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Design of a Medical Walker with an Integrated Crutch Mechanism

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By

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ABSTRACT

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Many elderly people and injured people suffer from physical complications that make it difficult or dangerous for them to perform everyday activities, thereby inhibiting their mobility. Some of these activities include walking, standing, and sitting. As a result, it is no surprise that many companies in the medical industry have already attempted to construct an array of options to aid these people, including basic medical walkers, and standing-assist furniture, poles, and machines. Although these options are fair choices, they fail to integrate portability, simplicity, and multi-functionality together. Therefore, this thesis focuses on designing and building a dual purpose machine that can function as a portable medical walker as well as a standing and sitting aid. The purpose of this is to increase the mobility of independent and resilient people who struggle to move around on their own.

A thorough investigation was conducted to determine the natural motion of a person going from the seated to standing position and vice versa. From that analysis, it was determined that both the standing and sitting motions were identical, and that the upper body of a person naturally arced in a manner consistent with a circle. Using the data acquired from this analysis, the natural upper body motion was replicated by designing a crutch mechanism/linkage. Then, a walker frame was modeled around the crutch mechanism. Once the final detailed design was in place, a prototype was constructed and its range of capabilities was examined.

TABLE OF CONTENTS

I. INTRODUCTION

Some elderly people have physical complications that make it difficult/dangerous for them to sit down or stand up under their own power. Three particular complications include muscle deterioration, an aging vestibular system, and abnormal blood pressure regulation. As people get older, some become accustomed to a sedentary lifestyle that can lead to sarcopenia, which is defined as the loss of roughly ten ounces of muscle a year [1]. On average, a person will lose around 30 percent of their strength between the ages of 50 and 70. As a result of this muscle deterioration and loss of strength, elderly people can have trouble moving around and performing everyday activities. Furthermore, an aging vestibular system can cause elderly people to struggle with sitting down and standing up. The vestibular system is essentially a complex construction of chambers in the inner ear that are vital to controlling balance [2]. When people reach 55 years of age, the number of nerve cells in their vestibular system decreases significantly; this can make it increasingly difficult for an elderly person to maintain their balance. Likewise, elderly people are more apt to develop postural hypotension, wherein a rapid drop in blood pressure occurs while sitting or standing, and can ultimately cause dizziness and faintness [3]. These three reasons illustrate that some elderly people are at a serious risk when attempting to sit down or stand up.

However, the elderly population is not the only group of people that can experience a variety of complications when trying to sit down or stand up. Some people who sustain severe leg or spine injuries may have to relearn how to use their leg muscles to perform tasks that were once second nature to them. These individuals will need the support of a walker/harness system to guide and assist them as they regain their mobility.

Moreover, nearly 9 million Americans are afflicted with knee osteoarthritis, which occurs when cartilage in the knee joint slowly erodes [4]. This type of arthritis greatly affects the mobility of people since the knee can become stiff, swollen, and painful. In some cases, this medical disability can become severe and ultimately make it difficult to perform daily activities like walking, sitting, and standing.

It is clear that many people around the world are limited by their lack of mobility due to physical complications caused by age or injury. Therefore, it is no surprise that many companies have designed an array of options to aid these resilient people that strive to be independent and functional. However, most of these options are both awkward and difficult to use, or are bulky and expensive. In general, there are four main options that stand out in the current market: (1) standard medical walkers, (2) basic standing-assist bars/poles (3) costly standing-assist furniture, and (4) medical standing-assist machines that require the help of an assistant to operate. It is important to note that the first two options require a person to use their own strength to operate, and the last two options are complex, bulky, and expensive. An example for each of these four options is presented in Figure 1 below.

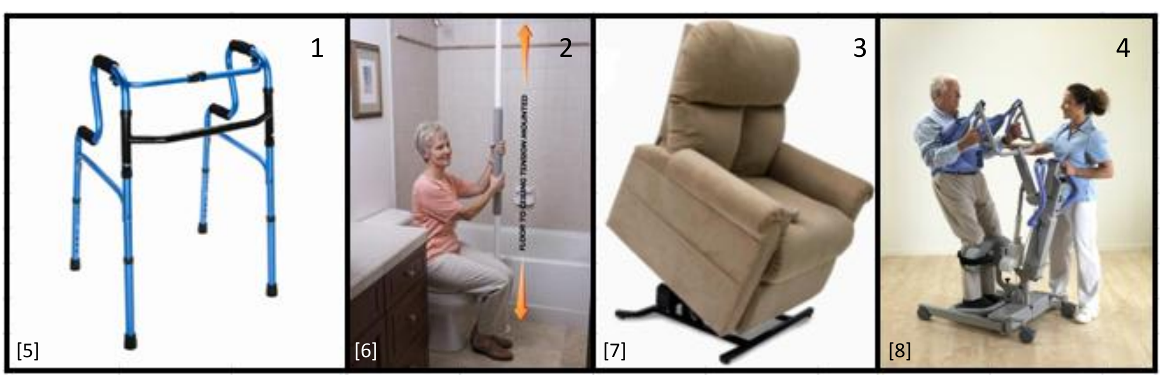

Figure 1: (1) Medical Walker, (2) Standing-Assist Pole, (3) Standing-Assist Chair, (4) Standing-Assist Machine

Each of the four options displayed in Figure 1 have their strengths and weaknesses, but none of them combine portability, stability, and a mechanized system in one complete package. In particular, the medical walker is designed with two sets of handles that are positioned at different levels so that a person can stabilize themselves as they go from the seated position to the standing position and vice versa. Although the medical walker is light weight and portable, it requires a person to exploit their own upper body strength; this could present a serious problem to people that suffer from severe muscle deterioration. Furthermore, the standing-assist pole can be easily positioned anywhere in a home, however, it is not portable and can be dangerous since a person must twist their body awkwardly. The standing-assist chair is another option that can gradually raise or lower a person via a remote. On the other hand, the chair itself is extremely heavy, cannot be easily moved around a home, and limits the mobility of a person since it is not portable. Moreover, standing-assist machines are complex apparatuses that cannot be operated by a single person. Therefore, these expensive machines are most often limited to various applications in hospitals or senior living venues.

After considering the available options for the elderly population and people affected by limited mobility, it was concluded that a simple, automated, and portable aid that can provide essential stability features at a reasonable price is needed. The overall objective for this study is to develop an altered walker frame that can be easily integrated with a light weight crutch mechanism. Ultimately, this design will be able to support regular weight transitions from the seated to standing positions and vice versa. The basic design of the walker/crutch mechanism consists of attaching two crutches to either side of an altered walker frame that is powered by two linear actuators and a $12\ V$ battery. Most importantly, the design will be able to attain duel functionality since it is intended to be used as a standing/sitting aid and a medical walker that will be employed as a primary supporting device.

In order to achieve a product with dual functionality, some design restrictions needed to be established. This process included defining essential aspects of the walker/crutch mechanism such as: (1) its overall size, (2) its total weight, (3) its stability, (4) its ergonomic factors, (5) its low key profile, and (6) its ease of use. These six restrictions put constraints on the design of the walker/crutch mechanism that dictated which models were feasible options and which models would not be suitable. In particular, the walker/crutch mechanism needs to fit through an average sized doorway of $36''$, while maintaining a strong frame that is fairly light weight (under 35 lbs) and is easy to push around. It is also important to note that the design cannot be bulky so that it does not attract any unwanted attention, and it must take into account ergonomic factors. But, most importantly the design must include factors of safety so that it will not fail under unexpected conditions. See section II. Design Requirements for more information.

Furthermore, it was critical to devise a design strategy. Initial research steps were taken by determining the natural motion of a person sitting down and standing up. Once that field was explored, various methods for obtaining that motion were developed along with a way to power the system. After those design concepts were formulated, the walker frame was designed to fit around the crutch mechanism, and a model was constructed in SolidWorks. Then, an in depth finite element analysis (FEA) was performed on the crutches (the most critical components) to examine the overall rigidity of the system. Upon completion of the detailed design, a prototype was constructed to test its ergonomic factors and its range of capabilities. The following sections outlined in this design report explain these steps in greater detail.

II. DESIGN REQUIREMENTS

During the initial phase of the design process, a set of design requirements were established so that various aspects of the walker/crutch mechanism could be constrained. The requirements included addressing (1) overall size, (2) total weight, (3) stability, (4) ergonomic factors, (5) low key profile, and (6) ease of use. An outline of the requirements is provided in Table 1:

Table 1: Design requirements for the walker/crutch mechanism

#	Major Need	Requirement
1	Overall Size	Must fit through an average sized doorway of 36" without difficulty
		Height of the armpit support bar relative to the floor when the crutch is in its fully retracted position = 32"
		Walker must be wide enough to comfortably accommodate an average sized person (roughly 5′9" and 170 lbs)
2	Total Weight	Walker must be light enough to be easily portable (< 35 lbs)
3	Stability	All wheels must have breaks
		Crutch mechanism must incorporate armpit supports and handles so that a person can steady themselves if necessary
		Must be able to support up to 300 lbs of weight
4	Ergonomics	Motion of the crutch mechanism must be smooth and resemble the natural arcing upper body motion
		Comfortable armpit supports that are adjustable
5	Low Key Profile	Bare-bones so that is does not attract any unwanted attention
		Walker cannot be bulky and must be able to be stored easily in a closet so that it can be out of sight
6	Ease of Use	All wheels must swivel so that it is easier to maneuver
		It must be easy to release from the machine
		Starting and stopping the mechanism needs to be a tip-of-the-fingers option (the on/off buttons should be located on the hand grips)

Using these design requirements as a building block, the design space for the walker/crutch mechanism was fully defined. It is important to note that the aforementioned constraints were a way to easily identify viable design options that had the potential to yield a working prototype. Section IV. Detailed Design of this report will discuss how these design requirements were met and how they were implemented into the final design of the walker/crutch mechanism.

III. PHYSICAL MOTION

The human body is able to move due to contractions of muscles, wherein parts of the skeleton are allowed to move relative to one another. Anatomical motions can be classified into various categories, two of which include flexion (the bending of a joint) and extension (the straightening of a joint) [9]. A healthy person who does not suffer from physical complications will be able to flex their knee joints to sit down, and extend their knee joints to stand up. These two anatomical motions explain how the lower body functions during the sitting and standing processes. However, it is also important to consider how the upper body moves while sitting and standing from an ergonomics standpoint. It is not so uncommon for a person to experience excruciating pains in the lower back, side, or neck regions of the body if they sit down or stand up awkwardly. Hence, it is vital that the walker/crutch mechanism does not exert any additional stress on the lower body or upper body of a person using the device.

To ensure that the walker/crutch mechanism is comfortable to use, a study was performed to determine the natural sitting and standing motions of healthy people. In the early stages of the design process, it was determined that the crutch mechanism would engage a person at two main points to provide support, stability, and safety. These two contact points were identified to be underneath the armpit and at the center of the hand, much like traditional crutches. In particular, focus was directed on determining the path of the armpit contact point since it dictated the motion of the upper body. Therefore, it was concluded that data needed to be acquired at the armpit in order to design a functional crutch mechanism.

Data was obtained by videotaping the sitting and standing motions of two test subjects. High-speed video at 240 frames per second, regular-speed video, and burst photos were taken for each sitting and standing motion performed. The video files of each test were then analyzed using VideoPoint, a video-based motion analysis software that allows a particular point in space to be tracked through consecutive frames. For each video file uploaded to the motion analysis software, a scale was set and the origin was defined at a specific point. Figure 2 shows the scale for the video files, and the placement of the origin for Test Subject 1 for the sitting to standing motion analyses and the standing to sitting motion analyses.

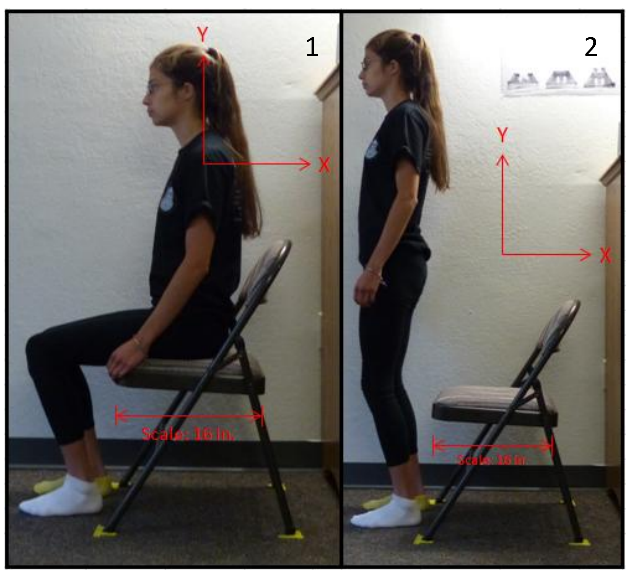

Figure 2: (1) Origin location: sitting to standing, (2) Origin location: standing to sitting

It is important to note that the origin was positioned at the same point in space for every video file regardless of if the test subject was standing up or sitting down. This was done so that the data points collected in VideoPoint would be consistent for both motions and yield similar armpit profile curves. It was crucial to collect data with the origin defined at the same point in space so that the standing and sitting underarm curves could be assessed.

Armpit profile data was collected for two reasons: (1) to determine the natural standing and sitting upper body motions of people, and (2) to establish if the natural standing and sitting motions are similar. It was essential to resolve the latter so that the walker/crutch mechanism could be designed for its particular function. If the motions were observed to be similar, then the crutch would only be required to follow one armpit profile path, which would simplify the design of the crutch/linkage system. The armpit profile curves for both motions were graphed using MATLab from the discrete points mapped in VideoPoint; the data for Subject 1 and Subject 2 can be observed in Figures 3 and 4 respectively.

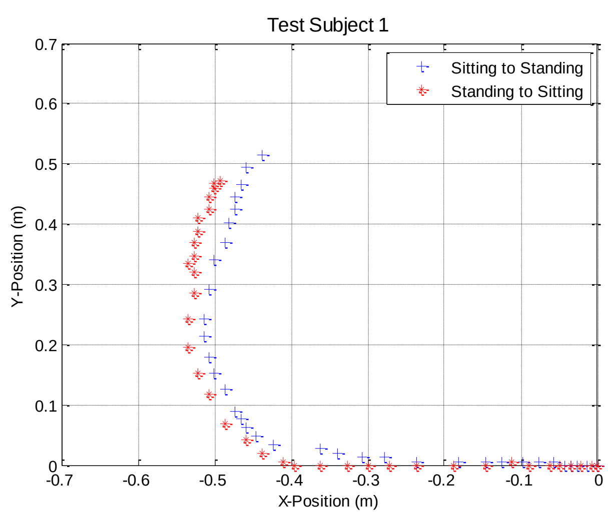

Figure 3: Standing and sitting data for Test Subject 1

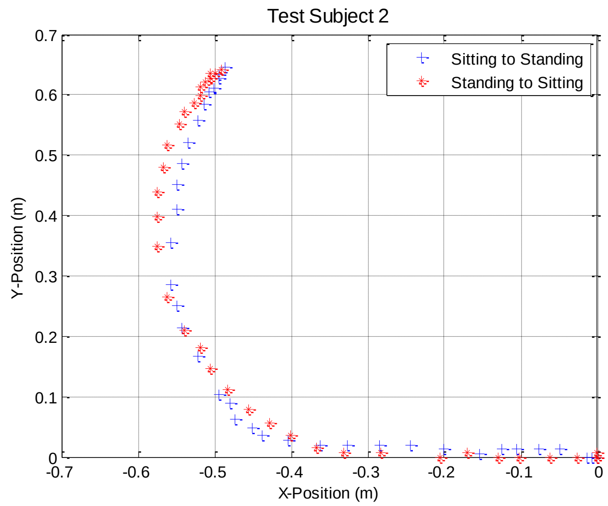

Figure 4: Standing and sitting data for Test Subject 2

A few important conclusions can be drawn from analyzing the data displayed in Figures 3 and 4 respectively. Firstly, the data shows that the standing and sitting motions are, in fact, the same. Second, the motions can be broken down into two separate components: (1) translating of the shoulders, and (2) upward/downward arcing of the armpit contact point. The former can be attributed to flexing of the hips and back, which translates the shoulders over the knees so that a person can shift their center of gravity. The latter can be attributed to extension of the knees, thereby driving a person upward into the standing position.

For this particular application, it was assumed that a person can translate their shoulders without experiencing any complications. Hence, component (1) of the standing motion was not considered when designing the walker/crutch mechanism in order to simplify its overall design. As a result, a person will begin in a slightly bent over position to eliminate the need for the mechanism to translate. Moreover, it was observed that the armpit contact point arced upwards as a person extended their knee joints, which was particularly interesting. The motion itself was determined to be that of a circle.

Once a circle was fit to the data, the radius of curvature was found so that the initial and final angles of the armpit contact point relative to the center of curvature could be properly identified. These angles are important because they represent the initial and final angles of the drive and follower linkages of the walker/crutch mechanism (see section IV. Detailed Design for more information on the linkage design). Figure 5 displays the angles and radius of curvature determined from this analysis for Subject 2.

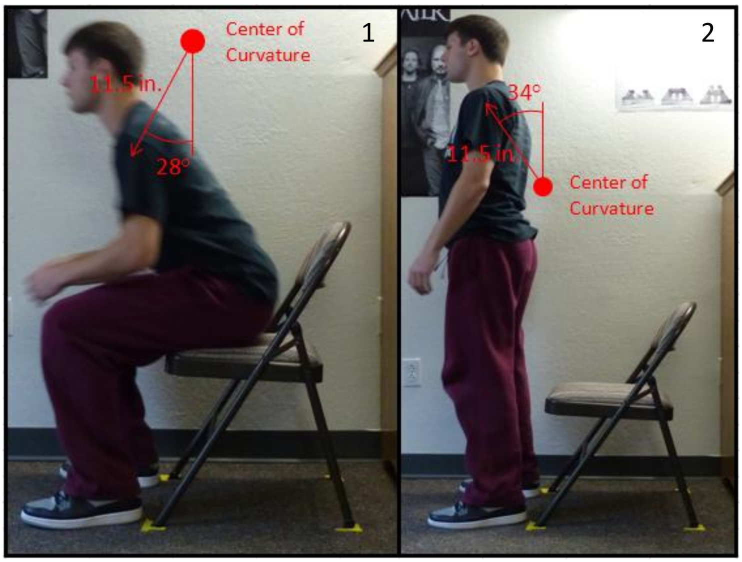

Figure 5: Figure not to scale. (1) Initial angle in bent over seated position, (2) Final angle in standing position

From Figure 5, the radius of curvature for Test Subject 2 was 11.5". It is important to note that the radius of curvature will change slightly for each test subject depending on their height (taller people will have longer curvature radii). Test Subject 2 represents an average male of 5′9" and 170 lbs. For the purposes of this research and design, the walker/crutch mechanism was specifically developed to accommodate an average male of the aforementioned qualities. It is important to state that the walker/crutch mechanism could be built to adjust to different people, however, those adjustability options were not completely implemented in this particular design concept and prototype. Table 2 summarizes the data collected for the test subjects and compares individual physical features:

Table 2: A summary of the data collected for the natural motion of each test subject

	Physical Features	**Physical Motion Data**		
	Height	Radius of Curvature (in.)	Initial Angle	Final Angle
Test Subject 1	5′5"	8.5	28°	34°
Test Subject 2	5′9"	11.5	28°	34°

The variation in the radius of curvatures between the two test subjects can be attributed to their height differences. Ultimately, this implies that the linkages for the crutch mechanism must be adjustable to accommodate people of different heights. However, as mentioned before, the walker/crutch mechanism prototype constructed for this research was not made to be adjustable in order to speed up the building and testing process. Section IV. Detailed Design discusses the linkage produced to replicate the natural circular motion examined in this section, and presents some possible adjustability features that could be implemented.

It is also important to consider how the position of the center of curvature for a person will shift when they sit in chairs of different heights. If a person sits in a tall chair, their center of curvature will be located at a higher position with respect to the floor than if they sit in a short chair. Ultimately, this means that the walker/crutch mechanism frame must be adjustable up and down to accommodate different chair heights.

From the data obtained by analyzing the natural upper body motion of people standing up and sitting down, important information was acquired in order to design an ergonomic crutch mechanism. Data and/or information acquired included: (1) verifying that the standing and sitting motions are the same, (2) the crutch mechanism will follow a circular motion, (3) armpit contact point angles in the seated and standing positions, (4) the radius of curvature. Refer to section IV. Detailed Design for information regarding the final design.

IV. DETAILED DESIGN

a. Overview of the Final Design

An isometric view of the assembled first generation prototype and SolidWorks model is provided in Figure 6, which indicates the main features of the machine. In general, raw stock 1026 steel was used to construct the components, and a control system was integrated into the design. The components that were constructed from steel included: (1) the U-shaped frame, (2) the mounting brackets and support plates, and (3) the four-bar parallelogram linkages (which guided the crutches along the natural circular motion). Two linear actuators, a control box, and a $12\ V$ lead-acid battery were wired together in order to provide power to the four-bar linkages. Additionally, total locking casters were implemented into the design to fully lock the machine in place as it was being operated.

