WALKING FACILITATOR FOR CHILDREN WITH SPINA BIFIDA
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Abstract

People with Neuromotor disabilities, such as Spina Bifida, can have significant problems walking, primarily caused by gait inefficiency and instability. Currently, assistive devices are bulky, difficult to maneuver, socially awkward, and fail to promote a more normal walking pattern and arm motion leading to further degeneration of the lower quarter. The goal of this project is to design and build a walking facilitator for children that is easy to use, is socially acceptable, and encourages an improved gait and reciprocal arm movement.

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EXECUTIVE SUMMARY

Spina Bifida is a Neuromotor disease that can cause inefficient and unstable walking patterns. There is a need for a new device to assist people with Spina Bifida as they walk in everyday life. Current devices in the market such as walkers, crutches, and canes, provide a level of support for the safety of the individual, but are detrimental to one's gait instead of promoting leg muscle development and normal walking patterns. Research shows that pelvic lateral stabilization can increase one's walking efficiency in terms of normalized step width and step length [1]. Using this information, the task is to design a new walking facilitator that will improve one's gait and be easy to use, while maintaining the safety of the individual.

Based on the engineering specifications determined by sponsor requirements, a preliminary functional decomposition of the device (Figure 2 pg. 8), and sessions of brainstorming, numerous concepts were generated and later eliminated using a Pugh chart (Appendix E) among other methods. This analysis determined that the final concept would be automatic canes, which attach to the hip and have the ability to rotate in the direction of motion of the user as well as translate in the vertical direction. They will provide medial lateral stability to improve the gait of the user and safety stability to prevent injury. These concepts were incorporated into the Alpha design and physical mock-up for Design Review #2. The design has now been modeled in CAD and an initial prototype has been manufactured. The following chart shows the methods and results for validation that the design meets the sponsor needs.

Sponsor Requirements	**Engineering Specifications**	**Target Values**	**Validation Test**	**Goal Met?**
Safe to use	Rough surfaces/sharp edges	0	Rub balloon over all parts of device	No
	Cane yield strength [2]	100-200 MPa	Physical	Yes
Improves gait/no negative impact	Increase step length* [1]	5%	GaitRite mat, force plate treadmill	
	Decrease step width* [1]	20%	GaitRite mat, force plate treadmill	
Adjustable	Cane length adjustability [3]	0.2 m	Physical	Yes
Durable	Life Cycle	> 3 years	HALT Life Cycle Test [XXX]	
Low cost	Price	< $400	Budget check	No
Light	Weight	< 5 kg	Physical	No
Community accessible	Width [4]	< 0.76 m	Physical	Yes
Socially acceptable	Aesthetically pleasing	> 3 on survey	Survey	
	Comfortable	> 4 on survey	Survey people after wearing device for 5 min.	

*change relative to the user's previous gait

Table 1. Summary of device performance compared to requirements and specifications

The device achieved the specifications of strength, adjustability, and width and failed on sharp edges, price, and weight. The remaining specifications are indeterminate to date based on limited time to complete testing, for which a full discussion is in Section 9. The device functioned and demonstrated the design concept but needs many improvements, most of which are easily done with increased design time, resources, and funding. These improvements will allow the device meet all the specifications and increase the functionality of the device and are found in Section 10. The device is a working initial prototype, which needs iterations through the design process as it progresses towards being usable to the general public as a walking facilitator.

1. INTRODUCTION

1.3 Problem Description

Over the course of the project, the task is to design and prototype a walking facilitator for children with Spina Bifida that will improve walking efficiency, be more socially acceptable, and be easier to use and maneuver. People with Spina Bifida often have difficulty walking due to an inefficient and energy costly gait. For safety reasons, a variety of assistive devices is available, but fails to foster better walking habits, reciprocal arm movement, and lower quarter muscle development. Most devices are also bulky and socially awkward, especially for children. The user needs an innovative device to allow unrestricted arm motion, pelvic stabilization to improve gait, and ease of use. Jennifer Sansom, of the Neuromotor Control Lab at the University of Michigan, does research with children affected by Spina Bifida in an attempt to learn how to improve their quality of life through a combination of physical therapy and assistive technology. She, along with Dr. Beverly Ulrich also working in the Neuromotor Control Lab, is sponsoring the development of this device.

1.4 Literature Review

This section contains a discussion of background on the Spina Bifida disease, research on assistive walking technology, and the current assistive devices in the market.

1.2.1Disease Background

Spina Bifida is a neural tube birth defect that affects a person's gait or walking pattern [5]. Translated from Latin, Spina Bifida literally means 'split spine' and it is biologically when spinal nerves are not fully encased in the spinal column leaving it open to damage. The three different types of this disease from least severe to most severe are Occulta, Meningocele, and Myelomeningocele. These disease types are categorized by the amount of damage to the spinal cord [6]. Research has shown that humans with normal walking ability have functional gait meaning that they can walk in a variety of different environments overcoming various obstacles [7]. As of 2007, there have been approximately 2500 births of children with Spina Bifida per year in the United States. In 1998 The United States Food and Drug Administration mandated that all enriched grains must be fortified with folic acid. There has been a 26% decrease since 1996 due to this discovery of the preventative role of 400 micrograms of folic acid consumption during or before pregnancy [8]. The problem with this type of prevention is that almost 50% of the pregnancies in the United States are unplanned [8]. Therefore, many women do not receive the proper prenatal nutrition required to prevent this birth defect.

1.2.2The Gait Cycle

The walking pattern of an average healthy person can be broken down in a variety of ways, shown here into 6 phases classified as the loading response (LR), midstance (MSt), terminal stance (TSt), preswing (PSw), initial swing (ISw), and late swing (LSw) (Figure 1, below). The normal gait cycle can serve as a reference point for improving the gait of someone with a Neuromotor disease. At about 20% into the gait cycle, there is 2 times one's body weight applied to the hip joint [9]. It is often that people with Spina Bifida have a Trendelenburg Gait Pattern, which is from a disturbance in the function of the hip abductors during the stance phase causing a larger amount of internal rotation of the pelvis in order to provide stabilization [10].

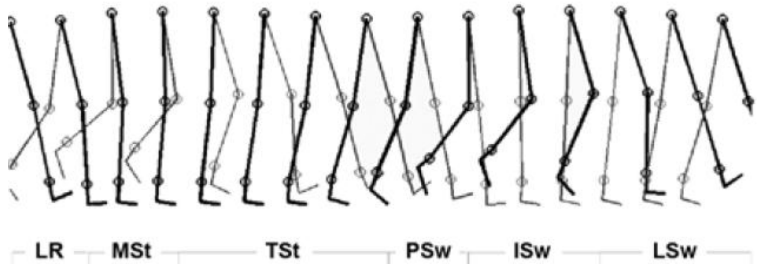


Figure 1: The gait cycle in 6 phases [11]

1.2.3 Walking Device Studies
There have been various research studies done on the use of walking facilitators in youth who have Spina Bifida. One survey of 178 people ages 13-17 from a children's hospital database showed that 35% of these patients use braces and 23% use walking aids [5]. It was determined that assistive technology was important to increase the independence of young adults with Spina Bifida. The study also showed that spinal lesion levels tend to determine the type of mobility assist device that one most likely will use. Subjects with more severe lesions tended to become wheel chair bound at an earlier age. However, the level of Spinal Lesions being thoracic, lumbar, or sacral, does not always determine the child's walking ability. Instead, each patient must be looked at as a case-by-case basis (J. Sansom, personal communication, September 19, 2009).

Another research study conducted by Dr. Beverly Ulrich investigated how external lateral stabilization of children with Spina Bifida affect their gait pattern and balance [1]. By examining 12 people with Myelomeningocele (MMC), a type of Spina Bifida, it was determined that with an external stabilizer the normalized step reduced by 4.17%, which indicated an overall gait improvement [1]. There was also a 13.43% decrease in pelvic motion which reduces the oxygen cost to the subject, therefore reducing energy expenditure. This study also emphasizes the need for a walking assist device that does not interfere with regular arm swing which balances rotational trunk forces while walking [1].

1.2.3 Benchmarks
Market research shows that current assistive walking devices for children with Spina Bifida can be grouped into five categories shown in a comparison matrix below (Table 2), which include: Loftstrand forearm crutches [12,13], rolling walkers [14], canes or quad-canes [15,16], walking poles [17], and braces[18]. There are various versions of all of these devices with different materials, aesthetics and features available in the market. One can see from Table 2, that no device completely meets the customer requirements. There was one study that investigated the material choice of the common ankle foot orthosis (AFO), a brace usually used in accordance with one of the other available assist devices [19]. The study showed that using laminated carbon fibers as elastic material in an AFO, showed no significant improvement in the gait of the test subjects when compared to the more typical hinge joint AFO made of plastic [19]. For more detail on how all five benchmark categories match to the customer's requirements for an assistive device design refer to Appendix A.

	Benchmark Categories				
Requirements	Loftstrand Forearm Crutches	Rolling Walkers	Canes/Quad Canes	Walking poles	Braces
Improves gait				X	X
Community Accessibility					X
Safe to use		X			
Discreet/Hidden					X
Low price			X		
Adjustable	X		X	X	

Table 2: Matrix comparing the different benchmark groups, X symbol signifies that it meets the customer requirement

Many companies also try to improve designs of conventional walking aids by adding a feature that is to be used simultaneously with crutches or a walker, as well as other braces. For example, Polymedic, a medical equipment company, advertises a device called the Walkabout™, which is a metal stabilization device that can be attached to different braces and used with crutches to improve gait for people with Spina Bifida and other disorders [20].

2. SPECIFICATIONS

To determine the eventual degree of success of the final product, there must be a list of targets specifications that the device must meet. These targets listed in engineering terms with quantitative values are derived from general requirements of the device that are dictated by the current benchmark shortcomings and conversations with the project sponsor.

2.1 Customer Requirements

The needs of the device were defined by discussion with the project sponsor and through literature surveys on the previous products and the disorder description. The target demographic of the walking facilitator is ages 5-12, primarily due to the fact that the sponsor's interests lay with this group. The device needs to be safe enough for a child to use, including designing for possible misuse. The design of the device should be less socially awkward than current devices for a child in school and recreational environments. Hence, the device should be aesthetically pleasing, be less bulky, and allow for community accessibility. Additionally, the device will need to be adjustable for a child as he or she develops. Lastly and most importantly, the device will need to improve or not negatively impact the child's gait. For a comprehensive list of requirements, refer to the Quality Functional Diagram (QFD) in Appendix A. The customer requirements have been ranked from lowest to highest in importance to filter out the customer's needs from desires. These rankings, which can be seen in the QFD (Appendix A), showed that being a safe device, improving one's gait, meeting the target age group, having community accessibility, and being less socially awkward were the top five customer priorities to be met.

2.2 Engineering Specifications

The customer requirements mentioned above were quantified by setting specific target values in engineering design terms. The maximum weight of the device will be 5 kg so that a child can use it safely and move around comfortably. This corresponds to the weight of a typical walker currently used by children (J. Sansom, personal communication, September 19, 2009). The target cost of the device will be $400 based on the given budget, but a lower price is desirable so that families should be able to purchase the device without insurance coverage. A variety of color choices and patterns will be provided on the device to make it aesthetically pleasing for the target age group. The maximum width of the device was set to be 0.76m which is the width of a typical house interior door [2]. This feature will help a child access and navigate through any house, school, or other community setting. Due to the high growth rate of children, the device needs to have ample height flexibility so a child can wear the device for sufficient amount of time without need of replacement. Therefore, the target life cycle of the device will be set to approximately 3 or more years of full-day use in order to minimize replacement due to growth or device failures (J. Sansom, personal communication, September 19, 2009). The required height flexibility for a growing child was determined by determining the growth rate for children between the ages of 6 to 9 years old and 9 to 12 years old. From this analysis, the height flexibility of the device will be approximately 0.2 m. This will allow for sufficient use of the device for the intended lifecycle [3]. The device will not have any sharp edges or rough surfaces to prevent possible injuries. Previous research shows that stabilizing medial lateral movement of the pelvis results in gait improvement by decreasing the normalized step width by approximately 20% and increasing the normalized step length by approximately 5% [1]. Using this result as a reference, these values will be the targets for improving the gait of the patients. Lastly, the yield strength of a weight bearing component highly correlates with the safety and durability requirements. Previous market devices often use aluminum which has proven to have sufficient yield strength in the range of 100 to 200 MPa, so this will be set as the target yield strength range for such an element. For more information on correlation between engineering requirements and specifications of this project refer to Table 2 below or the QFD in Appendix A.

Sponsor Requirements	**Engineering Specifications**
Safe to use	Rough surfaces/sharp edges
	Cane yield strength
Improves gait/no negative impact	Increase step length
	Decrease step width
Adjustable	Cane length adjustability
Durable	Life Cycle
Low cost	Price
Light	Weight
Community accessible	Width
Socially acceptable	Aesthetically pleasing
	Comfortable

Table 3: The correlation between the defined engineering specifications and the most relevant project requirements.

As previously mentioned, the products out in the market can be classified to five main groups: the Loftstrand crutches, the posterior rolling walker, the cane/quad cane, walking poles, and braces. On the QFD chart (Appendix A) these devices have been ranked in terms of how well they meet the project requirements. The Loftstrand crutch was highest ranked in adjustability while being the weakest in the aesthetically pleasing and unobtrusive/comfortable. The posterior rolling walker ranked highest in safety, but was weakest on being aesthetically pleasing, accessible to community and less socially awkward. The cane/quad cane was strongest in the categories of low price, durability, and portability, but was weakest in safety. The walking poles excelled in being low price, durable, portable, and cleanable but failed in height flexibility and safety. Lastly an Ankle Foot Orthosis (AFO) [21], a common brace for high functioning children with Spina Bifida, ranked highest in safety and community accessibility, but lacked comfort and adjustability. The QFD (Appendix A) shows specific rankings of how all devices met all of the customer requirements.

3. CONCEPT GENERATION

To develop as many ideas as possible, the team arranged regular meetings to both share individual ideas and to collaborate and expand on the group's collective knowledge. As a tool to help brainstorming, the team created a functional decomposition to understand all the different components and their functions shown in Figure 2 below.

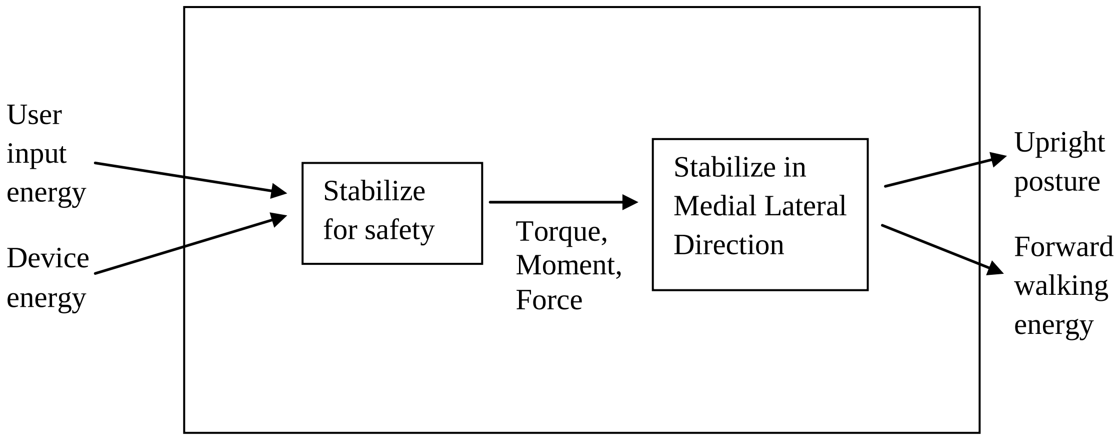


Figure 2. Functional decomposition of a walking assistive device

Breaking down the device into two major functions focused the ideas into different ways of achieving stability for safety and for the medial lateral direction. The ideal device does both of these tasks, while also complying with the engineering specifications for this design. Using this functional decomposition as well as the combined brainstorming effort, the team developed a pool of 24 design concepts. The following sections explain five of the major different concepts generated. For concept sketches and descriptions of the other 19 concepts, refer to Appendix C.

3.1 Automatic Canes

This concept is a device that consists of a cane -like object that is manipulated to move in the forward and backward directions as well as vertically following the gait cycle of the user (Figure 3, below). One cane device would be attached to both sides of the body to a fixture or belt around the waist. There will be actuators to cause the cane to move in all of the specified directions. Each cane will touch the ground simultaneously with the opposite leg during the stance phase of the gait cycle. The vertical motion of the canes can be controlled in several different ways. One way to cause extension and retraction of the cane would be by using pneumatic cylinders inside each cane device. Another possibility would be using driving rollers which use frictional forces to maneuver the cane upward. This could be attached to a rotating disk on each side of the body to create translational movement in the anterior and posterior direction. The canes would be a certain distance from the body in the lateral direction to provide more stability. The motion of the canes will be controlled based on sensor input to actuate movement correlating to the motion of the legs. A concept sketch of the device is shown in Figure 3 below.

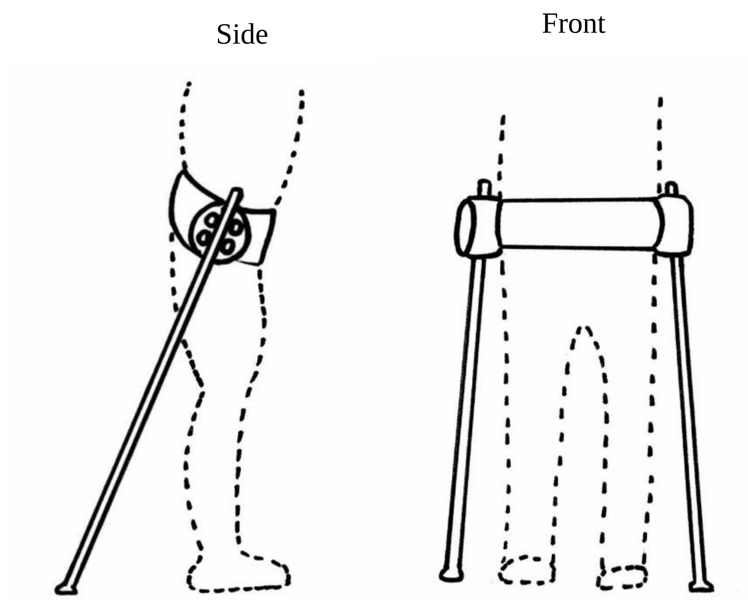


Figure 3. Concept sketch of automatic canes

3.2 Medial Lateral Weight Shift Vest

The weight shift vest attempts to limit the motion of the center of mass to indirectly improve a person's gait. There are a variety of methods of implementation for this vest, but the underlying physics of this device is to create a moment around the hip to counteract a person's torso as it sways. Refer to Appendix C.19.1 for the preliminary free body diagram of this device. A control system in this device will constantly shift the position of the weight on the body to provide force only when necessary. This can be done with a weight on a track, fluid in a tube, swinging discs, or myriad other methods so long as the weight of some object is opposing the moment created around the hip by the upper body. A sketch of the weight on a track concept is shown in Figure 4 below.

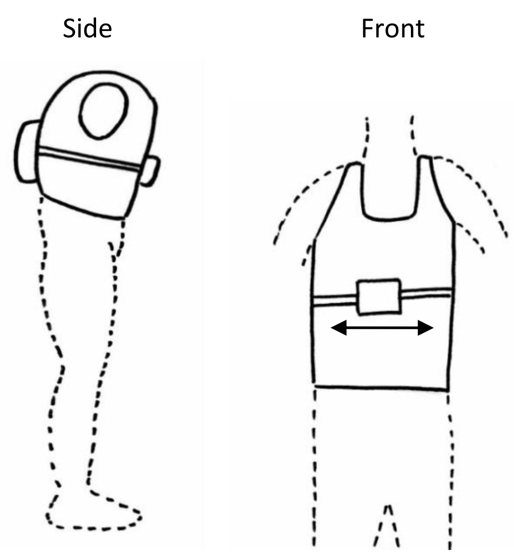


Figure 4. Concept sketch of medial lateral weight shift vest

3.3 Hammer Hip Device

The main idea of the hammer hip concept is to assist people in lifting each leg during the swing phase of the gait cycle. People with Spina Bifida often shuffle as a result of an insufficient bend of their knee. In this design two parts are fixed to the outside of the hip joint, one connected to the thigh and the other extending beyond the joint, giving a moment arm for the weight at the end of the segment. At the initial lift of the leg, the weight rotates back, causing a moment at the hip to help the leg rise. As the leg comes back to contact the ground, the weight swings through a full rotation to provide forward momentum. A motor and an electronic brake control the position of the weight throughout the cycle. Figure 5 below shows a concept sketch of this hammer hip device.

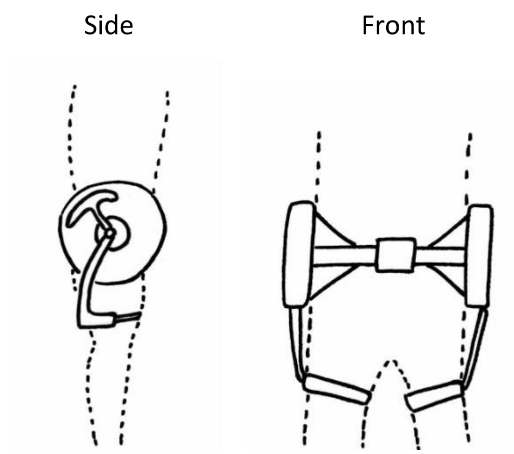


Figure 5. Concept sketch of hammer hips

3.4 Flamingo Legs

The Flamingo Legs design concept is to create a metal four bar linkage for each side of the body (Figure 6, below). These linkage systems would attach to a brace around one's lower back. Each system can be looked at as an external metal leg where the middle or knee joint is bent in the opposite direction of the human knee. To put on this device the user would step backwards into it and pull a strap horizontally over his or her lower abdomen. This concept could also be used as a gait trainer that pulls the user into a squat position if he or she starts to fall. In this case, the joint between the two longer links would have an electronic brake to aid in the falling process. A basic concept sketch of the Flamingo Legs is shown in Figure 6 below.

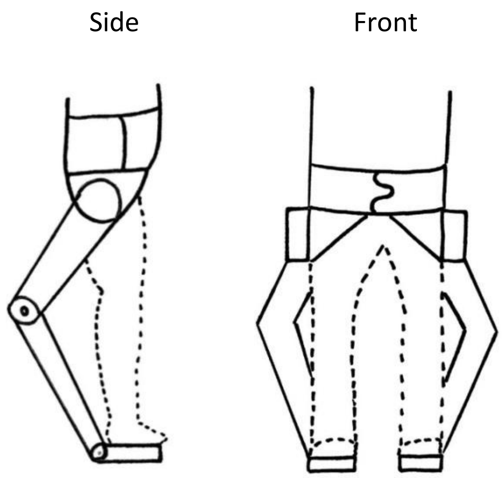


Figure 6. Concept sketch of flamingo legs device

3.5 Novel-Shaped Crutch
This idea is a redesign of a currently available walking facilitator. However, this new Loftstrand crutch is shaped differently to eliminate misuse and provide additional points of contact with the arm. The new crutch also provides damping when striking the ground to absorb impact that would be translated into the body. Lighter materials will decrease the weight and make the crutches easier to use and move around. A side view of the crutch is shown in Figure 7 below.

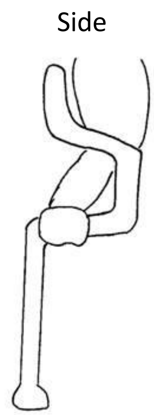


Figure 7. Concept sketch of novel-shaped crutch

4. CONCEPT SELECTION
To begin the idea elimination process, the group assessed the complete list of 24 concepts from brainstorming in two different ways: a feasibility scoring matrix and group discussion. Each member assessed the concepts individually using the preliminary feasibility matrix shown in Appendix D. This matrix allowed each member to rank the concepts in the categories of innovativeness, time to design, time to manufacture, gait improvement, medial lateral stability, safety, and social awkwardness. The individual rankings were averaged for each category and device to ensure that all team members' opinions were taken into account. Rather than discard ideas based on this initial matrix, the team used it to initiate thought as to which devices were clearly superior to others. Subsequent to a limited discussion, the team unanimously decided to eliminate ideas. However some ideas that were removed from the list were

deemed useful as concepts to be incorporated into the final design. At the end of this process there were five complete concepts that were successful enough to merit further investigation and physical analysis.

4.1 Selection Matrix

To further differentiate the final five concepts, the team used a Pugh Chart (Appendix E). Below is a modified version of that chart (Table 4) which more clearly shows the advantages and disadvantages of the devices with respect to the customer requirements and engineering specifications. In this simplified version the scores for each device have been changed from numbers to symbols corresponding to satisfactory, neutral, and poor to provide further clarity.

	Flamingo Legs	**Automatic Canes**	**Weight Shift Vest**	**Hammer Hip**	**Novel Crutch**
Weight	X	-	X	X	O
Safety	-	-	-	X	-
Less Socially Awkward	X	-	-	-	-
Community Accessibility	X	-	O	-	-
Improve Gait	-	-	-	-	X
Medial Lateral Stability	-	O	O	X	-
Creativity	O	O	O	O	X
O: Satisfactory - : Moderate X: Poor					

Table 4. Modified Pugh chart showing satisfactory, moderate, and poor correlation to specifications

4.1.1 Flamingo Legs

This concept is very innovative which provides a drastic change from the currently available devices; however, it has several faults that were apparent through further investigation. The team hypothesizes that with the amount of material and actuators used in this device it is the heaviest design concept. Also, because this device extends out from the body the most in comparison to the other devices, this would probably be one of the most socially awkward devices for the user to wear. The bulkiness of this device would also make it more challenging to move through doorways and narrow passages in the community environment. Lastly, the physics behind the mechanics of the device has proven to be too complex for timely analysis. By using oversimplified free body diagrams, the true physical feasibility of the device could not be determined. Therefore, the device could not be rejected based solely on physics. However, the team decided that based on the device’s complexity and failure to meet multiple engineering specifications it should be eliminated. Refer to Appendix C.19.1 for further information on the physical feasibility of this device.

4.1.2 Automatic Canes
The Pugh chart (Appendix E) shows that the automatic canes satisfy all of the specifications to a moderate degree. This device allows for increase in mobility from the currently available devices, because the arms of the user remain free. This mainly allows for reciprocal arm movement which would in turn give the user a more natural and proper gait. External medial lateral stability is provided to the user by applying forces from the ground through the cane to the pelvis. The canes also provide stability against falling by having a wide support base and with multiple points of contact on the ground at a single time. The team decided that since the canes could dramatically improve the users gait, the positive psychological side effect that this will have on someone's self esteem will overcome the socially awkwardness of this device.

4.1.3 Weight Shift Vest
The center of gravity stabilization from the weight shift vest helps reach the goal of gait improvement in a way that is different than any of the five main concepts. Although this device is one of the most innovative, the amount of weight being shifted on the body is a large load for a person to sustain on a daily basis. Appendix C.11.1 shows a physical analysis of the device and the equations of motions used to calculate this load. However, this device could be considered the most discreet and least socially awkward for the user since it is kept the closest to the body and could be hidden under a larger piece of clothing. This device also allows for the most community accessibility because it does not contact the ground or extend from the body. Since this device does not impede arm motion, it allows for reciprocal arm movement which encourages proper gait (J. Sansom, personal communication).

4.1.4 Hammer Hip
The primary drawbacks to the hammer hip design are the lack of safety and the lack of medial lateral stability. The swinging mass will need to be fully enclosed so both the user and others cannot injure themselves. Secondly, this device does not prevent the user from falling, should he or she lose balance, because there is nothing in the device that touches the ground. The amount of weight also affects the safety of the device because the user carries the total weight of the system including the swinging mass and the actuators. Creating medial lateral stability to improve gait is a key focus of this project, but the hammer hip only provides forward momentum and not force acting in the medial lateral plane. Although the hammer hip device allows for community accessibility and is very innovative, it does not meet enough of the main engineering specifications for the design to be pursued further.

4.1.5 Novel Crutch
This design was eliminated despite the score it received in the Pugh chart analysis. This design improves on the current market products, but this project allows for more innovation than a redesign of a benchmark. The crutch meets all of the specifications at least as well as the other devices in the narrowed pool, but the team unanimously decided that creativity and a new approach to a walking facilitator are more important. Though it is obviously the lightest choice, the crutch will not improve the gait as much as the other devices because the user will still tend to lean over the crutches for support as one does with the benchmark device. The new design focuses on aesthetics rather than solving specific problems with the Loftstrand crutch, which would be more useful to the user.

4.2 Final Selection
From the Pugh chart and feasibility studies of the 5 main concepts, the chosen device was the automatic canes design. The elimination process left two devices with the most positive attributes, the automatic canes device (section 6.1) and the weight shift vest (section 6.2). The weight shift fell short in two main ways. First, through static analysis of this device, shown in Appendix C.11.1, it was determined that for

an 80 kg person, there would need to be 5 kg of moving weight. Although this mass value meets the team's engineering specifications, the weight of the actuators and vest were not considered. Therefore, after taking this additional weight into account, the device could be too heavy for a child to wear. Lastly, this device would solely stabilize the center of mass of the person. The research on gait improvement focuses on external medial lateral stability, but not center of gravity shift. Therefore, there is no direct evidence to support gait improvement from the weight shift device.

5. CONCEPT DESCRIPTION

The automatic canes device mimics the sensation and assistance given by walking poles. Walking poles give stabilization by providing additional contact points with the ground, providing forward thrust when needed, and encouraging reciprocal arm motion (J. Sansom, personal communication). The canes differ from walking poles because they are automated, allowing the hands to be free during use, and they provide force directly to the pelvis, offering medial lateral stabilization. They also are fixed to the waist of the user in a way that is not conducive to improper use by a child. A fully assembled model is shown in Figure 8 below.

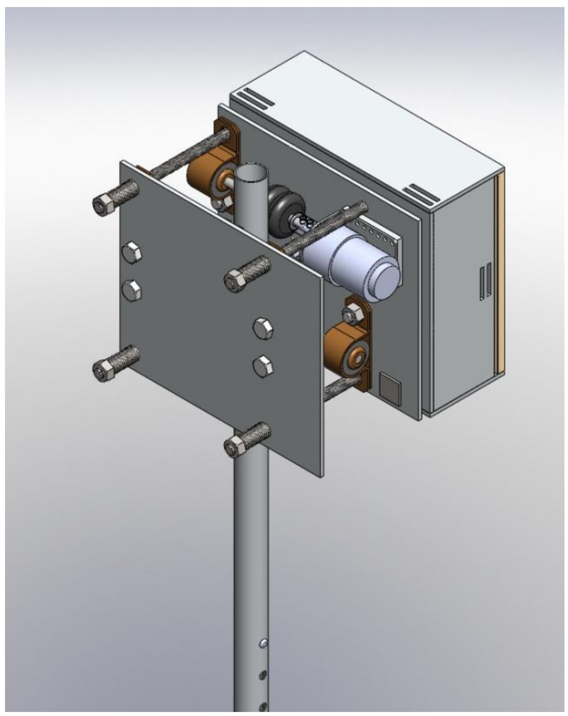


Figure 8. Computer aided design model of automatic canes

5.1 Functions of Device

This device provides three types of mobility assistance. The canes will contact the ground a distance outside of the user's step width, which will exert medial lateral force onto the pelvis, which will indirectly improve a person's gait [1]. Secondly, the canes offer up to two additional point of contact with the ground, extending the base of support to stabilize and prevent falling. Finally, forward momentum can be given by forcing the cane vertically into the ground in the terminal stance part of the gait for the opposite leg, shown in leftmost image of Figure 9. The forward motion will only be used when the user requires the additional help.

5.2 Motion of the Canes

The device features two canes with two degrees of freedom relative to the user. There is one rotational and one translational joint which are located directly outside the hip. The translational motion moves the cane vertically using the frictional force from contact with spinning rollers. The rotational motion moves the cane forward and backward relative to the user to advance the canes in conjunction with the pace of the user. The motion of the automatic canes directly correlates to the movement of the leg through the gait cycle. When a leg swings, the opposite cane rotates forward, a reciprocating pattern, as is shown in Figure 9 below.

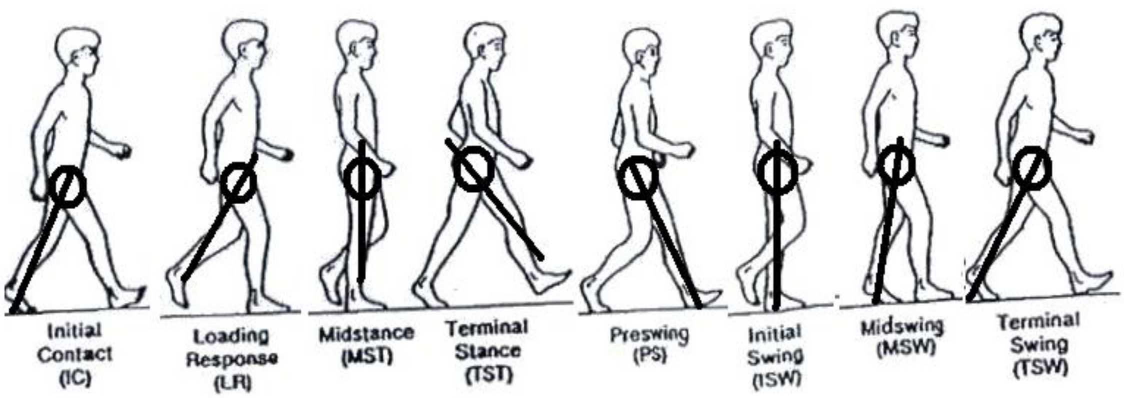
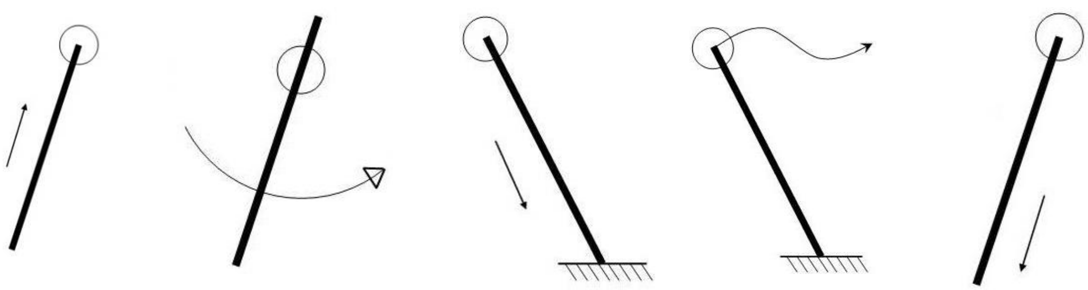


Figure 9. Visualizing cane motion through a complete gait cycle for one side of the body [22]

The automatic cane's path can be simplified to five stages, shown in Figure 10 below. The figure shows the cane's position relative to the user throughout the gait cycle beginning with initial contact. It also demonstrates how the cane retracts to allow the user to move forward past the cane while walking. Next, the cane is behind the user and it pushes on the ground to provide an assistive force forward. Following this phase, the cane retracts to clear the ground and any obstacles before it swings forward. During the swing phase of the gait cycle, the cane is held still in translation and rotated to the front at the same speed as the alternate leg. As the cane touches the ground, it should be parallel to the toes of the alternate leg and approximately two foot widths outside the edge of the foot on the side it is located, shown in Figure 11 on the following page.



1. Translation up to allow for free rotation

2. Rotation forward following the leg

3. Translation down to contact the ground

4. User walks over the cane as it freely rotates backward and translates up

3. Translation down to contact the ground and push user forward

Figure 10. Cane movement through gait cycle, oriented with the user walking to the right

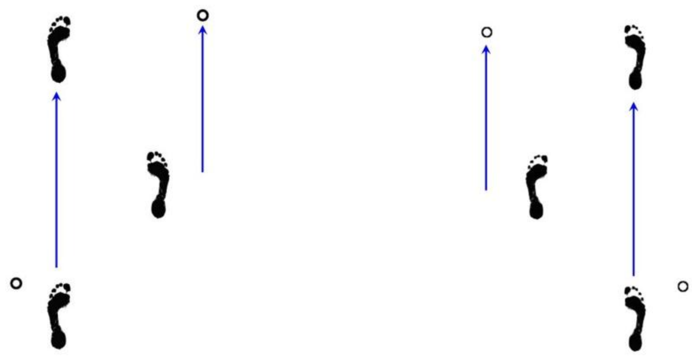
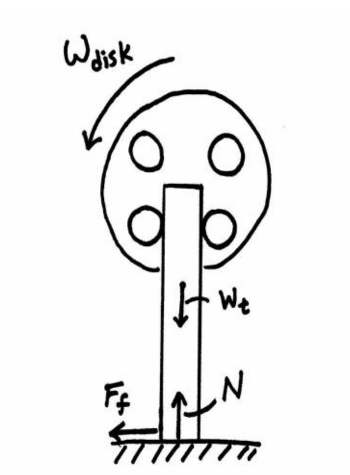


Figure 11. Footprint diagrams for a left and right step, blue arrows indicate motion

5.3 Preliminary Analysis

5.3.1 Rotation of the system

The rotational joint analysis is useful to determine the necessary actuators for this device. An applied rotational torque on the disk from an actuator will move the cane creating an opposing frictional force applied by the ground in the anterior/posterior direction of movement. Figure 12 shows the free body diagram of the left side cane system.



ω_{disk}: Angular velocity
W_t: Total weight of system
F_f: Force of friction
N: Normal force

Figure 12. Free body diagram of rotational motion

The following equations govern this motion:

$$\tau = I\,\alpha \quad \text{Equation 1 [23]}$$

$$\theta = \omega_0 t + \frac{1}{2}\,\alpha t^2 \quad \text{Equation 2 [23]}$$

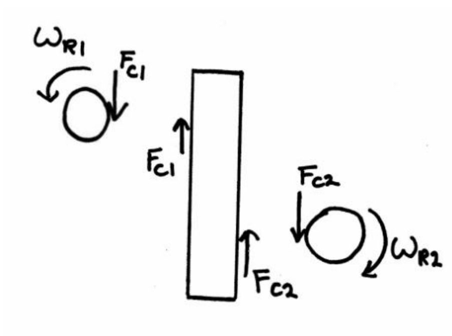
In these equations, τ is the motor torque on the disk, I is the moment of inertia taken at the end of the cane, α is the angular acceleration of the cane system, t is the available time for the cane swing, ω_0 is the initial angular velocity of the cane system and θ is the angular displacement of the cane. Since the cane will initially be at rest, ω_0 is assumed to be 0. The values for θ and t can be found by comparison with the desired gait cycle; hence α can be determined. The value of I can be determined by using Equation 3 below.

$$I = \frac{1}{3}ML^2 \qquad \text{Equation 3 [24]}$$

For the above variables, M is the total mass of the system and L is the length of the cane. Equation 3 gives an estimate for the moment of inertia of the system by simplifying it as a single rod. Hence, after all the necessary components for the device are decided, the parallel axis theorem will be used to calculate a more accurate value for the moment of inertia. After α and I are determined, the necessary value of the torque needed to rotate the disk can be determined which impacts the decision for which actuator is appropriate for the device.

5.3.2 Vertical translation of the cane

By creating a rotational velocity of the rollers that are attached to the disk, a frictional force will be created between the rollers and the cane. This frictional force will provide a vertical translation of the rod depending on the direction in which the rollers are spinning. Figure 13 shows the free body diagram of the translational movement. The frictional force between the rollers and the cane needs to be high enough in order to overcome the weight of the cane under static conditions. By determining the weight of the cane, the necessary force required by the rollers can be found; in turn, an appropriate actuator to be used for the rollers can be chosen.



$\omega_{R1,}\omega_{R2}$: angular velocities of rollers 1 and 2

F_{C1}, F_{C2}: contact force between cane and roller

Figure 13. Free body diagram of translational motion of cane through rollers

5.4 Functional Decomposition Refinement

Upon deciding upon automatic canes as a general design, the team made a more specific functional decomposition of the device on the different functions that it performs. The specific functions are actuation, rotation, and translation. The team brainstormed on the different ways to achieve the aforementioned tasks, generating possible design features and deciding from that list (complete list shown in Appendix F). The team also brainstormed possibilities for the point of contact with the ground, the method of adjustability, and the belt design and decided on the final components based on these concepts.

6. PARAMETER ANALYSIS

6. 1 Translational Motion

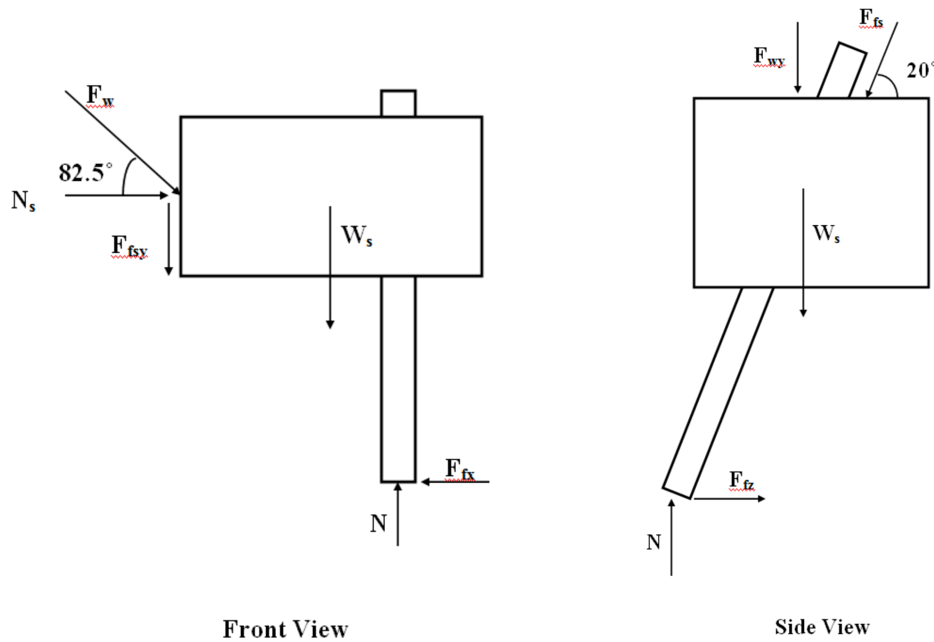
When the cane is touching the ground, it needs to support some of the body weight to help prevent the user from falling. A normal cane supports approximately 10%, on average, of the body weight [25]. Because the main purpose of the automatic canes device is to help patients become more independent, it was designed to support only 5% of the body weight. It requires less torque to translate the cane upwards than to support the weight of a person, so the latter torque was the motor's maximum torque requirement. In order to determine this torque, the system was analyzed in three main steps: the entire system including the rotational/translational module and the cane, the cane, and the driven roller. Figure 14 shows the free body diagram of the entire system in front and side views. For the extreme case, the body weight of 200 lbs was used for the calculation.

6.1.1 System level analysis

For the entire system, there will be body weight of the user transferred through the pelvic joint, applied at 82.5 ˚ when a person is in a one leg stance [26]. The straps that keep the system fixed to the pelvic joint will provide a normal force which corresponds to N_s and also creates a frictional force F_{fs} when the cane is in contact with the ground. Using the equations of motion Eq.4 and Eq.5 below, the ground normal force was calculated.

$$N - W_S - F_W sin82.5° - F_{fsy} = 0 \quad \text{Equation 4.}$$

$$F_{fsy} = N_S \mu_{S-F} sin20° \quad \text{Equation 5.}$$



F_w : 5% of the body weight
F_{wy} : Fw in y direction
N_s : Normal force from the skin
F_{fs} : Skin friction
F_{fsy} : Ffs in y direction
W_s : Weight of the system
N : Ground normal force
F_{fx} : Ground friction in x direction
F_{fz} : Ground Friction in z direction

Figure 14: Free body diagram of the entire system.

In these equations, μ_{S-F} is the coefficient of friction between the skin and the polyurethane foam with the value of 0.6 [27]. The normal force, $N_{s,}$ was determined empirically by placing a weight on a team member lying down until the maximum comfortable force was found. From the force balance analysis, the ground normal force was determined to be 15.64 lbs.

6.1.2 Cane Analysis

The cane analysis was done separately for further insight into the translational module force interactions. Figure 15 shows the free body diagram of the cane. Because the cane itself is very light, the weight of the cane was neglected. Hence, the friction on the cane was determined to be the ground normal force divided by cosine of 20˚, resulting in 16.64 lb.

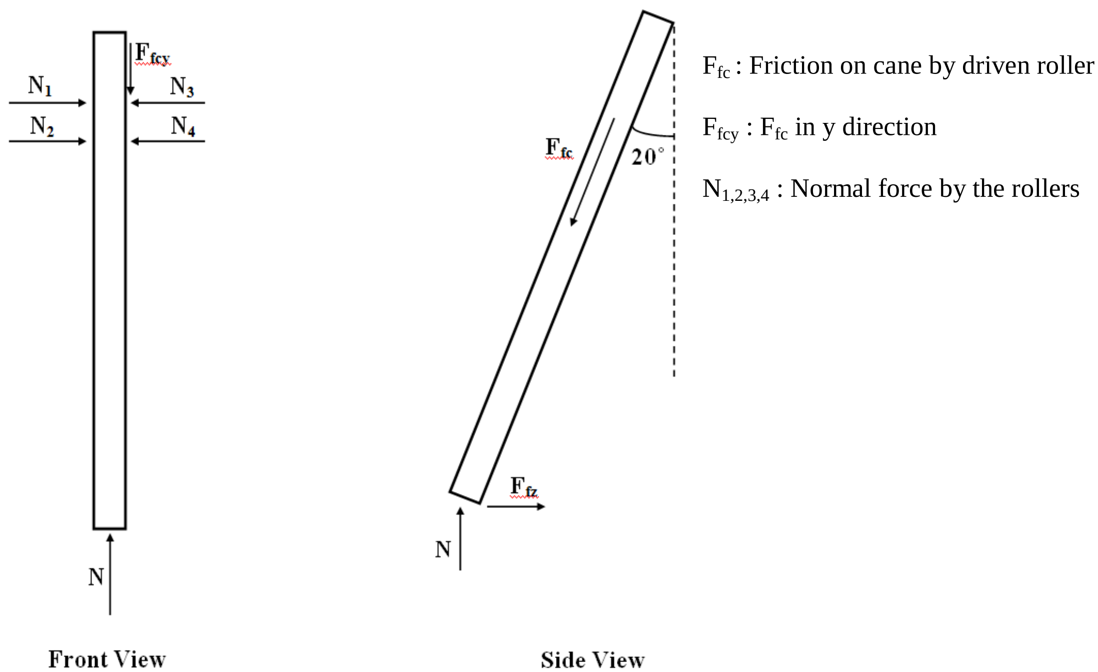
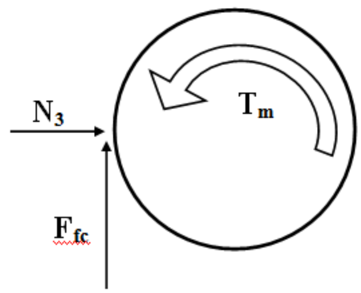


Figure 15: The free body diagram of the cane.

6.1.3 Motor Torque Determination

The equation $T_m = F_{fc} * R$, where *R* is the radius of the roller was used in accordance with the free body diagram of the driven roller in Figure 16 to determine the required torque to support 5% of the body weight. This resulted in the required motor torque to be 10.4 lbs-in. This analysis was used as a reference to determine the torque for the translational motor. The motor chosen has a stall torque of 10.4 lb-in with a no load speed of 200 RPM. The translational motor will be operated at 12 V with 5A when stalling, which results in a power consumption of 60 W. Additionally, assuming that the coefficient of friction between the aluminum and rubber is 0.51, the normal force on the cane was determined to be 32.6 lbs. Hence, each spring will need to provide a force that is half of this value at 16.3 lbs.



T_m : Motor torque

N_3 : Normal force on the driven roller

F_{fc}: Friction

Figure 16: The free body diagram of the driven roller.

6.2 Rotational Motion

Adams software was used to determine the torque needed for desired output of the rotational motion of the cane. Figure 17 shows the system with the cane translated up and positioned 8 degrees behind the vertical axis. The length of the cane was set to 45 inches long which is the fully extended length. The total weight of the translational module is 4.25 lbs and the motor needs to rotate the module a total of 28 degrees, resulting in 20 degrees forward of vertical. The angle of the cane backward and forward was based on the angle of the leg during the gait cycle and is shown in Figure 17 [22]. The average time for a single gait cycle was determined by measuring the walking speed of each team member with a stop watch and the average time was found to be approximately 1 second. Then, each cane was modeled as a broom stick which was used to simulate the movement of the cane while walking. During 1 second of gait cycle, the duration of cane movement was measured with a stop watch and was approximately 0.642 seconds. Hence, the angular speed of the cane was calculated to be 28 degrees/0.642 sec = 0.76 rad/sec.

