Equinus Exoskeleton

Final Report

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EXECUTIVE SUMMARY

The overall objective of this project was to improve the gait of individuals suffering from equinus by designing an assistive exoskeleton device. Equinus is common in children with cerebral palsy; as such, children ages 5-12 are the intended users of the device. Equinus is a condition in which the patient's ankle motion is restricted. As a result, gait becomes awkward and inefficient, and the propulsive force a typical human body would receive from ankle motion is significantly reduced or lost completely. Patients with equinus tend to develop detrimental gait patterns, most notably toe-walking. Improving their gait with an assistive device should help these patients manage their condition.

The goal of improving gait was accomplished by designing an exoskeleton device that provided an assistive propulsive force to the patient's foot. To begin the design process, customer needs were outlined, based on requirements and specifications provided by the client, Dr. Zachary Lerner (the director of NAU's Biomechatronics Lab). Engineering requirements were then developed to meet the customer needs. Primary requirements included the use of a Bowden cable system to provide propulsion, adjustability of the device for a range of equinus severity, a need for reduced weight, and a minimum torque applied at the foot.

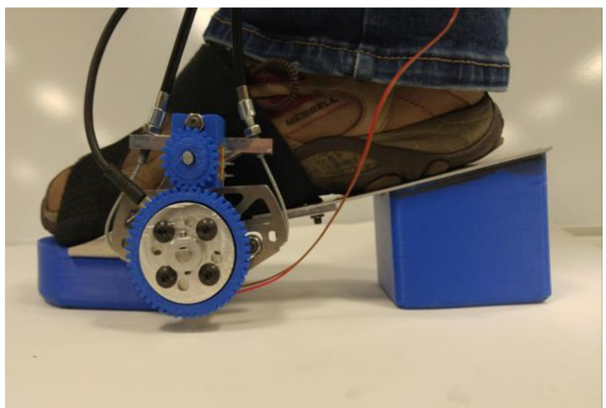

Figure 1: Equinus exoskeleton device

Research was conducted on existing exoskeleton technology. This research encompassed various current foot and ankle exoskeleton devices, as a foundation for the design of this project's device. Since this is an original concept, no current technology performs exactly the same function. After completing research, concept generation began. Multiple design concepts were produced, involving various propulsion systems and structural designs. The final design was powered by motors that attach at the patient's waist. The motors, when engaged, tensioned the Bowden cables, which transmitted force to a drive assembly at the patient's foot. The drive assembly converted tension from the cables into torque, which was transmitted through a shaft to a hinge at the ball of the foot. As a result of this motion, the heel would lift, providing a propulsive force to the foot. A timed control system coordinated actuation of the device.

Testing of the device revealed that the overall system functioned mechanically, and that timed walking controls functioned. Testing was conducted on healthy adults; therefore, further testing would be required to determine whether or not the exoskeleton would provide helpful assistance to children with equinus. Proposed improvements included redesign of certain components, including the hinge and the motor pulleys, in order to transmit torque more effectively and provide added safety for the motors. Additionally, a more intelligent control scheme would be implemented.

The design developed during this project provided a foundation for possible future work with the equinus condition. The design also had potential for applications with other exoskeleton devices.

ACKNOWLEDGEMENTS

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TABLE OF CONTENTS

1. BACKGROUND

1.1. Introduction

The team was tasked with creating an exoskeleton device that would help improve the gait of individuals with equinus. Equinus is a condition in which an individual suffers from restricted ankle motion, often leading to an inefficient "toe-walking" pattern, where the patient walks on the balls of the feet. The exoskeleton device the team created assisted in re-distributing weight across the foot and provided a propulsive force to help the patient walk. The team designed an appropriate drive system to provide propulsion and designed the device to allow for adjustment for a range of equinus severities.

1.2. Project Description

The team's client, Dr. Zachary Lerner, is the director of the Biomechatronics Lab at NAU. The Biomechatronics Lab uses robotic exoskeletons to improve walking biomechanics in individuals with neuromuscular disorders. Some individuals with cerebral palsy walk with a pattern known as equinus, which has an inefficient energy expenditure. These individuals have limited ankle range of motion, so assistance must be applied in series to the ankle joint. The goal of this project was to design an ankle exoskeleton attachment that supports the foot and can be used improve walking economy.

2. REQUIREMENTS

The intended consumers (and stakeholders) of this project were children with equinus deformities. The project was not intended to help people with extreme cases; rather, it was meant to assist with management of milder deformities. The target age range was for children between 5 and 12 years old.

2.1. Customer Requirements

The client outlined customer requirements at the beginning of the project. The primary requirements are outlined below:

- Use Bowden cable system
- Interface with footwear
- Easy to put on/take off
- Measure applied torque
- Compliant with heel strike

The device required a Bowden cable system to provide propulsion. The exoskeleton needed an interface with the patient's foot, or footwear, to secure the device while in use, and it was necessary to make the device easy to attach and remove. Additionally, the device required a method for sensing how much torque was being applied at the foot. The exoskeleton also required compliance with heel strike, to ensure that the exoskeleton was comfortable when walking.

2.2. Engineering Requirements

The team developed engineering requirements in order to establish the target values and ranges needed to satisfy the customer requirements. Table 1, below, outlines the primary engineering requirements.

Table 1: Engineering requirements

Engineering requirement	Target value/range
Scalable	5-30 degrees
Torque	10-15 Nm
Weight	< 0.25 kg per limb
Rotation	5 degrees

The device required scalability to accommodate a range of equinus severities, between 5 and 30 degrees (referring to the angle between the foot and the ground). The client required that 10-15 Nm of torque be applied to accomplish the assistive propulsive motion. The device needed to be as lightweight as possible, no more than 0.25 kg per limb (only accounting for the weight of the components attached to the feet or legs). Additionally, the device required 5 degrees of rotation about the ball of the foot to provide sufficient propulsive motion.

2.3. Testing Procedures

The exoskeleton should be tested on a benchtop. This should consist of two people, at minimum. One person should be controlling the mechanical device, and the other person should be operating the user interface. The person controlling the mechanical device needs to stimulate the sensors in a way that simulates how walking would occur. He or she should press the force sensor and then apply torque the plate to simulate walking. He or she should also not let the mechanical system go out of the operating range (unless testing the potentiometer stop). If the mechanical system goes outside of its operating range, 5 degrees below the standing level or 25 degrees above the standing level, the device should be set into zero-torque control. This essentially means that the device will stop trying to push the foot.

The person operating the user interface should confirm that the state machine is operating in a reasonable way. This essentially means that the state machine changes in accordance to the user controlling the mechanical systems actions. Once the person operating the user interface and the person controlling the mechanical system concur that the state of the state machine is acting in a behaved, predictable way, the motors should be enabled. The first test should be done while ensuring that the torque setpoints are zero, regardless of the state. The on switch should be quickly turned on and off to test stability. The user controlling the mechanical system should ensure that he or she has a firm grip on the system. If the system convulses, something is wrong. If the system seems stable, then the system is most likely working correctly. The person controlling the mechanical system can further confirm this by torquing the system; if the system is significantly easier to move, then the test is a success. Once this test has succeeded, the system should be hard reset. The user should disconnect the battery, wait 5 seconds, and reconnect the battery. For extra assurance, the MATLAB user interface can be closed and re-opened, though this is optional. Once the system has been reset, the user interface operator should provide a non-zero setpoint to the feet. The team then needs to continue stimulating the sensors; if the states of the state machine are reasonable, then the team can proceed. The on switch should be switched on, and the device should move forward; if a person was wearing the device, it should push on the heel of the person. If the device moves away from the heel, then the test fails. Once this test passes, the team can move on to tests where somebody is wearing the device.

The process for testing when a subject is wearing the device is essentially the same as for testing on the tabletop. The user wearing the device should walk and the user operating the interface should confirm that the states of the state machine are reasonable. If the states of the state machine are reasonable, then the motors can be activated. Careful attention should be paid to the state of the mechanical system to ensure that nothing breaks or is in danger of breaking. Either of the users should have their hand on the switch at all times in case something unforeseen happens.

In addition to testing the controls and overall function of the system, the engineering requirements will also be tested. Scalability of the device will be tested by measuring the angle that the foot plate can be adjusted using customizable parts. Torque will be tested by activating the motors and reading sensor data from the torque sensor at the foot. The weight of the system will be tested by weighing the final device on a scale. Lastly, rotation of the foot plate will be tested using a digital angle finder to measure the range of motion that the foot plate is able to move at the most restricted severity level.

2.4. House of Quality

After the customer requirements and engineering requirements were decided, they were integrated into a house of quality (QFD), shown in Appendix A. The customer requirements were placed on the left side of the QFD and the engineering requirements at the top center. The customer requirements were rated by the team relative to their importance. The highlighted cells indicate absolute requirements by the client. They may be rated at a lower importance since they may not relate to the management of equinus gait as heavily as other requirements. The relationships are weighted 1 through 9 (9 being the highest weight). The top portion relates engineering requirements. The bottom portion indicates the required range and the importance of the engineering requirements. It can be seen that the top three engineering requirements are to increase actuated ankle motion, to increase sensor accuracy, and to increase propulsion provided to the foot.

3. EXISTING DESIGNS

3.1. Design Research

During the preliminary stages of the project, research focused on medical background for equinus. The research established a clear understanding of the condition. Consulting a variety of medical journals and articles helped define the mechanics of equinus, a useful foundation for the eventual design of a device intended to help patients manage the disorder. Patients suffering from equinus tend to plantarflex (bend the foot downward) excessively and are unable to dorsiflex (bend the foot upward). The result is some degree of “toe-walking.” This causes unbalanced muscle development and severe wear on the forward areas of the foot, which are not intended to carry the weight of the entire body. If the ankle could bend sufficiently, weight could be redistributed towards the heel, and such problems could be avoided.

The focus of this project was equinus management, not treatment. Accordingly, research was directed at helping patients live with the condition, without trying to improve the condition. The prevailing medical opinions on managing equinus emphasize redistribution of weight away from the front of the feet. Ideally, a device employed to assist a patient would help restore balance when walking, would provide increased comfort, and would help to correct problems in gait. Orthopedic specialists and physical therapists employ combinations of orthotic devices and exoskeletal attachments to meet these requirements.

Further research indicated that current devices used to manage equinus vary in terms of mobility. Some orthotic and exoskeletal devices are static, locking the patient's ankles and feet into a fixed position, with the intent of restricting plantar flexion while forcing dorsiflexion. Other devices allow for some range of motion, so that a dynamic element (natural to walking) is still present. This may allow for some plantarflexion to remain, as long as the heel is taking more weight than the forefoot.

Even in devices that allow for adjustment or range of motion, motorization and propulsion are absent. A propulsive exoskeletal device could, theoretically, apply an assistive force to a patient's feet and ankles, making walking easier. A propulsive exoskeleton for equinus is an original concept, with limited technological basis in any current orthotic or exoskeletal equinus management devices. However, the components utilized by such a device (such as the motors, cables, sensors, and orthotic attachments) can be found in use elsewhere and were researched thoroughly.

3.2. System Level

Because the project aimed to create a device that did not yet exist, the team researched system level designs of exoskeletons and prostheses that represent design components relative to the project goals and requirements.

One exoskeleton design that was researched was US patent No. 8876123, an exoskeleton and foot attachment system. The exoskeleton has two over-the-foot straps that hold the top of the foot to the rigid base, a front strap to adjust the ankle cuff, and two back straps to secure the heel to the boot. The rigid ankle cuff provides support for the ankle, and the rigid base allows for the exoskeleton to be attached to sporting equipment. This over-the-foot exoskeleton is applicable to our design in that it provides a way to connect a device to any standard shoe type and is adjustable to accommodate different shoe and ankle sizes [1].

Another exoskeleton design that was researched was US patent 20160331557, which describes an ankle exoskeleton that assists in gait for users in different walking conditions. This patent describes, in detail, control algorithms and different types of sensors that can possibly be used. The patent stresses the need for two sensor types, force sensors and motion sensors. The sensors are used to determine which part of the gait cycle the user is in. This patent can serve as a resource for the electronics portion of the design. It can be used as a basis for developing the control algorithm, and also for a basic mechanical design [2].

A third exoskeleton design that was researched was the Berkeley Lower Extremity Exoskeleton (BLEEX). The BLEEX incorporates the degrees of freedom at the hip, one degree of freedom on the knee, and three degrees of freedom at the ankle. The patent describes how each of the components were designed in order to help augment the user's movements. This could help provide insight into an equinus exoskeleton device [3].

3.3. Functional Decomposition

The functional decomposition of this project returned simpler results than expected. The project begins with numerous deliverables and constraints but condensing all of the requirements into the basic physical functions of the product improved the team's understanding of the task. The black box model shown below (Figure 2) details inputs and outputs, while the functional model below (Figure 3) shows the process and the feedback loop controlling the product.

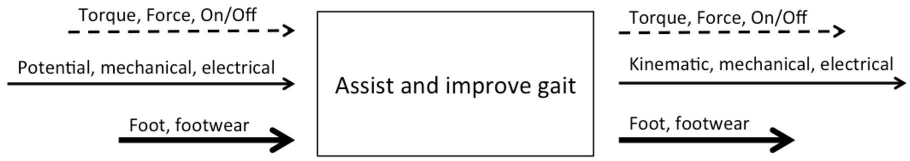

Figure 2: Black box model

The black box model focuses on the task of the product - provide support and gait assistance to the user. Given this simplified task, the team could focus on the minimum inputs and outputs in their most basic form. Each of these inputs contributed to developing systems and subsystems, as we were able to map out signals to movements. Further, the functional model provides the real-time function of the product. Timing is crucial to the success of the product, as the walking cycle must be measured for each user. The process of how information is generated and sent to the controller dictates speed and productivity.

When simplified, the product is a feedback loop - sensors provide information that the controller uses to know when to provide assistance to the user. The loop repeats multiple times during a single gait phase, even though the actual mechanical propulsion will only be provided once on each foot per cycle.