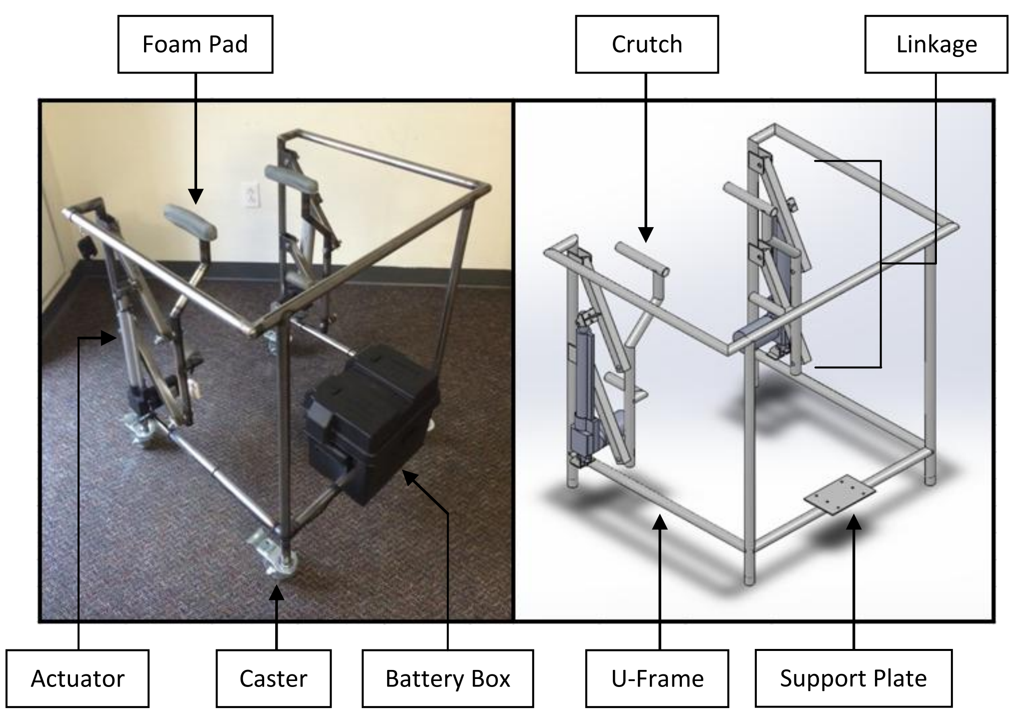

Figure 6: Isometric views of the prototype and SolidWorks model

Operation of the walker/crutch mechanism is fairly straightforward. In order to use the machine, a person can position themselves over the armpit supports and take hold of the handles. Depending on if a person is initially sitting down or standing up, the linkages/actuators will be in the fully retracted or extended positions respectively. It is important to mention that the frame of the walker was designed to be wider than an average sized chair so that the machine can easily roll up to a seated person. Once a person has been engaged to the crutches, they can use the machine by pressing the up/down button on the wireless remote located on the handle, which will activate the two linear actuators. As the linear actuators extend/retract simultaneously, they will raise/lower the four-bar parallelogram linkages that were designed to copy the natural upper body motion of a person. Once the full range of motion has been completed (the actuators will stop automatically once they have been fully extended/retracted), a person can easily disengage from the machine by releasing the handles. A person can then simply roll the machine away from them if they are seated, or continue using it as a walker in the standing position. Figure 7 illustrates the proper steps to operate the walker/crutch mechanism:

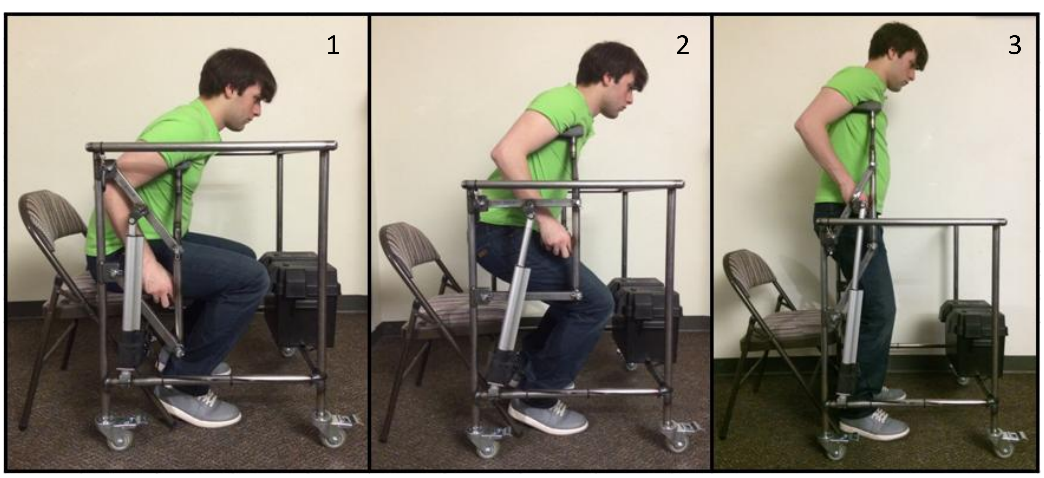

Figure 7: A test subject using the machine: (1) Seated, (2) Middle, (3) Standing

From Figure 7, it can be observed that each of the test subjects must begin in the slightly bent over position and align their heels with the hand grips. As discussed in section III. Physical Motion, the test subjects needed to begin in the slightly bent over position to eliminate the need for the crutch to translate horizontally. Ultimately, this reduced the complexity of the linkage implemented in the prototype, and it allowed the mechanism to maintain a low key profile. Also, it was estimated that a test subject would only be required to bend over at the hips approximately 35° if they situated themselves in the machine properly. In addition, the motion of the armpit support bar was confirmed to imitate the natural arcing motion of the armpit contact point, which satisfied the ergonomics design requirement.

It was important for the test subjects to align their heels with the hand grips on the crutch so that their center of gravity would stay over their feet as they were being raised or lowered. In the sequence of photos displayed in Figure 7, it can be observed that the shoulders of the test subject are always located directly over their feet. This ensured that the prototype would not shift in any unexpected direction while the machine was being operated. However, if the test subject felt inclined, they could have engaged the locking lever breaks on each caster to secure the machine and guarantee that it would not move out of place.

b. Crutch Design

Since the crutch is the interface between a person and the walker/crutch mechanism, it is the most vital component of the design. It was essential for the crutch to incorporate ergonomic features so that it did not exert any superfluous discomfort on a person as they operated the walker mechanism. Furthermore, the crutch needed to support a person adequately so that the machine would be safe to use as a standing/sitting aid. It was identified that the crutch would supply the greatest amount of comfort and stability to a patient if an armpit support bar and a handle were incorporated into the design. Figure 8 shows the unique features of the left and right crutches:

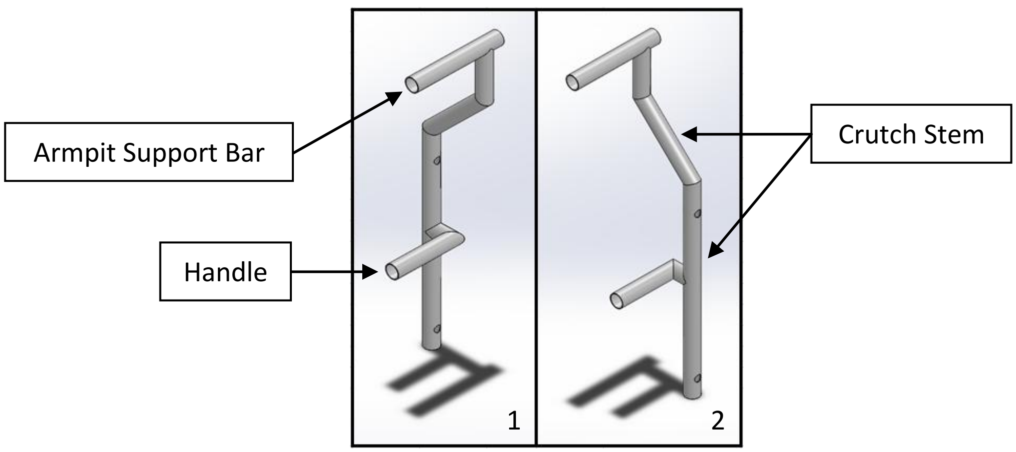

Figure 8: (1) Isometric view of the left crutch, (2) Isometric view of the right crutch

From Figure 8, it can be observed that the crutch was designed with a few unique features that separate it from a traditional crutch. In particular, the armpit support was offset from the center of the crutch stem. This feature was implemented into the design so that a person would not come in contact with the crutch stem once they rested their armpit on the support. From an ergonomics standpoint, it was imagined that this feature would decrease restriction and increase the overall comfort of the walker/crutch mechanism. Moreover, the crutch stem was designed to flare outward (from the top to the bottom) to provide the most amount of leg space for a person in the seated position. Once more, this feature was employed to allow a person to freely adjust themselves after they get situated in the machine. Along with a few of these distinctive features, the crutch was also designed to be compatible with commonly available crutch accessories (i.e. crutch pads and hand grips). As a result, the length and placement of the armpit support bar was crucial so that the crutch pad could fit snuggly in place (see Figure 9).

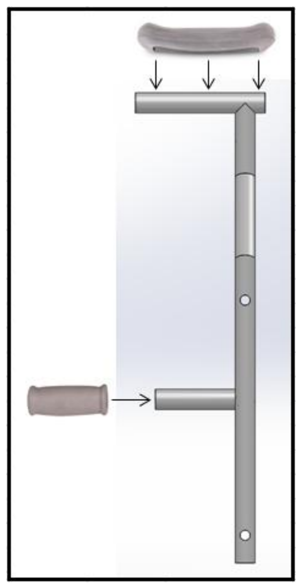

Figure 9: Illustration of how the crutch pad and hand grip were fitted to the support bar and handle

The armpit support bar was designed to be the same length as the interior section of the crutch pad in order to form a secure connection and to eliminate any possibility of it detaching from the crutch unexpectedly. Also, since the crutch pad was not permanently attached to the crutch itself, a patient could easily add to, remove, or replace the underarm padding if necessary. In addition to the underarm padding, a hand grip was also fit to the crutch handle to increase the overall comfort of the machine.

Two half-inch holes were drilled into the crutch stem, which allowed the crutch to be pinned to the linkage. Adjustable clevis pins were used in order to adjust the space between the left and right armpit support bars to accommodate patients with distinct torso sizes.

c. Linkage

In order to raise/lower a person in a manner consistent with their natural circular upper body motion (discussed in III. Physical Motion), a four-bar parallelogram linkage was designed to replicate the upward/downward arcing of the armpit contact point. As shown in Figure 10, the parallelogram linkage integrated a ground link, a follower link, a drive link, and a coupler link. It is important to note that links 2 (follower) and 3 (drive) were equal in length, which is the main feature of a four-bar parallelogram linkage. Since these two links were equal, it allowed the coupler link (otherwise known as the crutch) to remain in a perfectly vertical orientation as the linear actuator extended/retracted, thereby raising/lowering the crutch. As a result, the crutch itself was stable throughout the lifting/lowering process.

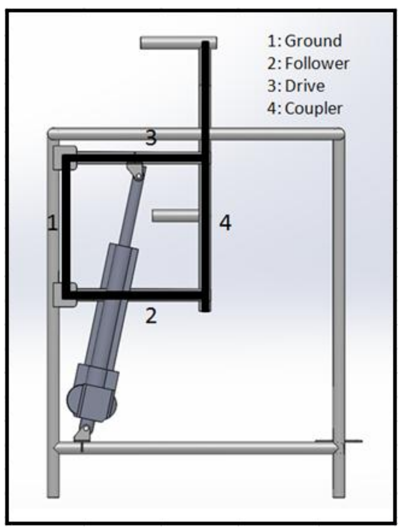

Figure 10: Four-bar parallelogram linkage design that yields the circular motion

Steel clevis pins and hitch pins were used to assemble the four-bar parallelogram linkage as shown in Figure 10. Both links 2 and 3 were pinned at each end which connected them to the brackets on the frame (link 1) as well as to the crutch (link 4). It is important to note that a plate and gusset were attached to link 3 so that the linear actuator could be pinned to the linkage (see Figure 11). Once the linear actuator was pinned to the bracket connected to link 3, that bracket was able to rotate around the actuator as it extended or retracted. Furthermore, since link 3 was connected to the linear actuator, it was considered to be the drive link. Please refer to Appendix 6: Drawings – Lift-Arm/Linkage for the exact dimensions of the gusset and plate as well as their positioning along link 3.

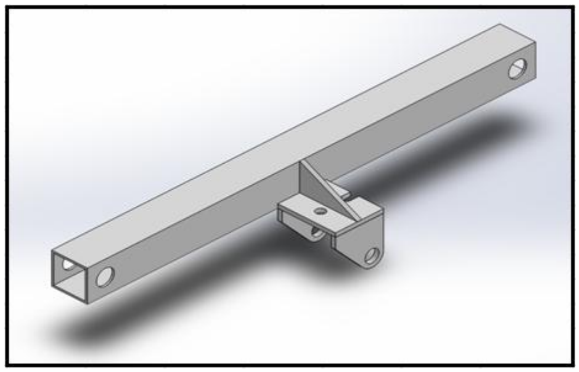

Figure 11: Lift-arm and bracket design utilized to connect an actuator

It was critical for the four-bar parallelogram linkage to duplicate the radius of curvature created by the armpit contact point of a person sitting down or standing up. As discussed in section III. Physical Motion, the radius of curvature for each individual test subject varied depending on their height. For the purposes of this thesis, the initial linkage prototype was based on the radius of curvature for Test Subject 2, which equaled 11.5". For the parallelogram linkage to reproduce this radius of curvature, the center-to-center distance between the pin holes on links 2 and 3 was established to be 11.5" as well. Due to the nature of a parallelogram linkage, the length of links 2 and 3 were responsible for creating the radius of curvature for the armpit contact point. To adjust the length of the links to accommodate people of various heights, telescoping tubing could be implemented in future designs.

Another important aspect of the four-bar parallelogram linkage design was its initial and final positions when the actuator was fully retracted or extended. After the physical motion of each test subject was analyzed, it was determined that the initial and final angles of the armpit contact point relative to the center of curvature was $28°$ and $34°$ respectively. These angles were then transcribed to the four-bar parallelogram linkage so that links 2 and 3 also began and ended exactly in those two positions. The actuators limited the range of motion of the linkages to the starting and ending angles respectively. Furthermore, these angles ensured that a person would start and stop at the correct positions during the sitting/standing process, thereby relieving any extraneous discomfort when the mechanism was being used.

d. Construction of the Frame

The frame of the walker/crutch mechanism was designed to address important ergonomic and portability requirements. From an ergonomics standpoint, the frame needed to be wide enough so that a person could comfortably sit in the crutch mechanism without feeling cramped or restricted. Conversely, the frame also needed to be narrow enough so that it could fit through an average sized doorway (36" wide) without becoming jammed. Ultimately, it was concluded that a basic U-shaped frame was the best option. Nearly every walker on the market today uses a U-shaped frame design because it is simple, sturdy, and bare-bones. The frame designed for the walker/crutch mechanism can be observed in Figure 12:

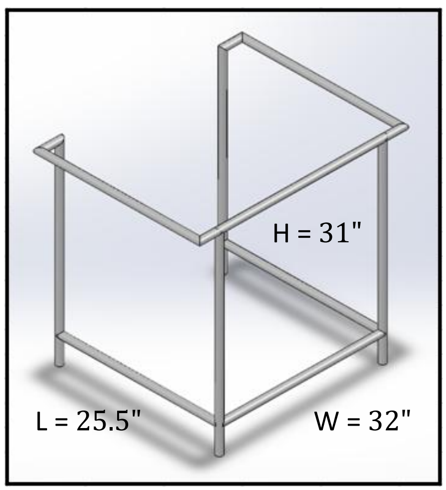

Figure 12: Isometric view of the entirely constructed frame design

It was also essential to eliminate any cantilevered beams in the frame design to improve the overall rigidity of the structure. In general, if a force is applied to the end of a cantilevered beam, it will create a moment. The magnitude of the moment depends on the magnitude of the force as well as the distance of that force away from the fixed end of the beam. If the applied force is great enough, a very large stress could be created, ultimately causing the beam to yield. The walker frame needs to withstand a maximum 300 lb loading to ensure that the mechanism will not fail while a person is operating it. It can be observed in Figure 12 that the frame does not incorporate any cantilevered beams, which improves its structural integrity.

The tubing used to construct the walker frame was 1026 steel. In general, this is a type of mild steel that offers good strength and is readily available. However, this type of steel is very dense, and caused the walker frame to be heavier than desired. Aluminum 6061 was originally the material of choice to construct the frame, but there were restrictions with manufacturing the frame from this material. To speed up the manufacturing process for the prototype, 1026 steel was chosen in place of Aluminum 6061. Table 3 displays the properties for 1026 steel and the tubing sizes used to construct the frame:

Table 3: Properties of 1026 steel, tubing size, and dimensions

	Outer Diameter (in.)	Wall Thickness (in.)	Type	Yield Strength (psi)	Density (lb/in^3)
1026 Steel	1	0.049	Cold-Rolled	60,200	0.2839

In section III. Physical Motion, it was discussed how the center of curvature for a person will shift if they sit in chairs of different heights. Even though adjustability features were not incorporated into the design of the prototype due to time constraints and manufacturing purposes, a solution to this problem was identified. To address this issue, the legs of the frame could be made adjustable by using a telescoping tube design. Four steel tubes (with an outer diameter less than 0.902") could be placed inside the legs of the walker, which would be held in place by a push button locking pin. When the locking pin is pinched together, the legs will be able to adjust up or down depending on the height of the chair. Ultimately, adjusting the entire frame of the walker will adjust the height of the crutch pads that rest underneath the armpits.

e. Wheel Integration

In order to make the walker/crutch mechanism portable, wheels were attached to the four legs of the frame. For this particular application, 3" locking polyurethane casters were chosen since they provide superior stability due to their locking lever break design. The brakes are easy to engage by stepping on the locking lever and will effectively immobilize the entire caster from spinning and swiveling. As a result, when the four casters are set in the brake position, the walker/crutch mechanism will be completely stationary. Figure 13 shows the caster and the locking lever brake design:

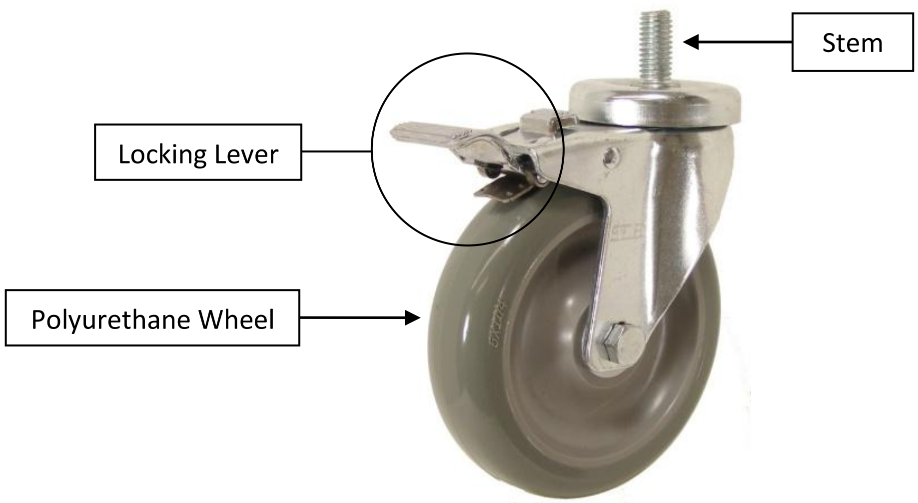

Figure 13: 3" Locking lever swivel polyurethane caster with threaded stem

In general, polyurethane wheels have some advantages over rubber wheels, including an increased capacity rating. Under normal operating conditions, polyurethane wheels can safely handle three times the capacity of similar sized rubber wheels, which reduces the risk of the walker/crutch mechanism failing under the maximum 300 lb load requirement [10]. Moreover, the polyurethane wheels chosen for this application will not damage floors since the wheel will slightly deflect under load, effectively creating a cushioning effect. When the load is released, the wheels will return to their original form. Polyurethane wheels also offer more traction than steel wheels, and are more resistant to abrasive wear than rubber. In addition, each polyurethane caster is rated to safely perform at the maximum 300 lb weight.

The bearing for the wheel shown in Figure 13 is made out of Delrin, otherwise known as polyoxymethylene (POM). This material is a thermoplastic that is commonly used for precision parts that require high strength-to-weight ratios, low coefficients of friction, and good corrosion resistance [11]. It is critical for the bearing to have a high strength-to-weight ratio in order to reduce the overall weight of the walker/crutch mechanism, and also withstand the 300 lb maximum load rating of the machine. Furthermore, since these bearings have lower coefficients of friction than steel bearings, the casters attached to the frame will be able to roll more smoothly over rougher surfaces. Therefore, these bearings will improve the mobility of the mechanism and will reduce the amount of force a person will need to apply to the walker frame to move it around on a daily basis. It is also important that these bearings have good corrosion resistance as well as high fatigue strength. If the walker/crutch mechanism is to be used daily, the wheels must be able to withstand the fatigue that they will experience; these bearings will increase the longevity and life-span of the casters.

In addition to the locking lever brakes, polyurethane wheels, and the Delrin bearings, the casters have the ability to swivel. This feature is important because it allows a person to navigate the machine with greater precision and with less effort. Ultimately, swivel casters are the best choice for this application because they increase the degree of mobility, and will allow a person to make tighter turns more smoothly. However, even though the swivel feature is necessary to increase the overall portability of the machine, it can yield some stability issues. These problems can be addressed by outfitting the swivel caster with the aforementioned locking lever brake which will stop the wheel from both spinning and swiveling. After the mechanism has finished its raising or lowering motion, the locking lever brakes can be released. This will then reactivate their swivel and rolling capability.

The casters chosen for this application have threaded stems to ensure good contact and stability when screwed into place. At the center of the cross-sectional face of a $1''$ steel rod insert, a hole was tapped which coincided with the size of the thread on the caster $(1/2'' - 13)$. Following this process, the insert was welded to the bottom of the four legs. The casters were then screwed onto the bottom of the machine. In addition to being relatively easy to install, the casters are easy to remove by unscrewing the stem from the steel rod insert. This also allows the casters to be replaced if necessary.

It is also important to note that the locking casters add roughly $4.25''$ of height to the walker/crutch mechanism. This information was crucial to consider when designing the length of the legs. The machine was designed so that the top of the crutch (i.e. the armpit support bar) would sit $32''$ above the ground, and therefore the length of the legs plus the height of the casters needed to coincide with this design requirement.

f. Powering Method

The crutch mechanism is powered by dual linear actuators that work simultaneously and are powered by a $12\,V$ battery. Linear actuators were chosen over other options, such as motors and pneumatics, because they are light weight and were relatively easy to integrate into the frame of the walker. In general, linear actuators are specified by their maximum dynamic lift capacity and their extension/retraction speed. It is important to note that dynamic lift capacity refers to the maximum load that a linear actuator can handle without stalling as it extends or retracts. For higher lift capacity ratings, higher gear ratios are utilized. As a direct result, the speed of a linear actuator decreases. Therefore, there is a tradeoff between lift capacity and speed.

Table 4 provides a summary of the specifications for the linear actuator chosen for this application. It can be observed that each actuator only weighs 4.55 lbs, which is extremely light weight in comparison to its 200 lb maximum lift capacity. It was crucial to implement light weight actuators into the design to increase the portability of the crutch mechanism and improve its ease of use. Moreover, it can be noted that each actuator is safely rated to lift a 200 lb dynamic load. Although this value is less than the 300 lb maximum weight requirement, two actuators were used in order to increase the effective load capacity to 400 lbs. These linear actuators have such a substantial dynamic load capacity because of their significantly high gear ratio of $38{:}1$, which is nearly double the next comparable non-industrial actuator.