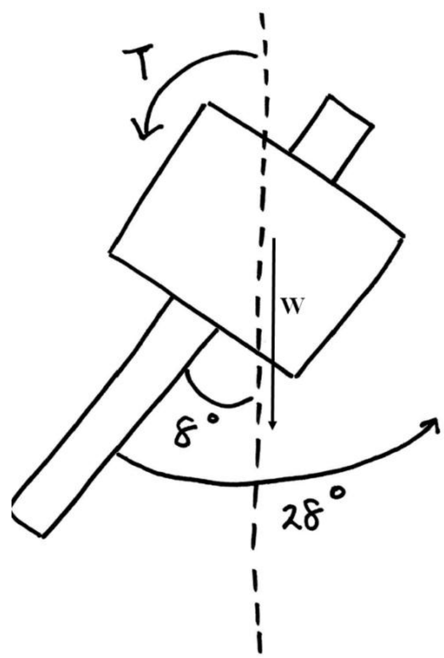


Figure 17: Free body diagram of the rotational module

Through Adams model simulation, it was found that 11 lbs-in of torque input will rotate the cane from its upright position (0 degree) to 20 degrees in 0.642 seconds. The model started from vertical because that is the lowest energy state of the cane to fully forward, which is the highest energy state, because this is the maximum amount that the motor will need to work. Figure 18 shows the output of this model with a screenshot of the simulation in Figure 19.

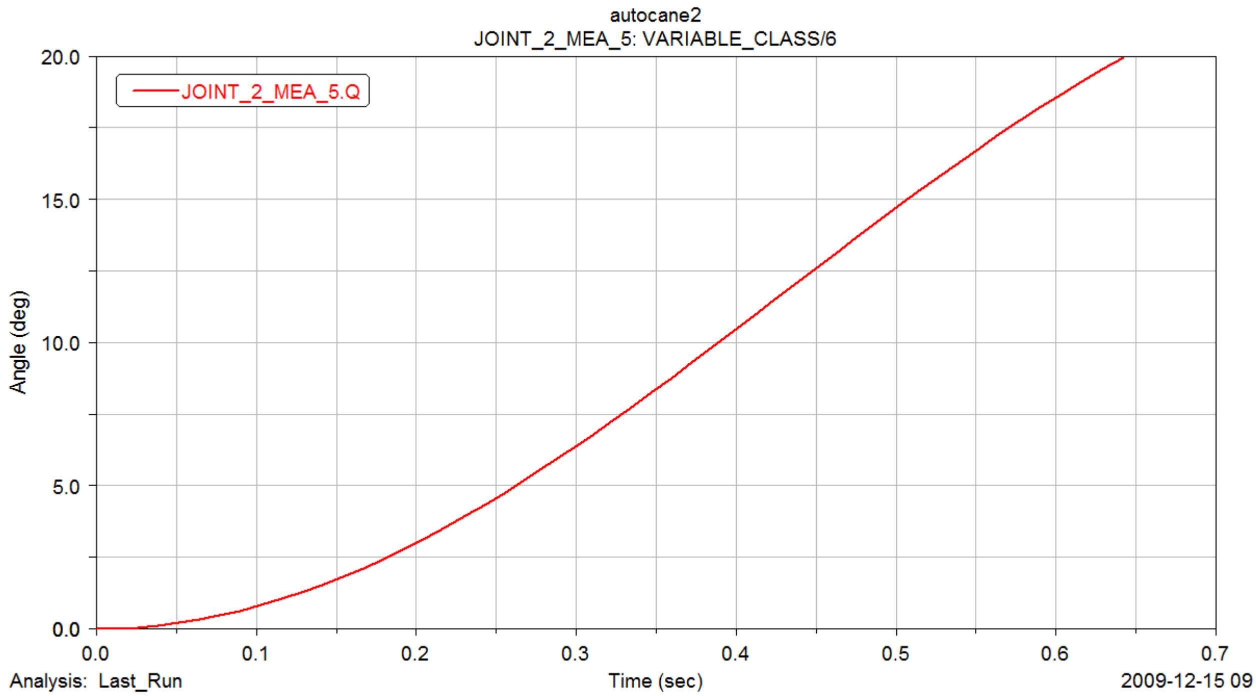


Figure 18. Angular Displacement of the Cane During Rotational ADAMS Simulation

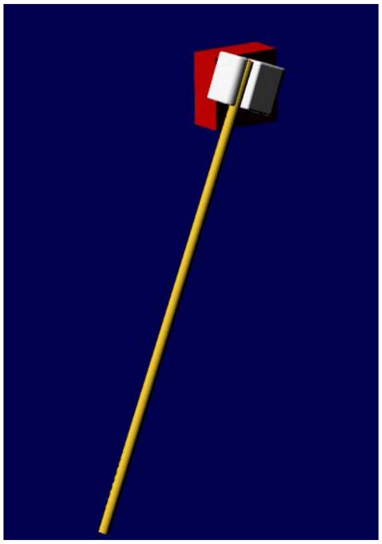


Figure 19. Screenshot from ADAMS Simulation

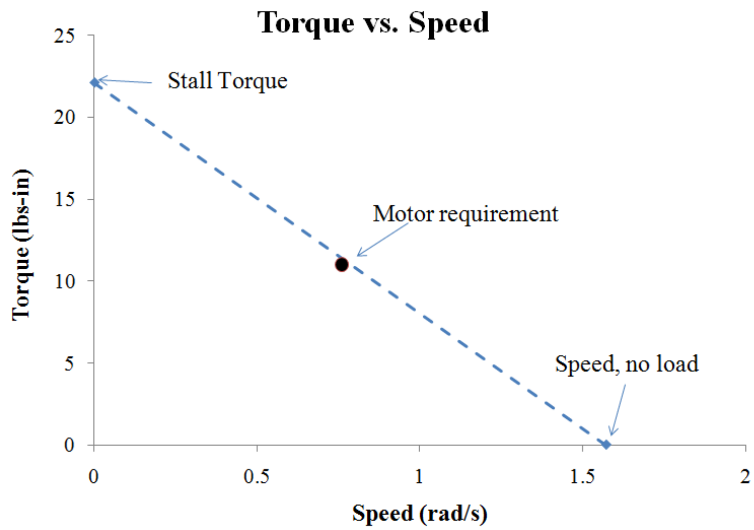


Figure 20: A motor with an appropriate stall torque and no load speed was chosen to meet the motor requirement.

The rotational motor was chosen based on the 11 lbs-in torque with 0.76 rad/sec requirement to rotate the module. Figure 20 shows how the motor specifications (stall torque and no load speed) were used to choose a motor that could operate at the necessary torque and speed for this system. The motor chosen for the rotational motion has a stall torque of 22.08 lbs-in with no load speed of 1.57 rad/sec. This motor consumes 7.2 W based on stall torque, representing the maximum draw.

6.3 Material Selection

6.3.1 Cane

The material chosen for the canes was Aluminum 6061 because of the low cost, ready availability, low density, and sufficiently strong [28]. The team used CES software to confirm this design decision, summarized in Table 5. Refer to Appendix M.1 for a full analysis.

Property	Aluminum 6060	Magnesium AM 100A	Beryllium grade I-400	Mg-30%B4C	Al-60%C-M40
Yield Strength (ksi)	29.6	9.57	36.3	37.7	145
Density (in^3)	0.0965	0.0648	0.0665	0.0717	0.0795
Price (USD/lb)	0.692	2.26	346	11.3	376

Table 5: Comparison among the top 5 materials based on the yield strength and density

6.3.2 Foam

The team chose polyurethane foam for padding for places where the device contacts the body. It needed to have sufficient density and compressive strength to support and cushion against the skin [27]. This information is summarized in Table 6 and a full analysis is in Appendix M.2

Property	Polyurethane	Polyethylene	Phenolic Foam	Polyvinylchloride	Polyethersulfone
Compressive Strength (ksi)	0.145	0.1	0.406	0.235	0.58
Density (lbs/in^3)	0.0253	0.00361	0.00697	0.00311	0.00686
Price (USD/lb)	3.76	1.41	3.76	5.64	16.9

Table 6: Comparison among the top 5 materials based on the compressive strength and density.

6.3.3 Environmental Analysis
The team used SimaPro to obtain the environmental impact of the chosen material for the cane against another possible cane material choice. The EcoIndicator 99 values are shown in Figure 21 below and the full analysis is in Appendix N.

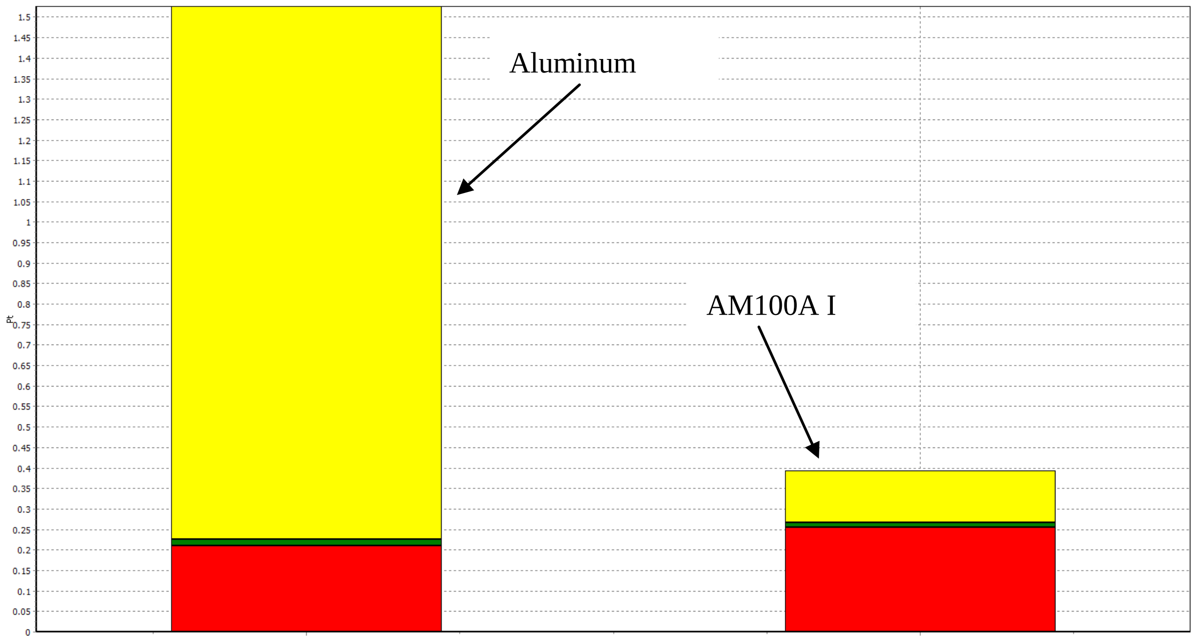
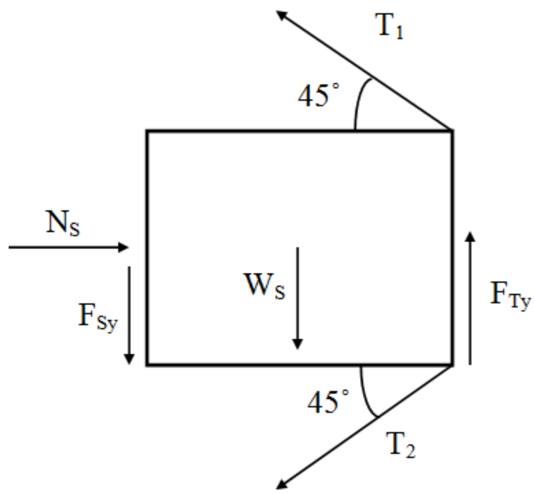


Figure 21. Total EI99 Points Comparison of Aluminum 6060 and AM100A I

6.4 Belt Analysis
Securing the hip module to the person is critical for the device to work properly to transfer the medial lateral force to the body. To do this, the belt attachment must be limited in as many directions of motion as possible. Using straps tightened to the body connecting to the hip module in 4 places, a strap in tension is always opposing the motion of the module no matter what force is exerted onto it. The straps are also pulling the hip module into the body at a distance away from it. This ensures that the module is always in contact with the body and opposed the moment of the module to rotate towards the ground caused by its own gravity. The associated free body diagram is shown in Figure 22.



N_S : Normal force from the skin
F_{Sy} : Skin friction in y direction
W_S : Weight of rotational module
F_{Ty} : Force from translational module in y direction
$T_{1,2}$: Tension of the upper and lower straps

Figure 22. Free Body Diagram for Hip Module Strap Analysis

$$\Sigma Fx = N_S - (T_1 + T_2)cos45° = 0 \qquad \text{Eq. 6}$$

$$\Sigma Fy = (T_1 - T_2)sin45° + F_{Ty} - W_S - F_{Sy} = 0 \qquad \text{Eq. 7}$$

The tensions T_1 and T_2 are important to provide a normal force onto the hip. This keeps the rotational module in the correct position on the hip. The tension in these straps is found by using Eq. 6 and 7 above. The values for these forces are listed in Table 7 below.

Force	Value	Source
N_s	5 lbs.	Found empirically (see Section 6.1)
F_{sy}	2.82 lbs	Ns, mu
W_s	2.8 lbs	Empirical weight test
F_{ty}	8.64 lbs.	Weight of module subtracted from cane friction in vertical direction

Table 7. Values for Forces in Hip Module Free Body Diagram

Using these values and Eq. 6 and 7, T_1 and T_2 are calculated to be 1.4 lbs and 5.6 lbs respectively. An assumption to make the problem solvable, the effects of the horizontal straps are neglected because they do not affect this analysis and only maintain the module's position in the anterior/posterior direction.

7. FINAL PROTOTYPE DESIGN

This prototype device can be split into four subassemblies: cane, translational module, rotational module, and belt. There will be one device for the left and right sides of the body which are mirror images of each other. The following section explains each component that is involved in the separate subassemblies of the device on one side of the body and how the assemblies combine to make the total hip module for one side of the automatic canes device. Each manufactured component and all assemblies are accompanied by a schematic and a computer aided design (CAD) model with detailed dimensions. There is also a description of the mechatronic system that will be used to control the motion of the cane (see section 7.5). For a detailed list of the multiple design changes that were made during the manufacturing process refer to Appendix Q.

7.1 Cane

The cane is made of two pieces of aluminum that fit inside one another to allow for adjustability. The adjustability follows the telescoping tube design that exists for various crutches in the current market [29]. A .25 inch bolt fits inside the inner shaft protrudes about .375 inches total through .25 inch holes in the cane acting as a telescoping pin. A .25 inch nut tightens this bolt down onto the shaft. This telescoping pin can be moved up and down the cane fitting through a set of nine .25 inch holes that are spaced one inch apart. This spacing allows for eight inches of height adjustment meeting the engineering height flexibility specification. An additional feature that the team added to this common design is an 8 inch slot in the interior cane with a 1.25", .25" in diameter nut and bolt assembly. This pin acts as a telescoping hard stop to ensure that the two shafts of the cane will not separate and that the inner shaft will not rotate during adjustment. As a safety feature there will be a third nut and bolt assembly 10 inches from the top of the cane. This pin will serve as a mechanical hard stop in case of motor or total electronic failure. If the cane slips through the wheels upwards, the pin will catch on the shafts of the wheel sets in the device. The cane will be able to be removed from the complete device by sliding it out through the bottom of the translational module. The cane will then be functional as a walking pole should the control system fail or the user encounters terrain that is too rough for the canes to function effectively. Lastly, the bottom, shown in the Figure 24, will be a flexible rubber tapered end [30] that will be purchased from a supplier because the focus of the project was not to redesign the bottom of the cane. The same concept applies to the top of the cane (Figure 23), but the end is straight and smooth instead of tapered.

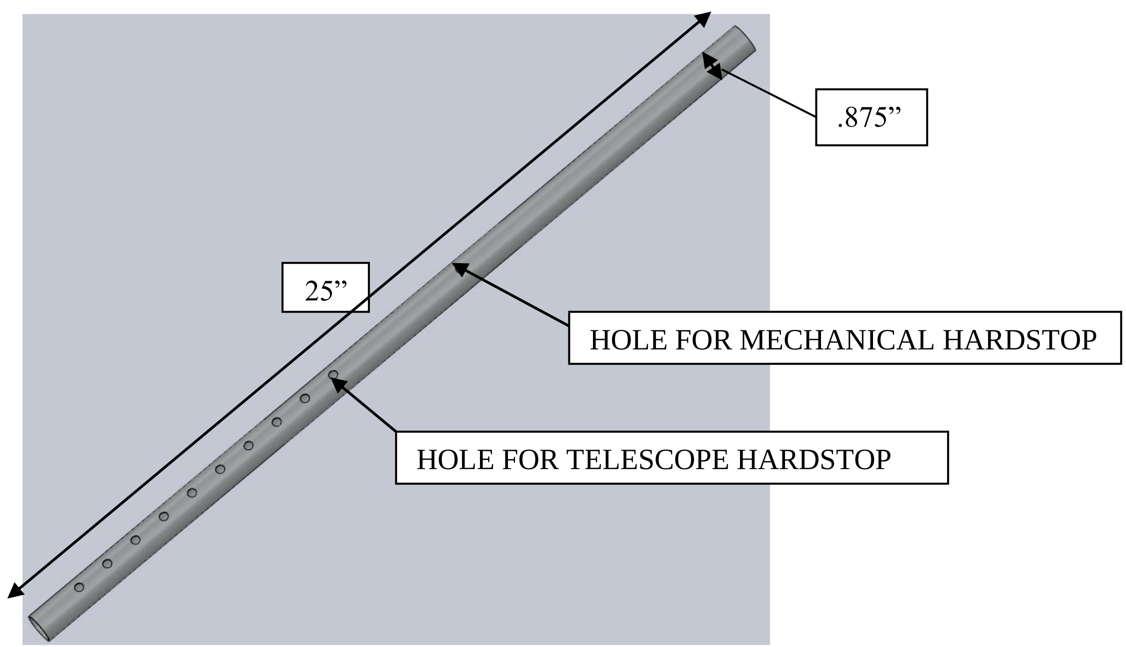


Figure 23. CAD model of outer tube

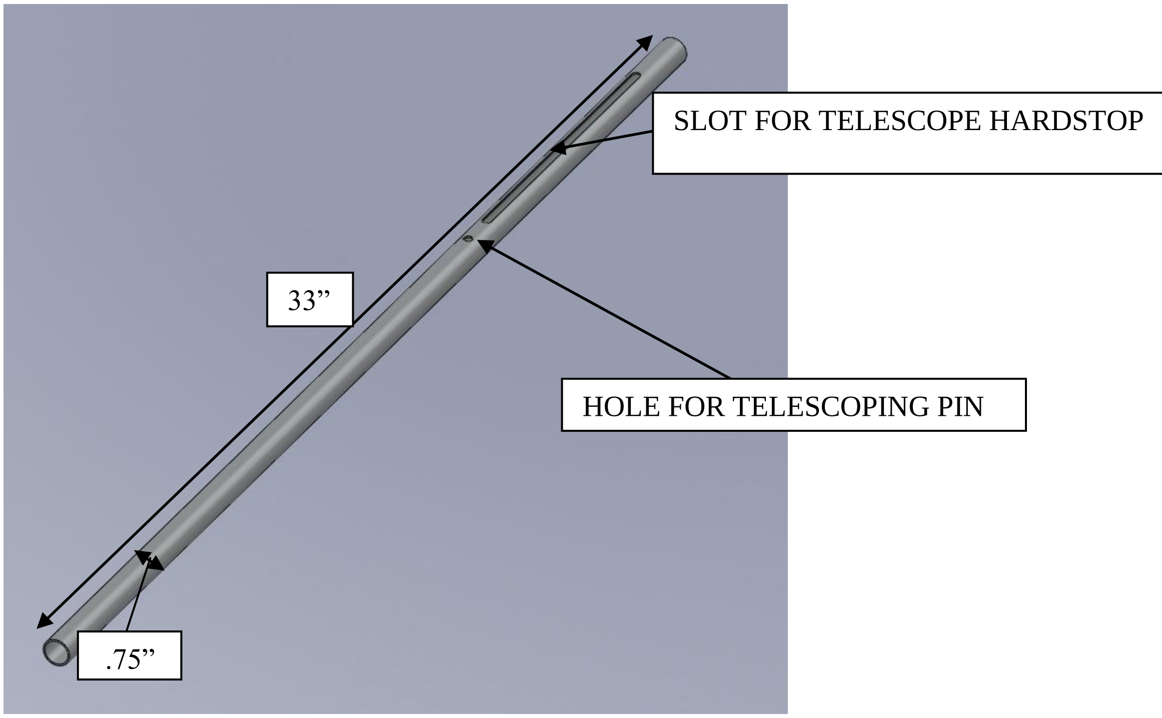


Figure 24. CAD model of inner tube

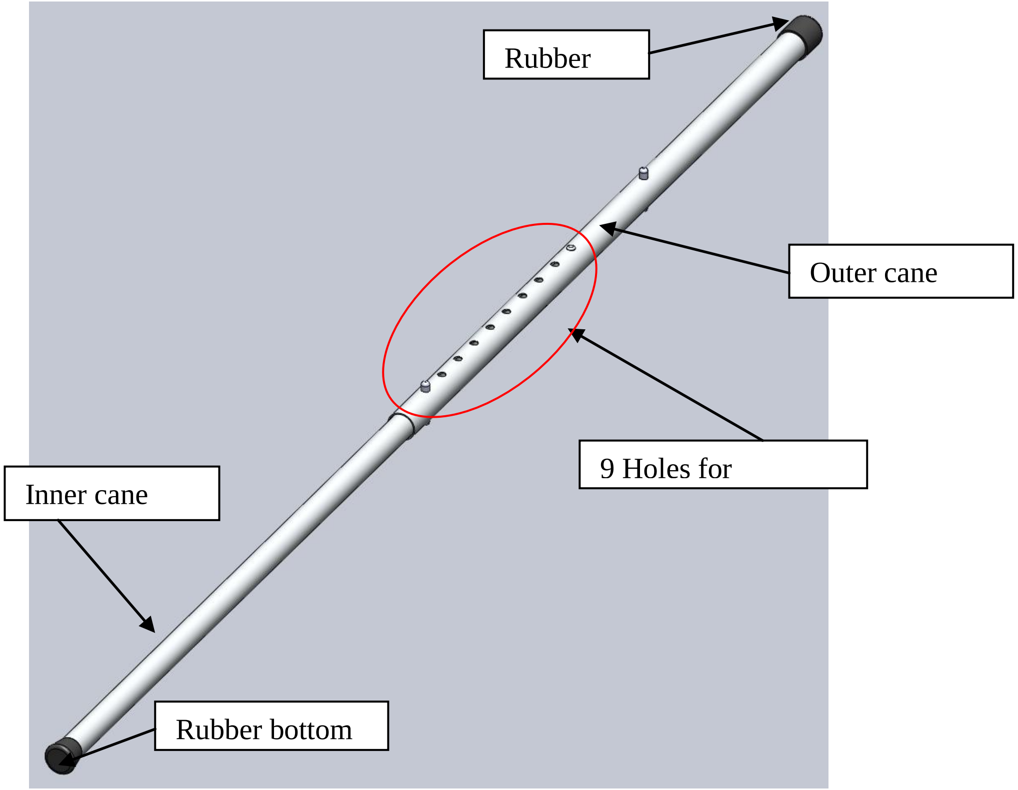


Figure 25. CAD Cane assembly model

7.2 Translational Module

The primary components inside the rotary module are the translational motor, wheels or rollers, bearings, shafts and springs. These components along with several other smaller parts like nuts, bolts, and screws, are all housed between two 1/8 inch aluminum plates. A CAD model of the entire translational assembly with the cane can be seen in Figure 26. The translational D.C gear motor has a 50:1 gear ratio, outputs 10.4 Nm torque and is mounted to a bracket. There is a 3/16" aluminum plate between the translational motor and the inner aluminum plate to maintain its alignment with the drive wheels. There are 4 sets of rubber wheels, with 2 wheels on each shaft to provide additional contact with the cane. Between all wheel sets there is a .25" spacer to maintain a grip on the cane. The wheels have aluminum hubs with slightly less than .25 inch holes. One set of wheels is driven by the motor and the other three sets provide stability as the cane translates in the vertical direction. The set of driven wheels are pressed onto a ¼ inch steel shaft attached to a mounted bearing on one side and attached to the translational motor via a shaft coupler. The driven wheels have an applied torque from the D.C. gear motor allowing them to provide a frictional force that drives the cane upwards.

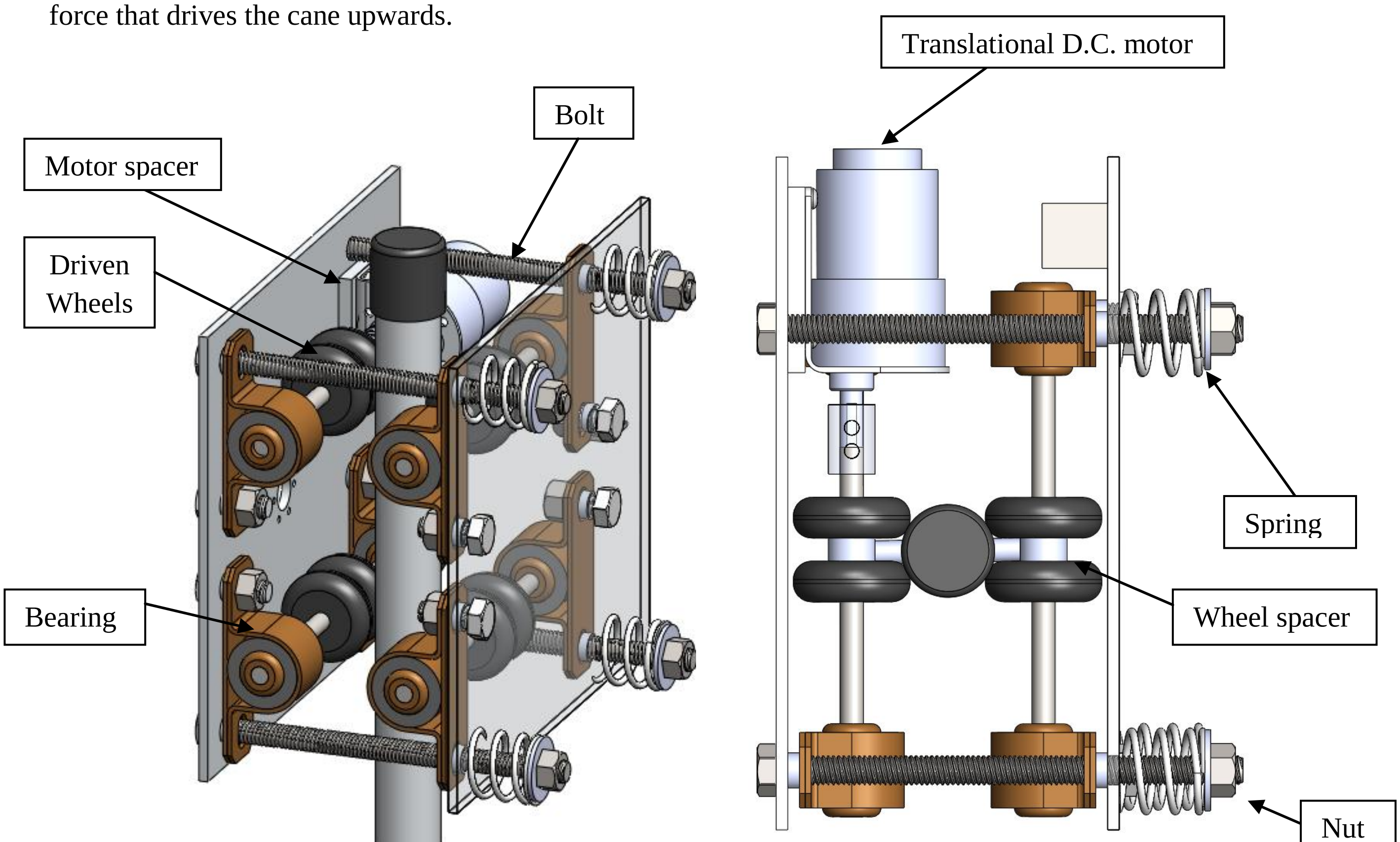


Figure 26. CAD model of translational module assembly isometric view (left) and top view (right)

As shown in Figure 27 below, the stability wheel sets are also on ¼ inch steel shafts but are allowed to spin freely between two mounted bearings. These wheel arrangements are fixed to aluminum plates using 5/16 inch bolts which are held together using ¼ inch bolts with springs on them. By tightening or loosening a nut at the end of the bolt, the springs will compress or extend to provide additional normal force of 32 lbs maximum at each wheel set to increase the friction between the wheels and the cane. The wheels are aligned with the center of rotation of the system so that the system will be easier to spin by the rotary motor. Also there is are two 1/16 inch spacers between each of the bearings and the aluminum mounting plates so that the rubber wheels do not rub against the walls of the system. For a complete list of the bill of materials for the translational module refer to Appendix I.

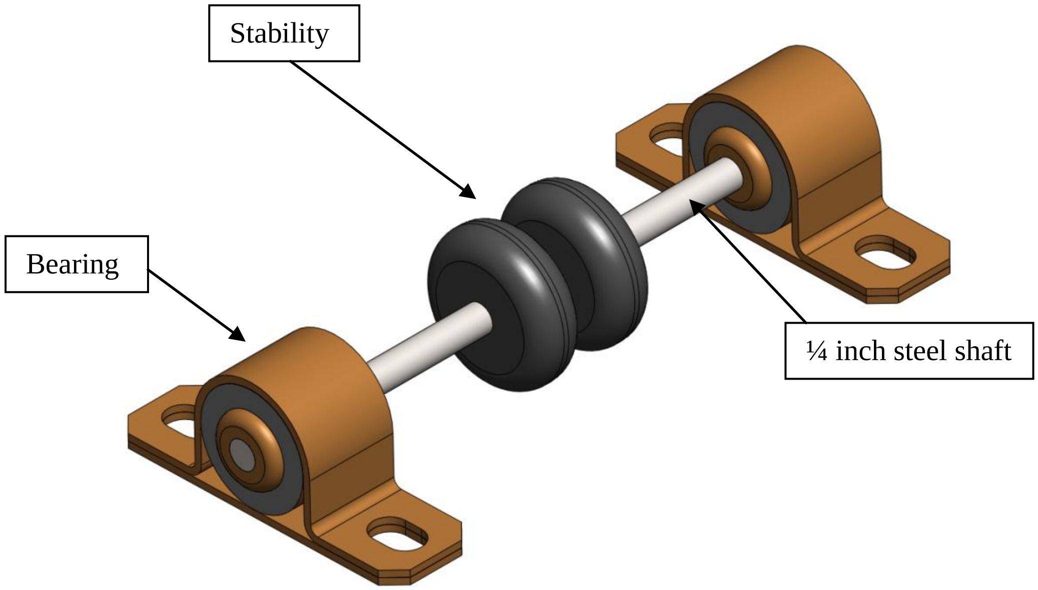


Figure 27: CAD model of stability wheel sets

7.3 Rotational Module

This module is fixed to a belt that the user wears on the inner side and to the translational module on the outer side to provide rotation. This section contains a D.C. motor inside an aluminum box made of bracketed aluminum plates. The size of the containing box is the same width and height of the translational module for aesthetic purposes and the depth is determined by the length of the rotary D.C. gear motor. This gear motor has a pre-geared output of 22.1 inch pounds of torque at maximum efficiency. For more details on the rotational motor refer to Appendix I. There are 5- .375 inch wide by .375 inch long X .125 inch thick aluminum plates with 2 holes in them on the rotational module. These plates have two size 10-24 screws through them and hold D-rings for the nylon strap belt attachments. There is 2 D-ring holders with one D-ring each on the top plate. On the front and back plate there is one holder with 2-D-rings on each. Lastly, on the bottom plate there is one holder with 1 D-ring. On the front and back plates there is a 5/16" hole for the translational rotational motor wires to come out of the module. On the back of the box there is a piece of plywood that is bolted to the inner plate with ¼ inch hex bolts. The plywood acts as another heat sink for the rotary system and provides easy attachment for polyurethane foam padding to make the device more comfortable for the user. A 6 mm shaft motor hub (Appendix I) is attached to rotational motor shaft to aid in attaching the rotational motor to the translational module. The two systems are also attached on the outer plate of the rotary module and the inner plate of the translational module by a turntable that aids in rotation of the translational module. In the figure 19 below, the turntables should be aligned with each other and not offset as shown in this CAD assembly of the rotational module right side view. The full hip module for one side of the body with the cane and no belt can be seen in Figure 28 below.

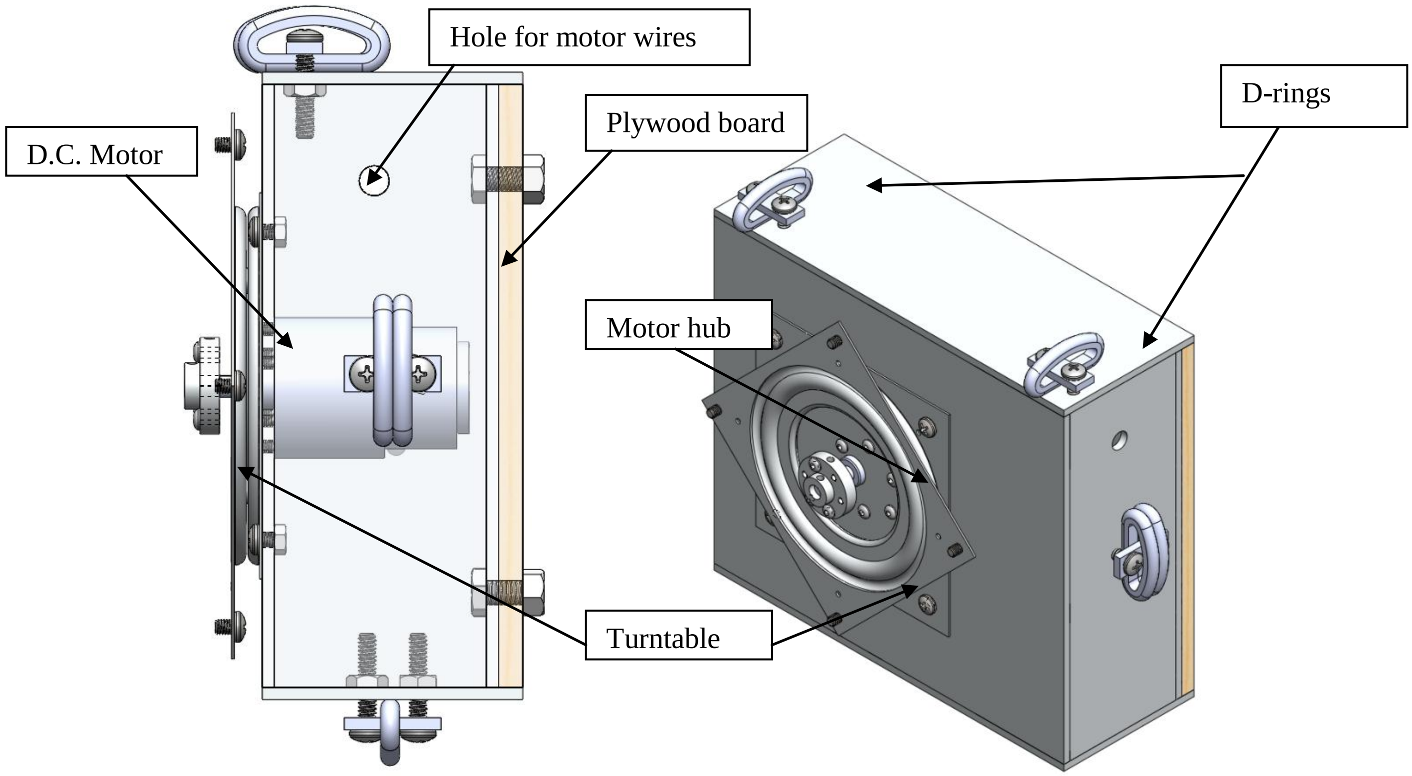


Figure 28. CAD model of rotational module- side view (left), isometric view (right)

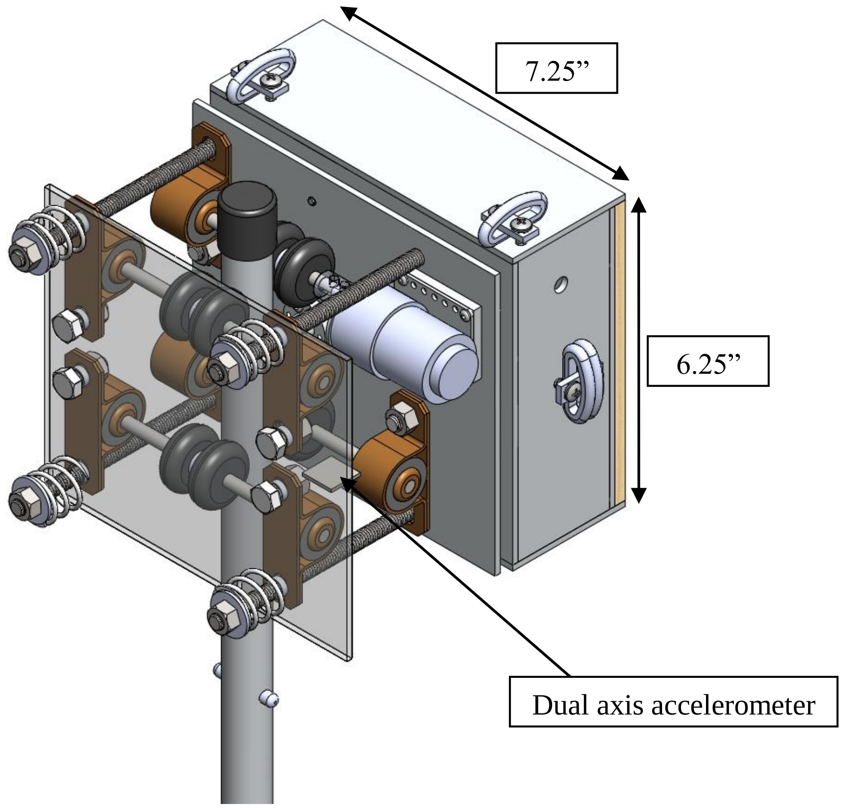


Figure 29. CAD model of the Final hip module assembly

7.4 Belt
The belt connects the device to the body using several nylon straps and a Polyvinyl Chloride back piece. The 1 inch wide nylon straps adjust to fit a wide range of hip and waist sizes to accommodate different body shapes. The adjustable sections are strap 1 the upper waist strap length, strap 2 the length between the hip modules over the front of the body, strap 3 the connection between the hip module and strap 1, strap 4 between the plastic piece and hip modules and straps 5 and 6 that attach around one's leg. The hard plastic backing measures 8 inch long, 5 inch tall, and .125 inch deep and contains the microcontroller. The plastic section will be lined with the same polyurethane foam as the rotary module to better fit the shape of the user's back. See Figure 30 below for a model of the belt with the straps numbers labeled.

Strap 1: 54 inches
Strap 2: 36 inches
Strap 3: 12 inches
Strap 4: 24 inches
Strap 5: 12 inches

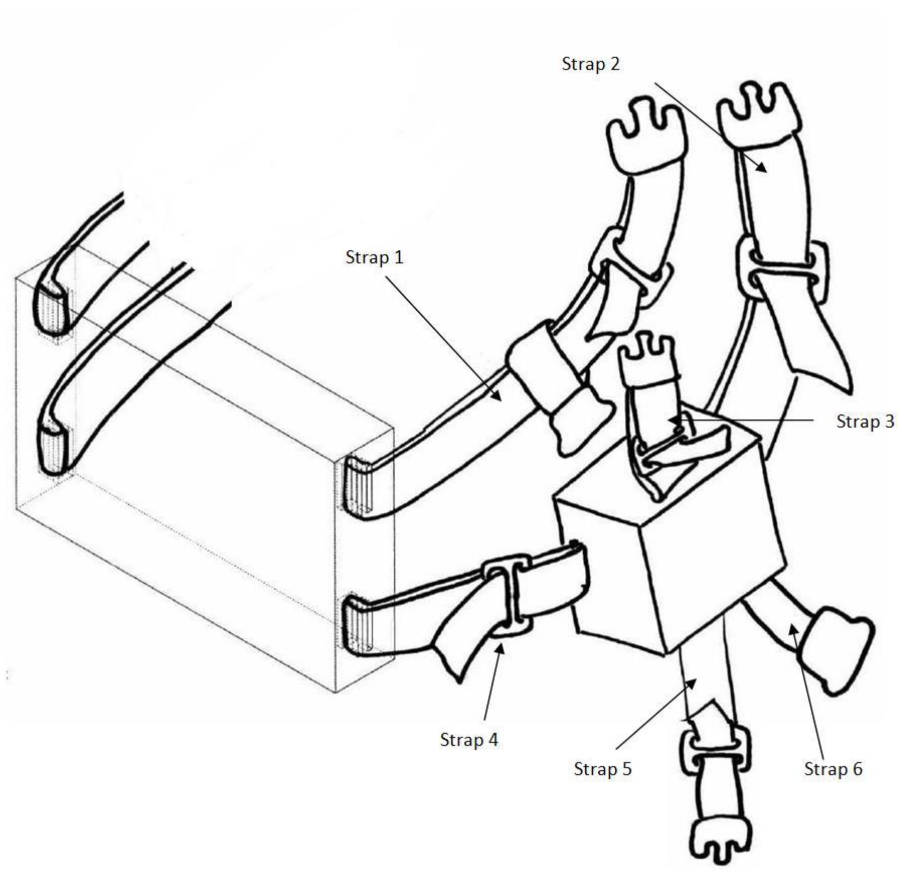


Figure 30. Drawn model of belt with labeled straps

7.5 Mechatronics

The electrical system consists primarily of one microcontroller, two motor controllers, four motors, two accelerometers, one force sensitive resistor, and two voltage sources. The microcontroller is a Parallax BasicStamp 2 which carries its own voltage source, a 9 Volt (V) alkaline battery. The microcontroller is programmed using a language called PBASIC which is a version of BASIC created by Parallax Inc. This microcontroller iteratively collects inputs, performs calculations on those inputs, and sends outputs to the motor controllers when required by the preprogrammed computer code. The microcontroller, through the hardware it contains, converts the 9 V power source to a regulated 5 V signal. This 5 V signal is used to power both the motor controllers as well as the accelerometers. In addition to the 9 V battery, the four motors require an additional voltage source. The voltage source that will be used for the prototype and any initial testing will be a lab power supply which operates through an extension cable to the device.

Each motor controller controls two motors. To distribute power dissipation equally between the motor controllers, each side of the body uses one motor controller for both the rotational and translational motors. In this configuration, each motor will be able to turn clockwise and counterclockwise, brake, and spin freely. The speed of rotation in either direction is variable using pulse width modulation (PWM) output from the microcontroller to the motor controller. The function of each motor is independent of the other motors. Each accelerometer is powered by the 5 V signal provided by the microcontroller. Each accelerometer measures dynamic as well as static accelerations up to ±1.2 times gravitational acceleration. The accelerometer sends acceleration data to the microcontroller using PWM where the width of the pulse corresponds to the acceleration along an axis. Each of the two accelerometers measures accelerations on two orthogonal axes and outputs these four signals to the microcontroller. The force sensitive resistor is inserted into the user's shoe and measures between 10 grams and 100 kg of force. This sensor is for synchronization with the user's stride and initiates the walking sequence. These components are rated to withstand the voltage, current, and power dissipation they will experience.

The following is a diagram (Figure 31) of the connections between the various components. Attached in Appendix H are the truth tables that will be used in the control system as well as some of the final computer code.

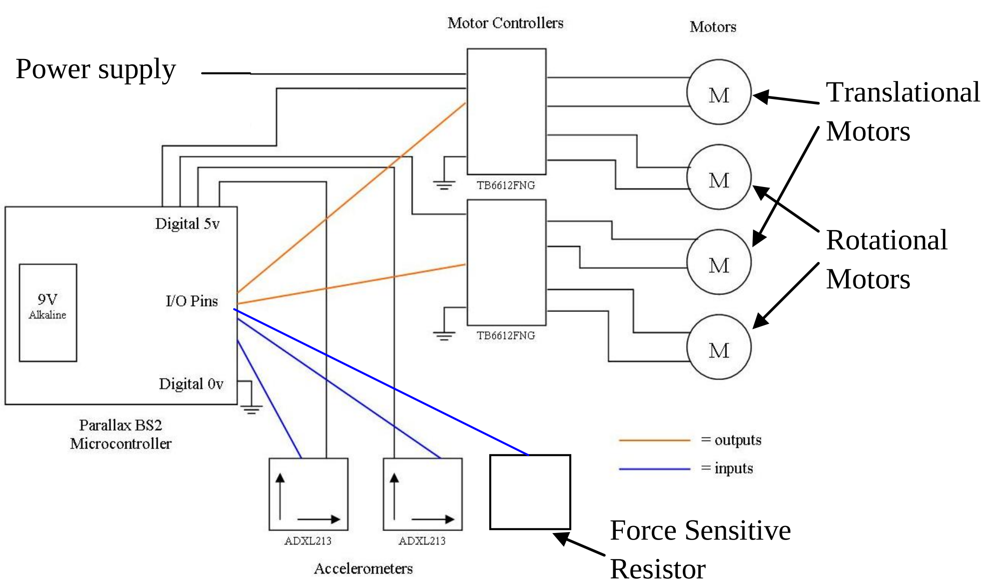


Figure 31. Diagram of control system connections including motors, power sources, sensors, motor controllers, and microcontroller

8. FABRICATION PLAN

A complete list of CAD drawings, Bill of Materials, and Safety Report can be found in Appendices G, I, and J respectively. Machine speeds and tools are taken from the Machinery's Handbook [31].

8.1 List of Major Pre-Manufactured Components

In addition to the standard large-scale manufacturing companies, this device uses many parts obtained from hobby manufacturers. The parts can be used in the same applications as small robots and machines. Hobby supplies tend to be cheaper than industrial quality parts, but there is negligible difference in performance for the application of this prototype. Standard sizing of bolts and brackets were attempted for all parts to make it easier to assemble and troubleshoot during manufacturing.

8.1.1 Translational Motor

Description: This is a gear motor of internal gear ration of 50:1 that supplies the actuation for the cane to move vertically. The stall torque is 12 kg-cm has a no-load speed of 200 RPM. It draws 300 mA of current off of a 12 V battery. Using an internally geared motor allows for a high torque and low speed without using gears and thus increasing the number of components.

Table 8.

Quantity	2
Vendor	Pololu
Part Number	1104

8.1.2 Motor Mounting Bracket

Description: This bracket is the suggested one to accompany the chosen translational motor to mount to the rotary frame. It includes 6 screws that will attach the motor to the bracket.

Table 9.

Quantity	2
Vendor	Pololu
Part Number	1084

8.*1.3 Shaft Coupler*

Description: This component serves to increase the shaft length coming out of the motor. It comes with set screws to connect the output shaft of the motor to the shaft that runs through the wheels and bearing.

Table 10.

Quantity	2
Vendor	Climax Metal
Part Number	138288

8.1.4 Bearings

Description: This particular bearing minimizes noise and vibration to achieve a quieter device with less undesirable motion. The bearing allows for the requisite speed and torque of the output shaft of the motor, which is also the speed of the other shafts connected to the dummy rollers.

Table 11.

Quantity	14
Vendor	McMaster Carr
Part Number	7930K11

8.1.5 Rotary Motor
Description: Similar to the translational motor, this motor has an internal gear box that yields an output with high torque and low speeds. The motor runs of a 12 V battery and outputs 250 N-cm of torque at a speed of 15 RPM.

Table 12.

Quantity	2
Vendor	Virtual Village
Part Number	001480-114

8.1.6 Bolts
Description: These bolts are 5/16" in diameter and 5.25" in length. They fit through the bearing mount holes for better transmission of the force

Table 13.

Quantity	8
Vendor	Carpenter Brothers
Part Number	N/A

8.1.7 Springs
Description: These compression springs have closed and ground ends and output a maximum of 21.59 lbs of force. The outer diameter is 5/16", free length is 2 1/32", and compressed length is 0.64". Using four springs on a side to increase the normal

Table 14.

Quantity	8
Vendor	McMaster Carr
Part Number	9657K101

8.1.8 Turntable
Description: This component connects the hip and rotary modules while allowing the rotary module to rotate. It is connected with screws and turns to allow access to all holes.

Table 15.