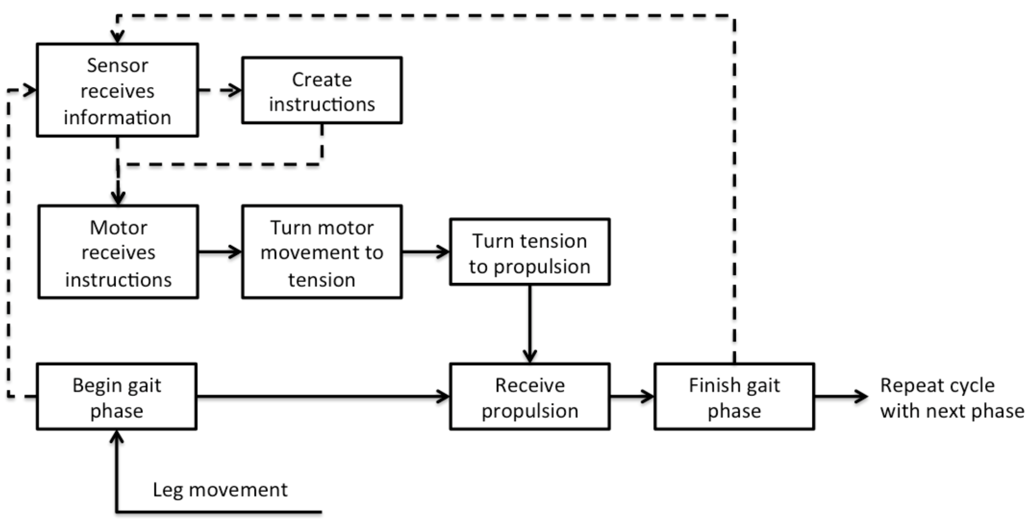

Figure 3: Functional model

3.4. Subsystem Level

Three major subsystems of this design are the mechanical aspects of the exoskeleton, the orthotics, and the electronics of the exoskeleton. The mechanical aspects of the exoskeleton include the propulsive device, the Bowden cable system, and the actuation method. The orthotics subsystem incorporates the interface between the device and the user, including the adjustable heel height and any method to provide added comfort. The electronics subsystem involves the sensors, the signaling processing system, and the control system.

3.4.1. Exoskeleton Subsystem

The primary goal of the device was to supply an assistive propulsive force to the user. This force needs to push the foot upward and forward. One example of a foot propulsion device is the BiOM prosthetic ankle. This prosthetic mimics the human muscle/tendon system to provide a propulsive force during walking by rotating the ankle joint [4].

One of the design constraints for this project required that the design must interface with a Bowden cable system. A Bowden cable is a cable within an outer cable housing. When the inner cable is tensioned, a force is applied to the other side of the cable. Kirby Witte has previously done work with an ankle exoskeleton device that incorporated Bowden cables to give propulsion to the ankle. The device had a range of motion of 30 degrees for plantar flexion and 20 degrees for dorsiflexion [5].

The Massachusetts Institute of Technology (MIT) created an ankle robot that is actuated through two brushless motors. Actuation is important, since it moves the device, which translates into an assistive force. Series elastic actuation is commonly used in lower extremity exoskeletons; it offers advantages such as greater shock tolerance, lower reflected inertia, and more accurate and stable force control [gatech]. MIT locates the motors near the hip and uses two linear screw actuators to provide forces at the ankles. The MIT design can be extrapolated for an equinus device [6].

Pneumatics have also been used as an actuation system. In 2011, Shorter published a paper showing the feasibility of pneumatic actuators in ankle exoskeletons. Shorter used liquidized carbon dioxide to provide the force. For pneumatic actuators, a pressure regulator would need to be included in order to control the pressure being released by the liquidized carbon dioxide. The design changes the direction of the torque using two valves (potentially controlled using Bowden cables, to meet our requirements) [7].

3.4.2. Orthotic Subsystem

Using stackable shoe insole orthotics is a common method for providing heel lift for equinus and other gait deformities. The heel inserts provide a way to increase the heel angle and offer a comfortable interface between a shoe and the wearer. Patent 5732481 illustrates this concept with a design of stackable heel lifts that progressively increase in hardness, with the top layer being softest to maximize user comfort [8].

Another form of heel lift is adjustable shoe heel height. An example of this type of design is Patent 3464126. The shoe heel is hinged to the toe portion of the shoe, while a support member rests on the ground. The hinge is held in place by a lock that holds the heel at different positions relative to the support member. The heel is adjusted by freeing the locking mechanism and adjusting its angle about the hinge [9].

Besides providing heel lift and comfort to the user, the orthotics need to provide a way to attach mechanical components and be stiff enough to transmit force. For equinus deformity, ankle foot orthotics (AFO) are the most commonly used form of orthotics. The orthotics are worn inside the shoe and are secured to the leg by Velcro straps. The purpose of these orthotics is to provide support or resistance to the leg. While this was not a required function for our device, it offers a way to attach components to the body and provide additional support to the ankle [10].

3.4.3. Electrical Subsystem

In order to actuate the ankle sufficiently and still have a human in the loop control, different sensors are required to determine the user's intent of motion. Zhang describes two different types of sensors - force sensors and position sensors. The force sensors are used to indicate what part of the gait cycle the user is in. The position sensors tell the device what positions the legs are in. Combining the information received from both of these sensors, the controller implemented within the device can determine which phase of gait the user is in [11].

Aleksandr Sergeyv describes an exoskeleton system that uses an electromyographic (EMG) sensor. This EMG sensor senses the electrical inputs directly from the muscles, as opposed to sensing the secondary movement caused by the muscles. The signal from the EMG is extremely small, and thus requires amplification for the microcontroller to be able to interpret what the muscles are doing. A similar method could potentially be applied to the torque sensor required for the equinus device, to ensure that the microcontroller reads the torque sensor's output correctly [12].

4. DESIGNS CONSIDERED

Using the research, the team generated design concepts for each of the major subsystems of the exoskeleton device. These concepts included various ideas for propulsion systems, actuation systems, methods for heel lift, orthotics, and sensors. Design concepts are shown in Appendix B.

These combined subsystem designs formed the basis for complete designs. The team considered multiple exoskeleton designs, created around different propulsion systems. Designs were evaluated based on how they met the customer and engineering requirements.

To meet customer requirements, the devices considered should utilize a Bowden cable system to provide propulsive force; any propulsion provided should be driven by the cables. The designs should also interface with footwear, and they should be easy to take off and put on. When the device is attached to a patient, it should fit over the foot (or shoe) and should have a simple method of attachment and removal. The designs should be able to measure torque; when the required torque is transmitted to the ball of the foot, there should be a method to read how much is applied. Additionally, the designs should be compliant with heel strike. When the foot (with the exoskeleton attached) makes contact with the ground, no discomfort should be felt.

To meet engineering requirements, the designs considered should provide 10-15 Nm of torque. When the motors engage and tension the Bowden cables, rotation should be induced at the ball of the foot. allow for adjustability for equinus severity. The designs should also allow for adjustability for a range of equinus (between 5 and 30 degrees); therefore, the devices should provide a means for adjusting the angle of the structural components under the heel. The designs should provide rotation. When torque is applied, the devices should be able to rotate freely 5 degrees. Additionally, the designs should reduce weight where possible, to keep the weight per limb below 0.25 kg. To accomplish this, the designs should use lightweight materials or reduce the amount of material being used.

The following figures show the four primary design concepts considered.

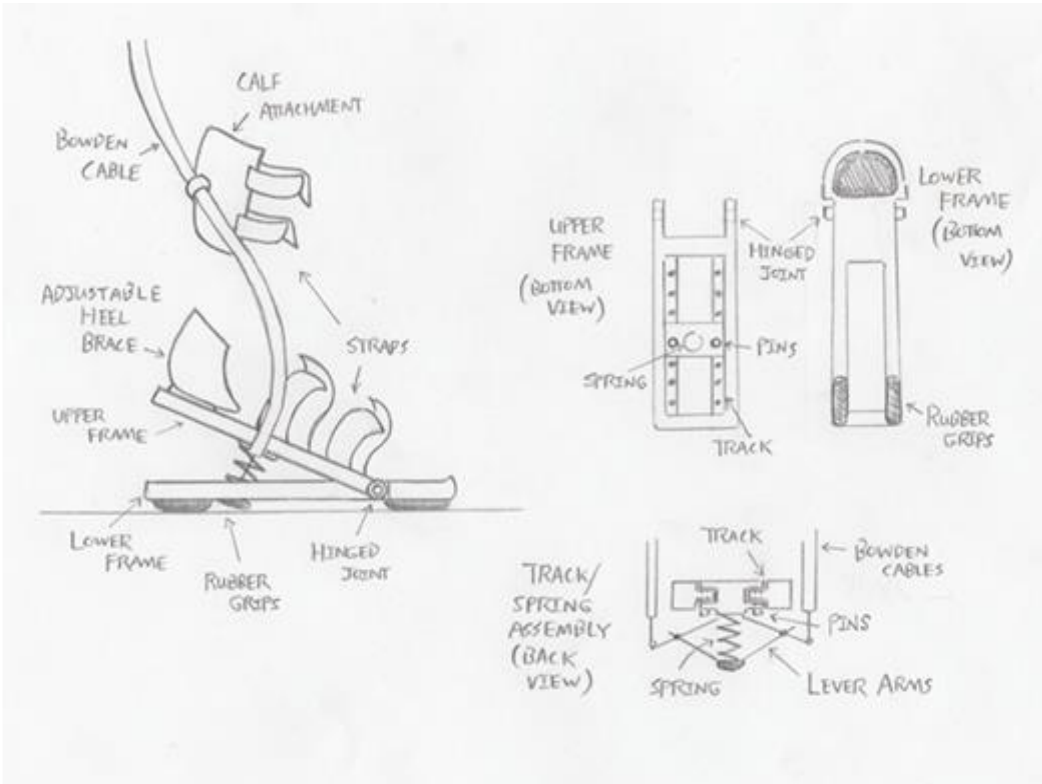

Figure 4: Spring propulsion design

The design in Figure 4 provides an assistive propulsive force using a spring attached to the bottom of the foot. Attached to the spring are lever arms, the outer ends of which connect to the Bowden cables. When the motors (which attach at the waist) engage, the cables are tensioned, and the spring compresses. The cables are then released, and the spring recovers to its free length, thus supplying a force to the ground, and propelling the foot forward. The exoskeleton device consists of an upper frame, which features a track along which the spring assembly can be positioned, and a lower frame, which provides support at the toe. The upper plate is hinged to the lower plate at the ball of the foot. Analysis of this system proved that the design was not feasible (due to the required spring sizes), and the design was therefore discarded.

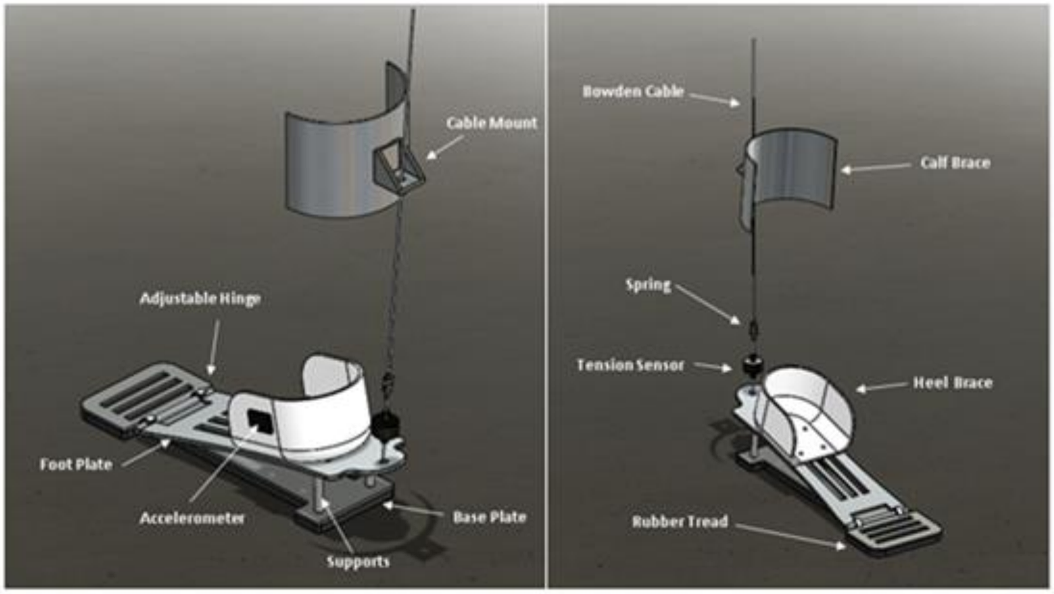

Figure 5: Direct-pull propulsion design

This design in Figure 5 provides propulsion directly at the heel. The Bowden cables, powered by motors at the waist, provide a tensile force at the rear of the foot plate. The foot plate is hinged to the base plate, allowing the foot plate to rotate. The cables are mounted to a calf attachment. An adjustable heel brace and adjustable supports at the rear of the base plate provide scalability for a range of equinus deformities. This design ultimately proved unable to provide rotation, and as a result could not provide propulsion.

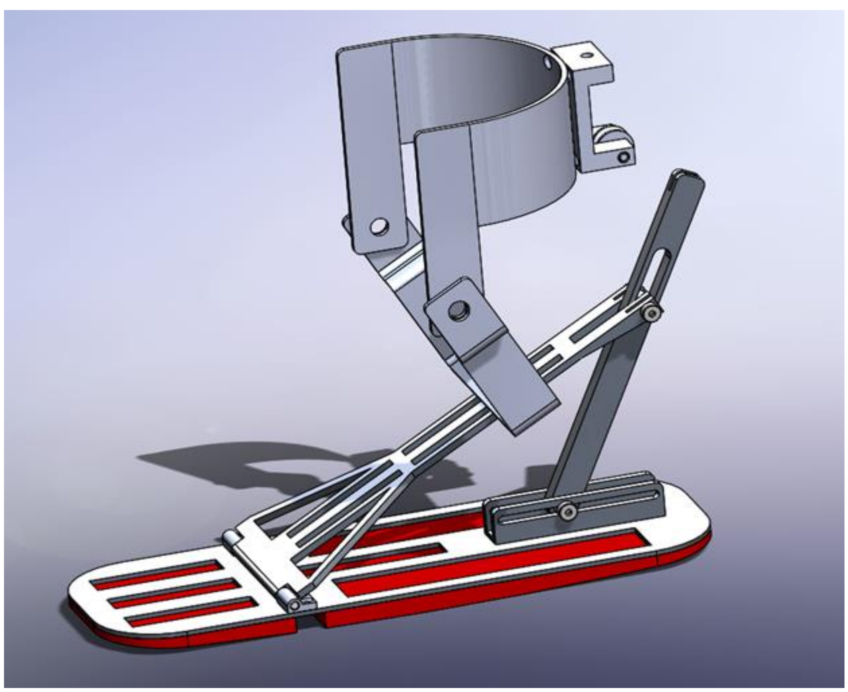
Figure 6: Lever arm propulsion design

The design in Figure 6 provides propulsion through an adjustable lever arm at the heel. The lower end of the lever arm hinges to a track along the rear of the base plate (the track provides adjustability for the lever arm). A slot in the lever arm is pinned to the rear of the foot plate. The upper end of the lever arm attaches to a Bowden cable. When the motors (attached at the waist) engage, the cables are tensioned, pulling the upper end of the lever arm upward and forward. The arm rotates about its lower end (pinned to the track on the base plate), and the arm pushes the foot plate upwards, thus providing propulsive force to the foot. The foot plate is hinged to the base plate at the ball of the foot, allowing for rotation. An adjustable U-bracket attaches to the foot plate and connects to a calf attachment. At the rear of the calf attachment is a mount for the cable, which features a pulley (to allow for the cable to attach perpendicularly to the lever arm). This design, while it provided the necessary motion, contained significant frictional losses.

