Executive Summary

The objective of this project was to provide a more accessible and user friendly method of kinesiotherapy for individuals without the use of their legs. This type of therapy concept was brought to us from our sponsor, Dr. Ben Dwamena, who insisted that we call him Ben. Ben, originally from Ghana, works in Nuclear Medicine at the VA Hospital and does not have use of his legs. He asked us to make this therapy device for his wheelchair that would mimic a walking motion by moving his legs up and down. Ben's wheelchair has a standing mechanism built into it and he requested that this new therapeutic functionality be used while he is in the standing position. This therapy would increase blood flow to the muscles, reduce muscle atrophy, decrease joint stiffness, and increase bone density by applying pressure to the joints.

The leading requirements, outlined through many interviews with Ben, were externally automating the legs, mimicking a walking motion with the movement of his legs in the mechanism, and the ability to move, at minimum, 16 kg which is the percentage of the mass of a 100kg adult's leg. These requirements, in conjunction with 7 others, outlined a general idea that each team member developed on their own. After each team member came up with 20 general ideas on their own the team as a while were able to compile these concepts into six main concepts that encapsulated the total project. These six main ideas were then put into a Pugh Chart to rate and determine the best overall concept. The leading determinants of the overall design were location of the actuation, what type of upper body support, and the type of actuation i.e. hydraulics, pneumatics, or linear motor. The concept chosen was a rotary gear motor actuated at the feet. To properly fit this motor into the existing wheelchair the upper body needed to be fully supported by the wheelchair. The actuation would be limited to moving the individual's leg only. This concept was chosen due to its simplicity of actuation and its simplicity of design.

After the total design of the project was selected we had to determine the manufacturing plans and evaluate the cost analysis of the project and its scope. We were able to finalize the design and begin the manufacturing of all the major components to complete the prototype before Design Review 5. After the finalization of the design was completed we were able to determine the cost of the total prototype to be under $600. Originally, the total budget was to be under $400, but after initial analysis of the necessary materials and transmission that would be necessary to handle the load required it approved to be increased to $600.

The final stage of the project was to validate the prototype and to objectively critique our project from start to finish. The majority of the validation tests necessary were completed by a Boolean natured procedure as most of the requirements were true/false in nature. The two main validation tests that were completed were measuring the angles between the different joints to analytically evaluate the walking motion in which we were to mimic and loading the mechanism with, at minimum, 16kg. Both of these tests were successful and in its raw form, validated the project as a whole. The advancements in the proof of concept only draw the picture for future iterations of the same project. We have pointed the project at its conclusion to integration and implementation with the wheelchair as a total package. The groundwork is laid for the next team to send Dr. Ben Dwamena into the second iteration of the prototype production phase.

MECHENG 450 Design and Manufacturing III

Fall 2015

Kinematic Leg Therapy Device (KLTD)

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This project’s sponsor, Dr. Ben Dwamena, was a young aspiring engineering student in Ghana until he was encouraged down the medical path in his early schooling. Dr. Dwamena has no use of his legs and needs a wheelchair to move about. There are many downsides that are associated from this type of physical assistance: bed sores, muscle atrophy, poor blood circulation, kidney stones, and urinary health issues. Dr. Dwamena was able to purchase a standup wheelchair that helps with a few of these ailments, but he wanted to create a better wheelchair.

To improve blood circulation, decrease muscle atrophy, and lessen the chances of bed sores Dr. Dwamena asked the University of Michigan to create an automated leg moving device that would work in his standup wheelchair. The device would mimic a stand-still walking motion while he is in the standing position in his wheelchair. This would help with all the ailments listed above. The objective of this project was to provide a more accessible and user friendly method of kinesiotherapy for individuals without the use of their legs.

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Problem Description and Background

Dr. Ben Dwamena is a physician in nuclear medicine at the VA Hospital in Ann Arbor, MI. Through his many years of use, he has identified a number of possible improvements to his stand up wheelchair. The bulk of these requests could be split into three categories: increased maneuverability, automated leg therapy, and better support while standing. Dr. Dwamena wants the end prototype to be usable on multiple types of wheelchairs if possible, as he will soon be receiving a new wheelchair and does not know any details about its design yet. It is also so that the device can be used by people other than Dr. Dwamena without changing their wheelchair. A number of stand-up wheelchair designs will need to be considered in order to provide this capability such as the Levo C3, Deka iBot, Redman Power Chair, Permobil F5 Corpus VS, and Karman XO-202 [1-5]. Because of our limited resources for this project and the prioritization that Dr. Dwamena gave to us, we have limited our project to designing an automated leg therapy system that can attach to Dr. Dwamena's wheelchair only.

The automated leg therapy combats a number of conditions arising from having one's lower body seated and immobile for extended periods of time, as it is in a wheelchair. When combined with the act of standing vertically, leg movement helps to counter problems including urinary tract infections, bone density, pressure sores and digestion [6]. The leg movement helps improve blood circulation, puts weight on the legs, promoting bone strength and stretches out muscle groups that have remained contracted for extended periods of time [7-9]. Just 30 minutes of assisted cycling can decrease muscle spasticity in those with incomplete spastic paraplegia [10-11].

Not only are there a physiological advantages to a standing automated leg therapy system, but there are also psychological benefits. The ability to stand, in itself, provides the user with a large degree of independence [12]. It provides the benefits of eye to eye conversations, which can improve self-confidence, and also allows for more equal treatment in society [13]. With standing leg therapy, the user also gains the psychological benefit of the societal normality of walking [6].

Dr. Dwamena has had experience with different products and has also been researching existing methods of leg therapy. He provided us with a handful of examples that he would like us to consider in our design. These include designs for standing and seated leg movement, and products like the Erigo, the SportsArt ICARE, and the KidWalk Dynamic Mobility System [14].

While researching what currently exists on the market, we were only able to find one example of a stand-up wheelchair that had a cyclic leg movement feature; and this product is only in the prototype phase. This wheelchair is being developed in Japan and is currently in the prototype phase, seen in Figure 1. It has the ability to go from a sitting to standing position, mimic a walking movement while in the standing position, mimic a stair climbing motion in the standing position, and can also do a knee exercise while in the sitting position. However, it does not do everything that Dr. Dwamena would like. There are a multitude of different stand-up wheelchairs, with the style currently used by Dr. Dwamena seen in Figure 2. Stand-up wheelchairs have been around for many years now [17], and there have been advances on the mechanism used to stand the patient up [18].

Figure 1: The prototype of the wheelchair currently being made in Japan [15].

Figure 2: The wheelchair that Dr. Dwamena is currently using [16].

Figure 3: An example of a tilt table used for Leg Movement Therapy. This make is called Erigo, made by Hocoma [19]

There are also many kinds of therapeutic leg movement devices; one example is shown in Figure 3. Tilt tables work by having the patient strapped onto the table by a therapist. The table then tilts onto an upright position, and the leg movement therapy can begin [20].

User Requirements and Engineering Specifications

After talking with Dr. Dwamena we were able to construct a list of his wants and needs in creating an ideal wheelchair. In that list we had to separate what was a want, a need, and an unattainable request given the resources we are allotted. We were able to compile 18 user requirements and from these we were able to derive the necessary engineering requirements and specifications. The first 10 requirements listed in Table 1, Appendix A.1, page 16, outlined the needs of Dr. Dwamena that we will be able to address this semester. These 10 requirements are associated with the kinematic leg therapy device (KLTD) that was illustrated by Dr. Dwamena as his number one overall priority for our team.

He also was able to outline enhanced maneuverability and better upper body support as it is broken up in the requirements 11-18, in Table 2, Appendix A.1, page 18. To fulfill these requirements we would have to create a complete prototype wheelchair from the ground up wherein the standing mechanism was to be moved back to the center of the wheelchair and a new style of support mechanism would be used. The requirements 11-18 will be unattainable for this semester.

Concept Generation and Selection

Before arriving at our final design, concepts were generated individually by each team member; the presented ideas were discussed as a team and they were combined to form six full concepts. These concepts were compared and evaluated using a Pugh chart which evaluated each concept based on chosen criteria and a winner was determined. Detailed descriptions of the concept generation process and the Pugh Chart methodology can be found in Appendix B.1 and B.2, pages 19-21.

Key Design Drivers

We have identified four main design drivers: constrict the motion of the legs, body weight support, space constraints, and power consumption. Constricting the motion of the legs means we need to create a system that only allows the legs to move in a specific motion (i.e. mimic walking in place). Body weight support is very important for both safety, comfort, and the feasibility of the project as a whole. To ensure that our user is safe, the weight will need to be supported and constrained in a way such that the user will not fall out of the wheelchair or slide down while in the standing position. We also have a very limited amount of space to work with. Most of the available space is below the seat near the feet. For ease of integration, this space should be utilized. Finally, power consumption is very important. We need to insure that the actuation of the leg movement does not surpass the limits of the power supply. There is a limited amount of energy that can be stored on the wheelchair and supplied to the actuators.

Challenges

With this complex project, there will be three main challenges that will follow us throughout the semester. The first of these challenges is that we will have limited access to the wheelchair that our prototype is to be compatible with. To overcome this obstacle, we have decided to build a simple frame which will represent the wheelchair's frame. We will keep this frame on the U of M campus and do most of our testing on it. This simple frame is shown below is Figure 4.

Figure 4: The wooden frame dimensioned from Ben's wheelchair.

Our second challenge is that Dr. Dwamena will be receiving a new wheelchair at some point in the future. This means that, ideally, we would design a prototype that can work with both his current wheelchair and his new wheelchair. However, given the time constraints, we are proceeding with designing a device to work with only his current wheelchair.

The third challenge we have to overcome are the space constraints of the wheelchair. The device, actuators, and any external power sources will need to attach to the wheelchair with a limited amount of space. The current wheelchair already has a battery, pneumatic pistons, and links in the area that we will also need to utilize. This is one of the main reasons we chose to actuate the feet versus hip or thigh, as the foot area of the wheelchair has the most available space.

Concept Description

General Concept Description

The chosen concept, shown in Figure 5, actuates the leg movement from the foot. There are two key advantages to powering from the foot. Firstly, the foot area is where there is the most available space on the current wheelchair, allowing for easy integration. Secondly, when the leg movement is powered from the foot, the supporting frame and the actuator can be in the same location, as opposed to having an actuator on the upper leg and a separate supporting frame on the foot. For this design, the weight of the user’s upper body will be fully supported using the current arm support system and a secondary support system. The details of the upper body secondary support system will not be a part of the scope of this semester's project. To guide the leg motion and to prevent the knee from moving laterally, an “L” shaped bracket, which we will refer to as the boot (Figure 13, page 8), will attach to the lower leg and foot and will lock the ankle at a 90 degree angle. We have discussed the lack of ankle movement with Dr. Dwamena and he expressed that this would not be an issue because the ankle movement is not key to his therapy. The vertical movement of the boot will be fully constrained by controlling the motion of the actuator. The boot will be free to move forwards and backwards.

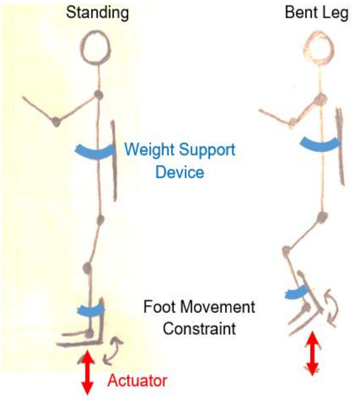

Figure 5: General concept sketch. The wheelchair would be in its upright position behind the user.

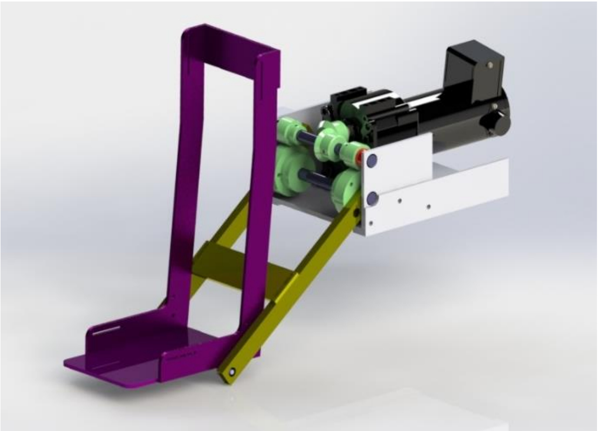

Figure 6: Full color coded SolidWorks model. Boot (purple), links (yellow), gears (green), axles (blue), gearbox (gray), motor (black).

Mechanism Description

To accomplish the desired constrained motion and to actuate the vertical movement of the boot, a simple mechanism was conceived. The mechanism (Figure 6) consists of a single link that connects the motor to the boot. The rotating of the link would produce the vertical movement of the foot. The boot would be allowed to rotate freely around a pin joint at the link-boot interface. When the user's foot is in the boot and the user's hips are constrained, the powered link, upper leg, lower leg, and wheelchair frame form a four bar mechanism which fully constrains the motion of the legs. A linkage modeling program called Linkage Mechanism Designer and Simulator (Version 3.0.9) was used to simulate the four bar movement (Appendix B.4, page 24).

SolidWorks Sketch

To determine the needed link lengths of our mechanism and to visualize how our mechanism would move during the stand/sit movement of the wheelchair, we created a sketch in SolidWorks using sketch relations. This sketch (Figure 7-9) was drawn to scale with the dimensions taken from Dr. Dwamena's wheelchair.

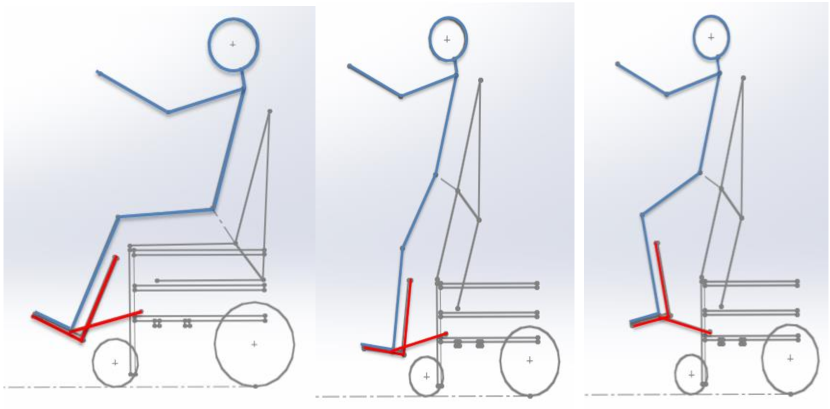

Figure 7-9: The user is shown in blue, the mechanism is shown in red and the current wheelchair is shown in gray. Three user positions are shown from left to right, sitting, standing, and raised leg position for therapy.

SolidWorks Model

We created a SolidWorks model (Figure 6, page 6) of our lower leg and foot constraining mechanism. A stress analysis, detailed below, was conducted to determine the materials to use for the input links. The connection between the links and the boot will be accomplished by running a shaft under the boot that will connect to each of the links allowing the links to rotate as the boot is raised and lowered (Figure 11, page 8). The mechanism will connect to two cross supports located under the wheelchair seat using the gearbox corner brackets shown in Figure 12, page 8. The analysis conducted to determine the specifications of our motors and to get a rough estimation of how much space we need to allow for the motors is detailed below.

Transmission Discussion

The major challenge associated with the transmission was figuring out a way to change the axis of rotation by 90 degrees, while also transmitting power to both sides of the linkage assembly. We decided to use bevel gears to change the axis of rotation, and the idler has a shaft going all the way through to connect both sides of the linkage assembly. Each side of the shaft is connected to a pinion 16 tooth 12 pitch spur gear that mates with a 32 tooth 12 pitch spur gear, adding an additional 2:1 ratio to what is already accomplished with the selected gear motor. The gear motor already has a 69:1 ratio, yielding a final gear ratio of 138:1. The transmission assembly can be seen in Figures 17-18, page 8.

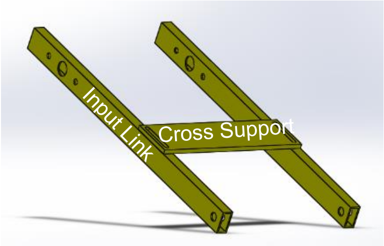

Figure 10: Model showing the link assembly.

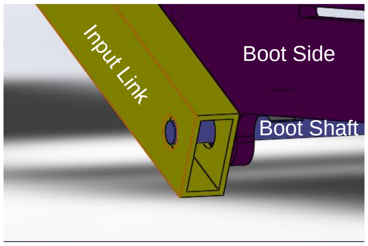

Figure 11: Shaft connection between input link and boot.

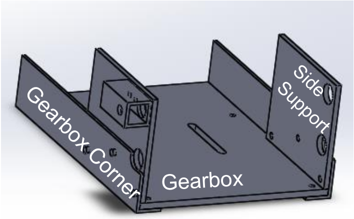

Figure 12: Gearbox frame.

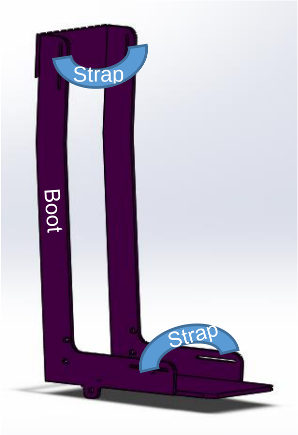

Figure 13: Model of boot highlighting straps that will be added in the future (blue).

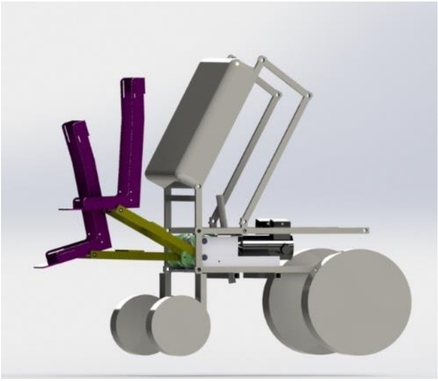

Figure 14: Full mechanism on SolidWorks model of wheelchair.

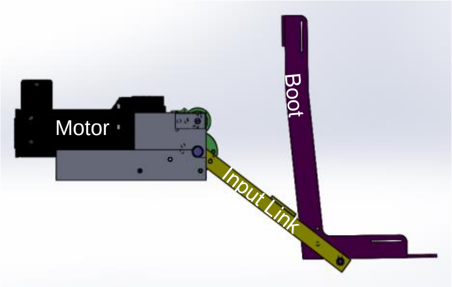

Figure 15: Side view of mechanism highlighting the input link (yellow). The actuator would apply a torque to the input link.