Quantity	2
Vendor	McMaster Carr
Part Number	6031K2

8.1.9 Wheels
Description: The wheels are the contact points on the cane. The outer diameter is 1 ¼" and have a solid aluminum hub with a 1/16" axle hole. The tires are made of rubber and have a complex curved shape on the outer rim.

Table 16.

Quantity	16
Vendor	Robot Marketplace
Part Number	0-SUL353

8.1.10 Waist Belt Straps

Description: These straps connect the device to the body. Straps connect the plastic backing to the hip modules, connect the hip modules in front of the body, circle the legs and the waist, and connect the hip modules to the waist and leg straps. Each strap is 5 feet long and can be cut to length for each of the individual straps

Table 17.

Quantity	6
Vendor	REI
Part Number	709053

8.1.11 Motor Hubs

Description: The hubs will attach the rotational motor to the inside plate of the rotary module. The included set screw will secure the hub to the output shaft and the hub has 6 screws to attach the hub to the plate

Table 18.

Quantity	2
Vendor	Pololu
Part Number	1083

8.2 Cane

The team will use the band saw to cut the stock to the appropriate length for both the larger diameter and smaller diameter shafts. To make the cane adjustable, the holes will need to be cut out so that the pin can be inserted. The holes will be cut into the larger diameter section using the drill press according to the picture in Section 4, cutting through the material to ensure that the holes are aligned correctly along the center of the shaft. For the slot in the smaller diameter section, a hole will be drilled for the spring mechanism and then through one end of the slot. The mill will then be used to make the slot down the cane. This manufacturing plan, along with tools and speeds, is listed in Table 19.

Step	Operation	Machine	Tool	Cutting Speed
1	Cut to Length	Band Saw	-	275-300 fpm
2	Drill Pin Holes (Large Shaft)	Drill Press	¼ inch Drill	N/A
3	Drill Pin Hole (Small Shaft)	Mill	¼ inch Drill	3000 rpm
4	Make Slot	Mill	¼ inch End Mill	2500 rpm

Table 19. Manufacturing Plan for Cane

8.3 Wheel Hubs

The wheels have a solid aluminum hub with a 1/16 inch hole for an axle. In order to fit the shafts of this device, the diameter of the axle hole needs to be drilled out to press fit over the shaft. This operation will be done using the lathe, first with a 7/32 drill bit and then reamer. The wheels will be press fit onto the shafts to the appropriate position of cane contact.

8.4 Plates

The plates will be made from 1/8 inch aluminum from various sizes of stock material. The plates will be cut, milled, and drilled according to drawings in Appendix G. The dimensions of the 8 total plates to be cut are 7.25 inch by 6.25 inch. The various drill bits that will be used to make holes in the more complicated plates are listed in Tables 20 and 21. The mill will be used to cut the holes for accuracy of position at a cutting speed of 2200 rpm. All of the holes will go the entire way through the material. To cut the holes in the side plates for connection to the D-rings, the hand drill will be used. The hole in the inner rotary plate will be milled out using a ¼ inch end mill. The plywood will be cut to 7.25 inch by 6.25 inch using the band saw and the holes drilled using the drill press.

Operation No.	**Drill Size**	**No. of Holes**
1	½ inch	1
2	No. 43	14
3	5/16 inch	7
4	M4	4

Table 20. Drilling Operation for One Inner Translational Plate

Operation No.	**Drill Size**	**No. of Holes**
1	31/64 inch	1
2	¼ inch	4
3	M4	4

Table 21. Drilling Operation for One Outer Rotary Plates

8.5 Shafts

The 6 dummy shafts will be cut to 5.75 inch using the band saw. The 2 driven shafts will be cut to 3.875 inch using the same settings on the band saw and then have a flat milled 0.4 inch long onto one end of each using a ¼ inch end mill at a speed of 2500 rpm.

8.6 Belt

The lengths of the straps will be cut with a utility knife. The sections for connection of the plastic backing to the hip modules will be 24 inches long and the leg sections will be 36 inches long. The hip module to the waist belt will be 2 inch sections attached to an 8 inch section. The hip belt will be 36 inches long and the waist belt will be 54 inch long. Buckles will be on all sections except the back plate to hip module.

8.7 Assembly

The assembly will be done in the major parts and then combined together. The respective assemblies for each side will be done immediately following one another to ensure consistency between the two sides of the device.

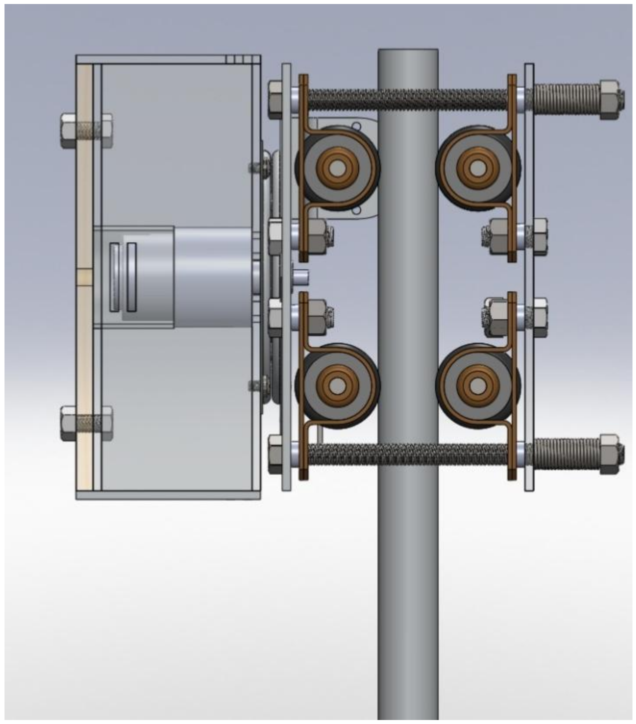


Figure 32. Assembly of Rotary Module, Translational Module, and Cane

8.7.1 Translational Module

The first attachments to the inner translational plate are the motor spacer and mount. Once that is secure, the motor will be attached to the mount using the provided M3 screws. The coupler and shaft are attached to the output shaft of the motor. The bearing of the plate are then attached using 5/16" bolts and nuts on the interior side that does not use the long bolts and the shafts with wheels on them are put into the appropriate holes in the bearings. The same bearing, shaft, and wheel attachment is done for the outer translational plate. The hub is also attached to the inner translational plates at this point.

8.7.2 Rotary Module

First, the outer plate and the box walls will be attached with brackets and 10-24 bolts and nuts. The motor will be inserted into the appropriate hole in the outer rotary plate and screwed in using M3 screws. Next, the turntable will be screwed into the outer plate with M4 bolts and nuts. Finally the inner rotary plate is attached to the rest of the box using a hinge at the top and Velcro for the other sides.

8.7.3 Attaching the Translational and Rotational Modules

To attach the two modules, the bolts should be put through the turntable when it is unattached. Then, the turntable should be attached to the inner translational plate and tightened. With the turntable facing up on the inner translational plate, the rotational box should be lined up so that the flat in the rotational motor shaft lines up with the set screws in the hub and the holes for turntable attachment line up with the bolt in the turntable. Then, all nuts and bolts should be tightened. Finally, the modules should be rotated relative to one another so that the holes for the long bolts are exposed. The long bolts should be inserted and tightened to the inner translational plate and the outer translational plate should be attached with the springs, washers, and nuts on the outside.

8.7.4 Cane
Once the cane has been appropriately cut to the specification in Figure 16 in Section 9, the inner shaft will then be inserted into the outer shaft and bolts will be inserted through both the canes through slot and for adjustability. The cane will then be inserted into the translational module after the belt assembly is complete.

8.7.5 Belt
The first step in assembling the belt is the plastic backing. The D-Rings will be attached on the four corners and the appropriate straps will be sewn in loops to the bottom rings. The foam will be attached to the backing and the microcontroller will be mounted to the back. Next the straps that connect the hip modules to the waist will be sewn to the D-rings on the top of the box. The waist belt will be threaded through the top straps with the buckles for attachment to the modules threaded through, one before threading through the back and the other after.

9. VALIDATION RESULTS
A series of tests must be performed on the device to determine whether the device meets the engineering specifications derived from sponsor requirements. Below Table 22 shows the progression from the requirements to the method for checking that the device meets those requirements. The prototype does not meet all the specifications, but Section 10 details potential changes to achieve those specifications where the current prototype failed.

Sponsor Requirements	Engineering Specifications	Target Values	Validation Test	Goal Met?
Safe to use	Rough surfaces/sharp edges	0	Rub balloon over all parts of device	No
	Cane yield strength	100-200 MPa	Physical	Yes
Improves gait/no negative impact	Increase step length	5%	GaitRite mat, force plate treadmill	
	Decrease step width	20%	GaitRite mat, force plate treadmill	
Adjustable	Cane length adjustability	0.2 m	Physical	Yes
Durable	Life Cycle	> 3 years	HALT Life Cycle Test [33]	
Low cost	Price	< $400	Budget check	No
Light	Weight	< 5 kg	Physical	No
Community accessible	Width	< 0.76 m	Physical	Yes
Socially acceptable	Aesthetically pleasing	> 3 on survey	Survey	
	Comfortable	> 4 on survey	Survey people after wearing device for 5 min.	

Table 22. Summary of device performance compared to requirements and specifications

9.1 Physical Measurements
Many of the specifications involved the actual size and properties of the device. These specifications are number of sharp edges, yield strength, adjustability, price, weight, and width. To test the device for safe edges and potential harm when touching the device, a balloon was moved over all the surfaces, edges, and corners of the device. If the balloon popped, that part was determined sharp and further filed down to produce a safe surface until all edges were rounded and smooth. The parts of the device that were still sharp after filing were the electrical wire ends and motor connections. In a future design, these portions would be inside a case making them inaccessible to the user, but the current prototype pops the balloon at 3 locations on the device.

The cane is made of 6061 aluminum, which has a yield strength of 193-290 MPa which exceeds the target range. This yield strength ensures that the cane will hold the user's weight during a fall without bending or deforming, which is crucial to the safety of the user. The adjustability and width were measured with a measuring tape. The cane has 8 holes spaced 1 inch apart, allowing for different leg length variability of 8 inches and the overall width of the device itself is 0.49 meters. This width measurement does not take into account the width of the user, thus the width during use is larger. The overall width for the device in use is dependent on the hip width of the user, so the ability to be community accessible in fitting through doorways is inconclusive because each user will be different.

Two specifications the device did not meet are price and weight. The cost to build the device was $611.86 and the overall weight is 6.9 kg. The price is high because prototype costs are much higher than mass production. Using different processes and having more time to do more manufacturing would dramatically reduce costs, making an affordable model for the consumer. The weight is highly correlates to the budget because the device could be made lighter using different materials, which are more costly. Manufacturing some parts instead of buying them would also reduce the weight due to material choice.

9.2 Gait Testing

Two of the main engineering specifications that the automatic canes device needs to meet involve the gait improvement of the user. This device should decrease a person with Spina Bifida's normal step width and increase the normal step length. Since the device's target age group is 5-12 years old children with Spina Bifida, the prototype needs to be tested by subjects from this group to validate these targets. However, to test minors who are under the age of 18 special consent is needed from guardians and is usually not encouraged [32]. On top of the age obstacle, it would take several months to obtain the necessary approval from an Institutional Review Board (IRB) to do a research experiment (J. Sansom, Personal communication). Lastly, it would take too much time to obtain participants with a Neuromotor disability for testing the device at this point to be feasible.

Further testing of this device can and should be done in the future. A GaitRite mat can be used to determine appropriate placement of the cane with respect to the user and whether the canes are moving at the appropriate speed in accordance with the opposite leg. Additionally, the kinetics of the device can be tested using an instrumented treadmill, which can take force data during walking. The instrumented treadmill also provides the advantage of allowing the user to walk much longer and for many more gait cycles. To test the life cycle of the device, a method such as the Highly Accelerated Life Testing (HALT) process used at Dayton T. Brown can be used to estimate the projected length of time the device can be used before failure [33]. The conditions would be estimated at 6 hours of use daily and the target would be 3 years under this condition.

9.3 User Survey

To validate the more subjective specifications, user surveys must be conducted to determine if the device will be worn by an actual patient. A sample survey is included in Appendix P and inquires about the appearance, comfort, and ease of use of the device using the Likert scale [34]. This survey will be given to children with Spina Bifida, as well as their parents. Similarly to the gait testing, there is not time to find enough participants for a survey to be valid, but it could be done in the future.

As a preliminary test, the device was fitted to 10 different healthy adults who wore the device for a period of 5 minutes as they both stood still and walked a 3 meter track 5 times. The device was turned off while worn by the test subjects for safety precautions. Afterwards, these subjects were asked to rate the comfortableness and appearance of the device on a scale of 1-5. The participants gave the device an average score of 4.1 on comfort and 3.2 on aesthetics (full table of results in Appendix P). Though these results are consistent with the specification values (Table 22), they are inconclusive because they are not part of the target demographic, the duration of the comfort test was insufficient to gather reliable data (too little time to test longer wear times), and the number of participants tested was too small to provide usable data. It is sufficient for preliminary testing, but is inconclusive when determining whether or not the specifications are met.

10. DESIGN CRITIQUE

This design for the automatic canes demonstrates all of the concepts of the device and functions the same way, however the available time and budget limited some areas of the design. For a final market device, some changes would be made to the materials and the design that would optimize the device and meet all of the engineering specifications. There were also many issues that the team did not find until post-manufacturing during device testing.

10.1 Belt Improvements

The material choice for the foam in the current device was limited by the high cost and limited availability of quality foams [2]. In the final design, higher quality foam like memory foam or other foams used in ergonomic practices and orthotics would be used for padding. When the prototype was worn, it had a tendency to bend inward towards the person which was not what the team had intended for the design. Through empirical testing it was determined that by replacing the side release buckles with triglides, there will be more room to tighten these side straps. By tightening these straps, the device will sit more snug to one's body keeping the canes at a 90 degree angle with the ground. In Figure X below the prototype is shown at a slightly exaggerated tilt angle. The angle is around 10-15 degrees from the ground when the device is worn properly as originally designed.

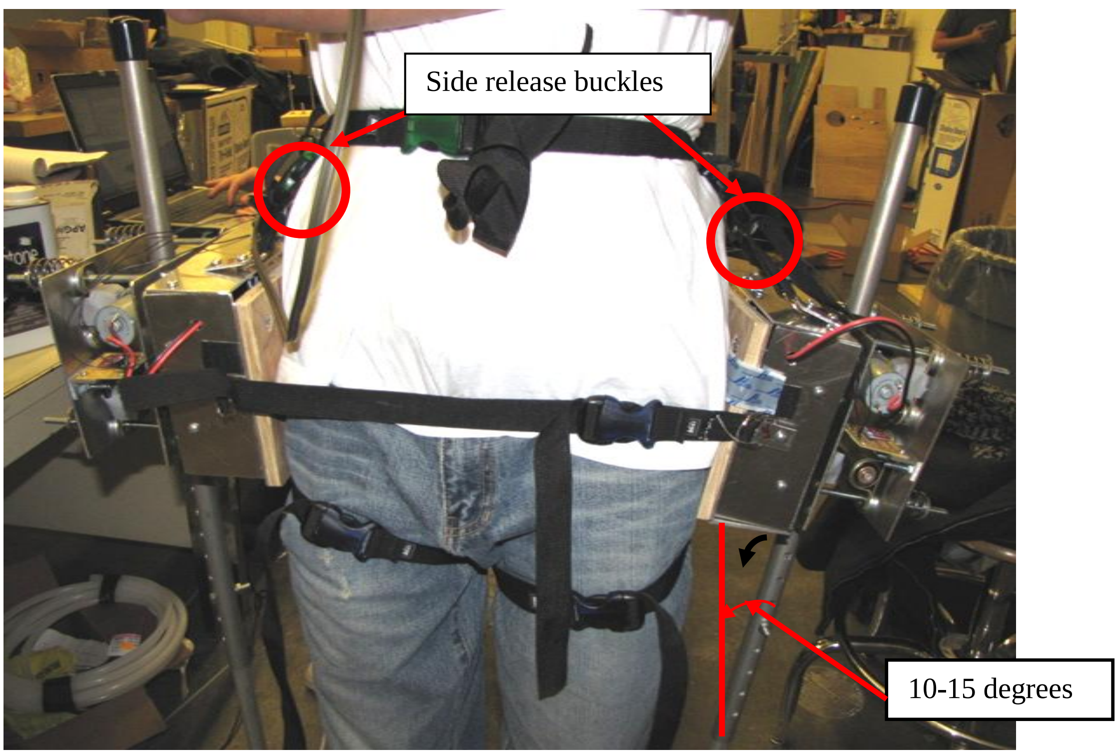


Figure 33. Figure to demonstrate inward tilt of the canes during wear

10.2 Translational Module Improvement

10.2.1 Translational module exterior

To make the device more aesthetically pleasing and safer, a plastic case with customizable décor would be placed around the translational module. This will prevent pinch points as well as act as a shield from debris and weather. Also both modules would also be circular instead of square in the final device. This would decrease the size of the overall size of the device while also giving it a sleeker look by mimicking the hip joint. This shape would also help to reduce stress concentrations and increase durability.

10.2.2 Normal force

The engineering specifications called for 0 sharp edges and 0 rough edges on the device. Although the device had smooth external edges, protrusions were not specifically covered in this specification. The bolts protruding from the translational module that holds the compression springs for normal force could be associated with the device safety as well. It is possible that during use these bolts could be caught on another person or external obstacle causing injury to the user or his or her peers. They also might make it hard for the user to maneuver through narrow doorways. To solve this problem, the team proposes that the final design will replace the 4 external compression springs with 4 tensile springs that will be on the inside of the device . These springs will provide a force that pulls the device inwards creating the same normal force needed to keep the cane from slipping through the wheels. This solution allows for the springs to be protected from debris, while decreasing the device width outward from the body, and removing the protruding bolts.

10.2.3 Cane Removal

Though in the prototype the cane is removable through the bottom of the module, the final design would include an easier system to disengage the cane from the hip module. For safety and convenience a door would be added to the plate facing outward from the body. By pressing a button a latch would unhook, in a spring loaded fashion, so that the user could easily remove the canes. This would mean that the bearings on the outer translational plate would have to move inwards and be attached to the door portion of the module (Figure x. Below). In the final design the canes would have an ergonomic shaped rubber grip on the top to ensure that the canes could be used comfortably as manual walking poles in case of electronic failure and the need for cane removal.

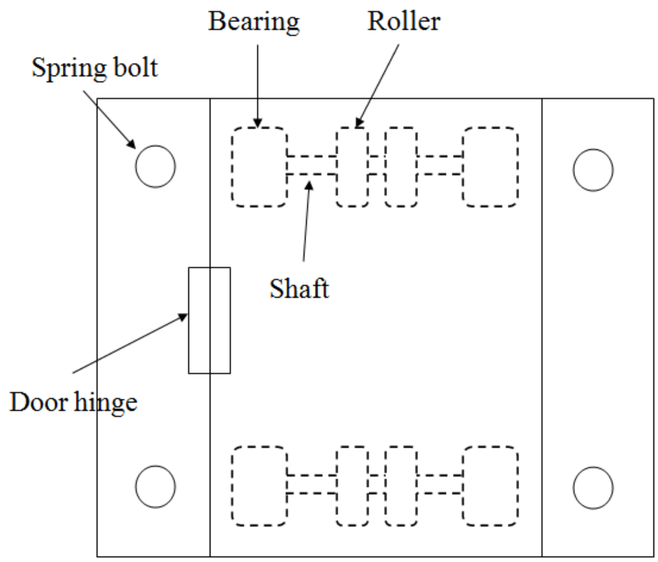


Figure 34. Schematic of cane removal door.

10.2.4 Wheel alignment/assembly

In the prototype the wheels that were chosen within the budget and size constraints, needed to have the holes in the hubs reamed out to slightly smaller than ¼ inch hole for a press fit to the shafts. Because the material of each wheel hub was aluminum, the press fit did not hold due to the material's ease of deformation. In the final design instead of press fitting the wheels onto the shafts, the team would make two collars of .25 inch inner radius with set screws. These screws will work to clamp the collar to the shaft and the wheel to the collar. With the proper spacer in between the two wheels, these collars will be placed on either side of the drive wheels. For the stability wheels there will be 2 spacers instead of collars on either side of the wheels to keep them from moving outward towards the bearings while allowing them to spin freely (See Figure 35). Lastly, the current thrust bearings used in this assembly were made out of a bronze alloy. Each bearing weighed approximately .1 kg with this material, and by changing the outer mount to aluminum this would reduce the overall weight of the device. These bearings would also have closed ends so that the shafts would not slip through them which happened with the prototype device.

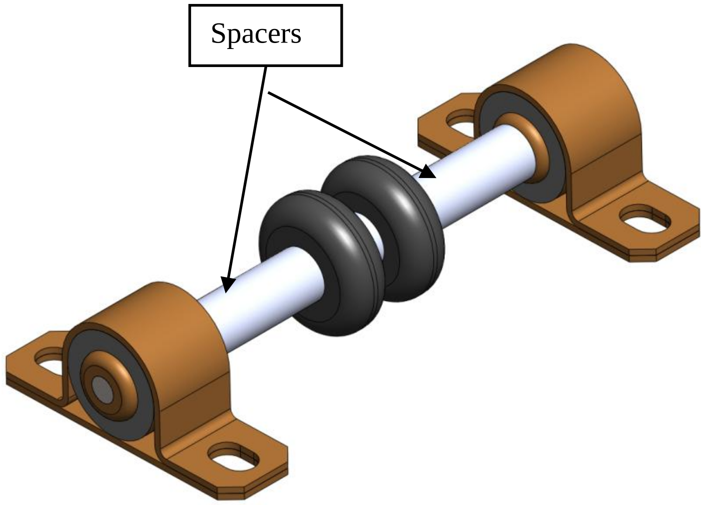


Figure 35. Stability Wheel Assembly with spacers

10.3 Rotational Module Improvements

10.3.1 Size Decrease

To decrease the distance of the device away from the body in the medial lateral direction, the rotational module would need to decrease in width. The width of the rotary module was limited by the length of the motor that contained the necessary specifications to provide the proper torque for rotation within the given budget. One way to accomplish width reduction would be to use a right angle motor instead of the straight motor used in the prototype. This motor would be mounted to the inner rotational plate with a bracket similar to that used with the translational motor). This will decrease the width by approximately .75 inches and make device less bulky.

10.3.2 Attachment to Translational

The hub used to attach the rotational module to the translational module, used two machine set screws in parallel pressing on the flat of the D-shaft on the rotational motor. With this method the team saw during functionality tests that the set screws could loosen and cause the motor shaft to spin freely within the hub prohibiting rotation. By using a key way attachment between the hub and the motor shaft, the hub will be more secure and ensure rotation.

10.3.3 Rotational module Exterior

To help with the aesthetics of the device as well as decrease the total weight. There should be a case that matches the circular shape of the final translational module case (section 10.2.1 above).This means the front and back as well as the top and bottom aluminum plates of the module would no longer be necessary which would directly decreasing the weight of the overall device. There also is no true need for the plywood board with this case, because it would act as the surface between the foam and the device.

10.4 Cane Improvements

Due to issues with press fits and budget the prototype ¼ inch hex head nuts and bolts were used for the hard stop pin, the alignment pin, and the adjustable pin. The final cane will have a 1” long by ¼” diameter metal dowel pin with rounded edges pressed into place for the alignment pin. The hard stop will also have a ¼” metal dowel pin pressed into the hole, but it will be 2 inches long to catch on the shafts in the module. The hard stop pin would also be covered with rubber to help dampen the collision on the shafts if the cane slips upwards during motor failure. On the inner cane section the alignment slot would change so that it spans to the top of this inner portion (see Figure 36. below) so that the hard stop would not inhibit adjustability. In the prototype budget prevented the team from using the torsion spring telescoping pin, but in the final device this type of pin would be used for adjustment. Lastly, the bottom of the cane will have a variety of removable end sections with the original being much more flexible then the end chosen for the prototype with an ability to rotate giving the user better ease of movement during use. These ends will be interchangeable with others so that the user can choose one to suit the weather conditions and type of terrain.

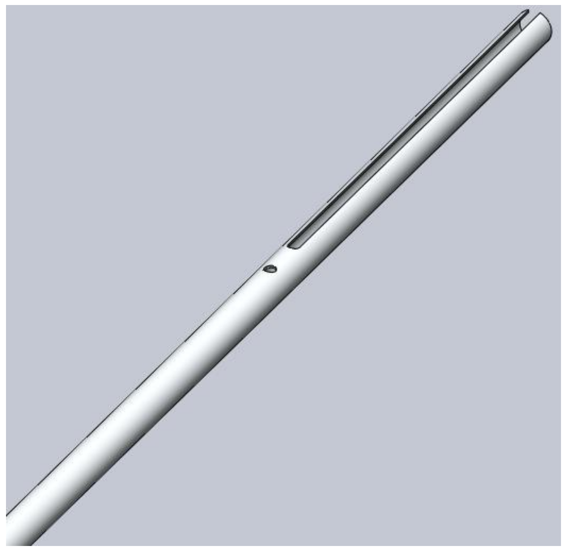


Figure36. CAD model new inner cane

10.5 Mechatronics Improvements

Budget, electronics knowledge, and time for program debugging limited the team's ability to construct the best mechatronic system. In the final design, the mechatronics would be encased on the back panel of the belt instead of left open as seen in the prototype (Figure 37). This will prevent debris from entering the system, insulate the device to protect the user and others from the electronics, and better secure the wire connections. This back belt panel would also contain a lithium ion battery to make the device remote and last for several hours. In the prototype, stray wires were hanging between the hip module and the belt. In the final design motor wires would be in a thick insulated sleeve or harness and follow the strap of the belt to remain out of the way of the user and to prevent the wires from coming loose. In the prototype a kill switch to cease power if there is a problem with the device was made so the person must hold it while wearing the device. Since the team wants this device to be completely hands free, the final design will have the kill switch wired to a button on the front of the belt. This way the user can still press it when there is a problem, but their hands will be free during use.

With more time and money, more sensors would be implemented to better synchronize with the gait. This is important because people with Neuromotor disabilities each have different rhythms and strides and this device should be applicable to all types of gaits. In further models the ability of the user to walk backwards, change directions, walk sideways, and go up stairs would all be programmed, probably using additional sensors as well. To achieve these goals, several pieces of hardware will have to be upgraded and added. Though the current microcontroller was sufficient for initial prototype purposes, a future design would implement a more advanced microcontroller such as the Arduino Mega [35] or Arduino Bluetooth [36]. The former offers many more input and output ports that would facilitate additional sensors. The latter is a wireless device that operates with Bluetooth technology, thus minimizing the need to have wiring and hide and protect it from the user. To obtain better data for the movement of the modules, gyroscopes would be added to complement the accelerometers. Gyroscopes would give velocity data in addition to accelerations, which makes the measurements more accurate and useful. A possible gyroscope would be a Dual Axis Gyro Breakout from SparkFun.com [37]. For the system to handle the addition power, a more resilient H-bridge to drive the motors is needed. The prototype was operating very close to the operational limit of the H-bridges, so a better circuit would use one that can operate under higher currents. A possible choice is very similar to the current model from Pololu, but it has a 2.5 A continuous operating condition and peak amperage at 5 A, which will be sufficient to handle the increased power requirements [38].

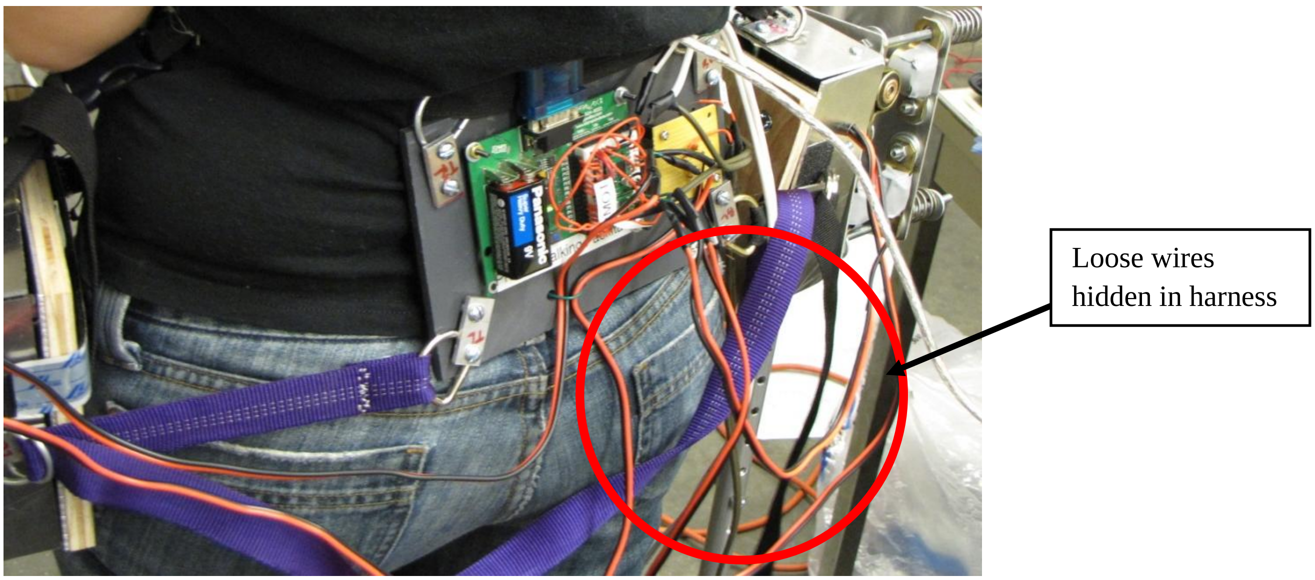


Figure 37. Prototype demonstration of hanging wires and need for casing over electronics

11. RECOMMENDATIONS

It is the recommendation of this team that the sponsor continues the development of this device in design development and validation testing. The design improvements in Section 10 will make the device meet more specifications, but the current project timeline and resources restricted a lot of potential progress. One possible route of continued design development is more sponsorship of this project for at least one additional semester in the context of ME 450. Future design teams could implement some of the suggestions made by this team as well as improving and designing other parts of the device that the timeline of this project made impossible for the current team.

The sponsor should also conduct additional testing of the device. Some of the validation tests to determine the degree of assistance of this device were outside the ability of this team to perform given time and resource limitation. Section 9 describes a few of the initial experiments that would validate the specifications, but many additional tests could be performed to investigate other aspects of the affects of the device on the gait of the individual that would affect people with Spina Bifida as well other demographics including people with balance disorders and the elderly among others.

12. CONCLUSION

The goal of this project was to design and build a new walking facilitator for children with Spina Bifida. The team researched, brainstormed, and came to the decision to pursue the automatic canes concept. After CAD modeling of the final design, the team manufactured the device to achieve a functioning prototype. The team performed some initial specification validation tests, meeting width, strength, and adjustability and failing at weight, sharp edges, and cost. More testing to check for gait improvement and more design modifications should be done in the future as this device progresses towards a usable walking facilitator for the target demographic.

13. ACKNOWLDGEMENTS

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APPENDIX A. QUALITY FUNCTIONAL DIAGRAM

	Weight	Cost per Device	Maximum Width	Cane Adjustability	Yeild Strength	Normalized Step Width	Normalized Step Length	Aestheically Pleasing	Comfortable	No Sharp Edges/Rough Surfaces	Life Cycle
Weight											
Cost per Device	3										
Maximum Width	3	3									
Cane Adjustability											
Yeild Strength		3									
Normalized Step Width											
Normalized Step Length											
Aestheically Pleasing		3	9								
Comfortable								9			
No Sharp Edges/Rough Surfaces								9	9		
Life Cycle		9									

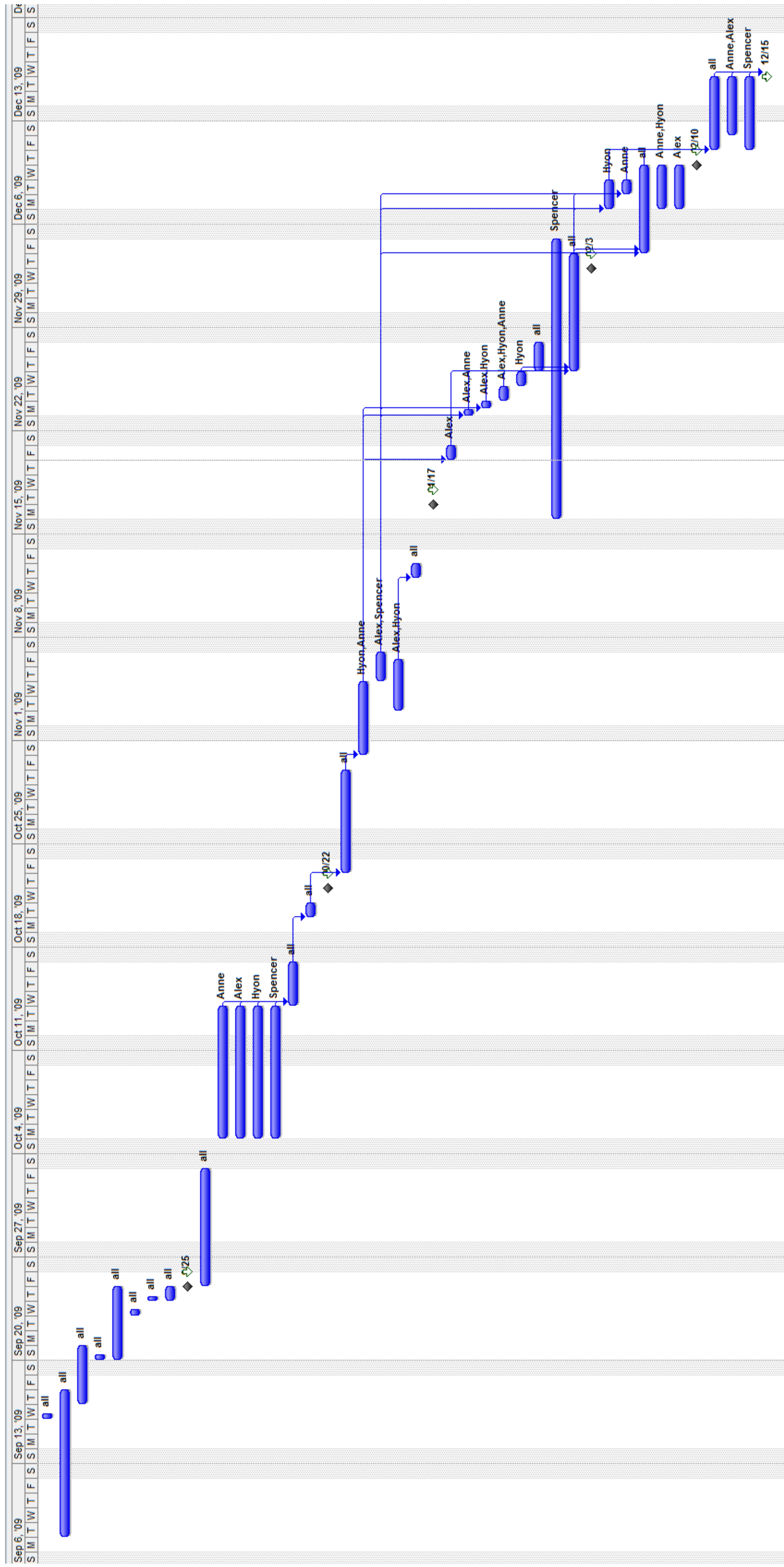
Customer Needs	Customer Weights	Weight	Cost per Device	Maximum Width	Cane Adjustability	Yield Strength	Normalized Step Width	Normalized Step Length	Aesthetically Pleasing	Comfortable	No Sharp Edges/Rough Surfaces	Life Cycle	Loftstrand Crutches	Posterior Rolling Walker	Cane/Quad Cane	Walking Poles
Safe to Use	10					9					9		3	5	2	3
Improve Gait	10	3					9	9					3	2	2	3
Low Price	5	3	9									3	4	2	5	5
Durable	6					9						9	4	5	5	5
Unobtrusive/Comfortable	7	9		9					3	9	3		1	2	4	2
Portable	4			9	3								4	3	5	5
Community Accessibility	8			9							3		4	1	4	4
Adjustable	7				9								5	2	4	1
More Socially Acceptable	8			9					9				2	1	2	2
All-surface, All-weather Use	4								3			9	2	2	2	3
Ergonomic	6	9								9	3		2	2	2	3
Target Age 5-12 Years Old	10	3			9				3		3	3	5	5	5	5
	Raw score	192	45	243	165	144	90	90	135	117	183	135				
	Scaled	0.79	0.185	1	0.679	0.593	0.37	0.37	0.556	0.481	0.753	0.556				
	Relative Weight	14%	3%	17%	12%	10%	6%	6%	10%	8%	13%	10%				
	Rank	2	10	1	4	5	8	8	6	7	3					
Technical Requirement Units		kg	$	m	m	MPa	%	%	%	%	#	years				
Technical Requriement Targets					0		20	5	60	80	0	3				
Technical Requriement USL		5	400	0.76		200						2				
Technical Requriement LSL						###						4				

Technical Requirements

How Well Benchmarks Fit Requirements
1- not at all
2- slightly
3- okay
4- good
5- strong

APPENDIX B. GANTT CHART

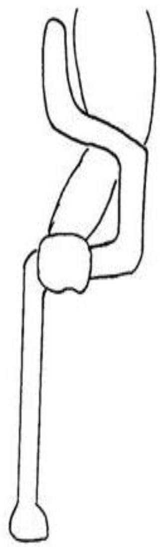
	ℹ	Task Name	Duration	Start	Finish	Predeces	Resource Names
1		Sponsor Meeting #1	2 hrs	Wed 9/16/09	Wed 9/16/09		all
2		Find 10 Journal Articles, 5 Patents	8 days	Tue 9/8/09	Thu 9/17/09		all
3		Read Aquired Literature	3 days	Thu 9/17/09	Sun 9/20/09		all
4		Sponsor Meeting #2	2 hrs	Sun 9/20/09	Sun 9/20/09		all
5		Produce Deliverables for Design Report #1	5 days	Sun 9/20/09	Thu 9/24/09		all
6		DR#1 Oral Presentation Rehearsal	3 hrs	Wed 9/23/09	Wed 9/23/09		all
7		Design Review #1 (3:40 - 4:15pm, 1018 DOW)	30 mins	Thu 9/24/09	Thu 9/24/09		all
8		DR#1 Finishing Report	1 day	Thu 9/24/09	Thu 9/24/09		all
9		Design Review #1 Written Report - Due 5pm	0 days	Fri 9/25/09	Fri 9/25/09		all
10		Blue Sky Thinking	6 days	Fri 9/25/09	Fri 10/2/09		all
11		Concept Generation #1	7 days	Mon 10/5/09	Tue 10/13/09		Anne
12		Concept Generation #2	7 days	Mon 10/5/09	Tue 10/13/09		Alex
13		Concept Generation #3	7 days	Mon 10/5/09	Tue 10/13/09		Hyon
14		Concept Generation #4	7 days	Mon 10/5/09	Tue 10/13/09		Spencer
15		Collaborate, evaluate, combine ideas	3 days	Wed 10/14/09	Fri 10/16/09	14,11,12,	all
16		Consult sponsor on alpha design	1 day	Tue 10/20/09	Tue 10/20/09	15	all
17		Design Review #2	0 days	Thu 10/22/09	Thu 10/22/09		all
18		Revise alpha design	5 days	Fri 10/23/09	Thu 10/29/09	16	all
19		Final Design CAD	4 days	Sat 10/31/09	Wed 11/4/09	18	Hyon,Anne
20		Safety Report	2 days	Thu 11/5/09	Fri 11/6/09		Alex,Spencer
21		Materials Research	3.5 days	Tue 11/3/09	Fri 11/6/09		Alex,Hyon
22		Materials Selection and Order	1 day	Thu 11/12/09	Thu 11/12/09	21	all
23		Design Review #3	0 days	Tue 11/17/09	Tue 11/17/09		all
24		Machining- cutting plate stock	1 day	Fri 11/20/09	Fri 11/20/09	19,20	Alex
25		Machining- Belt	3 hrs	Mon 11/23/09	Mon 11/23/09	19,20	Alex,Anne
26		Machining- Inner Trans. Plate, Outer Cane, Motor Sp	0.5 days	Mon 11/23/09	Mon 11/23/09	19,20	Alex,Hyon
27		Machining- Outer Trans. Plate, Inner Cane, Rotary S	1 day	Tue 11/24/09	Tue 11/24/09		Alex,Hyon,Ann
28		Machining- Outer Rotary, Wheel Hubs	1 day	Wed 11/25/09	Wed 11/25/09		Hyon
29		Thanksgiving Break	2 days	Thu 11/26/09	Fri 11/27/09		all
30		Mechantronics	15 days?	Mon 11/16/09	Fri 12/4/09		Spencer
31		Assembly	6 days	Thu 11/26/09	Thu 12/3/09	24,25,26,	all
32		Design Review #4	0 days	Thu 12/3/09	Thu 12/3/09		all
33		Testing- force plate	2 days	Mon 12/7/09	Tue 12/8/09	31,20	Hyon
34		Testing- GaitRite	1 day?	Tue 12/8/09	Tue 12/8/09	31,20	Anne
35		Mechatronics Optimization	4 days	Fri 12/4/09	Wed 12/9/09	31,20	all
36		Design poster	3 days	Mon 12/7/09	Wed 12/9/09		Anne,Hyon
37		Final Presentation	3 days	Mon 12/7/09	Wed 12/9/09		Alex
38		Design Expo	0 days	Thu 12/10/09	Thu 12/10/09		all
39		Write Remaining Report Sections	4 days	Fri 12/11/09	Tue 12/15/09	33,34,35	all
40		Proofreading/Editing Report	3 days?	Sat 12/12/09	Tue 12/15/09		Anne,Alex
41		Appendices	4 days?	Fri 12/11/09	Tue 12/15/09		Spencer
42		Final Written Report Due	0 days	Tue 12/15/09	Tue 12/15/09	39,40,41	all


Sep 6, '09
Sep 13, '09
Sep 20, '09
Sep 27, '09
Oct 4, '09
Oct 11, '09
Oct 18, '09
Oct 25, '09
Nov 1, '09
Nov 8, '09
Nov 15, '09
Nov 22, '09
Nov 29, '09
Dec 6, '09
Dec 13, '09
all
9/25
Anne
Alex
Hyon
Spencer
10/22
Hyon,Anne
Alex,Spencer
Alex,Hyon
11/17
Alex,Anne
Alex,Hyon
Alex,Hyon,Anne
12/3
Anne,Hyon
12/10
Anne,Alex
12/15

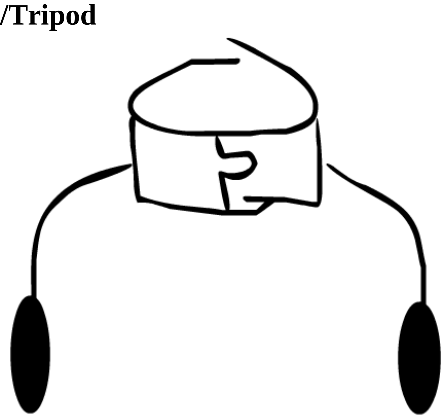
APPENDIX C. COMPLETE LIST OF CONCEPTS

C.1 Novel-shaped aesthetic Loftstrand crutch

- An innovation of the Loftstrand crutch, complex shape provides additional support to arm.
- A more aesthetic Loftstrand crutch.

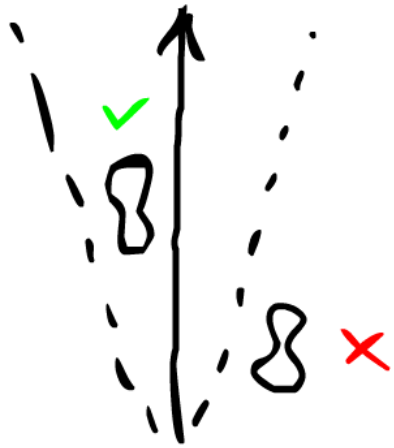


C.2 Bipod/Tripod



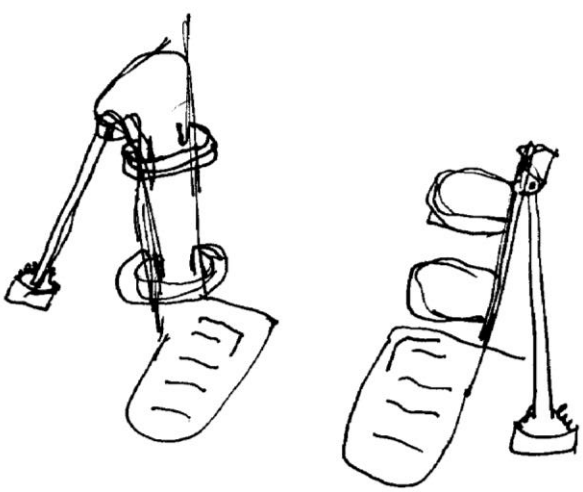
- Two or three wheeled device which is worn around waste.

C.3 Boundary Buzzing Shoes



- Shoe insert in each shoe buzzes (neutral-negative feedback) when foot travels outside of proper area for gait.

C.4 Outside of lower leg crutches

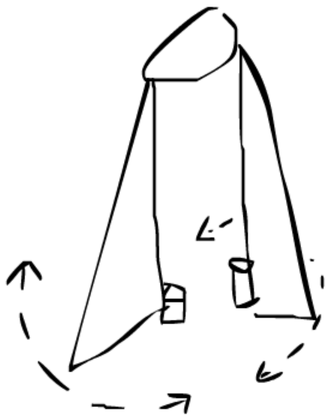


- Provides stability for leaning outwards with a crutch which is attached to the lower quarter.

C.5 Novel Linkage

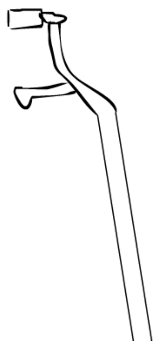
- Uses some sort of novel linkage to harvest energy from a certain part of gait and impart it on another.
- Note that we have not designed any linkage for this concept.

C.6 Triangular segments rotate around legs



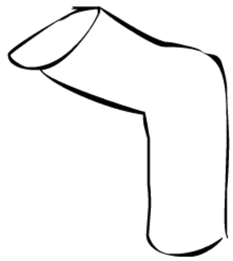
- Triangular segments rotate about legs, attached at hips and ankles.

C.7 Smart Loftstrand Crutch



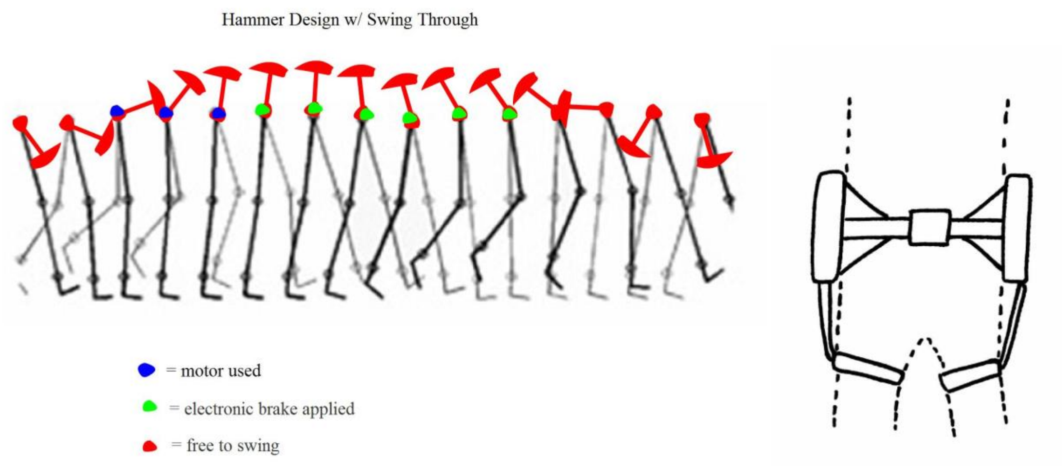
- Very similar to current Loftstrand crutch
- ‘smart’ shape, aka make it curvy
- Possibly mechanism to move handle mid stride, shock absorbing?
- Variable pressure at arm cuff
- Mp3 player?

C.8 Ham/Quad Selector



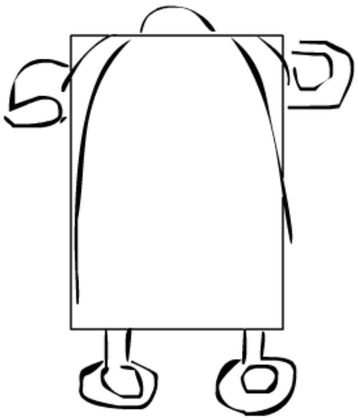
- A device which mechanically puts more force onto hamstring or quadriceps so that in the long run lagging body parts will develop.
- No actual mechanism was conceptualized.