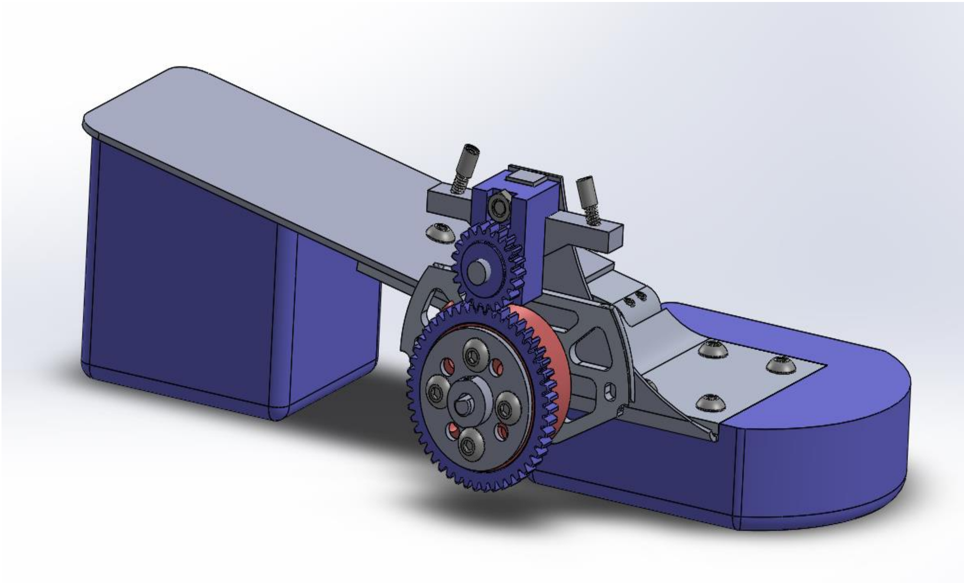

Figure 7: Pulley propulsion design

The team incorporated elements of the previous designs into the final design considered (shown in Figure 7). This design converts force from the Bowden cables (driven by motors at the waist) into torque at the ball of the foot. The Bowden cables rotate a pulley, which transmits torque through a shaft to a hinge. The forward section of the hinge attaches to a 3D-printed toe support and an L-bracket, which secures a T-bracket above the pulley. The T-bracket provides a mount for the Bowden cables, and it provides a mechanical stop for the pulley. The rear section of the hinge connects to a foot plate. At the rear of the foot plate is a 3D-printed heel support. A torque sensor and a potentiometer are mounted to the shaft and to the L-bracket, respectively.

5. DESIGN SELECTED

5.1. Rationale for Design Selected

The final design selected was the pulley propulsion design. This design incorporated multiple elements from the other designs considered, including a rotating foot plate, an adjustable heel attachment, Velcro straps, and the use of a pulley at the foot. The design consisted of a motor assembly, attached at the waist, connected through Bowden cables to exoskeletons on each foot. The exoskeleton on each foot consisted of a hinged foot plate (with a heel support at its rear) connected to a toe support, with a drive assembly (consisting of a pulley, torque sensor, potentiometer, and sensor attachments) connected at the ball of the foot. Velcro straps allowed for the device to be worn.

The design satisfied customer requirements. The torque sensor provided a means for measuring the applied torque, and the Velcro straps allowed for both an interface with footwear and for the device to be easily put on and taken off. Compliance with heel strike was accomplished through attaching the foot exoskeletons to footwear (the patient would wear the device over the shoe, making the device more comfortable to wear).

The design also satisfied engineering requirements. The design allowed for 5 degrees of rotation, before the pulley makes contact with the mechanical stop built into the T-bracket (this also provided a safety measure, ensuring that the device did not over-rotate and injure the foot). The device provided the required torque to the foot. The motors, capable of a 6.7 Nm output at the motor shafts, were able to provide at least 15 Nm (the target value) of torque at the ball of the foot. This was due to the 3:1 ratio of the diameter of the primary pulley (at the ball of the foot) to the diameter of the motor pulley on the motor shaft. The 3D-printed heel, printed for each individual, was able to provide the necessary adjustability. Based on the geometry of the device and the equinus severity of the patient, the heel support could be printed so that the necessary angle (between 5 and 30 degrees) is achieved. The toe supports and heel supports, made from 3D-printed plastic, and the majority of the mechanical components (as well as the hinges and foot plates), made from aluminum, reduced weight in order to meet the original weight requirement (no more than 0.25 kg per limb).

5.2. Design Description

5.2.1. Electrical Subsystem

A teensy 3.6 microcontroller was selected as the means for controlling the entire electrical subsystem. This microcontroller was selected as it had two built-in digital-to -analog converters (DAC) as output pins and could be easily incorporated into printed circuit board (PCB) designs. It is important to have two DACs because we are running two motor driver boards, which correspond to motor driver boards for the left and right ankles. The motor driver boards each require true analog inputs, and a pulse width modulation (PWM) wave would not suffice. Another advantage for using a teensy 3.6 is that the board could be programmed using the Arduino internal development environment (IDE). The teensy 3.6 is responsible for taking in sensor inputs, such as the torque sensor, force sensitive resistor (FSR), and potentiometer (POT).

The torque sensors have a relatively small output voltage, 2 mV/V. This required the inclusion of an amplifier. The range of output voltages available are 0 V to 6.6 mV. This range is too small to be of any use without an amplifier. The amplifier that was chosen was a INA125P. This is an instrumentation amplifier that has very low power loss and could set the voltage range to a level in which it could be easily picked up by the microcontroller. The gain was chosen to be 304 in order to bring the range of output voltages to 0 V to 3.25 V, which is less than the maximum voltage of our teensy (3.3 V). At 3.25 V the sensor is experiencing a torque of 500 inch-pounds, and at 0 V the sensor is experiencing a torque of -500 inch-pounds.

The FSRs have a range of resistances that vary from approximately 300 Ω to 100 kΩ. The FSRs have a range of forces from 11 g to 10 kg. The larger the force on the resistor, the smaller resistance. The FSRs were put into a voltage divider configuration with other, static, resistors. The static resistors were chosen to be relatively low. This was rationalized as the point of the FSRs were not to measure the actual force on the ground, but to determine whether or not there was any force. It is apparent if the foot is on the ground, but not how much force, which was sufficient for the team's purposes. The team placed the FSRs on the toes of the individuals, as the state machine produced better results in this case.

The primary purpose of the POTs was to measure if the mechanical system was over-rotating and needed to be stopped. The potentiometer circuit is, straightforwardly, 3.3 V on one pin, signal to the center-tap pin, and ground to the other pin. The POTs also enable the team to quantify how much rotation is achieved.

5.2.2. Control Subsystem

The device uses a timing control system. A finite state machine is used as a roadmap to determine the basic intent of the user. The system uses the force sensor to identify the heel strike within the whole gait cycle. Once heel strike has been identified, the system initiates a counter, which is used to determine the amount of time between heel strike events. The time between heel strike events is averaged. This average value is then used, in parallel with sensor inputs, to determine when to provide the assistive force. The device waits until heel strike happens, then waits 40% of the average cycle. Once 40% of the average cycle time has passed, the device checks if the footplate is being torqued. If the footplate is being torqued, it is indicative that the user is attempting to move forward. If both of these conditions are met, the assistive force is given. The system then waits for 15% of the average cycle time. Once 15% of the average cycle time has passed since the assistive phase began, the system will then enter into the swing phase. During the swing phase, the system checks several parameters before being able to enter the stance phase again. First, the system checks if the foot has actually come off the floor. This is to ensure that the user is not just standing still. If this is the case, the system then checks if the floor has come back down to the ground. The system then checks if 500 ms has passed since the last time the user has been in the stance phase. This is to ensure that the system does not accept an obviously false positive.

5.2.3. Mechanical Subsystem

The mechanical system (incorporating the orthotic and exoskeleton subsystems) is driven by motors at the patient's waist. The motors are mounted to a plate with the battery and the control boards. The motor assembly is shown in Figure 8, below.

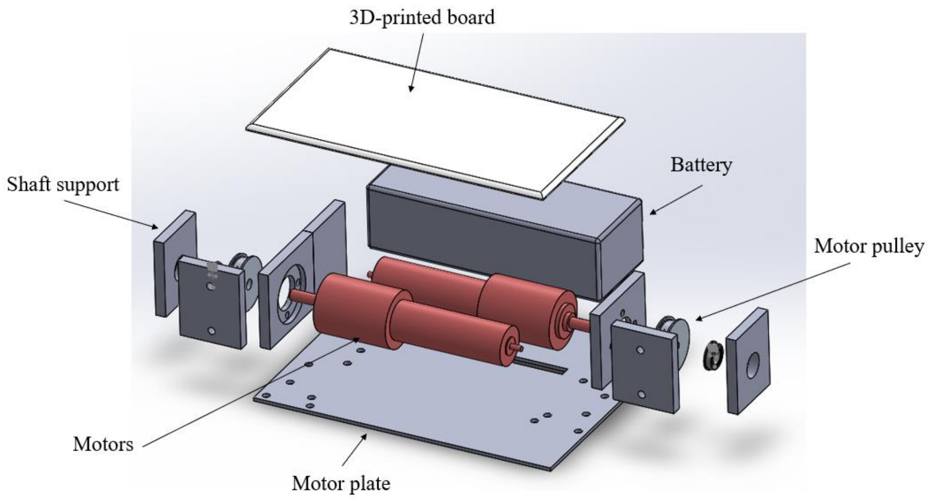

Figure 8: Motor assembly, exploded

Brackets, bolted to the motor plate, secure the motors. A motor pulley fits over each motor shaft and is secured using a setscrew. The ends of the Bowden cables are secured to each motor pulley. Bearings fit over the outer ends of the motor shafts, so that shaft supports can then fit over the ends of the shafts. The shaft supports are bolted to the motor plate. A bracket bolts onto the motor plate beneath each motor pulley; the Bowden cable sheaths are secured at the holes in these brackets. The battery attaches to the top of the motor plate, secured with Velcro straps (which pass through the slots in the plate). A 3D-printed board sits over the motors, and the electrical control boards attach to the 3D-printed board. The Bowden cables extend down the length of each leg and attach to the foot exoskeletons on each foot.

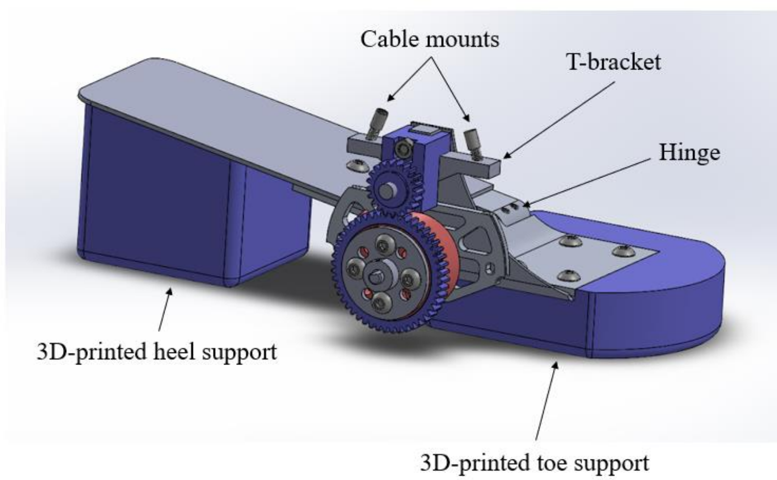

Figure 9: Foot assembly

Figure 9 shows the foot exoskeleton assembly. A 3D-printed toe support attaches at the forward section of the hinge, and a 3D-printed heel support attaches beneath the rear of the foot plate (connected to the rear section of the hinge). The Bowden cables connect to the cable mounts on the T-bracket. The cables then pass through the T-bracket and attach to the pulley.

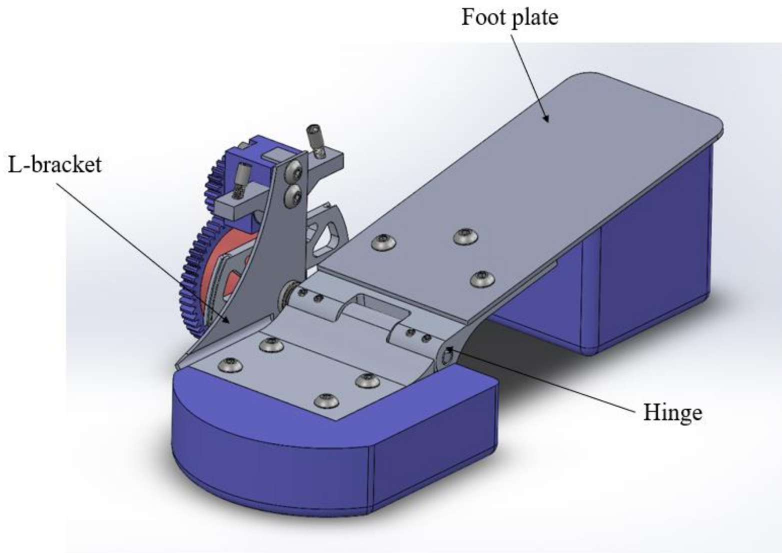

Figure 10: Foot assembly

In Figure 10, it can be seen that the T-bracket attaches to an L-bracket, secured to the forward section of the hinge (the flange of the L-bracket sits between the hinge and the toe support). A shaft passes through the hinge and is secured to the rear section of the hinge (the section of the hinge fixed to the foot plate) using four setscrews. The shaft passes through the L-bracket, the pulley, the torque sensor, and the torque sensor attachment.