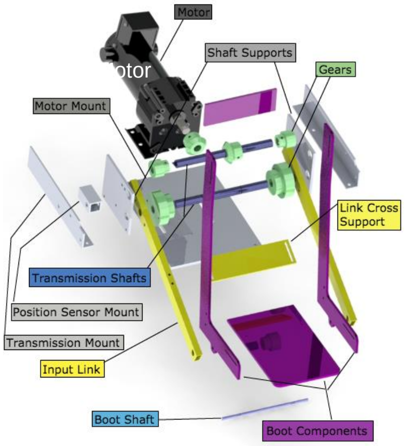

Figure 16: Exploded view of full mechanism.

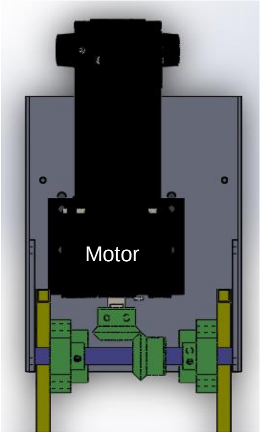

Figure 17: Top view of transmission assembly

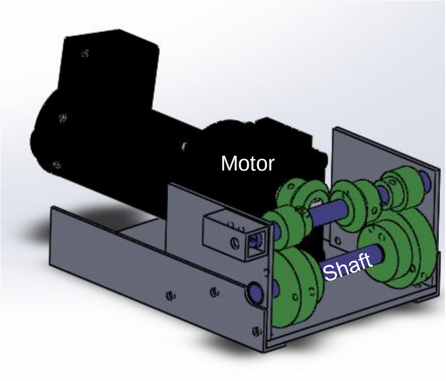

Figure 18: Isometric view of transmission assembly.

Controls Discussion

The mechanism is controlled through an arduino uno controller. The user has four controls that they can use to manipulate the motion of the linkage: a mode switch, on/off switch, voltage control, and speed control. The modes switch allows the user to select between automatic and manual control. The automatic mode creates a target position function that follows a sinusoidal wave with the frequency set by the speed control and then uses the motor position and a PID controller to calculate an motor voltage that keeps the motor at the target position. There are limit switches placed at the end of the input link's range of motion that prevent the motor from overshooting the upper and lower limits of its programmed range of motion. When either of the limit switches are depressed, the motor voltage control is temporarily transferred to the manual voltage controller. When the mode switch is changed to the manual mode, the voltage controller is used to adjust the voltage that the motor receives. When the voltage controller is moved counterclockwise to the last 80 degrees, the mechanism will move downwards, and when the voltage controller is moved clockwise to the last 80 degrees, the mechanism will move upwards. If the controller reads that the motor position is at or past its upper or lower limit the controller will not let the user move the linkage further past that limit.

Engineering Analysis

In our engineering analysis, the focus was on the input link shown below in Figure 19. We needed to determine the power required to move our linkage at the required rate of speed, as well as determine the stress that the input link would receive from the weight of the user. Assumptions used during these analysis are shown in Appendix C.1, page 25.

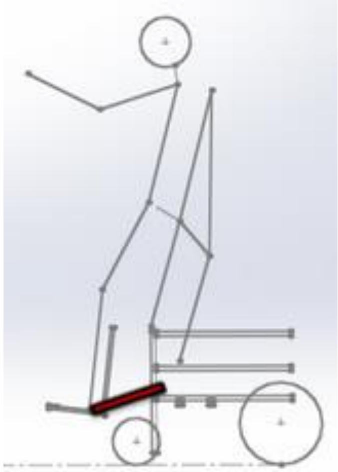

Figure 19: The input link, shown in red, where we concentrated the analysis.

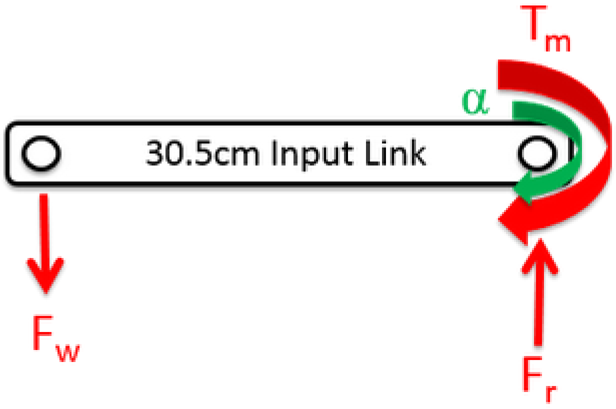

Figure 20: A Free Body Diagram of the input link.

Figure 19 shows the position of the input link while Figure 20 shows a Free Body Diagram of the input link. The following equations were used to determine the power required.

$$P = T\omega$$ Eq. 1

$$\sum T = I\alpha$$ Eq. 2

$$I = mr^2$$ Eq. 3

$$\omega(t) = \int \alpha\, dt$$ Eq. 4

Where P is power, T is torque, ω is angular velocity, I is moment of inertia, α is angular acceleration, m is the mass of the user's leg, and L is the length of the input link. To find the angular velocity, we found an average angular velocity required based upon the time required to go through one cycle (one foot being raised and lowered, 1.6s), and assumed a sinusoidal angular velocity, shown in Figure 21, page 10.

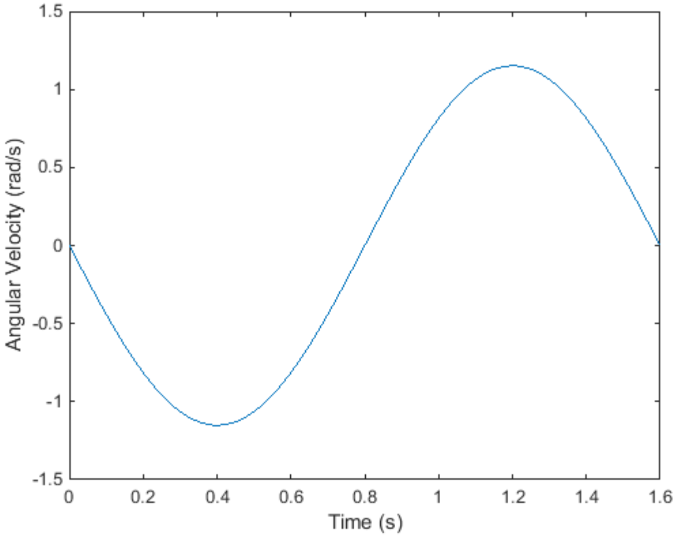

Figure 21: The angular velocity profile assumed to solve this problem.

Angular velocity was both integrated and differentiated to find the angular displacement and angular acceleration. With the angular velocity and acceleration now known, we used Equation 2 to find the torque required by the motor, where $\Sigma T = T_m - F_w * L = I\alpha$. L and I are both functions of angular displacement, where $L = L * \cos(\theta)$ and $I = m * L^2 * \cos^2(\theta)$. This yields a torque that varies with time, which can be multiplied by the angular velocity that is also a function of time to find the required power. The torque and power curves are shown in Figures 22 and 23.

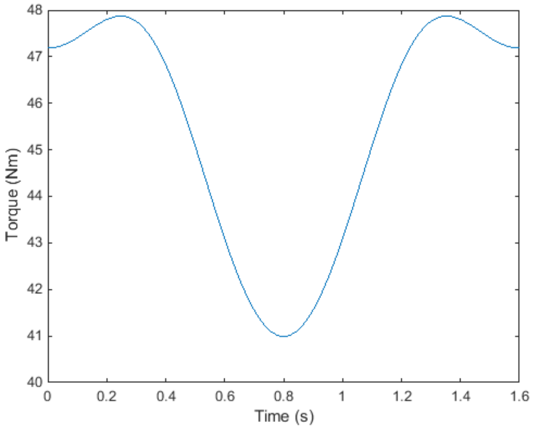

Figure 22: The torque as a function of time. The maximum torque was ~48 Nm

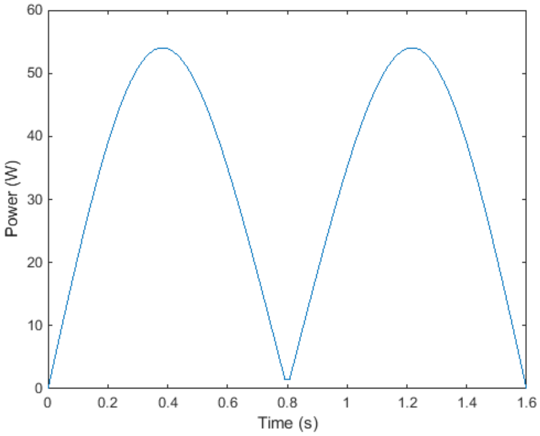

Figure 23: Power as a function of time. The max power required was ~54 W, which is equivalent to 0.07hp.

To determine the stress on the input link, we assumed that the link was stationary and would receive all of the weight of the user with the weight vector perpendicular to the input link. A Free Body Diagram of this set up is shown in Figure 24.

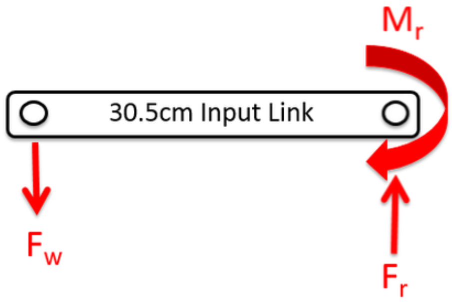

Figure 24: A Free Body Diagram of the input link while stationary position while parallel to the ground

The following equation was used for the stress analysis of the input link.

$$\sigma = MY/I \qquad \text{Eq. 5}$$

Where σ is stress, *M* is the reaction moment, *Y* is the distance from the neutral axis to the edge of the beam, and I is the second moment of area. The reaction moment is stated as $(M_r) = F_w{*}L$. There are also four of these beams that we are analyzing, so we can divide the stress by four, giving us a final stress of 100MPa. This is well below the yield stress of our chosen material (steel) which has a yield strength of 517MPa.

FMEA and Risk Analysis

First we had to determine if the project was process or product based. At the end of the project we want to have a product that creates a process in which the legs are moved in a stand still walking motion. So by having both these aspects in our project we determined it would be best to perform an FMEA and a risk analysis shown in Appendix D.1 and Appendix D.2 on pages 26 and 27 respectively. We created the FMEA and the Risk Analysis analyzing the same three major components of the project: upper body weight support, actuation, and the mechanical interface between the legs and the mechanism. Each major component was then broken down into smaller sections to isolate different concerns and then evaluated accordingly.

The aspect of our design with the highest risk is not having the weight supports properly fit to different users. This concern, if it occurs, could potentially physically harm the end user by causing him/her to fall out of the wheelchair while they are in the standing position. We evaluated this risk as a 9/10 based on the nature of its severity. There are to main potential causes of this failure; one is that the weight support is too tight and is restricting the end user from properly maneuvering in the standing position, the second, and the more dangerous, is that the support is too loose and the end user somehow slips out of the support and falls to the ground.

As the support mechanism is one of the most difficult aspects to integrate into our design given the sponsor's wants, we have developed many different options in which to support the end user properly. These designs include yet are not limited to: a pelvic harness that is supported like a rock climber's harness; an adjustable belt of sorts such like a seat belt strapped either around the chest and/or waist; straps that extend from the shoulders down to the waist from the back of the seat like backpack straps; and a seat that extends from the chair to go under the buttocks. These designs are to be used in accompaniment with the support from the lower body. The lower body support will be in the form of the two mechanisms that will be actuating the individual legs.

Discussion

Our team is proud of the final prototype that we have produced. We were able solve this challenging problem and accomplish all of the testable user requirements with a very limited time frame and limited resources. The chosen design was simple, functional and cost effective.

Design critique

Throughout the process of machining, assembling and testing our prototype we have learned a great deal about our mechanism. If we were to do this project again, there are some aspects of our design that we would change.

The biggest mechanical issue with our prototype was a lack of lateral stability in the gearbox. The lateral force induced by the torque transfer between the bevel gears can lead to a deflection in the gearbox side plates which allows the gears to skip. This only happens when the mechanism is loaded past our requirement of 16kg, but ideally the motor would stall before this mechanical failure takes place. For future iterations of the design, it would be recommended to strengthen the gearbox. This could be done by adding cross supports. However, another solution that would solve this problem, reduce manufacturing time, protect the gearbox from debris, and possibly increase efficiency would be to purchase an all in one gearbox that would provide the required torque.

Another aspect of our device that we would like to improve is the fluidity of the movement. When running in automatic mode, the mechanism exhibits vibrations in certain points of its range of motion. We have worked hard to determine if these vibrations are due to mechanical issues such as friction or issues arising from the implemented proportional controller. Our team hypothesizes that the vibrations are due to fluctuations in the potentiometer readings. The potentiometer readings were observed to vary up to ±4 bits. The current potentiometer was mounted to a shaft that only rotated 65˚. Mounting to a shaft that used the more of the potentiometers range (270˚) would increase the resolution. An encoder built into the motor could also increase the resolution.

Future work

There is additional work that needs to be done before the mechanism could be used on a wheelchair. Firstly, mechanical hard stops to limit the link’s range of motion would need to be constructed and attached to the wheelchair. We have two concepts for these hard stops. The hard stops could either be a cross bar connected to the wheelchair frame in front of the mechanism (Figure 25) or a nub which would come into contact the extra length on the link (Figure 26).

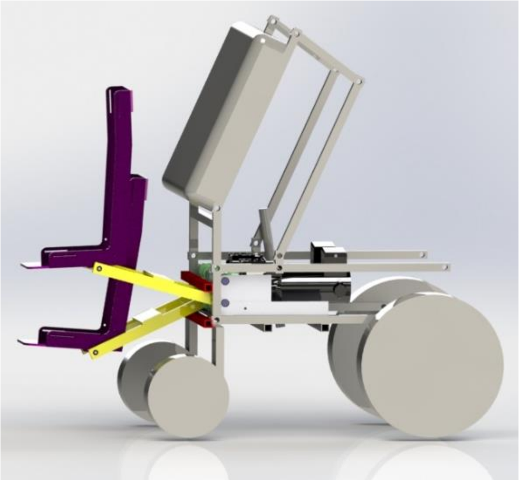

Figure 25: Cross bar hard stop concept. The hard stops are shown in red and would limit upper range and bottom range.

Figure 26: Nub hard stop concept. The hard stop would only limit lower range.

A decision would need to be made regarding how we will be powering the mechanism. The mechanism could either be powered by plugging into a wall outlet or we could run the system off of a battery. Each method has its strengths and weaknesses. Running off of a battery would add weight to the wheelchair. Plugging into a wall would limit use to only when near an outlet.

The electronics and gearbox are currently open to the environment. This could present issues during day to day use, especially when the mechanism is used outdoors. The electronics and gearbox would need to be encased to prevent debris from interfering.

Finally, an accelerated life test should be conducted to ensure that the system will maintain its structural integrity through a five year lifetime. The accelerated lifetime test would be developed by gathering user data to determine the amount of usage hours in five years and then running the mechanism continuously for that amount of time.

Works Cited

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Appendix A.1 – User Requirements

Table 1: User Requirements as defined by Dr. Dwamena for the Kinematic Leg Therapy Device

Priority	User Requirements	Engineering Requirements	Source	Rationale
Kinematic Leg Therapy Device (KLTD) requirements				
1	Actuated movement of legs	The movement of the legs shall be actuated by an external power source.	sponsor	Our sponsor does not wants to have to move his legs manually or have someone else move them for him, thus this motion shall be externally powered
2	The leg movement function is available when the wheelchair is in the standing position	The end user shall be able to use the leg movement function while the wheelchair is in the stand-up position.	sponsor	Moving the end user's legs while they are in a standing position will most accurately simulate a walking motion
3	The leg movement function needs to be reliable	Any added mechanisms shall meet the industry standard requirements of safety for 5 years.	Regulation	Insurance companies only cover wheelchairs for 5 years, so the wheelchair should be reliable past that time frame.
4	Mimic walking in place	The hip-knee (A-B) range of motion shall move 60 degrees in reference to vertical; the knee-ankle (B-C) range of motion shall move 60 degrees in reference to hip-knee (A-B) axis, the ankle-ball of foot (C-D) range of motion shall move 0 degrees in reference to knee-ankle (B-C).	sponsor	Giving the end user the ability to move their legs promotes their ligaments, joints, and muscles from atrophy. Mimicking the walking dynamics of the legs facilitates the natural physiological movements of the human body and promotes the psychological normalcies associated with the walking while standing.
5	Multiple speed settings for the walking motion	The end user shall have multiple speed settings for the walking motion ranging from 25 to 100 (steps/min).	sponsor	Comfortable walking speeds vary from user to user.

6	The leg movement function is available while the wheelchair is in motion	The leg movement function shall be available when the wheelchair's drivetrain is receiving power.	sponsor	This allows the end user more opportunities to move their legs.
7	The leg movement function is available while the wheelchair's drivetrain is powered off	The leg movement function shall be available when the wheelchair's drivetrain is not receiving power.	sponsor	When the end user is standing in one place the power down the drivetrain so that there is not risk moving unintentionally. During this the KLTD shall be available.
8	Mimic force on feet due to walking	There shall be an alternating loading and unloading force exerted on both feet.	sponsor	The end user wants the ability to feel the simulated force exerted on their feet while using the KLTD as mimicking the same force when walking.
9	Cost	The total cost allocated to this project is $600.	sponsor	The sponsor was open to the idea of providing more funding for materials if needed. Further funding will be discussed as necessary.
10	The kinematic leg therapy device needs to be adjustable for different body types	The leg movement mechanism shall have the ability to adjust for human weights from 110-260 lbs and for human heights from 59-72 inches [24]	sponsor	User sizes and weights vary greatly from person to person and this device should be able to account for that variability.

Table 2: User Requirements as defined by Dr. Dwamena for the Wheelchair Redesign

Priority	User Requirements	Engineering Requirements	Source	Rationale
Wheelchair redesign requirements				
11	The wheelchair must be maneuverable in tight spaces	The length (distance from front to back of chair) shall be less than 18 inches. The width (distance from side to side) shall be less than 20 inches [25]. The turning radius shall be less than 0.5 m.	sponsor	The end user wishes to have a more compact wheelchair base. A long train is difficult to maneuver as it trails behind the user and it limits mobility.
12	The redesign must be made before December 10th	The redesign for the new wheelchair shall be finished by December 10th	sponsor	This project is a semester long course.
13	The speed of the stand-up mechanism is to be fast	The stand-up mechanism shall go from the seated position to the stand-up position in less than a minute.	sponsor	The end user wants the stand-up mechanism to be fast so that it is convenient to switch between the seated and standing position.
14	End user needs to be able to interact with objects while in the standing position.	The end user shall be able to touch an object within 44 inches in front or to the side of him/her. [25]	sponsor	The end user wishes to interact with object in the standing position. This action shall not be prohibited by the wheelchair or wheelchair base.
15	End user wants to interact with objects on the ground while seated	The end user shall be able to pick up a pencil with his/her hand off the ground from the seated position.	sponsor	The end user wishes to interact with object in the seated position. This action shall not be prohibited by the wheelchair or wheelchair base.
16	End user wants upper body mobility while standing	The end user shall be fully supported in the standing position without the use of arms, while still having arm support be an option.	sponsor	The end user wants to interact with objects around him without being limited by his wheelchair.