C.9 Hammer Counter Weight



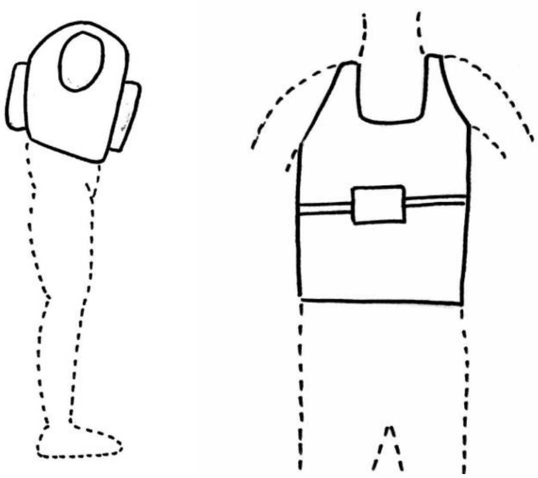
- Uses a hammer to create mechanical advantage in lifting leg and swinging leg forward.
- One conceptualization of this design incorporates the hammer completing a full swing through with each step, other conceptualizations don't.

C.10 Backpack Arm Cuff Rotate



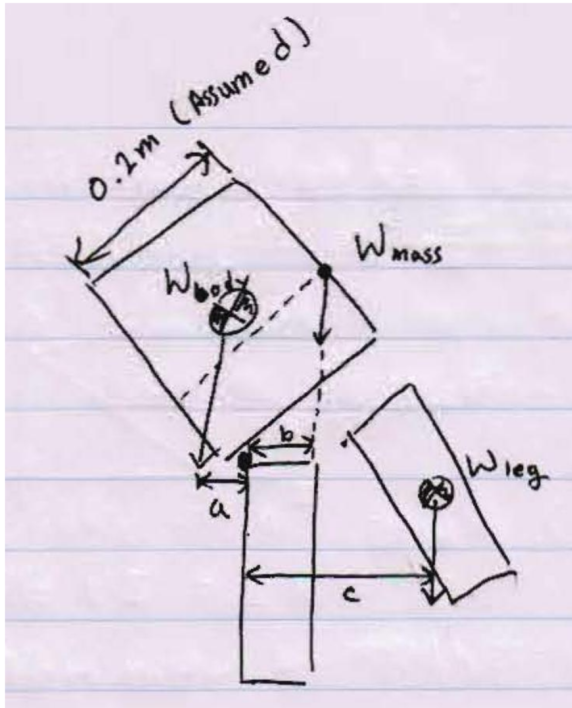
- A backpack type device which translates the torque created as the arms rotate into assistive energy at the legs. Possibly vice versa.

C.11 Medial Lateral Stabilizing Vest



- Uses weight shift to change center of gravity.
- Keeping the C of G over the feet on the ground means stability. However gait improvement is more uncertain.

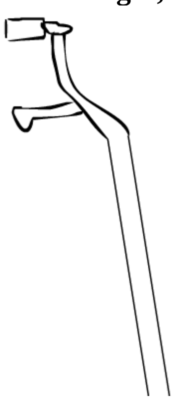
C.11.1 Free Body Diagram



$$\sum M_{hip} = M_{body} - M_{leg} + M_{mass}$$

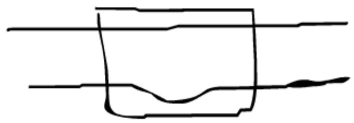
$$0 = W_{body} * a - W_{leg} * c - W_{mass} * b$$

C.12 Ultra Light, Tough Loftstrand Crutch



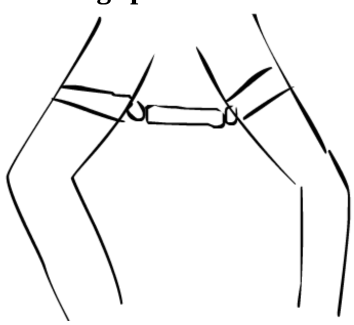
- Very similar to current Loftstrand crutch, however make them out of exotic materials to decrease mass.
- Increase toughness through material and geometry.

C.13 Elbow Bike Brake



- Uses bike brake type cable to actuate the swing of the arms by forcing a bend on the elbow.
- Device is located around elbow joint.
- Source of actuation not yet conceptualized.

C.14 Legs pushed in device

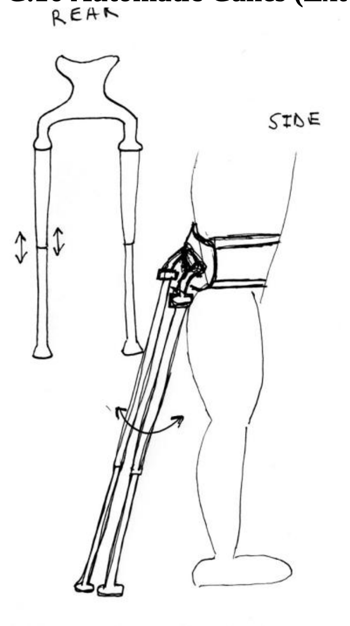


- Device pushes or pulls legs inwards. Position of device is between legs or on lower back connecting to back of upper legs.

C.15 Weight Shift Device (Up/Down Leg)

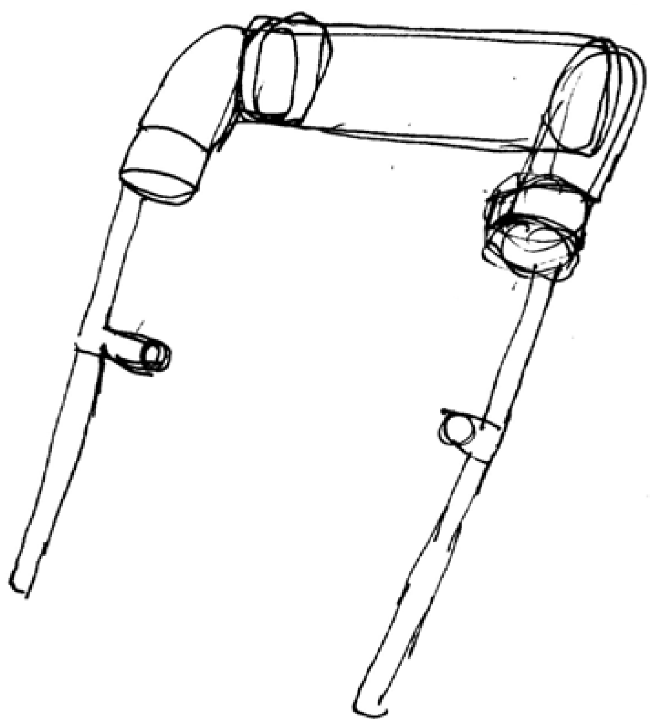
- Weight shifts up and down legs to attempt to directly make improvements to gait.

C.16 Automatic Canes (Extensible)



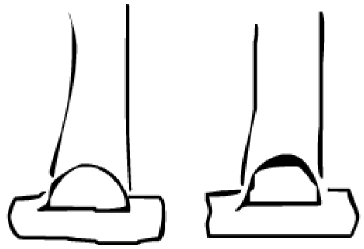
- Automatic Canes which, rather than a wheeled manipulator, have a telescoping or collapsing/extensible cane.

C.17 Powered Loftstrand Crutches



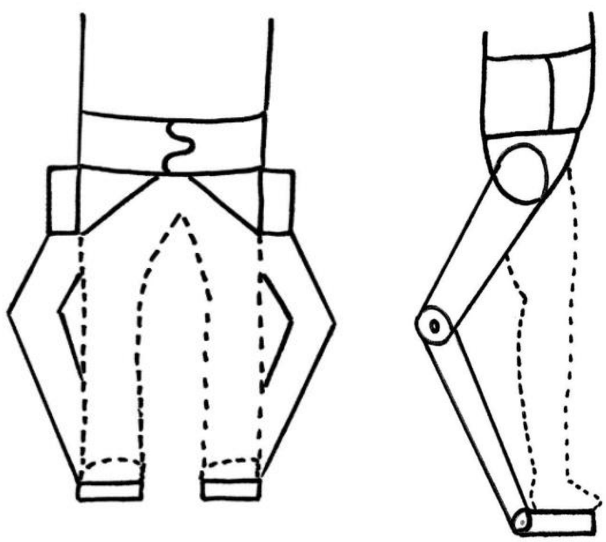
- Loftstrand crutches connected to actuators, a lower back support pad/battery compartment.

C.18 Sole-Leveling device



- Shoe type device which corrects ankle/foot position with respect to the ground.

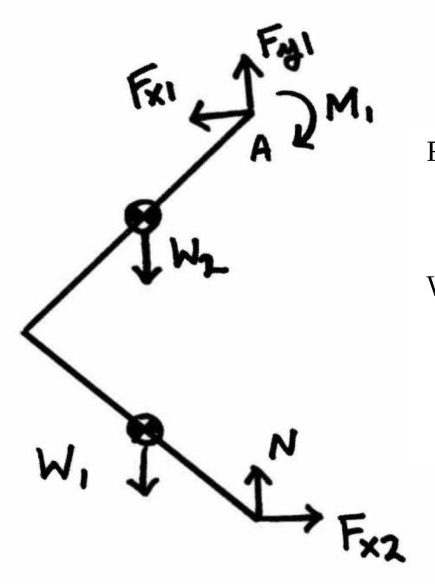
C.19 Flamingo Legs (gait trainer)



- Gait trainer – device which some may need to use to learn to walk.
- This concepts function is that it keeps one from falling completely forward or backward. Instead, should the user fall they will be guided downwards into a safe squat position.

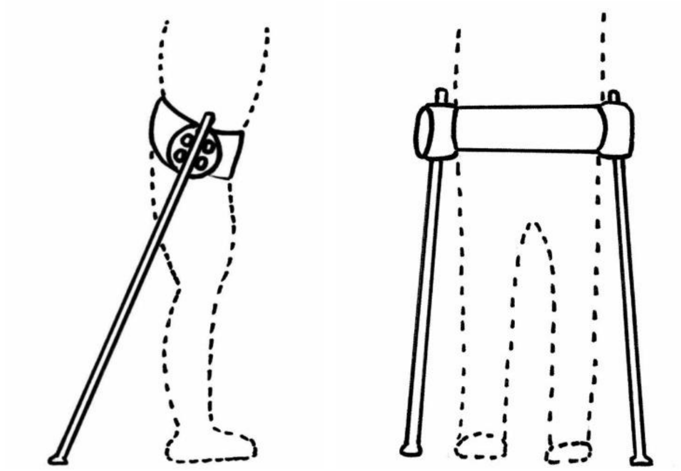
C.19.1 Free Body Diagram

A static free body diagram of the device in the posterior/anterior direction is shown below. For this analysis the footpad portion of the device are assumed to be sliding along the ground. Also, due to an electronic braking system, it is assumed that the two links are rigidly attached. Lastly, the weights of the two main links were neglected to simplify the analysis. Static analysis must also be done in the lateral direction of this device to prove feasibility. The complexity of this analysis lead the team to know concrete conclusions based on physical feasibility.



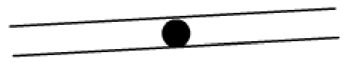
F_{x1}, F_{y1}: Reaction forces from interactions with the body
M_1: applied moment from an actuator
W_1, W_2: weights of the links
N: Normal force
F_{x2}: Reaction force from the ground onto the device

C.20 Automatic Canes – Wheeled Manipulator



- Automatic Canes which use a cane of fixed length which is manipulated around the user with one translational and one rotational joint per cane.

C.21 Weight Shift Device (Ball Bearings)



- Device which utilizes weight shift, but in this conceptualization, through moving ball bearings in tubes around the body.

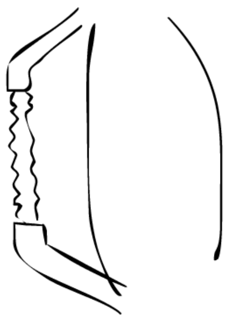
C.22 Skin Tight Suit which provides feedback

- Skin tight suit similar to a wetsuit, partial or full, which provides gait feedback onto the skin through sensation. (vibration)

C.23 Flamingo Legs (as stability device)

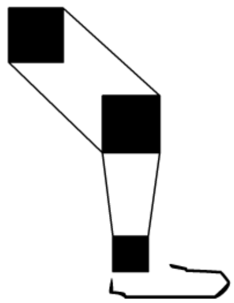
- Differs from gait trainer in that this device would try to provide useful work on person, assistive to the person.
- Lighter, skinnier, less restrictive than the gait trainer.

C.24 Pneumatic Hamstring Retraction



- Uses pneumatics directly attached from upper leg to lower leg and directly actuated upon.
- The idea would be to increase the 'push off' force from ground / assist the user.

C.25 Three Joint Robot Leg



- A fully robotic leg, wearable exoskeleton
- Actuated at hip, knee, and ankle.

APPENDIX D. FEASIBILITY MATRIX

Weights:		0.5	0.5		1.5				Total:
	Innovative	Time to Design	Time to Make	Improve Gait	Medial Laterial Stability	Safety	Socially Awkward		
Weight Shift and sole leveling	7.5	6	6.5	7.5	7.5	7.5	7		47
Medial Lateral Stable Vest	8.5	3	6	6	8.5	7	5.5		44.25
Flamingo Legs (As Stability Device)	8	3.5	4.5	8	7.5	7	1.5		39.75
Automatic Canes (Extensible)	8	3.5	5.5	6.5	5	7	4		37.5
Automatic Canes (Wheeled Manipulator)	7.5	3.5	5.5	6.5	5	7.5	4		37.5
hammer hip and bike brake knee bender	7	6	7	7.5	3.5	6.5	4		36.75
Ham/ Quad Selector	6.5	5	6.5	6.5	3.5	6.5	5.5		36
BackPack Arm cuff rotate -> quad rotate	7	4.5	6	7.5	2.5	6	6.5		36
Boundary Buzzing Shoes	7.5	6	8	6.5	1.5	5	7.5		35.75
Weight Shift Device (Up/Down Leg)	7	5.5	6	6	4	7	4		35.75
Hammer Counter Weight	7	5	7	7	2.5	6	5.5		35.25
Outside of Lower Leg Crutches	7	6	8	5.5	2.5	7	4.5		34.75
Flamingo Legs (As Gait Trainer)	8	3	4.5	7.5	4	7.5	1.5		34.25
Novel Linkage	7	3	8	6.5	2.5	7	4		33.75
Legs pushed in	4.5	5	7.5	6	4	6.5	4.5		33.75
Skin Tight Suit which provides feedback	7	3.5	6	7	1.5	3.5	8		32.5
Bipod / Tripod	2	8.5	7.5	3	5	9	2		31.5
Worlds first powered lofstrand crutches	3	5	6.5	3	5	8	4		31.25
Novelly shaped aesthic loftstrand crutch	1.5	8	7.5	2.5	5	7.5	4		30.75
Smart Loftstrand Crutch	4	4.5	6.5	3.5	4.5	7	4		30.75
Triangular Segments Rotate Around Leg	7	5.5	7.5	5	3	5.5	2		30.5
Ultra Light - Tough Loftstrand crutches	1.5	7	8.5	2	4.5	8.5	4		30.5
Elbow bike brake	4.5	7.5	8.5	6.5	1.5	4.5	4.5		30.25
Pneumatic Hamstring Retraction	7	4.5	4.5	6.5	2.5	4.5	3		29.25
3 joint robot leg	7.5	2	3	7.5	2	5	3.5		29

This chart summarizes the value of concepts based on this set of factors related to the feasibility of the design. The numbers are an average of each team member's individual assessment and the "Total" column sums the numbers from the columns including the weights given to each column. The team agreed that separating the time to design and time to make columns was valuable for the matrix, but did not merit twice the weight of other columns, resulting in the weight for those columns to be 0.5. The category of medial lateral stability got an additional weight because it is a driving idea behind the project and it is important for the final device.

APPENDIX E. PUGH CHART

Design Goals	Weight	Flamingo Leg	Automatic Canes	Weight Shift Vest	Hammer Hip	Novel Crutch
Safety	5	3	3	3	1	3
Improve gait	5	3	5	3	3	1
Low price	4	1	3	3	3	5
Durability	3	3	3	3	3	3
Unobtrusiveness	4	1	3	1	1	1
Community Accessibility	4	1	3	5	3	1
Adjustable	3	3	3	1	1	3
Less Socially Awkward	4	1	3	3	3	3
Medial Lateral Stability	5	3	3	5	1	3
Weight	5	1	3	1	1	5
Innovativeness	5	5	3	5	5	1
Weight on1-5 Scale		*15*	15	*15*	*5*	*15*
		15	25	*15*	*15*	*5*
		4	12	*12*	*12*	*20*
		9	9	*9*	*9*	*9*
1 = low		*4*	12	*4*	*4*	*4*
3 = medium		*4*	12	*20*	*12*	*4*
5= high		*9*	9	*3*	*3*	*9*
		4	12	*12*	*12*	*12*
		15	15	*25*	*5*	*15*
		5	15	*5*	*5*	*25*
		25	15	*25*	*25*	*5*
	Total Score	*109*	151	*145*	*107*	*123*

APPENDIX F. FINAL PROTOTYPE BRAINSTORMING

F.1 Actuation

- Motors
- Model airplane engine
- Compressed air
- Linear with a linkage

F.2 Rotation

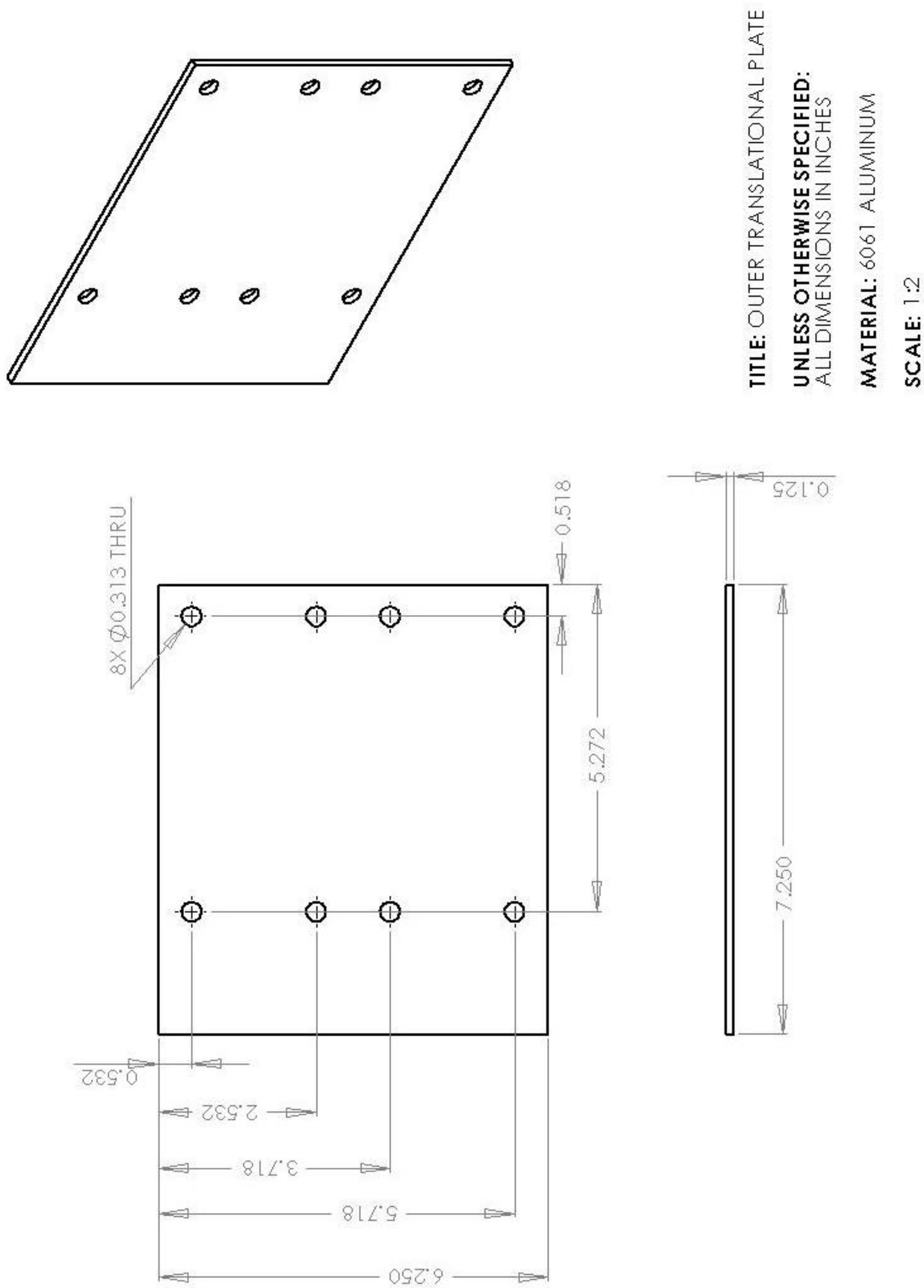
- Planetary gears
- Magnets
- Spring rotation- torsional
- Wound up energy storage, harvesting from movement

F.3 Translation

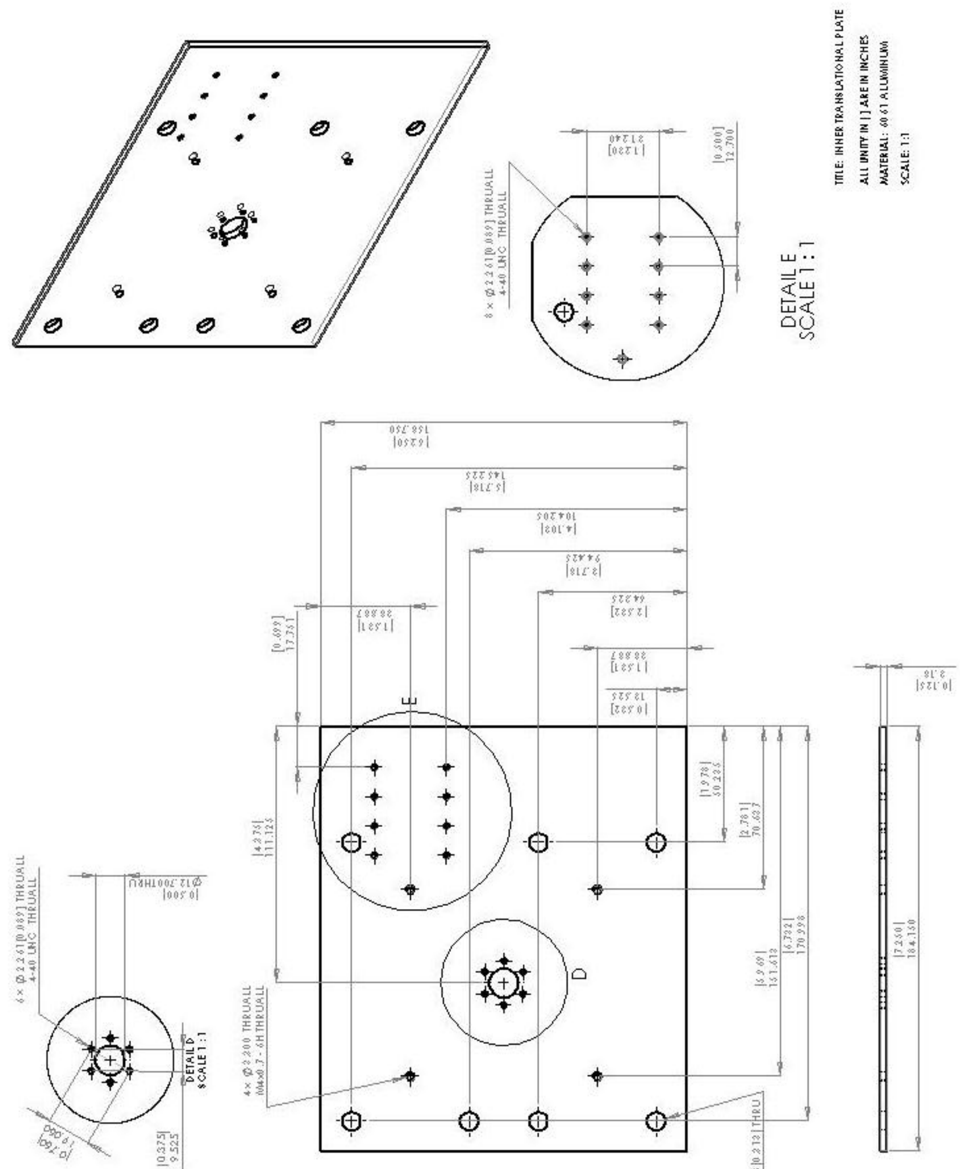
- Rack and pinion
- Rollers with or without belt
- Screw, worm gear