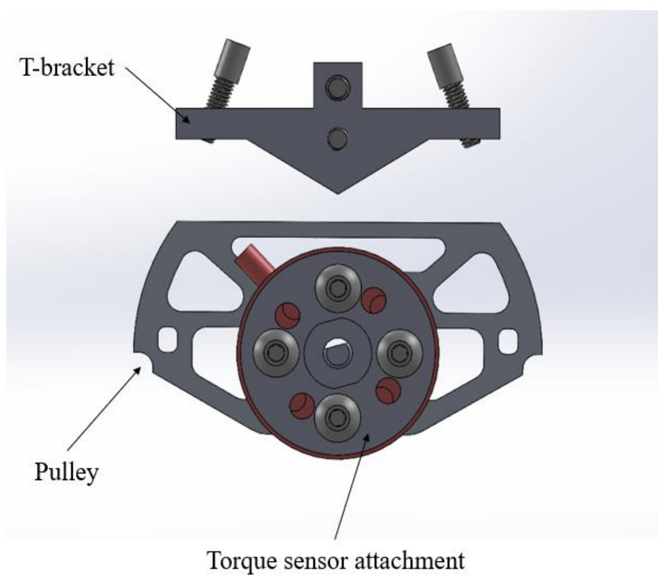

Figure 11: Pulley and T-bracket

Figure 11 provides a frontal view of the drive assembly, consisting of the T-bracket, pulley, torque sensor, and torque sensor attachment. The pulley secures to the torque sensor and the torque sensor attachment. The torque sensor attachment features multiple hole patterns, allowing for adjustment based on the required initial pulley alignment (this depends on the equinus angle). A setscrew secures the torque sensor attachment to the shaft, allowing the pulley to transmit torque to the shaft, and thus to the hinge. The T-bracket features a V-shaped mechanical stop, to prevent the pulley from rotating too far (potentially harming the patient or damaging the motors).

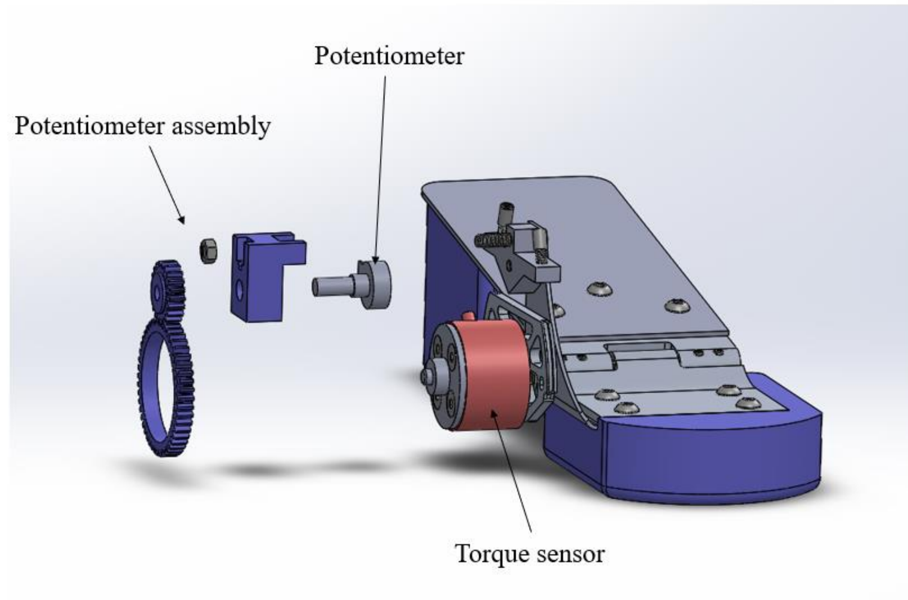

Figure 12: Potentiometer assembly, exploded

Figure 12 shows an exploded view of the potentiometer assembly. The potentiometer rests in a 3D-printed housing, which in turn mounts to the T-bracket (thus holding the potentiometer secure). A gear system allows the potentiometer shaft to read motion transmitted from the shaft. Not pictured in these figures are the Velcro straps (secured to the foot plate and toe support) used to secure the foot to the exoskeleton.

Appendix C contains dimensioned drawings for various components of the design, including the hinges, the torque sensor attachment, the L-bracket, the T-bracket, the motor pulley, the motor, cable, and support brackets, and the motor plate.

6. PROPOSED DESIGN

A bill of materials and complete task schedule helped guide the project. Table 2 shows the project schedule, detailing key tasks for the project. Parts listed in the bill of materials were ordered beginning in mid-January. The mechanical components of the design were intended to be built and assembled by the end of February. The team intended to build a fully operational exoskeleton device by the end of April. With the completed product, potential clinical trials on patients could be conducted. This would provide information on the patient's response to wearing and using the device. It would also indicate any required adjustments and determine if the design functioned as expected.

Table 2: Project schedule

Due Date	Course Assignment	Key Tasks
12/4/2017	Prototype, BOM, CAD package	● Working prototype
12/11/2017	Final proposal revision	
1/30/2018	N/A	● All materials obtained
2/28/2018	N/A	● Mechanically functioning device
3/15/2018	N/A	● Finite element analysis (FEA)
3/30/2018	N/A	● Fully functioning device
4/30/2018	Final BOM, CAD package	● Possible clinical trial
5/4/2018	Final report	

A complete bill of materials is given in Appendix D, listing each part, a description of the part, the material used to construct it, and the cost. These were the requirements for a single exoskeleton, for one leg. In the bill of materials, it can be seen that the highest expenses were in machined parts and control components (such as the PCBs and motors). A total budget of $3000 was provided for the project ($2000 from W.L. Gore, $1000 from the NAU Biomechatronics Lab). The amount spent on this project was $1,992. This price included prototyping and materials for the final product. Machining cost was not accounted for in the amount spent, since all parts were built in-house (at the NAU Engineering Fabrication Shop). The bill of materials, however, does take into account machining costs based on the Fabrication Shop rates ($50 per hour of service).

7. IMPLEMENTATION

7.1. Manufacturing

7.1.1. Primary Manufacturing

Due to the size and weight constraints given in this project, custom manufacturing was required to build the exoskeleton. All custom parts at the core propulsion assembly at the foot were CNC machined parts. The hinge pieces, foot pulley, T-Bracket, L-Bracket, and torque sensor attachment (TSA) were machined on a CNC out of 6061 Aluminum stock.

The hinge pieces each required 3 steps of manufacturing: initial curve of joint, drilling holes, and thinning the part. In order to save weight but remain structurally sound, the hinge had a 14mm diameter at the joint, and was brought down to a 3mm thickness where the foot plate is attached.

Initial hinge cutouts were made to a square of 14mm thick stock, before a ball endmill was used to mill a curve to the joint of the hinge. The hole for the hinge as well as the setscrew holes on the foot portion of the hinge were made in a manual mill, for more precise hole placement. After the holes were made, the piece was then milled out to the 3mm thickness in the CNC. The hole pattern was then drilled, either on the CNC or in a drill press.

The foot pulley has a complex shape, designed specifically to hold the cable ends, avoid the floor when actuated, and be as lightweight as possible. The piece was milled out of 4mm aluminum stock using an ⅛” flat endmill. After cutouts, initial pulleys used a 4th axis system to mill the groove on the side of the pulley for the cable to sit in. These pulleys also used an ⅛” ball endmill, which could not provide a groove deep enough, and the cable would slip out. To make the groove deeper, a 1/16” ball endmill was used. In addition, due to the flat on the pulley, the stock could be squared in a vice, negating the need for a 4th axis, expediting both the coding process and machine run time. For all subsequent pulleys the groove was machined using a 3-axis toolpath.

After incorporating the mechanical stop, the t-bracket was no longer in a T shape. The point on the end made the piece difficult to hold on a manual mill, and thus was made using a CNC. Due to the tapped hole placement, the front holes were drilled and tapped before the profile was cut out. The holes were then drilled and tapped manually on a mill with angle gauges. The angled holes are crucial to the cable placement to avoid both friction and cable failure in the system the holes have to align with the foot pulley, and thus have a tight tolerance.

The L-bracket is a sheet metal part milled out of 16 gauge sheet metal aluminum. All holes were circle-milled and the contour milled out with a 5/32” endmill on the CNC. After the contour was cut out, the tab on the bottom was bent to fit the toe portion of the hinge.

The TSA was milled to thickness from 8mm stock, leaving the center hub with two flats parallel to each other for drilling the pinning hole. After facing, all holes on the front of the piece are circle-milled out with a 5/32” endmill. The piece is then drilled for the pinning hole on a manual mill.

The motor pulley was also made by the shop and was turned down out of aluminum round stock on lathes in the shop. The groove and hub were turned down on the lathe, and the holes and set screw holes were milled out and tapped on a manual mill.

While all motor brackets were mostly machined manually, some of the holes were circlemilled on the CNC to provide a more accurate circle, rather than drilling. These parts were completed by the NAU machine shop, rather than a team member. All other parts mentioned were made by a member of the team. This significantly reduced the manufacturing costs of the parts. Using the price of work at NAU's machine shop, $50/hour, if the parts were made by an outside machine shop, estimated costs for one foot come to $850. This cost estimate does not include generating G-code, and setup and clean-up time, and these would incur additional expenses.

All CNC pieces were machined on Tormach 770 machines at the NAU machine shop. All G-code was written using MasterCAM for SolidWorks. All endmills, drills, taps, and other tools were provided by the machine shop, with the exception of the ⅛" and 1/16" ball endmills, which are less commonly used, and had to be purchased to machine the pulley grooves.

7.1.2. 3-D Printed and Customizable Parts

Several structural and non-structural components were manufactured by 3-D printing, a time-efficient method for creating lightweight parts that are difficult or time-consuming to make with subtractive manufacturing. The potentiometer mount and gear mesh are non-structural components that require minimal torque transfer and could be 3-D printed largely to save time and weight. In addition, the parts can be printed for a slip fit, sufficient for their purpose, and easier to apply than if there were additional fasteners.

The structural supports at the heel and toe are printed for customizability. When a different equinus angle is desired, the SolidWorks file can be edited by changing one dimension, and then printed for a new patient. For two heel and two toe supports, printing time is 12 hours. In addition, for different shoe sizes, the sheet aluminum plate that attaches the heel support to the hinge can be shortened or lengthened depending on the patient. This plate is cut out of sheet metal on a bandsaw, then drilled to match the hole pattern on the hinge. The heel is epoxied to the plate, and the toe support is attached to the hinge with M5 bolts.

7.1.3. Timeline

Initial scheduling required a complete prototype by February 28th, 2018. However, a design change at the beginning of this semester pushed that date back until the redesign could be completed. The final deadline was April 20th for completion of manufacturing. Tasks were assigned according to priority on a weekly basis.

The parts in Table 3 are listed in order of manufacturing priority for assembly of the exoskeleton. Initial allowances in time needed are listed, along with the stock required. The time needed is for one part and includes developing and generating G-code. Because the parts for the motor pack were completed by the shop, which requires a 2-week lead time on work orders, the expected time for each of those parts was 2 weeks. The final time is listed for all parts made by the team, rounded to the nearest hour, for cost estimates.

Table 3: Part stock and construction time

Part	Stock	Allotted Time	Final Time
Foot assembly parts			
Toe hinge	14mm Aluminum	1 week	4 hours
Foot hinge	14mm Aluminum	1 week	4 hours
Foot pulley	4mm Aluminum	2 days	3 hours
TSA	8mm Aluminum	1 day	1 hours
T-bracket	10mm Aluminum	3 days	3 hours
L-bracket	16 gauge Aluminum	1 day	1 hour
Foot plate	16 gauge Aluminum	1 hour	1 hour
Heel and toe support	ABS printer filament	6 hours	6 hours
Potentiometer system	ABS printer filament	1 hour	1 hour
Motor pack assembly parts			
Motor plate	16 gauge Aluminum	2 weeks	N/A
Support bracket	4mm Aluminum	2 weeks	N/A
Motor bracket	4mm Aluminum	2 weeks	N/A
Cable bracket	4mm Aluminum	2 weeks	N/A
Motor control board	PLA 3D Filament	2 days	N/A
Motor pulley	1” round Aluminum	2 weeks	N/A

Table 4 lists the total required stock for two exoskeletons. All material was purchased from McMaster-Carr. The prices listed are for the stock required to make two new exoskeletons and one motor plate, rounded up to the nearest size on McMaster-Carr.

Table 4: Part size and cost

Thickness	Stock dimension	Actual size	Cost
14mm Aluminum	150mm x 150mm	⅝" x 3" x 12"	$15.62
10mm Aluminum	100mm x 70mm	⅜" x 2" x 12"	$7.00
8mm Aluminum	100mm x 50mm	8mm x 40mm x 3'	$18.54
4mm Aluminum	150mm x 100mm	4mm x 40mm x 1'	$4.22
16 gauge Aluminum	600mm x 200mm	1/16" x 3" x 3'	$6.99

7.2. Design Changes

7.2.1. Manufacturing Timeline

As the team became more familiar with the manufacturing processes required, the manufacturing time was decreased significantly. Manufacturing the hinge pieces initially took one week for one set, and after making a few iterations, it took only 4 hours to manufacture one part, and two hinges could be made in 3 days. While manufacturing time was decreased, the timeline was not moved forward due to several issues that became apparent during assembly.

All manufacturing was completed on a prototype of the final design for one foot by March 15th. All manufacturing for 2 complete, final foot assemblies was completed by April 16th. This exoskeleton was used for controls testing as well as verifying the mechanical system to determine if any changes were necessary. All changes that were made are discussed in section 7.2.2.

7.2.2. Setbacks and Solutions

Hole tolerancing was initially done incorrectly and working with standard shafts altered the tolerancing process. An initial hinge caused a system failure because the hole in the hinge was too large and cause a slip around a setscrew. The hinge had to be remade with new tolerances before any further testing could occur.