17	Weight	The total weight of the wheelchair shall not exceed 50 kg.	Regulation	There are many weight limitations that affect the weight of a wheelchair, i.e. elevators, car lifting mechanism, and if there was a need to carry the chair upstairs.
18	The wheelchair should be mobile without power	The wheelchair shall be able to move without battery power.	sponsor	The end user does not want to be stranded in the case that the motors fail.

Appendix B.1 – Concept Generation

Concept #1, “4-Bar Linkage, Full Leg Support”, utilizes a 4-bar linkage to constrain the movement of the upper and lower legs to a walking motion. The linkage would be powered using a rotary motor at link 1 shown at the bottom of the sketch (Figure 1). The upper leg, lower leg, and foot would be secured to the frame, represented as the ground. Advantages of this design are that it fully controls the motion of the leg and also provides a motion very similar to walking. Disadvantages are that it would be difficult to integrate the frame into the current wheelchair, multiple connections are helpful for supporting the leg but they can cause issues with rubbing and causing sores and finally, the ankle would be locked in a ninety degree position and would not move throughout the motion making the overall motion slightly dissimilar to a walking motion.

Concept #2, “Foot Powered, Lower Leg Support”, has a heavy focus on consolidation of components to one location. The foot would be constrained to move in an up/down/tilt motion shown in Figure 2 and to prevent the knees from falling forward, backward, or to either side and to guide the leg motion, a lower leg support would be rigidly connected to the foot pedal. The actuation would be applied to the frame that constrains the foot motion. This design is desirable because all of the added components are at the foot making for easy integration into the current wheelchair. Some concerns with this design are that the lower leg support may end up taking a relatively large amount of the user’s body weight; this force on the shin could be dangerous, causing sores. This design also locks the ankle and does not incorporate ankle movement into the overall motion.

Concept #3, “Hip Powered, Spring Loaded Foot” (Figure 3), and Concept #4, “Upper Leg Linear Actuator, Spring Loaded Foot” (Figure 4), would actuate the movement by applying a force to the upper leg. Concept #3 would apply a torque at the hip using a rotary motor, whereas Concept #4 would use a linear actuator to apply forces to the back side of the upper leg. Both concepts would include a spring loaded mechanism to constrain the movement of the feet and apply a force to the bottom of the foot. These concepts would be complex to build because we would need to build a constraining mechanism at the feet and a frame for actuation on the upper leg.

Concept #4, “Upper Leg Linear Actuator, Constrained Foot Motion” is similar to concept #4 (Figure 4) in many ways. However, there are some key functional differences. The foot movement constraining mechanism would not be spring loaded and the upper leg motion would only be powered in one direction. This would allow the linear actuator to fully disconnect from the frame when the wheelchair is in the seated position. Having the actuator fully disconnect could add some difficulties. Also, this design would not apply any force to the bottom of the user's feet.

Concept #5, "Foot Powered, Bike Style" (Figure 5), focused on simplicity. It would utilize a rotary crank at the feet similar to what is used on a bicycle. This crank would be powered to produce the leg motion. For this concept, the weight would be fully supported using upper body supports and the legs would not be allowed to reach a fully extended position to prevent the knees from locking and causing physical harm to the user. One disadvantage to this design is that the legs would not be fully supported. This could be dangerous for a user with no control of their leg movements.

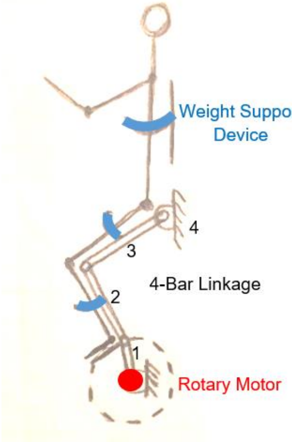


Figure 1: Concept #1, "4-Bar Linkage, Full Leg Support"

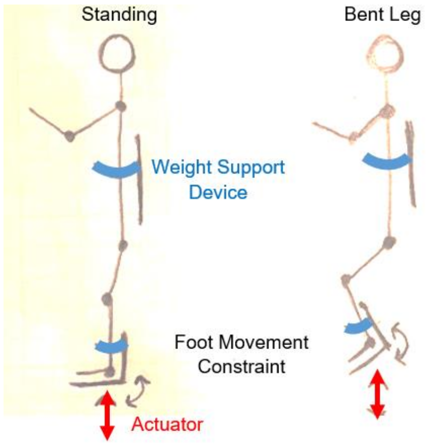


Figure 2: Concept #2, "Foot Powered, Lower Leg Support"

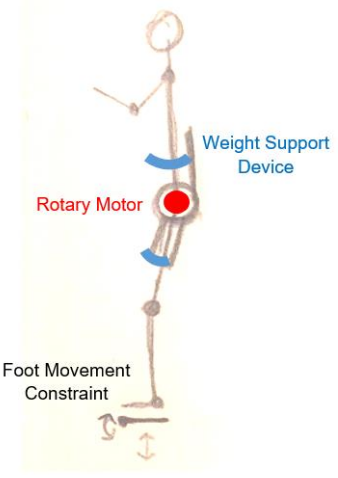


Figure 3: Concept #3, "Hip Powered, Spring Loaded Foot" and Concept #6, "Upper Leg Linear Actuator, Constrained Foot Motion"

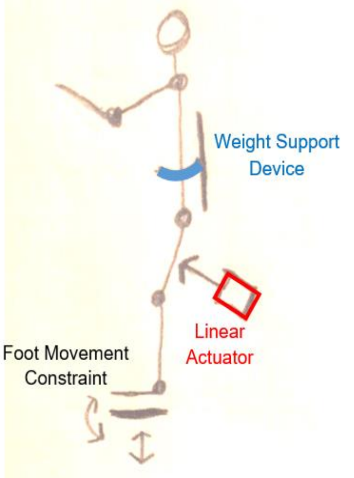


Figure 4: Concept #4, "Upper Leg Linear Actuator, Spring Loaded Foot"

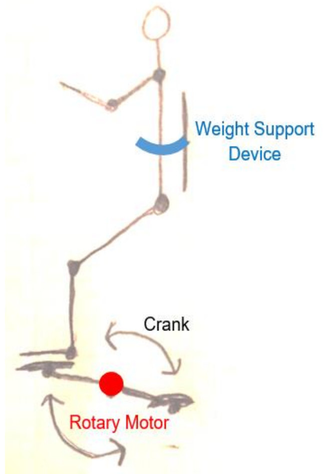


Figure 5: Concept #5, "Foot Powered, Bike Style"

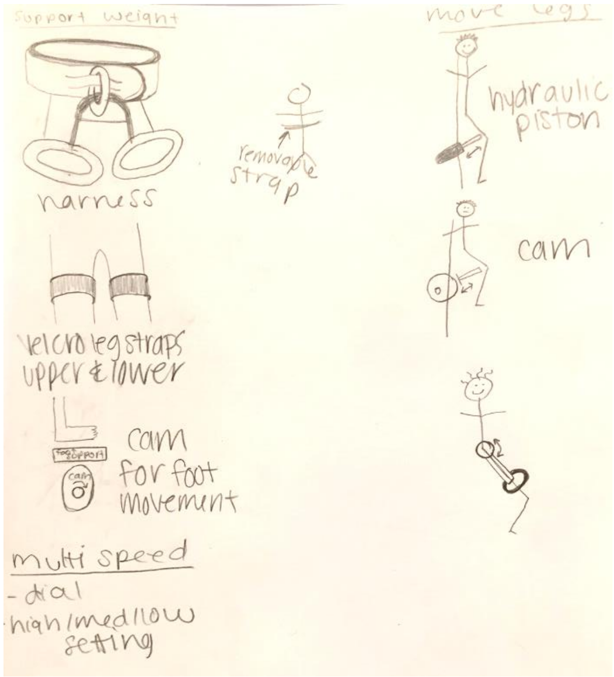


Figure 6: General concepts for leg movement and weight support

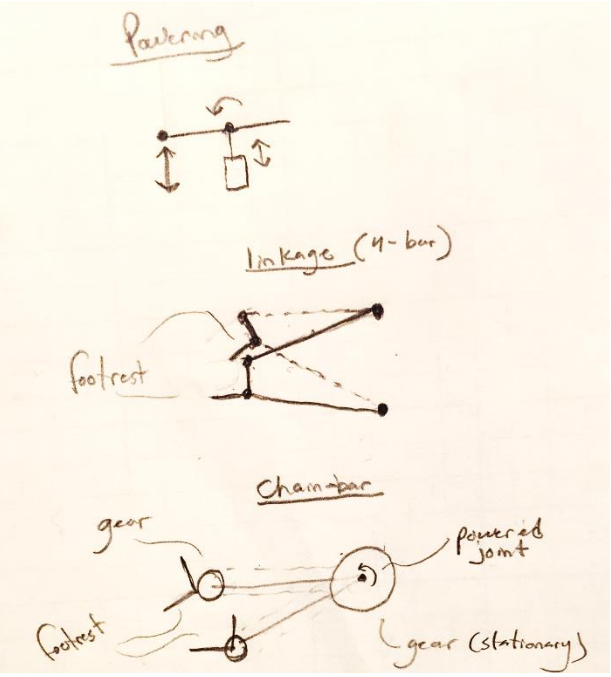


Figure 7: Concepts for powering concept #2

Appendix B.2 – Pugh Charts

To score each of our concepts in their respective categories we decided upon a group of important characteristics that each category's concept needed to contain. All three categories contained the categories of safety, user comfort, and ease of integration. Each category's individual scoring criteria can be seen in Tables 1-4 below. We chose our criteria based on our user requirements given to us by our sponsor and the engineering requirements that we previously derived from those user requirements. In addition to the criteria derived from user requirements and engineering requirements, we also considered each concepts ease of integration into the current wheelchair design and the availability of space required for each concept.

Each characteristic within a scoring category was assigned a relative weight so that it reflected the characteristic's relative importance. Each characteristic's weight total within a category added up to 100%. We then used these characteristics and weights in a Pugh Chart to score each category. Winners in the categories of Movement Design, Actuation Method, and Weight Support were the Lower Leg Supported and Foot Powered design (Concept #2), Rotary Motor, and Arm Supports respectively.

An additional Pugh chart and scoring category was created to evaluate the position of leg actuation. This was to allow us to double check that our selected Movement Design contained the best actuation method for accomplishing our requirements. The results confirmed our decision in Movement Design with the foot as a place for leg actuation.

In the Movement Design category, the Lower Leg Supported and Foot Powered Design won because of its simplicity and ease of integration into the existing chair. It was average scoring in all of the categories as can be seen in Appendix D.1, but it was the most well rounded design with no negative scores. This is because of the condensed nature of actuation method and location makes integration simpler and improves movement control. There are disadvantages to supporting the user from the leg. We may cause uncomfortable pressure points if the leg movement causes too much weight to be supported by the legs instead of the foot. Also, the torque required to move the lower legs may require a large motor and creating ankle movement will be a larger challenge with this design. Because of the large breadth of this project, simplicity of the design is very important for us to be able to create a usable prototype that can create the desired movement and have the safety and reliability desired. Concept #2 has the most capability in an easy to integrate design that will let us realize the concept's full potential.

The best scoring actuation method was the rotary motor. It was higher scoring than its competitors in cost and availability of space and had average to positive scoring in all other categories. The rotary motor is less power efficient than other methods and will require us to turn angular motion into vertical motion but other actuators were much larger or more expensive which led to their lower scores.

Arm supports were the winning concept in the weight support category because of their comfort and low cost. They were the most well rounded concept that had good scores in the highest weighted categories of safety and ability to support weight. This method of weight support relies on the user to support themselves from their arm but avoids the stigma of harnesses and safety issues of purely supporting the user by securing their lower body. We expect future testing to give us more insight into the challenge of supporting the user's weight while in motion. Our final decision will be based on that information along with the scoring from our Pugh chart.

Table 1: The Pugh Chart we created to help us decide on a movement design.

Design Criteria	**Weight**	**4-Bar Linkage, Full Leg Support**	**Foot Powered, Lower Leg Support**	**Hip Powered, Spring Loaded Foot**	**Upper Leg Linear Actuator, Spring Loaded Foot**	**Foot Powered, Bike Style**	**Upper Leg Linear Actuator, Constrained Foot Motion**
Controllability	7%	1	1	1	1	0	1
Compact	8%	0	0	0	0	0	0
Applied Force on Feet	7%	0	0	0	0	-2	-2
Accomplishment of Desired Motion	14%	0	0	1	1	-1	0
Simplicity	10%	1	1	-1	-1	2	-1
Power Consumption	5%	0	0	0	0	0	0
Reliability	12%	0	0	0	0	0	0
Safety	14%	0	0	1	1	-1	1
User Comfort	12%	0	0	0	0	0	0
Ease of Integration with Current Wheelchair	11%	0	1	-1	-2	2	0
Total	100%	0.17	0.28	0.14	0.03	0	-0.03

Table 2: A Pugh Chart to choose an actuation method.

Criteria	Weight	Pneumatics	Hydraulics	Rotary Motor	Linear Motor
Safety	17%	-1	-2	1	2
Reliability	10%	-1	-1	0	0
Availability of Space	13%	-1	-2	2	1
Cost	10%	-1	-2	2	0
Controllability	10%	-2	-1	1	2
Sound (dB)	9%	-2	1	1	1
Ease of Integration	17%	-1	-1	1	1
Power Consumption	10%	1	2	-1	-1
User Comfort	4%	-1	2	1	1
Total	100%	-0.99	-0.80	0.93	0.87

Table 3: The Pugh Chart used to help choose a method of body weight support.

Criteria	Rank	Weight	Seat	Arm Support	Lower Leg Support	Upper Leg Support	Torso Harness/Belt
Safety	1	18%	1	1	-1	-1	2
Manufacturability	8	7%	-1	-1	0	0	1
Cost	7	10%	-1	0	1	1	-2
Ease of Removability	5	12%	-1	0	1	1	0
Additional Volume	6	5%	-1	1	0	1	1
Ease of Integration	4	13%	-1	2	0	0	2
User Comfort	3	17%	0	1	-1	-1	-1
Ability to Support Weight	2	18%	0	1	-1	-1	2
Total		100%	-0.29	0.77	-0.31	-0.26	0.73

Table 4: The Pugh Chart we used to make a decision on the location of the actuator.

Criteria	Rank	Weight	Thigh	Knee	Calf	Foot
Safety	1	30%	0	0	0	0
Availability of Space	4	22%	-1	-2	2	1
Ease of Integration	2	30%	1	-1	-1	2
Force on Feet	9	18%	1	0	0	2
Total		100%	0.26	-0.74	0.14	1.18

Appendix B.3 – Functional Decomposition

We decided to split our concept selection process into multiple parts using our Functional Decomposition (Figure 8). We split our concept creation and selection into three pieces: Movement Design (Motion + Location of Actuation), Actuation Method, and Weight Support. Movement Design contains the largest portions of the overall design that the rest of our concept elements will need to work around. Actuation Method and weight support components are important for the overall design performance but are interchangeable within any Movement Design.

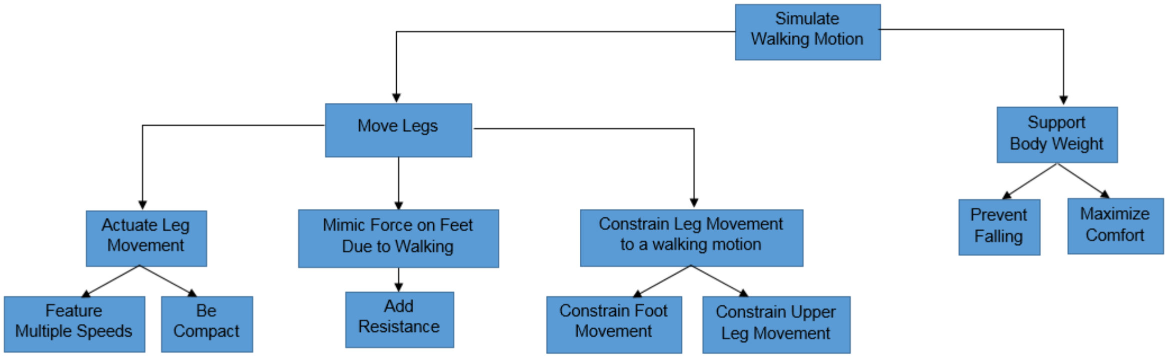


Figure 8: The Function Decomposition Diagram

Appendix B.4 – Models for Linkage Design

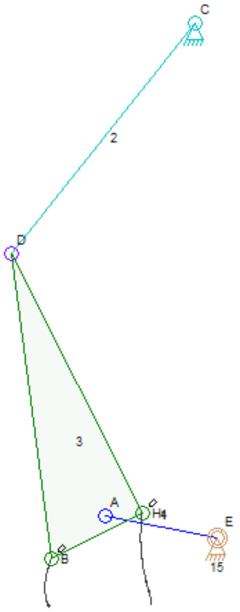


Figure 9: Screenshot of linkage simulation. The triangular (link 3) block represents the boot and lower leg. Link 2 is the upper leg. Link 4 is the powered input link.