Table 4: Specifications for PA-02 linear actuators provided by the manufacturer Progressive Automations [12]

Model	Stroke Size (in.)	Weight (lbs)	Gear Ratio	Max. Speed (in./sec)	Load (lbs)	Voltage	Current (A)
PA-02	10	4.55	38: 1	0.94	200	12 VDC	4.5

At this gear ratio, the actuator is able to achieve an extension speed of 0.94 in/sec without being loaded. However, there are some limitations with the actuators in terms of their speed output. As more weight is placed onto the actuator, the speed output will decrease linearly, thereby slowing down the motion of the crutch mechanism. Figure 14 shows this speed vs. load relationship. It can be observed that when the actuator is loaded to its maximum capacity, the speed drops to roughly 0.47 in/sec, which is only half of the maximum extension speed. Using the maximum and minimum extension speeds as limiting factors, it was ultimately estimated that the crutch mechanism will be able to successfully raise or lower a person in 10 to 20 seconds. Considering that this walker/crutch mechanism was designed for the elderly population or for people that are rehabilitating, this lift speed range was considered safe.

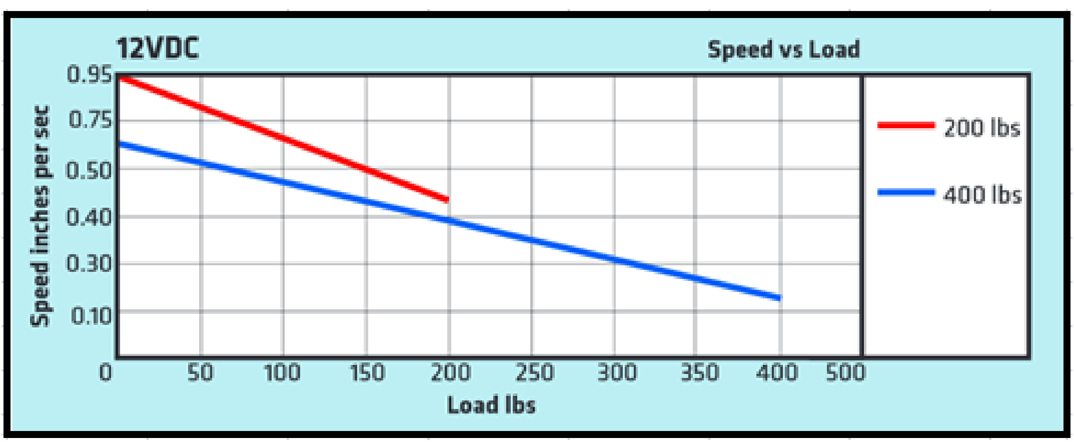

Figure 14: Speed vs. Load relationship for the PA-02 linear actuator. Note: reference the 200 lb curve. [12]

One of the most important features of these linear actuators is their ability to extend and retract simultaneously using a $12\,VDC$ control box manufactured by Progressive Automations. Simultaneous function is imperative to the safety of the mechanism because it ensures that a person will be raised or lowered steadily. Two wireless remotes also come with the control box, ultimately allowing a person to operate the machine at their finger tips, which improves its ease of use. Furthermore, since the control box and the actuators can be powered by an input voltage of $12\,VDC$, the walker/crutch mechanism can be portable. Instead of being restricted by the placement of wall outlets around a home, the machine has the potential to be powered by a light weight $12\,V$ lithium-ion battery. It is important to note that the budget for this design was limited, however, and therefore a lead acid battery was used instead. As a result, the total weight of the prototype exceeded the 35 lb threshold set in section II. Design Requirements. If it were possible, the lithium-ion battery implemented into this design would have only added a total weight of 1.8 lbs [13] to the walker. This is 6.0 lbs less than the lead-acid battery.

In order to fit into the frame design of the walker, a 10" actuator stroke size was chosen (please reference Appendix 1: Actuator Specifications for more information regarding actuator dimensions). As shown in Figure 15, the actuators were connected to the drive link at point A and to the bottom of the crossbar at point B using a bracket, plate, and gusset design. The two actuators were also offset to the outside of the four-bar linkage (i.e. crutch mechanism) so that they could extend and retract freely. As they extend and retract, they are free to rotate due to their pin joint connections which allow 180 degrees of rotation.

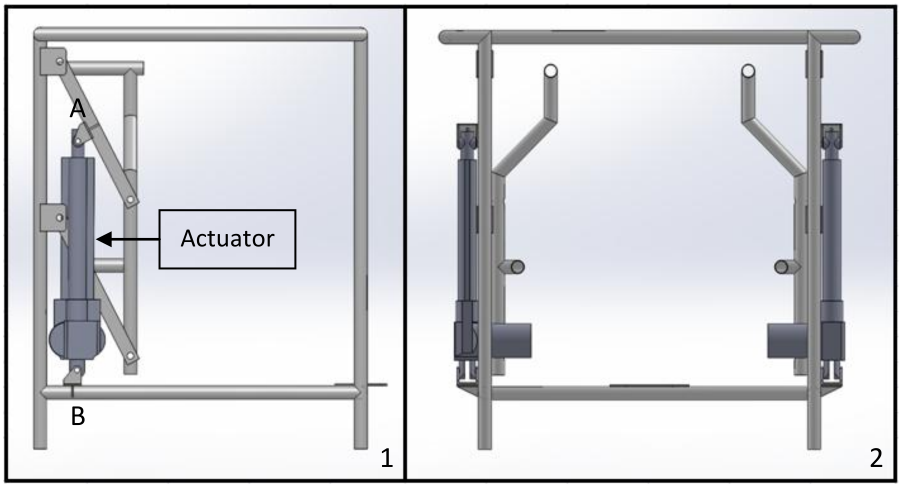

Figure 15: (1) Side view of the walker/crutch mechanism, (2) Back view of the walker/crutch mechanism

When the actuators were fully retracted or extended, the linkage was located in its initial 28° angle position and its final 34° angle position respectively. It is also important to note that when the actuators were in the fully retracted position, the armpit support bars were located 32" above the ground, which satisfied a design requirement. Figure 16 illustrates the initial and final positions of the linkage with the actuators fully retracted and extended for both the SolidWorks model and the constructed prototype:

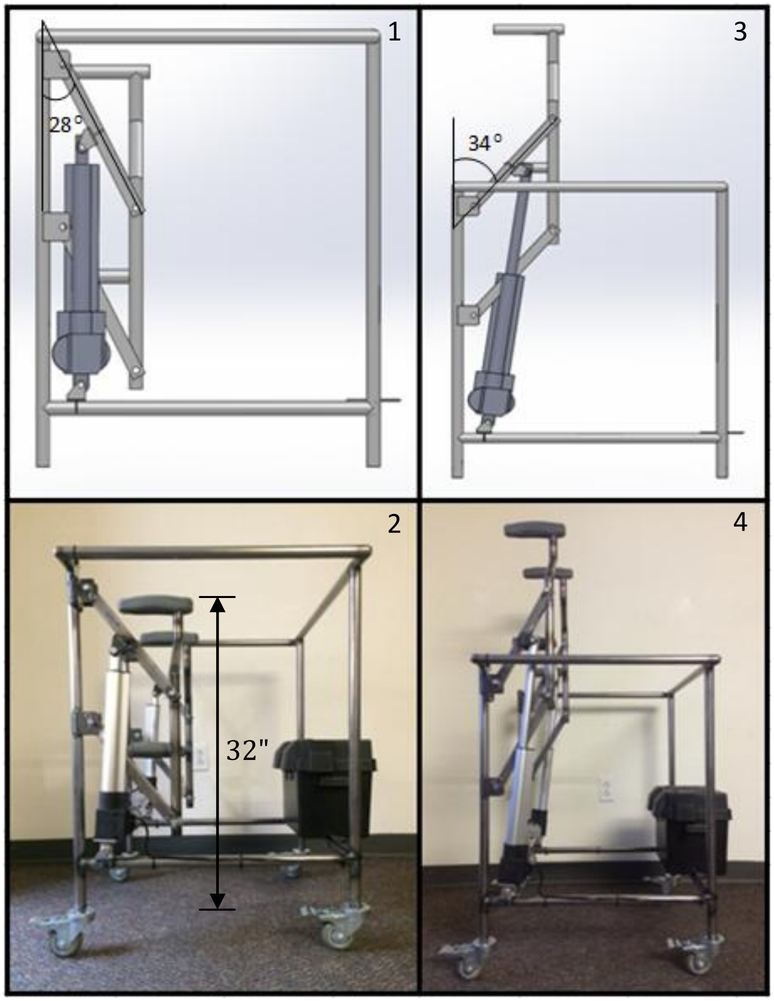

Figure 16: (1) and (2) Side view: linkages in retracted position, (3) and (4) Side view: linkages in extended position

g. Controls

To regulate the behavior of the mechanism, a control system was devised. It was stated briefly that two wireless remote controls were featured in the design so that a test subject could operate the mechanism at their fingertips. Since the remote controls were wireless, it allowed them to be fixed at any position on the frame and/or crutch, which enhanced its ease of use. As displayed in Figure 17, one remote control was positioned on the right crutch handle and the other was positioned on the top crossbar, which allowed a test subject to raise and/or lower the linkages while they were standing or sitting down. It is also important to note that the wireless remote controls could have been located on the left crutch handle and left top crossbar as well. However, the first generation prototype was planned to be right-hand friendly since the majority of test subjects were right-handed.

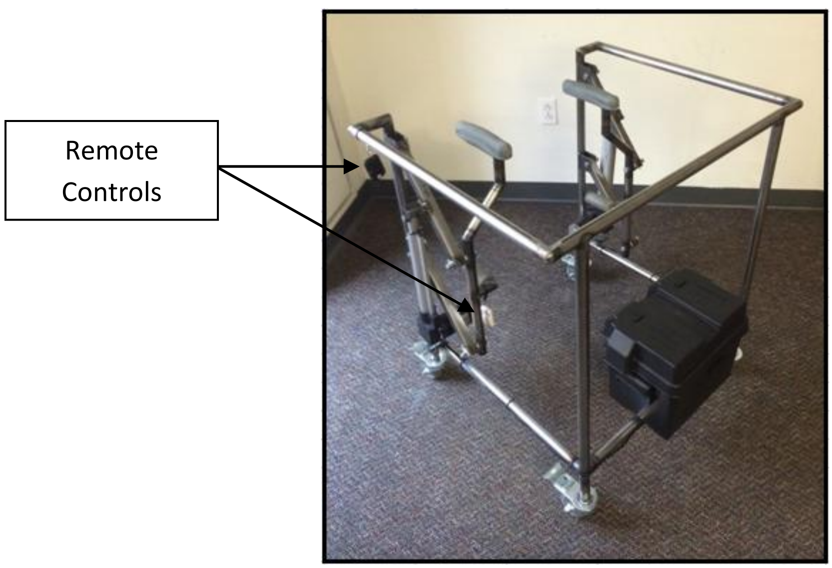

Figure 17: Isometric view showing the location of the remote controls

In addition, the wireless remote controls had three buttons denoting up, down, and stop. However, for safety reasons, the control box was set to momentary function, which rendered the stop button inactive and made the act of stopping the actuators from extending/retracting simpler. With the momentary function activated, a person did not need to press two separate buttons to start and stop the linear actuators (which was a rather clumsy task to perform). Rather, they only needed to press and hold the up/down button to start the actuators, and then simply release that button to stop the actuators. Ultimately, this provided a test subject with full control over the raising/lowering process.

The control box allowed the actuators to extend and retract in unison, which ensured that a person would be raised or lowered steadily. In addition to the simultaneous function feature, the control box was outfitted with potentiometers that controlled the amount of voltage being emitted through the two output terminals. Ultimately, the amount of voltage supplied through the terminals to the actuators directly affected how fast each one could extend or retract. As per a list of details provided by the manufacturer Progressive Automations, actuators of the same model can have up to a 10% speed difference between them. Therefore, the voltage supplied to each actuator was adjusted using the potentiometers in order to eliminate any speed differences and to ensure that the crutches would extend/retract at the same speed. A schematic of the electrical arrangement between the $12\,V$ battery, control box, and the two PA-02 linear actuators is presented in Figure 18:

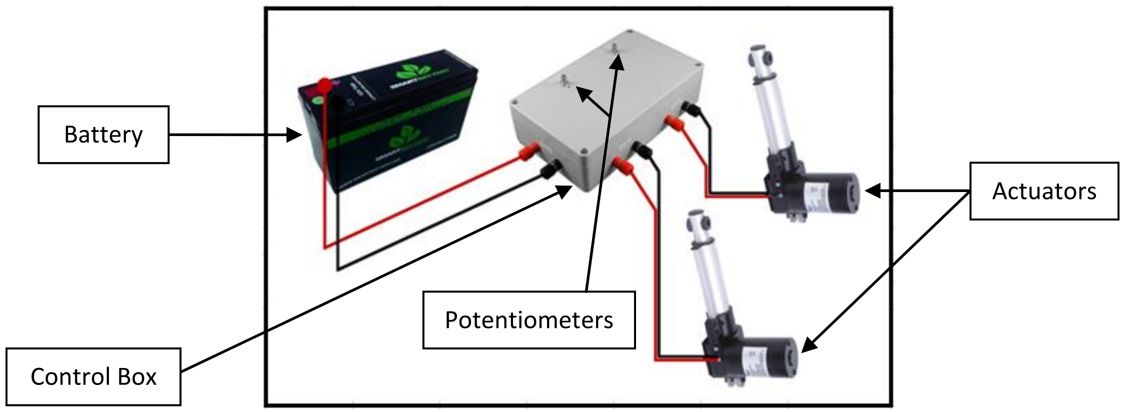

Figure 18: Schematic of the PA-25 control box connecting the 12 V battery and the two linear actuators

From Figure 18, it can be observed that the 12 V battery was wired to the input terminals and the linear actuators were wired to separate output terminals (so that the output voltage could be adjusted for each actuator) on the control box. As previously presented in Table 4 of section IV. Detailed Design, each actuator required 4.5 A of current to function at full load capacity. As a result, it was determined that the maximum amount of current to fully operate two actuators would be 9 A. The battery used in the first generation prototype provided 7 AH of current to the circuit, meaning that it provided 7 A of current for one hour. Therefore, it was expected that the battery would be able to last for nearly 47 minutes (roughly 180 lifts) to satisfy the needs of the actuators. Furthermore, it was essential to confirm that the control box could handle the total amount of current running through the system. The type of control box used was produced by Progressive Automations and was rated for a maximum of 30 A, which was more than three times the required amount. Table 5 outlines the specifications of the control box:

Table 5: Specifications for PA-25 control box provided by the manufacturer Progressive Automations [14]

Model	Voltage	Max. Current (A)	Weight (lbs)	Box Dimensions (L × W × H)	Function
PA-25	$12\ VDC$	30	1.00	6" × 3.5" × 1.5"	Simultaneous

The control box and battery were safely protected from outside elements and hidden from sight by using a battery box. As shown in Figure 19, the battery box was bolted to a steel plate on the front bottom crossbar of the machine, which ensured that it would not move around as a person was using the crutch mechanism. Industrial strength velcro was attached to the bottom of the control box, the $12\ V$ battery, and the battery box to secure the components. Using velcro allows the electrical components to be completely removed, or simply resituated in the battery box when needed. In addition, holes were drilled in the bottom four corners of the battery box roughly $3/8"$ in diameter so that the wires from the actuators could be connected to the concealed control box without being noticed by a person. The actuator wires were run along the lower crossbars of the frame, and then were individually fed through the appropriate holes on either side of the mounted battery box.

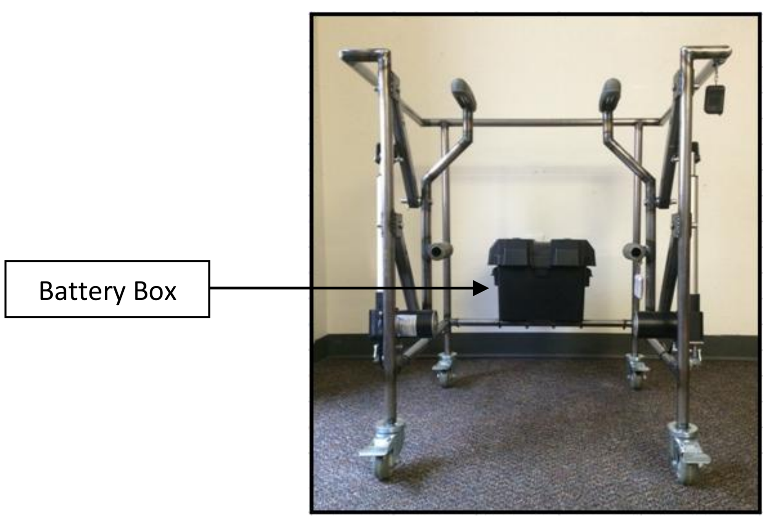

Figure 19: Back view of the walker/crutch mechanism prototype

The battery box used for the first generation prototype was oversized so that the electrical components could be easily secured into place. Future prototypes will not need a battery box this large, and a custom housing can even be constructed in lieu of the battery box. If a custom battery box were to be constructed, it would be thinner, which would allow a person to have far more leg room while they are operating the mechanism.

V. STRUCTURAL ANALYSIS

A couple methods were used to analyze the structural integrity and overall rigidity of the walker/crutch mechanism to establish that it would not fail under a 300 lb maximum loading. Specifically, a finite element analysis (FEA) was performed in SolidWorks on the crutches, and hand calculations were utilized to size the lift-arms and pins. It was critical to study the stress states occurring in the crutches due to different load scenarios (i.e. completely vertical loads, and loads applied at a 45° angle) since they were the interface between a patient and the machine. Additionally, the lift-arms and pins needed to be sized appropriately so that they would not fail due to bending stresses and shearing stresses generated from the sizeable loads.

Before conducting any structural analysis, the factor of safety for the components of the machine was established. In general, a factor of safety of 3 is most commonly used for materials with known properties, and that endure average conditions of environment, load, and stress on a regular basis [15]. Therefore, it was established that a factor of safety of 3 would be the best choice for this application.

FEA was performed in SolidWorks to identify the location of the maximum stresses in the machine when it was loaded with 300 lbs. In order to determine if the different components would fail (i.e. yield) under the maximum loading condition, the von Mises failure criterion was used. It is important to note the von Mises failure criterion could be used due to the fact that 1026 steel is an isotropic, ductile material. The factor of safety was computed using equation 1 for all critical locations and compared to the selected value of 3.

$$S.F. = \left(\frac{S_y}{\sigma_{vm}}\right) \tag{1}$$

where $S.F.$ is the factor of safety for a component, σ_{vm} is the von Mises stress gathered from the FEA, and S_y is the yield strength of 1026 steel.

Realistic loadings and boundary conditions for the FEA model were defined. In general, a simplified loading scenario was implemented into the SolidWorks FEA model since complex loading scenarios on the machine could not be accurately established. It was then reasoned that 150 lbs was supported by each crutch in order to handle the 300 lb load condition. Moreover, each crutch was loaded so that the 150 lbs was evenly distributed between the armpit support bar and the handle. Thus, the armpit support bar and the handle both supported a 75 lb point load, which was located at the center of the 1" diameter tubing. In addition to the loading scenario, a pin geometry boundary condition was applied at the two pin holes that were aligned along the crutch stem. In particular, this type of boundary condition was chosen since it fixed the crutch in the x, y, and z Cartesian coordinate directions, but allowed rotation at the two pin holes exactly like a functional pin joint. Figure 20 illustrates the loading scenario and the boundary conditions applied to the crutches on either side of the machine:

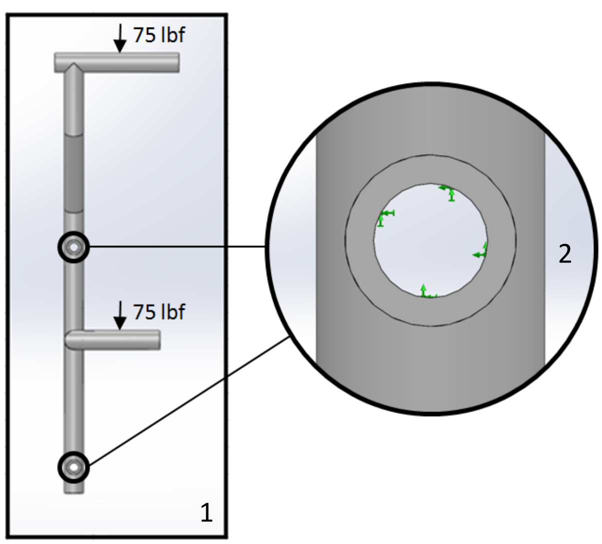

Figure 20: (1) Loading: side view of the right crutch, (2) Pin geometry boundary condition

Once the loads and boundary conditions were applied to the FEA, the crutch was meshed. In particular, a curvature based mesh was used, as opposed to various other mesh types, since the crutch was constructed from 1" diameter steel tubing. Accordingly, the total number of elements was maximized in higher-curvature areas to obtain the most accurate results from the FEA study. Figure 21 illustrates the distribution of stress in the crutch. From Figure 21, it can be observed that a stress concentration occurred at the bottom 45° angled joint on the crutch stem, which yielded a maximum von Mises stress of 35,260 psi. Once this was known, the von Mises failure criterion was utilized to calculate the factor of safety. The factor of safety was determined to be nearly 1.71, which was lower than the desired factor of safety of 3 for the mechanism.

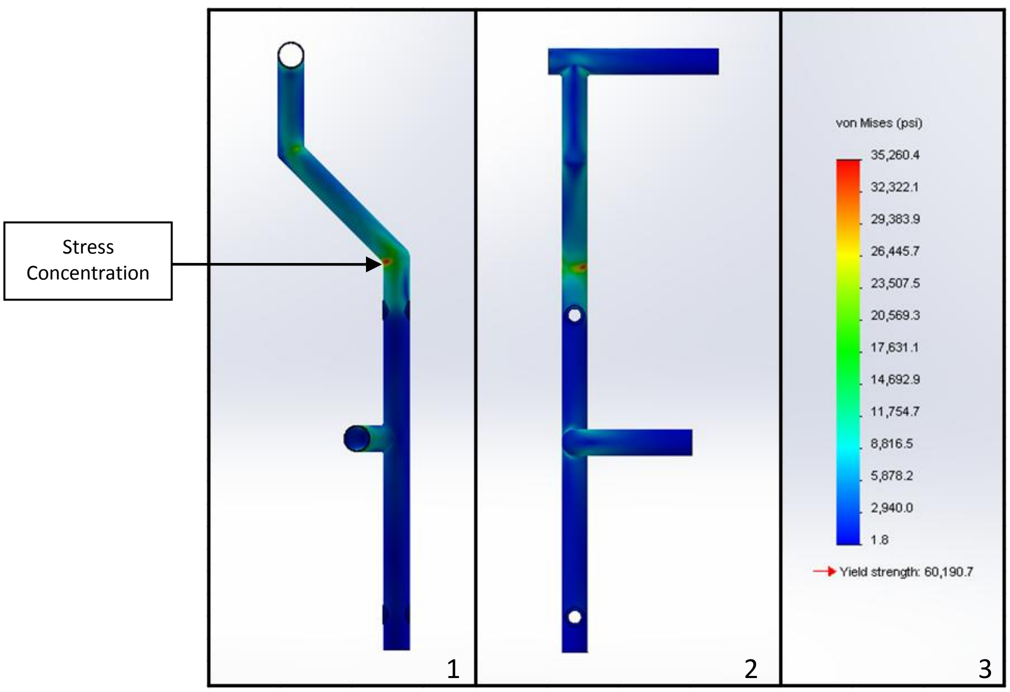

Figure 21: (1) Stress results: back of crutch, (2) Stress results: side of crutch, (3) von Mises stress scale

In order to establish the maximum load condition that would yield a factor of safety of 3, the stress states occurring in the crutch were analyzed for a range of point loads. The point loads applied to the FEA model ranged from 100 lbs to 300 lbs (which equated to 25 lbs to 75 lbs on each of the two handles and armpit support bars respectively). From the plotted data shown in Figure 22, it can be seen that the desired minimum factor of safety of 3 was achieved when the armpit support bar was loaded to 42.5 lbs (which was attained from interpolation). Hence, the maximum load that the walker/crutch mechanism can undergo to ensure a factor of safety of 3 is 170 lbs. This information revealed that the crutches needed to be slightly redesigned in order to increase their overall factor of safety. By doing so, the crutches will be able to support a 300 lb load with a factor of safety of 3 due to their improved structural rigidity.