Initial designs for the T- and L-bracket were geometrically sound but proved to have issues with bending, and required a redesign of the pulley system, including the T- and L-bracket and pulley. The resulting system is lighter, more compact, and was able to include the mechanical stop, a new addition at this point. The bottom of the pulley is angled away from the floor, to avoid interference issues, and the initial cable angle is inclined to bring the t-bracket closer to the shaft. In addition, the CNC could cut out an accurate curve in the L-bracket that could support the tension between the T-bracket and the pulley better.

The redesign of the pulley system allowed for a redesign in cable attachment. The initial pulleys that are currently being used by the Biomechatronics lab use setscrews to hold the cables in place on the foot pulley. However, there are very few threads and the threading is not very strong. The new pulley uses a through hole, where on the other side the cable can be clamped separately by cable anchor bolts. This secures the cable and allows for proper tensioning of the cable system.

Bringing the T-bracket so close to the pulley raised interference issues, so rather than treat it as a problem that needed a solution, the compactness of the system was repurposed to include a safety feature that would otherwise be added somewhere along the hinge, and removed it from the foot interface. The triangular stop is designed to prevent the hinge from rotating past 30 degrees from a 0 degree equinus angle.

After system assembly, the shaft could not rest at an equinus angle greater than 10 degrees, due to the mechanical stop in combination with the limiting angles of the hinge. The initial equinus angle was parallel to the flat on the D-shaft, which put that flat in parallel to the equinus angle, as well as the flat on the pulley. This was solved by creating a new torque sensor attachment, which has two offset hole patterns, at 5 degrees and 40 degrees. Both of the hole patterns have a range of equinus angle that can be serviced, with a corresponding range of motion. Between the two patterns, this exoskeleton can accommodate an equinus angle up to 35 degrees, in addition to the required 5 degrees of actuation.

Initially, due to space constraints, the TSA used a single M4 setscrew to transfer the torque from the motors to the shaft at the joint of the foot. However, setscrews are not reliable with D-shafts in high-torque applications, resulting in shifting in the system at the foot. This wore down the shaft, and very soon after assembly, the TSA could not reliably transfer the torque due to the setscrew slipping over the shaft. The TSA was then remade for a pin rather than a setscrew, and the TSA was pinned to the shaft, thus removing the shift in the system. The pinned shaft does not interfere with adjustment according to the equinus angle; the entire system can be adjusted while assembled by removing the bolts that attach the TSA to the torque sensor.

The potentiometer was initially connected to the shaft via a belt system. However, the tension required by the belt induced bending in the system, misaligning the cables from the T-bracket to the pulley. This system was then changed to a gear mesh, which actuates the potentiometer as intended, as well as supports the system to help prevent bending. The potentiometer mount does have potential to interfere with the torque sensor cable, however, as long as the torque sensor is in the right position in relation to the hole pattern on the pulley, the issue can be avoided.

Due to the fact that testing was conducted on adults, but the system was initially designed for a child, there were issues keeping the foot on the device. The primary problem was that the toe support was too small to hold the user’s shoe. The toe support was then redesigned to be wider and longer according to shoe size, which can again be printed and resized according to different patients.

7.2.3. Future Improvements

Torque transfer proved to be the biggest setback in the prototyping process. While the motors are capable of providing the torque needed, the only torque transfer from the motors to the shaft is the pin at the TSA. Beyond that, the hinge needs to move with the shaft, and 4 M4 setscrews are used to transfer the torque from the shaft to the hinge. Similar to the issues with the setscrew on the TSA, there can be some slippage in the shaft at those points. The team recommends pinning the hinge to the shaft in the future. This would increase assembly time, and make any adjustments difficult after the system is assembled, but would create a more stable system that did not require Locktite or other methods to secure the hinge.

The foot assembly did not meet the given weight requirement. While the machined parts were made to cut out as much weight as possible, there are areas where cutouts can be made to lighten the system. However, before such cutouts are made, it is advisable to conduct a stress analysis on the remaining material. Neglecting sensors, the hinge is the heaviest component in the assembly. The joint of the hinge could be cut out in sections to have only supports for the bearings and where the shaft would be pinned. In addition, the thinned flat of the hinge could have cutouts where the hole pattern was not present. A primary FEA analysis of the pulley gave a safety factor of 5, indicating that material could also be cut out of the system. The next component is the T-bracket, which is a solid piece, and could have material removed in the mechanical stop. It could also be thinned at the center of the part, away from the barrel adjuster holes.

The system was built as a prototype for testing on adults, and therefore is larger than the system would be for a child. In the future, when building the system for a child, the hinge could be shortened along the length of the joint, and possibly along the thinned flat. The infill on the 3-D printed heel and toe support could also be altered to reduce weight.

During testing, when the foot was improperly positioned on the toe support, the weight at the heel could be towards the front of the heel support, sometimes causing flexing in the foot plate. For future manufacturing, the recommendation is to make and position the foot plate so it sits under the heel for each patient, or alternatively print a heel support that extends farther along the foot plate. An improved velcro strapping system would also be beneficial to the interface.

In addition, the current control scheme can be improved by applying electromyography control scheme, incorporating a reaction torque control scheme, and creating a feed-forward feature.

8. TESTING

The team tested the system to ensure that it met each of the engineering requirements. Most of the requirements met or exceeded the target values given by the client, with the exception of the weight requirement. See Table 5 for a summary of the testing results.

Table 5: Testing results

Engineering requirement	Target value/range	Satisfied	Achieved Value
Scalable	5-30 degrees	Yes	0-35 degrees
Torque	10-15 Nm	Yes	15 Nm
Weight	< 0.25 kg per limb	No	0.6 kg per limb
Rotation	5 degrees	Yes	5-15 degrees

Scalability of the foot exoskeleton was tested by assembling the system, ensuring that the foot plate could rotate from 5-30 degrees without limiting the pulley rotation, and ensuring that the 3D printed heel could be made to hold the plate at that angle. The heel support was designed in SolidWorks to be adjustable for any angle between 0 and 35 degrees and was tested for strength by material analysis and direct loading. The team stress-tested the heel component by printing the heel support then stomping on it from all directions to ensure that it would not break.

Torque was tested by connecting the foot assembly to the motors and adjusting the torque through the control GUI from 0-15 Nm. The torque sensor at the hinge of the foot gave signal feedback about the amount of torque provided to the joint during motor activation. The motors were found to be capable of providing more than 20 Nm of torque at the hinge. However, the team also discovered that it is better to not exceed 15 Nm in the system, as anything above that value endangers the motor shafts and gearboxes. During testing with the motors to optimize the controls, the motors exceeded 20 Nm of torque at the foot, which resulted in a mechanical failure of the motor pulley and subsequent grooving of the motor shaft by the set screw.

Weight of the final system was assessed by weighing the foot assemblies on a digital scale. The requirement for weight was that each foot assembly would weigh less the 0.25 kg. The foot assemblies in our system weighed 0.6 kg each, which is more than double the target value. While this was an issue, it should be noted that the original requirements for the system were for a child between 5-12 years old, whereas our system was customized for an adult. For this reason, it is anticipated that the foot assemblies made for children would be smaller and much closer to the target weight. Although not part of the project requirements, the team also measured the weight of the cables and motor assembly. The cables for both legs weighed 0.2 kg, and the full motor assembly weighed 1.9 kg. In total, the complete system weighed 3.3 kg, largely due to the battery and motors used.

The rotation of the foot was assessed by inspecting the angle of rotation of the foot plate in relation to the toe using a digital angle finder. During initial testing, the team discovered that the system could not achieve the target rotation of 5 degrees at higher heel heights since the system was limited by the foot pulley and T-bracket which was addressed by redesigning the TSA. Testing of the angle with the new attachment showed that the foot plate could rotate up to 5 degrees at the most limited orientation of the pulley and up to 15 degrees at the pulley's optimum position.

In addition to testing the engineering requirements discussed above, the team also tested the control of the system during actuation. The controls were tested on a benchtop and by providing the user with a specified amount of torque in the timed control during steady-speed walking. Results were observed by watching/feeling how the timing controls activated during each step and assessing whether they were providing consistently timed torque at the right time during each step (i.e., did the system activate during the propulsive phase of each step). The team encountered errors during this testing as the timing method did not work consistently and would often skip steps or activate at wrong times. This is believed to have been caused by problems with the state machine. Further testing would have been conducted to address these issues and optimize the controls; however, mechanical failure encountered during testing resulted in motor damage that prevented any further testing.

9. CONCLUSIONS

For this project, the team designed an exoskeleton capable of improving the gait efficiency of children with equinus gait deficiency. This was accomplished by defining the customer needs, researching the current exoskeleton devices, generating design concepts, and selecting a final concept based on technical analysis. Iterations of machining, assembly, and testing of the final design resulted in the final product.

9.1. Contributors to Project Success

This project was successful due to an interdisciplinary team composed of electrical and mechanical engineers. In addition, each team member contributed with design, manufacturing, and 3D printing experience. Each team member contributed their own technical analysis when necessary, in order to verify and support design decisions. These allowed the team to iterate and solve issues by designing component solutions and manufacturing or printing as quickly as possible.

9.2. Opportunities and Areas for Improvement

During testing and troubleshooting, improvements to the motor pulley were designed and tested. An initial aluminum pulley was found to be reliable, but machining of the pulley was also difficult. Due to this and some other issues with torque transfer from the motor, a pulley made of 3D printed material was designed and tested. Initial testing was successful but the set screw within the pulley failed, and damaged the motor shafts. An improved aluminum motor pulley design is recommended. This design includes a machined D-hole to assist in efficient torque transfer, and provide the most reliable attachment with a lesser probability of motor shaft failure. Additional improvements include redesign of the footplate hinge and shaft. Improvements to the hinge are required as it is the next highest potential failure observed during testing. Further improvements should also be made to the control scheme.

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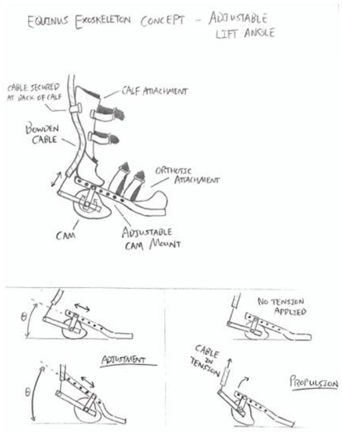
11. APPENDICES

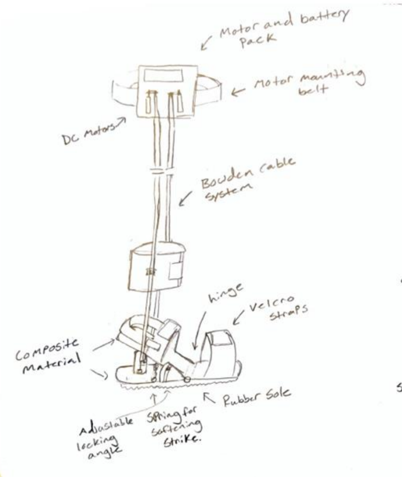
11.1. Appendix A: House of Quality

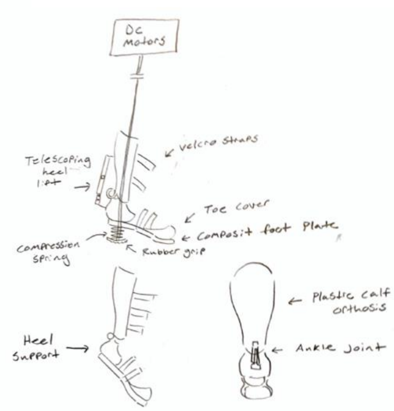
		Increase actuated ankle motion (degrees)	Increase ankle adjustment (degrees	Light weight (kg)	Increase number of mode attachments (#)	Increase propulsion provided: device to ground (Newtons)	Increase Sensor accuracy (%)	Increase Run time (hours)	Use Bowden cables (*)	Battery Supply (W)	Increase foot size range (in)	Increase torque transfer from cable(N-m)	Lower density of material (kg/m^3)	Increase Elasticity (N/m)
Increase actuated ankle motion (degrees)														
Increase ankle adjustment (degrees)														
Light weight (kg)														
Increase number of mode attachments (#)				-3										
Increase propulsion provided device to ground (N)		3												
Increase Sensor accuracy (%)														
Increase Run time (hours)				3		-3								
Use Bowden cables (*)				-3										
Battery Supply (W)								3						
Increase foot size range (in)														
Increase torque transfer from cable(N-m)									3					
Lower density of material (kg/m^3)				9										
Increase Elasticity (N/m)														

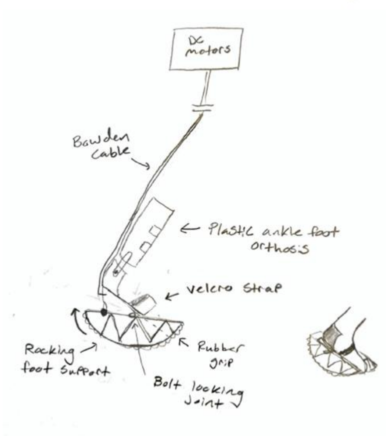
		Technical Requirements												
Customer Needs	Customer Weights	Increase actuated ankle motion (degrees)	Increase ankle adjustment (degrees	Light weight (kg)	Increase number of mode attachments (#)	Increase propulsion provided: device to ground (Newtons)	Increase Sensor accuracy (%)	Increase Run time (hours)	Use Bowden cables (*)	Battery Supply (W)	Increase foot size range (in)	Increase torque transfer from cable(N-m)	Lower density of material (kg/m^3)	Increase Elasticity (N/m)
Bowden cable system	4					3			9					
Attachment to calf	2				6									
Interface with the foot	4	1	1		3						3			
Scalable for foot sizes	2				1						9			
Adjustable for different severity levels	2	9	9		1							3		
Easy on/off	3				6		9							
Uses a torque sensor	4	3	3			1						6		
Uniform weight distribution on bottom of foot	4					3					3			
Soft interaction between the foot and the floor	4													3
Light weight	2			9									9	
Sense force	4	3	3			1	9					1		3
Works on children ages 5-12	3					9						1		
Safe	5	6			3			1						3
Reasonable run time	1			3		1		9		9			1	
Technical Requirement Units		Degrees	Degrees	Kg	#	Newtons	Percent	Hours	N/A	W	in	N-m	kg/m^3	N/m
Technical Requirement Targets		25-30	0-30	0.5		10-15	10-20	2				15-Oct		
Absolute Technical Importance		76	46	21	61	60	63	14	36	9	42	37	19	39
Relative Technical Importance		1	5	10	4	3	2	12	9	13	6	8	11	7