APPENDIX G. CAD DRAWINGS

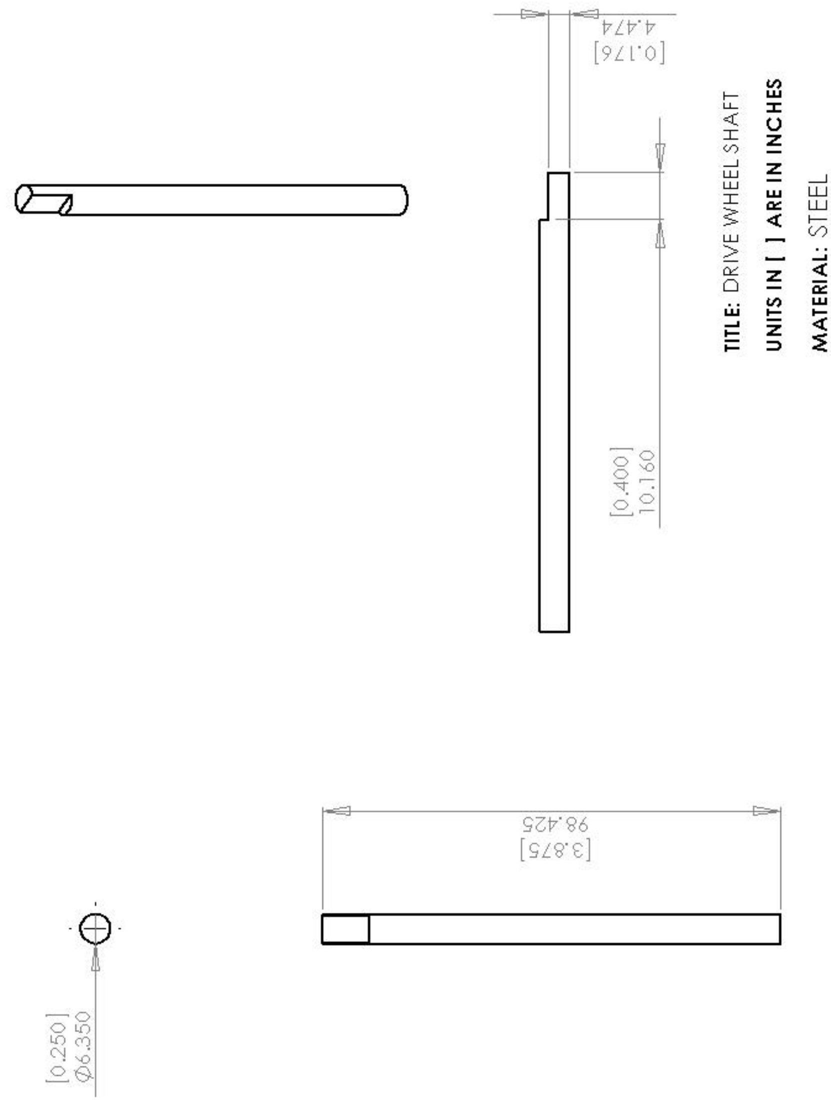
G.1 Outer Translational Plate



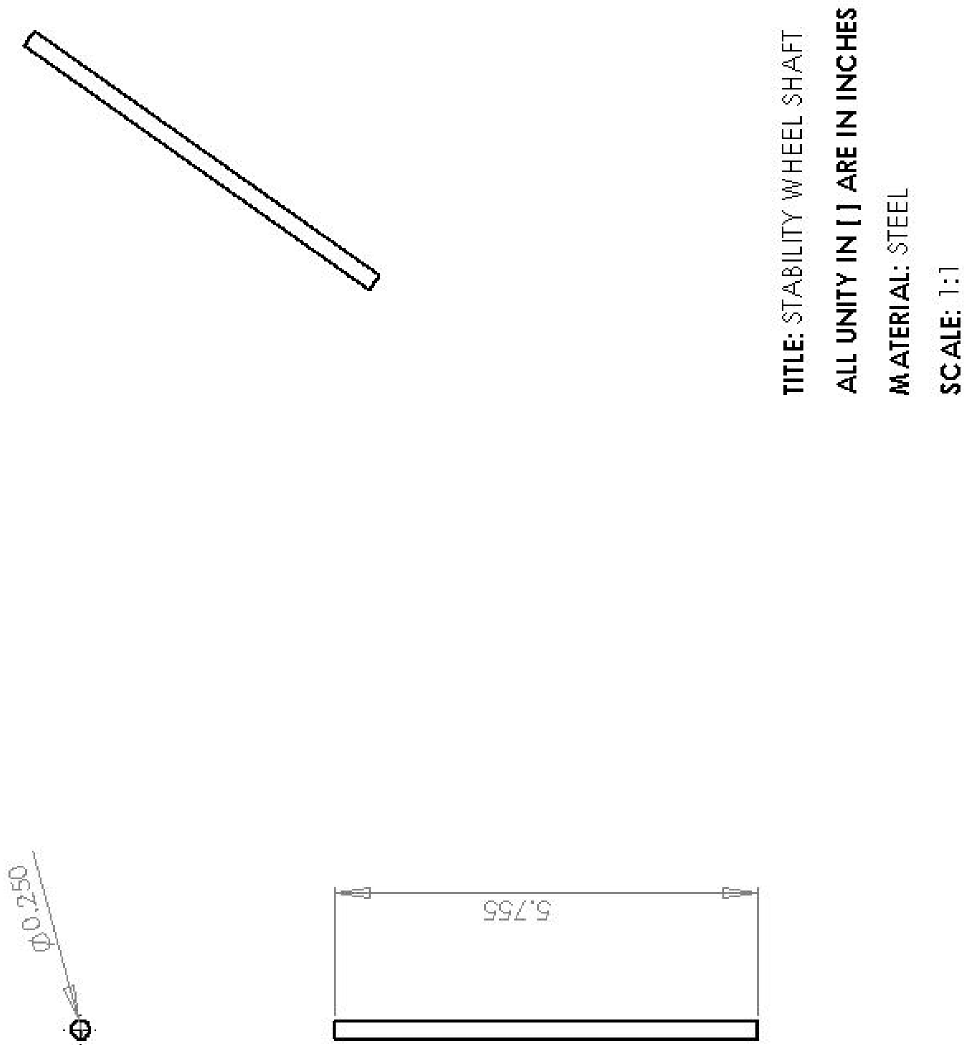
G.2 Inner Translational Plate



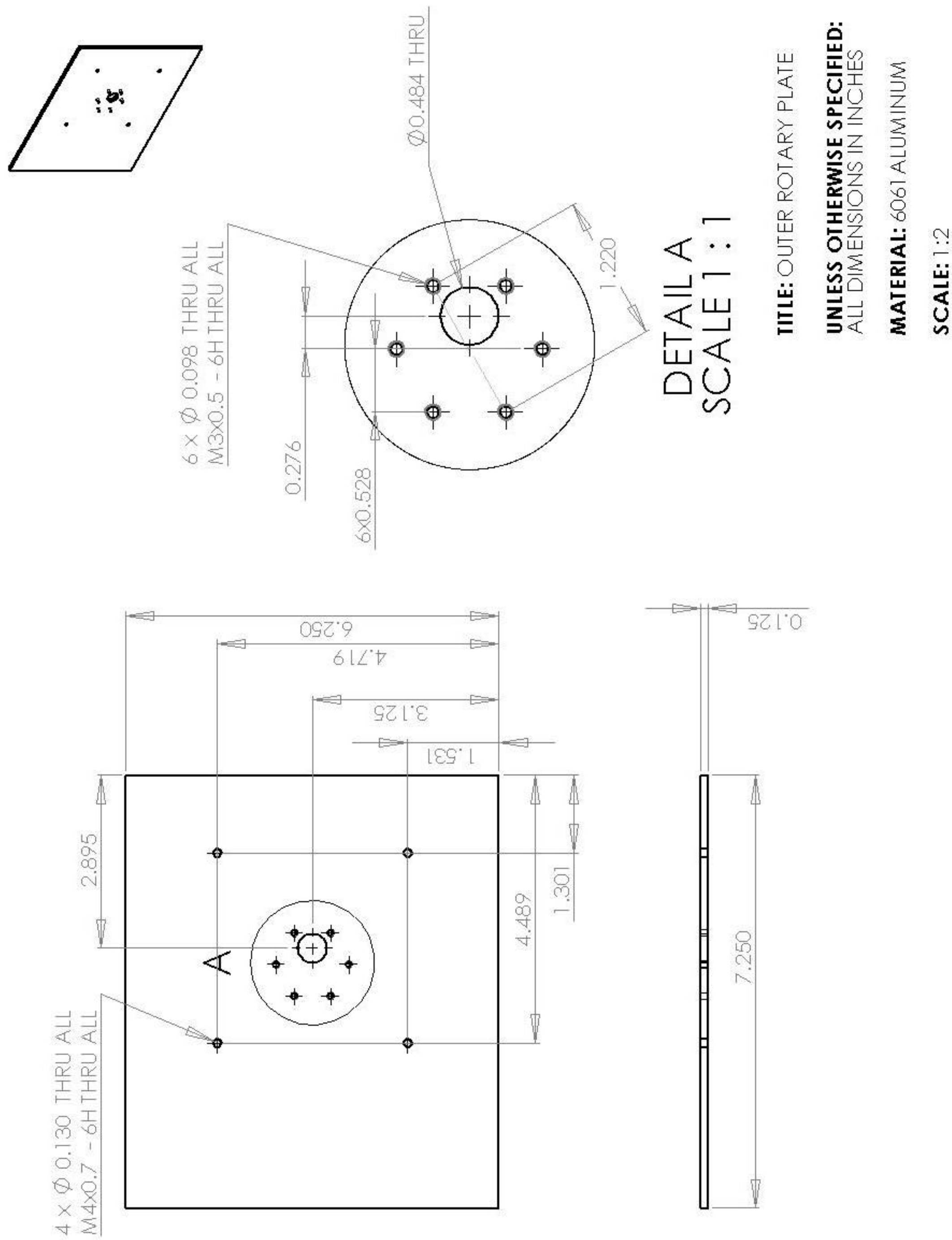
G.3 Drive Shaft



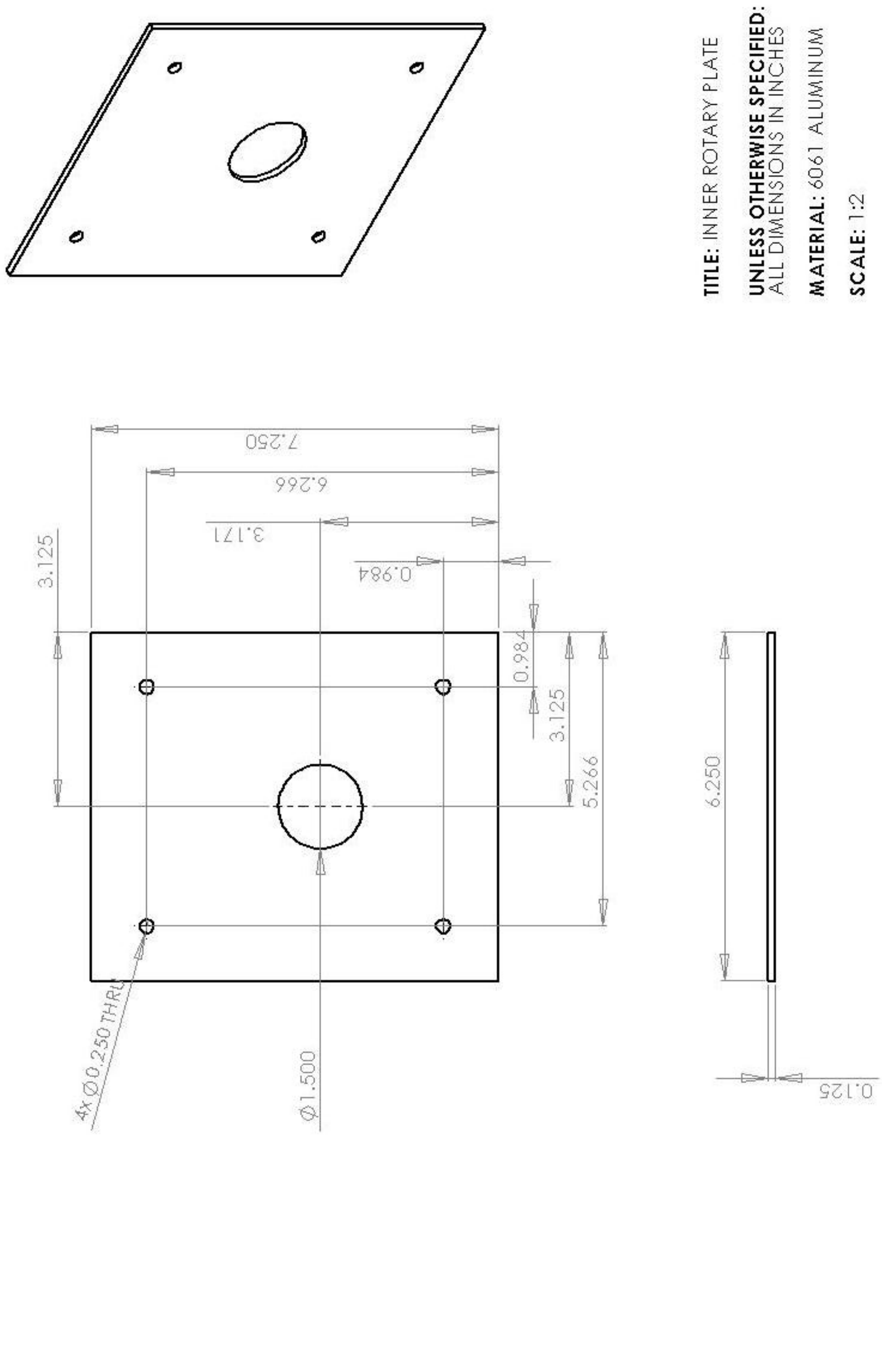
G.4 Dummy Shafts



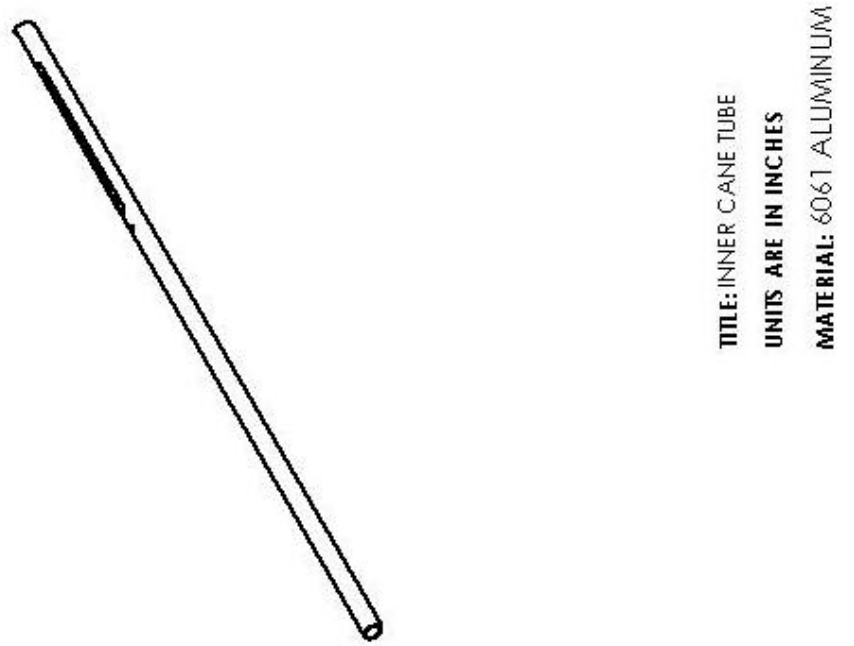
G.5 Outer Rotary Plate

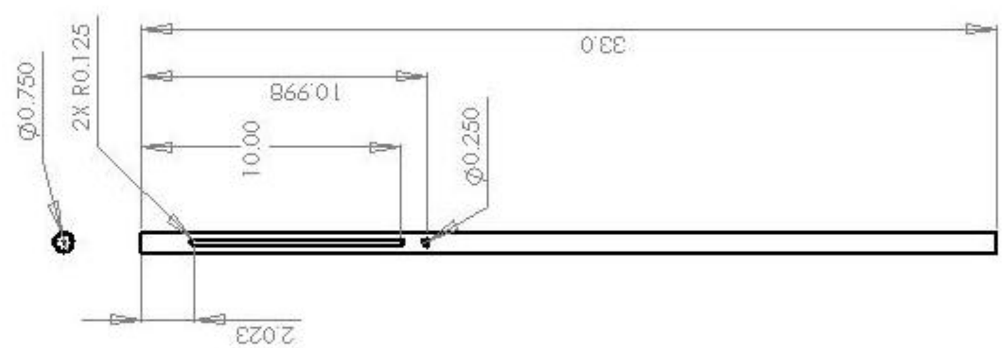


G.6 Inner Rotary Plate

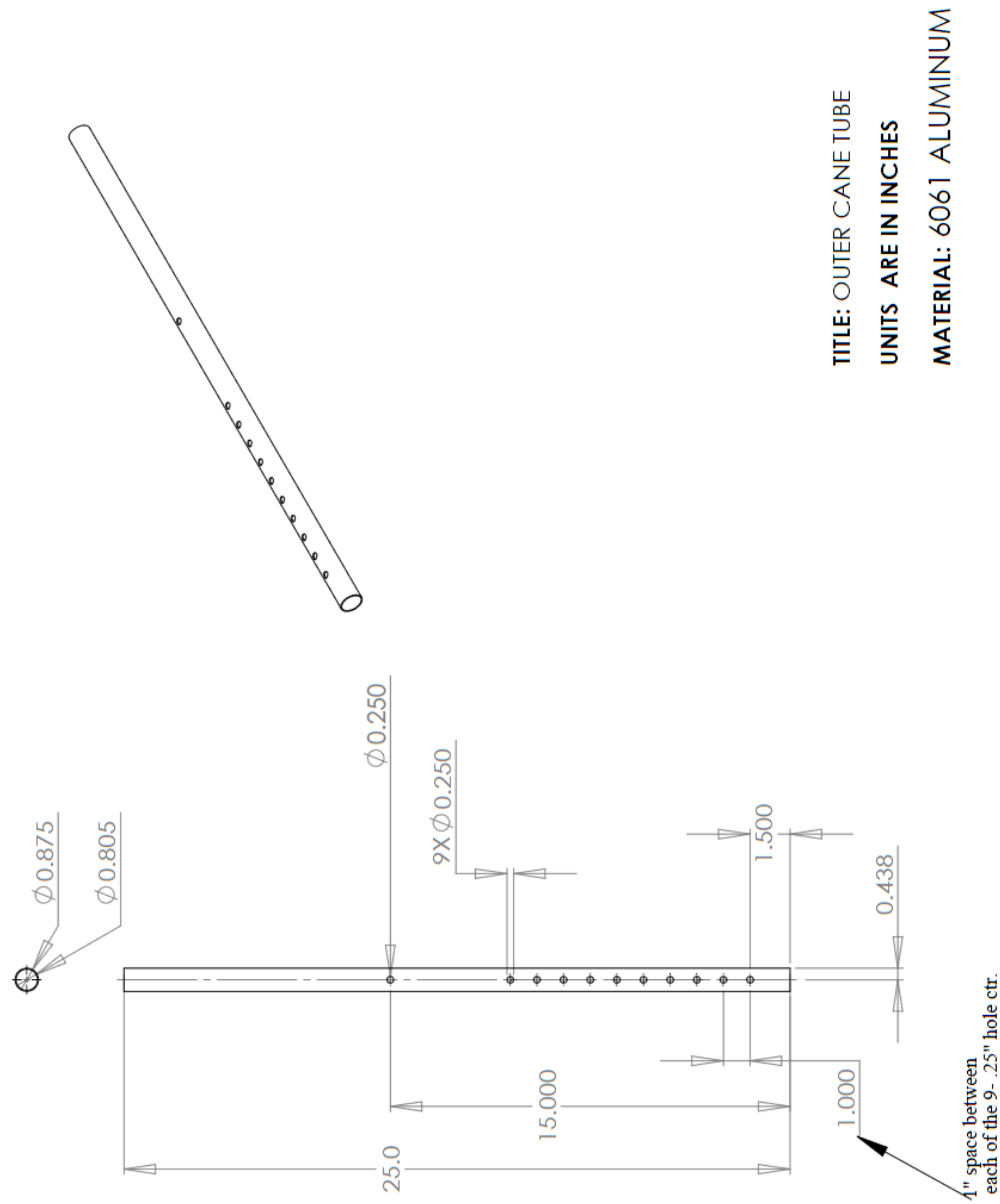


G.7 Interior Cane

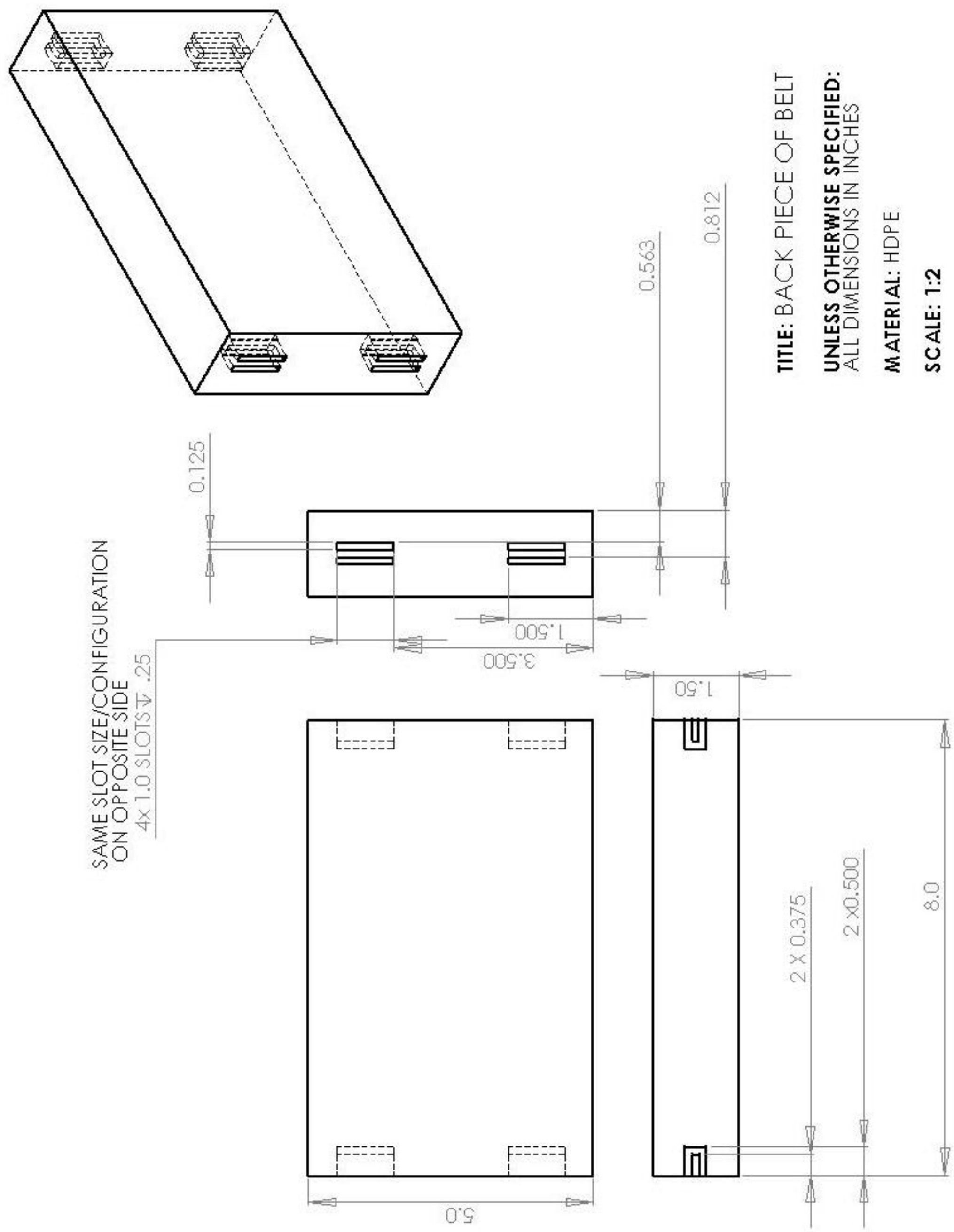




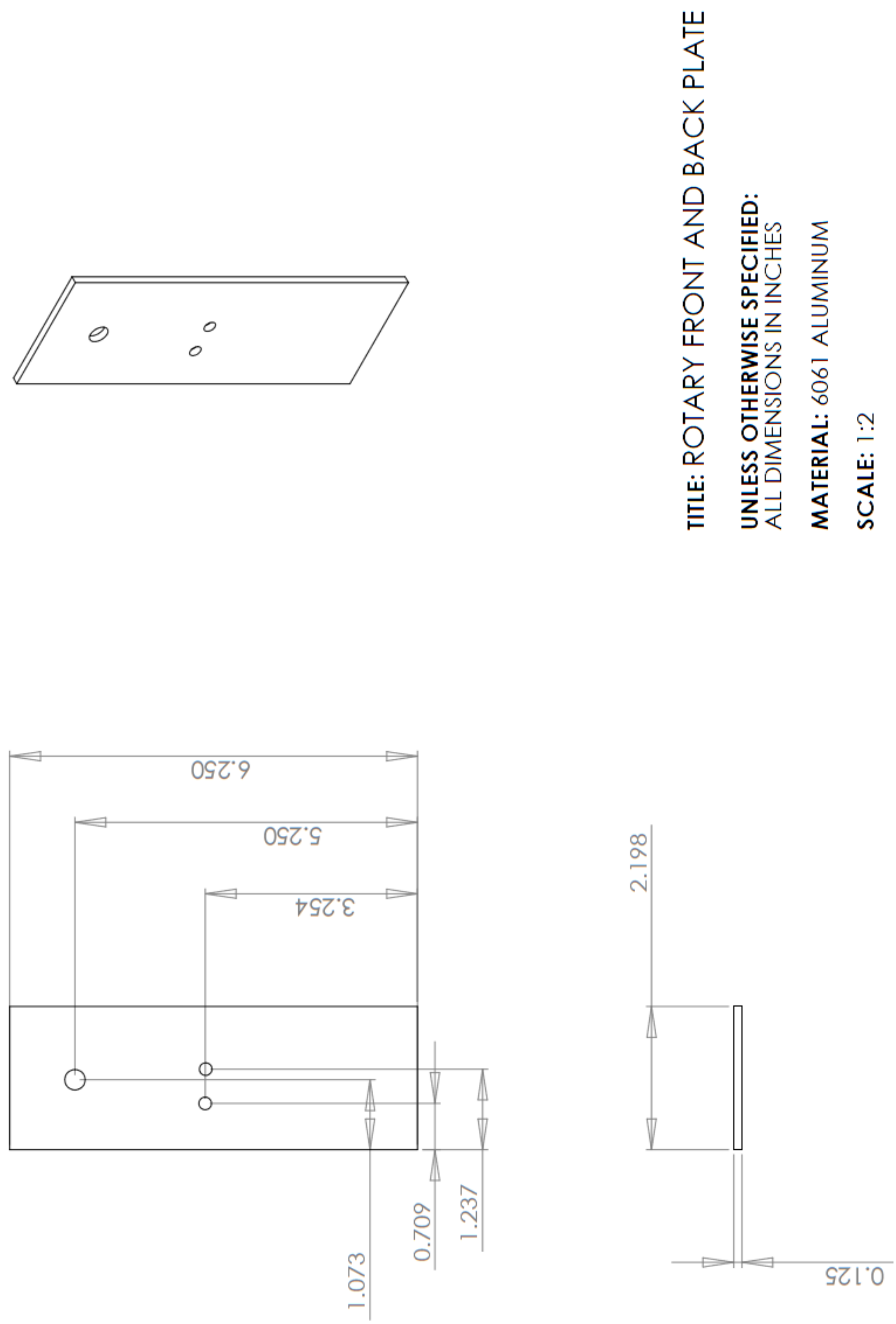
G.8 Exterior Cane



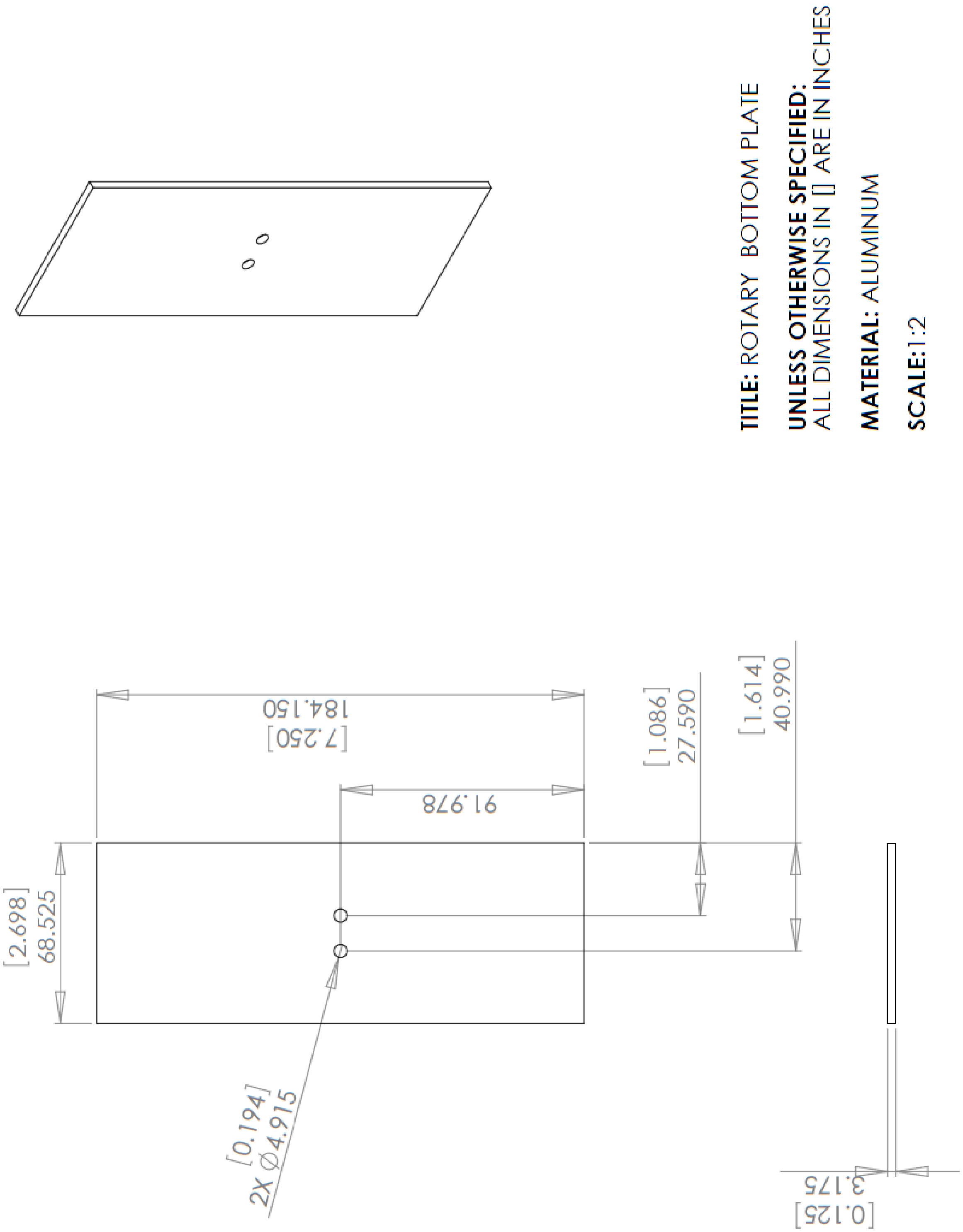
G.9 Belt Back Piece



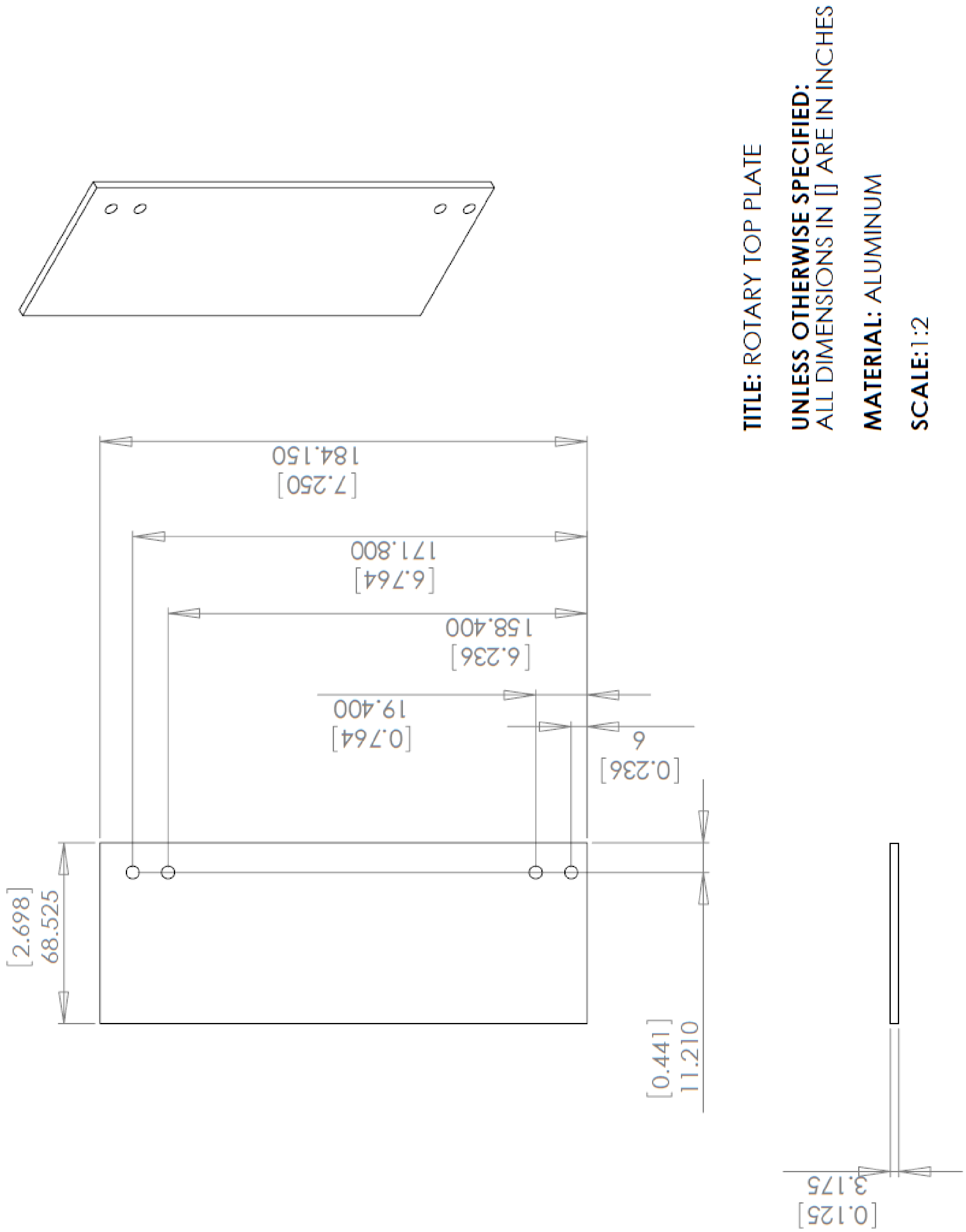
G.10 Rotary Side Plates



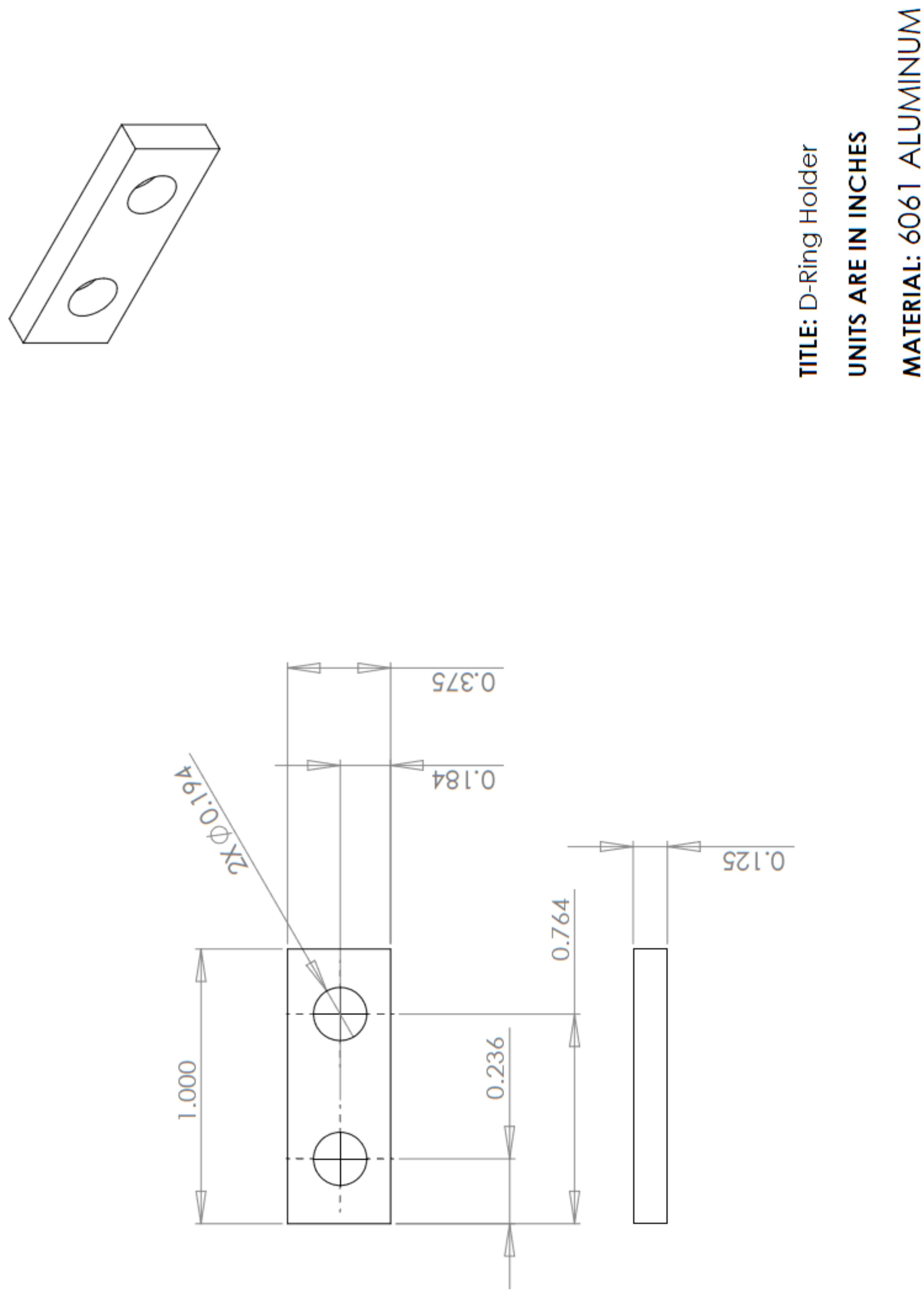
G.11 Rotary Bottom Plates



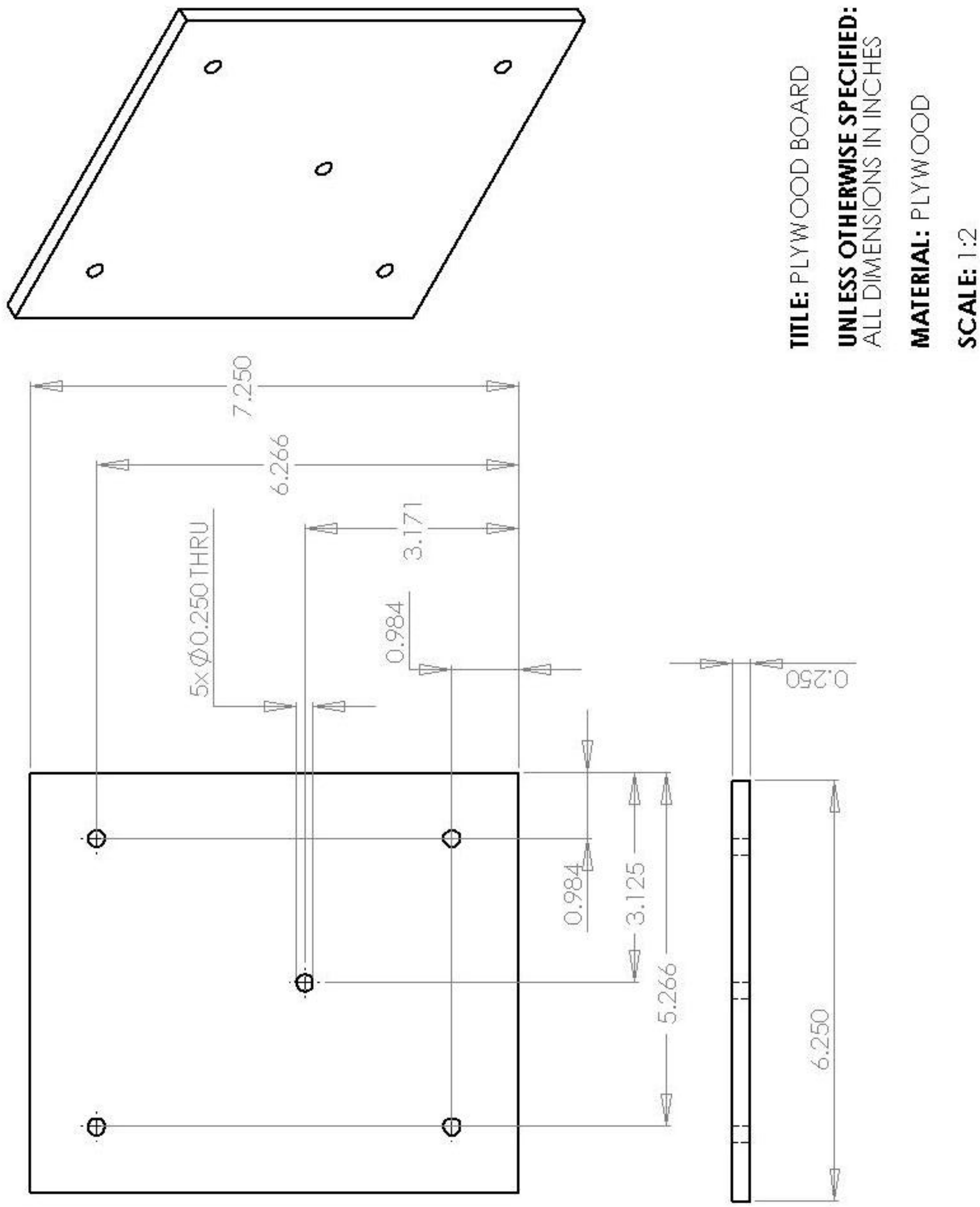
G.12 Rotary Top Plates



G.13 D-Ring Holder

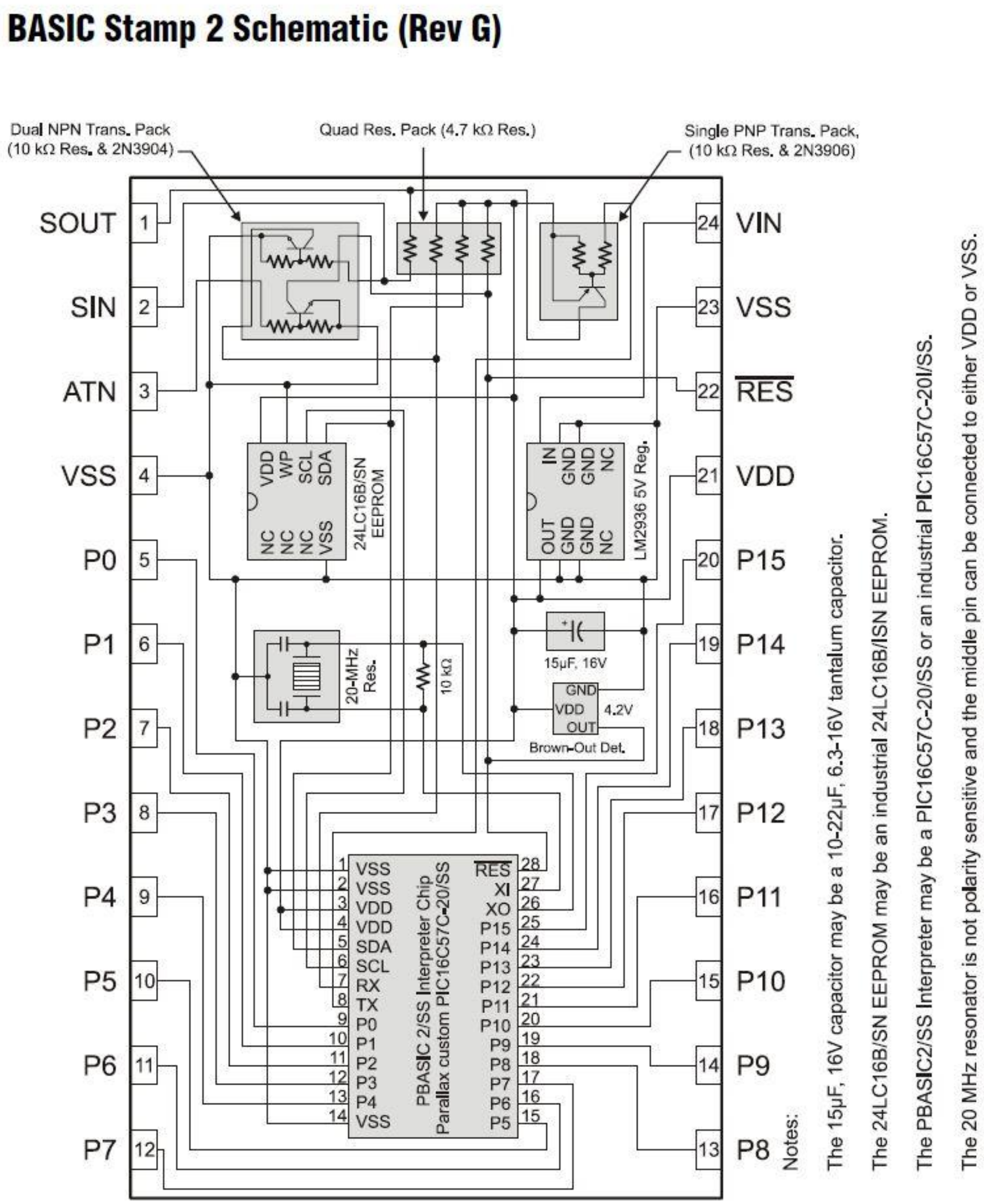


G.14 Plywood Board



APPENDIX H. MECHATRONICS

H.1 Microcontroller Schematic



H.2 Truth Tables

Input				Output		
IN1	IN2	PWM	STBY	OUT1	OUT2	Mode
H	H	H/L	H	L	L	Short brake
L	H	H	H	L	H	CCW
		L	H	L	L	Short brake
H	L	H	H	H	L	CW
		L	H	L	L	Short brake
L	L	H	H	OFF (High impedance)		Stop
H/L	H/L	H/L	L	OFF (High impedance)		Standby

Assumption: Clockwise looking out of rotation axis (motor shaft axis) with right hand rule
Assumption: Translational motor is located on side of cane opposite of users heading (right hand rule on the right side would give UP translation)

Left Side CHIP

PIN

15	AIN1
14	AIN2
13	PWMA
12	BIN1
11	BIN2
10	PWMB
Vdd	STBY

Right Side CHIP

PIN

9	AIN1
8	AIN2
7	PWMA
6	BIN1
5	BIN2
4	PWMB
Vdd	STBY

<u>Left Side Rotation:</u>

Swing Forward (Counter Clockwise)

15	LOW
14	HIGH
13	PWM H

Swing Backward (Clockwise)

15	HIGH
14	LOW
13	PWM H

Brake

15	HIGH
14	HIGH
13	PWM H/L

Free to Spin

15	LOW
14	LOW
13	PWM H

Left Side Translation:

Swing Forward (Counter Clockwise)

12	LOW
11	HIGH
10	PWM H

Swing Backward (Clockwise)

12	HIGH
11	LOW
10	PWM H

Brake

12	HIGH
11	HIGH
10	PWM H/L

Free to Spin

12	LOW
11	LOW
10	PWM H

Right Side Rotation:

Swing Forward (Clockwise)

9	HIGH
8	LOW
7	PWM H

Swing Backward (Counter Clockwise)

9	LOW
8	HIGH
7	PWM H

Brake

9	HIGH
8	HIGH
7	PWM H/L

Free to Spin

9	LOW
8	LOW
7	PWM H

<u>Right Side Translation:</u>

Swing Forward (Clockwise)

6	HIGH
5	LOW
4	PWM H

Swing Backward (Counter Clockwise)

6	LOW
5	HIGH
4	PWM H

Brake

6	HIGH
5	HIGH
4	PWM H/L

Free to Spin

6	LOW
5	LOW
4	PWM H

H.3 Sample Code and Subroutines

```
' {$STAMP BS2}
' {$PBASIC 2.5}


'PIN REFERENCE

'MOTOR CONTROLLER LOCATED ON USERS LEFT
'15  AIN1
'14  AIN2
'13  PWMA
'12  BIN1
```

```
'11  BIN2
'10  PWMB

'MOTOR CONTROLLER LOCATED ON USERS RIGHT
'9  AIN1
'8  AIN2
'7  PWMA
'6  BIN1
'5  BIN2
'4  PWMB

'SENSORS
'3  LEFT ACCEL X
'2  LEFT ACCEL Y
'1  RIGHT ACCEL X
'0  RIGHT ACCEL Y


'Initialize Variables

Duty            VAR    Byte
 'output voltage = (Duty/255) * 5 Volts
pulseDuration     VAR    Byte
 'pulseDuration specifies the duration of the pwm pulse in miliseconds
Left_Accel_X      VAR    Word
Left_Accel_Y      VAR    Word
Right_Accel_X     VAR    Word
Right_Accel_Y     VAR    Word



SETUP:
  Duty = 255
  pulseDuration = 50



MAIN:
  DO

  GOSUB Refresh
  GOSUB CalculateAccel_At_Accelerometer
  GOSUB CalculateAccel_At_Hip_Plane
  GOSUB Calculate_Heading_Angle
  GOSUB Special_Circumstances
  GOSUB Orchestra



  LOOP
```

```
'SENSOR SUBROUTINES ----------------------------------
 Refresh:
  PULSIN 3, 1, Left_Accel_X
  PULSIN 2, 1, Left_Accel_Y
  PULSIN 1, 1, Right_Accel_X
  PULSIN 0, 1, Right_Accel_Y
  RETURN

CalculateAccel_At_Accelerometer:
  'After Refresh, variables have units of (2usec/unit)
  'Left_Accel_X = ((Left_Accel_X * 2) / 8000) - 2) / 1.5
 ' Left_Accel_Y = ((Left_Accel_Y * 2) / 8000) - 2) / 1.5
  'Right_Accel_X = ((Right_Accel_X * 2) / 8000) - 2) / 1.5
  'Right_Accel_Y = ((Right_Accel_Y * 2) / 8000) - 2) / 1.5

  'LeftPitch = ((ATN Left_Accel_X )/ (COS Left_Accel_X)) */ 360
  'RightPitch = ((ATN Right_Accel_X )/ (COS Right_Accel_X)) */ 360
 ' LeftYaw  = ((ATN Left_Accel_Y )/ (COS Left_Accel_Y)) */ 360
  'RightYaw = ((ATN Left_Accel_Y )/ (COS Left_Accel_Y)) */ 360
  RETURN


'END SENSOR SUBROUTINES



'WALKING SPEED SUBROUTINES ----------------------------


WalkFaster:
  IF Duty < 255 THEN
    Duty = Duty + 15
  ENDIF
  RETURN

WalkSlower:
  IF Duty > 0  THEN
    Duty = Duty - 15
  ENDIF
  RETURN

'END WALKING SPEED SUBROUTINES ------------------------

'MOTOR CONTROL SUBROUTINES -----------------------------

LEFT_ROT_FORWARD:
  LOW 15
  HIGH 14
  PWM 13,Duty,pulseDuration
  RETURN
```

```
LEFT_ROT_BACKWARD:
 LOW 14
 HIGH 15
 PWM 13,Duty,pulseDuration
 RETURN

LEFT_ROT_SB:
 HIGH 15
 HIGH 14
 PWM 13,Duty,pulseDuration
 RETURN

LEFT_ROT_FREE:
 LOW 15
 LOW 14
 PWM 13,Duty,pulseDuration
 RETURN

LEFT_TRANS_UP:
 LOW 12
 HIGH 11
 PWM 10,Duty,pulseDuration
 RETURN

LEFT_TRANS_DOWN:
 LOW 11
 HIGH 12
 PWM 10,Duty,pulseDuration
 RETURN

LEFT_TRANS_SB:
 HIGH 12
 HIGH 11
 PWM 10,Duty,pulseDuration
 RETURN

LEFT_TRANS_FREE:
 LOW 12
 LOW 11
 PWM 10,Duty,pulseDuration
 RETURN

RIGHT_ROT_FORWARD:
 LOW 8
 HIGH 9
 PWM 7,Duty,pulseDuration
 RETURN

RIGHT_ROT_BACKWARD:
 LOW 9
 HIGH 8
```

```
  PWM 7,Duty,pulseDuration
  RETURN

RIGHT_ROT_SB:
  HIGH 8
  HIGH 9
  PWM 7,Duty,pulseDuration
  RETURN

RIGHT_ROT_FREE:
  LOW 8
  LOW 9
  PWM 7,Duty,pulseDuration
  RETURN

RIGHT_TRANS_UP:
  LOW 5
  HIGH 6
  PWM 4,Duty,pulseDuration
  RETURN

RIGHT_TRANS_DOWN:
  LOW 6
  HIGH 5
  PWM 4,Duty,pulseDuration
  RETURN

RIGHT_TRANS_SB:
  HIGH 5
  HIGH 6
  PWM 4,Duty,pulseDuration
  RETURN

RIGHT_TRANS_FREE:
  LOW 6
  LOW 5
  PWM 4,Duty,pulseDuration
  RETURN

'END MOTOR CONTROL SUBROUTINES -----------------------------
```

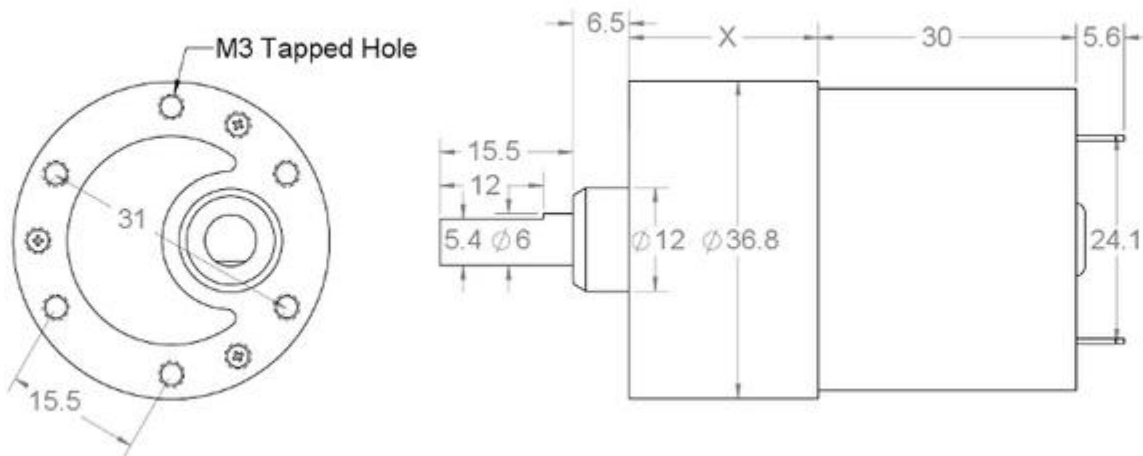
APPENDIX I. BILL OF MATERIALS

I.1 Purchased Parts

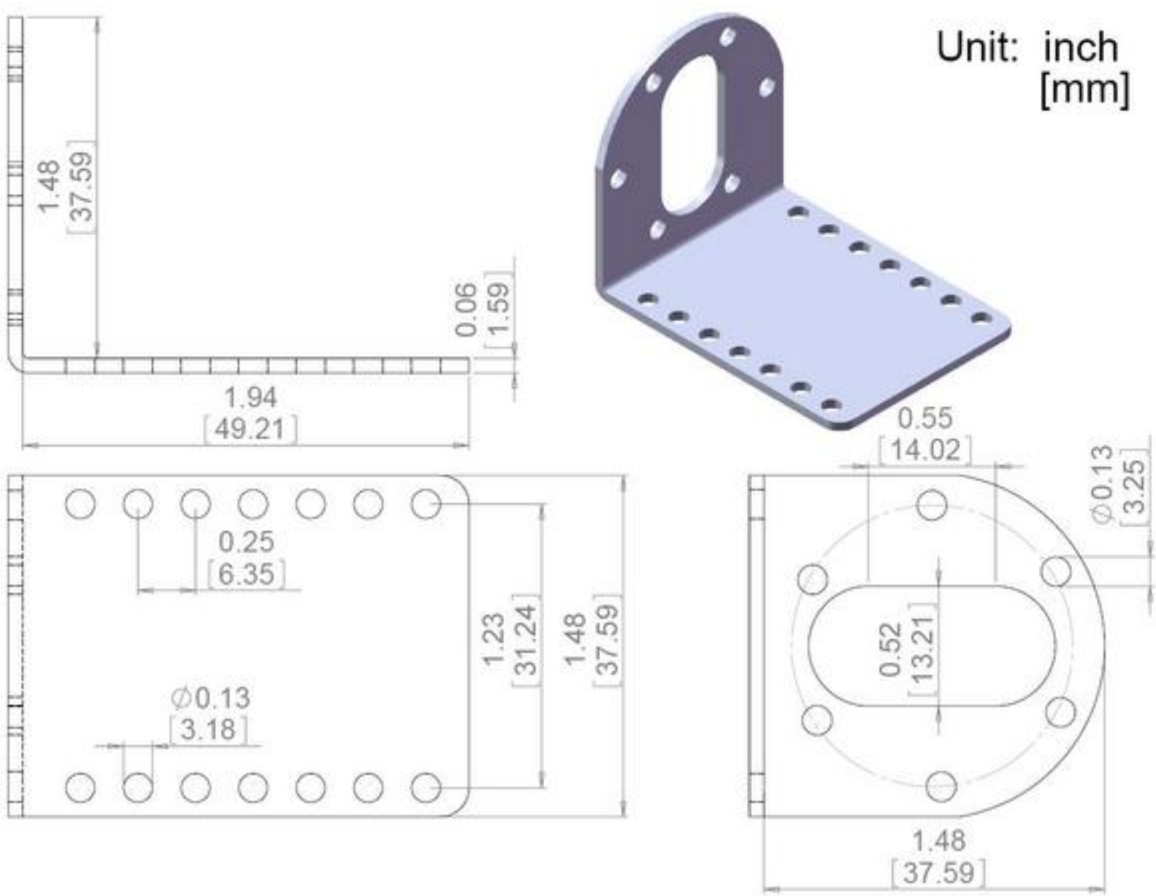
No.	Part	Material	Dimensions	Manufacturer	Part#	Cost per part	QTY	total cost
1	Metal Gearmotor (price+ ship)	steel	GR: 50:1 , RPM: 200 T: 12 kg-cm I: 300 mA (free) Diameter: 37 mm Length: 52 mm	Pololu	1104	$24.95	2	$60.85
2	Motor Bracket	steel	see drawing includes 6 m3 screws	Pololu	1084	$7.95	1	$7.95
3	Shaft Coupler	(metal)	OD: 0.5" Length:0.75" ID: 0.25"	Jameco Electronics	138288	$5.95	2	$18.90
4	Bearing (price+ship)	Bronze Alloy	see drawing, other sheet	McMaster Carr	7930K11	$11.48	14	$148.86
5	Electric Gearmotor	steel	T: 250 N*cm , w: 15 rpm Diameter: 37 mm Length: 73 mm	Virtual Village	001480-114	$9.99	2	$19.98
7	Springs	phosphor bronze	OD: 0.5" Free Length.: 31/32" Comp. Len: .71"	McMaster Carr	9657K255	$9.17	2	$17.73
8	Wheels (price+ship)	Aluminum /rubber	Diameter: 1 1/4" Axle Hole: 1/16" Width: 7/16"	Robot Marketplace	0-SUL353	$2.09	16	$67.11
9	Turntable	Aluminum	4"x4" plate Center Diameter: 2.16"	McMaster Carr	6031K18	$17.84	2	$35.68
11	Belt Straps	Nylon	Width: 3/4" Length: 60"	REI	709053	$3.00	2	$6.00
12	Belt Straps	Nylon	Width: 3/4" Length: 24"	REI	709048	$2.00	2	$4.00
13	Strap Triglide	Plastic	Fits 1" Straps	REI	612230	$0.80	1	$0.80
14	H Bridge	Electronic	Size: 0.6"x0.8" V Range: 4.5-13.5 Output: 1 A	Pololu	713	$9.95	2	$19.90
15	Accelerometer (price+ship)	Electronic	0.7"x0.7"	Spark Fun	843	$39.95	2	$83.12
16	Tubing	Aluminum	OD:.875", ID: .805",L: 6'	Alro Metals	n/a	n/a	1	$40.08
17	Various bolts and nuts	Steel	M4,M3, 6"-.25" bolts	Carpenter Brothers	n/a	n/a	-	$32.27
18	Bolts and nuts	Steel	Size #10-24	Home Depot	n/a	n/a	-	$10.82
19	Tubing	Aluminum	OD:1.5" ID:1.25"	Alro Metals	n/a	n/a	-	$13.20
20	Cane Tip/End	Rubber	ID= .875"	Carpenter Brothers	n/a	n/a	4	$5.17
21	Foam	HDPUR	High density polyurethane foam	Joann Fabrics	n/a	n/a	-	$8.47
22	Brackets		For Rotary back wall attachment	Carpenter Brothers	n/a	n/a	2	$3.02
23	Motor Hubs	Aluminum	Diameter: 1"	Pololu	1083	7.95	1	$7.95
	TOTAL							**$611.86**

I.2 Available Manufacturer Schematics

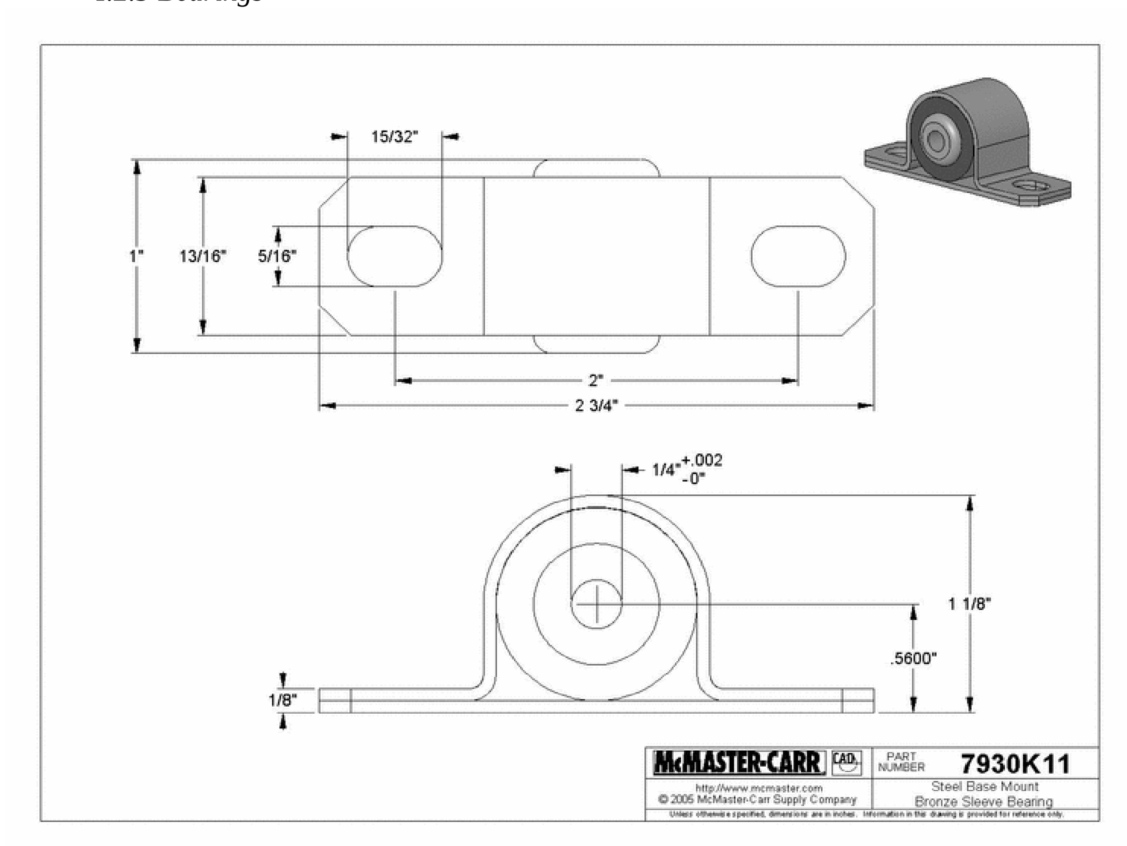
I.2.1 Translational Motor



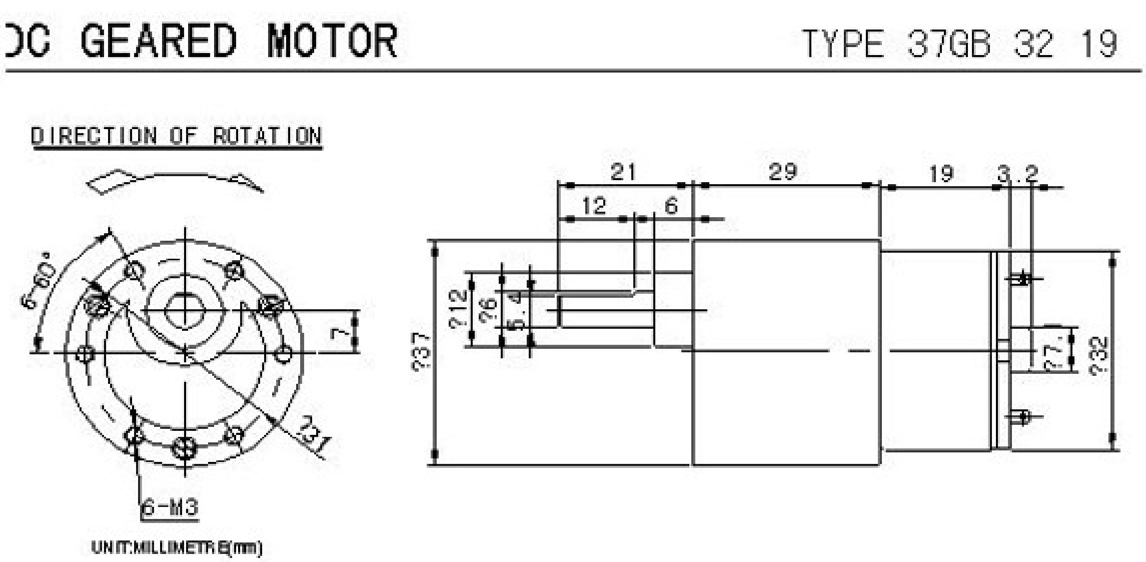
I.2.2 Motor Bracket



I.2.3 Bearings

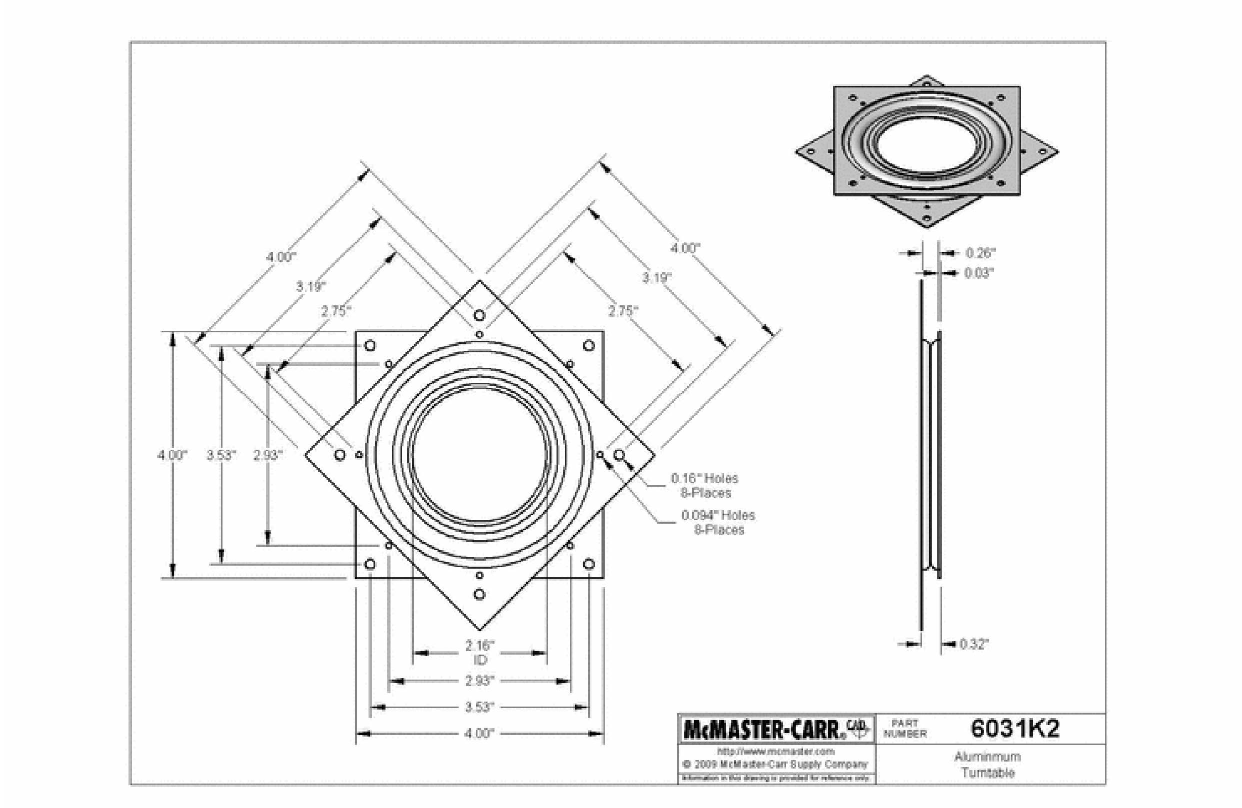


I.2.4 Rotary Motor

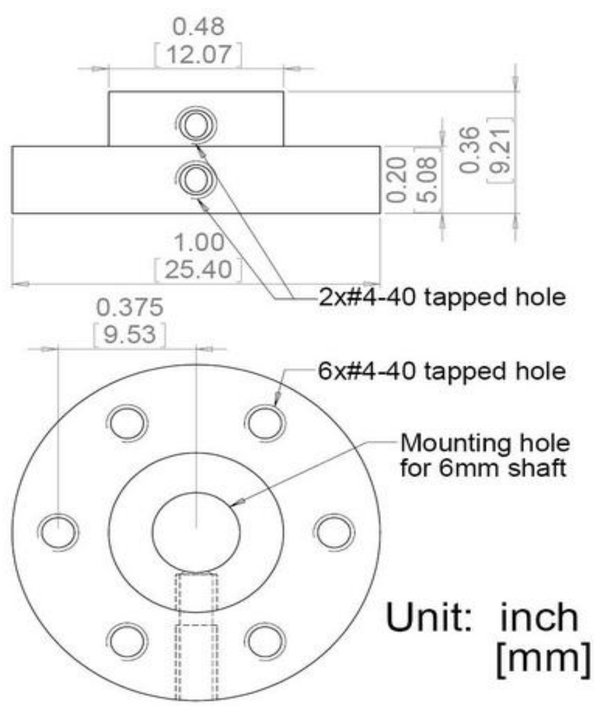


MODEL	VOLTAGE V	NO LOAD SPEED rpm	NO LOAD CURRENT mA	AT MAXIMUM EFFICIENCY SPEED rpm	AT MAXIMUM EFFICIENCY CURRENT mA	AT MAXIMUM EFFICIENCY TORQUE kg.cm	AT MAXIMUM EFFICIENCY OUTPUT W	AT MAXIMUM EFFICIENCY EFF. %	STALL TORQUE kg.cm	STALL CURRENT mA
12560-380	12	14	80	12	150	5.0			25	600

I.2.5 Turntable



I.2.6 Motor Hub



APPENDIX J. SAFETY REPORT

J.1 EXECUTIVE SUMMARY

This report details the safety analysis of the automatic canes in testing, use, and fabrication. The purpose of this report is to fully understand all the hazards associated with the project over the entire course of the device's life cycle. By investigating the risk involved with manufacturing and testing the device, the goal is to eliminate unnecessary risk in constructing the device and to increase the efficiency of manufacturing by having a detailed plan before beginning the process.

