
| Split Hanger | 0.38 | 0.47 | 0.45 | 0.4352758 |

| Number of Steps to Use | Horizontal T-Shirt | Belt Arm Puller | Split Hanger | Avg |
|---|---|---|---|---|
| Horizontal T-Shirt Puller | 0.09 | 0.10 | 0.08 | 0.0882021 |
| Belt Arm Puller | 0.64 | 0.68 | 0.69 | 0.6686969 |
| Split Hanger | 0.27 | 0.23 | 0.23 | 0.2431010 |

| Mean Time to Successfully Operate | Horizontal T-Shirt Puller | Belt Arm Puller | Split Hanger | Avg |
|---|---|---|---|---|
| Horizontal T-Shirt Puller | 0.08 | 0.10 | 0.05 | 0.0737721 |
| Belt Arm Puller | 0.54 | 0.68 | 0.71 | 0.6433889 |
| Split Hanger | 0.38 | 0.23 | 0.24 | 0.2828390 |

| Power Required | Horizontal T-Shirt | Belt Arm Puller | Split Hanger | Avg |
|---|---|---|---|---|
| Horizontal T-Shirt Puller | 0.20 | 0.18 | 0.25 | 0.2106061 |
| Belt Arm Puller | 0.60 | 0.55 | 0.50 | 0.5484848 |
| Split Hanger | 0.20 | 0.27 | 0.25 | 0.2409091 |

| Cost | Horizontal T-Shirt Puller | Belt Arm Puller | Split Hanger | Avg |
|---|---|---|---|---|
| Horizontal T-Shirt Puller | 0.20 | 0.20 | 0.20 | 0.1999066 |
| Belt Arm Puller | 0.60 | 0.60 | 0.60 | 0.6001200 |
| Split Hanger | 0.20 | 0.20 | 0.20 | 0.1999733 |

| | | | | Avg |
|---|---|---|---|---|
| Level of Automation | Horizontal T-Shirt | Belt Arm Puller | Split Hanger | Avg |
| Horizontal T-Shirt Puller | 0.08 | 0.10 | 0.05 | 0.0737721 |
| Belt Arm Puller | 0.54 | 0.68 | 0.71 | 0.6433889 |
| Split Hanger | 0.38 | 0.23 | 0.24 | 0.2828390 |

| | Physical Footprint | Mean Time to Successfully Operate | Cost | Number of Steps to Use | Power Required | Level of Automation |
|---|---|---|---|---|---|---|
| Horizontal T-Shirt Puller | 0.08 | 0.09 | 0.07 | 0.21 | 0.20 | 0.07 |
| Belt Arm Puller | 0.49 | 0.67 | 0.64 | 0.55 | 0.60 | 0.64 |
| Split Hanger | 0.44 | 0.24 | 0.28 | 0.24 | 0.20 | 0.28 |

| | Aggregate Weight |
|---|---|
| Horizontal T-Shirt Puller | 0.1148194634 |
| Belt Arm Puller | 0.5747874759 |
| Split Hanger | 0.3103930607 |
| | 1 |

| Checking Consistency | | | | | |
|---|---|---|---|---|---|
| Phys Foot | Mean Time | Cost | Num Step | Pwr Req | Automation |
| Ws | | | | | |
| 0.2347297147 | 0.2222526066 | 0.5997199333 | 0.2647639099 | 0.6343434343 | 0.2222526066 |
| 1.468997669 | 2.008310686 | 1.80036024 | 2.015414693 | 1.662121212 | 2.008310686 |
| 1.312665113 | 0.8661625113 | 0.5999199733 | 0.7306063113 | 0.7257575758 | 0.8661625113 |
| Cons | | | | | |
| 3.002953706 | 3.012691633 | 3.000000067 | 3.001786222 | 3.011990408 | 3.012691633 |
| 3.019163207 | 3.121456994 | 3.0000002 | 3.013943551 | 3.03038674 | 3.121456994 |
| 3.015708675 | 3.062386854 | 3.000000067 | 3.005361377 | 3.012578616 | 3.062386854 |
| Lambda | | | | | |
| 3.012608529 | 3.065511827 | 3.000000111 | 3.007030383 | 3.018318588 | 3.065511827 |
| CI | | | | | |
| 0.006304264742 | 0.03275591356 | 0.00000005561116301 | 0.003515191717 | 0.00915929406 | 0.03275591356 |
| CR (Must be less than 0.1) | | | | | |
| 0.01212358604 | 0.06299214146 | 0.000001069445442 | 0.006759984072 | 0.01761402704 | 0.06299214146 |