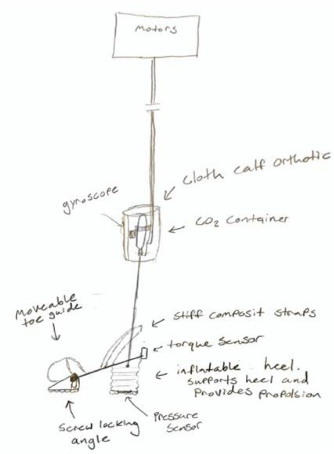
11.2. Appendix B: Design Concepts

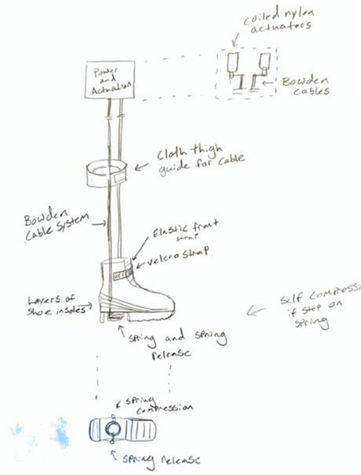


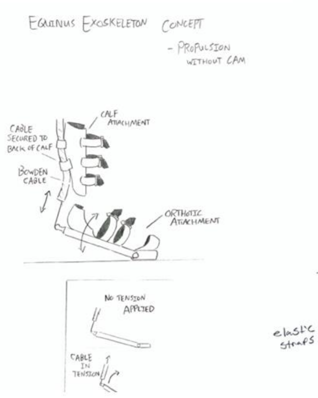


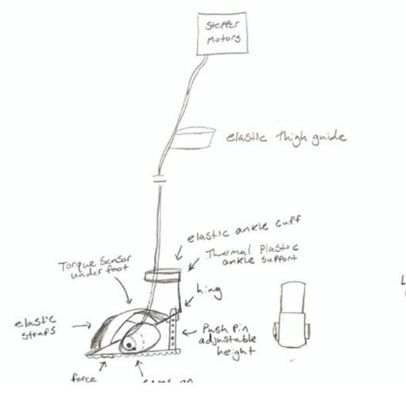


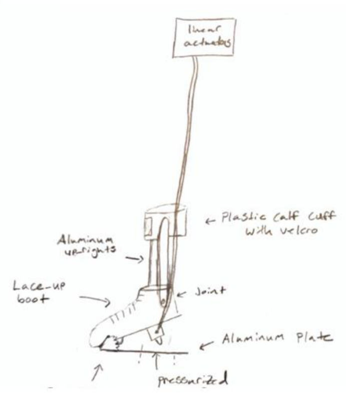


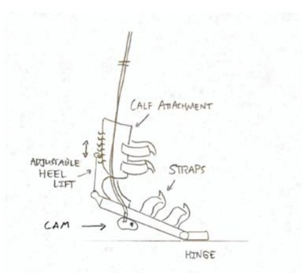




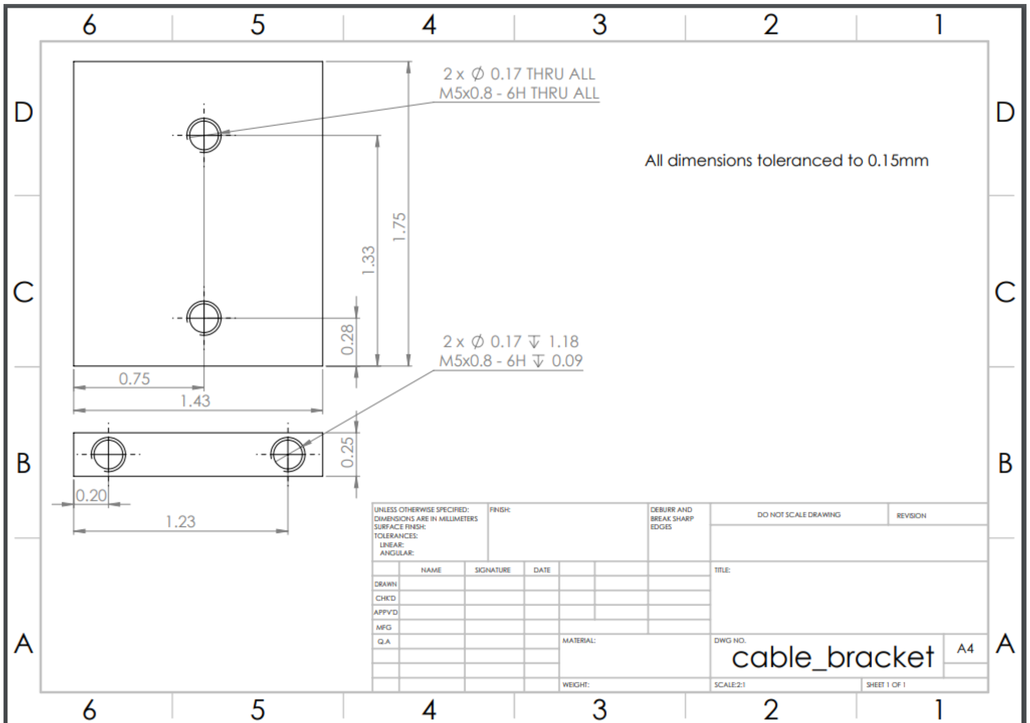


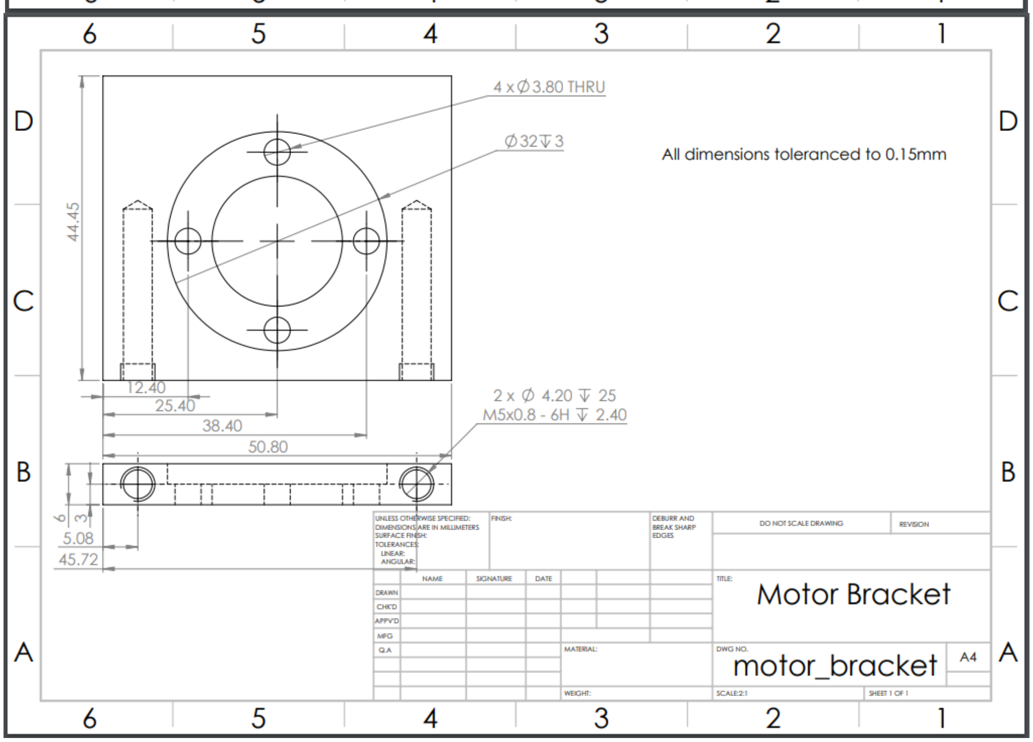


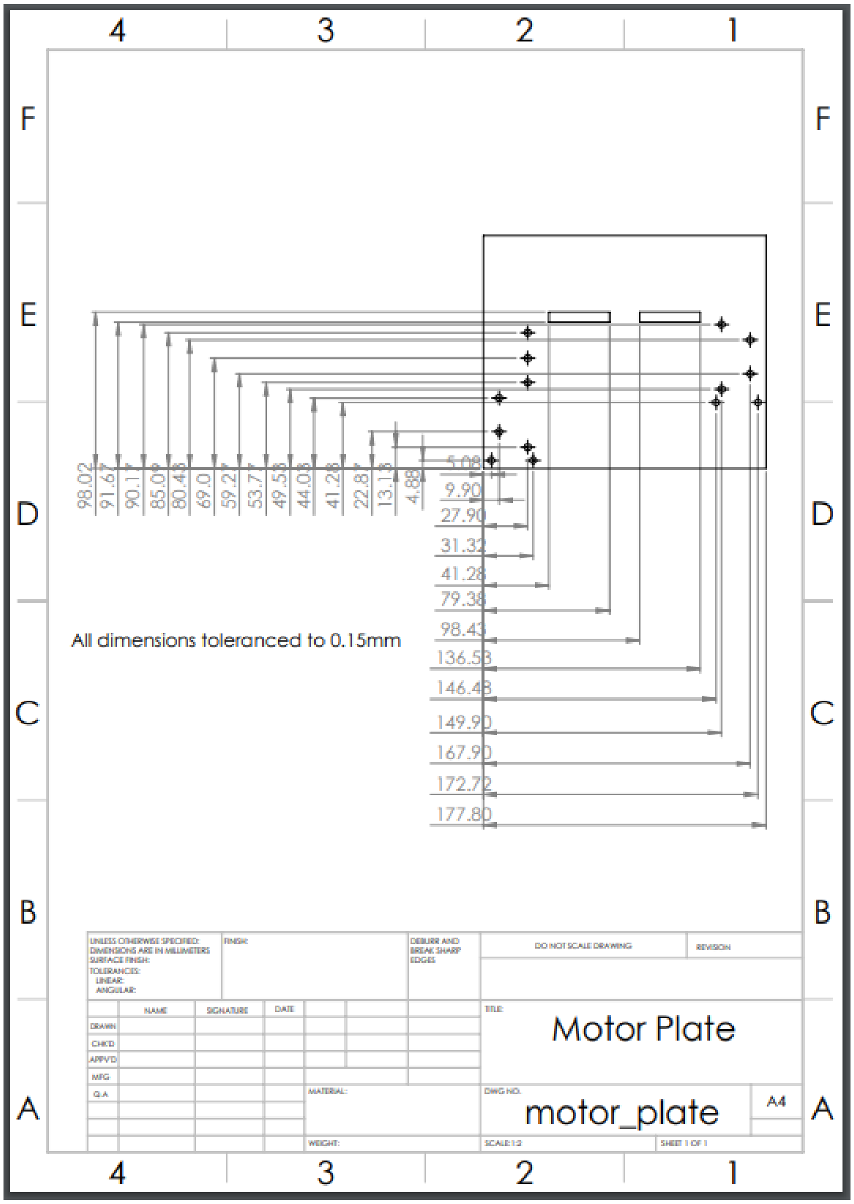


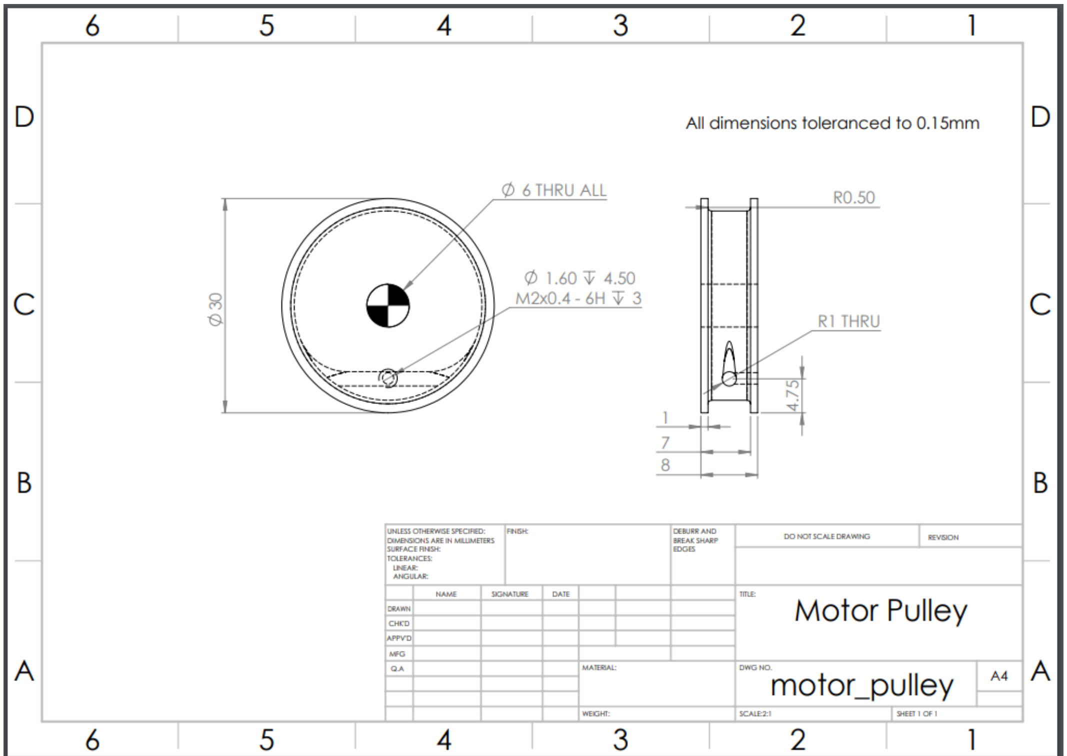


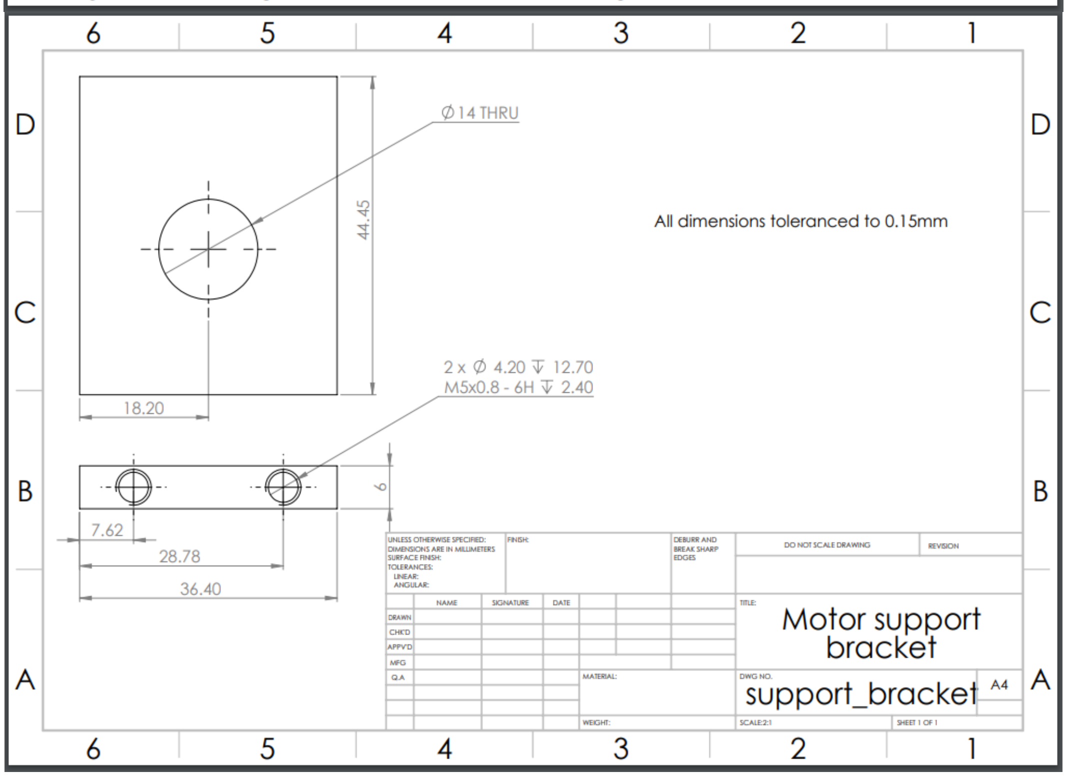
11.3. Appendix C: Dimensioned Drawings

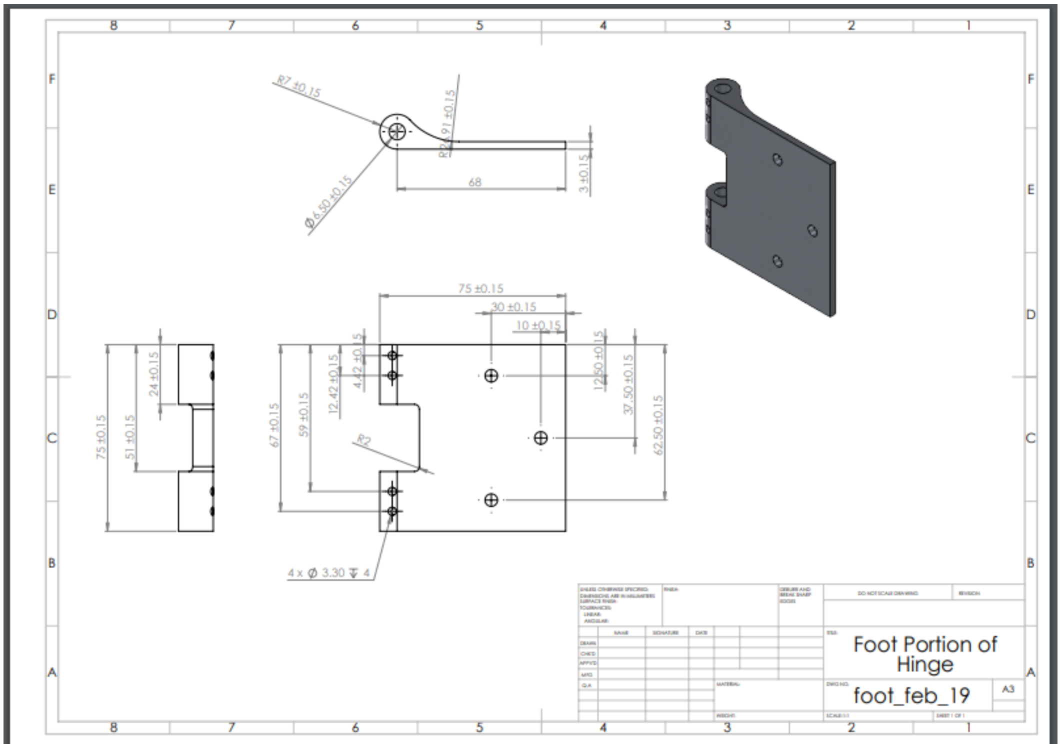


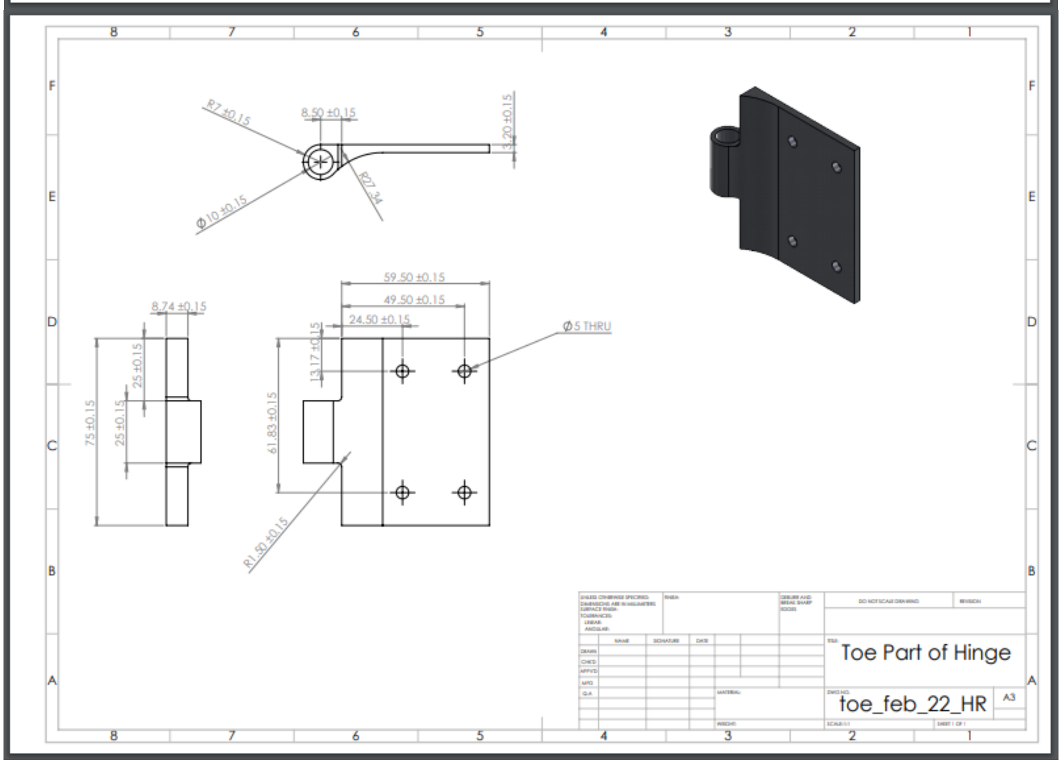


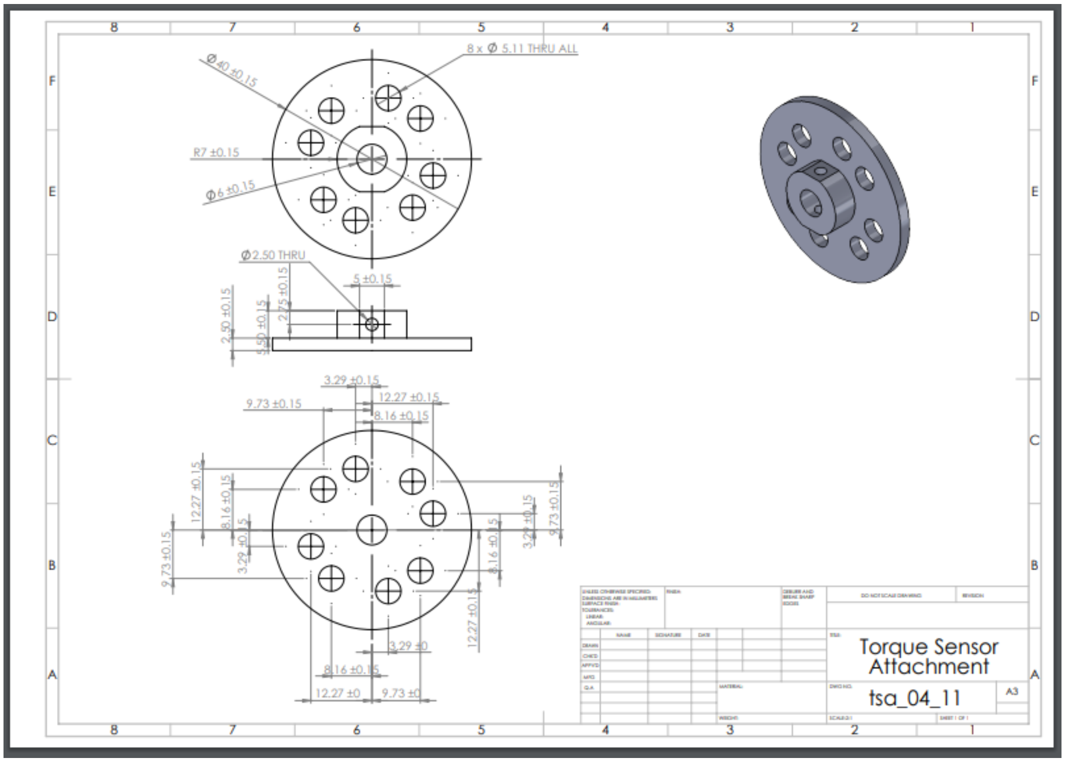

98.02
91.67
90.17