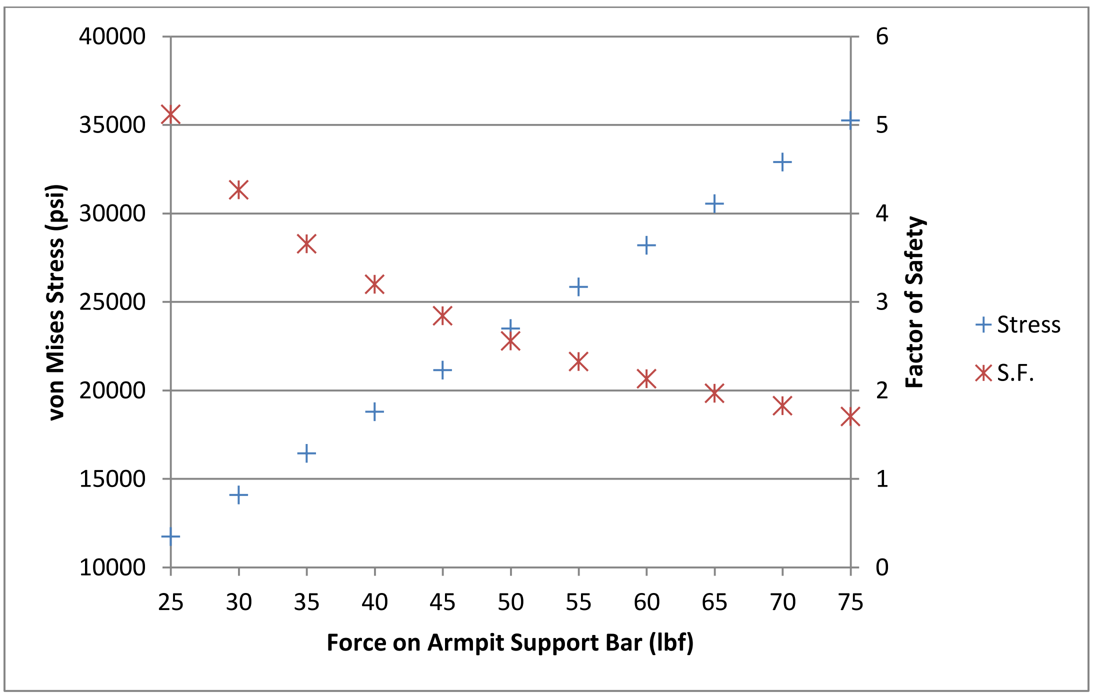

Figure 22: A graph of von Mises Stress and Factor of Safety vs. Force on the Armpit Support Bar

Two solutions were identified to eliminate the stress concentration that was occurring at the bottom 45° angled joint. The solutions included: (1) constructing the crutches from higher strength steel, and (2) welding additional struts to the crutches in order to triangulate the joint. The first solution is a much less viable option, however, because it will not reduce the overall weight of the crutches (it is envisioned that

Aluminum 6061 will be substituted in place of 1026 steel as the build material). Conversely, the second solution is promising since it adds structural rigidity to the design, and will also not increase the overall weight of the crutches by a very large amount. Therefore, this solution will strengthen the crutches and keep the weight of the entire machine to a minimum.

Another load scenario was also analyzed on the crutches to confirm that they would not fail when a 75 lb point load was applied at a 45° angle on the armpit support bar and handle. This type of loading was accomplished by splitting the 75 lb resultant load into equivalent 53 lb x and y components. Figure 23 shows this load scenario. From the FE analysis, it was observed that a stress concentration still arose at the bottom 45° angled joint, which yielded a maximum von Mises stress of 37,188 psi. The corresponding factor of safety was determined to be 1.62. Hence, it was confirmed that the crutches would not fail under this load condition.

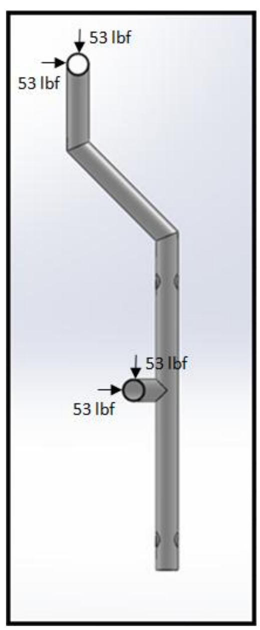

Figure 23: Load scenario to create a 75 lb load at a 45° angle on the armpit support bar and handle

In addition to analyzing the stress states in the crutches under different load scenarios, the lift-arms were sized so that they would produce a factor of safety of 3. The four-bar linkage was analyzed in its most critical position (when the lift-arms were positioned perfectly horizontal to the ground and the actuator was at a 15° angle from the vertical). The lift-arms were constructed from 1 in. × 1 in. square steel tubing, which had a wall thickness of 0.060 in. Figure 24 shows the cross-section of the lift-arm as well as the critical loading scenario. From this, the bending stress occurring in the lift-arm was calculated to be 13,490 psi, which ultimately yielded a factor of safety of 4.46. In addition, the reaction force that needed to be supplied by the linear actuator to hold the load successfully in this particular position was determined to be 155.3 lbs. Since the actuators were rated to safely push 200 lbs, they were appropriate for the job.

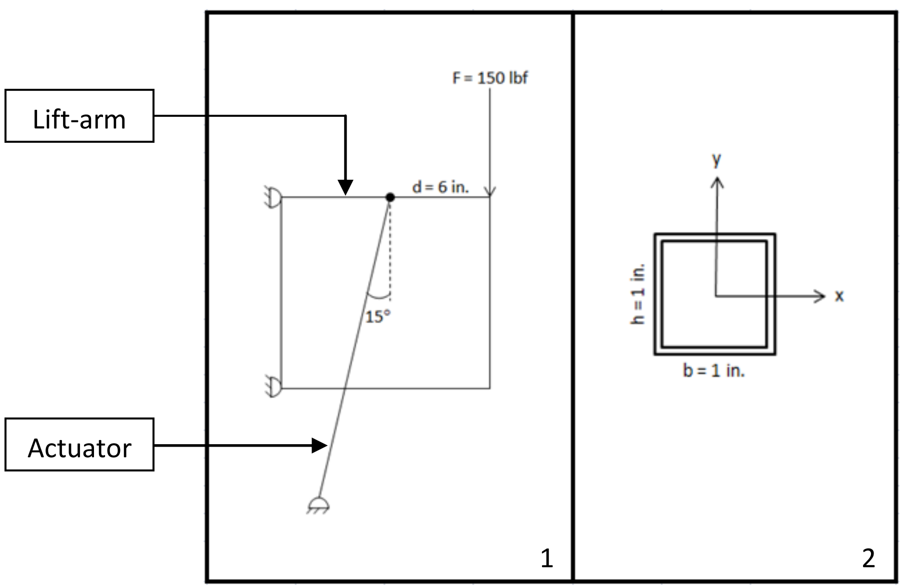

Figure 24: (1) Linkage loaded in the critical position, (2) Cross-sectional view of the lift-arm

It was critical to size the pins that fastened the ground, follower, drive, and coupler links together to ensure that they would not fail under a significant shear stress. In order to support the same load, the pins experiencing single shear needed to have a larger diameter than the pins experiencing double shear. Therefore, the diameter of the pins was calculated so they would not fail under a single shear loading scenario. The clevis pins were manufactured out of 316 steel, which has a yield strength of 29,733 psi, and also a corresponding shear strength of 17,840 psi. From an analysis, it was determined that the diameter of the pins needed to be 0.103" to safely support a 150 lb load. Ultimately, a pin diameter of 0.5" was chosen for the design.

VI. PROTOTYPE RESULTS

a. Evaluation of the Physical Prototype

Performance metrics were measured for the first generation prototype during the physical testing process and were subsequently compared to the design requirements. This allowed the overall function of the detailed design to be assessed. The key performance metrics included size, weight, stability, cost, and the time to raise and lower a patient. Table 6 displays the size, weight, and stability performance metrics. It can be observed that the prototype met the overall size design requirements, but was 10.1 lbs over the desired maximum weight. Consequently, the machine was slightly more difficult to maneuver, and could not be easily lifted off of the ground by a single person. Thus, this somewhat restricted its overall portability and accessibility for the subjects that participated in the testing process. On the other hand, it is important to note that the machine successfully accommodated test subjects that weighed from 100 lbs to 225 lbs, and confirmed that it could safely operate under the maximum 300 lb load condition.

Table 6: Design requirements compared to performance metrics

	Design Requirement	Performance Metric
Overall Size	Must fit through a 36" doorway	Width = 32"
	Armpit support height = 32" above ground	Armpit support height = 32"
Weight	Desired weight < 35 lbs	Measured weight = 45.1 lbs
Stability	All wheels must have brakes	Used locking lever brakes
	Must support a 300 lb load	Tested Range: 100 lbs to 225 lbs

In order for the machine to be easily portable around a home, its total weight needed to be kept to a minimum. The weight of each component is listed in Table 7. Using this information, the total weight of the walker/crutch mechanism was found to be 45.1 lbs, which exceeds the design requirement of 35 lbs. It is critical to note, however, that the weight can be significantly cut down in future designs. For the first generation prototype, 1026 steel needed to be used for the walker frame since Aluminum 6061 was much more difficult to weld using a MIG welder. But, this manufacturing restraint can be overcome by purchasing a TIG welder to construct any and all future generation prototypes. If Aluminum 6061 is used to construct the machine instead of 1026 steel, it is expected that the envisioned final model will be under the 35 lb weight limit. Since Aluminum 6061 is one-third as dense as 1026 steel, it was reasoned that the frame, crutch, and lift-arm would all be one-third of their current weight. Therefore, the total weight of the mechanism using Aluminum 6061 (including the actuators, wheels, and lead-acid battery) would be roughly 31.1 lbs. Furthermore, it is envisioned that a lithium-ion battery can be used in place of the lead-acid battery. If a lithium-ion battery were to be used, then it would reduce the weight of the walker/crutch mechanism by an additional 6.0 lbs.

Table 7: Weight of each component in the final assembly

	Frame	Crutch ($\times 2$)	Lift Arm ($\times 4$)	Actuator ($\times 2$)	Wheel ($\times 4$)	Lead-Acid Battery
Measured Weight (lbs)	13.6	1.3	1.2	4.55	1.8	7.8

Another key performance metric to evaluate was the time it took to raise and lower a test subject completely. Using the Speed vs. Load data provided in Figure 14 of section IV. Detailed Design, the time to raise an average sized person of roughly 5′9" and 170 lbs was calculated. In this scenario, it was assumed that each actuator could lift half of the total weight (85 lbs). Under this assumption, the corresponding speed of each actuator was found to be 0.70 in/sec, which yielded a 14.3 second estimated lift time. The average tested time to stand was measured to be slightly longer than the calculated value at roughly 15.0 seconds. In addition to this, the average measured time to sit was 9.5 seconds, which was lower than the estimated value.

It was also important to calculate the expected total cost of the machine so that it could be compared to the other available options on the market. It was a goal to construct a machine that could be readily purchased by patients that take home an average yearly income, or that rely on retirement funds to live. Table 8 provides a cost breakdown for the components. It can be seen that the overall cost of the walker/crutch mechanism is roughly $650.00 without factoring in manufacturing and production costs. All other comparable lift-machines on the current market are priced anywhere from $2,200 to $6,400 [8]. Thus, it was determined that this machine is a much more affordable option for the average person.

Table 8: Cost of relevant materials and parts for the walker/crutch mechanism

Relevant Material/Part	Amount	Cost per Single Item
Linear Actuator	2	$ 128.99
1026 Steel Tubing	-	$ 78.84
Control Box	1	$ 189.99
Mounting Bracket	2	$ 8.50
Stem Caster	4	$ 5.70
Battery Box	-	$ 7.97
Industrial Strength Velcro	-	$ 9.47
Lead-Acid Battery	1	$ 20.00
Hardware (Assortment)	-	$ 32.60
Crutch Accessories Kit	1	$ 14.49
		Total = $ 651.14

* Please see Appendix 2 for a more exhaustive breakdown of the cost

b. Results of Human Testing

Using Appendix 8: Prototype Evaluation Form, a number of test subjects were asked to provide feedback after using the machine on the functionality of the walker/crutch mechanism. For each test, an expert explained how to handle the unit properly so as to ensure that each test subject fully understood the operating process. The height, weight, and age of each test subject was then recorded to acquire data for a census as well as to confirm that they were within the functional capacity of the machine. Once these steps were thoroughly completed, each subject was asked to perform a few basic tasks required for everyday living, which included using the mechanism to stand up, sit down, and walk around.

To begin the testing procedure, the test subjects situated themselves in a chair with the walker/crutch mechanism off to their side. They were then asked to grab onto the machine and wheel it in front of them. Once the machine was in this position, the test subjects gripped the handles and leaned onto the crutches so that their armpits rested on the crutch pads. To ensure that their center of gravity would remain in the correct location throughout the lifting process, the subjects moved their heels so that they were in line with the handles. After the participants were situated in the machine, they pressed the up button on the remote control. This initiated the linear actuators located on either side of the walker/crutch linkages, thereby securely raising the participants into the fully standing position. Then, the test subjects pushed the machine out from under their body so that they were no longer engaged to the crutches, grabbed onto the crossbars for stability, and lowered the walker/crutch linkages.

Once the linkages were fully lowered, the test subjects grabbed onto the armpit support bars (which also served as handles) and walked around the room. This allowed the participants to experience the full range of the walker/crutch mechanism. When the participants were done walking around the room, they aligned themselves back up with the chair to sit down. Before each test subject sat back down in the chair, they were instructed to touch their calves to the front edge of the chair so that they would be as close as possible. Then, the test subjects re-extended the linear actuators using the controller until the crutches were at the right height. At this step, the participants rolled the walker/crutch mechanism back under their armpits, and slightly leaned onto the machine. Once they were secure, they pressed the down button on the remote control and were lowered back into the chair.

After performing all of these tasks, the test subjects were requested to fill out a prototype evaluation form, the results of which can be observed in Figure 25:

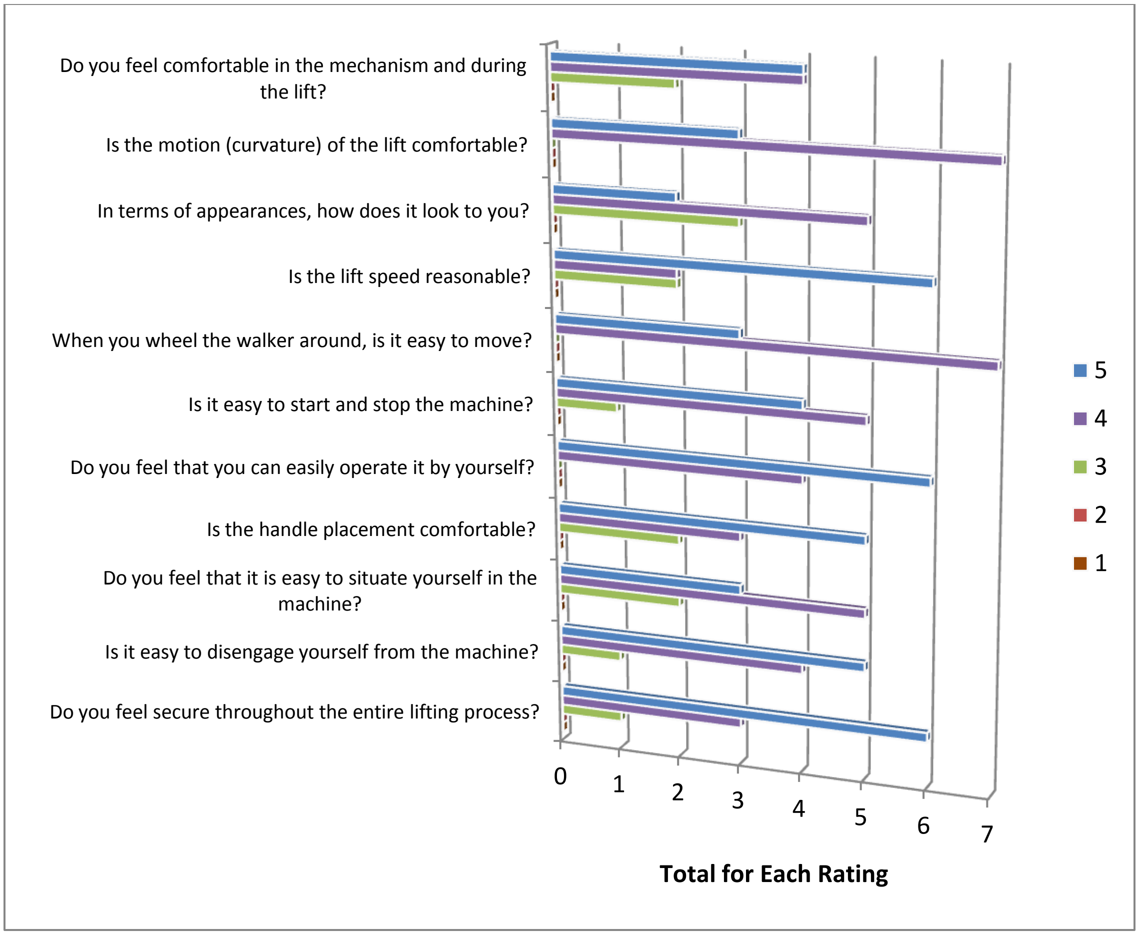

Figure 25: Bar graph displaying the ratings acquired from the evaluation questions.

In Figure 25, the questions are listed in order as they appear on the prototype evaluation form (see Appendix 8). For each question, the test subjects were asked to choose the rating that most closely coincided with their experience for that aspect of the testing process. On the rating scale, 1 signified a bad experience, and 5 signified the best experience. It is also important to grasp the overall significance of the various types of questions asked on the evaluation form. In general, the prompted questions covered a wide spectrum of topics related to the sitting, standing, and walking operations of the testing procedure. The questions addressed to the test subjects pertained to the arcing motion of the crutches, its ease of use, and its overall comfort to obtain useful feedback for future use. The prototype evaluation form also prompted test subjects to answer questions pertaining to the major needs that were outlined in section II. Design Requirements in order to see if they were successfully met. The acquired data suggests that the prototype performed well. Any suggestions and/or comments provided by the test subjects were organized into ideas to be implemented into future prototypes, which can be referenced in section VII. Conclusions and Recommendations.

In addition to acquiring feedback and comments from the test subjects about their overall experience, their height, weight, and age were also recorded in order to construct a census on the various demographics that participated in the testing process. In order to thoroughly analyze the responses gathered from the test subjects, it was essential to analyze the responses acquired from each demographic to establish the full functionality of the walker/crutch mechanism for each age subdivision. Since the prototype offered minimal adjustability features, it was expected that various demographics would respond differently to the prototype. These responses provided a superior amount of feedback on the walker/crutch mechanism, which helped to organize ideas for a second generation prototype. Figure 26 displays the total number of males and females that participated in the testing process for each age subdivision. For the purposes of this experiment, an effort was made to keep the number of males to females as close as possible.

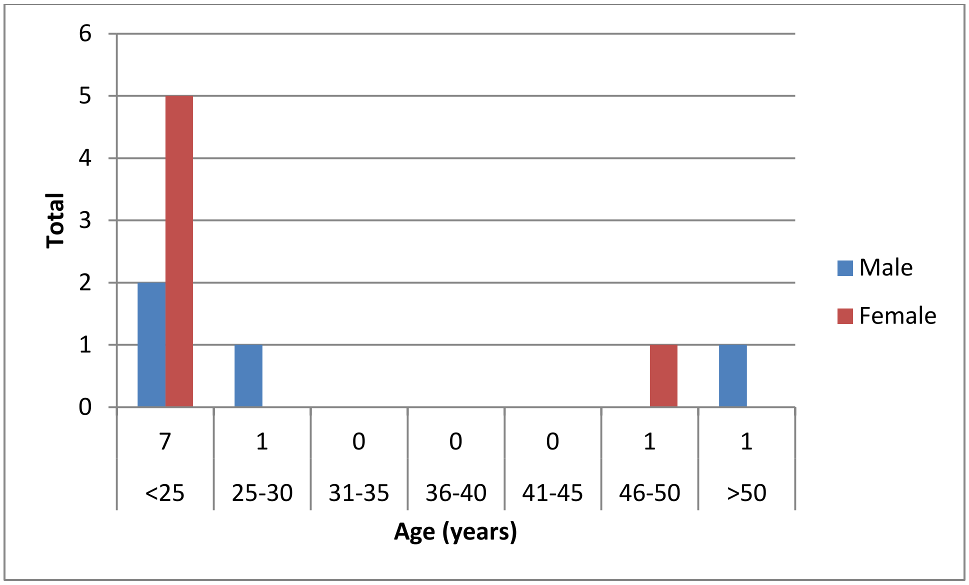

Figure 26: Bar graph displaying the total number of males and females for each age subdivision

As shown in Figure 26, most of the test subjects that participated were a part of the *under* 25 *years of age* subdivision. Although the main subdivision for the walker/crutch mechanism is the elderly population, people recovering and/or suffering from serious injuries at any age can use the machine. In addition, people whose weight and height varied were asked to participate in the prototype testing. Table 9 displays the weight and height of each test subject. It can be observed that the test subjects were all under the 300 lb weight limit of the walker/crutch mechanism, ensuring a safe experience.