Appendix C.1 – Engineering Analysis Assumptions

The following are the assumptions used for the Engineering Analysis

- Upper bound weight of a human is 100 kg (220 lbs)
- Entire upper body is supported (65% of weight)
- 18kg (one leg) is lifted by the leg movement device with a safety factor of 1.6 for the motor
- Horizontal forces are negligible
- Constant angular acceleration
- Maximum required torque occurs when input link is parallel to the ground
- Maximum angular velocity occurs when input link is parallel to the ground
- The fastest cycle required takes 0.8s and is defined as the leg moving up and down and back to its original position
- The input link's range of motion is 1/4 of a rotation
- The moment of inertia of the input link can be modeled as a point mass at the end of the input link (mass of the patient)
- Inertia of the input link is negligible
- The maximum required torque occurs on the upward motion
- Friction is negligible
- Efficiency of the transmission was neglected for this analysis
- The hip joint is grounded

Appendix D.1 – FMEA

Table 1: FMEA Analysis

Item	Function	Potential Failure Mode	Potential Effects of Failure	Severity of Effect (1-10)	Potential Causes of Failure	Probability of Occurrence (1-10)	Current Design Controls	Detection (1-10)	RPN	Recommended Action
Upper body weight support	Holding the user up when in the standing position	Material failure	Physical injury to user	9	Support breaks ie ripping or disconnects from the chair	1	Test and validate method	2	18	Research current weight support methods and technology
		Support not properly adjusted to the user	Physical injury to user	9	Support is not tight enough or too tight	3	Test and validate method	3	81	Test on many different body types
Actuation	Moving the mechanism that holds the legs	Mechanically malfunction	The user would not have use of the leg movement	3	Overheating, not properly greased, over/under powered,	2	Test and validate method	5	30	Use data and research the advanced life cycles of the actuators
		Electrical malfunction	The user would not have use of the leg movement	3	Faulty wiring, overheating, blown fuse	2	Test and validate method	5	30	Use data and research the advanced life cycles of electrical equipment
Mechanical interface between legs and mechanism	To guide the legs in a walking motion	Material failure	The user could potentially be harmed	7	Faulty fasteners, overused material, misuse of mechanism	2	Test and validate method	4	56	Material analysis and research
		Harmful contact surfaces	The user could potentially be harmed	3	Faulty fasteners, misuse of mechanism, lack of padding, misplaced support	1	Test and validate method	2	6	Ergonomics and material analysis

Appendix D.2 – Risk Analysis

Table 2: Risk Analysis

Hazard	Hazardous Situation	Likelihood	Impact	Level	Technical Performance	Cost	Action To Minimize Hazard
Material failure	Physical injury to user	Remote	Catastrophic	Low	Material failure	Budget increase > 5%	Research current weight support methods and technology
Support not properly adjusted to the user	Physical injury to user	Unlikely	Catastrophic	Medium	Support not properly adjusted to the user	No impact	Test on many different body types
Mechanically malfunction	The user would not have use of the leg movement	Unlikely	Minor	Negligible	Mechanically malfunction	Budget increase > 5%	Use data and research the advanced life cycles of the actuators
Electrical malfunction	The user would not have use of the leg movement	Likely	Minor	Low	Electrical malfunction	Budget increase > 5%	Use data and research the advanced life cycles of electrical equipment
Material failure	The user could potentially be harmed	Unlikely	Serious	Medium	Material failure	Budget increase > 5%	Material analysis and research
Harmful contact surfaces	The user could potentially be harmed	Remote	Moderate	Negligible	Harmful contact surfaces	No impact	Ergonomics and material analysis

Appendix E.1 – Manufacturing Plans

To fabricate our prototype we will utilize water jetting, band saws, lathes, and mills to create the pieces that we will use to assemble our design. Our design consists of a boot-shaped foot supporters and a link assembly for each foot. Each mechanism (including transmission and motor) is composed of 22 manufactured pieces along with bolts and press fit bearings. The manufacturing plans for the left and right units are the same; thus we will only be making one side for our prototyping purposes.

Each leg of the user will be moved by an independent foot support and linkage. To create this we will press fit bronze bearings into the two ends of the links shown in Figure 1 and use a shaft to attach the links to the side of the boot (foot support). The boot bottom and boot back will be attached to the side of the boot via welding to create a cohesive unit that will keep the foot moving in-line with the linkage. The other end of the link will be attached to a drive shaft running through two steel shaft supports that will be mounted onto the wheelchair.

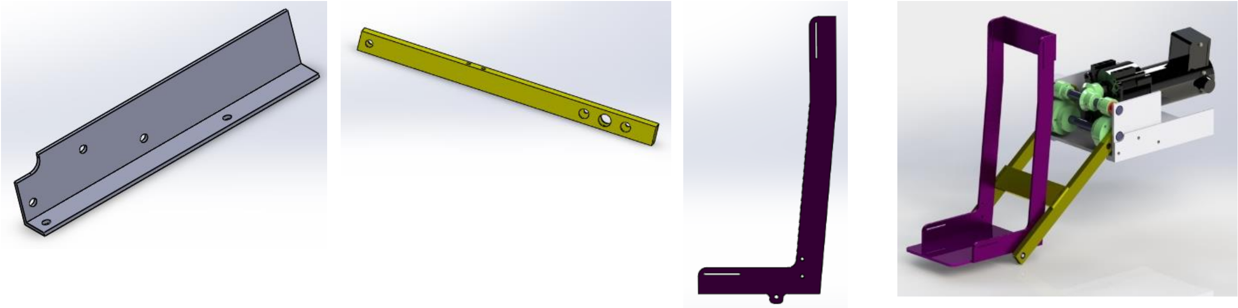


Figure 1: From left to right: shaft support, input link, boot side, and full foot mechanism

The individual manufacturing plans and drawings for the components that are in each foot support, linkage and transmission are below. These manufacturing plans and drawings were created with a focus on prototype manufacture instead of mass manufacture because of the nature of our project as a product for a specific individual.

Table 1: Boot Back Manufacturing Plan

Boot Back Manufacturing Plan

Raw Material Stock: Multipurpose 6061 Aluminum Rectangular Bar, 0.2" X 1’, 2' Long

Step #	***Process Description***	***Machine***	***Fixtures***	***Tool(s)***	***Speed***
1	Cut shape using Waterjet	N/A	N/A	Waterjet	N/A
2	File down sharp edges	N/A	N/A	File	N/A

Table 2: Boot Bottom Manufacturing Plan

Boot Bottom Manufacturing Plan

Raw Material Stock: Multipurpose 6061 Aluminum Rectangular Bar, 0.2" X 1’, 2' Long

Step #	Process Description	Machine	Fixtures	Tool(s)	Speed
1	Cut shape using Waterjet	N/A	N/A	Waterjet	N/A
2	File down sharp edges	N/A	N/A	File	N/A
3	Measure center points for the holes at the bottom of the boot	N/A	N/A	Micrometer/Height Gage	N/A
4	Center Drill the holes at the bottom of the boot	Mill	Vice	Center Drill	800 RPM
5	Drill preliminary holes at the bottom of the boot	Mill	Vice	#7 Drill	800 RPM
6	Countersink Holes	Mill	Vice	Countersink Drill Bit	800 RPM
7	Tap Holes	N/A	Vice	¼" Tap	N/A
8	File down sharp edges	N/A	N/A	N/A	N/A

Table 3: Boot Side Manufacturing Plan

Raw Material Stock: Multipurpose 6061 Aluminum Rectangular Bar, 0.2" X 1’, 2' Long

Step #	Process Description	Machine	Fixtures	Tool(s)	Speed
1	Cut Exterior Shape using Waterjet	N/A	N/A	Waterjet	N/A
2	File down sharp edges	N/A	N/A	File	N/A
3	Measure center point for the hole at the bottom of the boot	N/A	N/A	Micrometer/Height Gage	N/A
4	Center Drill the hole at the bottom of the boot	Mill	Vice	Center Drill	800 RPM

5	Drill preliminary hole at the bottom of the boot	Mill	Vice	7/32” Drill Bit	800 RPM
6	Measure shaft and ream the hole at the bottom of the boot for 0.001" larger than shaft diameter	Mill	Vice	Chosen Reamer	350 RPM
7	Measure the center point for the holes on back of the boot side	N/A	N/A	Micrometer/Height Gage	N/A
8	Center Drill the holes	Mill	Vice	Center Drill	800 RPM
9	Drill the preliminary holes on back of the boot side	Mill	Vice	#7 Drill	800 RPM
10	Tap Holes	N/A	Vice	¼" Tap	N/A
11	Measure center points for the slots at the top and bottom of the boot side	N/A	N/A	Micrometer/Height Gage	N/A
12	Mill Slots	Mill	Vice	1/8" end mill	600 RPM
11	File down sharp edges	N/A	N/A	File	N/A

Table 4: Link Cross Support Manufacturing Plan

Raw Material Stock: Multipurpose 6061 Aluminum Rectangular Bar, 0.2" X 1’, 2' Long

Step #	***Process Description***	***Machine***	***Fixtures***	***Tool(s)***	***Speed***
1	Measure correct cut length	N/A	N/A	Micrometer/Height Gage	N/A
2	Cut to slightly longer than length(≈0.25”)	Bandsaw	N/A	N/A	280(ft/m)
3	Mill to length	Mill	Vice	1” End mill	600 RPM

4	Measure center point for the slots at the side of the support	N/A	N/A	Micrometer/Height Gage	N/A
5	Mill Slots	Mill	Vice	1/8" end mill	600 RPM
6	File down sharp edges	N/A	N/A	File	N/A

Table 5: Link Manufacturing Plan

Raw Material Stock: Easy-to-Weld 4130 Alloy Steel Rectangular Tube, .065" Thk Wall, 1/2" X 1", 3'L

Step #	***Process Description***	***Machine***	***Fixtures***	***Tool(s)***	***Speed***
1	Measure correct cut length	N/A	N/A	Micrometer/Height Gage	N/A
2	Cut to slightly longer than length(≈0.25")	Bandsaw	N/A	N/A	280(ft/m)
3	Mill to length	Mill	Vice	1" End mill	300RPM
4	Measure center point for the holes on the link	N/A	N/A	Micrometer/Height Gage	N/A
5	Center Drill the holes at the ends of the link	Mill	Vice	Center Drill	300RPM
6	Individually measure the outer diameters of one SAE 841 Bronze Flanged-Sleeve Bearing for 3/8" Shaft Diameter, 1/2" OD	N/A	N/A	Micrometer	N/A
7	Drill preliminary holes at the ends of the link	Mill	Vice	¼" drill bit, 5/8" drill bit (check to make sure this matches the shaft diameter), 1/3" drill bit (check to make sure this	300 RPM

				matches sleeve bearing diameter)	
8	Ream the hole at the end of the link to interference fit with the 1/3" Sleeve Bearings	Mill	Vice	9/24” Reamer (check sleeve bearing diameter)	200 RPM
9	Widen inside holes	Mill	Vice	½" Drill Bit	300 RPM
10	File down sharp edges	N/A	N/A	N/A	N/A

Table 6: Shaft Manufacturing Plan

Raw Material Stock: Hardened Precision Steel Shaft 5/8" Diameter, 12" Length

Step #	***Process Description***	***Machine***	***Fixtures***	***Tool(s)***	***Speed***
1	Measure correct cut length	N/A	N/A	Micrometer/Height Gage	N/A
2	Cut to slightly longer than length(≈0.25”)	Bandsaw	N/A	N/A	280(ft/m)
3	Mill to length	Mill	Vice	1” End mill	300 RPM
4	File down sharp edges	N/A	N/A	File	N/A

Table 7: Boot Shaft Manufacturing Plan

Raw Material Stock: Hardened Precision Steel Shaft, 1/4" Diameter, 8" Length

Step #	***Process Description***	***Machine***	***Fixtures***	***Tool(s)***	***Speed***
1	Measure correct cut length	N/A	N/A	Micrometer/Height Gage	N/A
2	Cut to slightly longer than length(≈0.25”)	Bandsaw	N/A	N/A	280(ft/m)
3	Mill to length	Mill	Vice	1” End Mill	300 RPM
4	File down sharp edges	N/A	N/A	File	N/A
5	Measure and mark correct groove heights	N/A	N/A	Micrometer/Height Gage	N/A

6	Mill grooves	Mill	Vice	3/8" End Mill	300 RPM
7	File down sharp edges	N/A	N/A	N/A	N/A

Table 8: Bevel Gear Manufacturing Plan

<u>Raw Material Stock</u>: Steel Miter Gear, 10 Pitch, 20 Teeth, 0.44 inch Face Width, 2.000 inch Pitch Diameter, 0.625 inch Bore Diameter

Step #	***Process Description***	**Machine**	***Fixtures***	***Tool(s)***	***Speed***
1	Measure the center point for the hole on the gear	N/A	N/A	Micrometer/Height Gage	N/A
2	Center Drill the hole	Mill	Vice	Center Drill	300 RPM
3	Drill the preliminary hole on the gear	Mill	Vice	#7 Drill	300 RPM
5	Tap Hole	N/A	Vice	¼" Tap	N/A
6	File down sharp edges	N/A	N/A	N/A	N/A

Table 9: Big Gear Manufacturing Plan

<u>Raw Material Stock</u>: Spur Gear, 12 Pitch, Pitch Dia 2.667 In, Face Width 0.750 In, Number of Teeth 32, Bore Dia 0.625 In, Outside Dia 2.834 In, Overall Length 1.380 In, Hub Dia 1.92 In, Hub Projection 0.63 In, Pressure Angle 14 1/2 Deg

Step #	***Process Description***	**Machine**	***Fixtures***	***Tool(s)***	***Speed***
1	Measure the center points for the holes on the gear	N/A	N/A	Micrometer/Height Gage	N/A
2	Center Drill the holes	Mill	Vice	Center Drill	300 RPM
3	Drill the preliminary holes on the gear	Mill	Vice	#7 Drill	300 RPM
4	Countersink Holes	Mill	Vice	Countersink Drill Bit	300 RPM
5	Tap Holes	N/A	Vice	¼" Tap	N/A

6	File down sharp edges	N/A	N/A	N/A	N/A

Table 10: Gearbox Bottom Manufacturing Plan

Raw Material Stock: Multipurpose 6061 Aluminum Sheet 0.25" X 1' X 1'

Step #	***Process Description***	***Machine***	***Fixtures***	***Tool(s)***	***Speed***
1	Measure correct cut length and height	N/A	N/A	Micrometer/Height Gage	N/A
2	Cut to slightly longer than length(≈0.25”)	Bandsaw	N/A	N/A	280(ft/m)
3	Mill to length	Mill	Vice	1” End Mill	800 RPM
4	Measure the center points for the four tapped holes	N/A	N/A	Micrometer/Height Gage	N/A
5	Center Drill the holes	Mill	Vice	Center Drill	800 RPM
6	Drill the preliminary holes	Mill	Vice	#7 Drill	800 RPM
8	Tap Holes	N/A	Vice	¼" Tap	N/A
9	Measure center point for the slots at the front of the plate	N/A	N/A	Micrometer/Height Gage	N/A
10	Mill Slots	Mill	Vice	.3" end mill	600 RPM
11	File down sharp edges	N/A	N/A	N/A	N/A

Table 11: Gearbox Side Manufacturing Plan

Raw Material Stock: Multipurpose 6061 Aluminum Rectangular Bar, 0.2" X 1’, 2' Long

Step #	***Process Description***	***Machine***	***Fixtures***	***Tool(s)***	***Speed***
1	Measure correct cut length and height	N/A	N/A	Micrometer/Height Gage	N/A
2	Cut to slightly longer than length(≈0.25”)	Bandsaw	N/A	N/A	280(ft/m)
3	Mill to length	Mill	Vice	1” End Mill	800 RPM

4	Measure the center points for the two tapped holes	N/A	N/A	Micrometer/Height Gage	N/A
5	Center Drill the holes	Mill	Vice	Center Drill	800 RPM
6	Drill the preliminary holes	Mill	Vice	#7 Drill	800 RPM
8	Tap Holes	N/A	Vice	¼" Tap	N/A
9	Measure center point for the two ¾" clearance holes	N/A	N/A	Micrometer/Height Gage	N/A
10	Center Drill the holes	Mill	Vice	Center Drill	800 RPM
11	Drill holes	Mill	Vice	¾" Drill Bit	800 RPM
12	File down sharp edges	N/A	N/A	N/A	N/A

Table 12: Gearbox Left Corner Manufacturing Plan

Raw Material Stock: 4130 Alloy Steel Angle Steel

Step #	***Process Description***	**Machine**	***Fixtures***	***Tool(s)***	***Speed***
1	Measure correct cut length	N/A	N/A	Micrometer/Height Gage	N/A
2	Cut to slightly longer than length(≈0.25”)	Bandsaw	N/A	N/A	280(ft/m)
3	Mill to length	Mill	Vice	1” End Mill	300 RPM
4	Measure center point for the holes at the side of the angle steel	N/A	N/A	Micrometer/Height Gage	N/A
5	Center Drill the holes	Mill	Vice	Center Drill	300 RPM
6	Drill holes	Mill	Vice	.257" (F) Drill Bit	300 RPM
7	File down sharp edges	N/A	N/A	N/A	N/A

Table 13: Gearbox Right Corner Manufacturing Plan

Raw Material Stock: 4130 Alloy Steel Angle Steel

Step #	***Process Description***	**Machine**	***Fixtures***	***Tool(s)***	***Speed***

1	Measure correct cut length	N/A	N/A	Micrometer/Height Gage	N/A
2	Cut to slightly longer than length(≈0.25”)	Bandsaw	N/A	N/A	280(ft/m)
3	Mill to length	Mill	Vice	1” End Mill	300 RPM
4	Measure center point for the holes at the side and bottom of the angle steel	N/A	N/A	Micrometer/Height Gage	N/A
5	Center Drill the holes	Mill	Vice	Center Drill	300 RPM
6	Drill holes	Mill	Vice	.257" (F) Drill Bit	300 RPM
7	File down sharp edges	N/A	N/A	N/A	N/A

Table 14: Small Gear Manufacturing Plan

<u>Raw Material Stock</u>: Spur Gear, 12 Pitch, Pitch Dia 1.333 In, Face Width 0.750 In, Number of Teeth 16, Bore Dia 0.625 In, Outside Dia 1.500 In, Overall Length 1.250 In, Hub Dia 0.98 In, Hub Projection 0.50 In, Pressure Angle 14 1/2 Deg

Step #	***Process Description***	**Machine**	***Fixtures***	***Tool(s)***	***Speed***
1	Measure the center points for the holes on the gear	N/A	N/A	Micrometer/Height Gage	N/A
2	Center Drill the holes	Mill	Vice	Center Drill	300 RPM
3	Drill the preliminary holes on the gear	Mill	Vice	#7 Drill	300 RPM
5	Tap Holes	N/A	Vice	¼" Tap	N/A
6	File down sharp edges	N/A	N/A	N/A	N/A

Table 15: Upper Shaft Manufacturing Plan

<u>Raw Material Stock</u>: Hardened Precision Steel Shaft, 5/8" Diameter, 8" Length

Step #	***Process Description***	***Machine***	***Fixtures***	***Tool(s)***	***Speed***
1	Measure correct cut length	N/A	N/A	Micrometer/Height Gage	N/A

2	Cut to slightly longer than length(≈0.25”)	Bandsaw	N/A	N/A	280(ft/m)
3	Mill to length	Mill	Vice	1” End Mill	300 RPM
4	File down sharp edges	N/A	N/A	File	N/A
5	Measure and mark correct groove heights	N/A	N/A	Micrometer/Height Gage	N/A
6	Mill grooves	Mill	Vice	1/2" End Mill	300 RPM
7	File down sharp edges	N/A	N/A	N/A	N/A