The plans for testing this device fall into two categories: empirical testing for device optimization and validation testing to demonstrate achievement of engineering specifications. The empirical tests will take place as necessary during manufacture and assembly and the validation tests will be done once the prototype is complete. The hazards involved in testing this device are minimal, because University and national standards prevent the team from having children or people with disabilities test the device.

The majority of the components of the device are already manufactured; however mounting surfaces need to be machined to assemble the various components. Most processes are cutting and drilling to provide correctly shaped pieces to which to secure other components, but other processes include milling and tapping. A Failure Modes and Effects Analysis (FMEA) was performed on all of the purchased parts to determine the associated risk and DesignSafe was used to analyze the system as a whole for potential hazards.

The testing, manufacture, and assembly of the automatic canes is relatively low, most of which is reduced drastically by careful attention to assembly. The testing obviously offers the most potential for danger, but doing tests at a safe distance before the device is attached to a person should reduce the hazards dramatically.

J.2 EXPERIMENTATION DATA

J.2.1 Empirical Tests

Before we assemble the device, there are several empirical tests that need to be performed to ensure the correct performance and assist in design optimization. To verify the proper amount of normal force that spring needs to provide to the rollers load testing will be done. This external force will assist the frictional forces that prevent the cane from slipping while simultaneously allowing the motor to spin. The team will apply loads to the motor shaft in increments of 10 N while the motor is spinning. From engineering analysis based on assumptions and estimates the team determined that the normal force applied by the springs should be about 72 N. There will also be a loading test done on the cane in the perpendicular direction to make sure it will not deform under this amount of normal force. Since the maximum compression length of the spring is the limiting force value, the team will be able to adjust the length to decrease or increase the normal force applied.

J.2.2 Weight Verification

Since the device is used by human beings, the weight of the total system must be minimized to prevent a burden on the user as well as address safety concerns. Although the automatic canes device is targeted towards children, it was scaled up to an adult size for practicality in testing. The specification for a child size device stated that the system must weigh no more than 5 kg. Due to lack of materials and a longer cane length for an adult user, the device is predicted to weight approximately 6.5 kg which is 1.5 kg over the specification. This is an acceptable value since an adult user can take more load on their body. Prior to testing the system's functionality the team will weigh the belt assembly and both canes on a scale. This may be done during the manufacturing process as major parts are assembled as well.

J.2.3 General Functionality Test

The main function of this device is for the canes attached at your hip to move in accordance with the swing phase of the gait cycle. The canes must also touch the ground in the proper place for stability and gait improvement. To test the general functionality of the device, at least 3 adult users will participate in a trial run of the device. Since different people have different waist sizes and hip heights, this will demonstrate the adjustability of the belt of the device as well as the cane height.

To test the proper cane placement, swing rate, and path the team will be using a GaitRite mat in the University of Michigan Neuromotor Control Laboratory under the supervision of the project sponsor. This mat captures footfall data as someone walks and is used to determine a person's average over ground walking velocity [1]. It works via pressure sensors embedded in the mat that activate after a force is applied to it [33] meaning that it will be able to detect the movement of one's feet while walking as well as the movement of the canes. Each of the users will walk at a pace that feels comfortable to them for approximately 10 seconds across the mat wearing the device. To account for precision error in the velocity and placement results each user will perform this 10 second trial 5 times. To assure that the control system and mechanical components are functioning properly, we can initially observe the movement of the canes as the user walks forward paying close attention to the path of the cane. To document this testing the team will use a system of cameras available in the same laboratory. Observation will also allow the team to verify that the cane will translate in the vertical direction during the stance phase of the gait cycle. The design calls for the canes to move straight in the posterior direction when the alternate leg of the user enters the swing phase of the gait cycle (see Section 8.2 pg 15). Therefore, we can look at the walking path versus cane path results from the GaitRite mat to make sure the cane swings at the proper time. The placement of the cane can also be verified through the mat's results.

J.2.4 Load Test

Using a force plate in the biomechanics lab the team will apply incrementing loads of 2 lbs until the cane slips through the rollers. This will let the team know how much bodyweight the motor can withstand and it will confirm the motor selection. The test will be repeated at least 3 times to account for precision error during loading.

J.2.5 Gait Testing

Two of the main engineering specifications that the automatic canes device needs to meet involve the gait improvement of the user. These specifications state that the device should decrease a person with Spina Bifida's normal step width by 20% and increase the normal step length by 4%. Since the device's target age group is 6-12 years old children with Spina Bifida, the prototype needs to be tested by subjects from this group to prove its workability. However, to test minors who are under the age of 18 special consent is needed from guardians and is usually not encouraged [34]. On top of the age obstacle, it would take several months to obtain the necessary approval from an Institutional Review Board (IRB) to do a research experiment (J. Sansom, Personal communication). Lastly, to obtain participants with a Neuromotor disability we would need to do a large amount of searching.

The only testing the team will be able to do would be similar to the general functionality test. We have the ability to compare the normal step width and step length of the team members to the step width and step length with the cane. However, this type of test would be inconclusive for several reasons. First, the team of four group members and the project sponsor is not a random and diverse test group. Next, there would need to be several weeks of testing to prove gait improvement. Finally, the automatic canes were designed for someone with a Neuromotor disability that causes irregular gait and none of the team members possess this issue. The team hopes that if the device functions the way it was intended to without failure, then the project sponsor could set up future testing when there is more time to prepare.

J.3 PURCHASED COMPONENTS AND MATERIALS

The final device combines parts bought from manufacturers with a variety of joining and transmission pieces made from stock material.

J.3.1 Purchased Components

In addition to the standard large-scale manufacturing companies, this device uses many parts obtained from hobby manufacturers. The parts can be used in the same applications as small robots and machines. Hobby supplies tend to be cheaper than industrial quality parts, but there is negligible difference in performance for the application of this prototype. Standard sizing of bolts and brackets were attempted for all parts to make it easier to assemble and troubleshoot during manufacturing. Additional fasteners to attach components are standard sizes and can be found in the machine shop.

J.3.1.1 Translational Motor

Description: This is a gear motor of internal gear ration of 50:1 that supplies the actuation for the cane to move vertically. The stall torque is 12 kg-cm has a no-load speed of 200 RPM. It draws 300 mA of current off of a 12 V battery. Using an internally geared motor allows for a high torque and low speed without using gears and increasing the number of components.

Table J.1

Quantity	2
Vendor	Pololu
Part Number	1104

J.3.1.2 Motor Mounting Bracket

Description: This bracket is the suggested one to accompany the chosen translational motor to mount to the rotary frame. It includes 6 screws that will attach the motor to the bracket.

Table J.2

Quantity	2
Vendor	Pololu
Part Number	1084

J.3.1.3 Shaft Coupler

Description: This component serves to increase the shaft length coming out of the motor. It comes with set screws to connect the output shaft of the motor to the shaft that runs through the wheels and bearing.

Table J.3

Quantity	2
Vendor	Climax Metal
Part Number	138288

J.3.1.4 Bearing

Description: This particular bearing minimizes noise and vibration to achieve a quieter device with less undesirable motion. The bearing allows for the requisite speed and torque of the output shaft of the motor, which is also the speed of the other shafts connected to the dummy rollers.

Table J.4

Quantity	14
Vendor	McMaster Carr
Part Number	7930K11

J.3.1.5 Rotary Motor

Description: Again, this motor has an internal gear box that yields an output with high torque and low speeds. The motor runs of a 12 V battery and outputs 250 N-cm of torque at a speed of 15 RPM.

Table J.5

Quantity	2
Vendor	Virtual Village
Part Number	001480-114

J.3.1.6 Bolts

Description: These bolts are 5/16" in diameter and 5.25" in length. They fit through the bearing mount holes for better transmission of the force

Table J.6

Quantity	8
Vendor	Home Depot
Part Number	N/A

J.3.1.7 Springs

Description: These compression springs have closed and ground ends and output a maximum of 14.3 lbs of force. The outer diameter is ½", free length is 31/32", and compressed length is 0.71". Using four springs on a side to increase the normal

Table J.7

Quantity	8
Vendor	McMaster Carr
Part Number	9657K255

J.3.1.8 Turntable

Description: This component connects the hip and rotary modules while allowing the rotary module to rotate. It is connected with screws and turns to allow access to all holes.

Table J.8

Quantity	2
Vendor	McMaster Carr
Part Number	6031K2

J.3.1.9 Wheels

Description: The wheels are the contact points on the cane. The outer diameter is 1 ¼" and have a solid aluminum hub with a 1/16" axle hole. The tires are made of rubber and have a complex curved shape on the outer rim.

Table J.9

Quantity	16
Vendor	Robot Marketplace
Part Number	0-SUL353

J.3.1.10 Waist Belt Straps

Description: These 5' long straps connect the device to the body. Straps connect the plastic backing to the hip modules, connect the hip modules in front of the body, circle the legs and the waist, and connect the hip modules to the waist and leg straps.

Table J.10

Quantity	6
Vendor	REI
Part Number	709053

J.3.1.11 Motor Hubs

Description: The hubs will attach the rotational motor to the inside plate of the rotary module. The included set screw will secure the hub to the output shaft and the hub has 6 screws to attach the hub to the plate

Table J.11

Quantity	2
Vendor	Pololu
Part Number	1083

J.3.2 Raw Material Inventory

J.3.2.1 Box Walls

Description: The stock will be cut into appropriate dimensions from the available metal found in the shop. Holes of appropriate sizes for the bolts, motors, and hubs will be drilled and tapped.

Table J.12

Material	Aluminum Plate
Shape and Dimensions	1/8" thick
Source	Machine Shop

J.3.2.2 Shafts

Description: The stock will be cut to the appropriate lengths. The two driven shafts will have their centers machined into D-shapes to drive the wheels.

Table J.13

Material	Aluminum Shafts
Shape and Dimensions	¼ " thick
Source	Machine Shop

J.3.2.3 Inner Cane Stock

Description: The stock will be cut to the appropriate length. The slot and the hole for the pin will be drilled into the shaft and the pin will attach it to the interior of the shaft.

Table J.14

Material	Aluminum Hollow Shafts
Shape and Dimensions	¾" outer diameter
Source	Machine Shop

J.3.2.4 Outer Cane Stock

Description: The stock will be cut to the appropriate length and the holes for adjustability and the hard stop pin will be drilled.

Table J.15

Material	Aluminum Hollow Shafts
Shape and Dimensions	7/8" outer diameter
Source	Machine Shop

J.3.2.5 Foam

Description: The foam will be cut to the appropriate dimensions and glued to the plastic backing.

Table J.16

Material	Polyurethane
Shape and Dimensions	18"x18"x2"
Source	JoAnn's Fabrics

J.3.2.6 Plastic

Description: The foam will be cut to the appropriate dimensions and glued to the plastic backing.

Table J.17

Material	Polyvinyl Chloride
Shape and Dimensions	1/8" thick
Source	Machine Shop

J.3.3 FMEA Analysis

For the parts bought from external sources, the team performed Failure Modes and Effects Analysis (FMEA) to determine the hazards and their effects (Appendix XXX). The parts analyzed were the moving and rotating parts, which are the ones most important to the operation of the device and most likely to fail. The results of this analysis show that most of the effects of malfunctions will render the device non-functional for the intended effects. The canes will not move in the pre-determined motion, thus nullifying the benefit and functionality of the device. The causes for the failures will most likely lie in correct alignment of parts, which can be avoided by ensuring that parts have no obvious defects and that everything stays square during assembly.

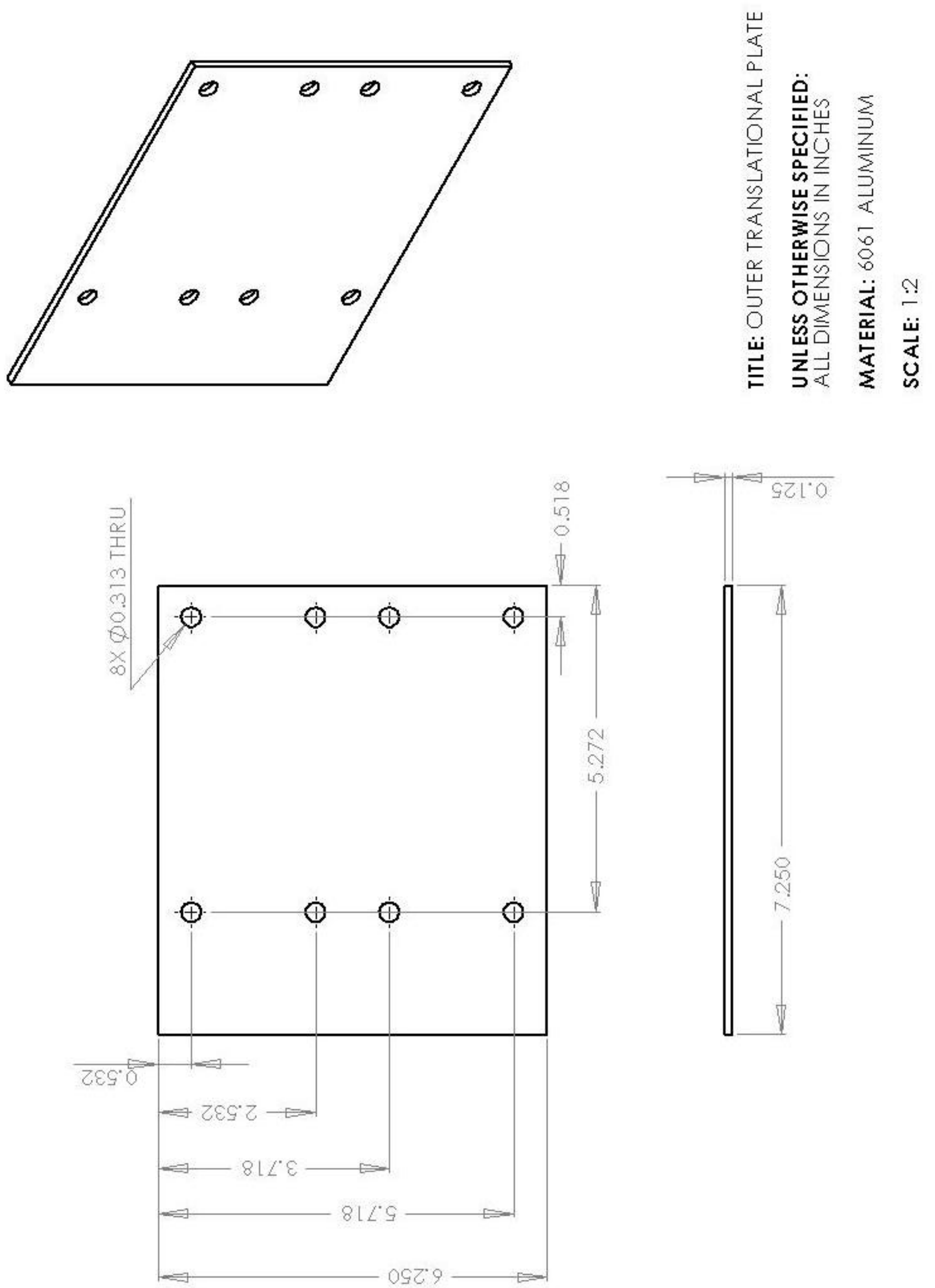
J.4 DESIGNED COMPONENTS

The majority of the parts of this device are pre-manufactured, so the only components designed were the pieces used to mount and hold the device to the body. Placement of holes and their alignment was the most important part of designing these pieces.

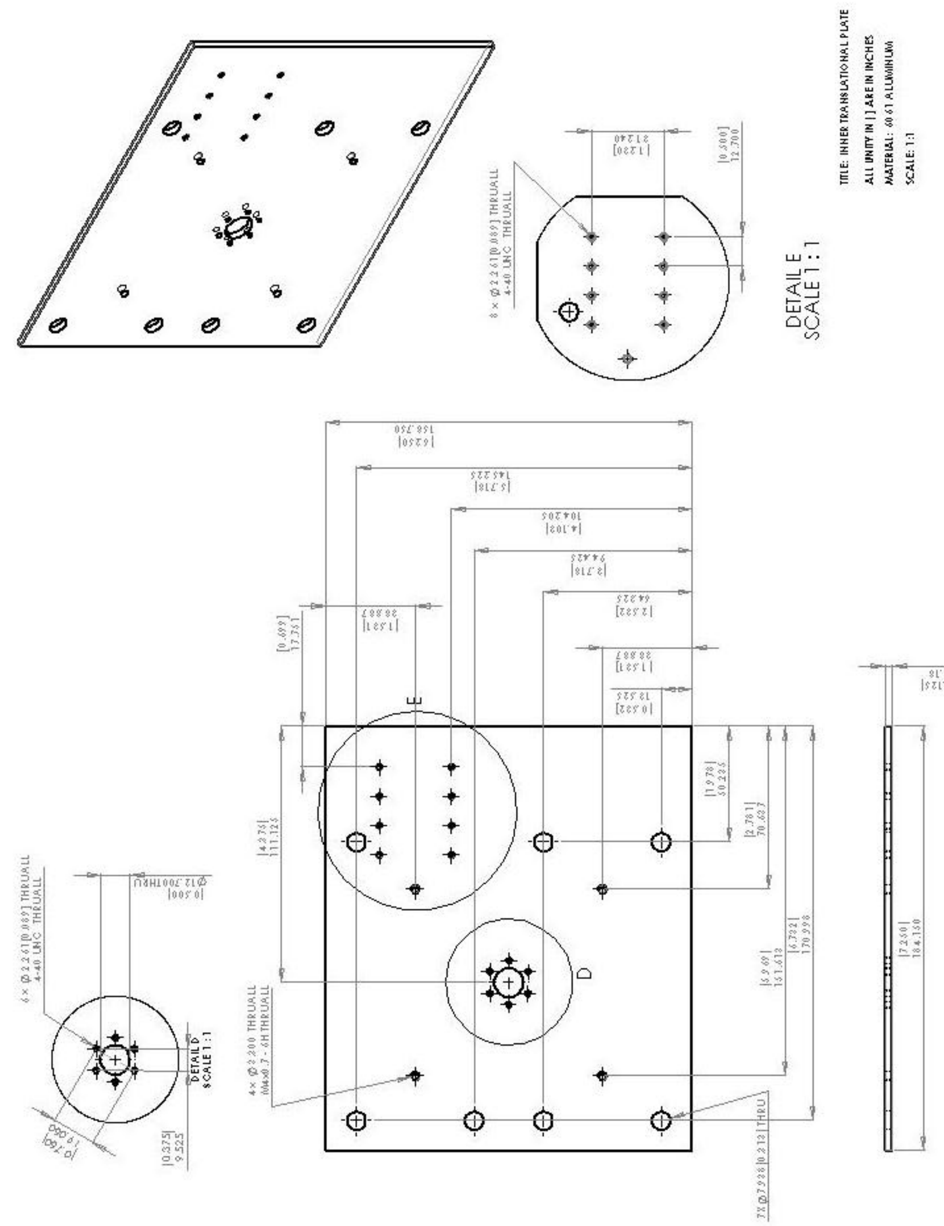
J.4.1 CAD Drawings

The following are CAD drawings of all the parts cut from stock. They hold together the primary components of the device, but needed correct hole placement to combine everything.