85.09
80.43
69.0
59.27
53.77
49.53
44.03
41.28
22.87
13.13
4.88
5.08
9.90
27.90
31.32
41.28
79.38
98.43
136.53
146.43
149.90
167.90
172.72
177.80
All dimensions toleranced to 0.15mm
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN MILLIMETERS
SURFACE FINISH:
TOLERANCES:
LINEAR:
ANGULAR:
FINISH:
DEBURR AND BREAK SHARP EDGES
DO NOT SCALE DRAWING
REVISION
NAME
SIGNATURE
DATE
DRAWN
CHK'D
APPV'D
MFG
Q.A
MATERIAL:
WEIGHT:
TITLE:
Motor Plate
DWG NO.
motor_plate
A4
SCALE:1:2
SHEET 1 OF 1

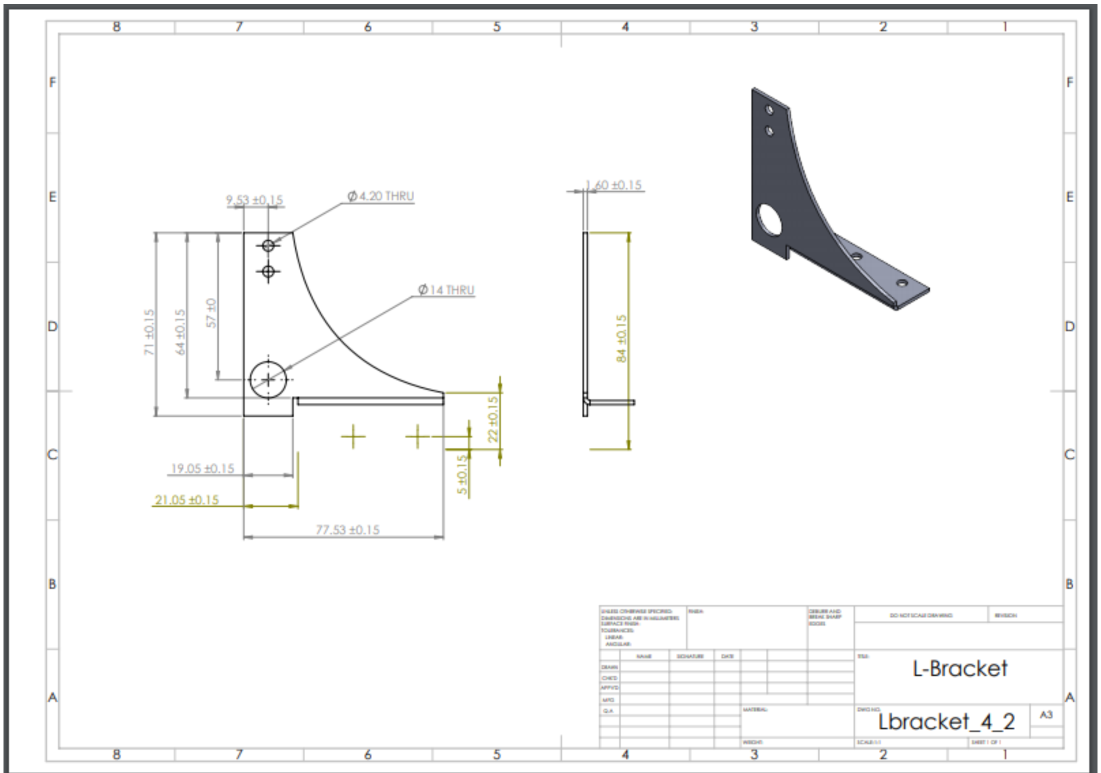

All dimensions toleranced to 0.15mm
Ø 6 THRU ALL
Ø 1.60 ↧ 4.50
M2x0.4 - 6H ↧ 3
Ø 30
R0.50
R1 THRU
4.75
1
7
8
Motor Pulley
motor_pulley
A4
SCALE:2:1
SHEET 1 OF 1