Table 16: Shaft Manufacturing Plan

Raw Material Stock: Hardened Precision Steel Shaft, 5/8" Diameter, 8" Length

Step #	***Process Description***	***Machine***	***Fixtures***	***Tool(s)***	***Speed***
1	Measure correct cut length	N/A	N/A	Micrometer/Height Gage	N/A
2	Cut to slightly longer than length(≈0.25”)	Bandsaw	N/A	N/A	280(ft/m)
3	Mill to length	Mill	Vice	1” End Mill	300 RPM
4	Measure correct groove hieghts on the shaft	N/A	N/A	Micrometer/Height Gage	N/A
5	Cut grooves into the shaft	Lathe	N/A	.05" grooving tool	500 RPM
6	File down sharp edges	N/A	N/A	N/A	N/A

Table 17: Motor Shaft Manufacturing Plan

Raw Material Stock: DC GEARMOTOR PARALLEL 1/5HP 12VDC 26RPM 280in-lb , 69:1 RATIO

Step #	***Process Description***	***Machine***	***Fixtures***	***Tool(s)***	***Speed***
1	Measure and mark correct feature depth	N/A	N/A	Micrometer/Height Gage	N/A

2	Cut to slightly longer than length(≈0.25”)	Bandsaw	N/A	N/A	280(ft/m)
3	Mill to length	Mill	Vice	1” End Mill	300 RPM

Table 18: Potentiometer Mount Manufacturing Plan

<u>Raw Material Stock</u>: .125" thick, 1x1" Multipurpose 6061 Aluminum Rectangular Bar

Step #	***Process Description***	***Machine***	***Fixtures***	***Tool(s)***	***Speed***
1	Measure and mark correct cut length.	N/A	N/A	Micrometer/Height Gage	N/A
2	Cut to slightly longer than length(≈0.25”)	Bandsaw	N/A	N/A	280(ft/m)
3	Mill to length	Mill	Vice	1” End Mill	800 RPM
4	Measure center point for the holes on the potentiometer mount	N/A	N/A	Micrometer/Height Gage	N/A
5	Center Drill the holes at the ends of the potentiometer mount	Mill	Vice	Center Drill	800 RPM
6	Drill preliminary holes at the ends of the link	Mill	Vice	#7 Drill, AND .359" Drill Bit	800 RPM
7	Widen exterior hole	Mill	Vice		
8	File down sharp edges	N/A	N/A	N/A	N/A