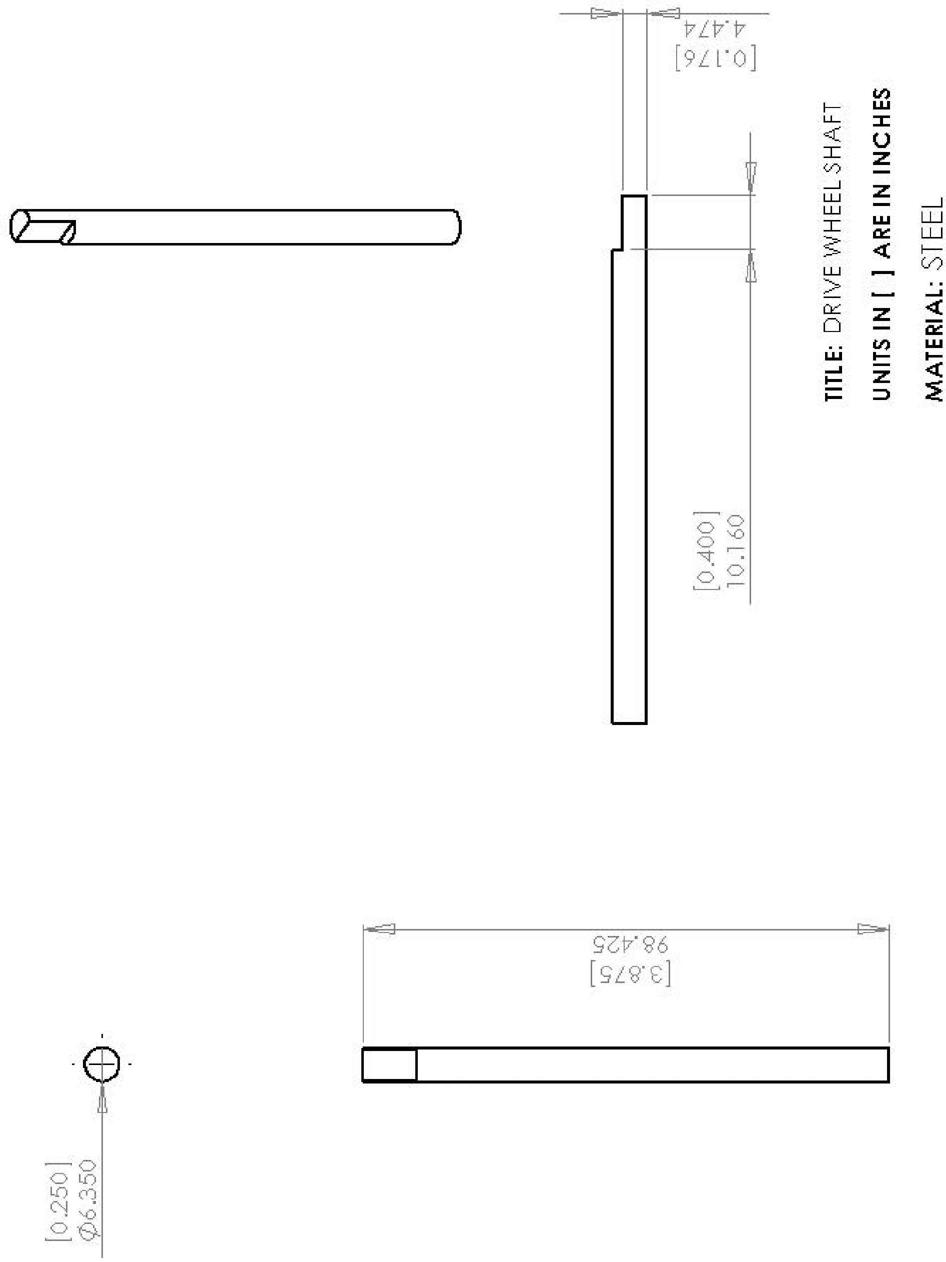
J.4.1.1 Outer Translational Plate



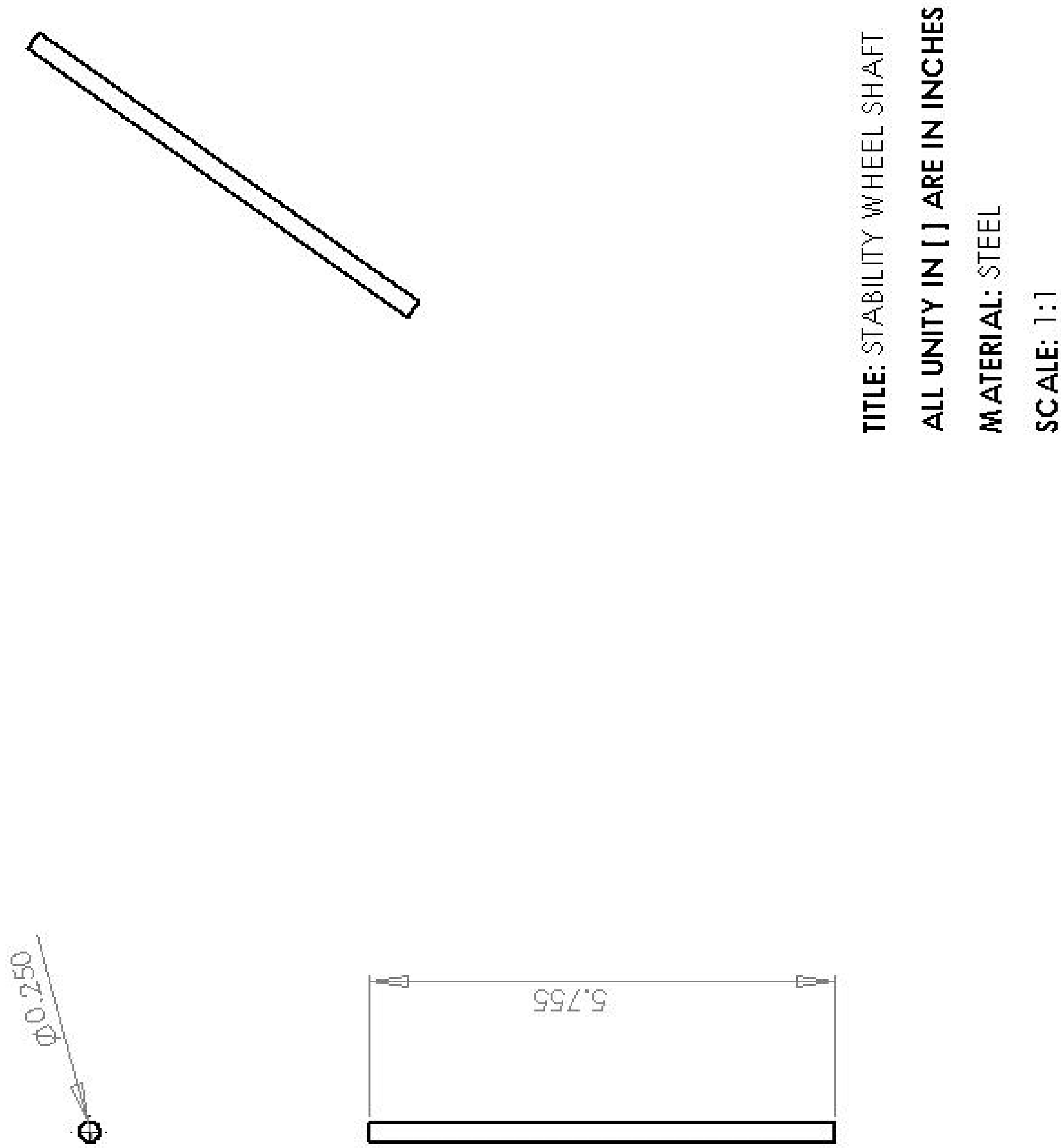
J.4.1.2 Inner Translational Plate



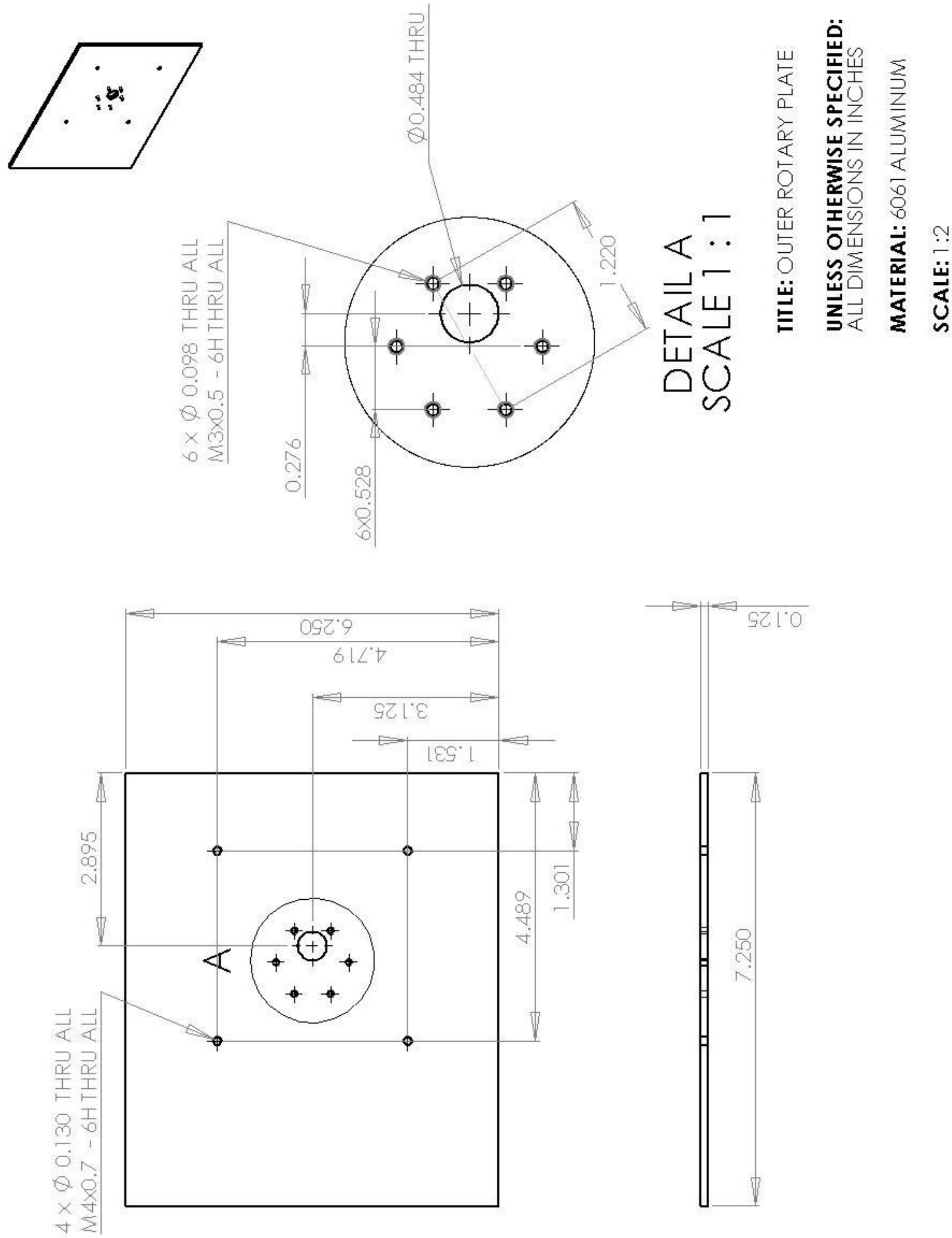
J.4.1.3 Drive Shaft



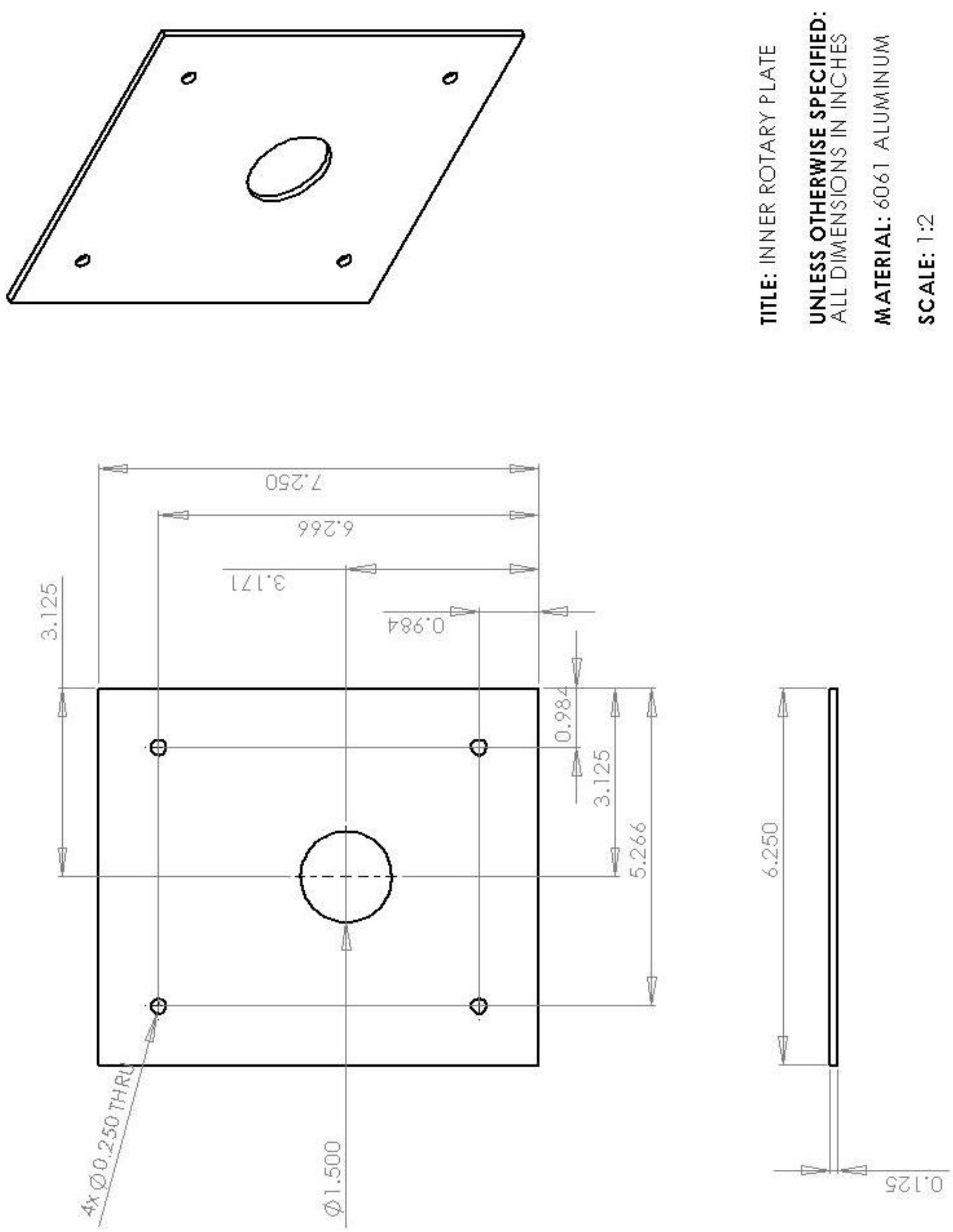
J.4.1.4 Dummy Shafts



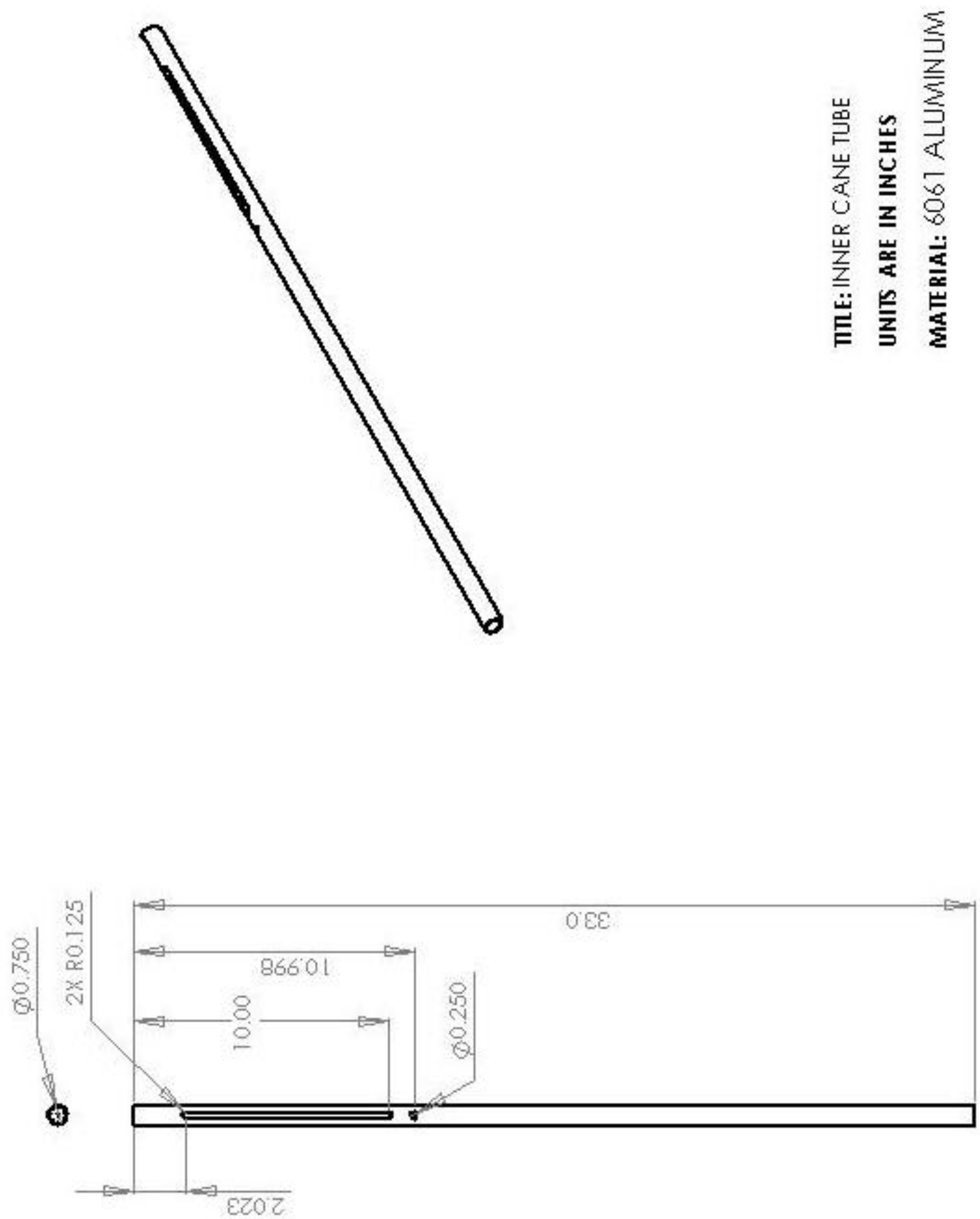
J.4.1.5 Outer Rotary Plate



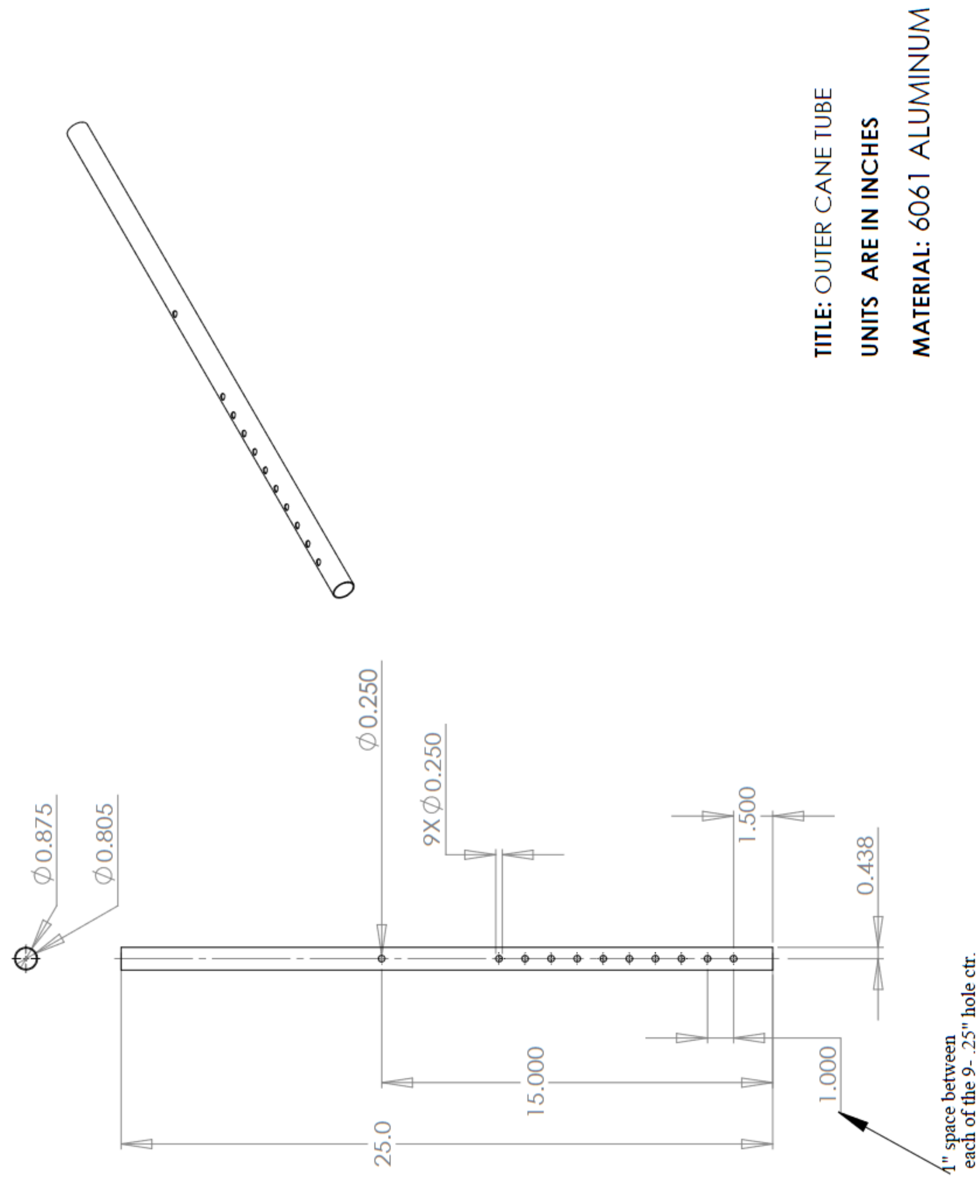
J.4.1.6 Inner Rotary Plate



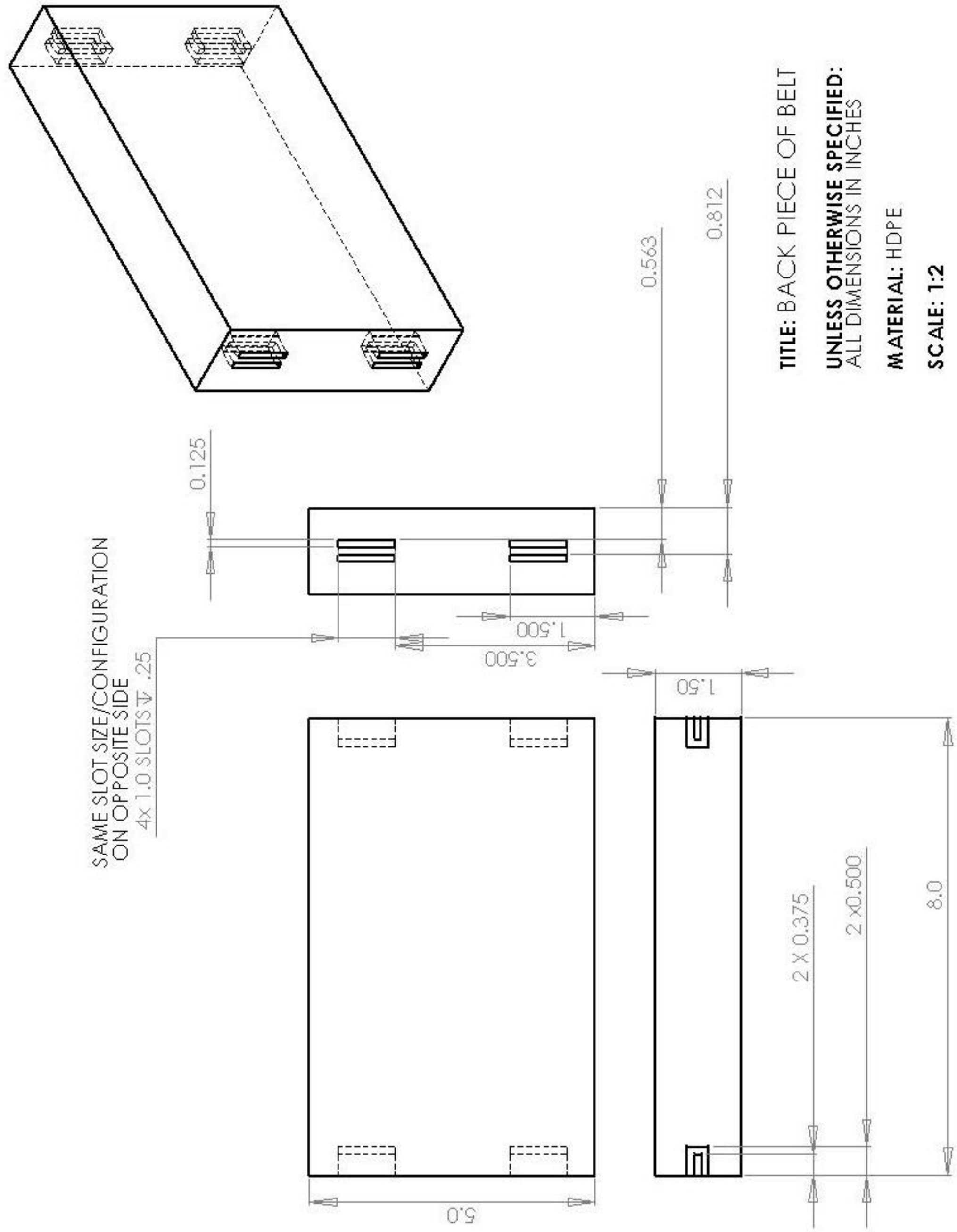
J.4.1.7 Interior Cane



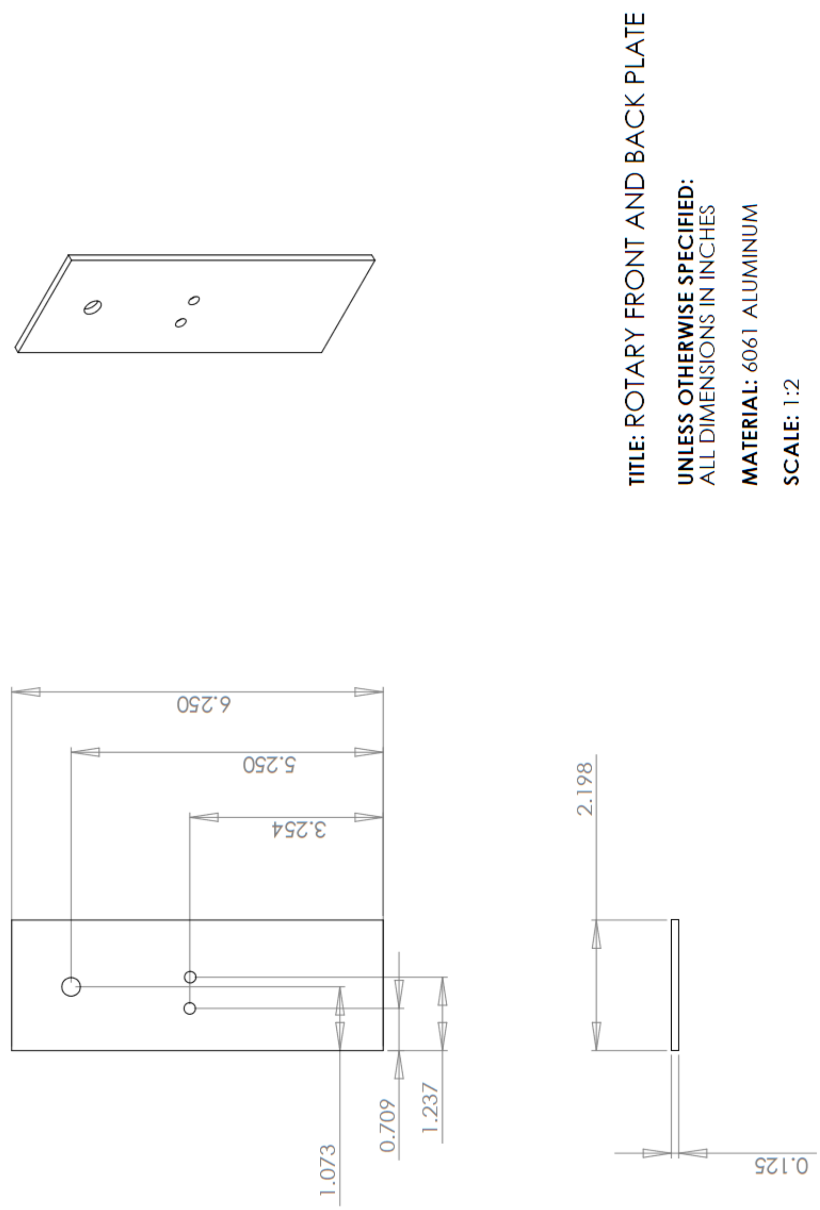
J.4.18 Exterior Cane



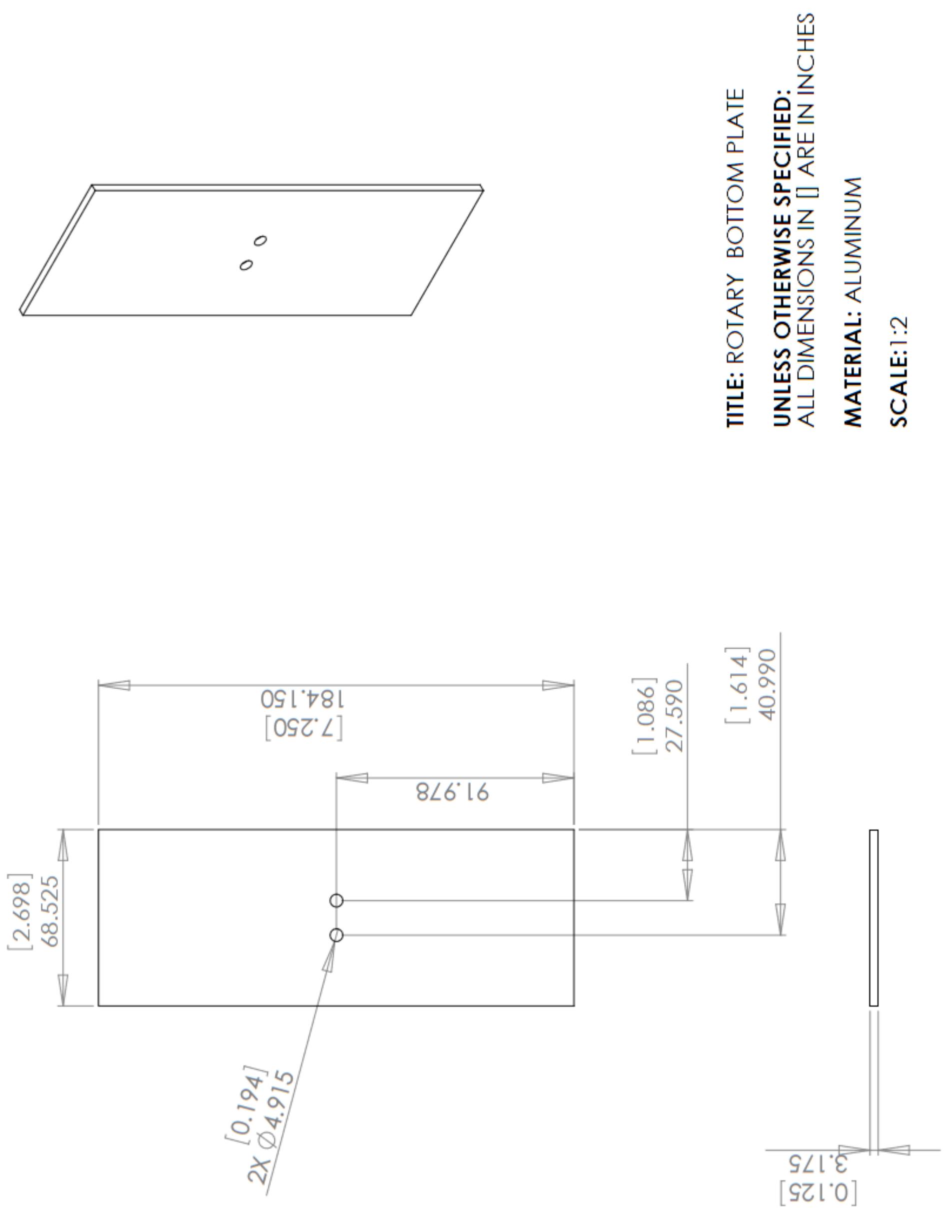
J.4.1.9 Belt Back Piece



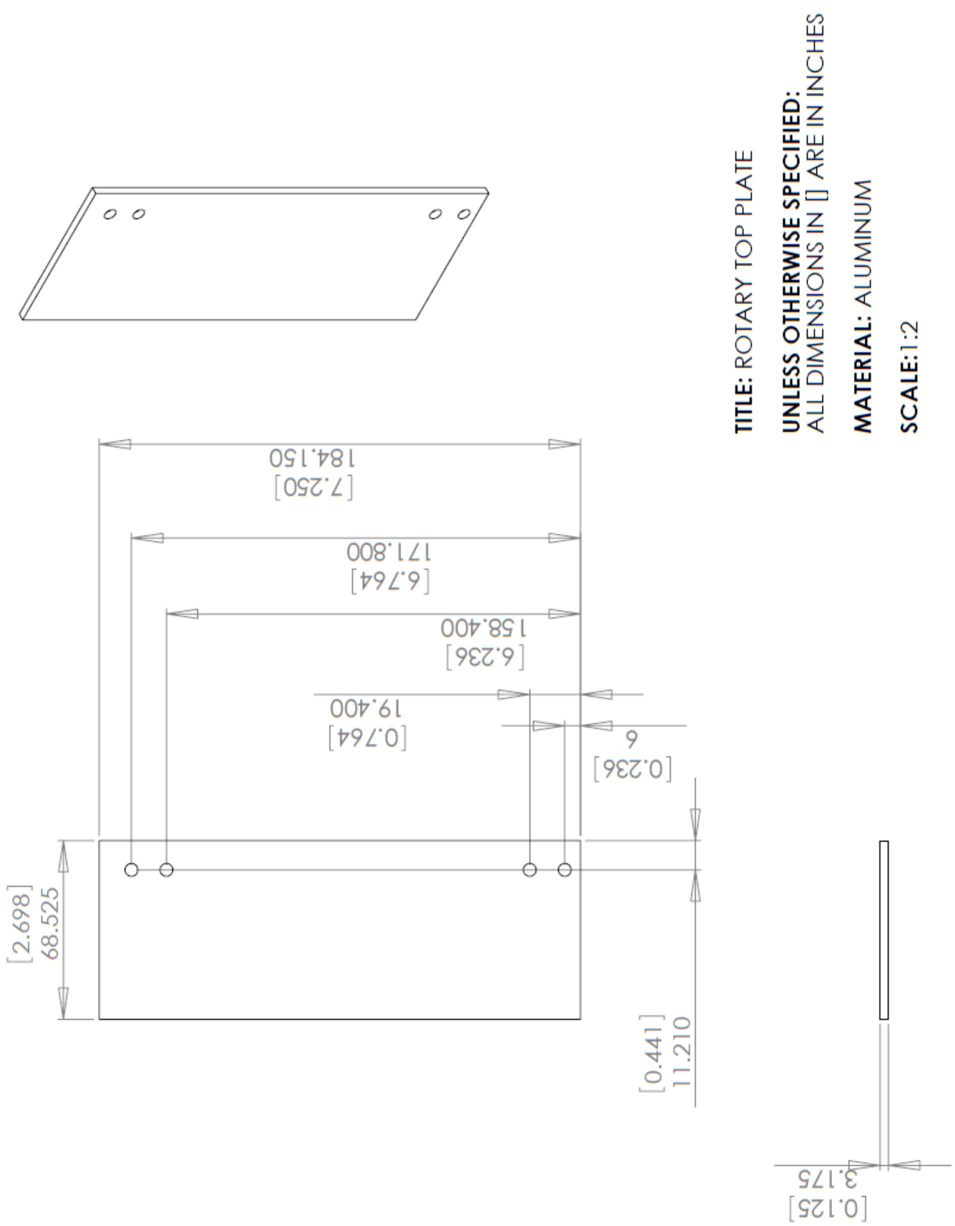
J.4.1.10 Rotary Side Plates



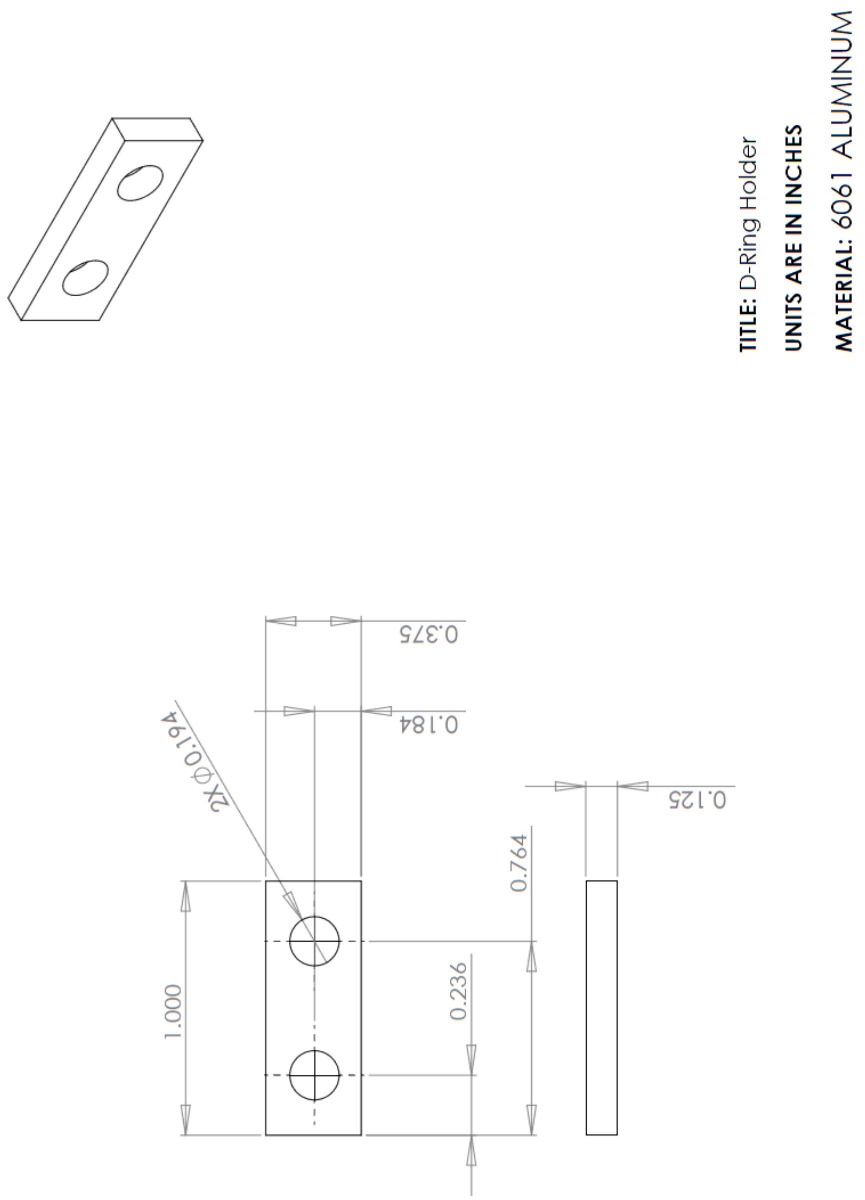
J.4.1.11 Rotary Bottom Plates



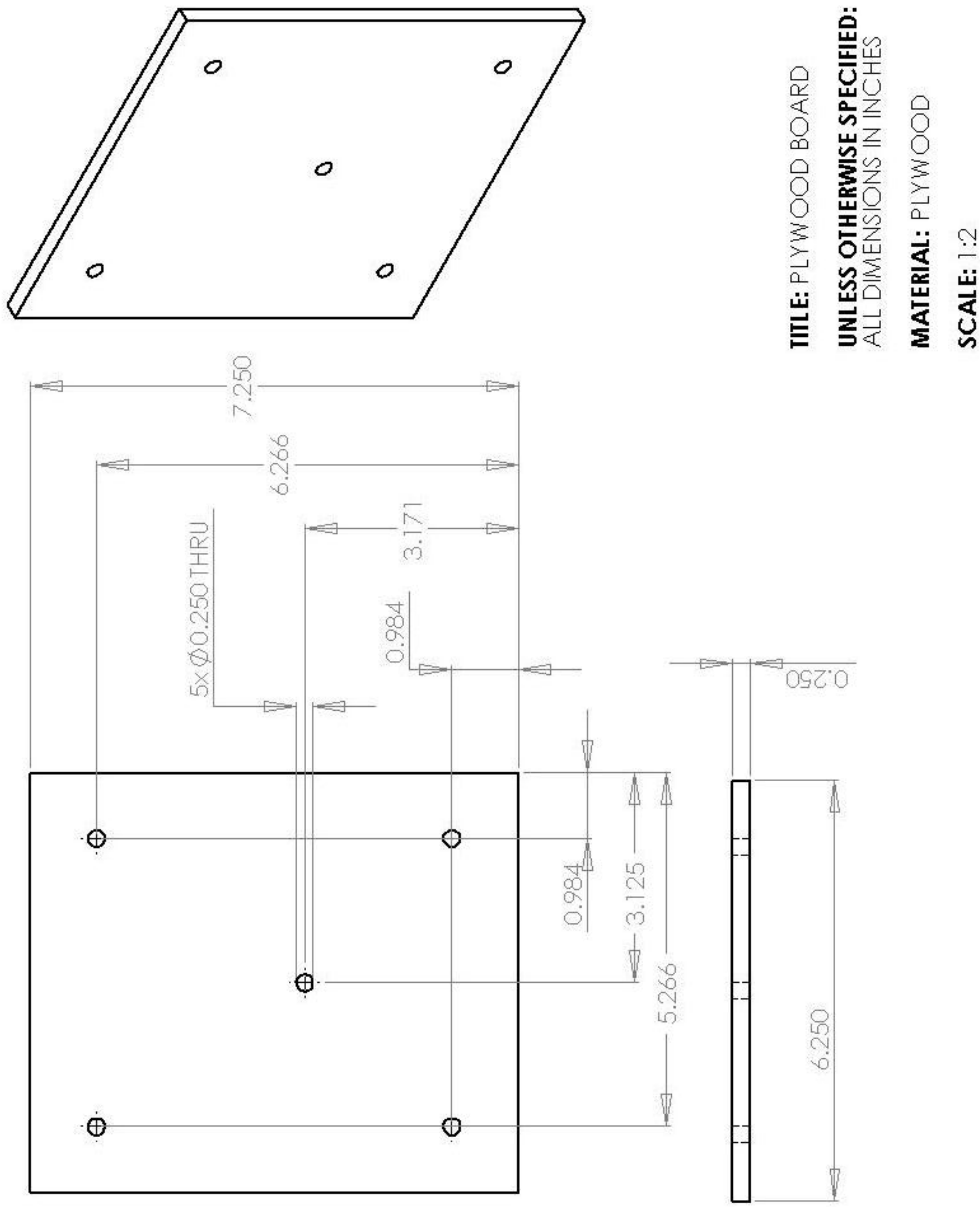
J.4.1.11 Rotary Top Plates



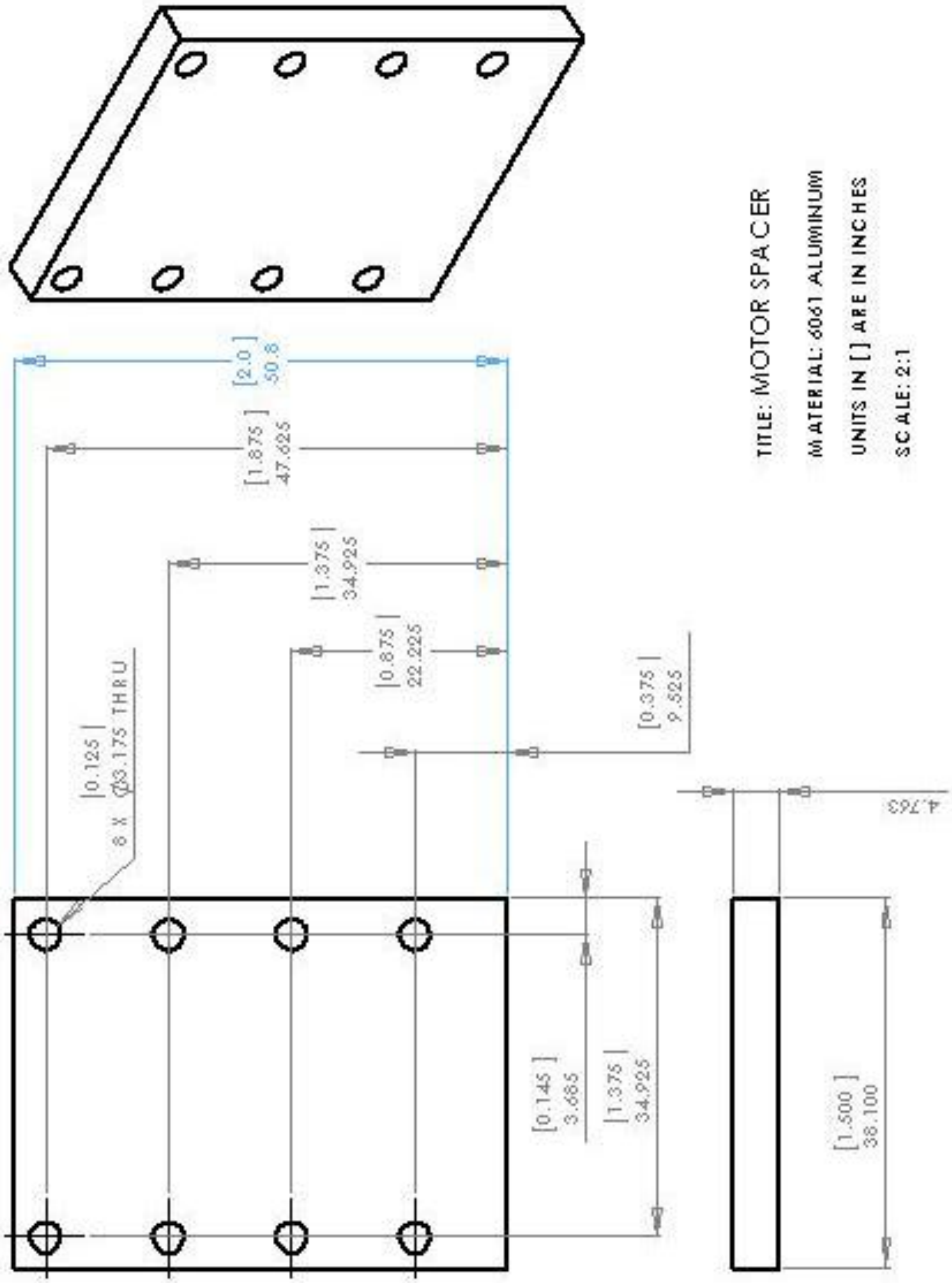
J.4.1.12 Motor Sleeve



J.4.1.13 Plywood Board



J.4.1.14 Motor Spacer



J.4.2 Belt
The belt connects the device to the body using straps and a plastic back piece. The ¾" nylon straps adjust to fit a wide range of hip and waist sizes and shapes. The adjustable sections are the pieces between the plastic piece and hip modules, the connection between the hip module and the upper strap, the length between the hip modules over the front of the body, and the upper waist strap length. The hard plastic backing measures 8" long, 5" tall, and 1.5" deep and contains the battery and microcontroller. The plastic section will be lined with the same polyurethane foam as the rotary module to better fit the shape of the user's back.

J.4.2 DesignSafe Analysis
The team did not have to design any components beyond containing and mounting objects, but DesignSafe was used to analyze the risks of the entire system in its operation. The greatest risk comes from the battery and electronics overheating. The battery and other parts of the control system were chosen to minimize weight and cost, but the drawback is operation close to peak current which gives a greater potential for creating hot surfaces. To help minimize this risk, the material selection for the foam includes some insulating capacity, so that the user's skin will be protected from the heat from the electronics and battery.

The other hazards of the system stem from misuse or the frequency that the person is in contact with the device. Since the user will be wearing the device whenever he or she wants to maneuver, the interaction with the device is substantial, which means that minimal risks are amplified.

J.5 MANUFACTURING PLAN

J.5.1 Cane
The team will use the band saw to cut the stock to the appropriate length for both the larger diameter and smaller diameter shafts. To make the cane adjustable, the holes will need to be cut out so that the pin can be inserted. The holes will be cut into the larger diameter section using the drill press according to the picture in Section 4, cutting through the material to ensure that the holes are aligned correctly along the center of the shaft. For the slot in the smaller diameter section, a hole will be drilled for the spring mechanism and then through one end of the slot. The mill will then be used to make the slot down the cane. This manufacturing plan, along with tools and speeds, is listed in Table 6.

Step	Operation	Machine	Tool	Cutting Speed
1	Cut to Length	Band Saw	-	275-300 fpm
2	Drill Pin Holes (Large Shaft)	Drill Press	¼ inch Drill	N/A
3	Drill Pin Hole (Small Shaft)	Mill	¼ inch Drill	3000 rpm
4	Make Slot	Mill	¼ inch End Mill	2500 rpm

Table J.18 Manufacturing Plan for Cane

J.8.3 Wheel Hubs
The wheels have a solid aluminum hub with a 1/16 inch hole for an axle. In order to fit the shafts of this device, the diameter of the axle hole needs to be drilled out to press fit over the shaft. This operation will be done using the lathe, first with a 7/32 drill bit and then reamer. The wheels will be press fit onto the shafts to the appropriate position of cane contact.

J.8.4 Plates

The plates will be made from 1/8 inch aluminum from various sizes of stock material. The plates will be cut, milled, and drilled according to drawings in Appendix G. The dimensions of the 8 total plates to be cut are 7.25 inch by 6.25 inch. The various drill bits that will be used to make holes in the more complicated plates are listed in Tables 7 and 8. The mill will be used to cut the holes for accuracy of position at a cutting speed of 2200 rpm. All of the holes will go the entire way through the material. To cut the holes in the side plates for connection to the D-rings, the hand drill will be used. The hole in the inner rotary plate will be milled out using a ¼ inch end mill. The plywood will be cut to 7.25 inch by 6.25 inch using the band saw and the holes drilled using the drill press.

Operation No.	Drill Size	No. of Holes
1	½ inch	1
2	No. 43	14
3	5/16 inch	7
4	M4	4

Table J.19 Drilling Operation for One Inner Translational Plate

Operation No.	Drill Size	No. of Holes
1	31/64 inch	1
2	¼ inch	4
3	M4	4

Table J.20 Drilling Operation for One Outer Rotary Plates

J.8.5 Shafts

The 6 dummy shafts will be cut to 5.75 inch using the band saw. The 2 driven shafts will be cut to 3.875 inch using the same settings on the band saw and then have a flat milled 0.4 inch long onto one end of each using a ¼ inch end mill at a speed of 2500 rpm.

J.8.6 Belt

The lengths of the straps will be cut with a utility knife. The sections for connection of the plastic backing to the hip modules will be 24 inches long and the leg sections will be 36 inches long. The hip module to the waist belt will be 2 inch sections attached to an 8 inch section. The hip belt will be 36 inches long and the waist belt will be 54 inch long. Buckles will be on all sections except the back plate to hip module.

J.6 ASSEMBLY

The assembly will be done in the major parts and then combined together. The respective assemblies for each side will be done immediately following one another to ensure consistency between the two sides of the device.

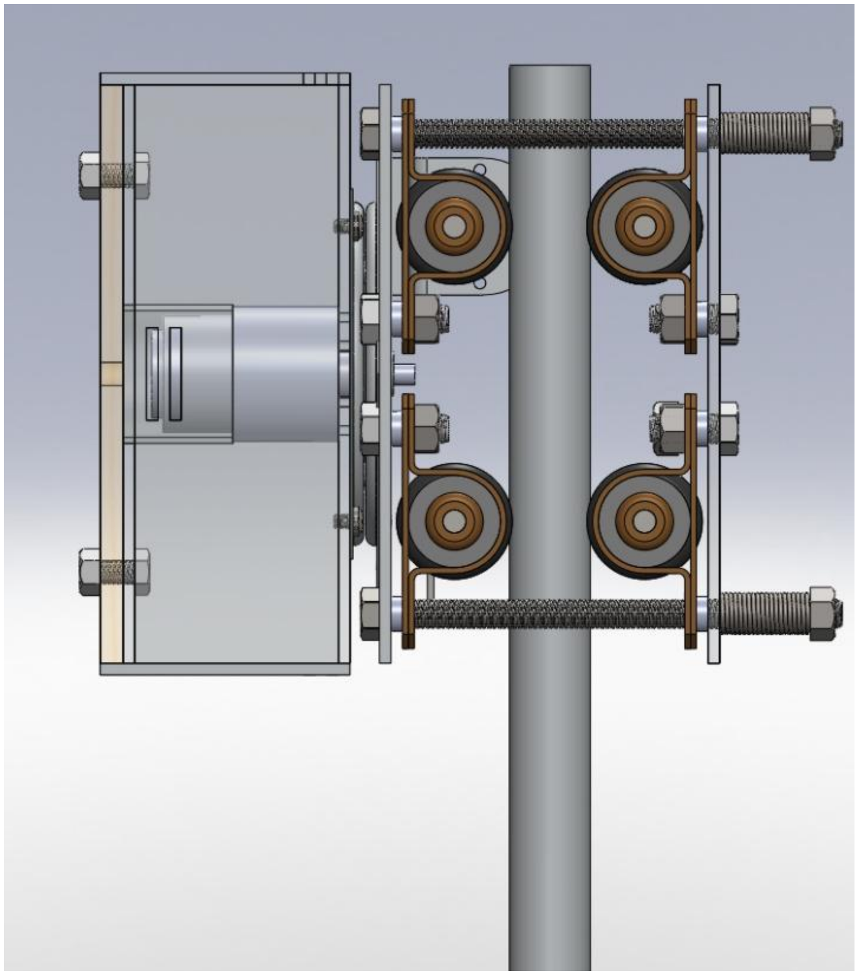


Figure J.1 Assembly of Rotary Module, Translational Module, and Cane

J.6.1 Translational Module

The first attachments to the inner translational plate are the motor spacer and mount. Once that is secure, the motor will be attached to the mount using the provided M3 screws. The coupler and shaft are attached to the output shaft of the motor. The bearing of the plate are then attached using 5/16" bolts and nuts on the interior side that does not use the long bolts and the shafts with wheels on them are put into the appropriate holes in the bearings. The same bearing, shaft, and wheel attachment is done for the outer translational plate. The hub is also attached to the inner translational plates at this point.

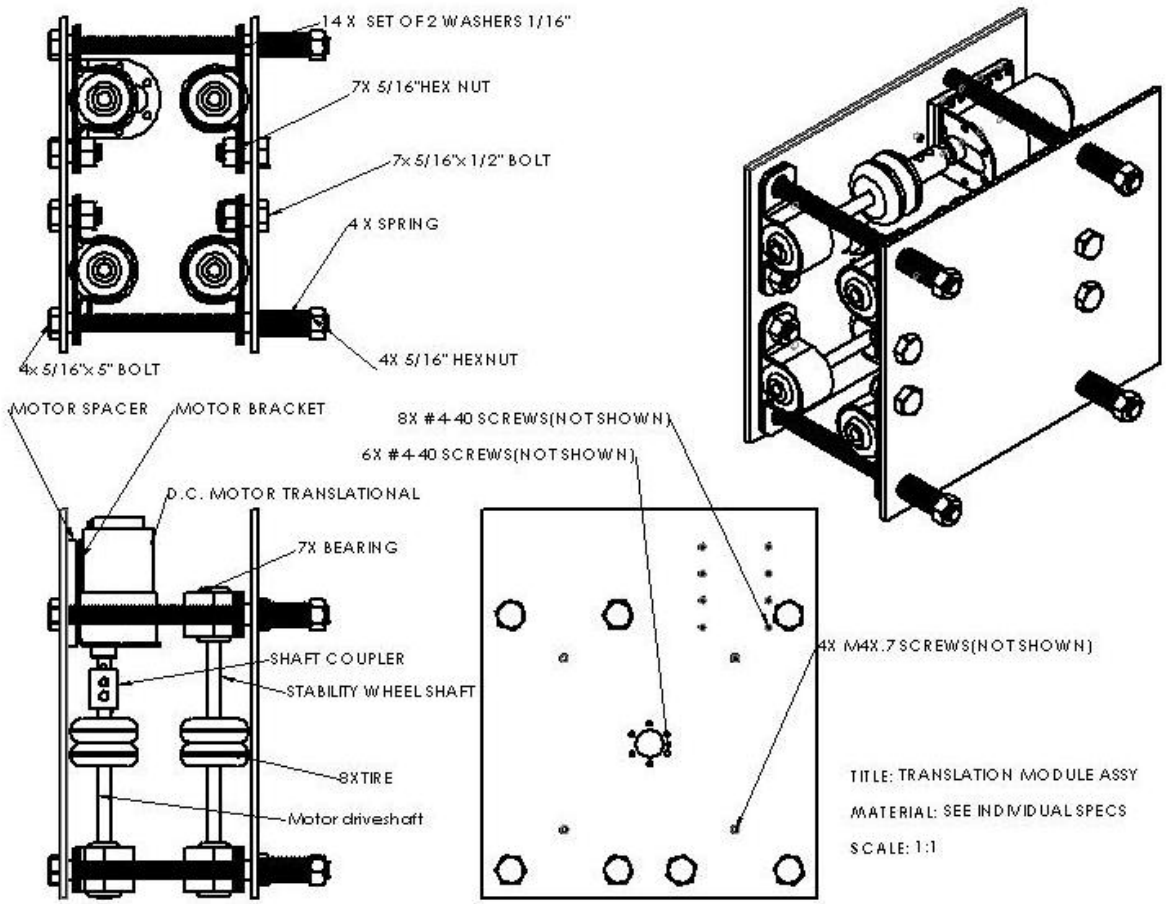


Figure J.2 Drawing of translational module assembly

J.6.2 Rotary Module

First, the outer plate and the box walls will be attached with brackets and 10-24 bolts and nuts. The motor will be inserted into the appropriate hole in the outer rotary plate and screwed in using M3 screws. Next, the turntable will be screwed into the outer plate with M4 bolts and nuts. Finally the inner rotary plate is attached to the rest of the box using a hinge at the top and Velcro for the other sides.

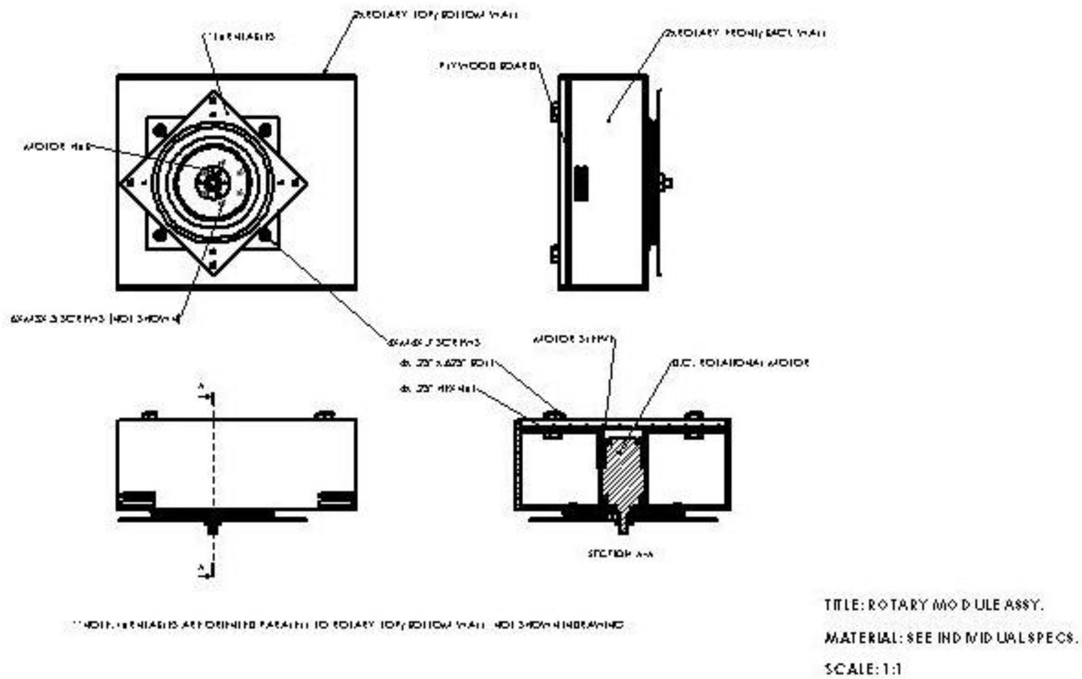


Figure J.3 Drawing of rotary module assembly

J.8.7.3 Attaching the Translational and Rotational Modules

To attach the two modules, the bolts should be put through the turntable when it is unattached. Then, the turntable should be attached to the inner translational plate and tightened. With the turntable facing up on the inner translational plate, the rotational box should be lined up so that the flat in the rotational motor shaft lines up with the set screws in the hub and the holes for turntable attachment line up with the bolt in the turntable. Then, all nuts and bolts should be tightened. Finally, the modules should be rotated relative to one another so that the holes for the long bolts are exposed. The long bolts should be inserted and tightened to the inner translational plate and the outer translational plate should be attached with the springs, washers, and nuts on the outside.

J.6.3 Cane

Once the cane has been appropriately cut to the specification in Figure 16 in Section 9, the torsion spring will fit into the inside cane through the one set of holes in that shaft. The inner shaft will then be inserted into the outer shaft so that the torsion spring locks into place into one of the adjustability holes. Next, the pin will be inserted through the top hole in the line of holes, through the shaft and secured in place so that the inner shaft can slide to adjust the total height by depressing the pin and pushing or pulling on the inner shaft until it locks into place in the desired position. The cane will then be inserted into the translational module after the belt assembly is complete.

J.6.4 Belt

The first step in assembling the belt is the plastic backing. The foam will be attached to the backing and the microcontroller will be mounted to the back. Next, the waist strap and straps that attach the hip modules to the back will be threaded through the slots of the back and the hip modules. Next the straps that connect the hip modules to the waist belt and leg belt will be threaded through the slots and buckled. Last, the hip strap will be inserted into the slots in the hip modules.

APPENDIX K. FAILURE MODES AND EFFECTS ANALYSIS

Identify subsystem and mode of operation	Potential Failure Mode	Potential Effect of Failure	Severity	Potential Causes of Failure	Occurrence	Current Detection and Prevention	Detection	Recommended Action	RPN
Translational Motor- rotates driven roller	power loss	canes roll freely	10	improper assembly, unexpected movement	2	connections secured	1		20
Rotary Motor- rotates hip module	power loss	canes can't rotate	8	improper assembly, unexpected movement	2	connections secured	1		16
Bearing- allows shafts to rotate freely or with motor	stick	cane can't move	6	improper assembly	4	careful alignment of translational joint	1		24
Cane- connects the device to the ground and supports a person's weight	yield	canes break and/or deform	9	manufacturing defect	1	built to sustain stresses from body (high yield strength)	1		9
Wheels- rotation causes cane to rise because of frictional forces	slip	canes cannot be raised	7	insufficient normal force, coefficient of static friction, improper assembly	2	spring forces to increase friction	1	change material, increase spring force, reassemble	14
		canes cannot bear weight of person during fall	10	insufficient normal force, coefficient of static friction, improper assembly	2	spring forces to increase friction	1	change material, increase spring force, reassemble	20
Shaft Coupler- connects motor output shaft to driven shaft	slip	canes cannot be raised	7	manufacturing defect, improper assembly	1	tightening of all parts	1		7

Turntable- connects rotary module to hip module		translational module does not move	7	manufacturing defect, improper assembly	1	tightening of all parts	1		7
Hub- connection to rotary motor output	slip	translational module does not move	7	manufacturing defect, improper assembly	3	tightening of set screws	1	change to keyway	21

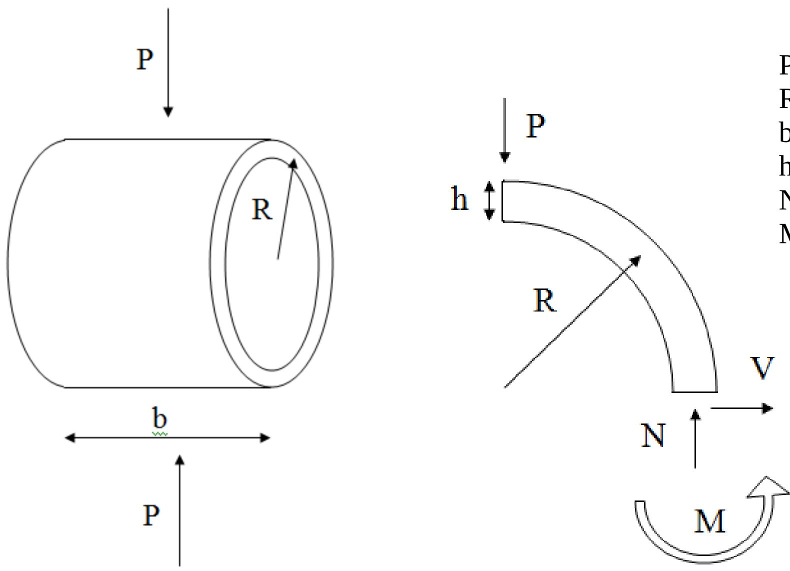
APPENDIX L. DESIGNSAFE RESULTS

User	Task	Hazard Category	Hazard	Cause/Failure Mode	Severity	Exposure	Probability	Risk Level	Reduce Risk	Severit	Exposure	Probability	Risk Level
All Users	All Tasks	mechanical	cutting / severing	sharp edges	Minimal	Frequent	Unlikely	Moderate	round all the corners or add plastic coverings	Minimal	Frequent	Negligible	Low
All Users	All Tasks	mechanical	drawing-in / trapping / entanglement	legs getting caught up in canes, clothing, hands getting caught in rotational joint movement	Slight	Frequent	Unlikely	Moderate					
All Users	All Tasks	mechanical	pinch point	fingers, clothing getting caught in springs, adjustable portion	Minimal	Occasional	Negligible	Low					
All Users	All Tasks	mechanical	fatigue	spring inside adjustable component loses strength	Minimal	Remote	Unlikely	Low					
All Users	All Tasks	electrical / electronic	lightning	having metal canes outside during storms increases risk	Catastrophic	Remote	Negligible	Moderate					
All Users	All Tasks	electrical / electronic	water / wet locations	liquid could leak through	Slight	Remote	Unlikely	Low					
All Users	All Tasks	electrical / electronic	unexpected start up / motion	motor could malfunction and start rotation or translation	Serious	Remote	Unlikely	Moderate					
All Users	All Tasks	electrical / electronic	software errors	motion of the canes in improper to person's gait	Minimal	Remote	Negligible	Low					
All Users	All Tasks	electrical / electronic	overvoltage /overcurrent	electronic devices fail, H-bridge doesn't limit current in microprocessor	Slight	Occasional	Unlikely	Moderate					
All Users	All Tasks	ergonomics / human factors	human errors / behaviors	people could misuse walk too close to objects or people causing interference with the canes	Slight	Remote	Unlikely	Low					
All Users	All Tasks	fire and explosions	hot surfaces	battery could overheat	Serious	Frequent	Unlikely	High	place in protective heat absobant casing to limit tphysical contact	Slight	Occasional	Unlikely	Moderate
All Users	All Tasks	ingress / egress	inadequate means of evacuation	during device malfunction, user cannot remove belt	Serious	Occasional	Unlikely	Moderate					

APPENDIX M. MATERIALS SELECTION ASSIGNMENT- FUNCTIONALITY

M.1 Cane

As the cane is being translated up and down, normal force will be applied by the rollers to the cane in radial direction. To make the device as light as possible, the mass of the cane needs to be minimized. While minimizing the mass, the cane needs to be fail-safe from plastically deforming due to the "crushing force" from the rollers. The radius of the cane and the thickness will be fixed.



P: normal force on the cane
R: Radius of the cane
b: Contact length with the roller
h: Cane Thickness
N,V: Internal forces
M: Moment at the fixed end

Figure M.1. The free body diagram of the cane section (left) and the model for the stress analysis (right).

The concept of a bending stress on a curved beam was used to approach the problem. Knowing that the maximum stress will be applied midway between the two forces, the following equations were applied.

$$\sigma = -\frac{Ry}{R+y}\frac{PR}{I_2} \qquad \text{Eq. M.1}$$

$$I_2 = bR^3\left[\ln\left(\frac{1+\frac{kh}{2}}{1-\frac{kh}{2}}\right) - kh\right] \qquad \text{Eq.M.2}$$

Where σ is the bending stress, *k* is the constant for $N - kM = 0$, and I_2 is the cane section's area property [XX]. The value *b* was determined empirically by actually pressing a painted roller against the cane like a stamp and measured the contact length between the two materials. Values *V*, *N* and *M* were determined by the following force and moment balance equations.

$$\Sigma Fx = V = 0 \qquad \text{Eq.M.3}$$

$$\Sigma Fy = N - P = 0 \qquad \text{Eq.M.4}$$

$$\Sigma M = PR + M = 0 \qquad \text{Eq.M.5}$$

From the equations N was determined to be 32.6 lbs since P is known, M was determined to be -13.7 lbs-in. Hence, k was calculated to be -2.4. Then, the values were plugged into Eq.5 and I2 was determined to be -0.00035, so the maximum bending stress was determined to be 656.1 psi. In order to ensure the fail-safe, a safety factor of 2 was applied to make the minimum yield strength to be 1.31 ksi. The volume of the cane is fixed as 6.41 in^3 from the design and in order to meet the weight specification of the device, the cane needs to be no heavier than 0.6 lbs. Hence, the density needs to be no greater than 0.1 lb/in^3. The constraint values were applied to CES software and the materials that meet the requirements of the cane were narrowed down as the Figure M.2 shows.

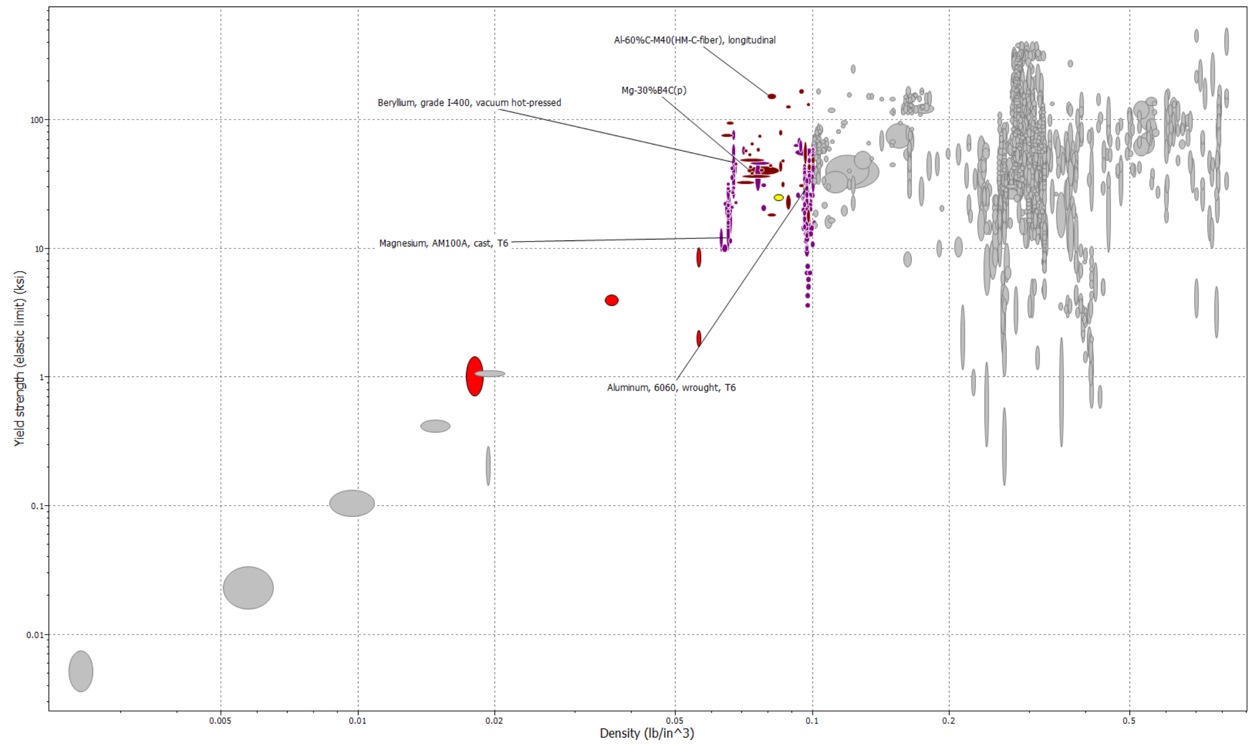


Figure M.2. The CES result shows the materials that are appropriate for the cane.

Property	Aluminum 6060	Magnesium AM 100A	Beryllium grade I-400	Mg-30%B4C	Al-60%C-M40
Yield Strength(ksi)	29.6	9.57	36.3	37.7	145
Density (in^3)	0.0965	0.0648	0.0665	0.0717	0.0795
Price (USD/lb)	0.692	2.26	346	11.3	376

Table M.1. Comparison among the top 5 materials based on the yield strength and density

From the top 5 materials chosen from the CES results, aluminum 6060 was the best choice for the device. Although it had the highest density and its yield strength was not the best, its price was significantly lower than the other 4 materials. Although not the best in its specifications, aluminum still has enough strength to be safe from failing and is light enough to meet the design goal. Hence, aluminum was chosen to be the material for the cane.

M.2 Foam

The walking facilitator has a plastic pad attached to the back with electronic components mounted to it. In between the plastic pad and the users back, a block of material is inserted. Due to the involvement of electrical components this material should be an insulator like a type of foam. The foam needs to be placed and compressed to support and cushion the user's back. In order to provide a sufficiently stable support on the foam pad, the density of the foam is important. Since this device must be all weather, the foam must also be closed end to be water resistant. The foam needs to have large compressive strength, so the pad does not contact the skin while not too large strength in order to provide comfort to the user.

Because the foam will be in contact with the skin, foams commonly used for orthotics were taken as a reference to set the range of compressive strength of the foam. The foam needs to have compressive strength ranging from 0.1 to 0.6 ksi to make sure that foam is strong enough absorb compressive stress from the pad while soft enough to provide comfort [XX]. From a literature survey, satisfactory foam needs to have density of 0.003 lbs/in^3 or greater [XX]. The CES software was utilized to determine the foam materials that meet these requirements and the Figure M.3 shows this result.

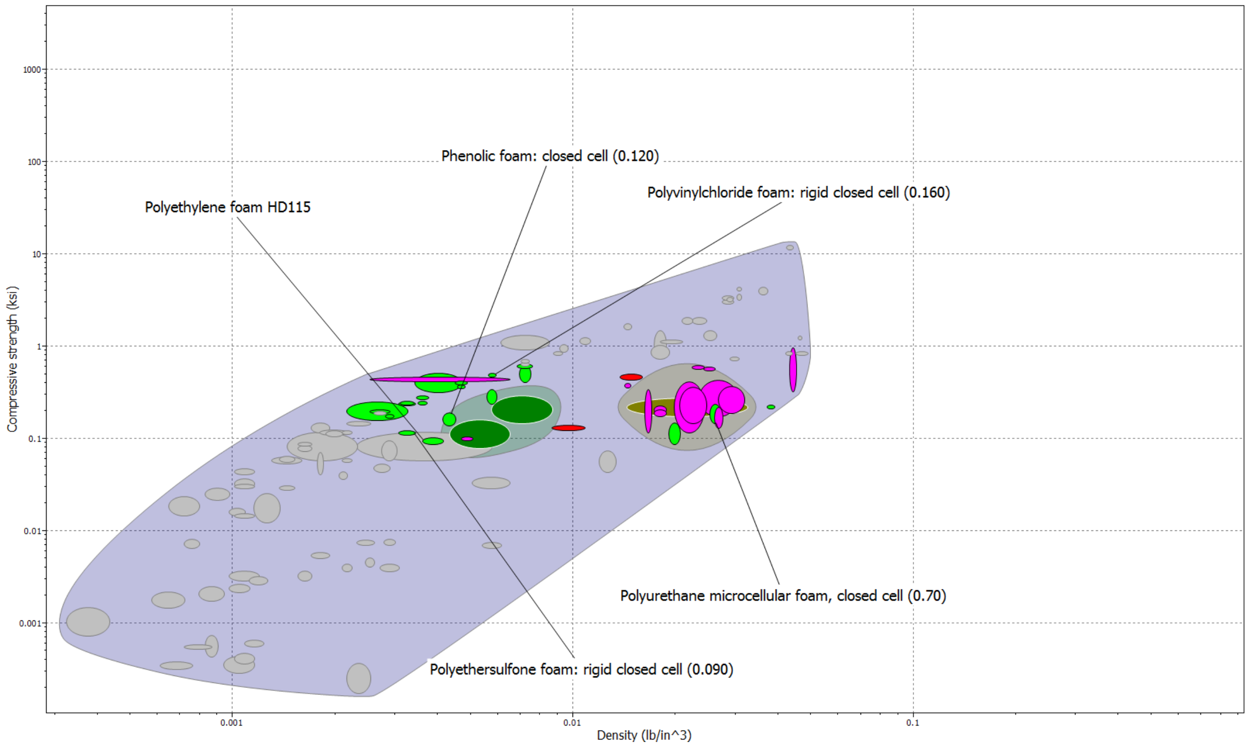


Figure M.3. The CES result shows appropriate foam materials to support the plastic back pad.