Table 9: Weights, heights, and gender of each test subject

Test Subject	1	2	3	4	5	6	7	8	9	10
Gender	F	M	F	M	F	F	M	M	F	F
Height	5′5"	6′2"	5′0"	5′6"	5′2"	5′3"	5′11"	5′8"	5′6"	6′0"
Weight (lbs)	100	188	154	215	135	165	195	225	145	155

VII. CONCLUSIONS AND RECOMMENDATIONS

In general, the first generation prototype of the walker/crutch mechanism functioned as expected in that it met the established design requirements (excluding its total weight). During the testing process, the machine successfully raised/lowered a diverse range of test subjects that were listed as weighing 100 lbs to 225 lbs. From the census data shown in Table 9 of section VI. Prototype Results, it was concluded that the walker/crutch mechanism was able to operate within the desired 300 lb maximum load capacity. In that sense, the prototype was considered a great success. On the other hand, it was also recognized that improvements could be made to improve the functionality and safety features of the machine.

As test subjects were operating the prototype, some features were identified as being too awkward to use or were simply lacking altogether. As a result, a list of supplementary features was created for use in future models. Table 10 displays these suggestions and reasons for their implementation in a second stage prototype. These additional features will eliminate any issues remaining from the original design.

Table 10: A list of recommendations for future prototypes to eliminate design concerns

#	Recommendation	Reason for Implementation
1	Telescoping tubing	Gives adjustability options for lift-arms (i.e. radius of curvature), width, and height of the walker frame
2	Low battery LED	Indicates when the battery is low and needs to be charged
3	Use Aluminum 6061	The total weight will be reduced by about 14.0 lbs
4	Rubber wheels	Reduces the bumpiness on rougher terrain and improves grip on slicker surfaces
5	Add hand brake	Will lock the four swivel wheels easily while using the machine
6	More cushioning	Will reduce discomfort while being raised/lowered
7	Pad the crossbars	Provides a fairly soft surface to hold onto while lowering and/or raising the linkages into position
8	Round corners	Eliminates sharp corners and will make the machine feel smaller
9	Reduce the size of the battery box	A thinner design will provide more leg room for a user and will decrease the length of the frame
10	Mount wireless remote	Eliminates the awkwardness of the remote control and will allow a user to operate the machine with their index/middle finger

From Table 10, it can be seen that the recommendations largely focused on increasing comfort, safety, and overall ease of use. Although the first generation prototype was a success, it lacked the aforementioned features, which will greatly improve the function of the walker/crutch mechanism. However, even with its shortcomings, it is important to note that the original design allowed for feedback to be collected on the natural arcing motion. From Figure 7 of section IV. Detailed Design, it was found that the natural arcing motion replicated by the four-bar linkages was, in fact, comfortable, and allowed for smooth operation. Therefore, it can be stated that the information gathered from the testing process was critical, and it validated the use of the natural arcing motion to raise and/or lower a patient.

In general, the walker/crutch mechanism was designed for in-home use so that resilient elderly and injured people did not have to compensate for their lack of mobility.

Overall, it was determined that the machine functioned well, but could benefit greatly from additional features. By adding these few features, comfort, safety, and ease of use would significantly increase. In addition, a number of other applications were also identified for the machine, including it being used in nursing homes as well as in hospitals.

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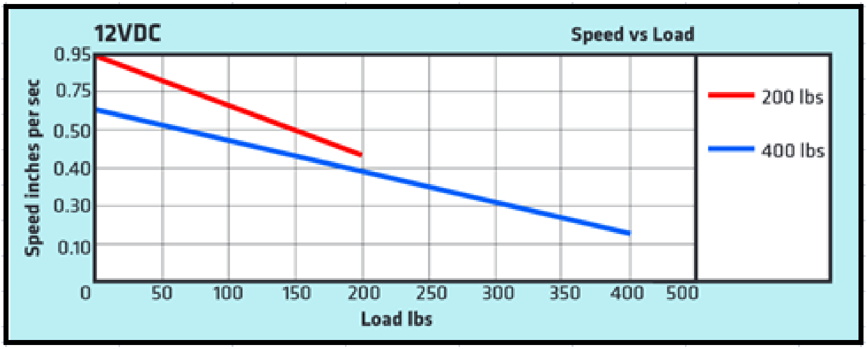
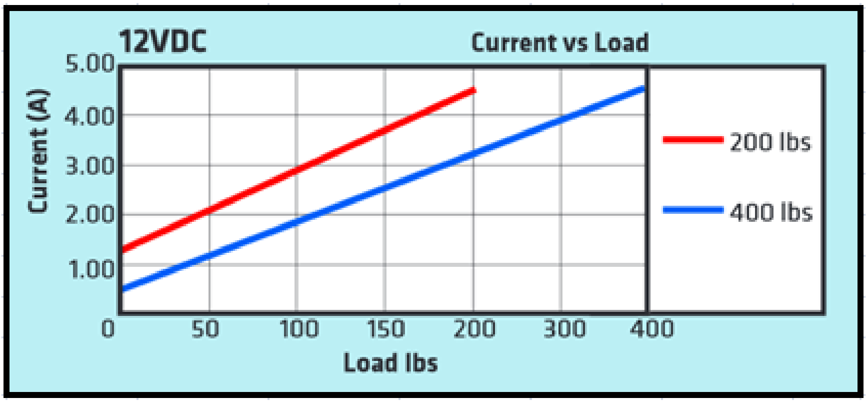
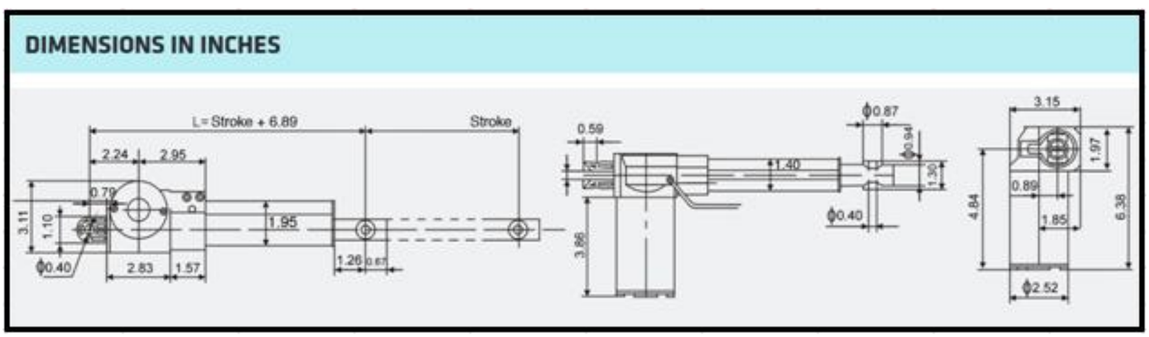
APPENDIX 1: ACTUATOR SPECIFICATIONS [12]



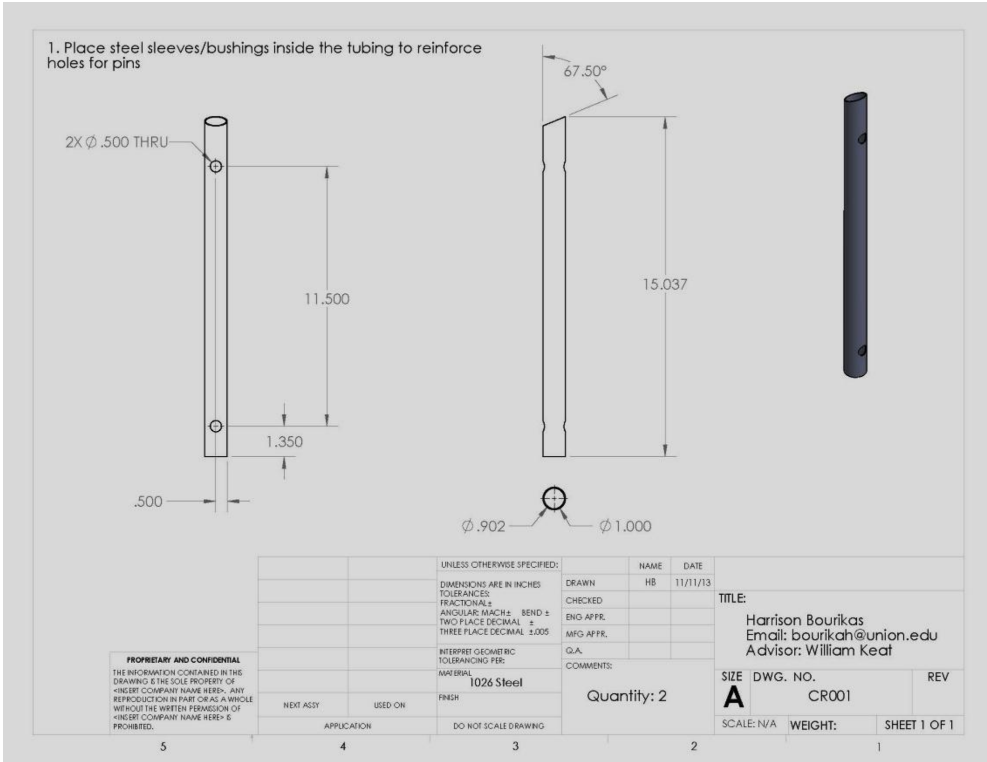


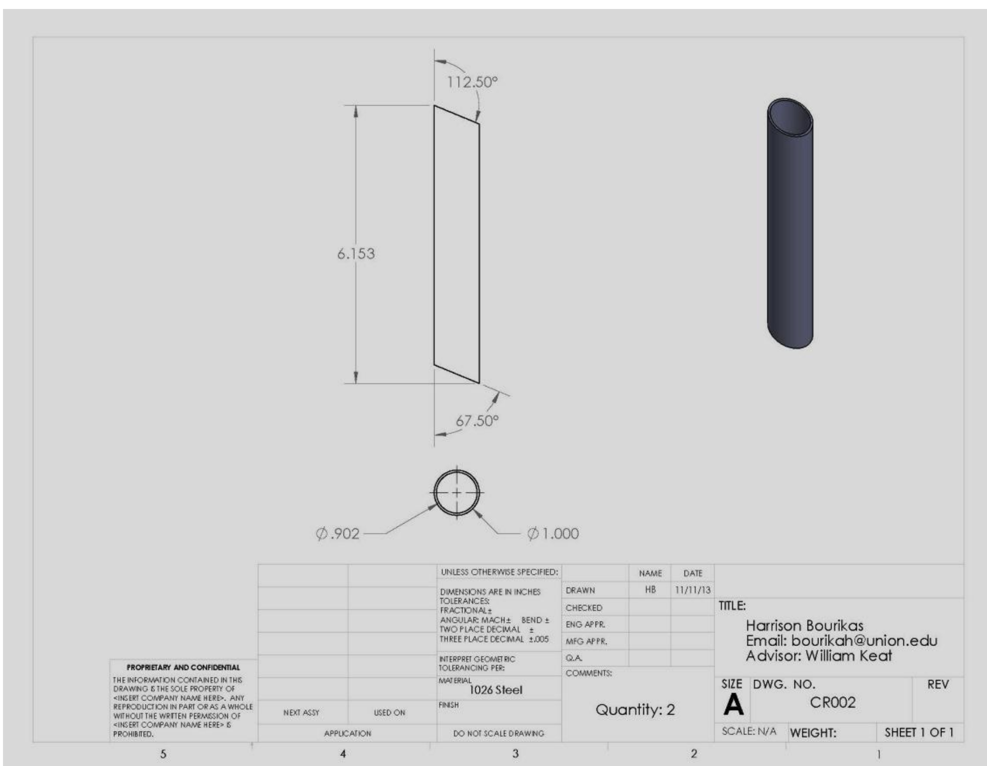


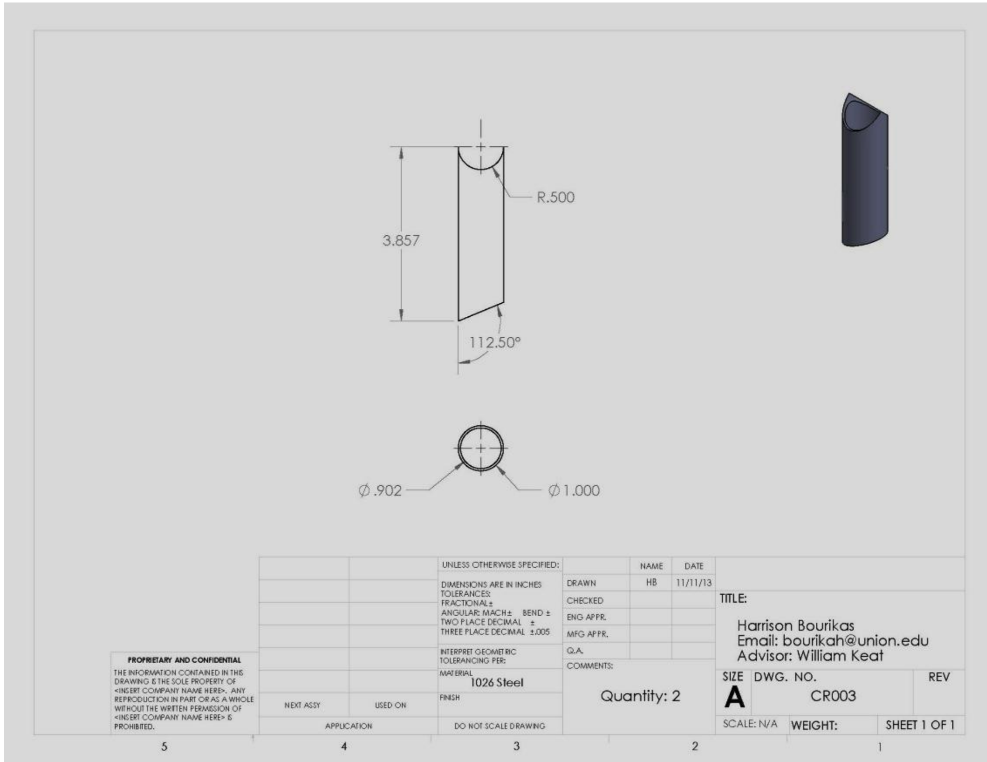
APPENDIX 2: VENDOR LIST AND COMPREHENSIVE BILL OF MATERIALS

Material/Part	Outer Dimension (in.)	Wall Thickness (in.)	Size	Exact Amount	Purchase Amount	Price ($)	Vendor
1018 Steel Sheet Metal	-	-	0.125 in. thick	69.5 in^2	8 in. × 12 in.	45.96	McMaster-Carr
1018 Steel Rod	1	-	-	4 in.	1 ft.	10.69	McMaster-Carr
1026 Steel Tubing - Circular	1	0.049	-	365.1 in.	36 ft.	61.08	McMaster-Carr
1026 Steel Tubing - Square	1	0.060	-	50 in.	6 ft.	17.76	McMaster-Carr
Hitch Pin Clip	-	-	5/64 × 1 - 5/16 in.	8	8 (4 pkg)	0.68 (pkg)	Lowe’s
Steel Clevis Pin	0.5	-	3 in. length	4	4	2.82 (each)	Lowe’s
Steel Clevis Pin	0.5	-	2 in. length	4	4	2.82 (each)	Lowe’s
Metric Bolt	-	-	6 × 20 mm	8	8 (4 pkg)	1.15 (pkg)	Lowe’s
Nylon Hex Lock Nut	-	-	6 mm	8	8 (2 pkg)	0.68 (pkg)	Lowe’s
Metric Flat Washer	-	-	6 mm (washer Ø)	12	20 (2 pkg)	0.68 (pkg)	Lowe’s
PA-02 Linear Actuator	-	-	10 in. stroke	2	2	128.99 (each)	Progressive Automations
PA-25 Control Box	-	-	-	1	1	189.99	Progressive Automations
BRK-02 Mounting Bracket	-	-	-	2	2	8.50 (each)	Progressive Automations
Battery Charger	-	-	-	-	-	-	-
Threaded Stem Caster	-	-	Wheel Ø = 3 in.	4	4	5.70 (each)	SES (eBay)
Snap-Top Battery Box	-	-	11 × 7.875 × 10.75	1	1	7.97	Walmart
12 V Lead-Acid Battery	-	-	-	-	-	-	-
Strong VELCRO	-	-	4 ft. × 2 in.	-	1 pkg	9.47	Home Depot
Stranded Wire	-	-	16 Gauge Wire	-	50 feet	13.47	Home Depot
Crutch Accessories Kit	-	-	-	-	1 kit	14.49	Walgreens

APPENDIX 3: DRAWINGS – CRUTCHES



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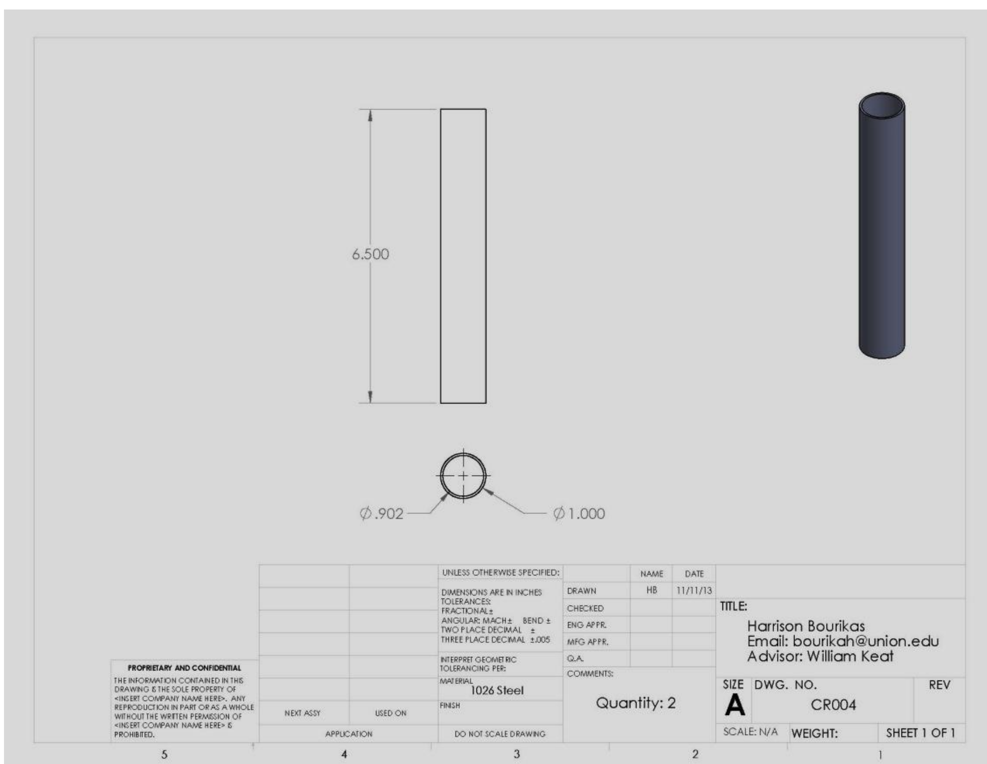
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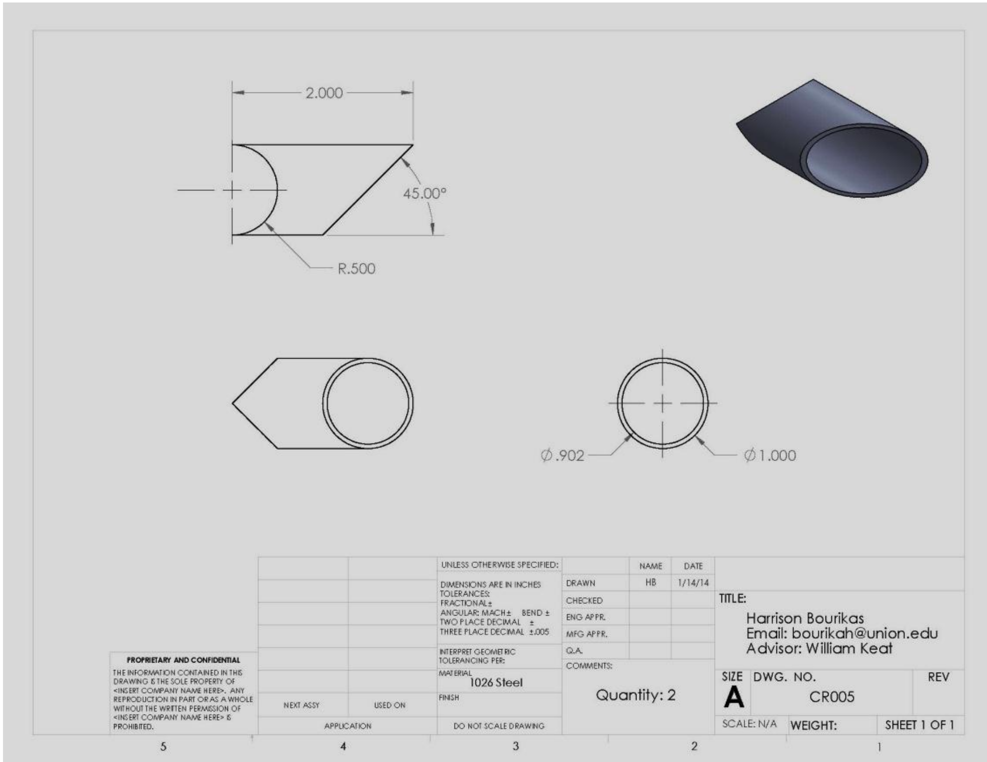
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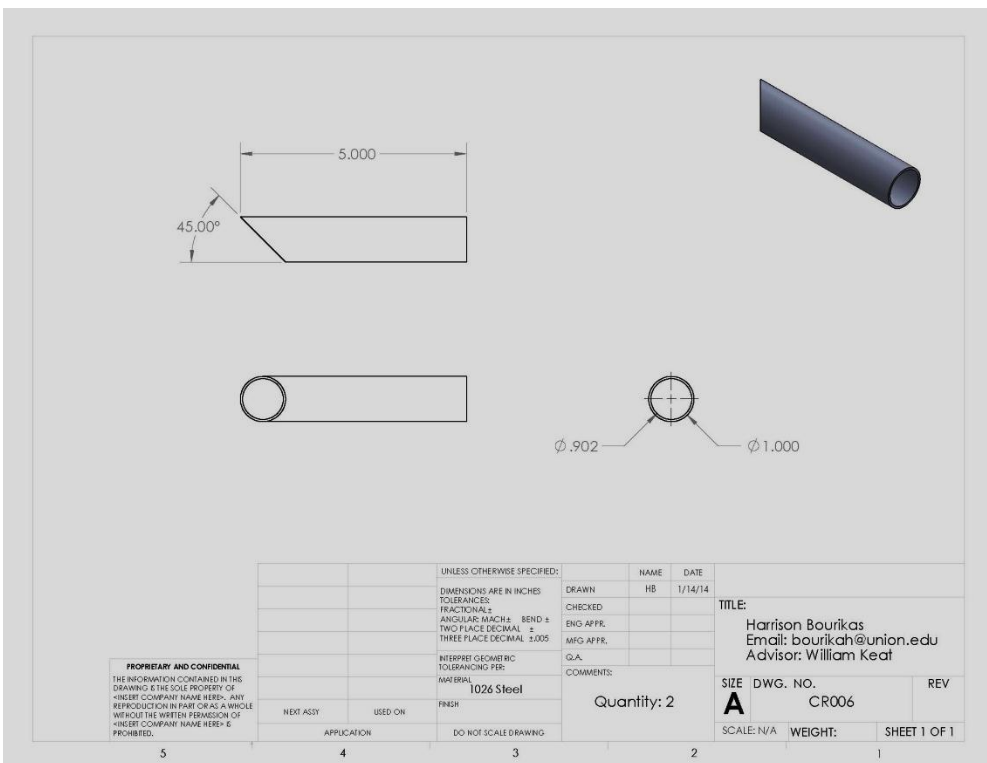
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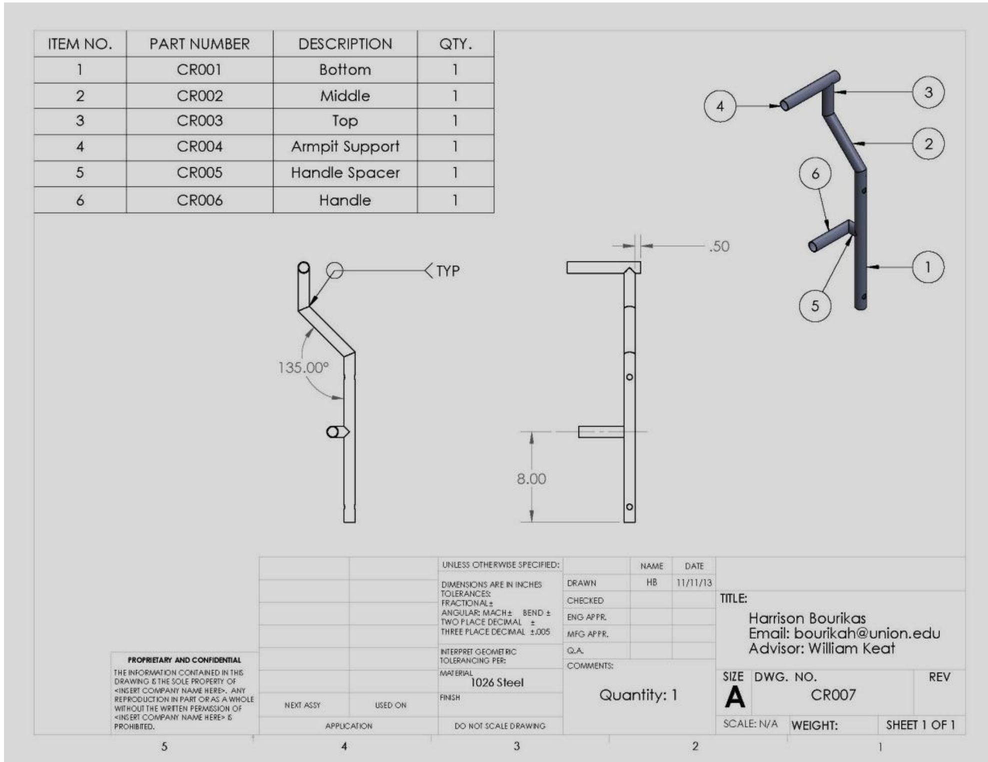