Appendix E.2 – Drawings

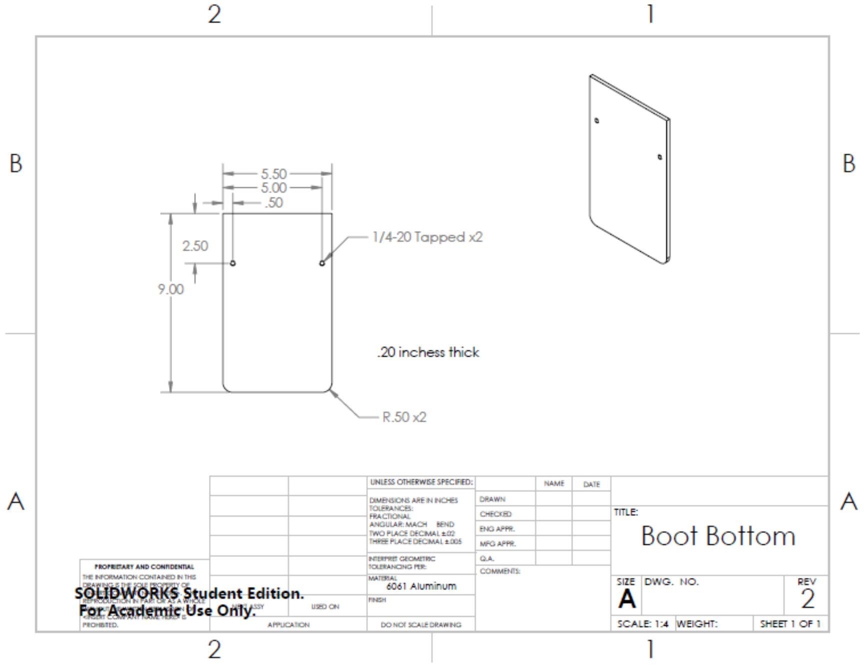


Figure 2: Boot Bottom Drawing

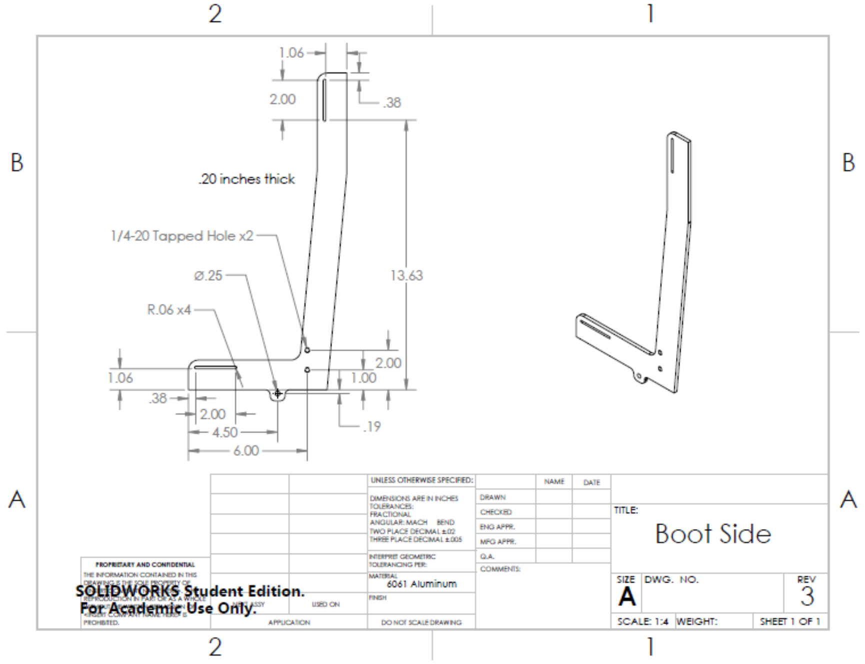


Figure 3: Boot Side Drawing

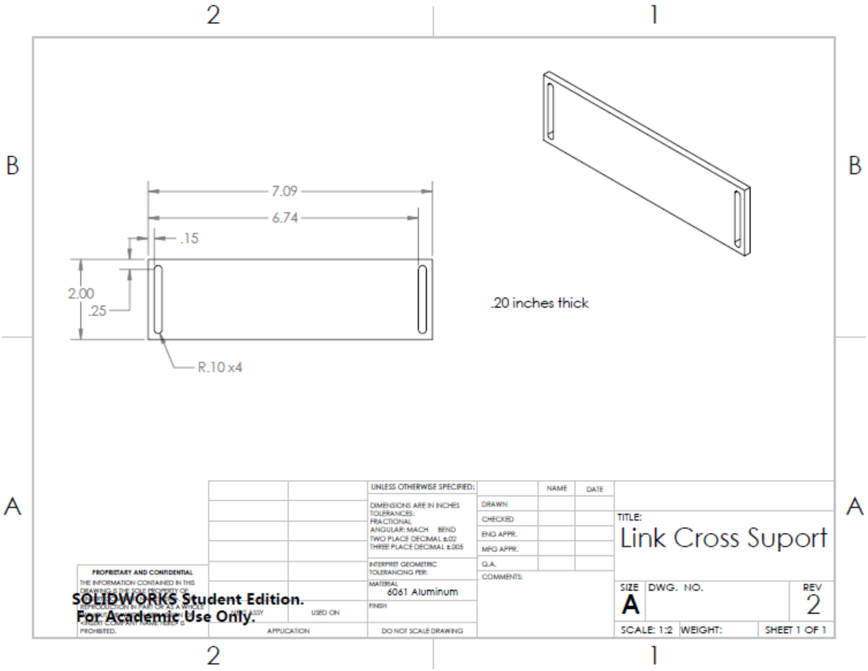


Figure 4: Link Cross Support Drawing

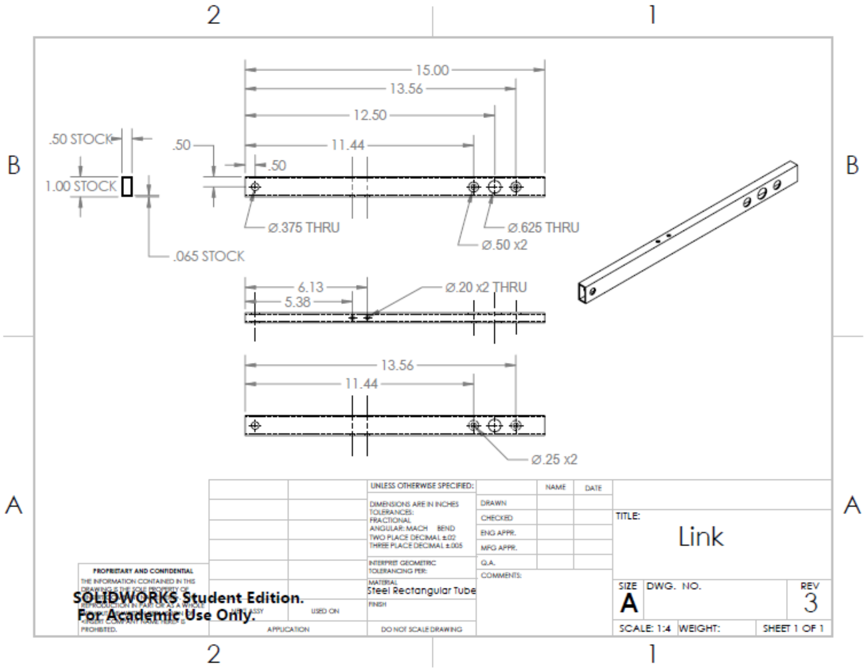


Figure 5: Link Drawing, Revised: See Appendix E.3

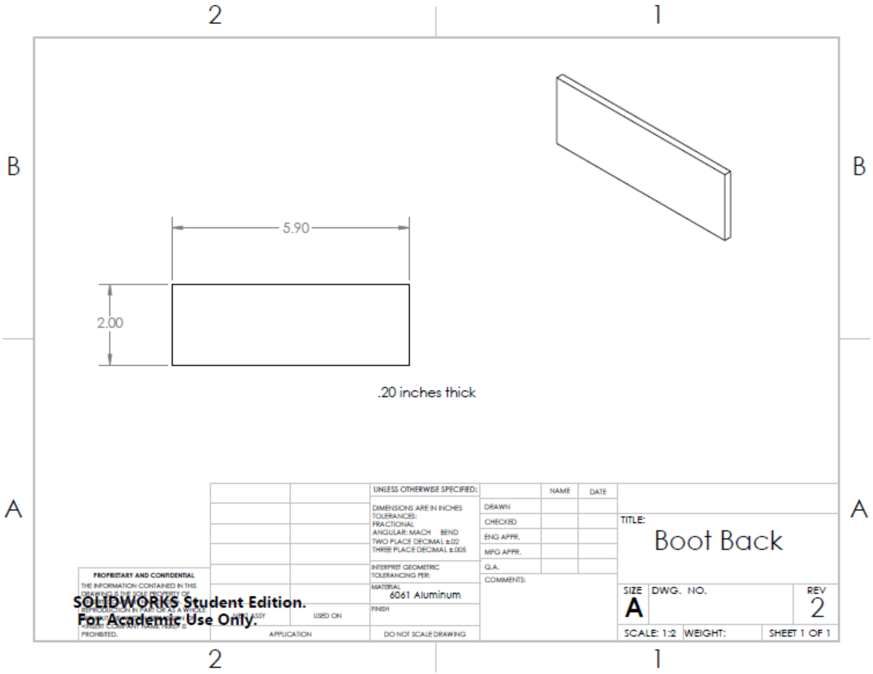


Figure 6: Boot Back Drawing

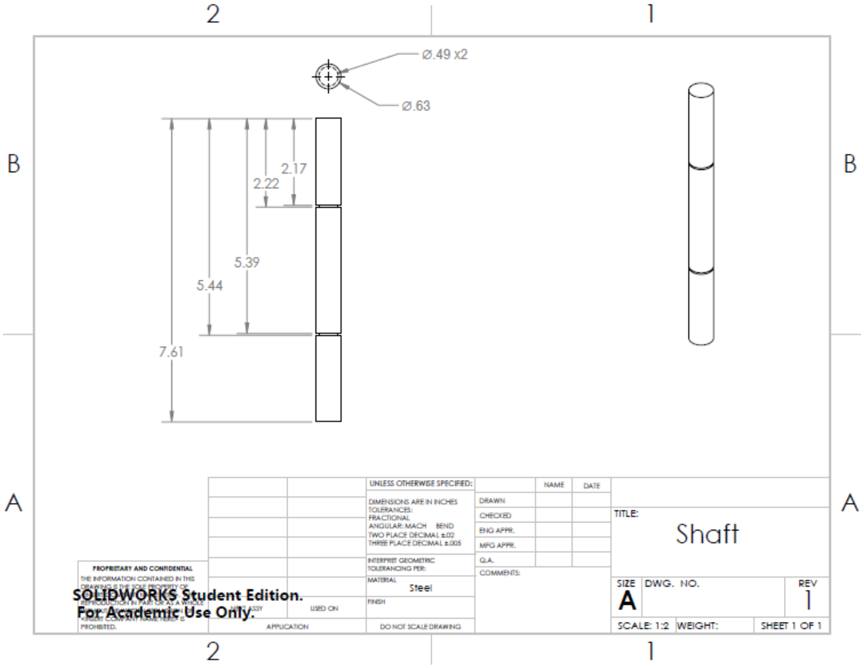


Figure 7: Shaft Drawing

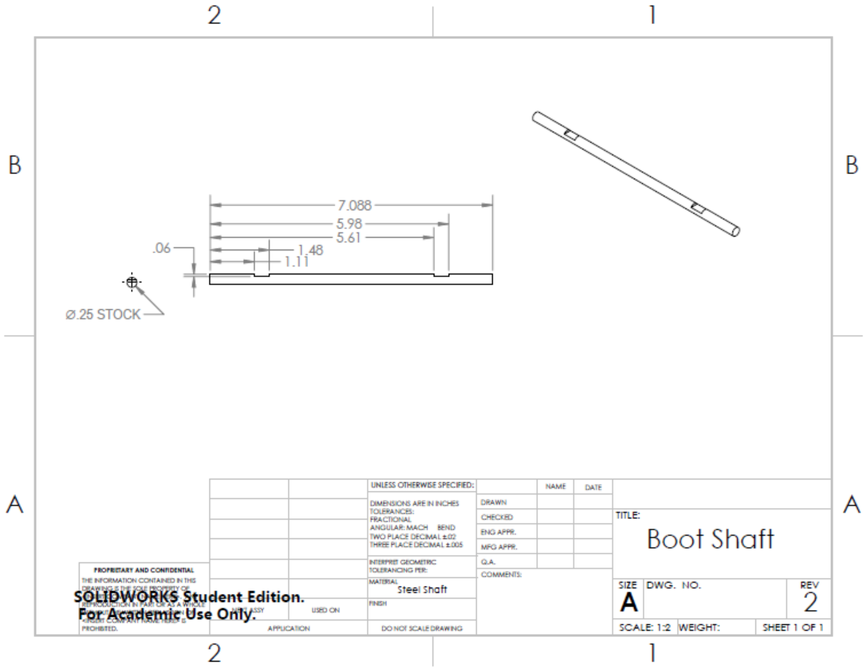


Figure 8: Boot Shaft Drawing

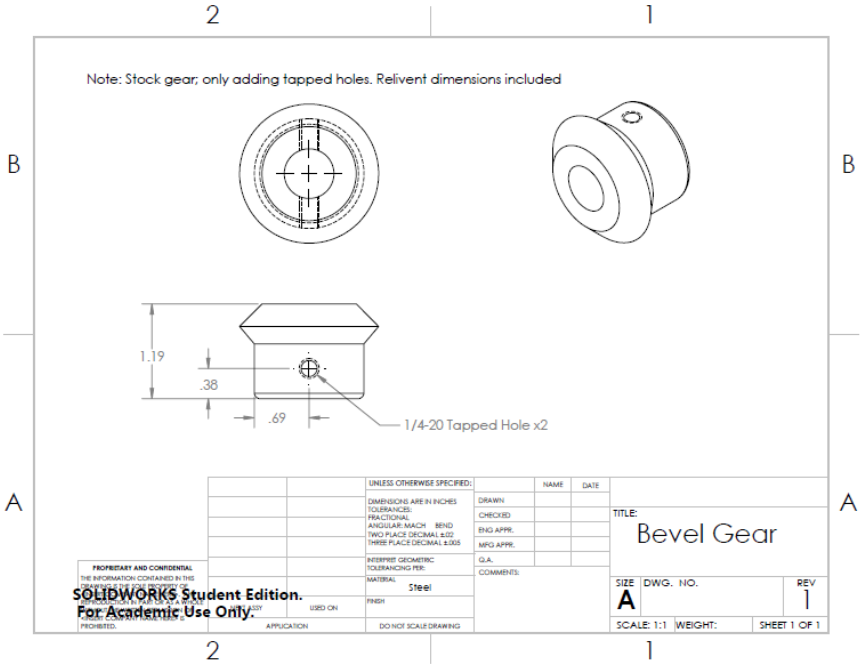


Figure 9: Bevel Gear Drawing

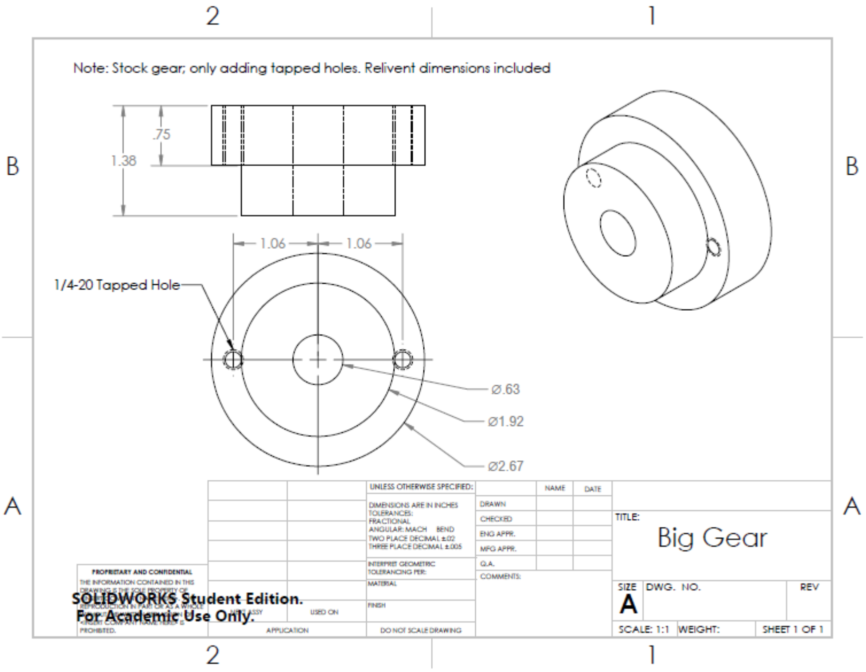


Figure 10: Big Gear Drawing

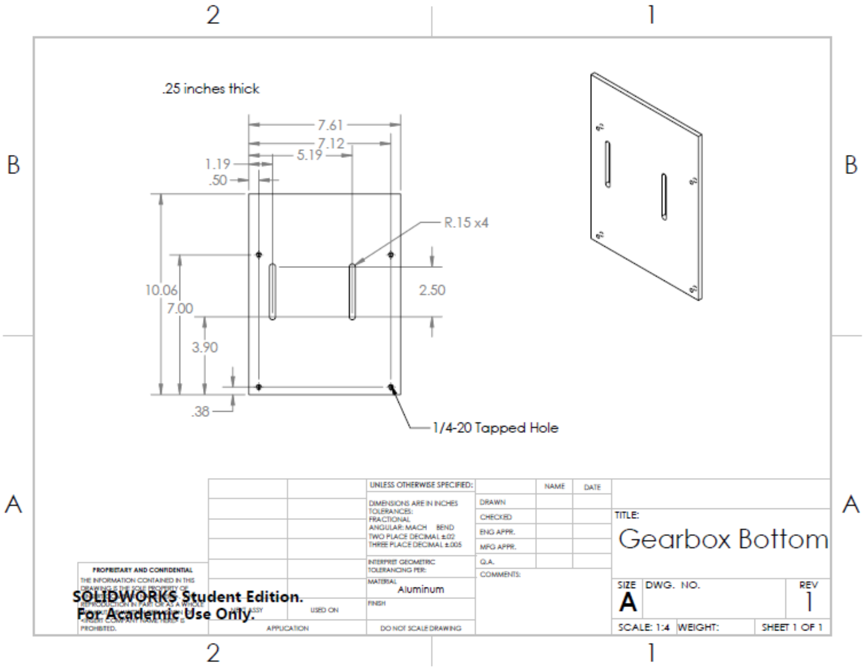


Figure 11: Gearbox Bottom Drawing

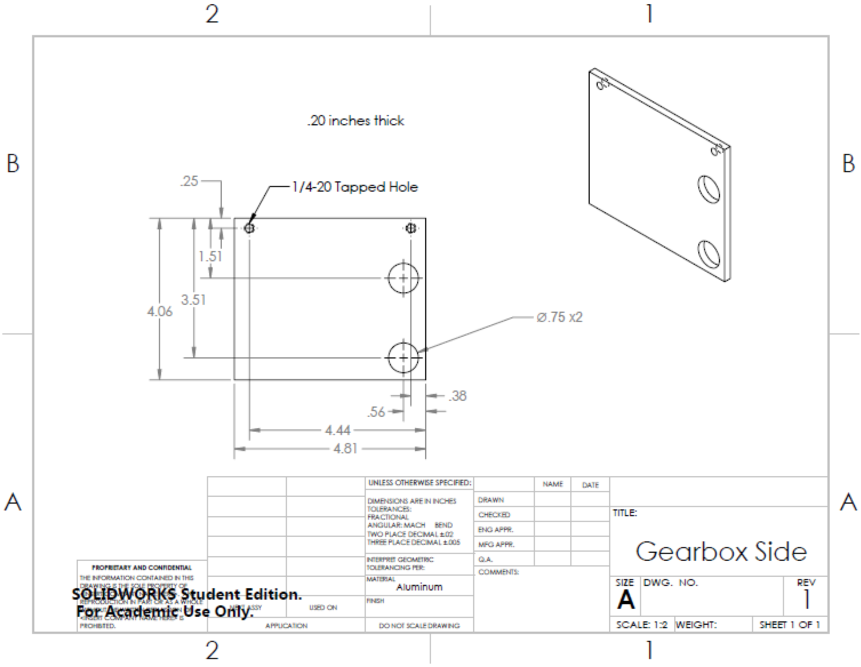


Figure 12: Gearbox Side Drawing. Revised: See Appendix E.3

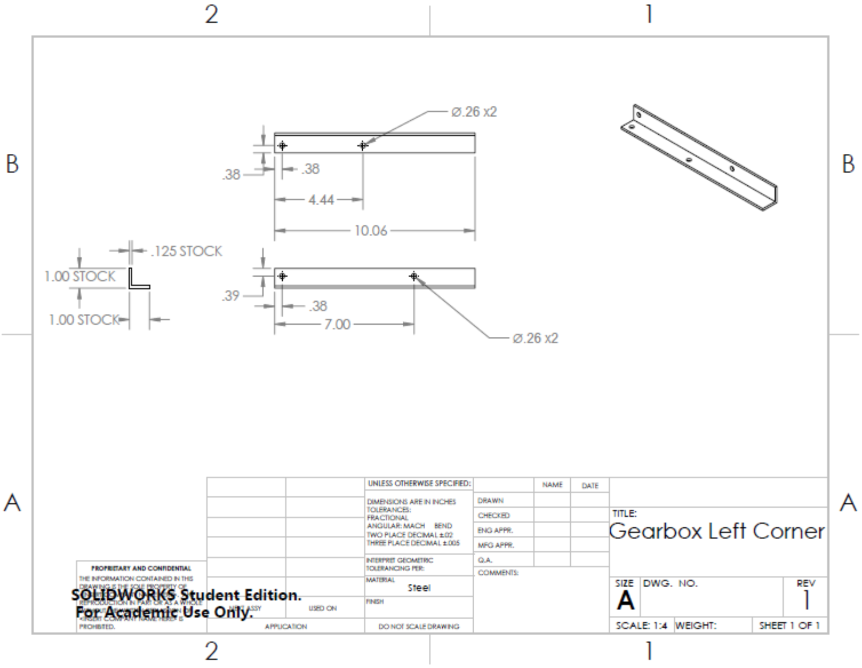


Figure 13: Gearbox Left Corner Drawing. Revised: See Appendix E.3

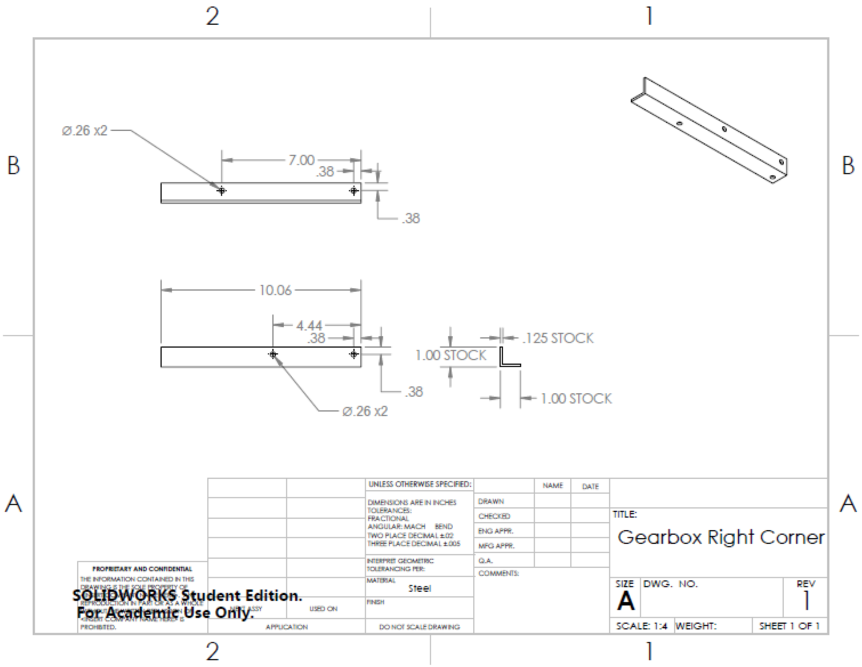


Figure 14: Gearbox Right Corner Drawing. Revised: See Appendix E.3

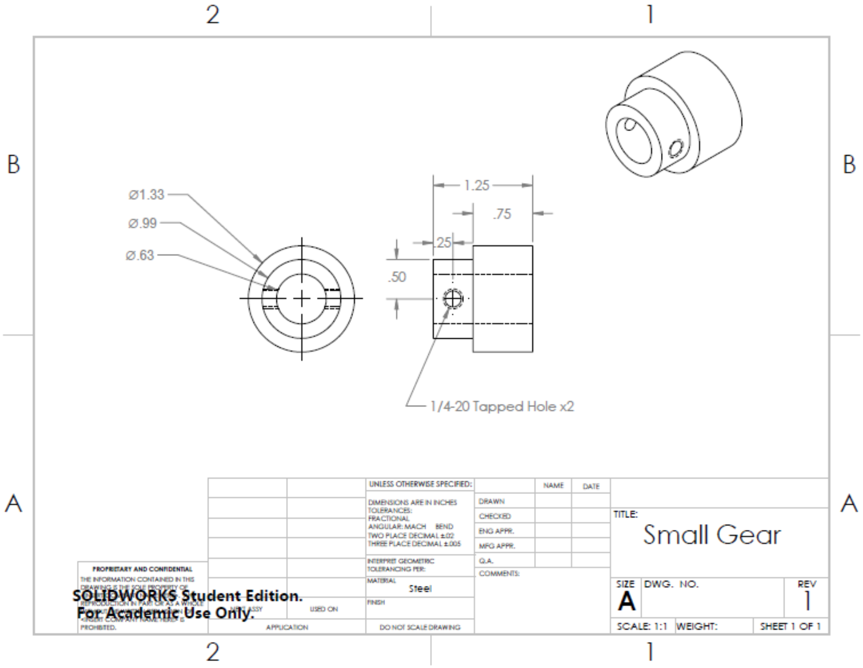


Figure 15: Small Gear Drawing

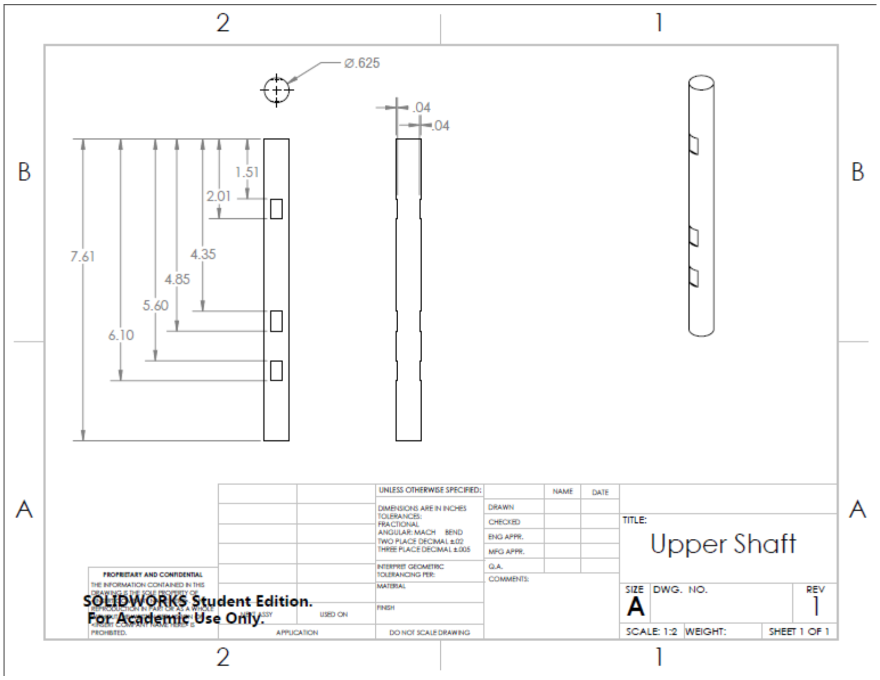


Figure 16: Upper Shaft Drawing. Revised: See Appendix E.3

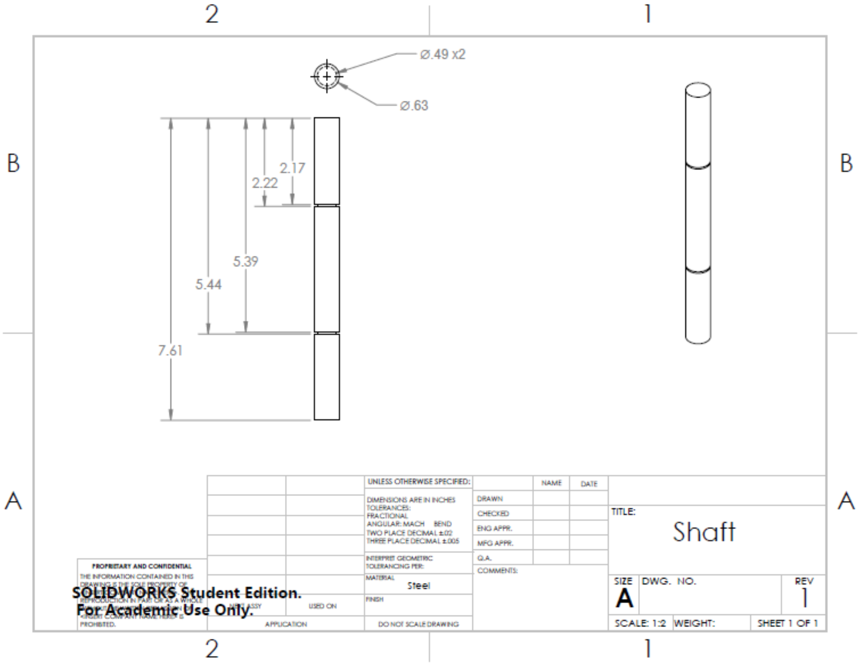


Figure 17: Shaft Drawing

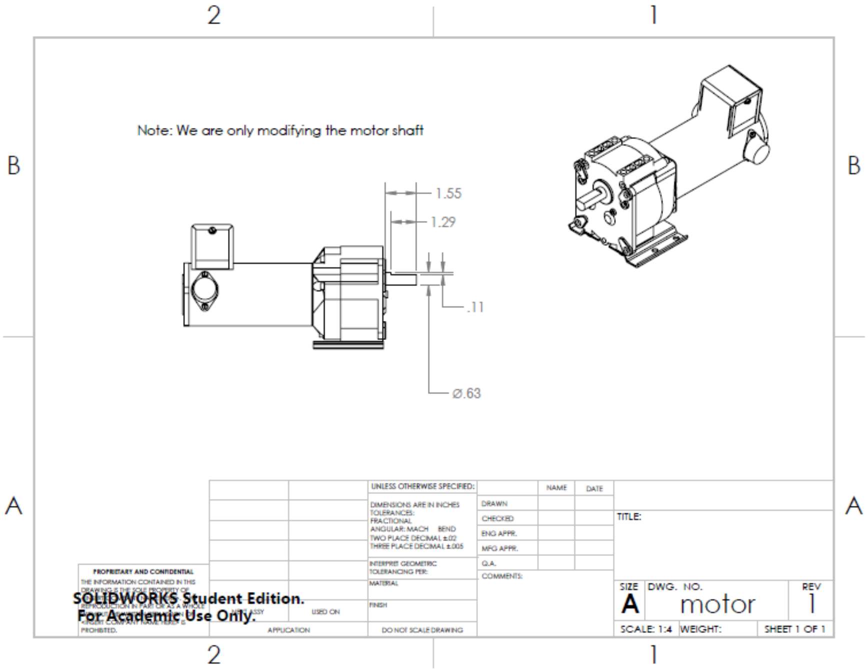


Figure 18: Motor Shaft Drawing

Appendix E.3 – Engineering Change Notices