Property	Polyurethane	Polyethylene	Phenolic Foam	Polyvinylchloride	Polyethersulfone
Compressive Strength (ksi)	0.145	0.1	0.406	0.235	0.58
Density (lbs/in^3)	0.0253	0.00361	0.00697	0.00311	0.00686
Price (USD/lb)	3.76	1.41	3.76	5.64	16.9

Table M.2: Comparison among the top 5 materials based on the compressive strength and density.

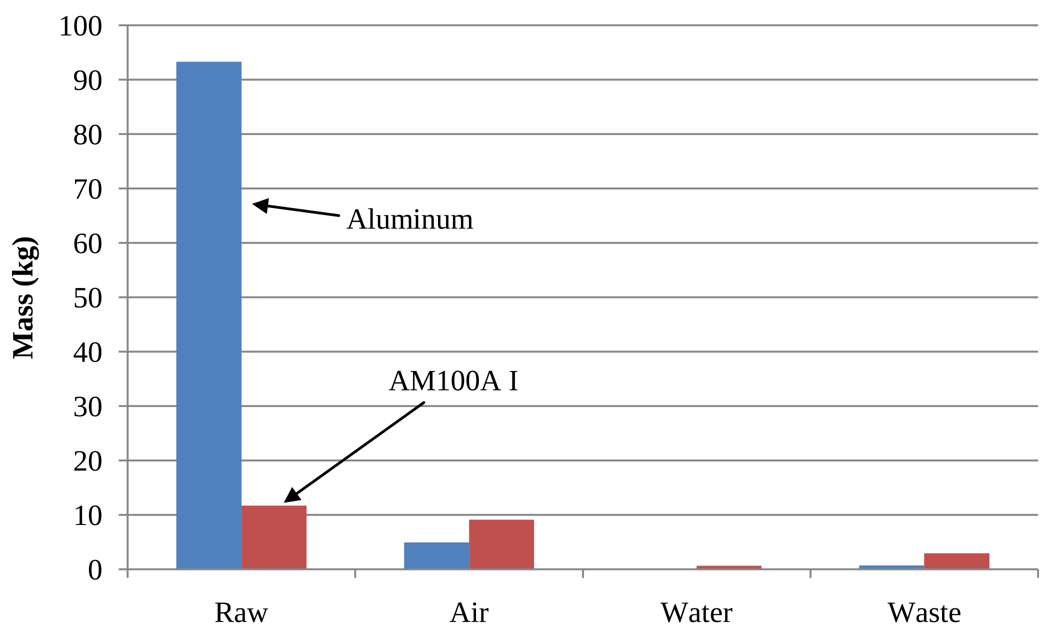
From the top 5 foam materials, polyurethane was the best choice, because it had the highest density. The price of the material was moderate among the 5 materials and the compressive strength was high enough to feel the comfort and to support the compressive stress from the back pad at the same time. Hence, polyurethane was used for the device.

APPENDIX N. MATERIALS SELECTION ASSIGNMENT- ENVIRONMENTAL IMPACT

To determine the environmental impact of the material chosen for the cane, EcoIndicator 99 (EI99) in SimaPro [XXX] can be used in comparison to a similar material. The material of the cane, Aluminum 6061, was not available in the software so Aluminum 6060 was used as the most like material, and the material to which the aluminum was compared was AM100A I, which was a possible material choice for the cane given by CES (see Appendix M). Overall, the environmental impact of the chosen aluminum is greater than that of the competing AM100A I according to this evaluation method.

To begin the process, the total mass emissions and consumptions is calculated as shown in Figure N.1 below. Using this, the impact in the myriad EI99 categories is graphed in Figure N.2 and then normalized to the amount a normal person would impact the three "Meta-Categories" of human health, eco-toxicity, and resource consumption (Figure N.3). From this graph, the extremely high value of Aluminum 6060's resource consumption is the likely factor to impact the total EI99 score.

On its own, Aluminum 6060 has the higher impact on the environment than the comparable AM100A I. The value for the chosen aluminum is just more than 1.5, which is relatively low. The total life cycle impact will be similar for both materials because they are so similar in their life spans and disposal. This environmental impact will not impact the material choice for the team because of the amount of convenience that using readily found aluminum gives. The prototype is the first model of its kind and many parameters will need to be reevaluated as the device moves through iterations of the design process. There is a possibility that in later redesigns an environmental impact will be important, but at this point it is insignificant.



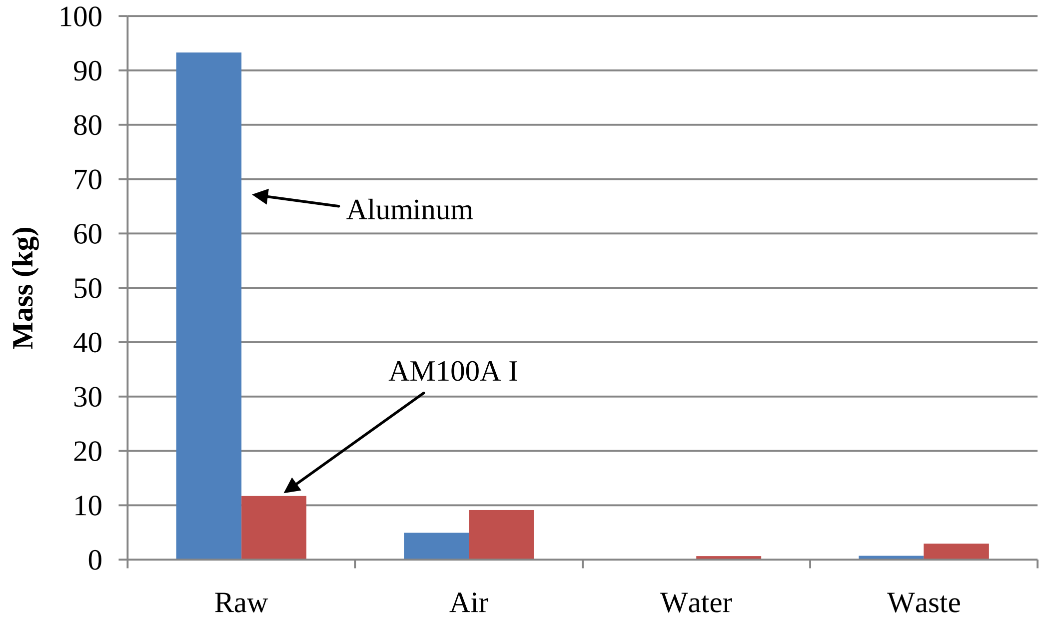


Figure N.1 Total Mass Comparison of Aluminum 6060 and AM100A I

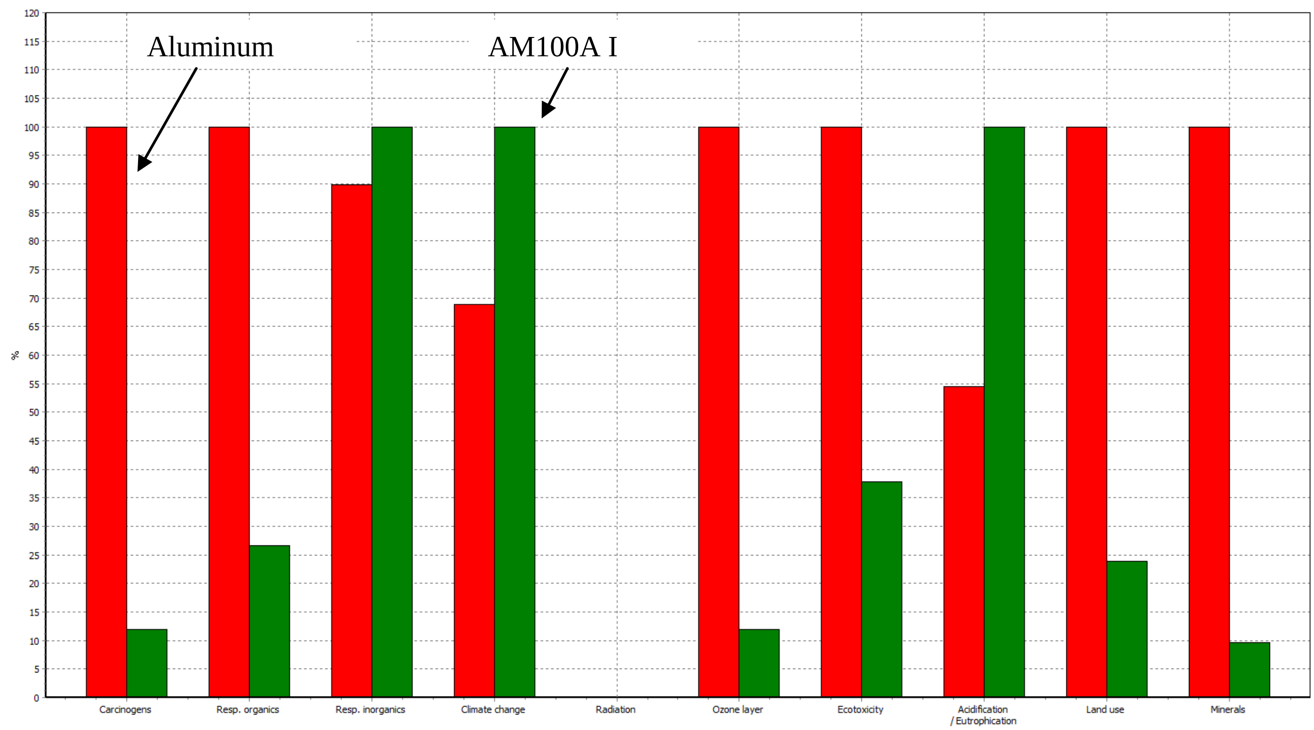


Figure N.2 EI99 Impact Category Comparison of Aluminum 6060 and AM100A I

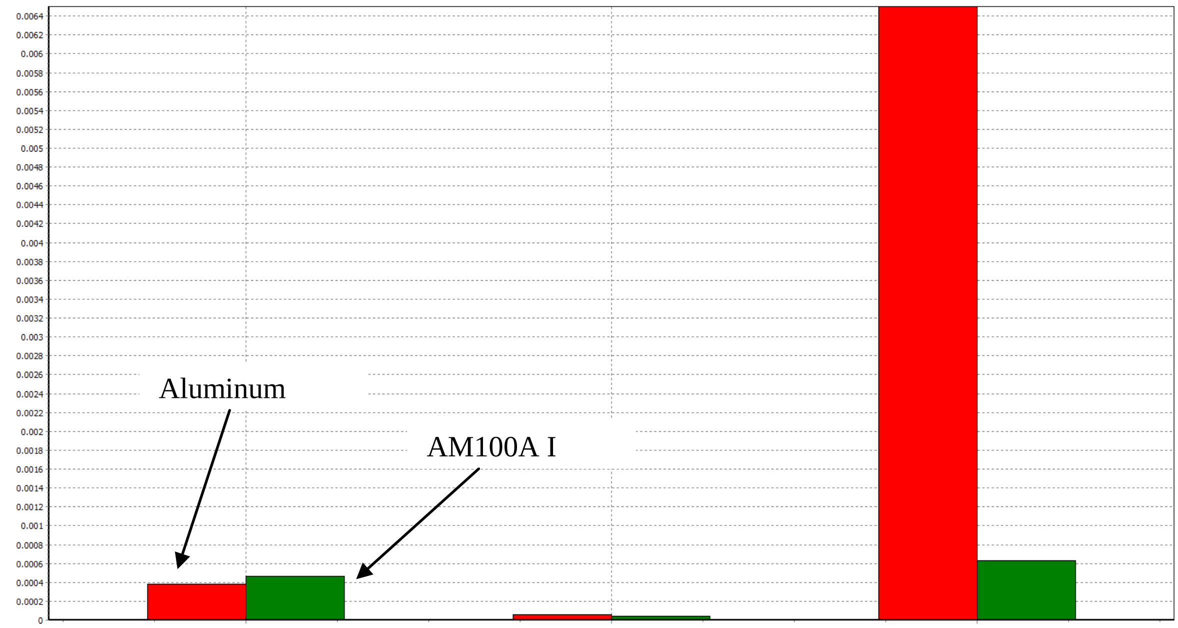


Figure N.3 Normalized “Meta-Categories” Comparison of Aluminum 6060 and AM100A I

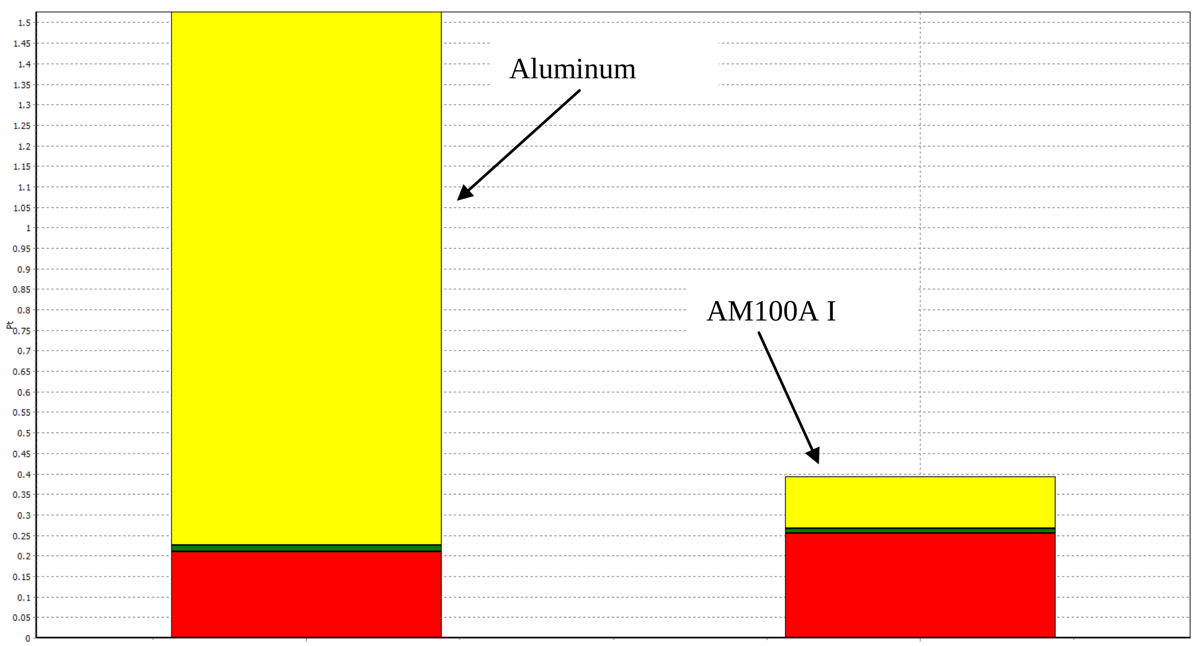


Figure N.4 Total EI99 Points Comparison of Aluminum 6060 and AM100A I

APPENDIX O. MANUFACTURING PROCESSES ASSIGNMENT

O.1 Batch Size Estimate

The appropriate number of devices that would be beneficial to society is dependent on the number of people who can potentially use this device. As discussed in the report, there is the possibility for broader applicability than the target demographic, which would increase the number of device to be produced. For the scope of this project, the number of devices to provide the mass market is derived from the target demographic, people with Spina Bifida. This is not limited to children because if this device works for children, it can also be used by adults with similar positive effects.

The number of people living with Spina Bifida in the United States is 166,000 people [XXX]. From this number, a number of assumptions made by the team narrowed this to a projected batch size. This number encompasses all of the reported levels of the disease; however this device is only useful for higher functioning individuals who can take some independent steps. Though this figure can be divided into the different types of Spina Bifida (occulta, meningocele, myelomeningocele) or the location of the lesion (thoracic, lumbar, sacral), this information does not directly impact the level of mobility and functionality the individual experiences. Additionally, adults already using different walking facilitators are unlikely to make the switch to a new device. These assumptions place the estimated mass production number of devices at between 40,000 and 75,000 devices.

O.2 CES Process Selector Results

O.2.1 Cane Process

To determine the appropriate process for manufacturing the cane, three different stages of the CES Process Selector were used. The first compared the material, aluminum, to the thin section thickness of 0.1 inch (Figure O.1). The next stage compared the shape, circular prismatic, against the mass of the cane, which further narrowed the available processes (Figure O.2). Finally, cost was incorporated into the decision by included the estimated batch size and then the estimated cost per unit (Figures O.3 and O.4, respectively). The estimated batch size is discussed above in XXX.1 and the cost per unit was set to less than $400 in keeping with the sponsor requirements of affordability. The following figures detail these images from the CES software [2]. The results of this process are that the cane should be manufactured by impact extrusion, which is consistent for many other similar parts.

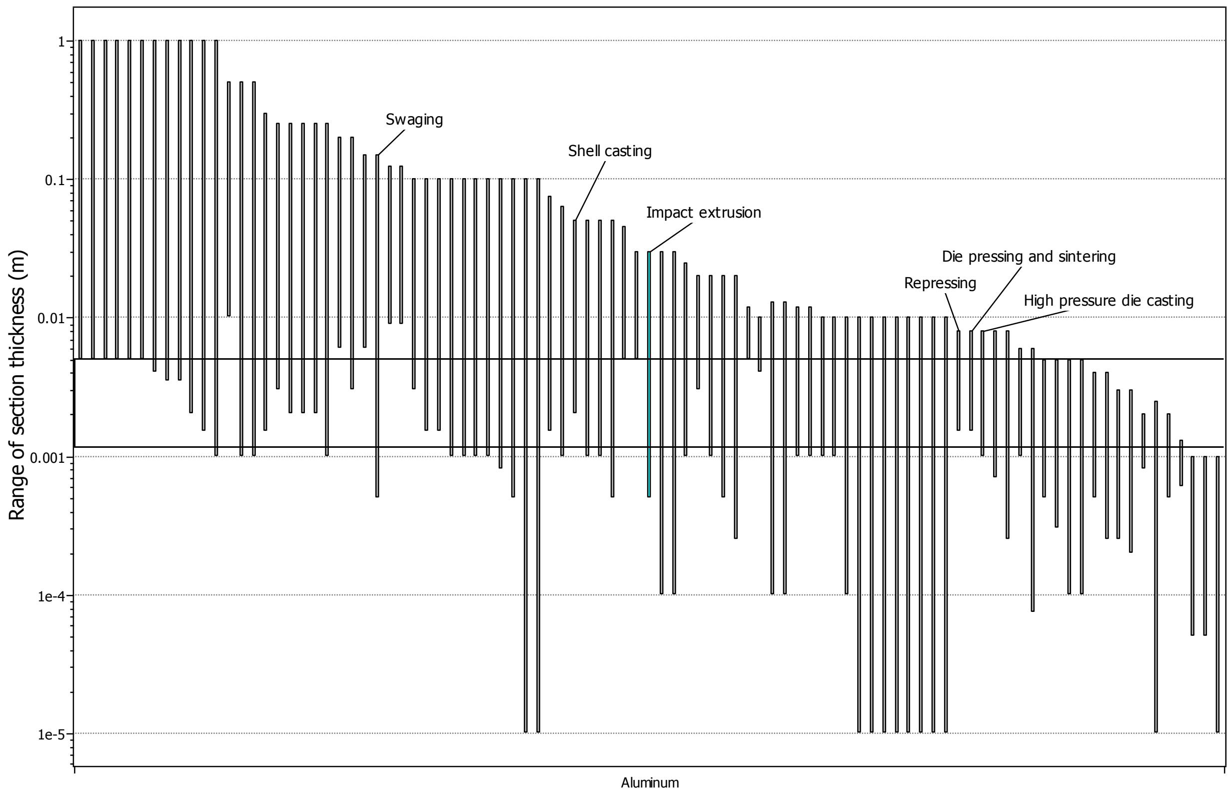


Figure O.1 Stage 1: Material vs. Range of Thickness in CES Process Selector

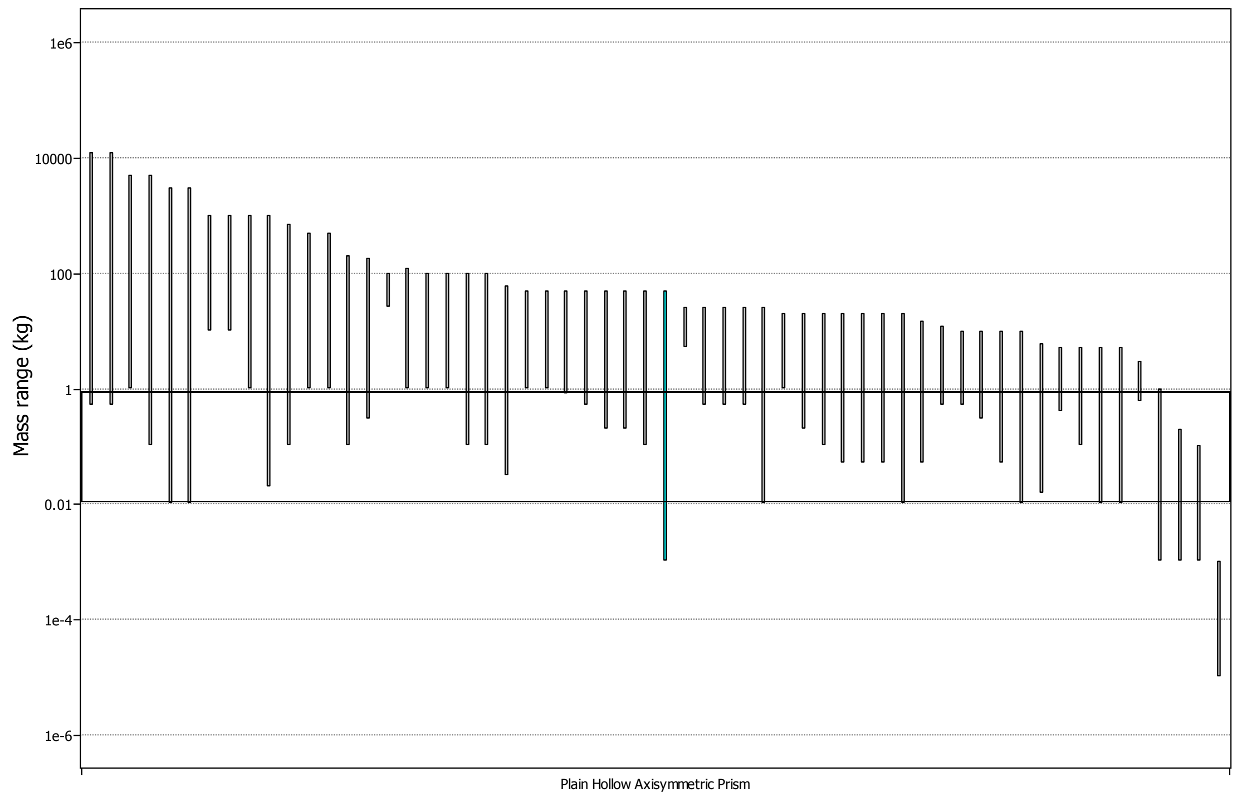


Figure O.2 Stage 2: Shape vs. Mass in CES Process Selector

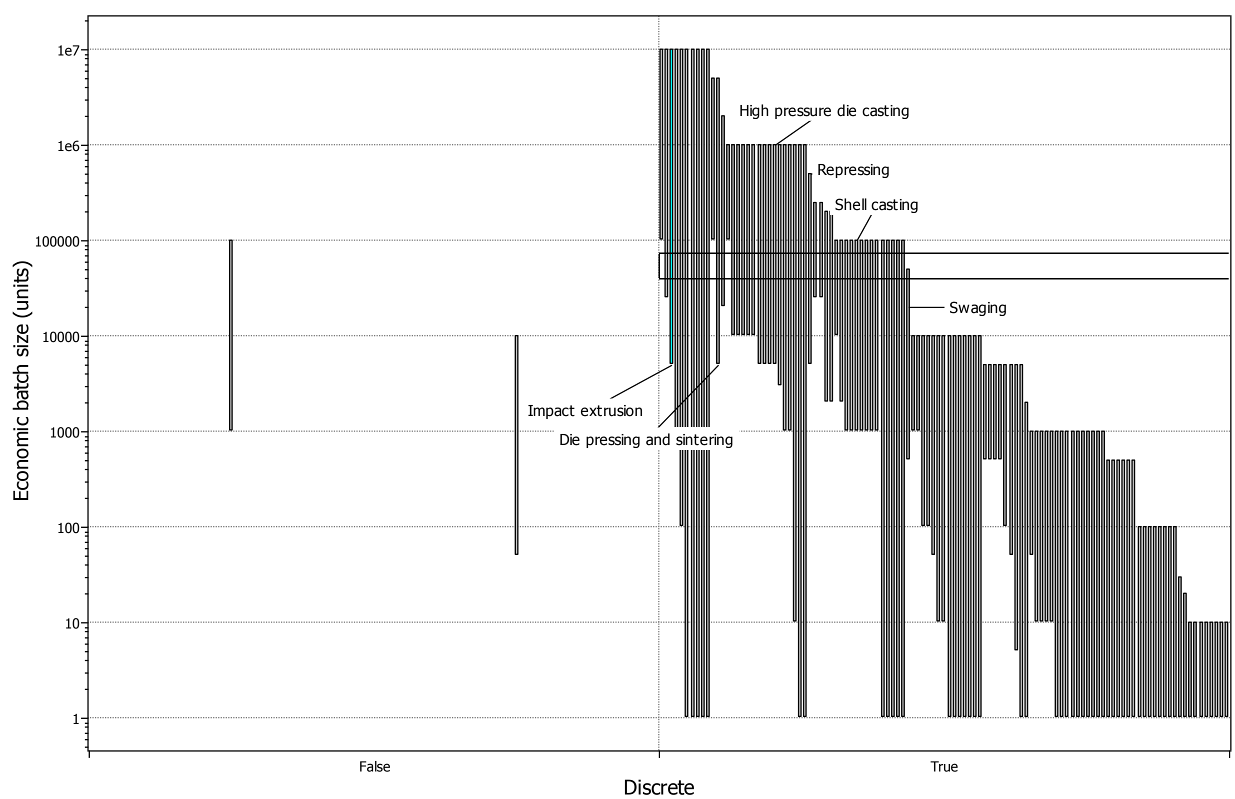


Figure O.3 Stage 3: Estimated Batch Size Feasibility in CES Process Selector

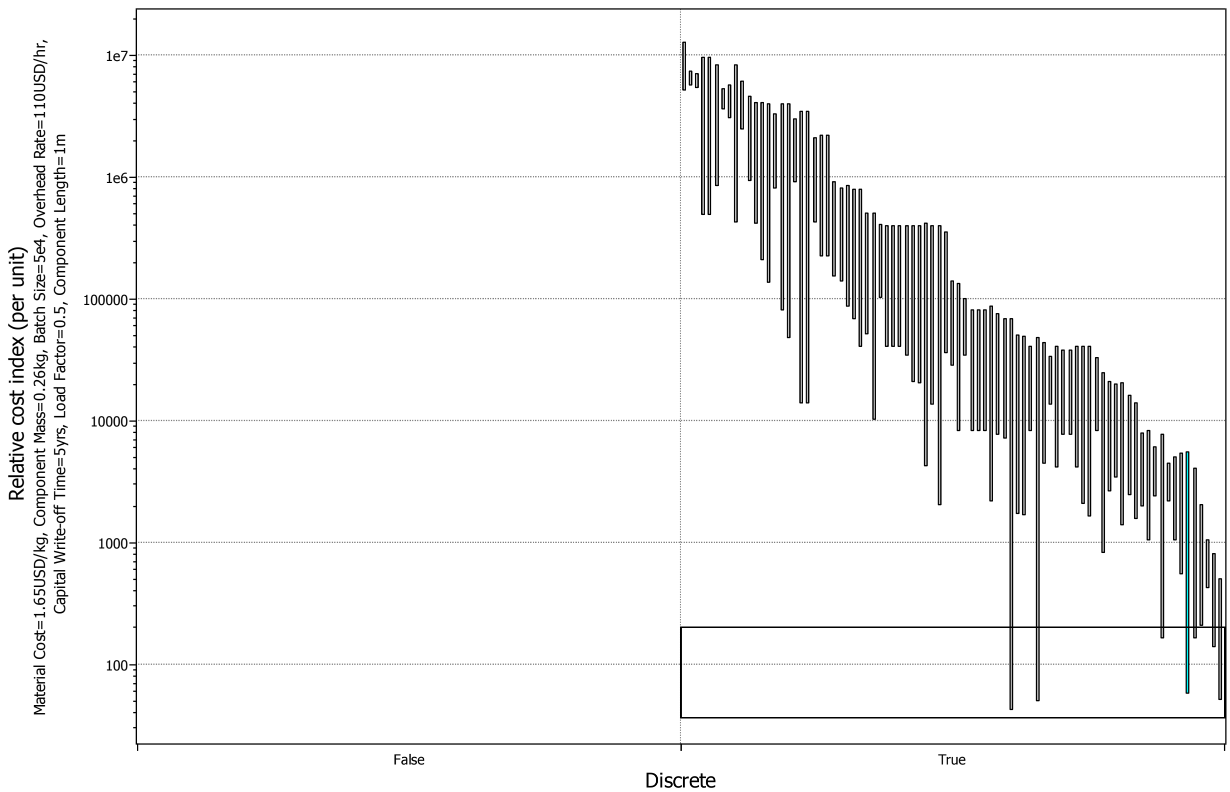


Figure O.4 Stage 4: Relative Cost per Unit Feasibility in CES Process Selector

O.2.2 Foam Process

To determine the process for manufacturing the foam, only a single stage in the process selector was needed. The parameters put the material, polyurethane, against the estimated batch size, which yielded only two possible processes: hot wire cutting and thermoplastic injection molding. Hot wire cutting should be the easier process to use to take the bulk material and cut to the simple shape that is necessary for this device. Below is the figure from the CES software.

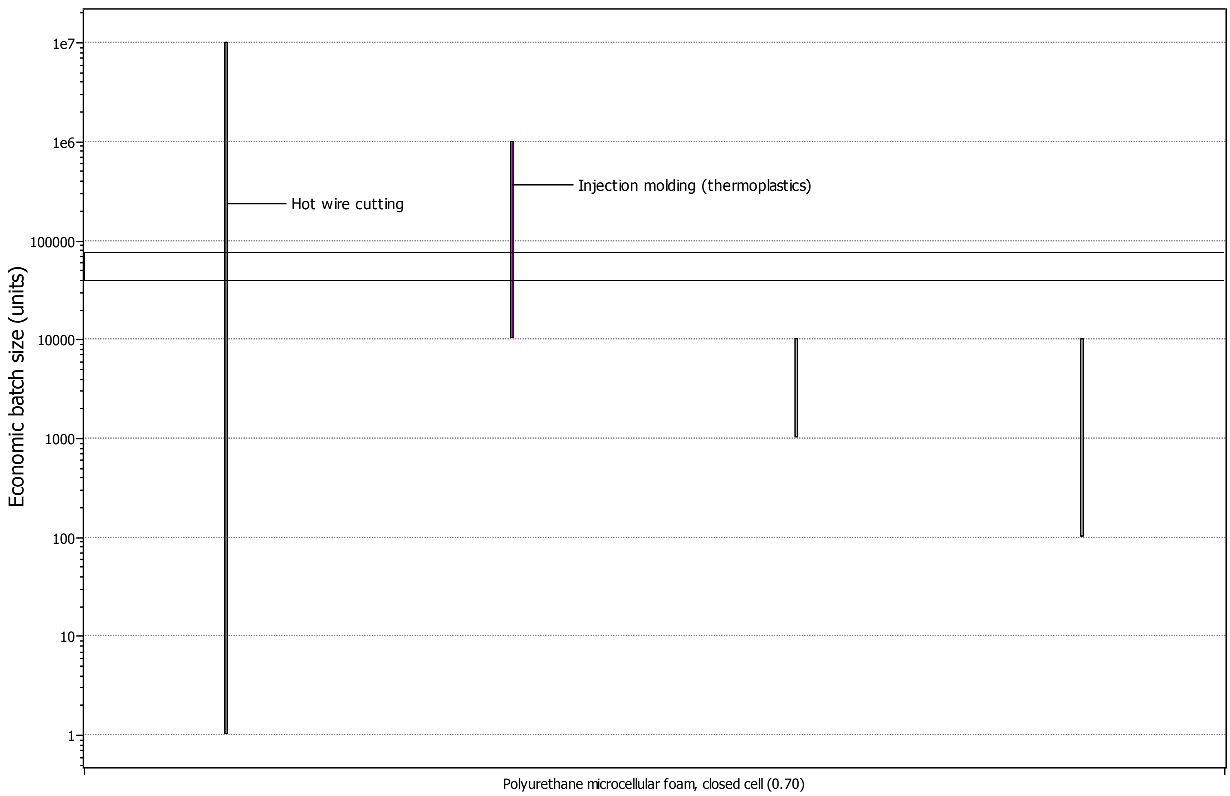


Figure O.5 Foam Process Selection

APPENDIX P. VALIDATION RESULTS

P.1 Physical Measurements

Specification	Target Value	Prototype Result

Rough surfaces/sharp edges	0	3
Cane yield strength	100-200 MPa	193-290 MPa
Cane length adjustability	0.2 m	0.2032 m
Price	< $400	$
Weight	< 5 kg	6.9 kg
Width	< 0.76 m	0.49 m

P.2 Sample Initial Survey

Circle the number corresponding to your opinion of the following statements.

1 = Strongly Disagree
2 = Disagree
3 = Neutral
4 = Agree
5 = Strongly Agree

1. This device is comfortable to wear.	1	2	3	4	5
2. I like the appearance of this device.	1	2	3	4	5
3. I feel safer walking with this device than walking independently.	1	2	3	4	5
4. I would wear this device on a daily basis.	1	2	3	4	5

P.3 Participant Survey Responses

Aesthetics:

No.	Score
1	4
2	3
3	3

4	5
5	4
6	5
7	4
8	4
9	5
10	4
Average	**4.1**

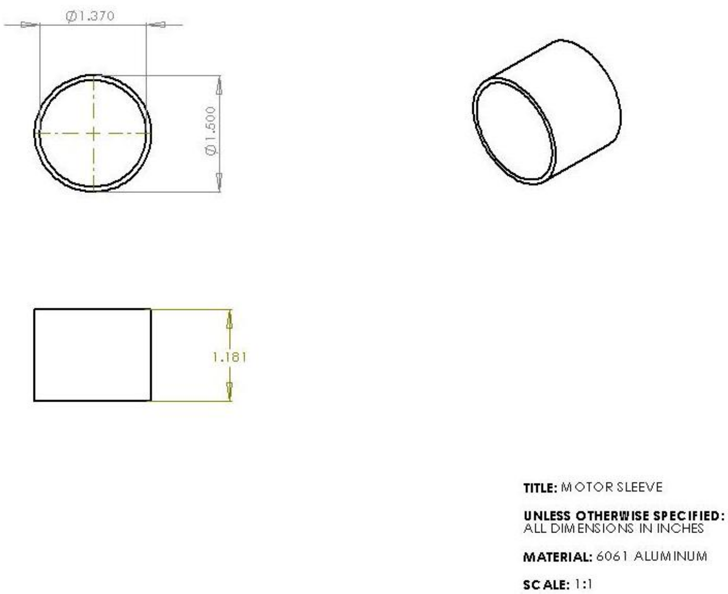
Comfort:

No.	Score
1	3
2	2
3	3
4	4
5	4
6	3
7	2
8	4
9	3
10	4
Average	**3.2**

APPENDIX Q. ENGINEERING CHANGE NOTICES

Q.1 Motor Sleeves

Was:



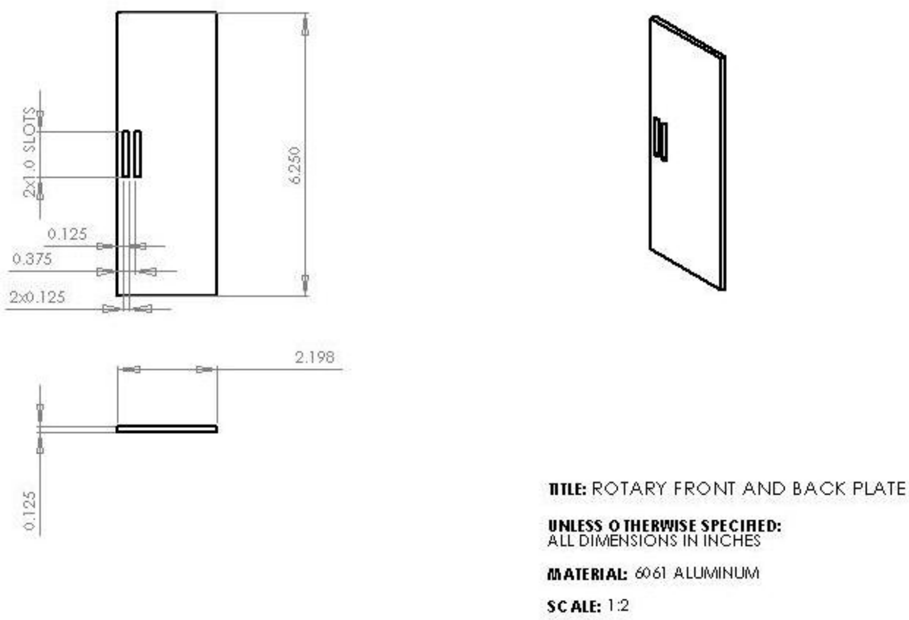
Is:

The motor sleeves securing the rotational motor to the inner rotational plate were removed from the design. Upon fastening the rotational motor to the outer rotational plate, the design decision was made to omit the motor sleeves because the additional stability appeared unnecessary and the time to manufacture the sleeves would have been useless unless they were absolutely necessary to the design. The decision was to proceed without the motor sleeve and then reintroduce the sleeve to the design if the screws were insufficient.

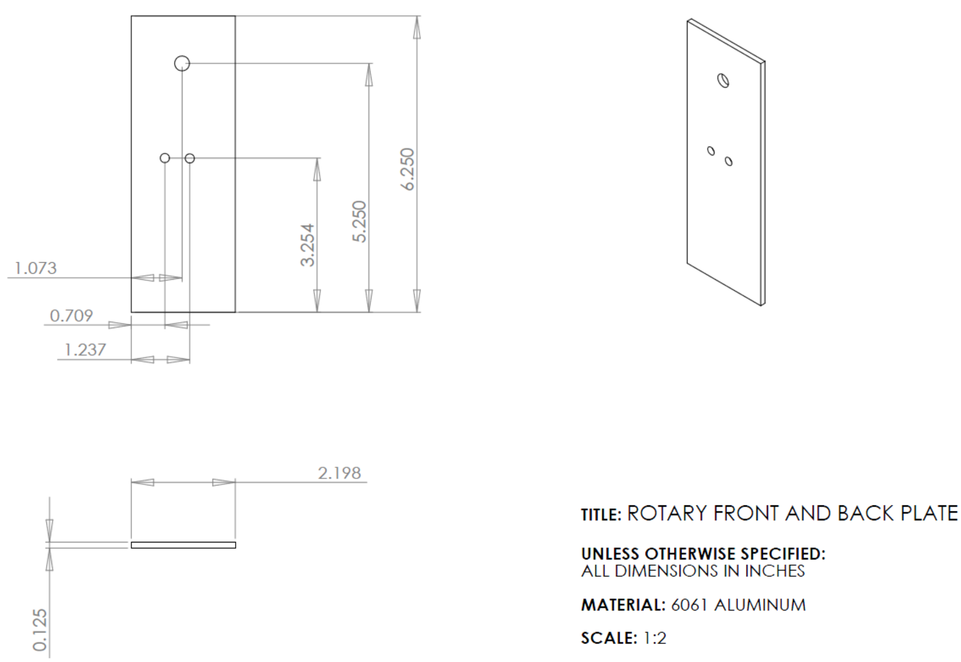
Person Responsible: Alex Lee
Date of Change: 12/1/2009

Q.2 Rotational Box Plates

Was:



Is:



The connection method of the straps to the rotational module plates was changed. Instead of slots through which the straps would be looped, D-rings were attached to the box using pieces of aluminum. This change puts less stress on the straps during use and allows more freedom in adjustment as the belt is fitted to the person. Additionally, it decreased the necessary manufacturing time.

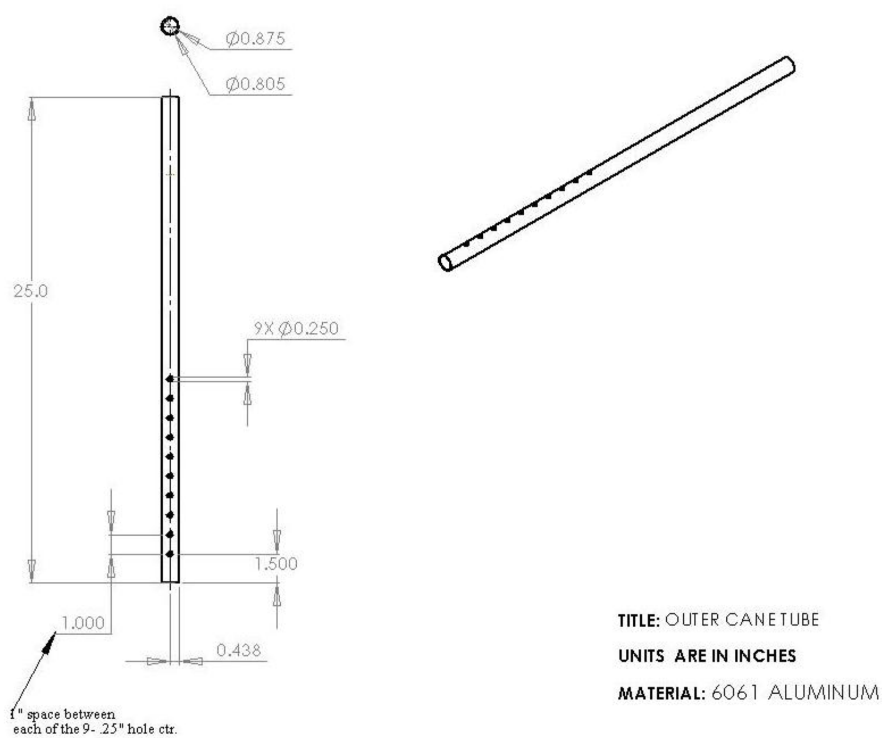
Person: Alex Lee
Date of Change: 11/14/2009

There were two additional holes drilled into the side plates of the rotational box for the wires from the translational motor and accelerometer to be held as they connected back to the microcontroller. The wires were initially going through the rotational axis, but time constraints dictated the quicker and easier solution of going through the sides of the rotational plate.

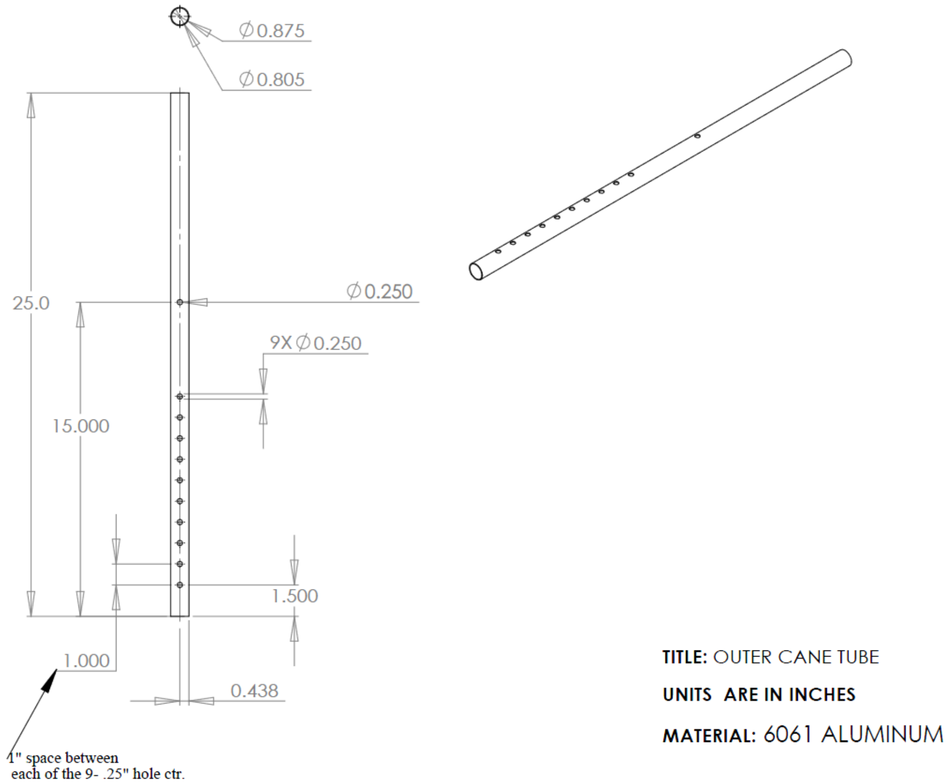
Person: Spencer Marsh
Date of Change: 12/2/2009

Q.3 Cane

Was:



Is:



The hard stop was added at the top of cane to ensure safety of the tester and user. The hard stop is a 2 ½" bolt that goes the entire way through the cane and catches on the shafts of the translational plate, preventing the cane from going as higher so as to be dangerous to the person wearing the device.

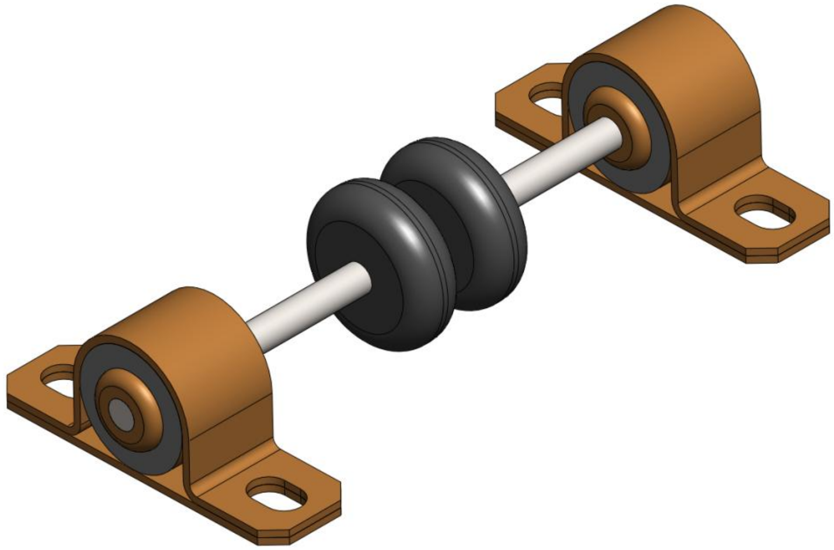
Person: Anne Kirsch
Date of Change: 12/7/2009

The available torsion spring meant to insert into the inner cane was too large, so bolts were used to keep prototype functionality. The torsion spring is still meant for the final design, but the budget did not allow the team to buy springs for the prototype and the one free of charge was not compatible with the design.

Person: Alex Lee
Date of Change: 12/1/2009

Q.4 Shafts

Was:



Is:
The press fit on all of the wheels did not work well enough to keep the wheels in the necessary place and the bearings did not function as expected. Due to this the team decided to use duct tape wrapped around the end of the bearing and around the shafts to keep the wheels in correct alignment to contact the cane.

Person: Alex Lee
Date of Change: 12/4/2009