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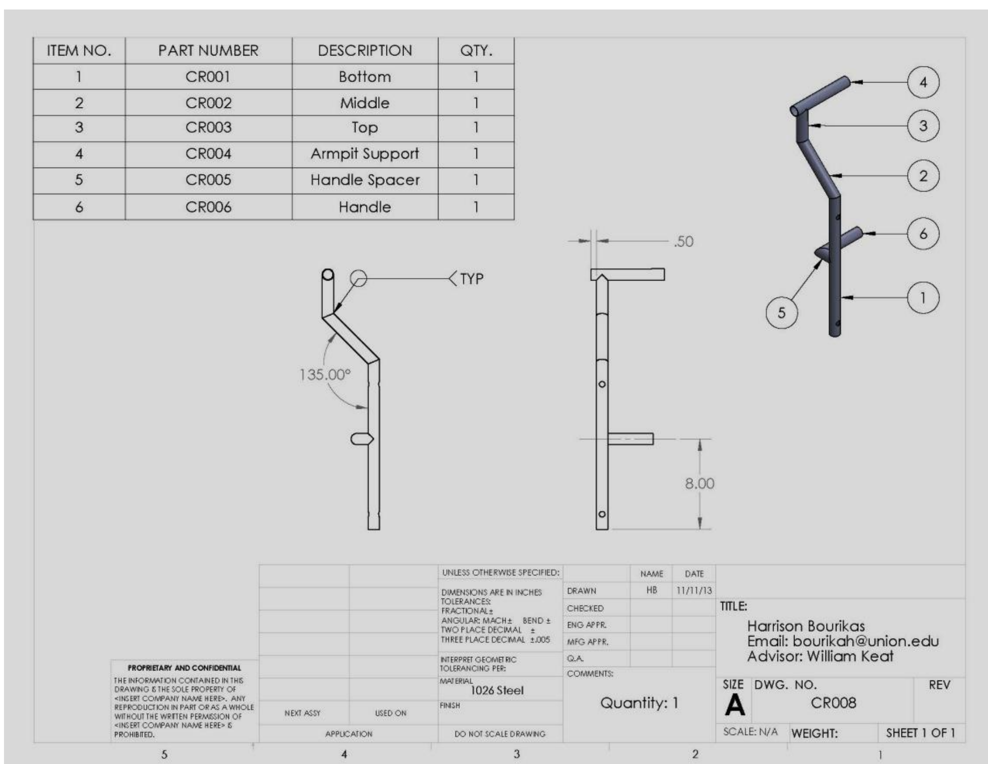

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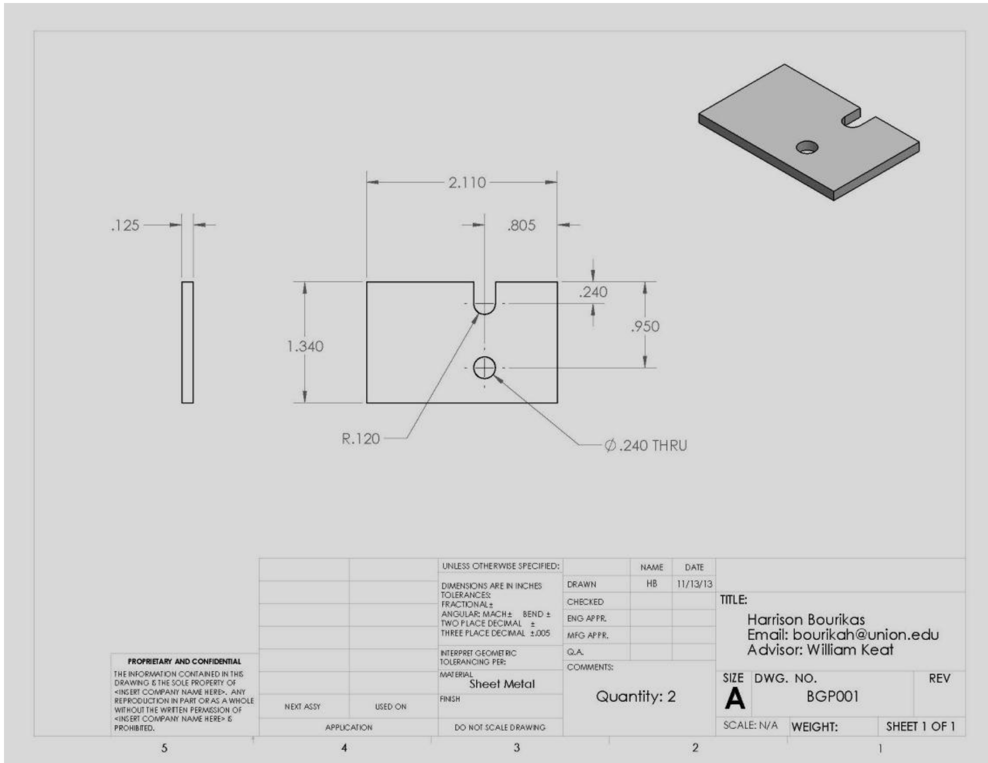
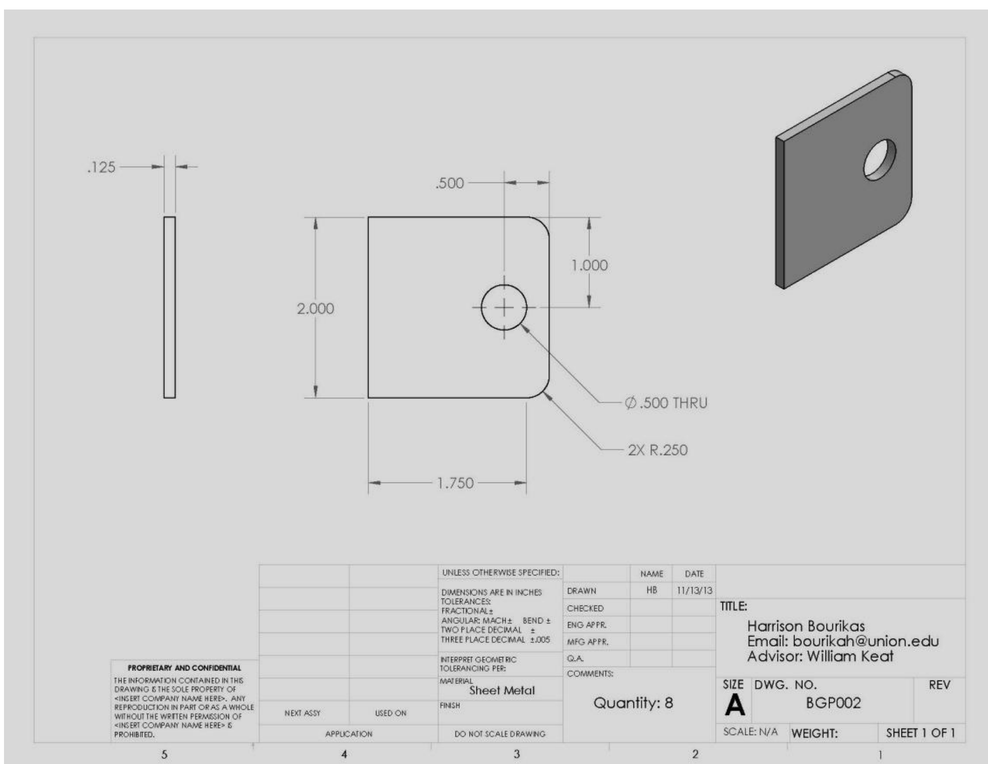
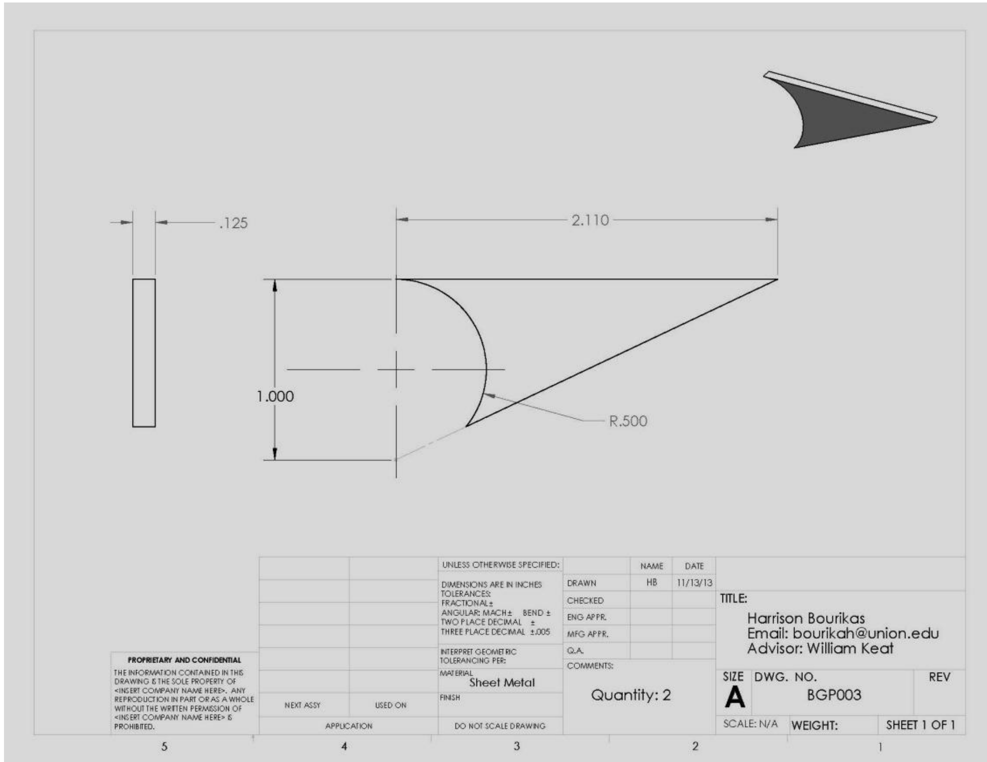
APPENDIX 4: DRAWINGS – BRACKETS, GUSSETS, PLATES



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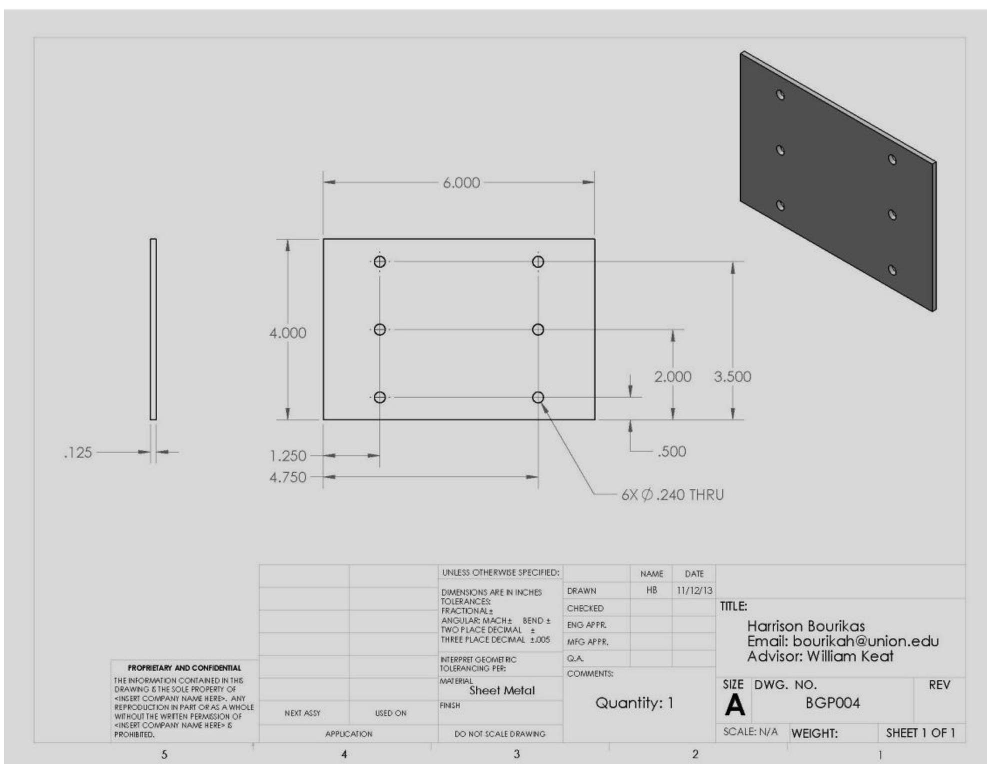
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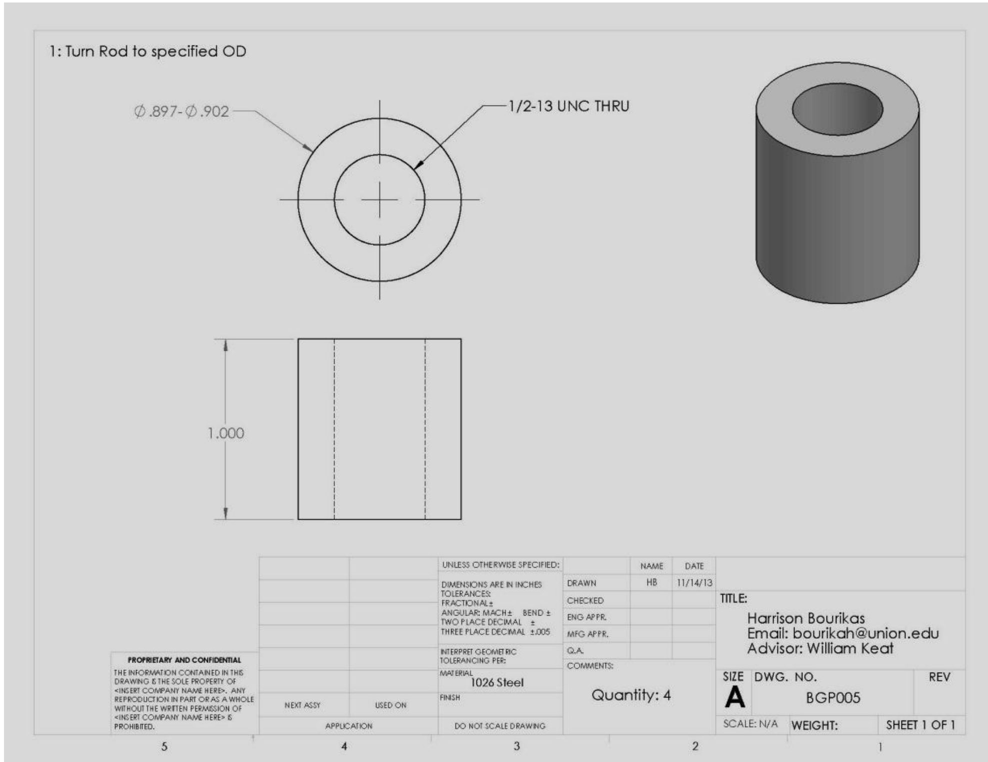
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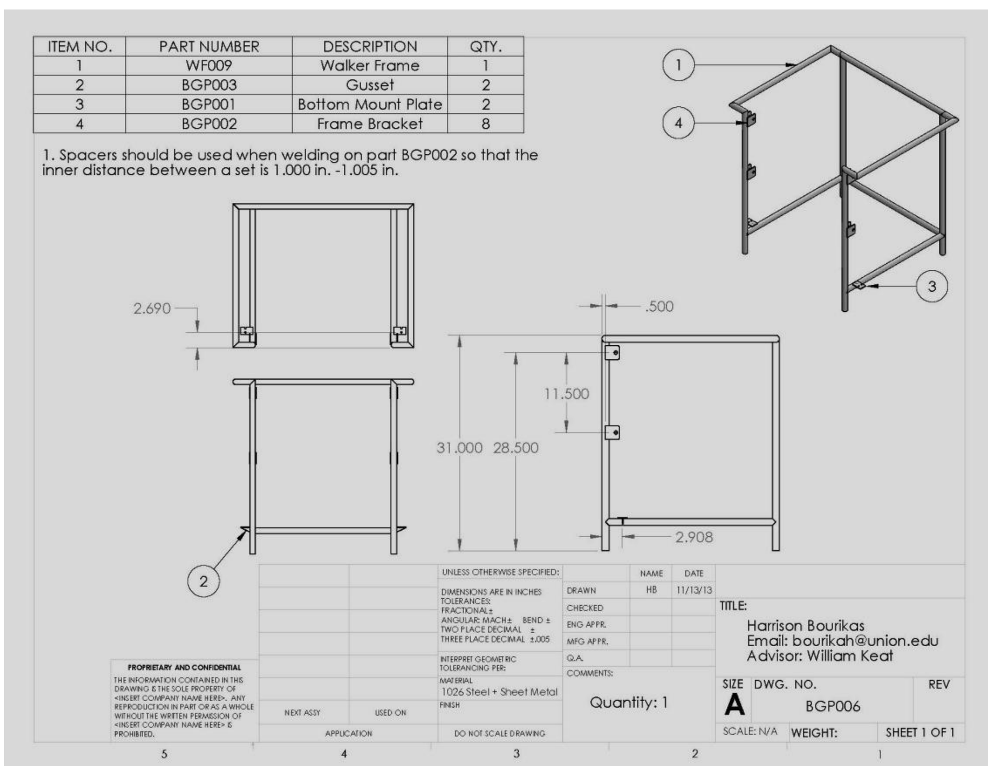
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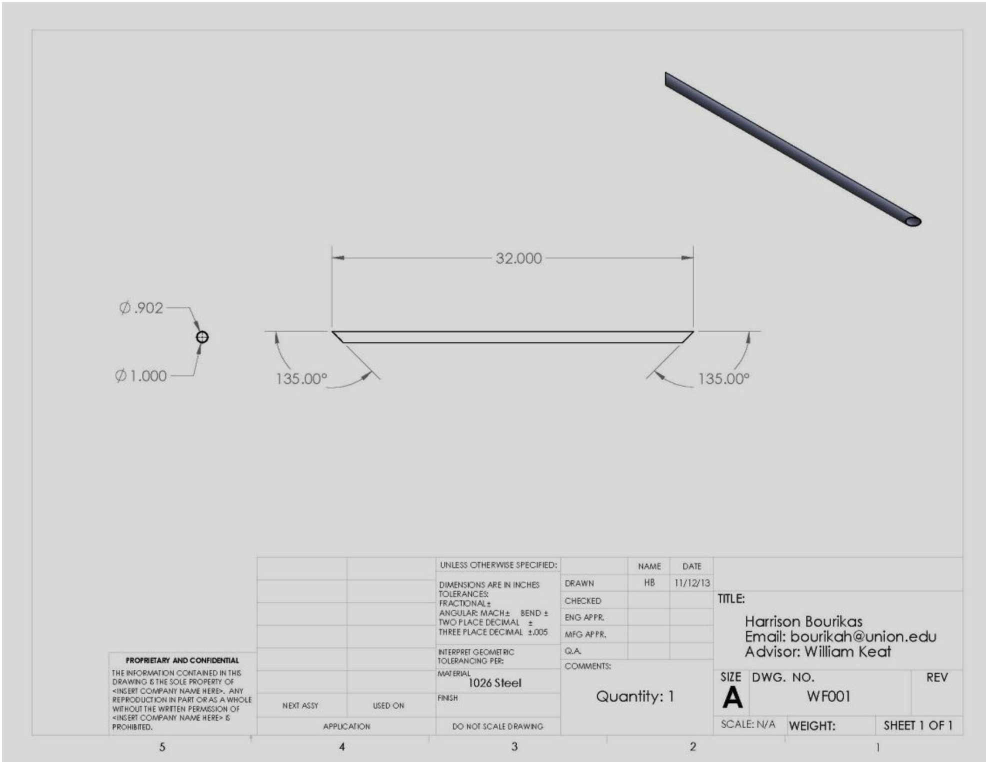
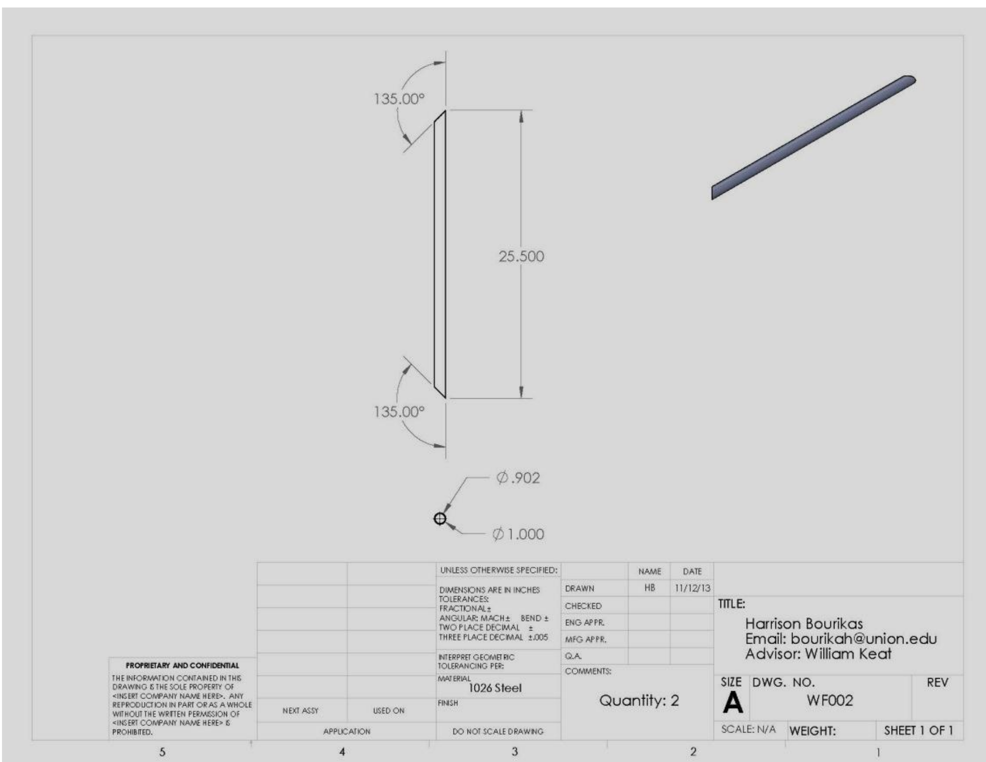
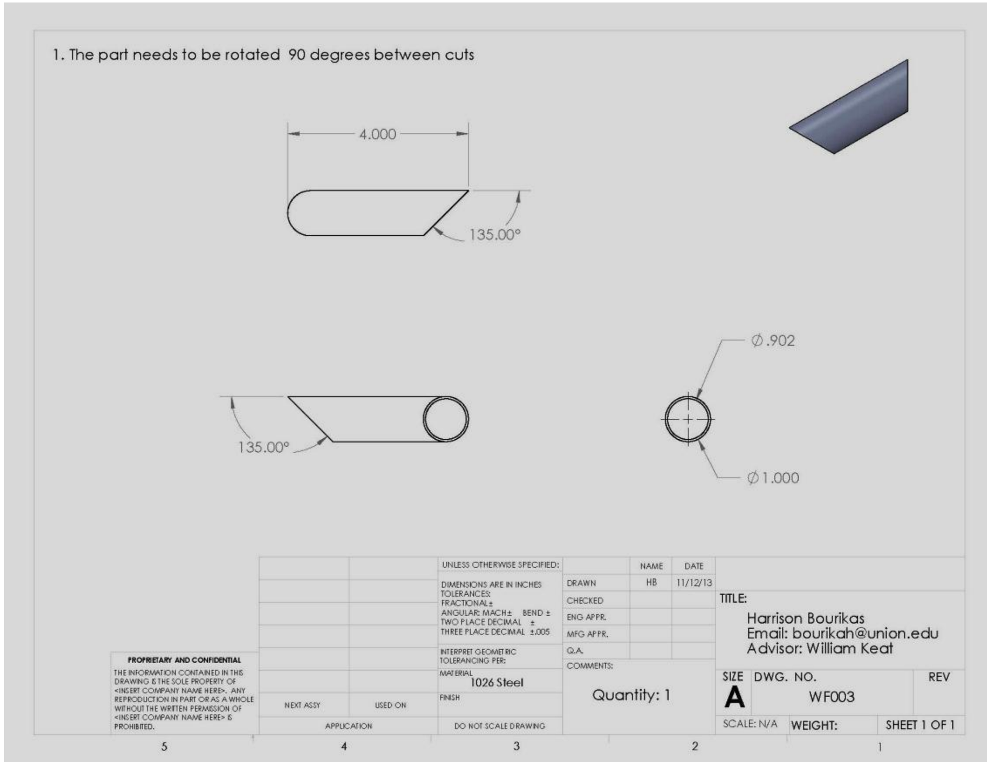
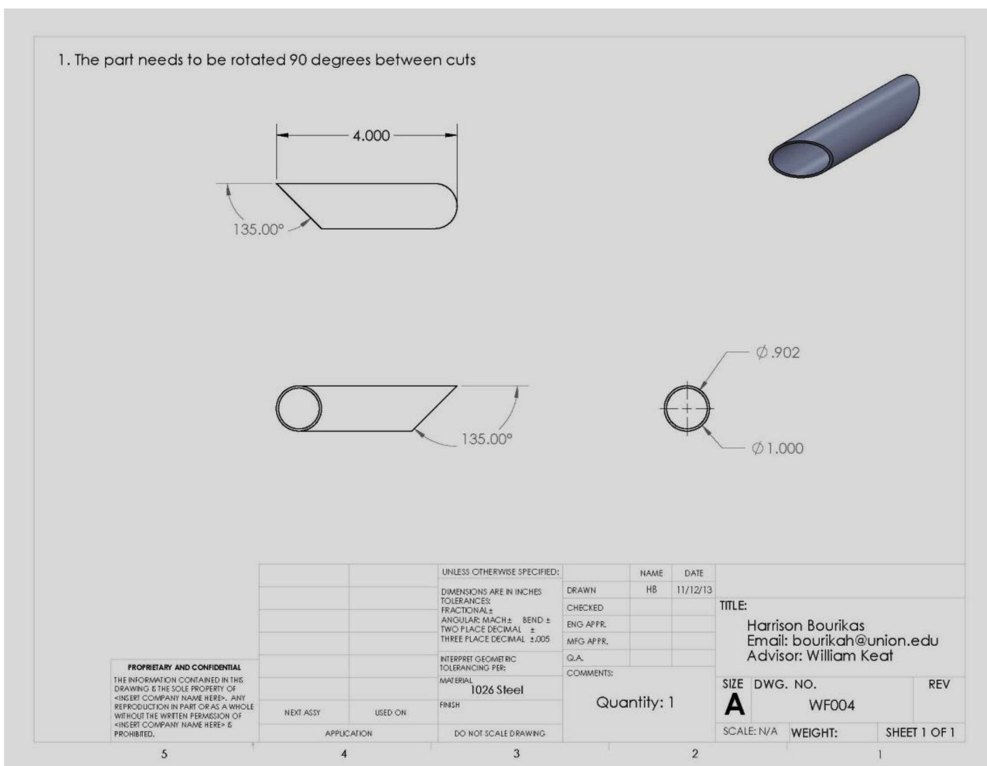
3 BGP001 Bottom Mount Plate 2
4 BGP002 Frame Bracket 8
1. Spacers should be used when welding on part BGP002 so that the inner distance between a set is 1.000 in. -1.005 in.
2.690
.500
11.500
31.000
28.500
2.908
UNLESS OTHERWISE SPECIFIED:
NAME
DATE
DRAWN
HB
11/13/13
TITLE:
Harrison Bourikas
Email: bourikah@union.edu
Advisor: William Keat
MATERIAL
1026 Steel + Sheet Metal
Quantity: 1
SIZE
DWG. NO.
REV
A
BGP006
SCALE: N/A
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL