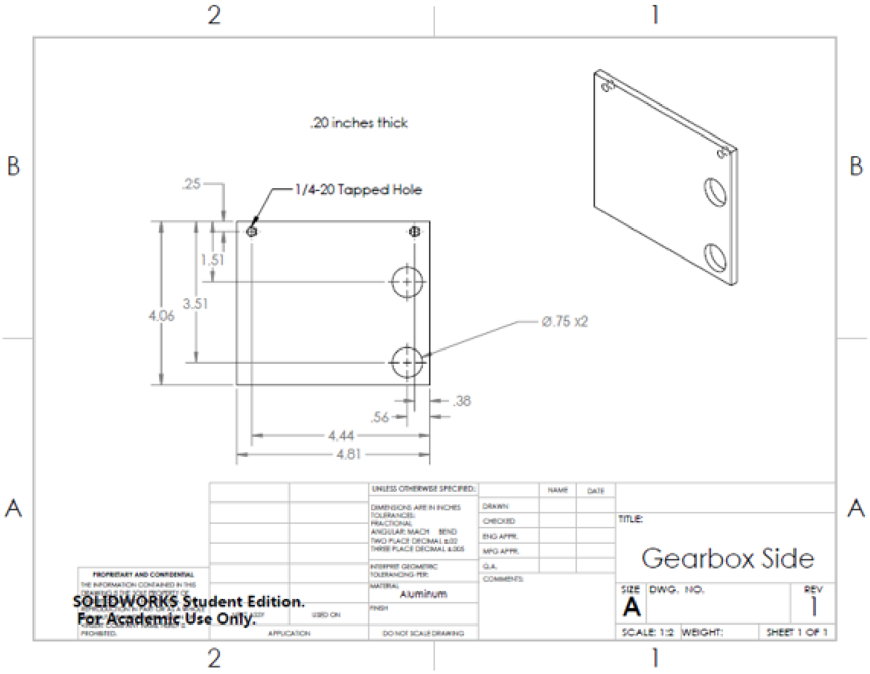


Figure 19A: Original Gearbox Left Side Drawing

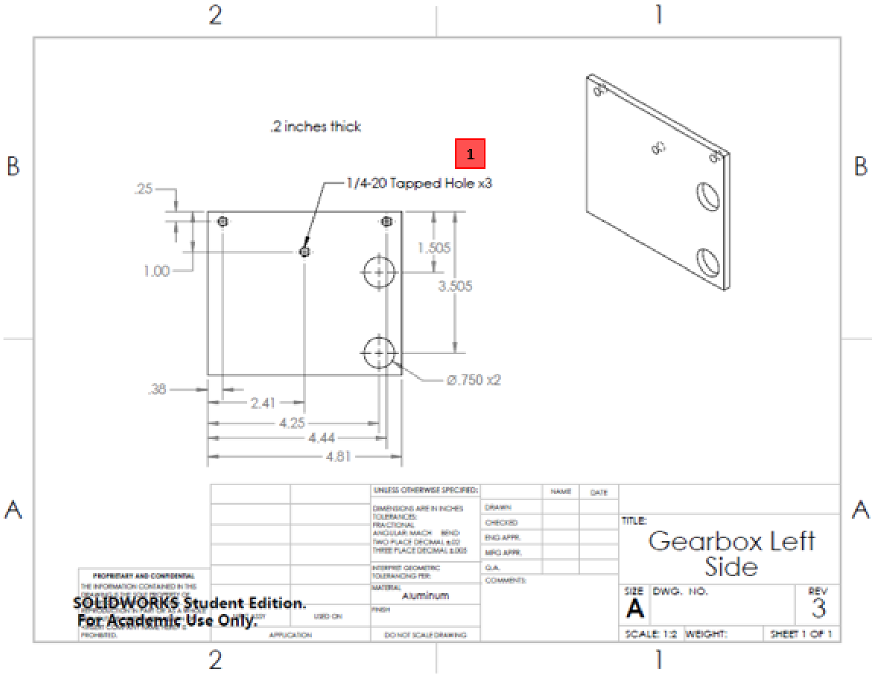


Figure 19B: Revised Gearbox Left Side Drawing

1: A third support hole was added to help with stability

Changed by: Adam Carlson 11/23/15

Authorized by: James Crowther

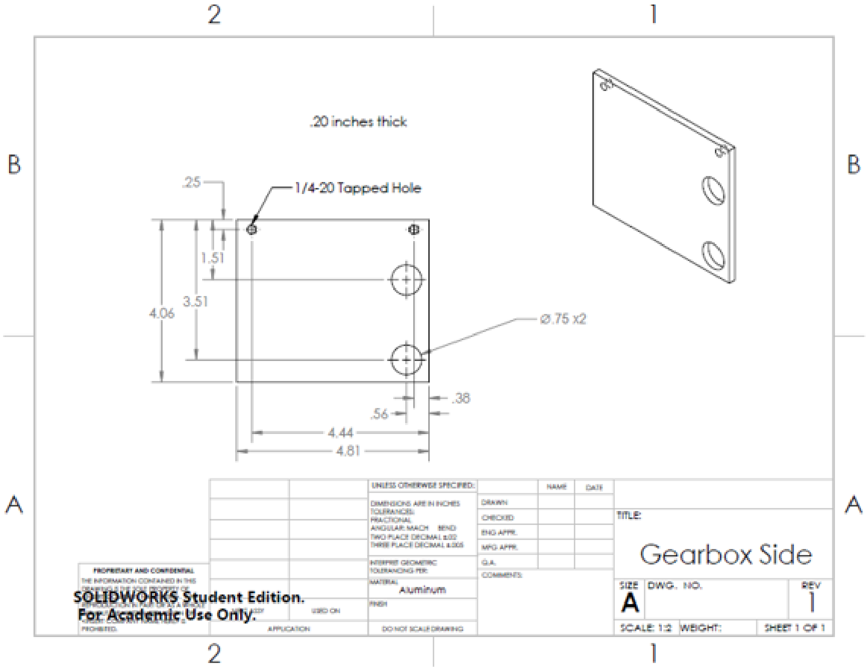


Figure 20A: Original Gearbox Right Side Drawing

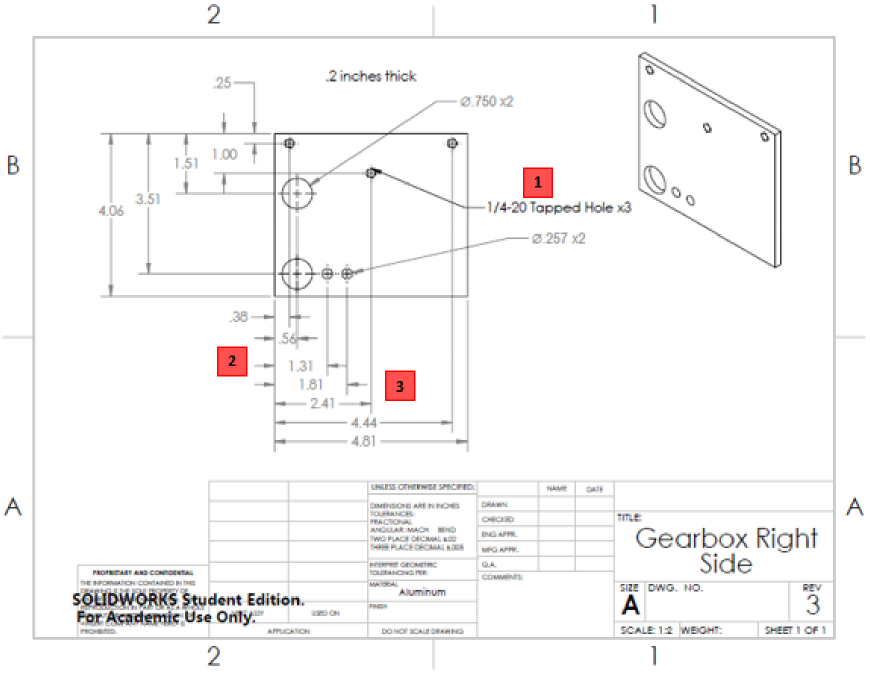


Figure 20B: Revised Gearbox Right Side Drawing

1: A third support hole was added to help with stability

2&3: Holes added to attached the potentiometer mount to accurately control our mechanism

Changed by: Adam Carlson 11/23/15

Authorized by: James Crowther

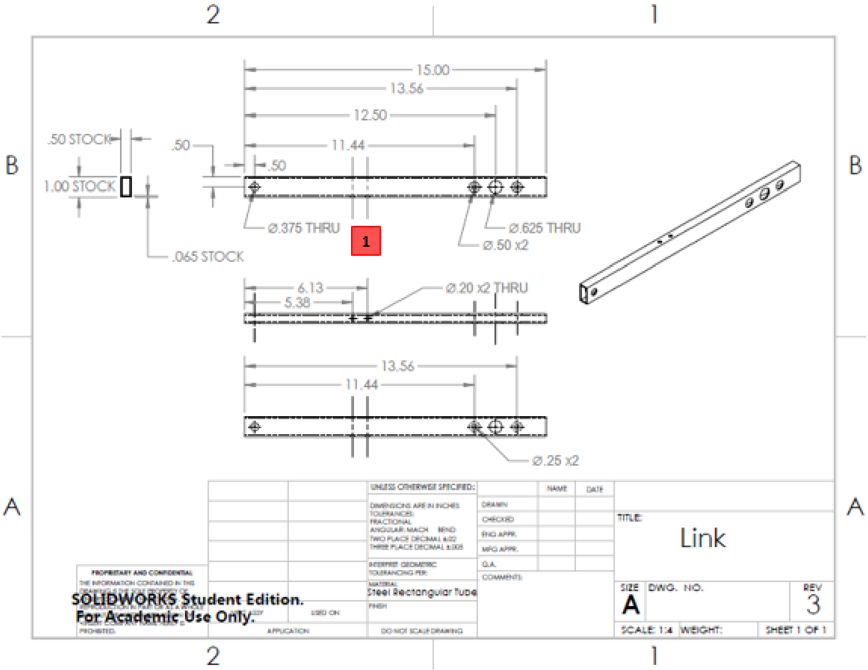


Figure 21A: Original Link Drawing

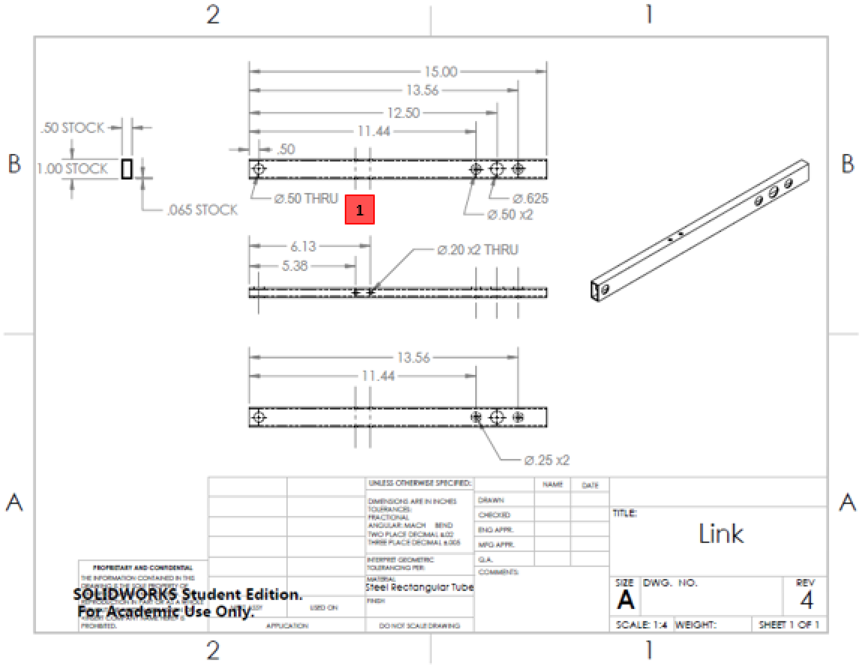


Figure 21B: Revised Link Drawing

1: We accidentally ordered the wrong size bushings. Because this didn’t affect the functionality of the mechanism we decided to change the dimension of the hole for said bushing.

Changed by: John Benjamin 11/24/15

Authorized by: Dana Barbera

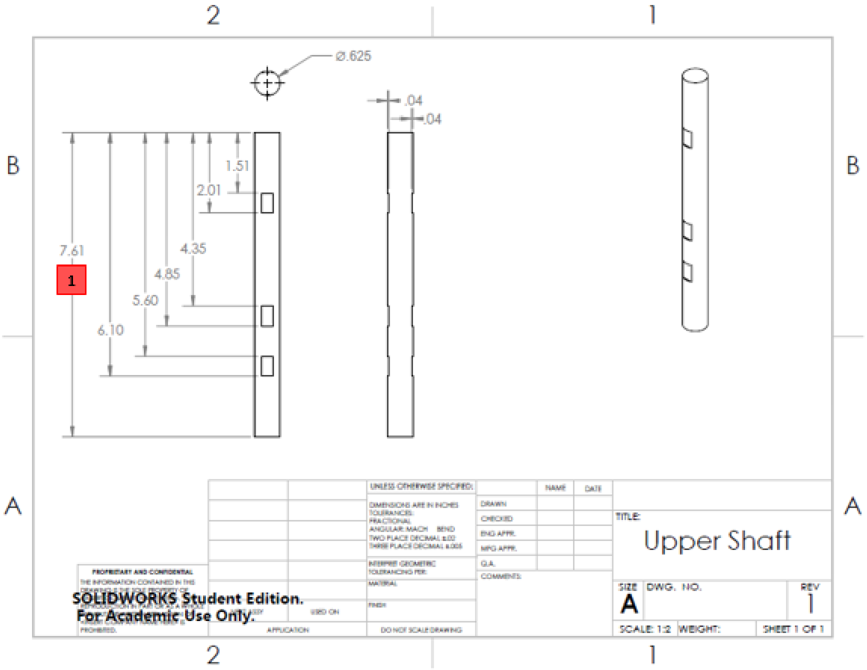


Figure 22A: Original Upper Shaft Drawing

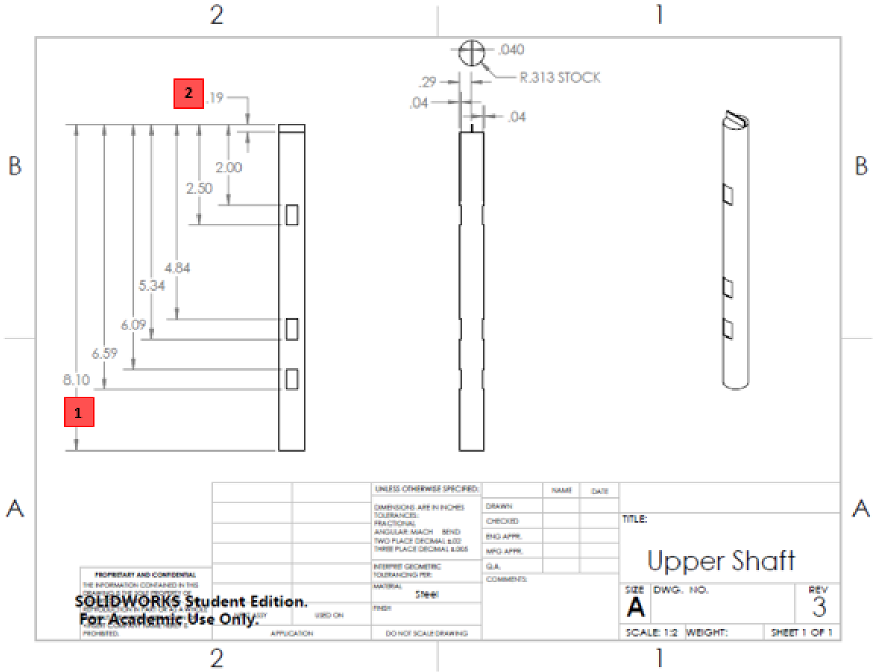


Figure 22B: Revised Upper Shaft Drawing

1: The length changed to allow for the shaft to appropriately mount to the potentiometer

2: The fin was added to mount the shaft to the mechanism to accurately control our mechanism