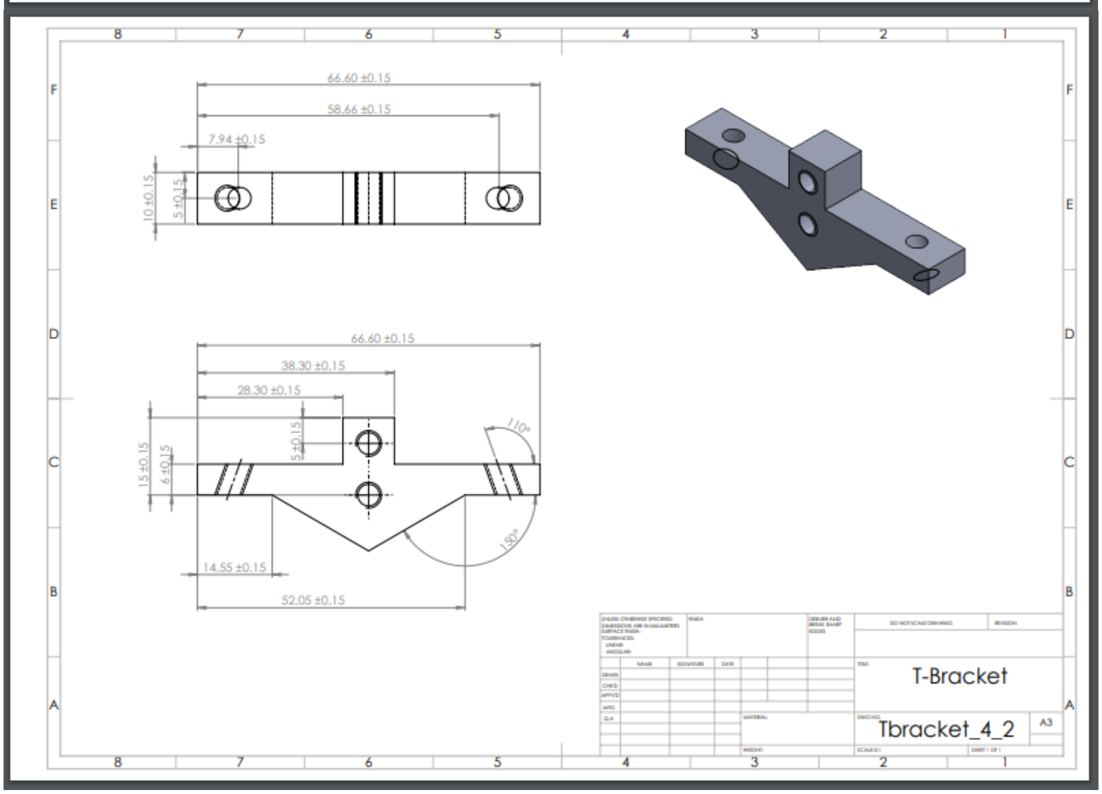

Ø 14 THRU
44.45
All dimensions toleranced to 0.15mm
2 x Ø 4.20 ↧ 12.70
M5x0.8 - 6H ↧ 2.40
18.20
6
7.62
28.78
36.40
Motor support bracket
support_bracket
A4
SCALE:2:1
SHEET 1 OF 1


R7 ±0.15
R23.91 ±0.15
Ø 6.50 ±0.15
68
3 ±0.15
75 ±0.15
30 ±0.15
10 ±0.15
24 ±0.15
75 ±0.15
51 ±0.15
67 ±0.15
59 ±0.15
12.42 ±0.15
4.42 ±0.15
R2
12.50 ±0.15
37.50 ±0.15
62.50 ±0.15
4 x Ø 3.30 ↧ 4
Foot Portion of Hinge
foot_feb_19
A3


R7 ±0.15
8.50 ±0.15
3.20 ±0.15
Ø 10 ±0.15
R27.34
59.50 ±0.15
49.50 ±0.15
24.50 ±0.15
8.74 ±0.15
Ø 5 THRU
25 ±0.15
75 ±0.15
25 ±0.15
13.17 ±0.15
61.83 ±0.15
R1.50 ±0.15
Toe Part of Hinge
toe_feb_22_HR
A3


8 x Ø 5.11 THRU ALL
Ø40 ±0.15
R7 ±0.15
Ø6 ±0.15
Ø2.50 THRU
5 ±0.15
2.50 ±0.15
2.75 ±0.15
5.50 ±0.15
3.29 ±0.15
12.27 ±0.15
9.73 ±0.15
8.16 ±0.15
Torque Sensor
Attachment
tsa_04_11
A3


9.53 ±0.15
Ø 4.20 THRU
Ø 14 THRU
71 ±0.15
64 ±0.15
57 ±0
1.60 ±0.15
84 ±0.15
22 ±0.15
5 ±0.15
19.05 ±0.15
21.05 ±0.15
77.53 ±0.15
L-Bracket
Lbracket_4_2
A3


66.60 ±0.15
58.66 ±0.15
7.94 ±0.15
10 ±0.15
5 ±0.15
38.30 ±0.15
28.30 ±0.15
5 ±0.15
15 ±0.15
6 ±0.15
110°
150°
14.55 ±0.15
52.05 ±0.15
T-Bracket
Tbracket_4_2
A3

11.4. Appendix D: Bill of Materials

Bill of Materials

Ankle Exsoskeloton Parts List

Part #	Part Name	Qty	Description	Material	Cost	Total Cost	Link to Cost estimate
1	Toe Hinge	1	Toe part of hinge	Aluminum 6061	$250.00	$250.00	https://www.cefns.nau.edu/Groups/fabricationShop/documents/work_orders_03_2018.pdf
2	Foot Hinge	1	Foot part of hinge	Aluminum 6061	$250.00	$250.00	https://www.cefns.nau.edu/Groups/fabricationShop/documents/work_orders_03_2018.pdf
3	Bearings	3	Flanged ball bearings	Steel	$3.75	$11.25	http://www.modernroboticsinc.com/1601-series-14mm-od-bearings-2-pack
4	D-Shaft	1	D-shaft	Stainless Steel	$2.80	$2.80	http://www.modernroboticsinc.com/6mm-d-shaft
5	Foot Pulley	1	Large pulley at the foot	Aluminum 6061	$300.00	$300.00	https://www.cefns.nau.edu/Groups/fabricationShop/documents/work_orders_03_2018.pdf
6	Torque Sensor	1	Torque Sensor	NA	$675.00	$675.00	https://www.transducertechniques.com/trt-torque-sensor.aspx
7	Torque Sesor Cable	1	Connecting cable	NA	$75.00	$75.00	https://www.transducertechniques.com/trt-torque-sensor.aspx
8	Torque Sensor Attachment	1	Attaches torque sensor to D shaft	ABS	$100.00	$100.00	https://www.cefns.nau.edu/Groups/fabricationShop/documents/work_orders_03_2018.pdf
9	Potentiometer	1	Measures joint rotation	NA	$11.00	$11.00	https://www.tme.eu/en/details/534-10k/wire-%20multitum-potentiometers/vishay/534b1103jcb/?brutto=1&gclid=Cj0KCQjAp8fSBRCUARIsABPL6JY1ZvbeKVJLbqu25-ewxpWL5Ynb_omIBnjj8GyqIFH-3qLuKGL_N6UaAgujEALw_wcB
10	Potentiometer Mount	1	Mounts the potentiometer	ABS	$10.00	$10.00	http://library.nau.edu/services/makerlab/submitjob.html
11	Potentiometer Gear	1	Connects to the potentiometer	ABS	$10.00	$10.00	http://library.nau.edu/services/makerlab/submitjob.html
12	Torque Sensor Gear	1	Gear over the torque sensor	ABS	$12.00	$12.00	http://library.nau.edu/services/makerlab/submitjob.html
13	L-Bracket	1	Bracket that holds the T-bracket	Aluminum 6061	$50.00	$50.00	https://www.cefns.nau.edu/Groups/fabricationShop/documents/work_orders_03_2018.pdf
14	T-Bracket	1	Bracket that holds the barrel adjusters	Aluminum 6061	$100.00	$100.00	https://www.cefns.nau.edu/Groups/fabricationShop/documents/work_orders_03_2018.pdf
15	Foot Plate	1	Main support plate for the foot	Aluminum 6061	$10.00	$10.00	https://www.cefns.nau.edu/Groups/fabricationShop/documents/work_orders_03_2018.pdf
16	Plastic Heel	1	3D printed heel	ABS	$15.00	$15.00	http://library.nau.edu/services/makerlab/submitjob.html
17	Plastic Toe Support	1	Support that sits under the toe	ABS	$12.00	$12.00	http://library.nau.edu/services/makerlab/submitjob.html
18	Force Sensor	1	Force sensitive resistor under the heel	NA	$9.95	$9.95	https://www.sparkfun.com/products/9376
19	6 Wire Ribbon Cable	2	Connecting cable	NA	$5.90	$11.80	https://www.sparkfun.com/products/10646
20	10 Wire Ribbon Cable	1	Connecting Cable	NA	$4.95	$4.95	https://www.sparkfun.com/products/10647
21	Cable Anchor bolts	1	Bolts that clamp the ends of the cable	NA	$0.20	$0.20	http://library.nau.edu/services/makerlab/submitjob.html
22	M4 Set Screws	6	Set screws for motor and D-shaft	NA	$0.15	$0.90	https://www.amazon.com/gp/product/B01N76NKU6/ref=ox_sc_act_title_6?smid=A1THAZDOWP300U&amp&psc=1
23	10-24x3/16" Screws	8	Screws for the troque sensor	NA	$0.10	$0.80	https://www.amazon.com/Team-Associated-9146-2-56-Screws/dp/B0006O3DZY/ref=sr_1_10?s=toys-and-games&ie=UTF8&qid=1525125820&sr=1-10&keywords=3%2F16+in+screws
24	M5X12mm Screws	6	Screws that connect the foot plate and T-Bracket	NA	$0.15	$0.90	https://www.amazon.com/gp/product/B01C3LHM5G/ref=ox_sc_act_title_7?smid=A1THAZDOWP300U&amp&psc=1
25	M5X16mm Screws	3	Screws for the toe support and potentiometer	NA	$0.26	$0.78	https://www.amazon.com/uxcell-M5x16mm-Button-Socket-100pcs/dp/B01B1PJTSQ/ref=sr_1_6?s=hi&ie=UTF8&qid=1525123854&sr=1-6&keywords=M5x16mm
26	Barrel Adjusters	4	Holds the cable ends	NA	$0.16	$0.64	https://www.amazon.com/IDS-Brake-Lever-Adjustable-Barrels/dp/B0775B83T7/ref=sr_1_sc_2?ie=UTF8&qid=1525124040&sr=8-2-spell&keywords=bvarrel+adjusters
27	M5 Nuts	8	Nuts for the toe support and foot plate	NA	$0.11	$0.88	https://www.amazon.com/gp/product/B012T3C8YQ/ref=ox_sc_act_title_3?smid=A1THAZDOWP300U&amp&psc=1
28	Bowden Cable	1	Cables	NA	$10.55	$10.55	https://www.amazon.com/Shimano-Universal-Standard-Brake-Cable/dp/B0050LUBZ8/ref=sr_1_cc_1?s=aps&ie=UTF8&qid=1525059874&sr=1-1-catcorr&keywords=shimano+bike+cables
29	Cable Ends	4	Conects to the end of the cable housing	NA	$0.17	$0.68	https://www.amazon.com/IDS-Brake-Lever-Adjustable-Barrels/dp/B0775B83T7/ref=sr_1_sc_2?ie=UTF8&qid=1525124040&sr=8-2-spell&keywords=bvarrel+adjusters
30	Cable Bracket	1	Holds the cable by the motor	Aluminum 6061	$100.00	$100.00	https://www.cefns.nau.edu/Groups/fabricationShop/documents/work_orders_03_2018.pdf
31	Motor Bracket	1	Holds the motor	Aluminum 6061	$50.00	$50.00	https://www.cefns.nau.edu/Groups/fabricationShop/documents/work_orders_03_2018.pdf
32	Motor Pulley	1	Connects to the motor shaft and the cables	Aluminum 6061	$100.00	$100.00	https://www.cefns.nau.edu/Groups/fabricationShop/documents/work_orders_03_2018.pdf
33	M2 Set Screw	1	Holds the cable in the motor pulley	NA	$0.24	$0.24	https://www.mcmaster.com/#catalog/92605A042
34	Motor Plate	1	Mounts all of the motor parts and controls	Aluminum 6061	$10.00	$10.00	https://www.mcmaster.com/#catalog/89015K256
35	Motor Shaft Support	1	Supports the end of the motor shaft	Aluminum 6061	$100.00	$100.00	https://www.cefns.nau.edu/Groups/fabricationShop/documents/work_orders_03_2018.pdf
36	Control Plate	1	Mounts the PCB board	ABS	$15.00	$15.00	http://library.nau.edu/services/makerlab/submitjob.html
37	PCB	1	Central control board	NA	$75.70	$75.70	https://www.maxonmotorusa.com/maxon/view/product/control/Positionierung/EPOS-4/504384?etcc_cu=onsite&etcc_med=Header%20Suche&etcc_cmp=mit%20Ergebnis&etcc_cty=Layer&query=504384
38	Teensy 3.6	1	Teensy that is connected to the control baord	NA	$29.25	$29.25	https://www.pjrc.com/store/teensy36.html
39	Bluetooth	1	Provides wireless conection to the controls	NA	$24.95	$24.95	https://www.sparkfun.com/products/12577
40	Motor Sheild	1	Motor control board	NA	$167.90	$167.90	https://www.maxonmotor.com/maxon/view/catalog?etcc_med=Navigator&etcc_cmp=Online-Shop&etcc_cu=onsite&etcc_var=%5bcom%5d%23en%23_d_&etcc_plc=NewsDetailPage
41	Motor	1	Maxon motor and gearbox	NA	$976.00	$976.00	https://www.maxonmotorusa.com/maxon/view/product/gear/planetary/gp32/166945
42	Switches	2	For Battery And Motor Connections	NA	$1.00	$2.00	https://www.sparkfun.com/products/11138
43	Battery	1	12V battery	NA	$55.76	$55.76	https://hobbyking.com/en_us/turnigy-battery-4000mah-6s-30c-lipo-pack-xt-60.html
44	Battery Connector	1	Connecting connector	NA	$0.95	$0.95	https://www.sparkfun.com/products/11864
45	Velcro Straps	1	Used to secure the battery and the foot	NA	$7.92	$7.92	https://www.amazon.com/VELCRO-1804-OW-PB-Onewrap-Velcro-Length/dp/B00I0TTPL8/ref=sr_1_8?ie=UTF8&qid=1525059195&sr=8-8&keywords=velcro+strap
46	Amplifier	1	To Amplify the Torque Sensor Signal	NA	$6.95	$6.95	https://www.mouser.com/ProductDetail/Texas-Instruments/INA125P?qs=sGAEpiMZZMsE1dKaA2ImUPh%2fgv48%2feoePbaebgHtKUQ%3d
Total Cost Estimate:						$3,659.70	