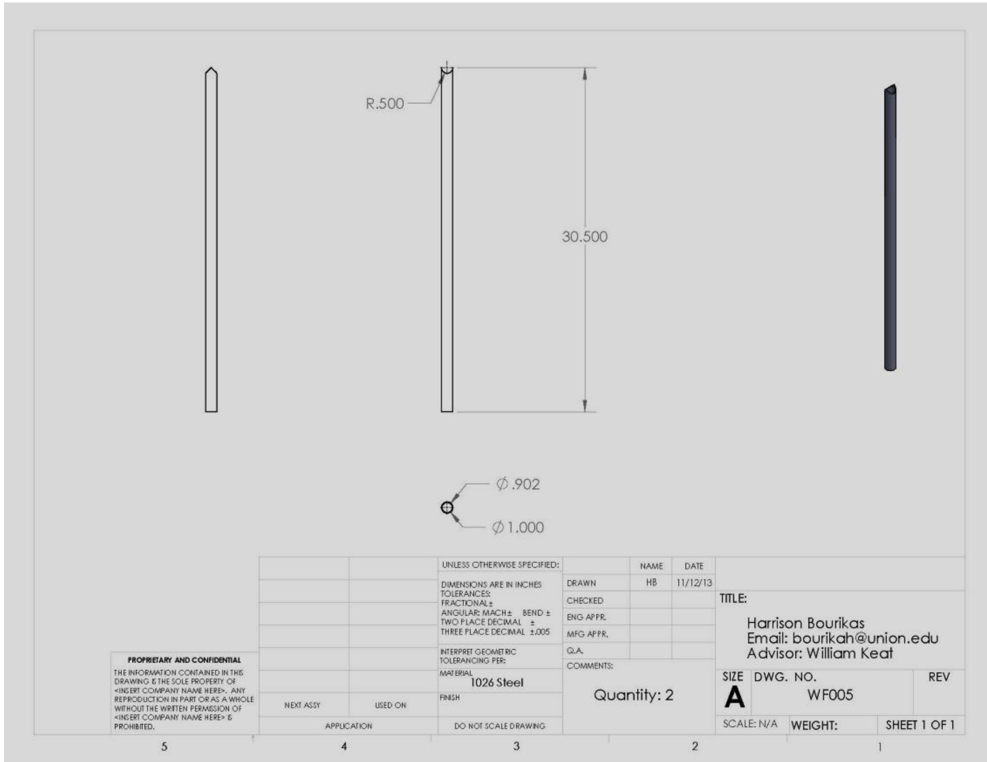
APPENDIX 5: DRAWINGS – WALKER FRAME

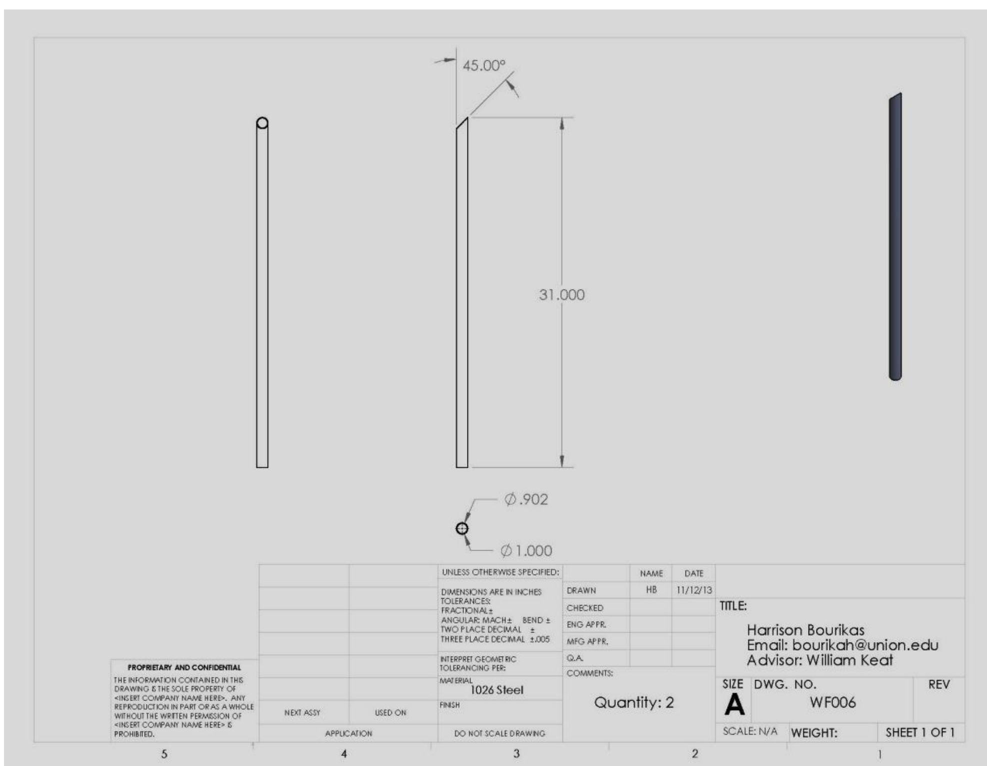


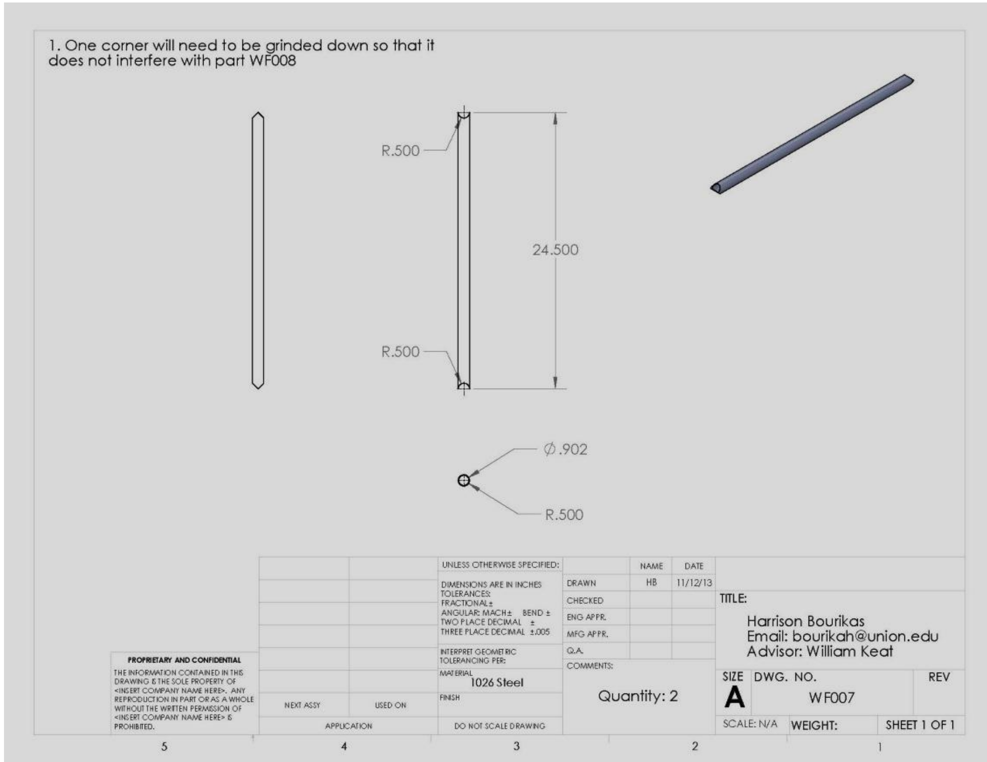


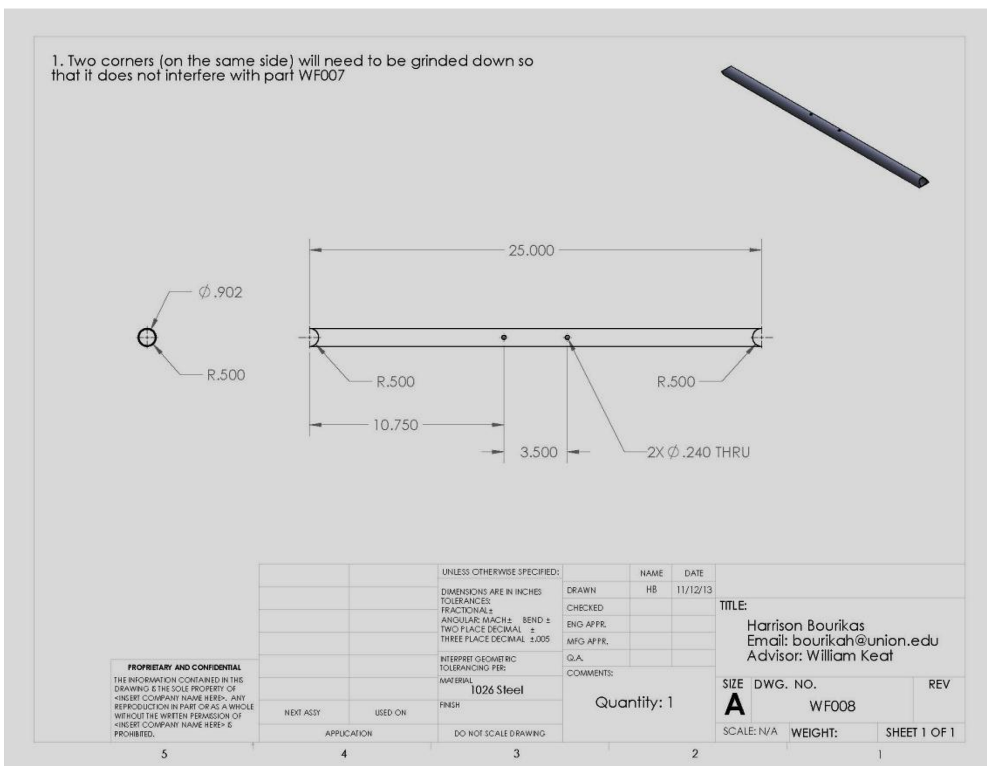

1. The part needs to be rotated 90 degrees between cuts
4.000
135.00°
135.00°
Ø.902
Ø1.000
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
NAME
DATE
DRAWN
HB
11/12/13
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
MATERIAL
1026 Steel
FINISH
Quantity: 1
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
TITLE:
Harrison Bourikas
Email: bourikah@union.edu
Advisor: William Keat
SIZE
DWG. NO.
REV
A
WF003
SCALE: N/A
WEIGHT:
SHEET 1 OF 1

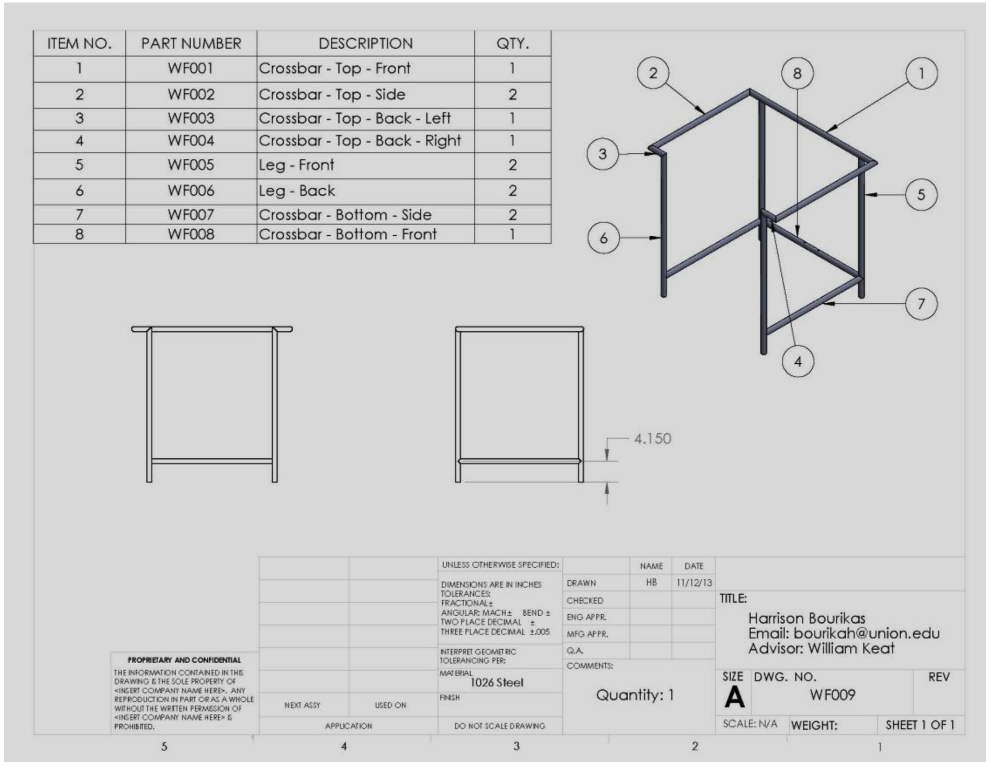

1. The part needs to be rotated 90 degrees between cuts
4.000
135.00°
135.00°
Ø.902
Ø1.000
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
NAME
DATE
DRAWN
HB
11/12/13
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
MATERIAL
1026 Steel
FINISH
Quantity: 1
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
PROPRIETARY AND CONFIDENTIAL
TITLE:
Harrison Bourikas
Email: bourikah@union.edu
Advisor: William Keat
SIZE
DWG. NO.
REV
A
WF004
SCALE: N/A
WEIGHT:
SHEET 1 OF 1


R.500
30.500
∅.902
∅1.000
UNLESS OTHERWISE SPECIFIED:
NAME
DATE
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±.005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
1026 Steel
FINISH
DRAWN
HB
11/12/13
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Quantity: 2
TITLE:
Harrison Bourikas
Email: bourikah@union.edu
Advisor: William Keat
SIZE
A
DWG. NO.
WF005
REV
SCALE: N/A
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
5
4
3
2
1