Changed by: Adam Carlson 11/23/15

Authorized by: James Crowther

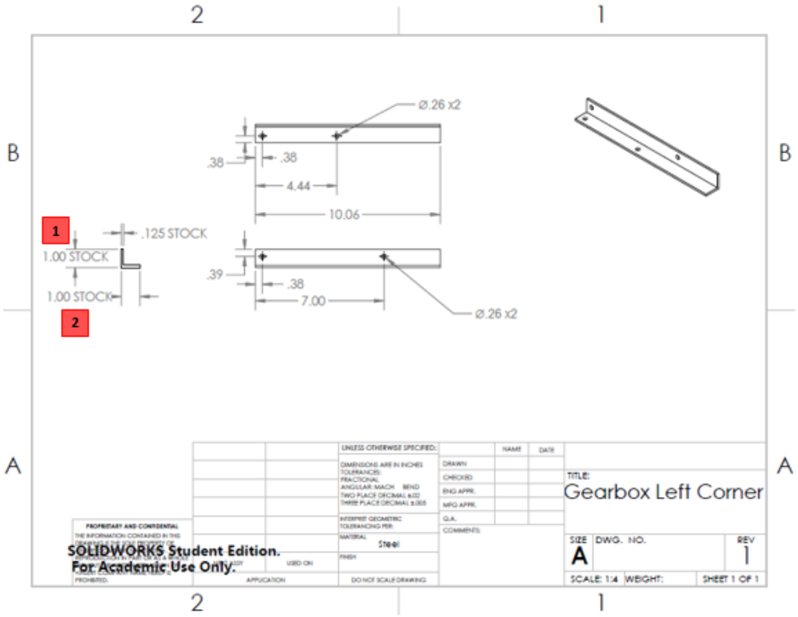


Figure 23A: Original Gearbox Left Drawing

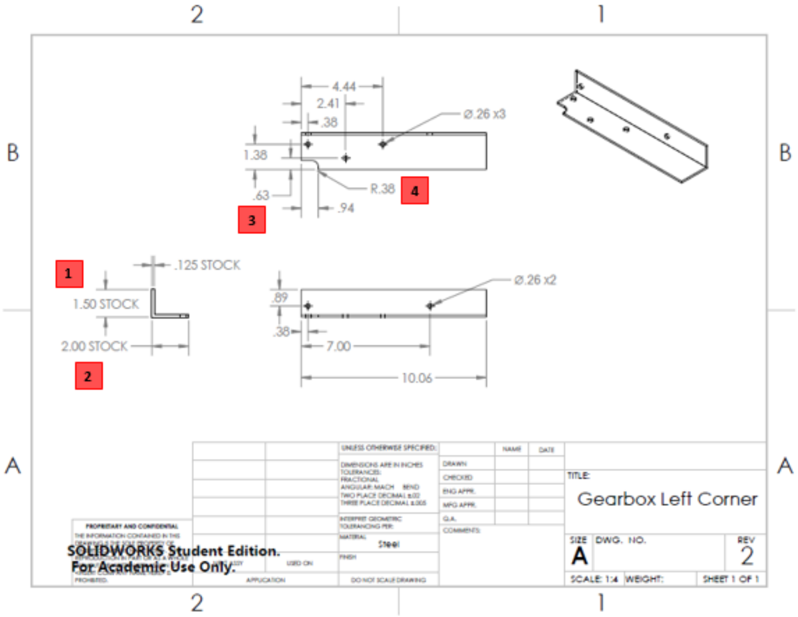


Figure 23B: Revised Gearbox Left Drawing

1&2: Size of stock material available changed

3: A third support hole was added to help with stability

4: Radius added to account for the end of the lower motor shaft

Changed by: Adam Carlson 11/23/15

Authorized by: James Crowther

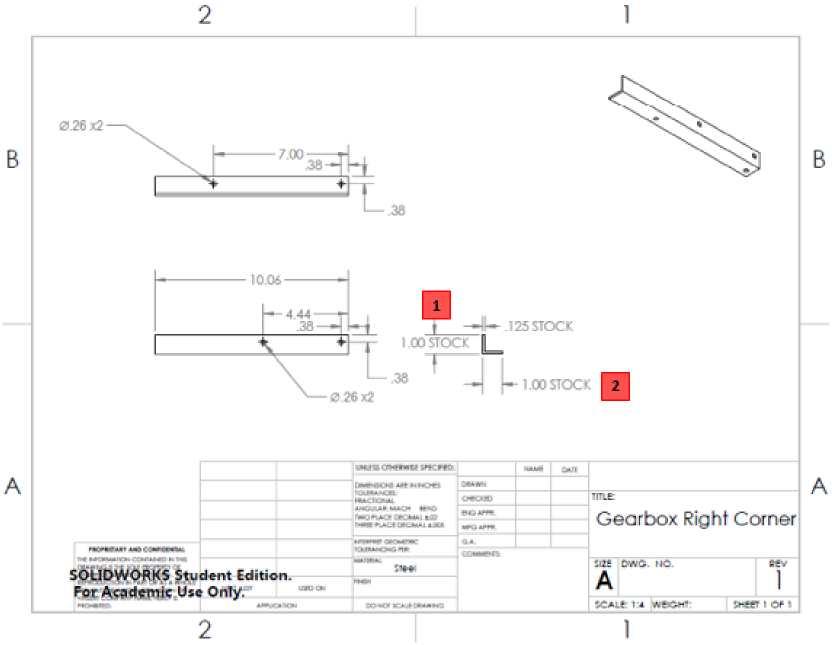


Figure 24A: Original Gearbox Right Drawing

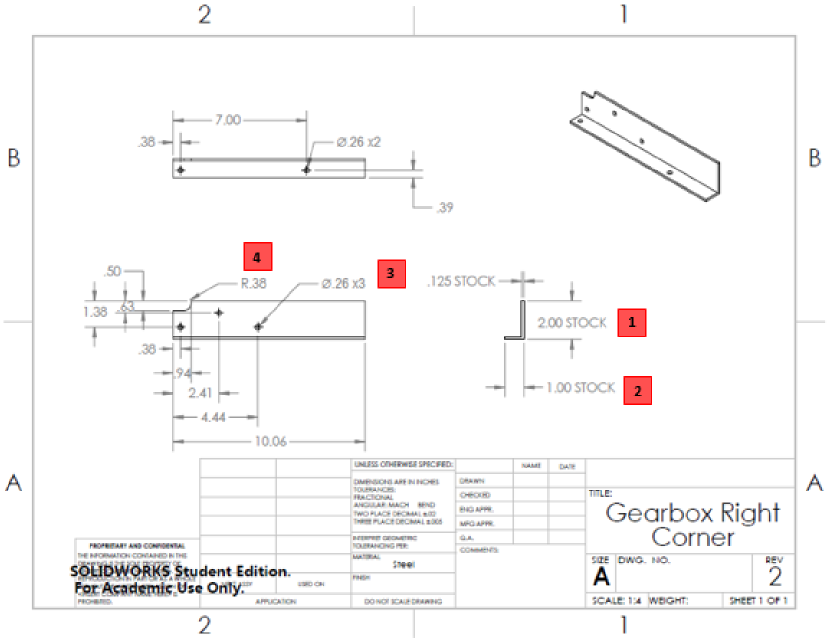


Figure 24B: Original Gearbox Right Drawing

1&2: Size of stock material available changed

3: A third support hole was added to help with stability

4: Radius added to account for the end of the lower motor shaft

Changed by: Adam Carlson 11/23/15

Authorized by: James Crowther

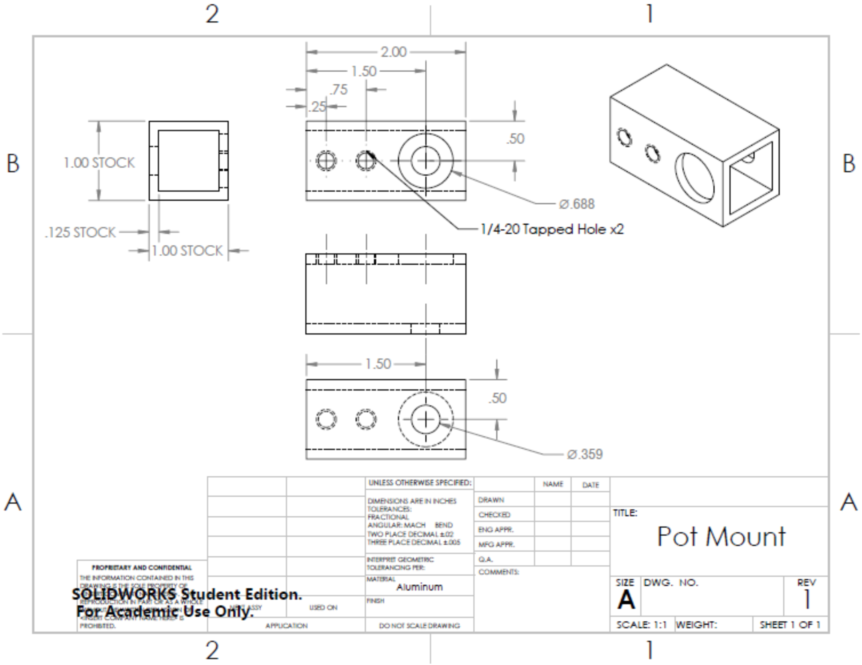


Figure 25A: New Part Drawing, Potentiometer Mount

Added another part to mount the potentiometer to the supper shaft in order to be able to control our mechanism

Changed by: Nate Erickson 11/22/15

Authorized by: Ben Dwamena

Appendix E.4 – Bill of Materials

Table 19: Bill of Materials

Product	Supplier	Part #	Quantity	Unit Price	Total Price
Multipurpose 6061 Aluminum Sheet 0.2" X 2' X 1'	Alro Metals Plus		1	$18.00	$18.00
Multipurpose 6061 Aluminum Sheet 0.25" X 1' X 1'	Alro Metals Plus		1	$9.00	$9.00
4130 Alloy Steel Rectangular Tube, 0.065" Thk Wall, 1/2" X 1", 3'L	Alro Metals Plus		1	$6.00	$6.00
4130 Alloy Steel Angle Steel, 2" X 1 1/2" X 3'L	Alro Metals Plus		1	$8.34	$8.34
Spur Gear, 12 Pitch, 2.67" Pitch Diameter	Zoro	G0890811	2	$32.09	$64.18
Spur Gear, 12 Pitch, 1.33" Pitch Diameter	Zoro	G2184226	2	$32.33	$64.66
Miter Gear, 10 Pitch, 2" Pitch Diameter	Amazon	L121Y	2	$27.80	$55.60
Hardened Precision Steel Shaft, 5/8" Diameter, 8" Length	McMaster-Carr	6061K104	1	$5.57	$5.57
Hardened Precision Steel Shaft, 5/8" Diameter, 9" Length	McMaster-Carr	6061K121	1	$6.27	$6.27
SAE 863 Bronze Sleeve Bearing,for 5/8" Shaft Diameter, 3/4" OD, 1/2" Length	McMaster-Carr	2868T15	4	$0.86	$3.44
Hardened Precision Steel Shaft, 1/4" Diameter, 8" Length	McMaster-Carr	6061K101	1	$4.55	$4.55
SAE 863 Bronze Sleeve Bearing, for 1/4" Shaft Diameter, 3/8" OD, 1/2" Length	McMaster-Carr	2868T3	2	$0.88	$1.76
DC GEARMOTOR PARALLEL 1/5HP 12VDC 26RPM 280in-lb , 69:1 RATIO	Automation Direct	MTGP-P20-1J026	1	$277.00	$277.00
Arduino Uno Rev 3	Amazon	A000066	1	$19.95	$19.95
microtivity IB402 400-point Breadboard for Arduino w/ Jumper Wires & USB Adapter	Amazon	B005H8MWU6	1	$9.99	$9.99
				Total	$554.31

Appendix F.1 – Validation Protocol

In order to know whether our solution meets our user requirements we created a validation protocol for our engineering specifications. Many of the engineering specifications for the kinematic leg therapy device cannot be empirically validated due to their qualitative nature. In our solution the legs are actuated by an external power source; the leg movement is available in the standing position; there is an alternating loading force on the feet, and the prototype was built within the budget of $600.

Some of the engineering specifications are no longer within the scope of our design and we can no longer validate them. Engineering specifications 6 and 7 in appendix A.1, page xx fall outside of the scope of the design because they are determined by the integration of the kinematic leg therapy device with the user's wheelchair. It was instructed that no modifications should be made to the wheelchair of the user. These specifications will need to be met when the design is integrated with a wheelchair. However, if these were to be validated it would be a simple yes/no validation.

Validation protocols for the empirically testable engineering specifications will be explained in the following sections. The measurements and equipment needed, as well as the basic steps that will be followed during the process of validation will be briefly discussed. The validation test set-up is shown in Figure 1.

Figure 1: Validation test set-up

Design must have a range of motion similar to walking

Summary: The hip-knee (105-175) range of motion shall move 60 degrees in reference to vertical; the knee-ankle (B-C) range of motion shall move 60 degrees in reference to hip-knee (A-B) axis, the ankle-ball of foot (C-D) range of motion shall move 0 degrees in reference to knee-ankle (B-C).

- Measurements: 3 angle measurements will be made at the top and bottom positions of the kinematic leg therapy device
- Equipment: Protractor, artificial leg with user dimensions

- Process: The device will be moved to the bottom of its range of motion and measurements will be taken at the hip joint, knee joint, and ankle joint. The kinematic leg therapy device will then be moved to the top of its range of motion and the joint measurements will be repeated. Joint measurements will be compared to determine each joints range of motion between the top and bottom of the device's range of motion.

Design must have a range of speeds from 25 to 100 steps/min

Summary: The end user shall have multiple speed settings for the walking motion ranging from 25 to 100 (steps/min).

- Measurements: The number of steps every minute at the highest and lowest speed settings in its automatic mode.
- Equipment: Stop-watch
- Process: The kinematic leg therapy device will be placed in its automatic mode and lowest speed setting. The number of complete cycles accomplished in one minute will be recorded. The same will be done at the highest speed setting.

Design must be adjustable for different heights and weights

Summary: The leg movement mechanism shall have the ability to adjust for human weights from 110-260 lbs and for human heights from 59-72 inches. The ability to support human weights up to 260 lbs involves the use of an additional upper body weight support. Since the scope of the design no longer includes this additional weight support, the weight capacity of the device was updated to 35 lbs. The rest of the user's weight will need to be supported by the upper body weight support.

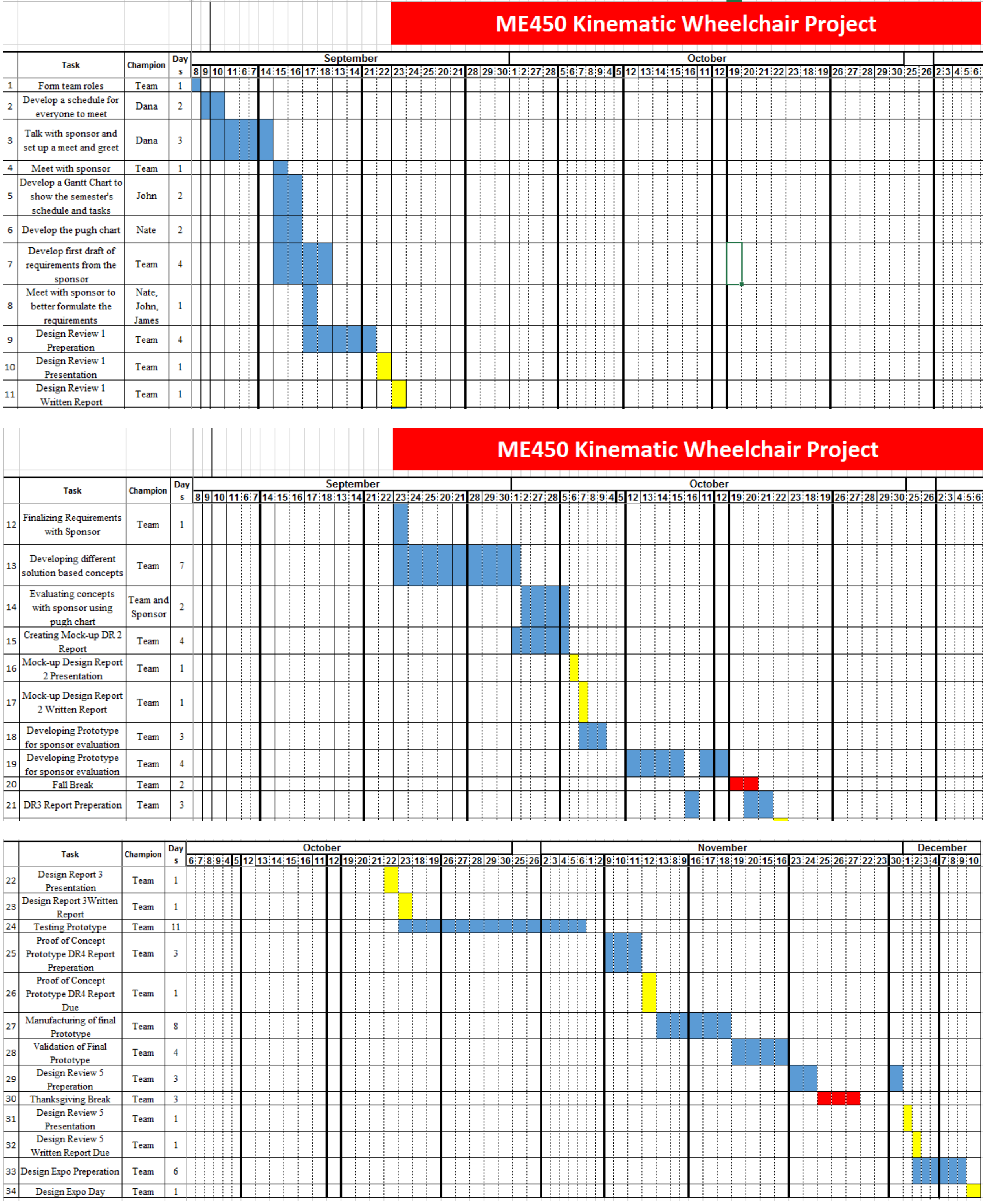
- Measurements: The distance from the knee to the bottom of the foot and the distance from the bottom to the top of the boot of the kinematic leg therapy device.
- Equipment: Tape-measure, weights, artificial leg
- Process: The distance from the knee to the bottom of the foot will be recorded for a sample set of users between the heights of 59 to 72 inches. If these distances are greater than the distance from the bottom to the top of the device's boot, the device will accommodate that user's dimensions. Weights will be added to the artificial leg to test the device's ability to lift the leg of a user up to a weight of 35 lbs.

Design must have a lifespan greater than 5 years

Summary: Insurance companies only cover wheelchairs for 5 years, so the wheelchair should be reliable past that time frame. [This is difficult to accomplish within this project's time constraints but should be done before the design is put in use. More data is needed to determine a standard frequency of use for this device]

- Measurements: The measurements required for the empirical validations in the appendix F.1 sections above.
- Equipment: The equipment required for the empirical validations in the appendix F.1 sections above
- Process: The device should be put in motion under worst case stress conditions for a time equal to five years of standard use. At the end of this stress test, the device should still pass all of the empirical and non-empirical design validation tests described in the appendix J sections above.

Appendix G.1 – Gantt Chart



	Task	Champion	Days
1	Form team roles	Team	1
2	Develop a schedule for everyone to meet	Dana	2
3	Talk with sponsor and set up a meet and greet	Dana	3
4	Meet with sponsor	Team	1
5	Develop a Gantt Chart to show the semester's schedule and tasks	John	2
6	Develop the pugh chart	Nate	2
7	Develop first draft of requirements from the sponsor	Team	4
8	Meet with sponsor to better formulate the requirements	Nate, John, James	1
9	Design Review 1 Preperation	Team	4
10	Design Review 1 Presentation	Team	1
11	Design Review 1 Written Report	Team	1
12	Finalizing Requirements with Sponsor	Team	1
13	Developing different solution based concepts	Team	7
14	Evaluating concepts with sponsor using pugh chart	Team and Sponsor	2
15	Creating Mock-up DR 2 Report	Team	4
16	Mock-up Design Report 2 Presentation	Team	1
17	Mock-up Design Report 2 Written Report	Team	1
18	Developing Prototype for sponsor evaluation	Team	3
19	Developing Prototype for sponsor evaluation	Team	4
20	Fall Break	Team	2
21	DR3 Report Preperation	Team	3
22	Design Report 3 Presentation	Team	1
23	Design Report 3Written Report	Team	1
24	Testing Prototype	Team	11
25	Proof of Concept Prototype DR4 Report Preperation	Team	3
26	Proof of Concept Prototype DR4 Report Due	Team	1
27	Manufacturing of final Prototype	Team	8
28	Validation of Final Prototype	Team	4
29	Design Review 5 Preperation	Team	3
30	Thanksgiving Break	Team	3
31	Design Review 5 Presentation	Team	1
32	Design Review 5 Written Report Due	Team	1
33	Design Expo Preperation	Team	6
34	Design Expo Day	Team	1

Figure 1: A Gantt Chart laying out important tasks for the semester.

Authors

Dana Barbera is a fifth year senior at the University of Michigan working towards her BSE in Mechanical Engineering. She transferred schools twice: starting at Michigan Technological University studying Biomedical Engineering, transferring to Washtenaw Community College to finish prerequisites, and finally to the University of Michigan. She has had two internships, one in Quality Engineering at Eberspaecher and the other in Technical Sales at MTU America. After graduation, she will be working as a Rotational Engineer at Lake Region Medical which is headquartered in Wilmington, Massachusetts. In her free time she enjoys rock climbing, hiking, and canoeing.

John Benjamin transferred from Washtenaw Community College to finish his studies in Mechanical Engineering here at The University of Michigan. He was born and raised here in the Ann Arbor area and has been a Wolverine fan since he was a child and is proud to go here! He worked in industry for 8 years before deciding to come back to school. He was a carpenter, industrial hydraulic mechanic, and a project manager that helped organize the build for the Courtyard Apartments here on North Campus. He has had two different internships, one as a systems engineer with Nexteer Automotive and another as a product engineer with NSK here in Ann Arbor. He wished to pursue a career in product design and concept generation.

Adam Carlson is a senior from Muskegon, MI studying Mechanical Engineering. He originally started college at Muskegon Community College, and transferred into the University of Michigan in September 2013. Adam chose Mechanical Engineering because he was not sure which type of engineering he was most interested in, so he chose the broadest major. Adam has since decided that his interests lie in manufacturing. This summer, Adam had an internship with GM in Powertrain Manufacturing in the Casting Department. Adam has accepted an offer to work for GM when he graduates this December. Adam wishes to pursue a career in Manufacturing Controls. Prior to attending Muskegon Community College, Adam joined the United States Marine Corps, where he spent six months in Afghanistan as a Combat Engineer.

James Crowther is a fifth year senior from Oakham, Massachusetts studying Mechanical Engineering. He transferred to the University of Michigan as a junior from Merrimack College. James has specific interests in design, controls, and mechatronics. In high school, James co-founded a competitive robotics team. This team became very successful, competed across the country, and won 3 Vex Robotics World Championship titles. James' interest in engineering was sparked during his participation in competitive robotics. He has also played soccer since the age of 5, and currently plays for the Maize FC Michigan club soccer team. James enjoys music, plays guitar, and worked for Bose Corporation this past summer.

Nate Erickson is a 21-year-old student at the University of Michigan who is working on his BSE in mechanical engineering. Nate grew up in Grosse Pointe Park, MI and is and planning on working in either the automotive or defense industry upon graduation this April. His interest in mechanical engineering originated from high school projects including building a guitar and creating/racing a 24 Hours of Lemons racecar from a 1980 Fiat X1/9. In his free time he likes to work with engines, play hockey and ride his motorcycle and write/play music. He can also frequently be found attending local music shows.