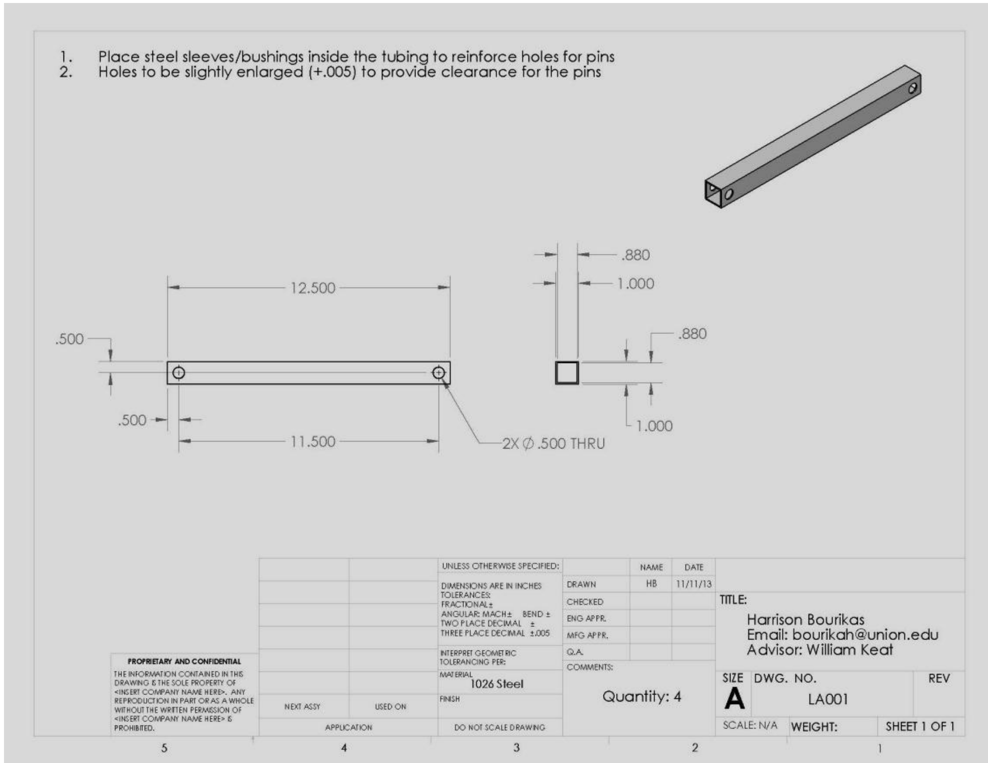

45.00°
31.000
∅.902
∅1.000
UNLESS OTHERWISE SPECIFIED:
NAME
DATE
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±.005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
1026 Steel
FINISH
DRAWN
HB
11/12/13
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
Quantity: 2
TITLE:
Harrison Bourikas
Email: bourikah@union.edu
Advisor: William Keat
SIZE
A
DWG. NO.
WF006
REV
SCALE: N/A
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
5
4
3
2
1

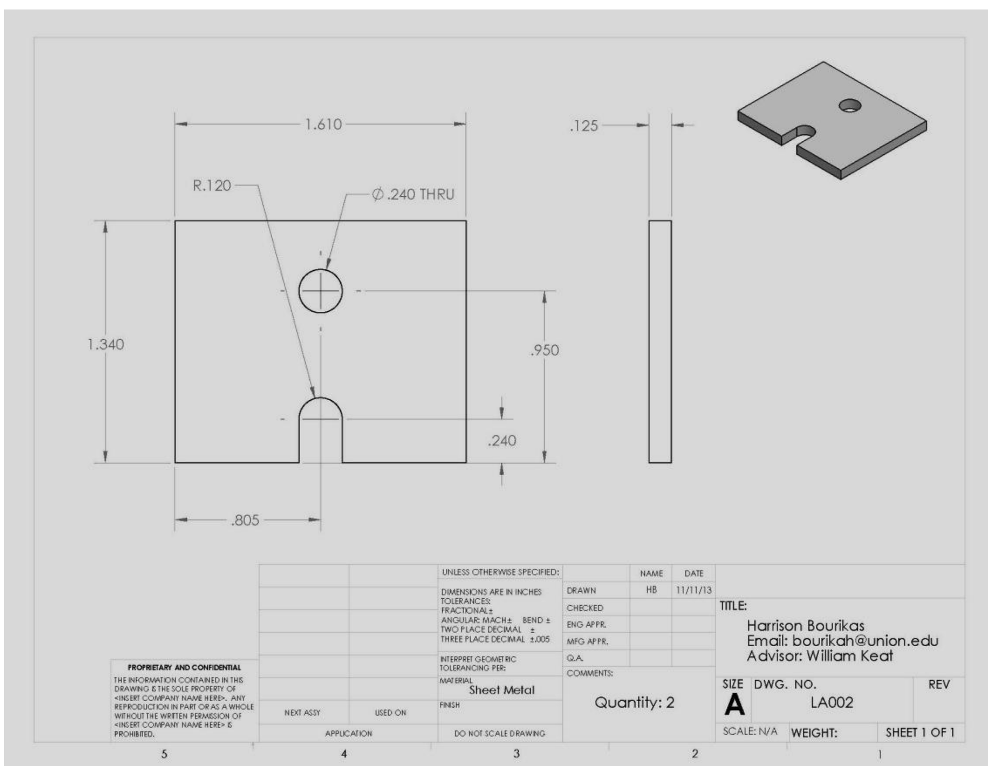

1. One corner will need to be grinded down so that it does not interfere with part WF008
R.500
24.500
R.500
Ø.902
R.500
UNLESS OTHERWISE SPECIFIED:
NAME
DATE
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±.005
DRAWN
HB
11/12/13
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
1026 Steel
FINISH
Quantity: 2
TITLE:
Harrison Bourikas
Email: bourikah@union.edu
Advisor: William Keat
SIZE
DWG. NO.
REV
A
WF007
SCALE: N/A
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
5
4
3
2
1

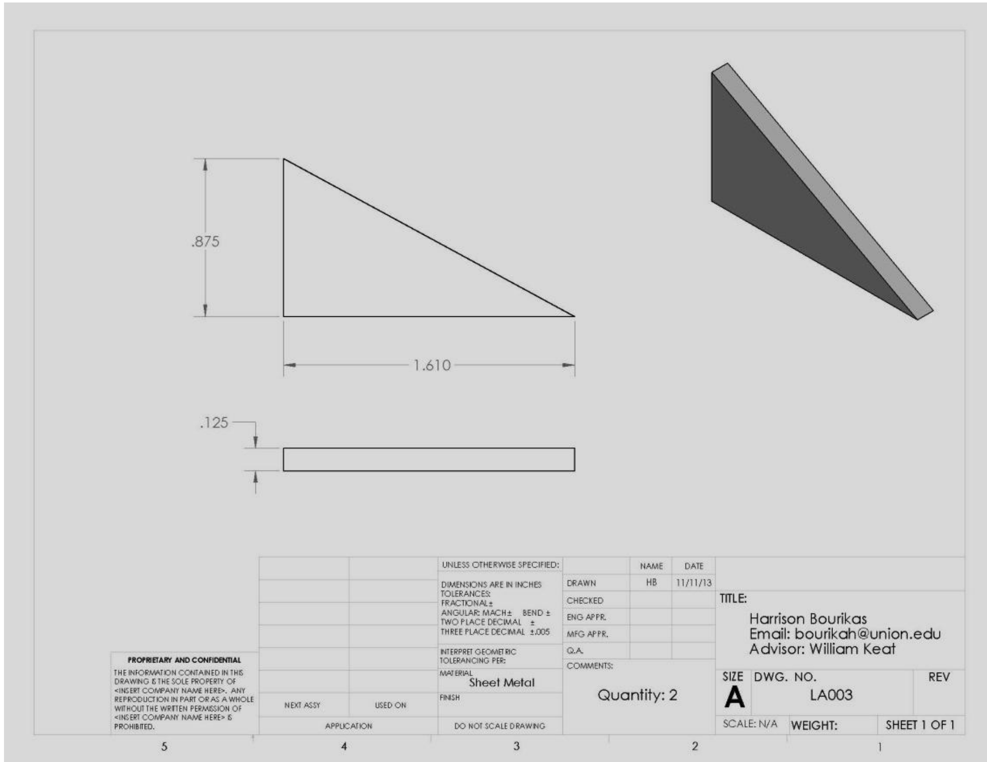

1. Two corners (on the same side) will need to be grinded down so that it does not interfere with part WF007
25.000
Ø.902
R.500
R.500
R.500
10.750
3.500
2X Ø.240 THRU
UNLESS OTHERWISE SPECIFIED:
NAME
DATE
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±.005
DRAWN
HB
11/12/13
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
1026 Steel
FINISH
Quantity: 1
TITLE:
Harrison Bourikas
Email: bourikah@union.edu
Advisor: William Keat
SIZE
DWG. NO.
REV
A
WF008
SCALE: N/A
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
5
4
3
2
1

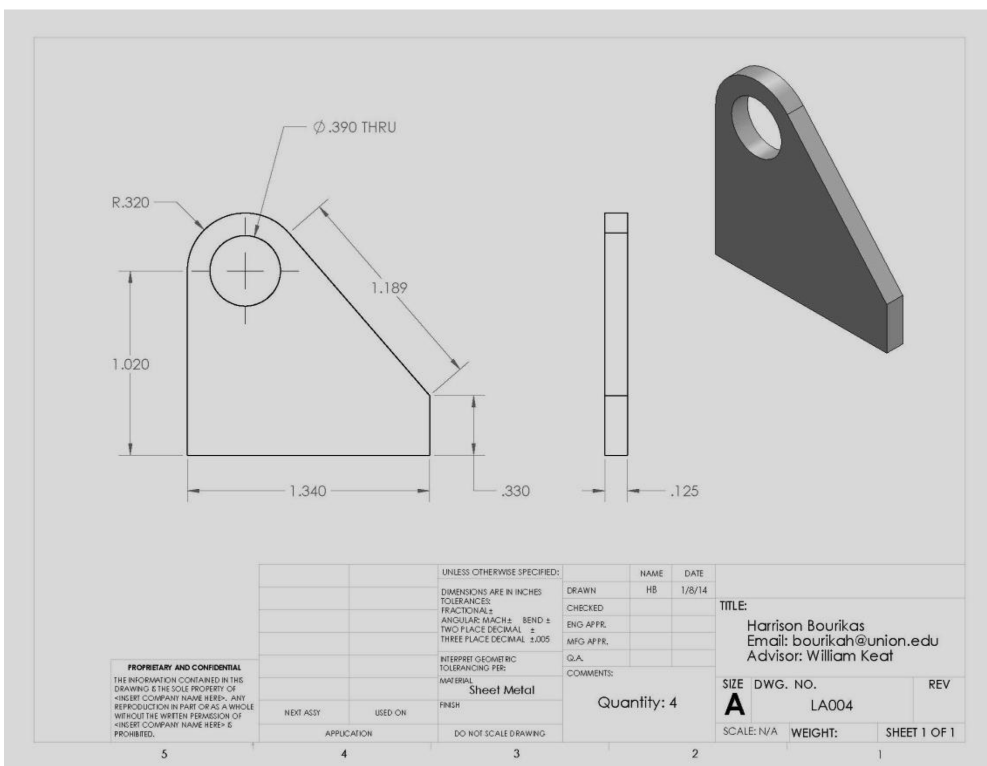

ITEM NO. PART NUMBER DESCRIPTION QTY.
1 WF001 Crossbar - Top - Front 1
2 WF002 Crossbar - Top - Side 2
3 WF003 Crossbar - Top - Back - Left 1
4 WF004 Crossbar - Top - Back - Right 1
5 WF005 Leg - Front 2
6 WF006 Leg - Back 2
7 WF007 Crossbar - Bottom - Side 2
8 WF008 Crossbar - Bottom - Front 1
4.150
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
NAME DATE
DRAWN HB 11/12/13
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
MATERIAL
1026 Steel
FINISH
Quantity: 1
TITLE:
Harrison Bourikas
Email: bourikah@union.edu
Advisor: William Keat
SIZE A
DWG. NO. WF009
REV
SCALE: N/A
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING

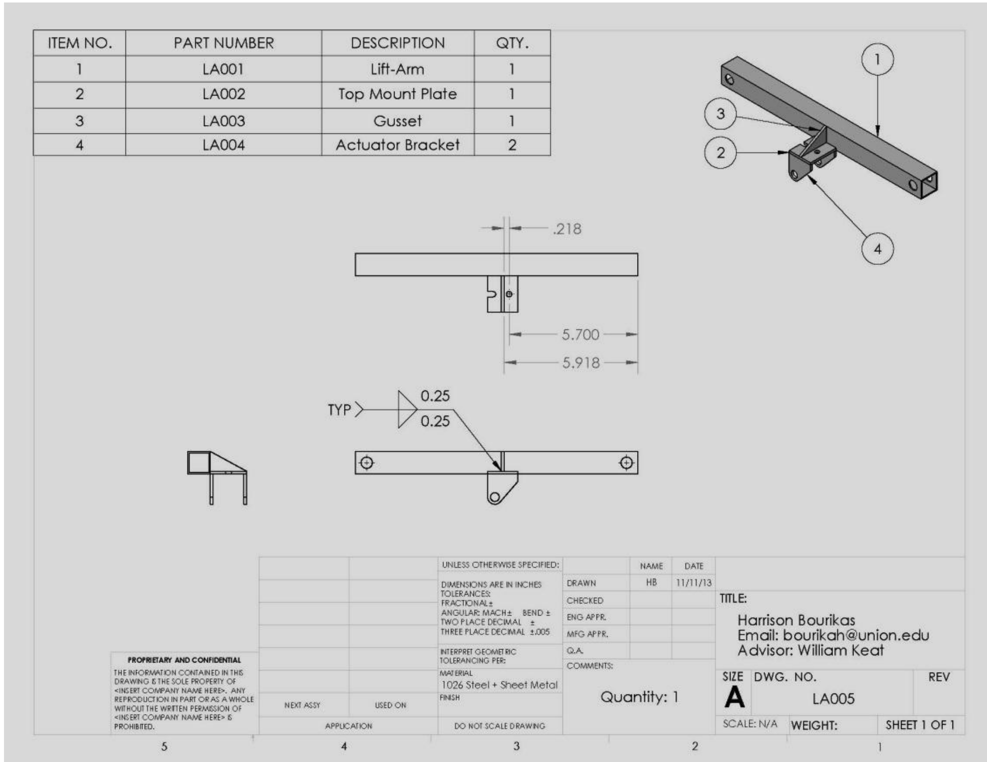
APPENDIX 6: DRAWINGS – LINKAGE



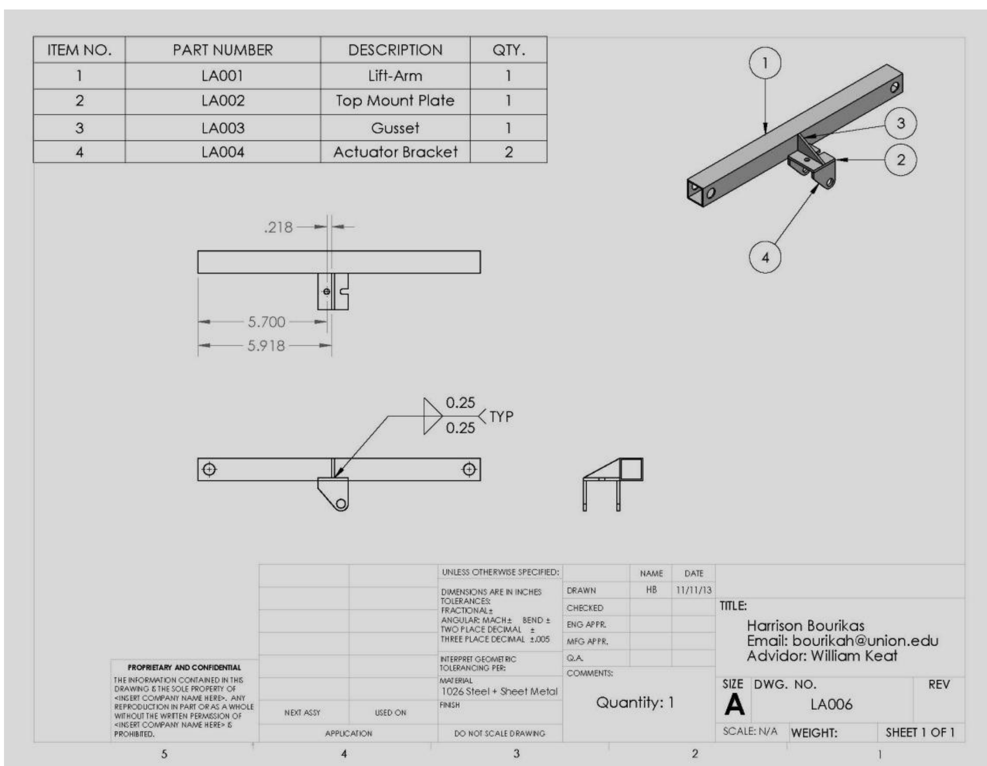



.875
1.610
.125
UNLESS OTHERWISE SPECIFIED:
NAME
DATE
DRAWN
HB
11/11/13
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
Harrison Bourikas
Email: bourikah@union.edu
Advisor: William Keat
PROPRIETARY AND CONFIDENTIAL
MATERIAL
Sheet Metal
FINISH
Quantity: 2
SIZE
A
DWG. NO.
LA003
REV
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
SCALE: N/A
WEIGHT:
SHEET 1 OF 1


∅.390 THRU
R.320
1.189
1.020
1.340
.330
.125
UNLESS OTHERWISE SPECIFIED:
NAME
DATE
DRAWN
HB
1/8/14
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
Harrison Bourikas
Email: bourikah@union.edu
Advisor: William Keat
PROPRIETARY AND CONFIDENTIAL
MATERIAL
Sheet Metal
FINISH
Quantity: 4
SIZE
A
DWG. NO.
LA004
REV
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
SCALE: N/A
WEIGHT:
SHEET 1 OF 1

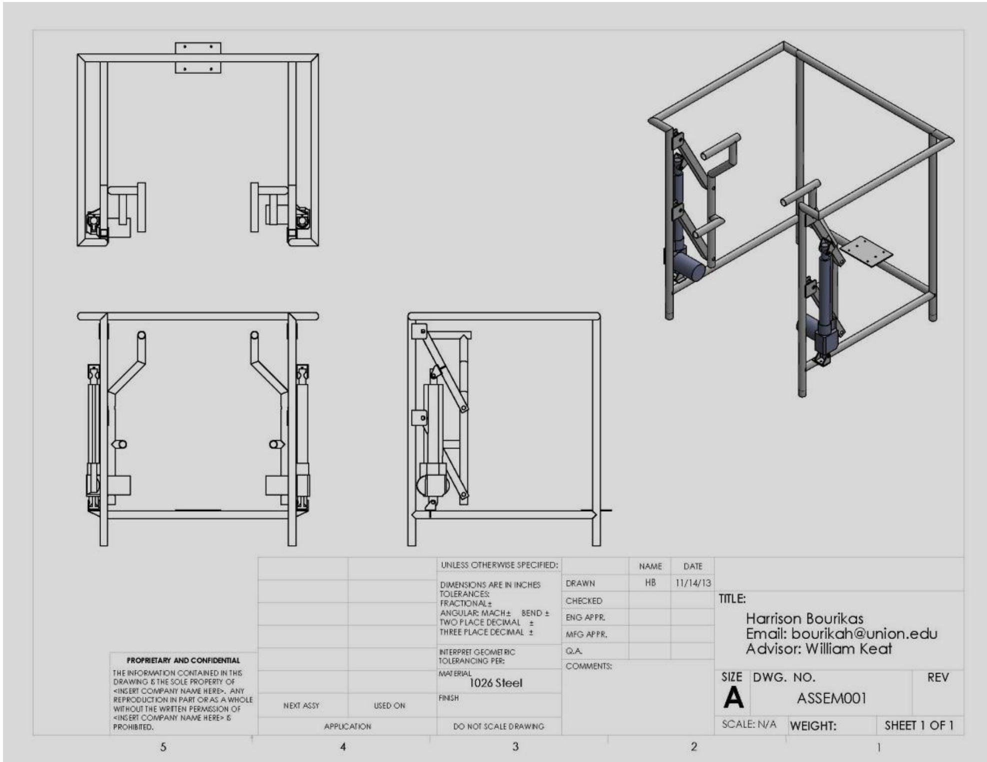


ITEM NO. | PART NUMBER | DESCRIPTION | QTY.
1 | LA001 | Lift-Arm | 1
2 | LA002 | Top Mount Plate | 1
3 | LA003 | Gusset | 1
4 | LA004 | Actuator Bracket | 2
.218
5.700
5.918
TYP
0.25
0.25
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
MATERIAL
1026 Steel + Sheet Metal
DO NOT SCALE DRAWING
PROPRIETARY AND CONFIDENTIAL
DRAWN HB 11/11/13
TITLE:
Harrison Bourikas
Email: bourikah@union.edu
Advisor: William Keat
Quantity: 1
SIZE A
DWG. NO. LA005
REV
SCALE: N/A
WEIGHT:
SHEET 1 OF 1



ITEM NO. | PART NUMBER | DESCRIPTION | QTY.
1 | LA001 | Lift-Arm | 1
2 | LA002 | Top Mount Plate | 1
3 | LA003 | Gusset | 1
4 | LA004 | Actuator Bracket | 2
.218
5.700
5.918
0.25
0.25
TYP
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
MATERIAL
1026 Steel + Sheet Metal
DO NOT SCALE DRAWING
PROPRIETARY AND CONFIDENTIAL
DRAWN HB 11/11/13
TITLE:
Harrison Bourikas
Email: bourikah@union.edu
Advidor: William Keat
Quantity: 1
SIZE A
DWG. NO. LA006
REV
SCALE: N/A
WEIGHT:
SHEET 1 OF 1

APPENDIX 7: DRAWINGS – ASSEMBLED WALKER/CRUTCH MECHANISM



APPENDIX 8: PROTOTYPE EVALUATION FORM

Height (in.)	Weight (lbs)	Age

1	Do you feel comfortable in the mechanism and during the lift?	1 2 3 4 5
Describe:		
2	Is the motion (curvature) of the lift comfortable?	1 2 3 4 5
Describe:		
3	In terms of appearances, how does it look to you?	1 2 3 4 5
Describe:		
4	Is the lift speed reasonable?	1 2 3 4 5
Describe:		
5	When you wheel the walker around, is it easy to move?	1 2 3 4 5
Describe:		
6	Is it easy to start and stop the machine?	1 2 3 4 5
Describe:		
7	Do you feel that you can easily operate it by yourself?	1 2 3 4 5
Describe:		
8	Is the handle placement comfortable?	1 2 3 4 5
Describe:		
9	Do you feel that it is easy to situate yourself in the machine?	1 2 3 4 5
Describe:		
10	Is it easy to disengage yourself from the machine?	1 2 3 4 5
Describe:		
11	Do you feel secure throughout the entire lifting process?	1 2 3 4 5
Describe:		
12	Do you have any additional comments / concerns?	1 2 3 4 5
Describe:		
13	What would you change, if anything, about the mechanism?	1 2 3 4 5
Describe:		